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Modeling Habitat Suitability of the Climate-vulnerable Plant *Thuja koraiensis* in Response to Climate Change

Seung-Jae Lee,[1] Jun-Gi Byeon,[2] Jun-Soo Kim,[3] Joon-hee Cho,[3] and Seung-Hwan Oh[4*]

[1]Department of Forestry, Graduate School, Kyungpook National University,
Daegu 41566, Republic of Korea
[2]Baekdudaegan National Arboretum, Korea Arboreta and Gardens Institute,
Bonghwa 36209, Republic of Korea
[3]Nature and Forest Research Institute, Daegu 41476, Republic of Korea
[4]School of Forest Sciences and Landscape Architecture, Kyungpook National University,
Daegu 41566, Republic of Korea

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In this study, we predict the habitat suitability of *Thuja koraiensis*, an endemic plant species on the Korean Peninsula, and establish management strategies for its conservation. To achieve this, field surveys were conducted on the Korean Peninsula and northeastern China to determine species occurrence points. An ensemble modeling approach was implemented, combining the Random Forest, Generalized Boosted Model, and Generalized Linear Model algorithms, to explore suitable habitats. Our results show that under current climate conditions, wide suitable habitats can be found in South Korea. Furthermore, our analysis indicated that elevation had the greatest impact on the availability of suitable habitats. On the basis of the shared socioeconomic pathway data presented in the Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report, changes in future habitat distribution were observed for the 2050s (2040–2060) and 2070s (2060–2080). The results indicated a significant decrease in the availability of suitable habitats in South Korea, while relatively wide suitable habitats were observed in North Korea. In particular, the elevation of suitable habitat areas gradually increased, suggesting that future suitable habitats may become isolated. These research findings substantiate the necessity for implementing appropriate measures to conserve and manage the climate-vulnerable species *T. koraiensis* to ensure its long-term preservation and sustainable management.

1. Introduction

Earth's surface temperature has increased by an average of 1.09 °C (0.95–1.20 °C) from 2011 to 2020 compared with the period 1850–1900, and it has been observed that land temperatures (1.59 °C [1.34–1.83 °C]) have risen more than ocean temperatures (0.88 °C [0.68–1.01 °C]).(1) Climate change causes changes in the boundaries of species habitats and has a decisive impact on biodiversity, altering the structure and function of ecosystems.(2,3) In particular, polar regions

*Corresponding author: e-mail: oshwan@knu.ac.kr
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and alpine species are vulnerable to global warming as their distribution ranges are constrained and movement is limited, compounded by the shrinking suitable habitat areas.[4–7] *Thuja koraiensis* Nakai (Korean arborvitae) is an endemic plant species on the Korean Peninsula[8,9] and belongs to the genus *Thuja* in the family Cupressaceae. It is distributed on the Korean Peninsula and the Mt. Baekdu (Changbai) region in China.[10] Trees belonging to the family Cupressaceae play a significant role in the supply of timber and as decorative items, and they are an important species in the dynamics of forest ecosystems.[11] However, *T. koraiensis* is limited in distribution to high mountainous regions and is classified as a vulnerable species according to the International Union for Conservation of Nature (IUCN) Red List categories and criteria, indicating the need for research on habitat conservation and management strategies.[12]

Research on the establishment of conservation policies in areas expected to be highly affected by climate change and the selection of priority survey areas is lacking, despite various studies being conducted on reproductive techniques,[13] seed characteristics,[14] and community structure[15] for conservation purposes. To understand and respond to the changes in forests caused by climate change, research analyzing the vulnerability factors of forests is necessary. Predictive methodologies for assessing the impacts of climate change on natural habitats can provide valuable insights into forest dynamics. Specifically, the changes in the distribution of *T. koraiensis* due to environmental changes can have implications for the biodiversity and dynamics of high mountain ecosystems, rather than just representing a change in a single species.[16] Therefore, a systematic approach is needed to assess the impact of climate change on areas where *T. koraiensis* grows and to select regions that are expected to be highly affected by climate change.

A Species Distribution Model that derives the potential habitat of a species based on the relationship between presence and absence data and environmental variables is utilized. It is useful for assessing changes in species habitat due to climate change.[17–19] In this study, we aim to reduce uncertainty and improve accuracy by applying an ensemble model that combines various models, addressing the limitations of a single model.[20] Additionally, we aim to investigate the trend of habitat changes caused by climate change, propose prioritized conservation plans, and identify the major environmental variables that affect the growth characteristics of *T. koraiensis*. The results of this study could serve as a valuable reference for the establishment of conservation and restoration systems, considering the effects of climate change, for *T. koraiensis* on the Korean Peninsula and in China.

2. Data, Materials, and Methods

2.1 Location data

Field surveys were conducted in the regions of South Korea and Mt. Baekdu in China from September 2019 to September 2022 to collect location coordinates. Additionally, coordinates were obtained from the Global Biodiversity Information Facility (GBIF) (https://www.gbif.org) to ensure the sufficient availability of location coordinates. To ensure the use of accurate location data, coordinates situated outside forested areas were excluded from the GBIF location coordinates. The geographic distribution of the coordinates of these biological species was verified using Google Earth. Furthermore, on the basis of the previous study by Kong[21] where the geographic distribution of *T. koraiensis* was documented, we removed location coordinates that fell outside the natural habitat of *T. koraiensis* (Fig. 1). For the absence coordinates, while constructing them through field surveys would be the most desirable approach, owing to the limitations of the survey, pseudoabsence (PA) data were used instead.[22] PA coordinates can have a substantial effect on the outcomes of the model; therefore, they should be used with caution.[23] In this study, the construction of PA coordinates involved randomly generating 10000 random points within the study area, repeated 10 times, to ensure the consistency in all models and their outcomes.[24]

To reduce sampling bias and mitigate the effect of spatial autocorrelation, the location coordinates were constructed to have one coordinate per environmental variable grid cell.[25–30] As a result, 32 occurrence and 10000 PA coordinates were utilized in the analysis.

2.2 Environmental data

The environmental variables used in the study were extracted from the Worldclim database (http://www.worldclim.org), which provides 30-arcsec (approximately 1 km) resolution data for 19 Bioclim variables. Furthermore, SRTMv3 digital elevation model data were processed to

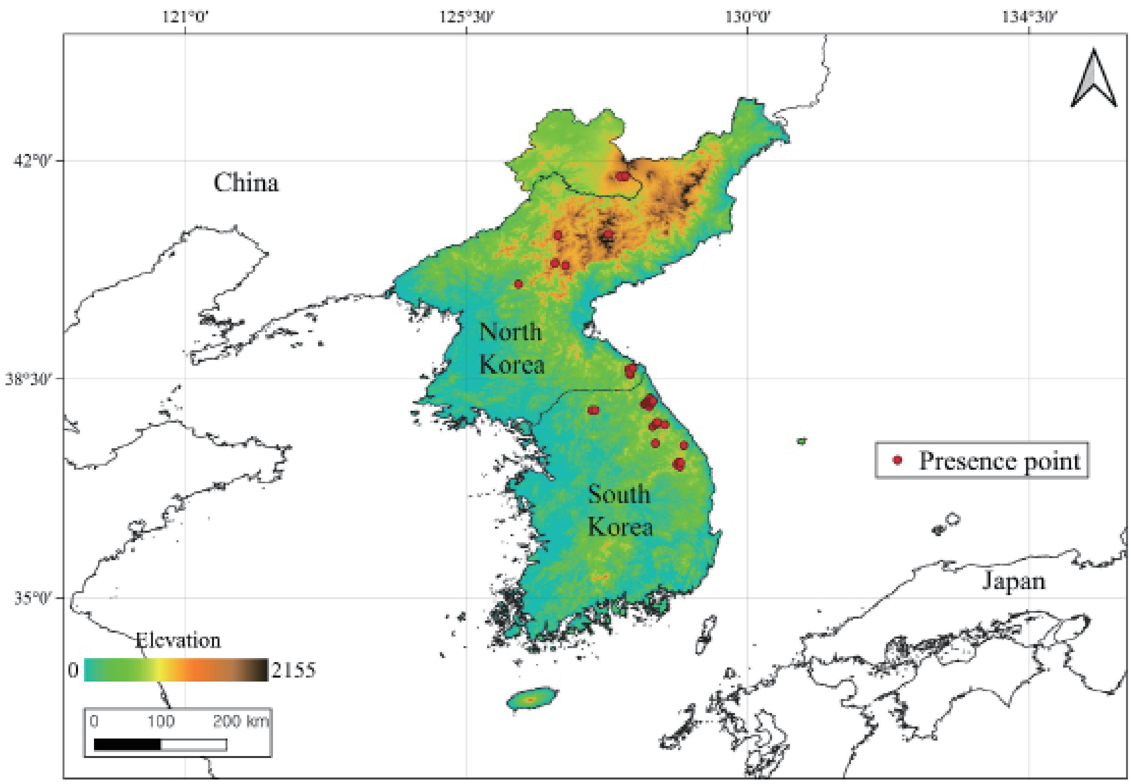

Fig. 1. (Color) Locations of the presence points of *T. koraiensis*.

match the resolution of the Bioclim variables. The SRTMv3 source is generated using remote sensing technology. However, owing to the potential occurrence of multicollinearity among the 19 Bioclim variables, a correlation analysis was performed. Variables that showed a correlation coefficient higher than 0.75 were constructed by removing one variable out of two.[31,32] As a result, six climate-related variables and one terrain variable were utilized in the analysis (Table 1).

The data for the future climate utilized in the analysis were derived from the UKESM1-0-LL climate dataset, which was jointly developed by South Korea and the United Kingdom, under the SSP2-4.5 and SSP5-8.5 scenarios. The data for the period from 2041 to 2060 were represented as the 2050s, whereas those for the period from 2061 to 2080 were represented as the 2070s.

The data construction and habitat evaluation processes were conducted using the ArcGIS 10.8 and QGIS 3.16 software programs, with the coordinate system set to WGS84. The correlation analysis between the Bioclim variables was performed using R Studio.

2.3 Species distribution modeling

Three algorithms, Random Forest (RF), Generalized Linear Model (GLM), and Generalized Boosted Model (GBM), were used to build species distribution models. The model development process involved the random splitting of occurrence/nonoccurrence data and environmental variables into training data (80%) and test data (20%). The test data were used for model validation, while the training data were utilized for model development. This process was repeated 10 times to reduce uncertainty in the model results.

To implement the ensemble model using the individual species distribution models, those with True Skill Statistic (TSS) values equal to or higher than 0.8 were selected and combined by assigning weights to them. The ensemble model implementation was carried out using the Biomod2 package in R (Fig. 2). The results of the species distribution models were presented as probabilities, ranging from 0 to 1, where a value of 1 indicated a higher probability of occurrence.

Table 1
Description of climate variables used for the prediction of suitable habitat.

Category	Variable Name	Unit	Description
Climate factor	Bio02	℃	Mean diurnal range [Mean of monthly (max temp − min temp)]
	Bio03	—	Isothermality (BIO2/BIO7) (×100)
	Bio10	mm	Mean temperature of warmest quarter
	Bio14	mm	Precipitation of driest month
	Bio15	—	Precipitation seasonality (coefficient of variation)
	Bio18	mm	Precipitation of warmest quarter
Topographical factor	DEM	m	Digital elevation model

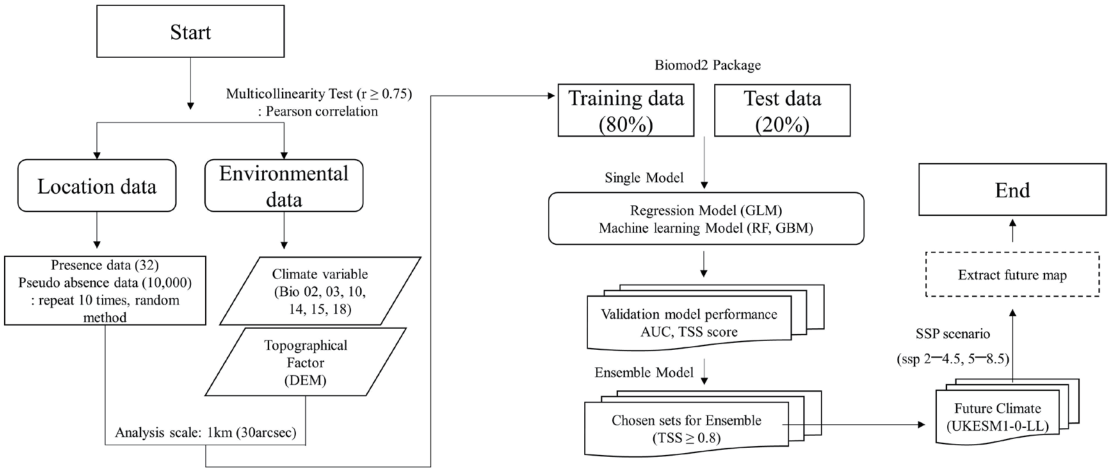

Fig. 2. Ensemble species distribution modeling flow chart.

2.4 Model accuracy assessment

The model validation was assessed on the basis of the area under the curve (AUC) value of the receiver operating characteristic and the TSS value. AUC represents the accuracy of the model, ranging from a minimum of 0.5 to a maximum of 1.0, with higher values indicating higher accuracy. According to Swets' classification[33], models with AUC values between 0.7 and 0.8 were categorized as "fair", whereas those above 0.8 were considered to have "good" model performance.[34,35]

The TSS value ranges from −1 to +1. In this study, the model's explanatory power was evaluated using the following classification: 0.4–0.6 as "moderate", 0.6–0.7 as "high", and above 0.7 as "excellent".[36]

2.5 Map for potential habitat area of *T. koraiensis*

On the basis of the cut-off values that can determine potential habitat areas within the range of species occurrence probability, the classification was made into three categories: low (≤472), medium (472–700), and high (≥700). This classification was applied from the current climate's potential habitat to the results obtained using data for the future climate.

3. Results

3.1 Model performance and importance of variables

To compare the performance characteristics of individual species distribution models, the average, minimum, and maximum values of AUC and TSS were calculated (Table 2). The results showed that most of the models exhibited high accuracy when applied to the current climate. In

Table 2
Accuracies of individual species distribution models.

Model	AUC			TSS		
	Average (SD)	Maximum	Minimum	Average (SD)	Maximum	Minimum
GBM	0.980 ± 0.035	0.999	0.809	0.927 ± 0.076	0.999	0.690
RF	0.980 ± 0.028	0.999	0.826	0.912 ± 0.078	0.999	0.690
GLM	0.971 ± 0.043	0.999	0.775	0.907 ± 0.086	0.999	0.570

particular, machine learning models such as RF and GBM consistently demonstrated superior performance. Moreover, the average AUC value for all models was above 0.8 and the average TSS value was above 0.7, indicating the high predictive accuracy and reliability of the models. By applying the ensemble technique with weights assigned to models with TSS values above 0.8, the AUC improved to 0.998 and the TSS increased to 0.989, representing enhanced results.

The key variables that affect the potential habitat of *T. koraiensis* on the Korean Peninsula, according to the implementation of the ensemble model, were elevation (83.4%), BIO2 (31.6%), BIO18 (16.0%), BIO10 (15.0%), BIO3 (10.7%), BIO14 (9.3%), and BIO15 (4.5%).

3.2 Potential habitat area for *T. koraiensis* in current climate

Weighted by models with TSS values above 0.8, an ensemble model was implemented (Fig. 3). The results showed that under current climate conditions, the suitable habitat area was most extensive in regions of South Korea. Suitable habitat areas were also observed in regions such as Mt. Sobaek, Mt. Deogyu, Mt. Jiri, and Mt. Halla, where *T. koraiensis* occurrence data were not available. In the regions of North Korea, additional suitable habitat areas were identified in mountains such as Mt. Sungjok, Mt. Bokgae, Mt. Jongsok, Mt. Buksu, and Mt. Horang. In China, suitable habitat areas were observed in the vicinity of Mt. Baekdu and in mountainous areas at elevations ranging from 1700 to 1900 m near Xianqiaogou. On the basis of the response curves of the seven environmental variables used in the analysis, a bivariate analysis was conducted. The results indicate that the most suitable habitat for *T. koraiensis* is at an elevation above 1500 m and BIO18 (precipitation of warmest quarter) above 800 mm (Fig. 4).

3.3 Potential habitat area for *T. koraiensis* in future climate

With the climate change scenario data of the SSP, the suitable habitat areas for *T. koraiensis* in the 2050s and 2070s were predicted and classified into high, moderate, and low categories. By comparing these results with the current suitable habitat area, it was observed that the high suitability area consistently decreased over time. On the other hand, the moderate suitability area initially increased but showed a decrease in the 2070s under the SSP5-8.5 scenario (Fig. 5).

Furthermore, it was observed that the suitable habitat area in South Korea significantly decreased. However, Mt. Seorak, Mt. Jiri, and Mt. Halla maintained high suitability areas across all scenarios. In North Korea, the largest suitable habitat area was identified, particularly in regions such as Mt. Buksu, Mt. Geumgang, and Mt. Baekdu, where wide suitable habitat areas were present. These areas showed larger suitable habitat areas in the future compared with the

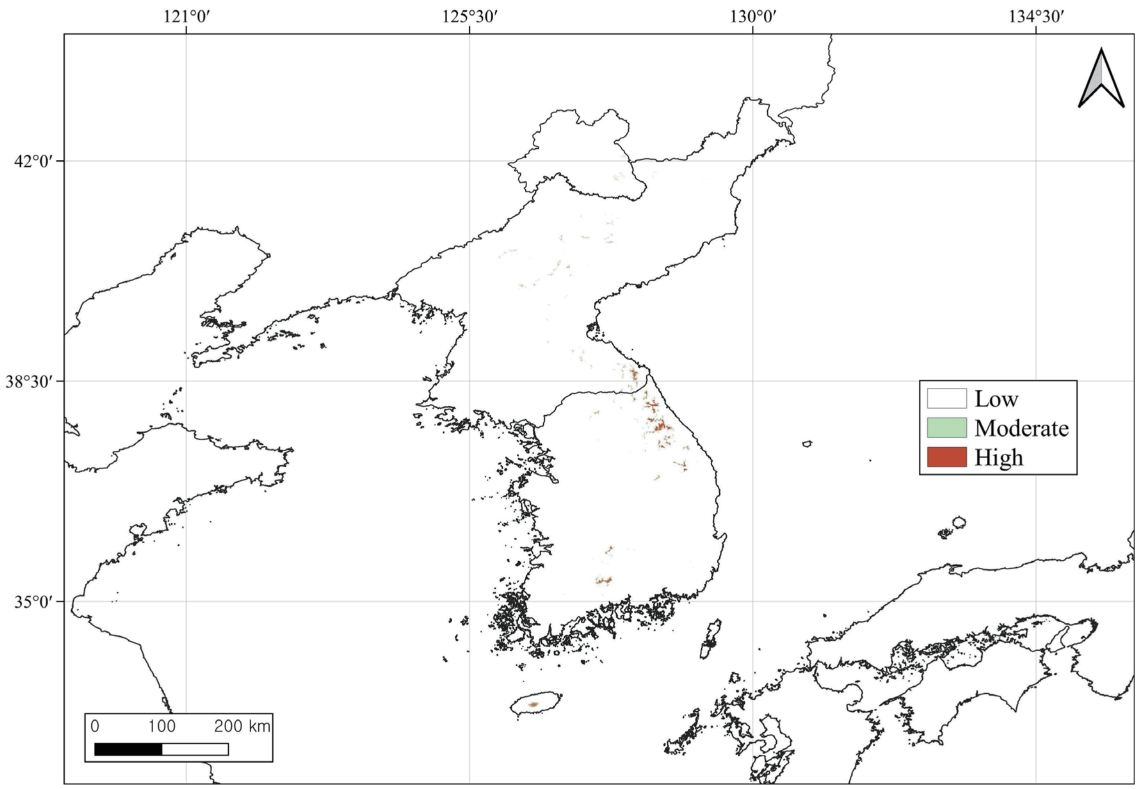

Fig. 3. (Color) Distribution of potential habitat for *T. koraiensis* under current climate conditions.

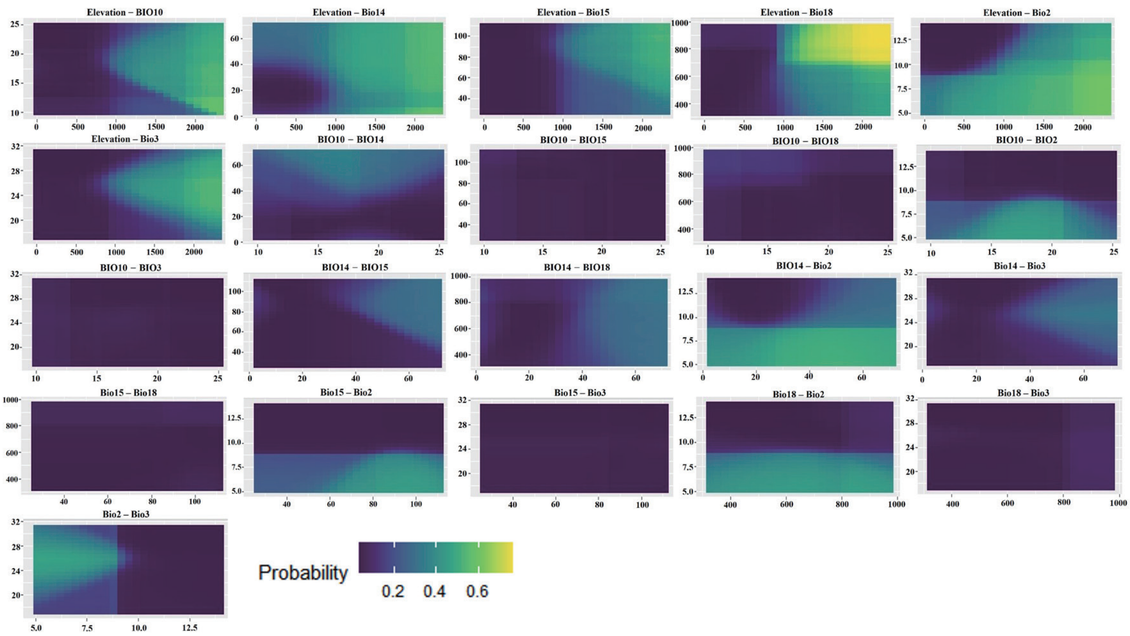

Fig. 4. (Color) Assessing *T. koraiensis* habitat suitability with bivariate analysis under current climate conditions.

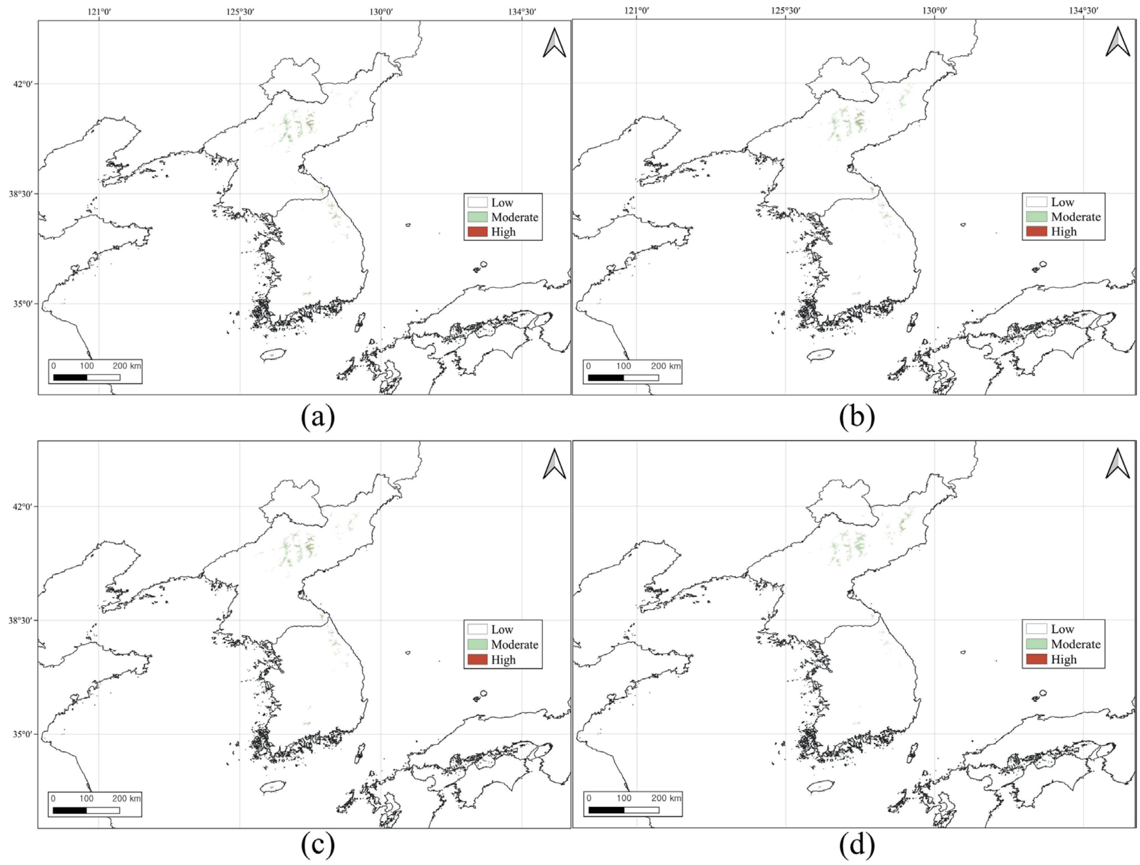

Fig. 5. (Color) Distribution of potential habitat for *T. koraiensis* based on future climate data. Potential distribution of *T. koraiensis* in (a) SSP 2–4.5 (2050), (b) SSP 5–8.5 (2050), (c) SSP 2–4.5 (2070), and (d) SSP 5–8.5 (2070). SSP = shared socioeconomic pathway.

current potential habitat area under all scenarios. In China, the suitable habitat area initially decreased but increased in the 2050s under the SSP5–8.5 scenario (Table 3). In the case of Table 3, changes in area, when applying future climate data to the current potential habitat area, have been presented in ratio, with the unit of numbers being %. Although no high suitability area was identified under the current climate data in China, a high suitability area in the elevation range of 2500–2600 m within Mt. Baekdu was projected when using future climate data.

The elevation within forested areas is recognized as a crucial factor in studying the relationship between climate change and vegetation distribution, as well as in investigating the distribution of biodiversity in response to environmental changes.[37,38] Under current climatic conditions, the mean elevation of the high suitability zone for *T. koraiensis* was 1145 m, with maximum and minimum elevations of 2427 and 527 m, respectively. The average elevation of the moderate suitability zone was 1328 m, with the maximum and minimum elevations of 2522 and 165 m, respectively. However, under the climate change scenarios, the suitable habitat elevation for *T. koraiensis* is projected to shift higher (Table 4).

Table 3
Changes in the distribution of *T. koraiensis* habitats by country according to SSP scenarios. The data are expressed in percentages. A dash is used to indicate areas that are not present under the current climate conditions, signifying that these areas cannot be quantified with a percentage change.

Country	Scenario	Period	Total	High	Moderate
South Korea			−28.22	−73.45	40.28
North Korea	SSP2–4.5	2050	318.27	210.72	342.76
China			−52.82	–	−55.59
South Korea			−39.07	−83.29	27.89
North Korea	SSP2–4.5	2070	360.34	174.73	402.61
China			−48.66	–	−56.16
South Korea			−41.53	−85.83	25.55
North Korea	SSP5–8.5	2050	393.27	177.80	442.29
China			6.90	–	3.04
South Korea			−59.16	−96.93	−1.94
North Korea	SSP5–8.5	2070	379.03	60.81	451.49
China			−45.88	–	−53.64

Table 4
Elevation changes in suitable habitat for *T. koraiensis* under climate change scenarios.

Model	High			Moderate		
	Average (SD)	Maximum	Minimum	Average (SD)	Maximum	Minimum
Current	1145 ± 240	2427	527	1328 ± 443	2522	165
2050 (SSP2–4.5)	1725 ± 383	2522	749	1534 ± 340	2471	527
2050 (SSP5–8.5)	1851 ± 340	2522	835	1593 ± 297	2471	527
2070 (SSP2–4.5)	1834 ± 356	2522	835	1579 ± 311	2404	527
2070 (SSP5–8.5)	2049 ± 246	2522	1011	1654 ± 275	2404	583

4. Discussion

4.1 Model performance evaluation and environmental variables affecting the distribution of *T. koraiensis*

In this study, we attempted to identify the potential habitats of *T. koraiensis* using an ensemble model that combines statistical and machine learning models. We also analyzed the environmental variables that affect the species distribution. The results showed that the average AUC and TSS values of all models demonstrated excellent performance, indicating that they can be prioritized for the future development of species distribution models.

Among the various variables that affect the potential habitat of *T. koraiensis*, terrain-related variables had the highest impact at 83.4%, followed by temperature-related variables at 57.3%, and precipitation-related variables at 29.8%. Among them, bivariate analysis revealed that elevation and BIO18 (precipitation of warmest quarter) had significant effects on the species habitat. This can be interpreted as reflecting the preference for a generally moist environment and specifically the main habitats of *T. koraiensis* in the highland regions. It is suggested that BIO18 plays a crucial role in providing sufficient moisture supply within the habitat, facilitating favorable growth conditions as it approaches a certain level. Furthermore, considering that the *T. koraiensis* community primarily inhabits the north-facing slopes with favorable moisture conditions,[15] it can be inferred that appropriate moisture conditions will be crucial for the suitability of its habitat under future climate change. However, while the importance of precipitation has been emphasized in numerous studies, the understanding of specific climate thresholds for the successful growth of the species remains limited.[39,40] Therefore, there is a need to install meteorological devices in areas of maintained suitable habitats and potential extinction to facilitate a comprehensive understanding of specific climate thresholds that will accompany future distributional changes.

Another significant variable that affects the habitat of *T. koraiensis* was identified as BIO2 (mean diurnal range),which is preferred in areas within the study site that experience relatively small temperature variations. Large diurnal temperature ranges can increase plant water loss, and high temperatures can lead to evaporation and water loss, while low temperatures can impair water absorption and utilization in plants, potentially impacting water stress and growth. These findings support the sensitivity of *T. koraiensis* to global warming in the future, highlighting the importance of temperature-related variables as crucial factors under suitable habitat conditions.

4.2 Assessing vulnerability of habitats of *T. koraiensis* to climate change

When using data for the future climate, significant changes are expected in the suitable habitat for *T. koraiensis*. In particular, the continuous decrease in the distribution range of high habit of suitability can serve as crucial decision-making data for conservation strategies and policy decisions regarding population maintenance for *T. koraiensis*. Our findings highlight the importance of variables such as BIO10, BIO2, BIO18, and elevation as key factors that affect habitat suitability and the reduction in distribution range for *T. koraiensis*. Depending on the scenarios, the habitat suitability of *T. koraiensis* decreases in the availability of regions with high values of BIO10 (≥22 °C), indicating that the species exceeds its physiological thresholds under extreme temperature increases. Regarding BIO2, a suitable distribution was observed in areas where the temperature did not exceed 12.4 °C, and this trend was observed in regions such as Hamgyeongnam-do and Ranggang-do in North Korea, as well as the northeastern part of Mt. Baekdu in China.

On the other hand, the range of BIO18 (precipitation of warmest quarter), with values greater than or equal to 730 mm, was identified as the most important factor for maintaining suitable habitats. This characteristic was observed in regions such as Hamgyeongnam-do in North Korea, the vicinity of Mt. Baekdu, and Mt. Halla. In particular, considering the shift of future suitable habitats to higher elevations, it can be inferred that there is a close relationship with temperature-related variables. However, to understand the environmental conditions in which the plant species thrive, additional variables must be considered. Nevertheless, owing to the distribution of *T. koraiensis* mainly in alpine and subalpine zones, there is a high risk of isolation and potential extinction.

4.3 Restoration strategies for *T. koraiensis*

Ecological restoration is insufficient with the existing approach, which solely relies on historical reference data as a key management tool for addressing climate change.(41) To prevent the extinction of *T. koraiensis*, it is crucial to have a specific understanding of "restoration sites", which are suitable habitats in the present and future, and strategies on "how to restore".(42)

As the first approach, comprehensive studies on forest floor substrates for effective restoration are crucial for the maintenance and regeneration of *T. koraiensis* populations.(43) This is considered an important element for *T. koraiensis* growth, enabling adaptation to rapid environmental changes caused by global warming and facilitating management activities to find suitable habitats.(44) In the second approach, considering that *T. koraiensis* has grown in isolation for an extended period, the degree of decline in response to global warming may vary depending on the growth environment and genetic diversity. Therefore, understanding the characteristics of *T. koraiensis* populations in different mountainous regions would allow for a flexible adaptation to climate change. To accomplish this, the establishment of long-term monitoring programs is essential, as they would be instrumental in evaluating the effectiveness of restoration strategies and tracking potential threats.

Additionally, on the basis of the continuous occurrence of suitable habitat distributions of *T. koraiensis* in South Korea, including Mt. Halla, Mt. Jiri, Mt. Deogyu, regions surrounding Mt. Baekdu in China, and Mt. Buksu and Mt. Geumgang in North Korea, we propose the concurrent implementation of *in situ* and *ex situ* conservation programs within the target areas.

5. Conclusion

In this study, we aimed to provide insights for the conservation and management of *T. koraiensis* by identifying suitable areas for current and future potential habitats and analyzing the key environmental variables that affect the distribution of the species. According to the results of the bivariate analysis, elevation and BIO18 (precipitation of warmest quarter) were identified as the factors with the highest effect on the species distribution, with a shortage of rainfall during specific periods expected to have a significant impact on the future species distribution. These results are consistent with studies on the distributional changes of species primarily inhabiting alpine zones. In South Korea, although existing suitable habitats have been identified over a wide area, it is predicted that these habitats will significantly decrease in the availability of response to future climate change, emphasizing the need for prompt action to address this issue. Furthermore, the assessment of the potential distribution of *T. koraiensis*, classified as a second-class protected plant within China, can be effectively utilized for the establishment of species conservation and management plans. However, apart from the variables used in this study, there may be other factors that can affect species survival. Conducting additional research through continuous monitoring and promoting international collaboration can further enhance our understanding of species conservation.

Our study has identified suitable habitat areas for the successful *in situ* and *ex situ* conservation programs of *T. koraiensis*, which is included as a vulnerable species in the IUCN

Red List. By proposing additional research, we have presented a perspective for effective restoration strategies. This can serve as a reference study for the future establishment of management measures and policies for the conservation of plant species inhabiting subalpine and alpine zones.

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