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Predicting the potential distribution of the subalpine broad-leaved tree species, *Betula ermanii* Cham. under climate change in South Korea

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Subalpine and alpine ecosystems are especially vulnerable to temperature increases. *Betula ermanii* Cham. (Betulaceae) is a dominant broad-leaved tree species in the subalpine zone and is designated as a 'Climate-sensitive Biological Indicator Species' in South Korea. This study aimed to predict the potential distribution of *B. ermanii* under current and future climate conditions in South Korea using the MaxEnt model. The species distribution models showed an excellent fit (AUC = 0.99). Among the climatic variables, the most critical factors shaping *B. ermanii* distribution were identified as the maximum temperature of warmest month (Bio5; 64.8%) and annual mean temperature (Bio1; 20.3%). Current potential habitats were predicted in the Baekdudaegan mountain range and Mt. Hallasan, and the area of suitable habitat was 1531.52 km^2, covering 1.57% of the Korean Peninsula. With global warming, future climate scenarios have predicted a decrease in the suitable habitats for *B. ermanii*. Under RCP8.5-2070s, in particular, habitat with high potential was predicted only in several small areas in Gangwon-do, and the total area suitable for the species decreased by up to 97.3% compared to the current range. We conclude that the dominant factor affecting the distribution of *B. ermanii* is temperature and that future temperature rises will increase the vulnerability of this species.

Keywords: *Betula ermanii*, climate change, habitat suitability, species distribution models, subalpine zone

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INTRODUCTION

Global mean temperature has risen by approximately 0.85°C over the last 130 years, and is likely to increase by 1.9–5.2°C depending on the level of greenhouse gas emissions until the end of the 21st century (National Institute of Meteorological Sciences, 2019). Species faced with climate change are responding in several different ways (e.g., geological range changes and phenological shifts) through species-specific physiological thresholds of temperature and precipitation tolerance (Walther *et al.*, 2002; Cahill *et al.*, 2014). In some cases, species that fail to adapt to the new climate regimes may go extinct (Wiens, 2016). The rate of future warming is likely to be faster (Loarie *et al.*, 2009), exceeding the adaptability of species and leading to biodiversity decreases (Dawson *et al.*, 2011; Richman *et al.*, 2020).

Subalpine and alpine ecosystems represent one of the most vulnerable regions due to climate change (Conlisk *et al.*, 2017; Adhikari *et al.*, 2018). With general warming trends, to the extent that dispersal and resource availability allow, plant species are expected to shift toward higher latitudes and elevations (Parmesan and Yohe, 2003; Chen *et al.*, 2011). Walther (2003) reported that the tree-line position had shifted upward by around 130 m (min. 5 m to max. 375 m) over the past 50 years. Plants in the subalpine zone must survive by shifting upward to habitats with suitable climatic conditions, but species or populations already distributed at the mountain peak no longer have a niche (Wiens, 2016; Shin *et al.*, 2021). In addition, the rate of warming is amplified with elevation so that high-mountain environments experience more rapid changes in temperature than environments at lower elevations (Mountain Research Initiative EDW Working Group, 2015). These trends in high-mountain climates increase the vulnerability of subalpine plants with limited distributions in the subalpine zone.

Betula ermanii Cham. (Betulaceae) is a dominant broad-leaved tree species of the subarctic and subalpine treeline ecotones in East Asia, and occurs in Korea, northeastern China, Japan, and Pacific Russia (Gansert *et al*., 2002; Shaw *et al*., 2014). In South Korea, this is a representative species of the subalpine zone of the Baekdudaegan mountain range and Mt. Hallasan (Kong *et al*., 2017; Shin *et al*., 2021). The average temperature in South Korea has risen 1.8°C over the past 100 years, exceeding the global average rate (National Institute of Meteorological Sciences, 2019). Elevation-dependent warming has also appeared; for example, the annual mean temperature of Mt. Banyabong (1732 m) increased by approximately 2.8°C in 2018 compared to 2012, while that of the lowland (Namwon-si) rose about 1.1°C (Korea National Park Research Institute, 2019). In South Korea, studies on the vulnerability of the subalpine plant species associated with climate change have made forecasts for coniferous species such as *Abies*, *Picea*, and *Pinus* (Park *et al*., 2014; Koo *et al*., 2017; Choi and Lee, 2018), while broad-leaved tree species remained largely out of focus. However, climate change may be considered a potential risk for broad-leaved tree species in subalpine zones that experience harsh environmental conditions; for example, rising temperatures has caused mass death of populations of *Fagus* spp. and *Populus* spp. (Geßler *et al*., 2007; Worrall *et al*., 2013).

Understanding the relationship between the species' distribution and environmental characteristics makes it possible to predict ecological responses to future climate change (Franklin, 2013). Species distribution models (SDMs) are based on the statistical association of species presence on the study sites with mapped environmental variables and can identify climatic controls for target species, as well as potential or vulnerable habitats under various climate change scenarios focused in the past, present, or future (Pearson and Dawson, 2003; Elith *et al*., 2006). SDMs can provide the conservation measures (e.g., assisted colonization) for target species (Villero *et al*., 2017). In Europe, *Betula* species are considered to be indicator species for climate-driven treeline dynamics and have thus become a target of studies on SDMs (Bobrowski *et al*., 2017). *Betula ermanii* has been designated as a South Korean 'Climate-sensitive Biological Indicator Species (CBIS)' (National Institute Biological Resources, 2010). Nevertheless, only a few studies of the potential impact of climate change on the geographical range of this species have been conducted. Therefore, there is a need for studies to evaluate the relationship between the current occurrence of *B*. *ermanii* and the environmental variables on those sites and to predict future changes in distribution range.

This study was conducted to predict potential distribution for *B*. *ermanii* under current and future climate conditions in South Korea using the MaxEnt model. The objectives of this study were: 1) to evaluate the influence of environmental factors on its suitable distribution; 2) to predict its potential distribution under current and future climate scenarios; 3) to evaluate changes in the area of suitable habitat. Our results could provide a reasonable basis for the assessment of habitat suitability and distribution range associated with climate change and assist with conservation and management planning for broad-leaved tree species in the subalpine zone.

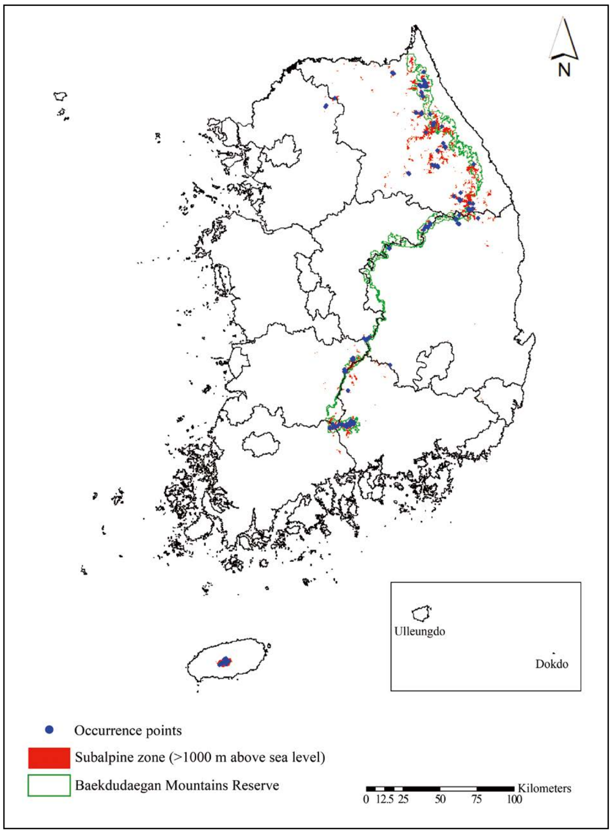

Fig. 1. The location of occurrence points of *Betula ermanii* in South Korea ($N = 162$).

Materials and Methods

Occurrence data collection

Presence-only occurrence data of *B*. *ermanii* were collected from the National Institute of Biological Resources Herbarium (https://species.nibr.go.kr/), the National Ecosystem Survey (http://library.me.go.kr/index.ax), and literature (Park, 2016) and field surveys (see Shin *et al*., 2021). Datasets derived from opportunistic observations or museum records rather than from planned surveys often exhibit a strong geographic bias and can lead to in-

Table 1. Bioclimatic variables used in the study and their percent contribution and permutation importance in predicting the potential distribution of *Betula ermanii*. The most important variables are highlighted in bold.

Variable code	Description (Unit)	Percent contribution (%)	Permutation importance (%)
Bio1	**Annual mean temperature (°C)**	**20.3**	**37.8**
Bio2	Annual mean diurnal range (°C)	1.2	1.1
Bio3	Isothermality {(Bio2/Bio7) × 100} (%)	2.3	4.7
Bio5	**Max temperature of warmest month (°C)**	**64.8**	**42.2**
Bio7	Annual temperature range (Bio5 - Bio6*) (°C)	3.9	3.5
Bio12	Annual precipitation (mm)	3.3	1.8
Bio13	Precipitation of wettest month (mm)	1.1	7.1
Bio14	Precipitation of driest month (mm)	1.6	1.5
Bio15	Precipitation seasonality (%)	0.6	0.1
Bio16	Precipitation of wettest quarter (mm)	0.9	0.2

Bio6: the minimum temperature of coldest month.

correct predictions (Fourcade *et al.*, 2014). To correct for sampling bias in the occurrence datasets of *B. ermanii*, we created a grid of a defined cell size (30 arc-seconds consistent with the resolution of climate data) and randomly sampled one occurrence per grid cell using ArcToolBox in Arc GIS 10.4.1 (Esri, Redlands, CA, USA). In total, 162 occurrence points of *B. ermanii* were used in modeling analysis (Fig. 1).

Environmental variables

Nineteen bioclimatic variables (Fick and Hijmans, 2017) for the current climate conditions were downloaded from the WorldClim dataset (version 2.1) (http://www.worldclim.org). These variables were recorded between 1970 and 2000 and represent annual trends (e.g., mean annual temperature and precipitation), seasonality (annual range in temperatures and precipitation), and extreme or limiting environmental factors (temperature of the coldest and warmest month, and precipitation in the wet and dry quarters). Many of the bioclimatic variables are spatially correlated and these can result in model over-fitting when simulating a species' potential distribution (Cook and Ranstam, 2016). To reduce multi-collinearity among these variables, highly correlated variables (Pearson's correlation coefficient $r > |0.90|$) were excluded from the modeling process. Ultimately, we used 10 bioclimatic variables (Bio1, 2, 3, 5, 7, 12, 13, 14, 15 and 16) in this study (Table 1).

According to the Fifth Assessment Report (AR5) redacted by the IPCC (Intergovernmental Panel on Climate Change), four Representative Concentration Pathways (RCPs) are agreed upon as scenarios of future emissions of greenhouse gases ranging low to high (RCPs 2.6, 4.5, 6.0 and 8.5) (IPCC, 2014). To predict the potential distribution of *B. ermanii* under future climate condition, data for RCP4.5 (Medium: Wm^{-2}, ~650 ppm CO_2) and RCP8.5 (High: 8.5 Wm^{-2}, 1370 ppm CO_2) climate scenarios (Vuuren *et al.*, 2011) in the 2050s (average for 2041–2060) and 2070s (average for 2061–2080) were selected from the Hadley Global Environment Model 2-Atmosphere Ocean (HADGEM2-AO: http://www.worldclim.org/). In our study, all climatic data had a spatial resolution of 30 arc-seconds (approx. 853 m at the Korean Peninsula).

Species distribution modeling

In our study, MaxEnt software v. 3.4.1 (www.cs.princeton.edu/*schapire/maxent/) was used to predict the potential distribution of *B. ermanii* in South Korea. Among many techniques for SDMs, the principle of maximum entropy algorithm (MaxEnt) has proved powerful when using small sample sizes and presence-only records (e.g., Elith *et al.*, 2011; Phillips *et al.*, 2017). We performed 10 random runs and selected 70% of the data for model training and 30% for model testing, keeping other values as defaults.

Model performance was evaluated with the area under the curve (AUC) values of the receiver operating characteristics (ROC) curves (Lobo *et al.*, 2008; Merow *et al.*, 2013). Area under the curve is a widely used statistic for the measurement of MaxEnt performance. The AUC values below 0.7 were considered poor, values between 0.7 and 0.8 were fair, values between 0.8 and 0.9 were good, and above 0.9 were considered excellent. The Jackknife procedure was used to assess the significance of these variables. The final potential species distribution map had a range of values from 0 to 1 which were reclassified into four categories of habitat suitability for *B. ermanii*: 'high potential' (>0.6), 'moderate potential' (0.4–0.6), and 'low potential' (0.2–0.4) and 'not potential' (<0.2). Additionally, the number of cells among the four classes of potential habitats was converted to surface area (km^2).

RESULTS

Model performance and key variables influencing the distribution

According to the obtained AUC (0.990 ± 0.002), the MaxEnt model had better performance than the random model (Fig. 2). The model output provided satisfactory results with both training and test data sets.

Among climatic variables, the maximum temperature of warmest month (Bio5) and the annual mean temperature (Bio1) had 85.1% contribution to the model (Table 1). The maximum temperature of warmest month (Bio5) explained 64.8% of the total variance and was thus identified as the main factor affecting the spatial distribution of *B. ermanii*. The Jackknife test also showed that *B. ermanii* distribution was largely affected by Bio 5 and Bio 1 (Fig. 3).

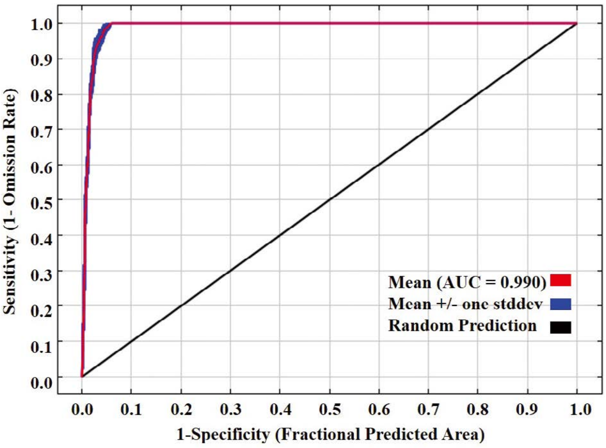

Fig. 2. ROC curve and AUC value in the current period (1970–2000).

Species response curves represent the relationship between the probability of *B. ermanii* occurrence and environmental variables. According to the obtained response curves for the largest contributing factors in the model, the maximum temperature of warmest month (Bio5) for *B. ermanii* occurrence ranged from 19.0–26.0°C, and the range of the annual mean temperature (Bio1) was 3.0–10.0°C (Fig. 4). In particular, *B. ermanii* preferred habitats with Bio5 below 23.0°C and Bio1 below 6.5°C (probability of presence > 0.6).

Potential distribution under current climatic conditions

The model showed that, based on current climate and occurrence data, the areas around the Baekdudaegan mountain range and Mt. Hallasan of Jeju-do have suitable environmental conditions for *B. ermanii* (Fig. 5A). Highly suitable habitats were appeared to occur in Mts. Seoraksan, Odaesan, Taebaeksan, Sobaeksan, Deogyusan, Jirisan, and Hallasan. Moderate and low suitable habitat occurred sporadically in Gangwon-do. Small parts of Gyeonggi-do (e.g., Mts. Hwaaksan and Myeongjisan) were also predicted to provide moderate or low potential habitat for *B. ermanii*. Jeollabuk-do (e.g., Mt. Unjangsan), where there was no record of the occurrence of *B. ermanii* in our analysis, was predicted to be a low potential habitat. The total range of potentially suitable habitat (>0.2) for *B. ermanii* was projected to be 1531.52 km^2, covering 1.57% of the Korean Peninsula (Table 2). The areas of high and moderate suitable habitat encompass 195.99 km^2 and 386.16 km^2, respectively.

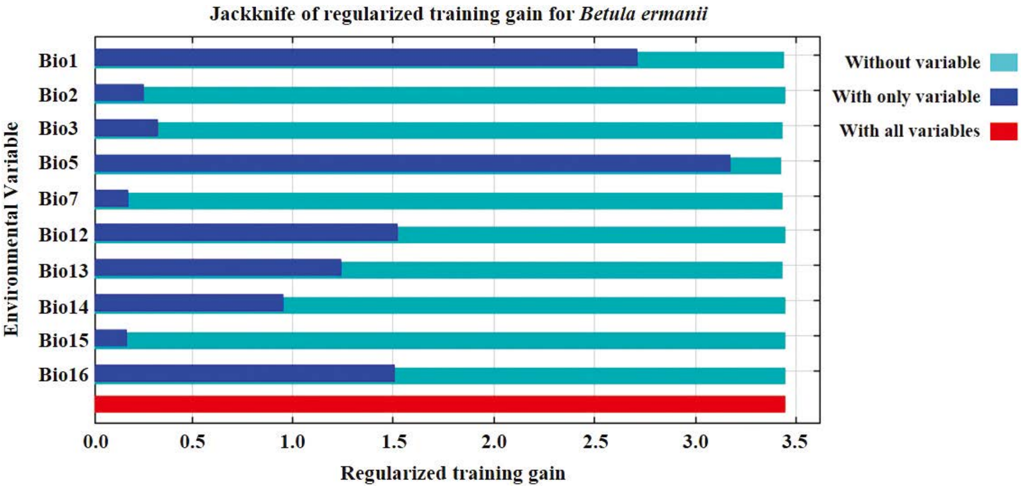

Fig. 3. The Jackknife test for evaluating the relative importance of environmental variables for *Betula ermanii* in South Korea.

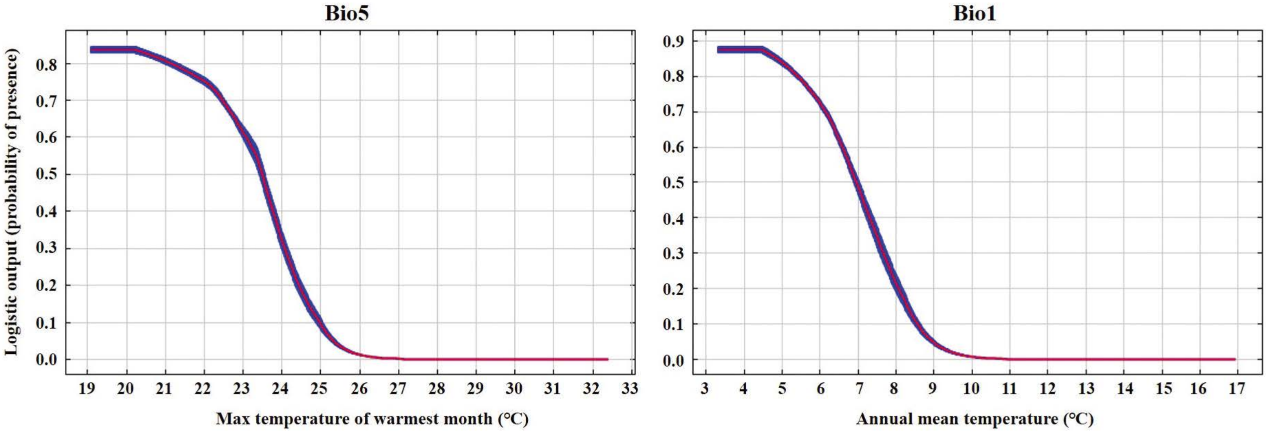

Fig. 4. The response curves for the two largest contributing variables for *Betula ermanii* under current climate conditions. Response curves indicate the correlation between the climatic variables and the probability of *B. ermanii* presence.

Table 2. Predicted suitable areas for *Betula ermanii* under current and future climate conditions in South Korea.

Habitat suitability classes	Area proportion (%)					Area (km^2)				
	Current	2050s		2070s		Current	2050s		2070s	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5		RCP4.5	RCP8.5	RCP4.5	RCP8.5
Not potential (<0.2)	98.43	99.12	99.21	99.30	99.96	96098.67	96768.99	96858.60	96947.49	97588.66
Low potential (0.2–0.4)	0.96	0.58	0.58	0.46	0.03	949.37	568.31	569.04	447.36	24.77
Moderate potential (0.4–0.6)	0.39	0.23	0.16	0.18	0.01	386.16	221.49	158.11	173.41	14.57
High potential (>0.6)	0.20	0.07	0.05	0.06	0	195.99	71.40	44.44	61.93	2.19

Future potential distribution under climate change scenarios

Under the RCP4.5-2050s scenario, the suitable habitat for *B. ermanii* was predicted to decrease compared with current conditions (Fig. 5B). In particular, the reduction in highly suitable habitats was significant in Mts. Deogyusan, Jirisan, and Hallasan in the southern region. The areas of potentially suitable habitat (>0.2) encompass 861.2 km^2, and around ca. 670.32 km^2 would be lost compared to the current habitat (Table 2). Compared with RCP4.5, in RCP8.5 (Fig. 5C), the suitable habitat was further reduced, and the suitable habitat for *B. ermanii* disappeared in Gyeonggi-do. Mt. Hallasan was no longer predicted to be a highly suitable habitat for *B. ermanii*. The area of potentially suitable habitat (>0.2) decreased to 771.59 km^2 (Table 2).

Under the RCP4.5-2070s scenario, it was predicted that the potential habitats in southern regions, including Mts. Jirisan, Deogyusan, and Hallasan, would decrease significantly (Fig. 5D). Mts. Sobaeksan and Deogyusan were only the low potential habitats for *B. ermanii*. The suitable habitat for *B. ermanii* (>0.2) occupied about 0.7% of the Korean Peninsula, amounting to 682.70 km^2 (Table 2). Under the RCP8.5 climate scenario (Fig. 5E), the potential habitats were predicted to be a few areas in Gangwon-do, Mt. Jirisan, and Mt. Hallasan. In addition, Mts. Sobaeksan and Deogyusan would become unsuitable habitat (not potential) for *B. ermanii*. The total range of potentially suitable habitat (>0.2) was predicted to be 41.53 km^2; among these, highly potentially suitable was predicted only for several small sites in Gangwon-do, with an area of 2.19 km^2 (Table 2).

DISCUSSION

This study revealed the potential vulnerability to climate change in the distribution range of *B. ermanii*, that only occur in subalpine ecosystems. Prediction of climate

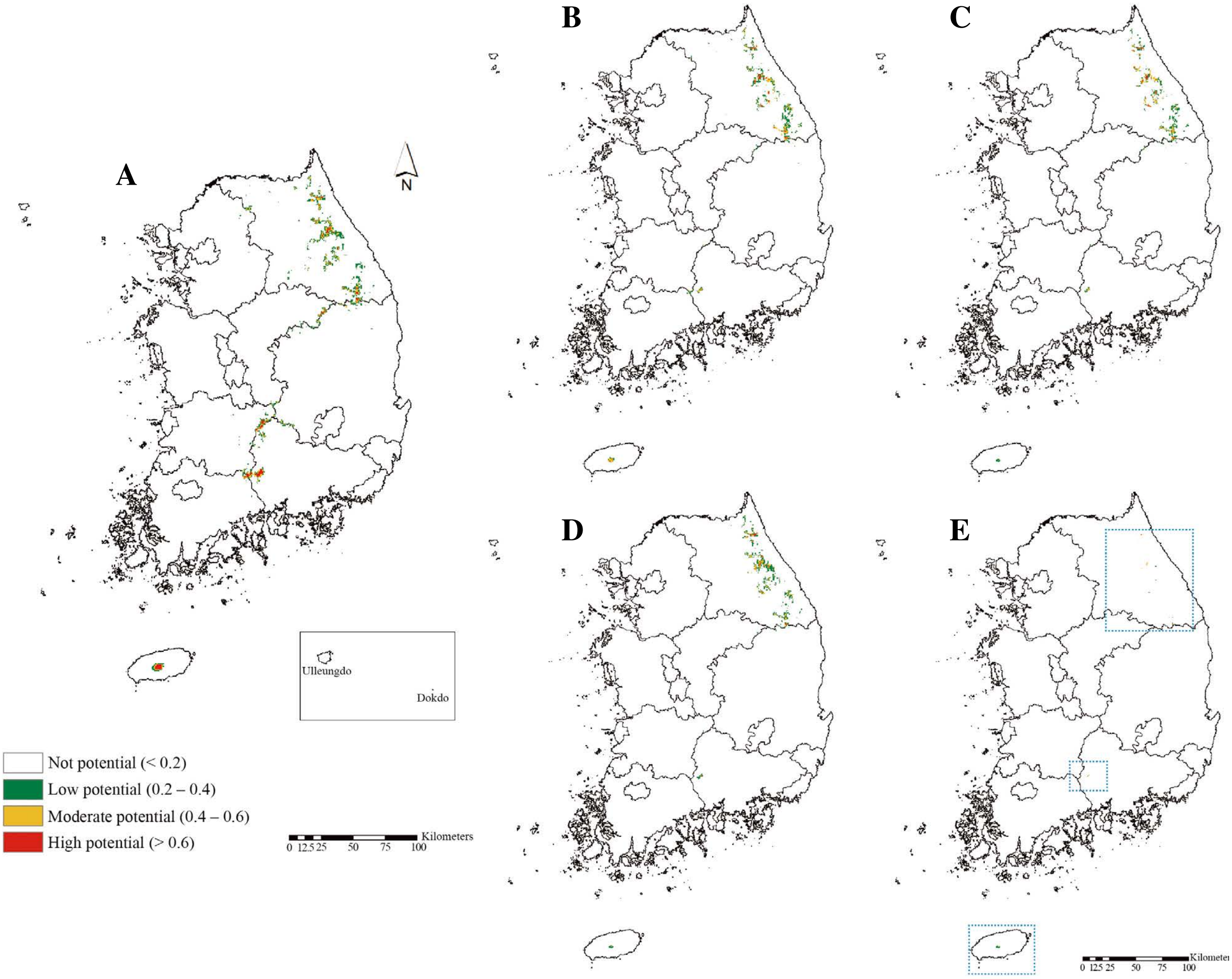

Fig. 5. The potential distribution of *Betula ermanii* under current and future climatic conditions (2050s and 2070s) based on RCPs4.5 and 8.5 scenarios. A. Current. B. 2050s-RCP4.5. C. 2050s-RCP8.5. D. 2070s-RCP4.5. E. 2070s-RCP8.5. Blue dotted lines indicate the locations of potential habitat.

change impacts on species distribution is required to reveal the potential ecological risks associated with environmental change, and it has become a primary research field to provide information for conservation and management planning (Sinclair *et al*., 2010; Booth, 2018). The MaxEnt model for *B. ermanii* showed an excellent fit with values of AUC (0.990 ± 0.002) as shown in Fig. 2 and was able to predict accurately the contribution of climatic variables and the locations of potentially suitable habitats for *B. ermanii*.

Our results revealed that two temperature-related variables (Bio1 and Bio5) were the major factors contributing to the current distribution of *B. ermanii* (Table 1, Fig. 3). In particular, the maximum temperature of warmest month (Bio5) explained 64.8% of the total variance and was thus identified as the main factor affecting the spatial distribution of *B. ermanii*, rather than precipitation. Adhikari *et al*. (2018) also reported that temperature was a dominant driving factor for subalpine species, and precipitation was a minor factor in a range of subalpine species. The annual mean temperature and maximum temperature of warmest month of South Korea during the current period (1970−2000) were 11.3°C and 28.0°C, respectively. The distribution probability of *B. ermanii* increased in areas with an annual mean temperature below 6.5°C and maximum temperature of warmest month (i.e., summer) below 23.0°C. Higher temperatures exceeding this range led to a decrease in the chance of this species occurring (Fig. 4). This indicates that temperature is an important limiting factor for the distribution of *B. ermanii*, and a cool temperature condition plays an important role.

Our study successfully modeled the distribution of *B. ermanii* and indicated that suitable habitats for the species will be negatively affected by climate warming in the

2050s and 2070s (Fig. 5B–E). The most obvious factor inducing degradation of populations or species is a temperature in excess of the physiological tolerance (Cahill *et al*., 2013). The temperature increase in South Korea is projected to be up to 0.63°C per decade by the 21st century (National Institute of Meteorological Sciences, 2019). In addition, the subtropical climate zone is predicted to expand to most of the Korean Peninsula, excluding some areas of the Baekdudaegan mountain range by 2100 (Park *et al*., 2013). These climatic conditions may induce a decline in species adapted to cool environments, and many studies have predicted that suitable habitats for subalpine species will decrease with increasing temperature (e.g., Park *et al*., 2014; Adhikari *et al*., 2018; Choi and Lee, 2018). The cold temperate climate zone in South Korea is a very small area covering only 1.7% of the peninsula (Korea National Arboretum, 2017). In our study, the current suitable habitat for *B. ermanii* was 1531.52 km^2, covering 1.57% of the peninsula (Table 2). *Betula ermanii* is already narrowly distributed in limited cool environments in South Korea. However, the future suitable habitats are projected to decrease continuously up to the 2050s and 2070s, and the decrease in distribution ranges appears to be more pronounced under the scenario with higher concentrations of emissions (Fig. 5B–E). Under RCP8.5-2070s, in particular, the potentially suitable habitats for *B. ermanii* decreased by up to 97.3% from the currently suitable area, and high potential habitat ($>$0.6) encompassing only 2.19 km^2 (Table 2). Our results revealed that *B. ermanii* prefers a cool environment with an annual mean temperature below 6.5°C and that there is no probability of presence in warm conditions above 10°C (Fig. 4). In the 2050s, the annual mean temperature of South Korea is projected to increase from 2.2°C (under RCP4.5) to 2.7°C (under RCP8.5) compared with the current conditions, and it is predicted to reach about 15.1°C under RCP8.5 scenario in the 2070s. Even if only the increase in annual mean temperature is considered, there will not be many habitats with suitable climatic conditions for *B. ermanii* in the future. Future climate projections in South Korea consistently predict a temperature rise, and this explains why potentially suitable habitat for *B. ermanii* decreased under all future climate scenarios.

Species' distribution is affected not only by climate but also by more complex factors including biotic and terrain factors (Leach *et al*., 2016); however, we only considered climatic factors for the construction of the species distribution model of *B. ermanii* in this study. Nevertheless, our results allowed the identification of the critical nature of temperature-related variables and revealed the reduction in the potential habitat areas under global warming with excellent model performance. To conserve the populations effectively with respect to future climate, we suggest intensive monitoring of *B. ermanii* populations in areas where this study shows occurrence will decrease the most.

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