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SPECIAL FEATURE

Climate Change and Biodiversity Conservation in East Asia as a token of memory for the 7th EAFES in Daegu, Korea

**Jong-Hak Yun · Katsuhiro Nakao · Ikutaro Tsuyama
Tetsuya Matsui · Chan-Ho Park · Byoung-Yoon Lee
Nobuyuki Tanaka**

Vulnerability of subalpine fir species to climate change: using species distribution modeling to assess the future efficiency of current protected areas in the Korean Peninsula

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Abstract To facilitate the adaptive management of subalpine ecosystems in the Korean Peninsula under climate change conditions, we identified the climatic factors that determine the distribution of two dominant subalpine firs (*Abies koreana* and *A. nephrolepis*). We also identified sustainable and vulnerable habitats for these species inside and outside of current protected areas under climate change scenarios. The minimum temperature of the coldest month, and the amount of precipitation in the warmest quarter were the most important climatic variables that determined the distribution of these two *Abies* species. Potential habitats for *A. koreana* and *A. nephrolepis* were predicted to decrease to 3.3% and 36.4% of the current areas due to climate change, irrespective of whether inside or outside the protected areas. It was predicted that the potential habitats for *A. nephrolepis* would be maintained in the northern part of the Korean Peninsula, and sustainable potential habitats outside the protected areas were predicted in central parts of the Korean Peninsula. The potential habitats for *A. koreana* were predicted to disappear from Is. Jeju and shrink significantly in the Korean Peninsula. These results suggest that, in central parts of the Korean Peninsula, revision of protected areas would be effective in preserving *A. nephrolepis* under conditions of future climate change. In contrast, revision of protected areas would be insufficient to conserve *A. koreana* due to their high vulnerability and limited populations. Active management is required to ensure the survival of *A. koreana* under future climate conditions.

Keywords Active management · Protected area · Sustainable habitats · General circulation models (GCM) · Vulnerability

Abbreviations DPRK Democratic People's Republic of Korea · MTCM The minimum temperature of the coldest month · MTWQ The mean temperature of the warmest quarter · PRWQ The precipitation level in the warmest quarter · PRCQ The precipitation level in the coldest quarter · PHs Potential habitats · ROK Republic of Korea

Introduction

The Intergovernmental Panel on Climate Change (IPCC) report projects that atmospheric temperatures will rise by 1.8–4.0 °C globally by 2100 (IPCC 2007).

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J.-H. Yun
Ecosystem Assessment Team, National Institute of Ecology,
1210 Geumgang-ro Maseo-myeon, Seocheon-gun,
Incheon 404708, Republic of Korea

K. Nakao (✉)
Kansai Research Center, Forestry and Forest Products Research
Institute, 68 Nagaikyutaroh, Momoyama, Fushimi,
Kyoto 612-0855, Japan
E-mail: knakao@ffpri.affrc.go.jp
Tel.: +81 32 590 7317

I. Tsuyama
Hokkaido Research Station, Forestry and Forest
Products Research Institute, 7 Hitsujigaoka, Toyohira-ku,
Sapporo, Hokkaido 0628516, Japan

T. Matsui
Center for International Partnerships and Research on Climate
Change, Forestry and Forest Products Research Institute,
1 Matsunosato, Tsukuba, Ibaraki 3058687, Japan

C.-H. Park · B.-Y. Lee
Plant Resources Division, National Institute of Biological
Resources, 42 Nanji-ro, Seo-gu, Incheon 404708,
Republic of Korea

N. Tanaka
Department of International Agricultural Development,
Tokyo University of Agriculture, 1-1-1 Sakuragaoka,
Setagaya-ku, Tokyo 1568502, Japan

Climate change is predicted to cause substantial changes to the structure and function of terrestrial ecosystems (Hannah et al. 2002). Cold temperate ecosystems, which are composed of cold-adapted organisms, are particularly sensitive to global warming (Körner 1999).

The Korean Peninsula is part of the Sino-Japanese forest region, which has various vegetation zone types, from a warm-temperate forest zone to a subarctic forest zone (Takhtajan 1986). In the Peninsula, subalpine forest areas are located in high mountains and are isolated from each other. Within the subalpine zone in the Peninsula, *Abies koreana* and *Abies nephrolepis* are dominant tree species (Yun et al. 2008, 2011a). *Abies koreana*, which is a Korean endemic species, occurs only in the high mountains, Mt. Jiri, Mt. Deukyu, and Mt. Gaya in the south of the mainland and Mt. Halla on Is. Jeju and this species has very small-scale spatial distribution (Yun et al. 2011a; Kong 2006). *Abies nephrolepis* occurs in high mountains of the Korean Peninsula, Northeast China, and in the extreme southeast of Russia at elevations varying from 500 to 700 m near its northern range limits, to 750–2000 m near its southern range limits (Kong 1989). The distribution of these two species only overlaps on Mt. Jiri, Mt. Deukyu, and Mt. Gaya. Two *Abies* species forms one of the key types of old-growth forest in the subalpine ecosystems of the Korean Peninsula, because they are dominant and climax species in the Korean Peninsula subalpine forests. Accordingly, assessing the impact of climate change and conservation planning for two *Abies* species should provide a useful milestone for planning the adaptive management of subalpine ecosystems in the Korean Peninsula.

Predicted future climate change would shift the areas of the subalpine zone upwards, and habitats for the two *Abies* species may decrease or disappear from relatively lower mountain areas. Regional population of *A. koreana* in Mt. Halla, Is. Jeju was found to be declining, and it was speculated that recent climate change has affected the growth of the tree (Koo et al. 2001). In addition, thermal potential habitat of *A. koreana* is predicted to dramatically decrease under two degrees increase scenario (Koo et al. 2017). Therefore, assessment of the impact of climate change on these *Abies* species is necessary to reveal the magnitude of the potential risks for the subalpine ecosystem in the Korean Peninsula.

Protected areas, including national parks, nature reserves, and multiple-use conservation areas, form the basis of modern conservation systems (Rodrigues et al. 2004), and are expected to remain an important conservation strategy under future climate change conditions (Heller and Zavaleta 2009). However, range shifts due to climate change may cause species to leave current protected areas. For instance, in Europe, 58% of species are projected to lose suitable climate conditions within protected areas (Araújo et al. 2011). The need for additional protected areas in anticipation of species range shifts due to climate change has been considered in many countries (Hannah et al. 2007).

Understanding the impact of climate change on species distribution is necessary to determine the potential ecological risk, and for the design of appropriate conservation strategies for adaptive management (Hannah et al. 2002). For studies aiming to assess these impacts, species distribution models (SDMs) are useful statistical tools (Elith and Leathwick 2009). Many studies have assessed the impacts of climate change on the distribution of forest plants in Europe and the United States using SDMs (Iverson and Prasad 1998; Thuiller et al. 2005; Benito et al. 2008). In East Asia, some predictions on the impacts of climate change using SDMs have been published (Matsui et al. 2004; Nakao et al. 2013, 2014; Tsuyama et al. 2011, 2012; Yun et al. 2011b, 2014). As for alpine and subalpine zones, previous studies have shown that the potential habitats would decrease or disappear (Guisan and Theurillat 2000; Benito et al. 2008; Horikawa et al. 2009; Tanaka et al. 2009, 2012; Tsuyama et al. 2015). It was also suggested that changes in current vegetation patterns as well as impacts on the stability of high mountain ecosystems, might occur due to climate change.

SDMs are not only useful for predicting future potential habitat shifts, but also for conservation planning and adaptation policymaking. Gap analyses overlay potential habitats and protected areas, and identify the gaps between them. This method is useful to assess the efficiency of existing protected area networks and to identify conservation priorities (Scott et al. 1993; Hannah et al. 2007; Nakao et al. 2013; Tsuyama et al. 2015).

Assessing the impact of climate change and current conservation planning for the two target species should provide useful information for planning the adaptive management of subalpine ecosystems on the Korean Peninsula. To achieve these objectives, this study aimed to address the following points: (1) to clarify climate factors that determine the distribution patterns of *A. koreana* and *A. nephrolepis* in the Korean Peninsula; and (2) to identify locations of sustainable and vulnerable habitats for the two *Abies* species inside and outside of current protected areas.

Materials and methods

Study area and plant distribution data

The study area was the Korean Peninsula in East Asia, which is comprised of Democratic People's Republic of Korea (DPRK) and Republic of Korea (ROK), and is bordered by China to the northwest and Russia to the northeast (Fig. S1 in ESM). Distribution data for two target species were extracted from the Korean Atlas of Vegetation Records (KAVeR; https://sites.google.com/site/kaveryun/). The KAVeR is composed of relevé data collected throughout Korea using the phytosociological method (Braun-Blanquet 1964). The relevé data were digitized into KAVeR from various sources including published and unpublished literature, and original data collected in the field. As of 2012, KAVeR included 5539 relevés digitized from all over Korea Peninsula by 30″ latitude × 30″ longitude resolution. However, the relevé data in DPRK were difficult to collect due to political reason. Alternatively, Kong's distribution records (Kong 1989) was used as the distribution data of *A. nephrolepis* in DPRK. This distribution records have the lower and upper limits of the vertical range of each mountain where *A. nephrolepis* are distributed in Korean Peninsula. Based on their geographical information, 30 arc-seconds grid cells that did overlap with the Kong's distribution records were defined as presence. Presence was recorded in 117 records for *A. koreana* and 436 for *A. nephrolepis*.

Climate data

Climatic factors were taken into account to build SDMs. Plant distribution is influenced by climatic factors as well as other factors such as soil and topography (Woodward 1996). Although, previous studies have shown that both the precipitation of warmest quarter and the minimum temperature of coldest month have mainly affected the distribution of *A. nephrolepis* on an East Asian scale (Tanaka et al. 2012). Data on the current climate were collected from WorldClim (http://www.worldclim.org/). This dataset was developed based on meteorological observations collected from 1950 to 2000 (Hijmans et al. 2005).

Considerable variation in climate simulations is caused by the difference in computational algorithms of climate phenomena among general circulation models (GCMs) (Meehl et al. 2007). Therefore, for more accurate and detailed assessments of the impact of climate change on species distributions, the use of multi-climate simulation data sets is necessary to assess SDM prediction uncertainty. To assess the impact of climate change, we used the World Climate Research Program's (WCRP) Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model data set (Meehl et al. 2007) as the future climate data set. The CMIP3 multi-model data set contains climate simulation data sets from 12 experiments (scenarios) generated by 24 GCMs from 21 climate research institutes. The A1B scenario (720-ppm stabilization experiment) from the Special Report on Emission Scenario (SRES) was used for future climate simulation, and the climate of the twentieth century experiment (20c3m) was used as the baseline for the current climate. The climate simulation data sets of these two experiments for the 20 GCMs were obtained from the Earth System Grid data portal site (http://esg.llnl.gov:8443/, last accessed 01 June 2012) for the CMIP3 multi-model data sets. Differences in the means and minimum daily temperatures, and ratios of precipitation flux between 1961 and 1980 of 20c3m and 2081–2100 of Special Reports on Emission Scenarios (SRES) A1B were spatially interpolated into 30 arc-seconds. Next, these differences and ratios for the two climate data sets were overlaid onto current climate data and used to represent future climate data.

The dataset was resolved at 30 arc-seconds, which was the same resolution of the KAVeR used for the explanatory variables of the SDMs. The following four climate variables, which are important for plant survival and growth, were used as explanatory variables in the species distribution model: The minimum temperature of the coldest month (MTCM), the mean temperature of the warmest quarter (MTWQ), the precipitation level in the warmest quarter (PRWQ), and the precipitation level in the coldest quarter (PRCQ). MTCM indicates extreme cold. MTWQ indicates heat in the growing season. PRWQ indicates water supply during the growing season. PRCQ indicates water supply during the winter season, and partly indicates the accumulation of snow in cool temperate areas.

Protected area data set

Data showing the location of the existing protected area in ROK were obtained from the Korea National Park service (http://www.knps.or.kr). These data comprise the boundaries of natural park areas. These comprise 17 parks founded by national administrations before 2010, with a total area of approximately 3214 km^2 (Fig. S2).

Species distribution models

SDMs of the target species were developed by multivariate regression trees (MRT) using the "MVPART" package (De'ath 2002) in R.2.11.1 (R Development Core Team 2011). MRTs are based on the same principles as classification and regression trees (CART), but are extended to include more than one response variable (De'ath 2002). MRT can be used to explore, describe, and predict relationships between multispecies data and environmental characteristics and can be viewed as a constrained clustering methodology that can explain as well as predict. Data regarding the presence of the target species were used as response variables and the four climate variables were used as explanatory variables. The most appropriate tree size in the MRT was obtained after estimate performance by cross-validation to avoid either under-fitting or over-fitting of the model (Clark and Pregibon 1992). Deviance-weighted scores (DWS) were defined as the sum of the reduction of deviance between parent nodes and children nodes (Matsui et al. 2004). Thus, DWS was calculated to evaluate the importance of each explanatory variable.

Assessing the impact of climate change and uncertainty

The area under the curve (AUC) value, which was extracted from the receiver operating characteristic analysis (Zweig and Campbell 1993), was used for assessing the prediction accuracy of the model. In this study, AUC value of target species was calculated based on the predicted presence/absence data and the validation data from presence/absence of the training data which were randomly selected from the training data with 100 repetitions (i.e. bootstrap method) (Efron 1979). Every bootstrap sample used for testing has the same number of presence as the training data.

Potential habitats of the target species under current climate conditions and 20 GCMs were predicted using the MRT. In this study, the inter-whisker range (IWR) was used as a measure of prediction variability. We calculated the median and variability of the occurrence probability among the future climate scenarios of 20 GCMs. To minimize the false-negative rate, we defined a threshold value by assigning a cutoff sensitivity 95%, as recommended by Pearson et al. (2004). The threshold was defined based on model predictions for the entire training data set. We defined areas with probabilities greater than or equal to the threshold probability as potential habitat and areas with probabilities smaller than the threshold value as non-habitat. Using these potential habitat maps, we calculated a proportion (%) of the areas under both current and future climate conditions. We calculated the median and variability among these proportions of all GCMs. In this study, area of one 30 arc-seconds grid cell (ca. 1 km × 1 km) was defined as 1 km^2 for convenience.

Results

Prediction accuracy and threshold probability for potential habitats

The MRT model had an AUC of 0.99 and 0.95 for *A. koreana* and *A. nephrolepis*, respectively. This value considered as ‘excellent’ according to the criteria established by Swets (1988).

The threshold of occurrence probability, defined by a sensitivity value of 95%, of *A. koreana* and *A. nephrolepis* was 0.268 and 0.005, respectively (Table 1). We defined the areas with probabilities larger than or equal to 0.268 and 0.005 as potential habitats of *A. koreana* and *A. nephrolepis*; areas with probabilities smaller than 0.268 and 0.005 were defined as non-habitats. The DWS were as follow: MTCM (0.45), MTWQ (0.22), PRWQ (0.30), and PRCQ (0.03) (Table 1). The MTCM accounting for DWS was the largest climate variable.

Climatic factors and threshold controlling two target species

The tree diagram for *A. koreana* and *A. nephrolepis* showed 14 terminal nodes (Fig. 1). In general, the climatic condition of potential habitats for these target species were distinguished depending on the magnitude of MTCM. The top-level node was split into two groups by a decision rule defined by MTCM.

Areas where *A. nephrolepis* was present were generally obtained on the right branch of the tree, on which MTCM was < -19.7 °C. The terminal node number 14 was predicted as the highest occurrence probability, which was obtained when MTCM was < -19.7 °C, PRWQ ≥ 652.0 °C, and MTWQ ≥ 17.3 °C. On the other branch, the terminal node number 9 was the lowest occurrence probability for potential habitats that have: MTWQ < 17.2 °C and MTCM ≥ -13.0 °C. Squares with predicted values of < 0.005 were classified as potential habitats of *A. nephrolepis* in the tree (terminal node numbers 2, 3, 4, 6, 7, 8, 9, 10, 12, 13, 14). The records of these squares were 95.0% (472/497 records).

Potential habitats under current climatic conditions

The distribution of predicted potential habitats of *A. koreana* was similar to the actual distribution, which occur in high mountains in the southern part of the Korean Peninsula and on Is. Jeju. Empty habitats, areas where current climatic conditions suggested potential habitats but where the species was not present (Armonies and Reise 2003; Tsuyama et al. 2014), were only identified on Mt. Odae, Mt. Gariwang, Mt. Cheongok, and Mt. Yukbaek in the central part of the Korean Peninsula. Under current climatic conditions, potential habitats of *A. koreana* were predicted to occur in the high altitude regions of Mt. Deukyu, Mt. Gaya, Mt. Jiri, and Mt. Halla. The areas of potential habitats of *A. koreana* were predicted at 329 km^2 accounting for 0.1% of the Korean Peninsula’s total land area.

Table 1 Area under the curve (AUC), thresholds of probabilities of potential habitat (PH) and deviance weighted score (DWS) of climatic variables in multivariate regression trees (MRT)

	AUC	Thresholds	DWS			
		PH	MTCM	MTWQ	PRWQ	PRCQ
Abies koreana	0.99	0.268	0.455	0.215	0.303	0.027
Abies nephrolepis	0.96	0.005				

MTCM the minimum temperature of the coldest month, *MTWQ* the mean temperature of the warmest quarter, *PRWQ* the precipitation level in the warmest quarter, *PRCQ* the precipitation level in the coldest quarter

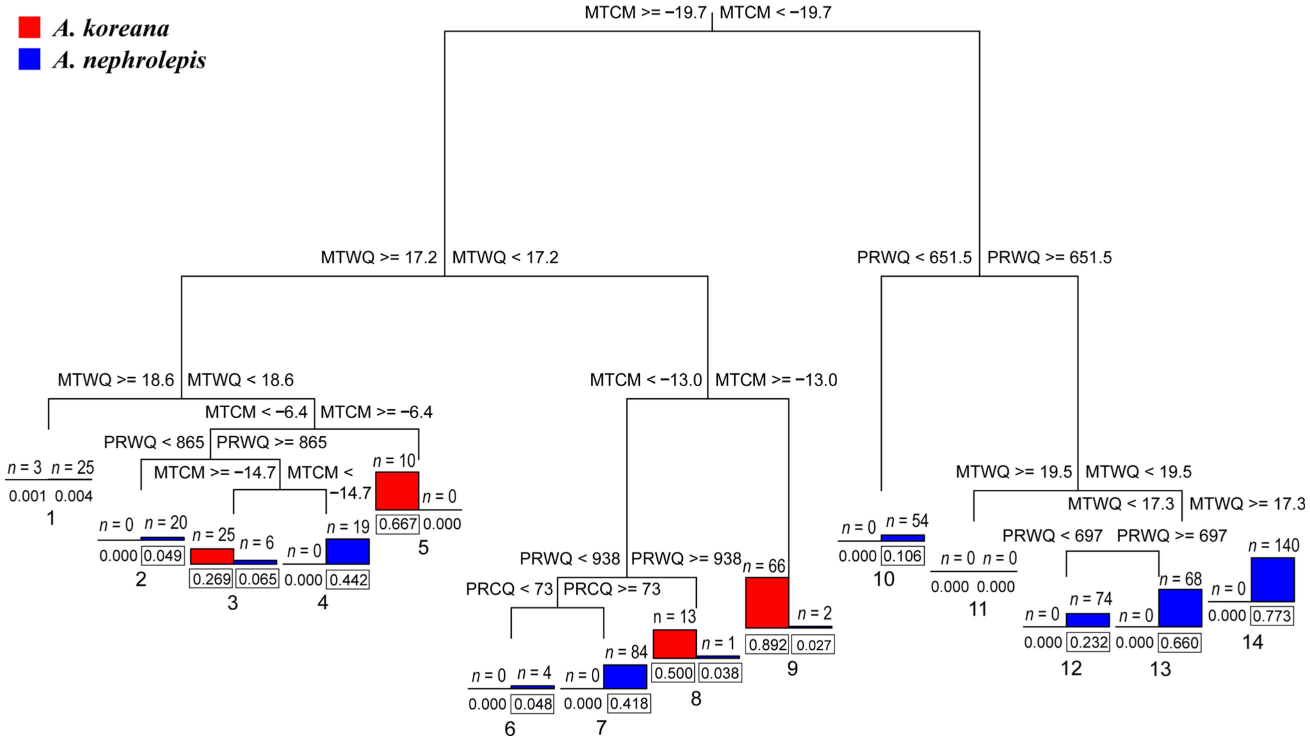

Fig. 1 Multivariate regression trees (MRT) for *Abies koreana* and *Abies nephrolepis* based on the four climatic variables. Climatic conditions, occurrence probabilities of two target species and number of records (*n*) are shown at all nodes. If the condition shown at the top of a branch is met, follow the left branch; otherwise follow the right branch, resulting in 14 terminal nodes from 1 to 14. Terminal node enclosed by the solid line show potential habitats, and all others are non-habitats. *MTCM* the minimum temperature of the coldest month, *MTWQ* the mean temperature of the warmest quarter, *PRWQ* the precipitation level in the warmest quarter, *PRCQ* the precipitation level in the coldest quarter (color figure online)

The distributions of predicted potential habitats of *A. nephrolepis* were almost consistent with the actual distribution, and were located in high mountains within the Korean Peninsula. The exception was Mt. Halla on Is. Jeju that was predicted as an empty habitat. The areas of potential habitats of *A. nephrolepis* were predicted to cover 82,496 km^2 accounting for 24.9% of the Korean Peninsula's total land area. The potential habitats of *A. koreana* and *A. nephrolepis* were projected to occur together on Mt. Gaya, Mt. Jiri, and Mt. Halla according to node numbers 3, 8, 9 of the MRT model (Fig. 2).

Potential habitat and prediction uncertainty under the climate change scenario

Potential habitats of two target species under 20 climate change scenarios (2070–2099) were predicted based on the MRT model (Fig. 2). The area of potential *A. koreana* habitats as predicted by the median value of the occurrence probability based on twenty GCMs (Mako) was 10 km^2 (Table 2). Potential Mako habitats were identified in a few places in the central region of the study area, but were very limited in the Korean Peninsula (Fig. 2). The areas of potential Mako habitats decreased to 3.3% of the current available area (Table 2). The areas of potential *A. koreana* habitat including inter-whisker range (IWRako) value were found at the top of Mt. Jiri, Mt. Taebaek, Mt, Odae, Mt. Seorak, and Mt. Geumgang in central and southern parts of the Korean Peninsula and on Mt. Halla on Is. Jeju.

The area of potential *A. nephrolepis* habitats predicted by the median of the occurrence probability based on twenty GCM (Mane) was 30,014 km^2 (Table 2). These areas were found at high altitudes in mountains, which located in southern parts of the Korean Peninsula (e.g. Mt. Deukyu, Mt. Gaya, Mt. Jiri) and Mt. Halla on Is. Jeju. The areas of potential *A. nephrolepis* habitats decreased to 36.4% of the current areas, which accounts for 9% of the Korean Peninsula's land area (Table 2). The areas of potential *A. nephrolepis* habitat including inter-whisker range (IWRane) value were found mainly along high mountains over latitude N39°30′ in northern parts of the Korean Peninsula and areas predicted to IWRako value in northern parts of the Korean Peninsula (Fig. 2). The IWRane values for *A. nephrolepis* were also high in Mt. Sungjeok, Mt. Maengbu, Mt. Yeonhwa, Mt. Munam, and Mt. Buksubaek projected at high probability for Mane (Fig. 2).

Gap analysis between potential habitats of two *Abies* species and protected areas in Korea

The potential habitats of two *Abies* species within the protected areas in ROK are predicted to decrease from

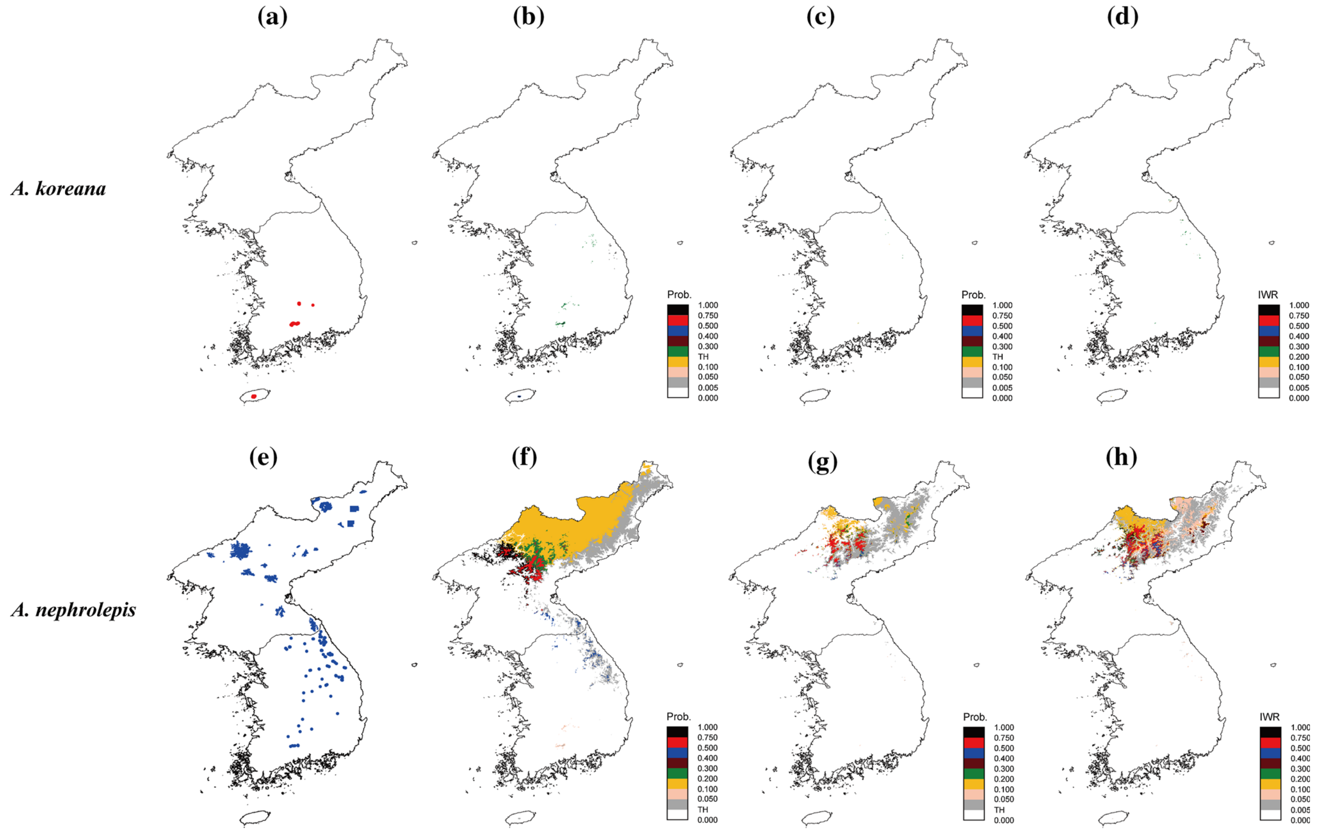

Fig. 2 Actual distributions (**a**, **e**) and potential habitats (**b**, **f**) for *Abies koreana* and *A. nephrolepis* under the current climate conditions in the Korean Peninsula. Median (**c**, **g**) and inter whisker range (IWR) (**d**, **h**) of potential habitats for two target species under 20 future climate simulations. *TH* threshold values dividing potential habitat and non-habitat (color figure online)

Table 2 The area of potential habitats (km^2) under current and future climate in the Korean Peninsula, and the area change rates (%) from current to future (future/current)

Plant species	Climate condition (km^2)		Future/current
	Current	Future	(%)
Abies koreana	329	10	3.3
Abies nephrolepis	82,496	30,014	36.4

The area of potential under future climate is median of probability based on 20 General circulation models (GCM). In this study, area of one 30 arc-seconds grid cell (ca. 1 km × 1 km) was defined as 1 km^2 for convenience

Table 3 The area of potential habitats (PH) inside and outside of protected area in ROK under current and future climate

Plant species	Protected area	Area of each climate condition (km^2)			
		Current		Future	
		Inside	Outside	Inside	Outside
Abies koreana		241	83	7	3
Abies nephrolepis		914	3047	27	10

In this study, area of one 30 arc-seconds grid cell (ca. 1 km × 1 km) was defined as 1 km^2 for convenience

241 km^2 at present to 7 km^2 in the 2080 s for *A. koreana,* and from 914 km^2 at present to 27 km^2 in the 2080 s for *A. nephrolepis* (Table 3). Accordingly, the area of potential habitats within the protected areas of *A. koreana* and *A. nephrolepis* were 7 and 27 km^2, respectively, most of which were predicted to be on Mt.

Seorak, Mt. Odae, in central parts, Mt. Jiri in southern parts of the Korean Peninsula, and on Mt. Halla on Is. Jeju (Fig. 3). Potential habitats *A. koreana* and *A. nephrolepis* without protected areas were predicted to decrease from 83 to 3 km^2, and from 3047 to 10 km^2, respectively (Table 3), while potential habitats in unprotected areas of these two *Abies* species were predicted on Mt. Gariwang, Mt. Balwang, Mt. Hambaek, and Mt. Taebaek in central parts of the Korean Peninsula (Fig. 3).

Discussion

Climatic controls and potential habitats of two target species under current climatic conditions

We identified the most important climatic variables and their thresholds values of the distribution of *A. koreana* and *A. nephrolepis* using a nationwide relevè database, high-resolution (ca. 1 km) climatic data and the MRT model. *Abies koreana* occurs only within the Korean Peninsula, and the southern limit of *A. nephrolepis* is within Korean Peninsula. Thus, the model for two target species based on Korean distribution data is appropriate. In addition, high accuracy of the model suggested that the distribution of two target species on a national scale could be explained by four climatic variables.

The MRT model and DWS revealed that MTCM contributed the most to the distribution of two target species, followed by PRWQ. In the model, the first divergence occurred at MTCM = – 19.7 °C, which was the most important explanatory variable, and divided the distribution of two target species. *A. koreana* occurred in areas where the MTCM was higher than – 19.7 °C. The summer precipitation affected the distribution of *A. koreana* positively in lower temperature areas. The distribution of *A. koreana* was limited to areas where the MTWQ was 18.6 °C, which defined the higher limit of temperature (Fig. 1), and where PRWQ was approximately 800 mm as the lower limit of precipitation (Fig. S3). The distribution of *A. nephrolepis*

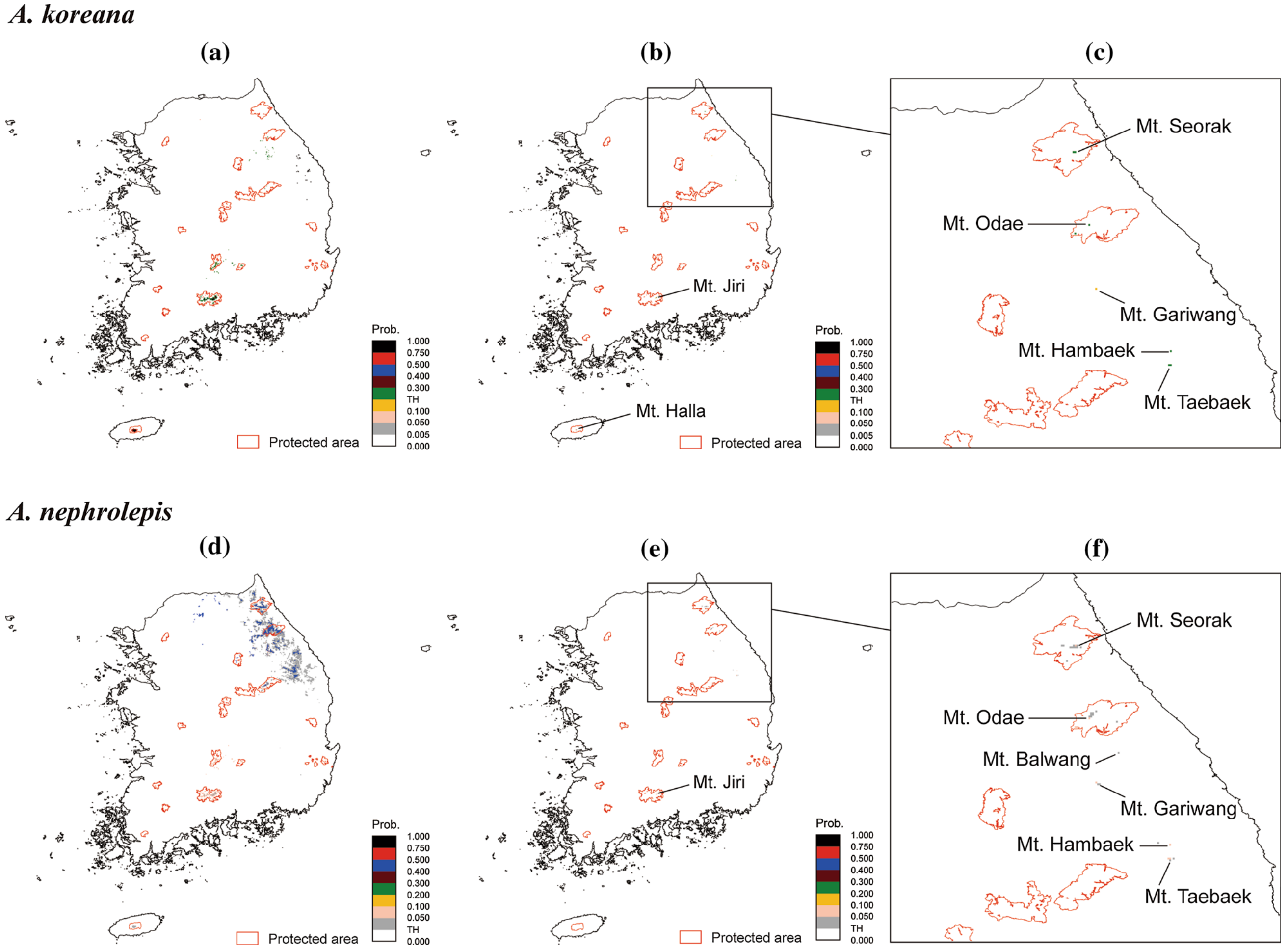

Fig. 3 Potential habitats inside and outside of the protected area in ROK for *Abies koreana* and *A. nephrolepis*, the current climate conditions (**a**, **d**), median of potential habitats for two target species under 20 future climate simulations (**b**, **e**). As visual aid, potential habitats inside and outside of the protected area of two target species in central parts were enlarged, and the mountains names were written (**c**, **f**). *TH* threshold values dividing potential habitat and non-habitat (color figure online)

mostly covered the same distribution conditions as *A. koreana* (Fig. 1; Fig. S3), which suggests that *A. nephrolepis* has greater resistance to low temperature and precipitation than *A. koreana*. The distribution of *A. nephrolepis* was controlled by a MTWQ of 19.5 °C, which was higher than that of *A. koreana* (Fig. 1; S2). These results support the hypothesis that *A. nephrolepis* is more able to adapt to cold and dry climates than *A. koreana*, which is associated with the process of speciation (Eo and Hyun 2013).

The potential habitats for two target species were similar to their actual distributions at present. However, the presence of empty habitats was projected at high elevations on Mt. Seorak, Mt. Odae, Mt. Gariwang, Mt. Cheongok, and Mt. Yukbaek in central parts of the Korean Peninsula for *A. koreana* and Mt. Halla on Is. Jeju for *A. nephrolepis*. According to phylogenetics studies, *Abies* species, including two target species, became both southward shifts and extinction from northern parts of the Northern Hemisphere during the LGM or former glacial periods due to cold and arid climate conditions (Xiang et al. 2015). Thus, even after minimum temperature and summer precipitation increased in the interglacial periods, *A. koreana* may have been unable to disperse to high mountain areas in central parts of the Korean Peninsula from the main habitat areas such as the tops of Mt Jiri and Mt. Halla on Is. Jeju as these areas are far from the empty habitat under current climate conditions.

Predicting changes in potential habitats of two target species for future conservation planning in the Korean Peninsula

Changes from the current climate to 20 climate change scenarios for 2070–2099 (20 GCMs), potential habitats of two target species were predicted to decrease or shift to higher elevations with lower uncertainties (Fig. 2). Our results show that potential habitats of *A. koreana* and *A. nephrolepis* will decrease to 3.3 and 36.4% of the current habitable areas due to climate change, respectively (Table 2). The potential habitats of *A. koreana* were predicted to disappear from Is. Jeju. The potential habitats of *A. nephrolepis* were predicted to be maintained in the northern part of the Korean Peninsula. These results suggest that *A. koreana* is more vulnerable to climate change than *A. nephrolepis*. However, it is highly possible that the actual migration rates during future climate change will be slower than the speed of the potential habitats change due to their dispersal abilities (Corlett 2009) and landscape fragmentation (Nakao et al. 2011). Therefore, we need to preserve actual habitats of the species under current conditions.

We suggest that optimum adaptive management of these two *Abies* species in ROK, and their geographical layout, should differ for each species. Certainly, sustainable habitats for *A. koreana* and *A. nephrolepis* are mostly designated as protected areas (Table 3; Fig. 3), such as Mt. Jiri. These areas are considered as future refugia for subalpine conifers and are highly valuable areas for conservation. Intensification of monitoring is important to preserve these populations in the future refugia for each species. In addition, the areas of sustainable potential *A. nephrolepis* habitats outside protected areas were 10 km^2 (Table 3), and those were mainly predicted to occur on Mt. Balwang, Mt. Gariwang, Mt. Hambaek, and Mt. Taebaek (Fig. 3e, f). These sustainable potential habitats are preferred candidates to be designated as additional protected areas under climate change conditions. Most candidates for additional protected areas were within the boundary of national forests, which are directly managed by the national government. Thus, revision of management policy, including reallocating management resources, raising the current protection level, and establishing surveillance programs, are required to reduce the impact of climate change on these species and their habitats.

Our results show that a large proportion of vulnerable *A. koreana* habitats are found within their current habitats, irrespective of whether these located within protected areas or not (Fig. 3). Active management including assisted regeneration and ex situ conservation may be required in the case of highly vulnerable habitats. If stakeholders (e.g., the government) have sufficient capacity to provide investment in ecological conservation, adaptive management may be conducted throughout the candidate areas. However, investment in all candidate areas is impractical due to socioeconomic constraints. Consequently, we must prioritize resource allocation between the candidate areas (Murdoch et al. 2007). In our case, if resources are insufficient, *A. koreana* populations identified as necessary for active management, especially the southern populations should be considered high-priority candidates for investment in climate adaptation practices due to their endemism and limited population size.

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