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RESEARCH

Development of a habitat suitability index for the habitat restoration of *Pedicularis hallaisanensis* Hurusawa

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Background: We developed a habitat suitability index (HSI) model for *Pedicularis hallaisanensis*, a Grade II Endangered Species in South Korea. To determine the habitat variables, we conducted a literature review on *P. hallaisanensis* with a specific focus on the associated spatial factors, climate, topography, threats, and soil factors to derive five environmental factors that influence *P. hallaisanensis* habitats. The specific variables were defined based on the collected data and consultations with experts in the field, with the validity of each variable tested through field studies.
Results: Mt. Seorak had a suitable habitat area of 2.48 km^2 for sites with a score of 1 (0.62% of total area) and 0.01 km^2 for sites with a score of 0.9. Mt. Bangtae had a suitable habitat area of 0.03 km^2 for sites with a score of 1 (0.02% of total area) and 0 km^2 for sites with a score of 0.9. Mt. Gaya showed 0.13 km^2 of suitable habitat for sites with a score of 1 (0.17% of total area) and 0 km^2 for sites with a score of 0.9. Lastly, Mt. Halla showed 3.12 km^2 of suitable habitat related to sites with a score of 1 (2.04% of total area) and 4.08 km^2 of sites with a score of 0.9 (2.66% of total area). Mt. Halla accounts for 73.1% of the total core habitat area. Considering the climatic, soil, and forest conditions together with standardized collection sites, our results indicate that Mt. Halla should be viewed as a core habitat of *P. hallaisanensis*.
Conclusions: The findings in this study provide useful data for the identification of core habitat areas and potential alternative habitats to prevent the extinction of the endangered species, *P. hallaisanensis*. Furthermore, the developed HSI model allows for the prediction of suitable habitats based on the ecological niche of a given species to identify its unique distribution and causal factors.

Keywords: endangered species, endemic species, habitat restoration, habitat suitability index, *Pedicularis hallaisanensis*

Introduction

Pedicularis hallaisanensis Hurusawa, endemic species to South Korea, belongs to the genus *Pedicularis* L., within the Scrophulariaceae family. Approximately 600 species of *Pedicularis* are distributed in the polar regions of the northern hemisphere and alpine regions of the temperate zone (Yang et al. 1998). Eleven species of this semi-parasitic plant have been identified on the Korean peninsula, with five species, *P. resupinata P. mandshurica*, *P. hallaisanensis*, *P. spicata*, and *P. ishidoyana*, found in South Korea (Cho 2010).

P. hallaisanensis was first discovered by Ichikawa in 1905 on Mt. Halla, Jeju Island, be called the two common names of the species, Halla-songipul and Seom-songipul in South Korea. Since 2012, the annual or perennial *P. hallaisanensis* has been designated as a Grade II Endangered Species for protection by the Ministry of Environment. The plants grow in full-sun locations on the rocky ridges of high-altitude mountains. The flowering period is from July to September and the distribution is considerably rare across the geographical regions of Mt. Halla, Mt. Seorak, Mt. Bangtae, and Mt. Gaya (National Institute of Biological Resources [NIBR] 2018).

Research on the genus *Pedicularis* in South Korea began with the first report on *P. resupinata* by Palibin (1900), followed by taxonomic studies by Nakai (1911), Jung (1956), Lee (1996a, b), as well as Cho and Choi (2011). Although *P. hallaisanensis* has been categorized as identical to *P. spicata* (Cho and Choi 2011), in our study, *P. hallaisanensis* and *P. spicata* are viewed as two distinct species owing to the lack of a comprehensive review with standardized collection sites, representability as an endemic species, and comparisons with other East-Asian species.

If species appearance data are abundant, statistical-based models can be used to measure species distribution. A variety of species distribution models can be used to define relationships between empirical distribution data and environmental data (Elith and Leathwick 2009). However, it is difficult to predict this distribution in the case of species whose ecological characteristics have not been properly studied or in the case of small populations. This requires a process-based approach. The habitat suitability index (HSI) is a case in point, which can leverage less data to provide efficient decision support tools for ecosystem conservation.

A HSI allows for the quantification of environmental factors that affect habitats and represent the quality of those habitats. An HSI is based on habitat variables that identify the habitat requirements of a specific biological species (Shim 2004).

Up to date, only four studies have used HSI models for the investigation of plants indigenous to South Korea, including *Aster altaicus* and *Polygonatum stenophyllum* (Lee et al. 2017), *Aerides japonica* (Shim et al. 2020), and *Cypripedium guttatum* (Yoon et al. 2020). Also, no study, has developed an HSI model for the habitat restoration and conservation of *P. hallaisanensis* in South Korea.

Thus, the purpose of this study was to develop an HSI model for *P. hallaisanensis* based on a review of the current habitat status and ecology of *P. hallaisanensis*, a Grade II Endangered Species. Especially, our results provide fundamental data for the identification and conservation of potential, alternative, and core habitats of *P. hallaisanensis* and the evaluation of possible restoration projects.

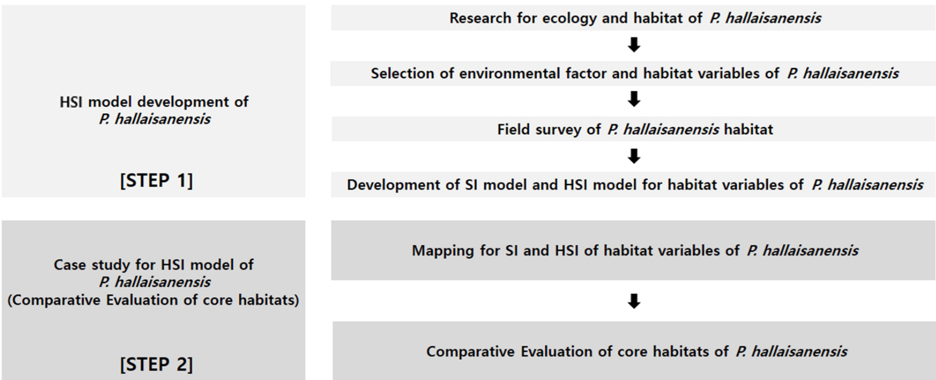

Fig. 1 Study flow. SI: suitability index; HSI: habitat SI.

Table 1 Literature review on *P. hallaisanensis* with a specific focus on the associated spatial factors

Environmental factor		Note	References
Habitat	Habitat distribution	Sub-alpine region within Mt. Halla	Kim et al. 2018
		Mt. Gaya Sangwangbong area	You et al. 2013 Kim et al. 2019
		Mt. Bangtae Kim et al. 2018	Kim et al. 2016
		Only a few individuals remain around Baengnokdam and Yeongsilgiam	Cho and Choi 2011
	Habitat environment	Growth in grasslands without upper vegetation (Mt. Halla)	Kim et al. 2018
Climate	Light intensity	Well lighted area (Mt. Gaya, Mt. Halla)	Kim et al. 2018
Topography	Slope	0–25° (Mt. Gaya), 60° (Mt. Halla)	Kim et al. 2018
	Aspect	Southwest slope (Mt. Gaya), Southeast slope (Mt. Halla)	Kim et al. 2018
	Elevation	Mt. Gaya 1,400 m (near the summit) Mt. Halla 1,500 m (near the ridge)	Kim et al. 2018
Threat factor		Being pushed out of competition by surrounding plants (Mt. Halla) Concerns about soil loss due to steep slopes (Mt. Halla)	Kim et al. 2018
		Concerns about soil erosion and sedimentation damage caused by rainfall (Mt. Gaya) Pressure by trespassing (Mt. Gaya)	You et al. 2013
		Sensitive to environmental changes in the habitat	Kim et al. 2016
Soil	Acidity	pH 6.1 (Mt. Gaya), pH 5.1 (Mt. Halla)	Kim et al. 2018
	Organic matter	7.5% (Mt. Gaya), 5.1% (Mt. Halla)	
	EC-meter	0.6 ds/m (Mt. Gaya), 0.5 ds/m (Mt. Halla)	Kim et al. 2018
	Total nitrogen content	0.7% (Mt. Gaya), 0.6% (Mt. Halla)	Kim et al. 2018
	EC	K 0.2, Ca 14.7 Mg 0.6, Na 0.1 (Mt. Gaya) K 0.1, Ca 2.3, Mg 0.8, Na 0.1 (Mt. Halla)	Kim et al. 2018

EC: exchangeable cation (cmol/kg).

Table 2 Georgraphic information data for habitat variables of *P. hallaisanensis*

Environmental factor	Geographic information data	Habitat variables	Data source
Climate	Weather map	Annual average temperature, annual average precipitation, warmth index, precipitation of blooming period	Open Weather Data Portal (https://data.kma.go.kr/resources/html/en/aowdp.html)
	Bioclim	Precipitation of driest month (BIO14), mean temperature of warmest quarter (BIO10)	Worldclim (https://www.worldclim.org/data/worldclim21.html)
	Lansat-8	Normalized difference vegetation index	Earth Explorer (https://earthexplorer.usgs.gov/)
Soil	Soil map	Effective soil depth , soil texture, gravel content, soil drainage class	Korea Soil Information System (http://soil.rda.go.kr/eng/overview/data.jsp)
Topography	Digital topographic map	Altitude, slope, direction	National Geographic Information Institute (https://www.ngii.go.kr/eng/main.do)
Light intensity	Forest type map	Distribution	KFS
Threats	Forest type map	Hiking trail	KFS

KFS: Korea Forest Service (https://map.forest.go.kr/forest/).

Materials and Methods

This study was conducted in two steps. First, we development a HSI model for *P. hallaisanensis* and, second, we applied the developed model using a field study for the identification of core habitats (Fig. 1).

To determine the habitat variables, we conducted a literature review on *P. hallaisanensis* with a specific focus on the associated spatial factors (habitat distribution and condition), climate, topography (slope, direction, and altitude), threats, and soil factors (acidity, organic content, electrical conductivity, total nitrogen, and exchangeable cations) to derive five environmental factors that influence *P. hallaisanensis* habitats (Table 1) (Cho and Choi 2011; Kim et al. 2016; Kim et al. 2018; Kim et al. 2019; You et al. 2013).

The specific variables were defined based on the collected data and consultations with experts in the field, with the validity of each variable tested through field studies.

And, using data from field studies and the national survey on the distribution of endangered species, we identified 14 natural habitats Mt. Seorak (4 sites), Mt. Bangtae (1 site), Mt. Gaya (4 sites) and Mt. Halla (5 sites) of *P. hallaisanensis*.

The data were analyzed regarding the historical distributions, ecological characteristics, topography, threats, and soil factors related to *P. hallaisanensis* populations. Based on the findings of our literature review, we selected environmental factors and primary habitat variables for *P. hallaisanensis*.

From the primary data set and through consultations with experts in the field, we derived the following five most influential habitat variables for *P. hallaisanensis*: vegetation zone, annual average temperature, precipitation of driest month, gravel content, and crown density.

Based on our findings, referring to Lee et al (2017), we determined a suitability index (SI) and, consequently, developed a HSI model. We used ArcMap 10.7 to construct

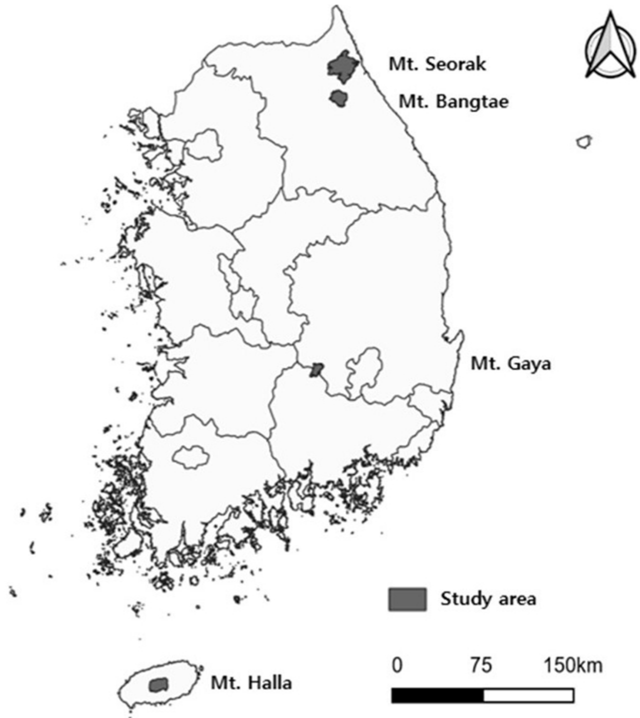

Fig. 2 Study area of *P. hallaisanensis* populations in South Korea, including Mt. Seorak and Mt. Bangtae in Gangwon-do, Mt. Gaya in Gyeongsangnam-do, and Mt. Halla on Jeju Island.

the data required in the spatial analysis for each SI model (Table 2). All raster layers were aligned with 30 m cell size, and SI layers were produced by the Reclassify tool. After that, the HSI value was obtained by the SI layers using the raster calculator. This allowed us to analyze the core habitats of *P. hallaisanensis* on Mt. Halla, Mt. Gaya, Mt. Bangtae, and Mt. Seorak (Fig. 2).

Results

Selection of environmental factors and habitat variables for *P. hallaisanensis*

Based on the findings of our literature review, we selected environmental factors and primary habitat variables for *P. hallaisanensis*. From the primary data set and through consultations with experts in the field, we derived the following five most influential habitat variables for *P. hallaisanensis*: vegetation zone, annual average temperature, precipitation of driest month, gravel content, and crown density.

Field investigation of *P. hallaisanensis* habitats

The field study of the natural habitats of *P. hallaisanensis* on Mt. Seorak, Mt. Bangtae, Mt. Gaya, and Mt. Halla showed an annual average temperature 3.71 ± 1.49°C, an annual average rainfall of 1,690.93 ± 366.97 mm, altitude of 1,454.71 ± 182.4 m, and a slope of 20–30°. For soil conditions, the highest distribution of *P. hallaisanensis* was found in areas with a 20–50 cm effective soil depth and primarily in subalpine vegetation zones. The average distance between *P. hallaisanensis* habitats and the nearest hiking trail was 0.38 ± 0.27 km, and the average air humidity during the flowering period (June–August) was approximately 92% or higher across all habitats. In addition, as *P. hallaisanensis* only grows to a small height, competitive exclusion and disturbance from trampling exert pressure on existing populations, and the majority of recorded plants were located in unstable habitats that seemed to be highly vulnerable to soil loss.

Development of the SI and HSI models for P. hallaisanensis

Vegetation zone (SI 1)

Results from our literature review and consultations with experts in the field indicated that *P. hallaisanensis* habitats are primarily distributed in subalpine zones at high altitudes (Kim et al. 2018; Korea National Park Research Institute 2016; You et al. 2013). Thus, we used a warmth index to distinguish between different vegetation zones (Table S1). With the exception of one site (located within a cool temperate broad-leaved deciduous forest near a subalpine zone), all *P. hallaisanensis* populations were located in subalpine zones equal to or below a warmth index of 45. Hence, taking the potential presence of *P. hallaisanensis* in areas near subalpine zones, an index of 0.2 was given to the cool temperate broad-leaved deciduous forest (Figs. 3 and 4).

Annual average temperature (SI 2)

Considering the characteristic distribution of *P. hallaisanensis* in subalpine zones, where climate change has a relatively strong impact (Kim et al. 2018), we identified temperature as having a significant influence on the distribution of *P. hallaisanensis.* We used the average annual temperature to include annual variation and abnormal temperatures, such as heat waves and cold spells. The suit-

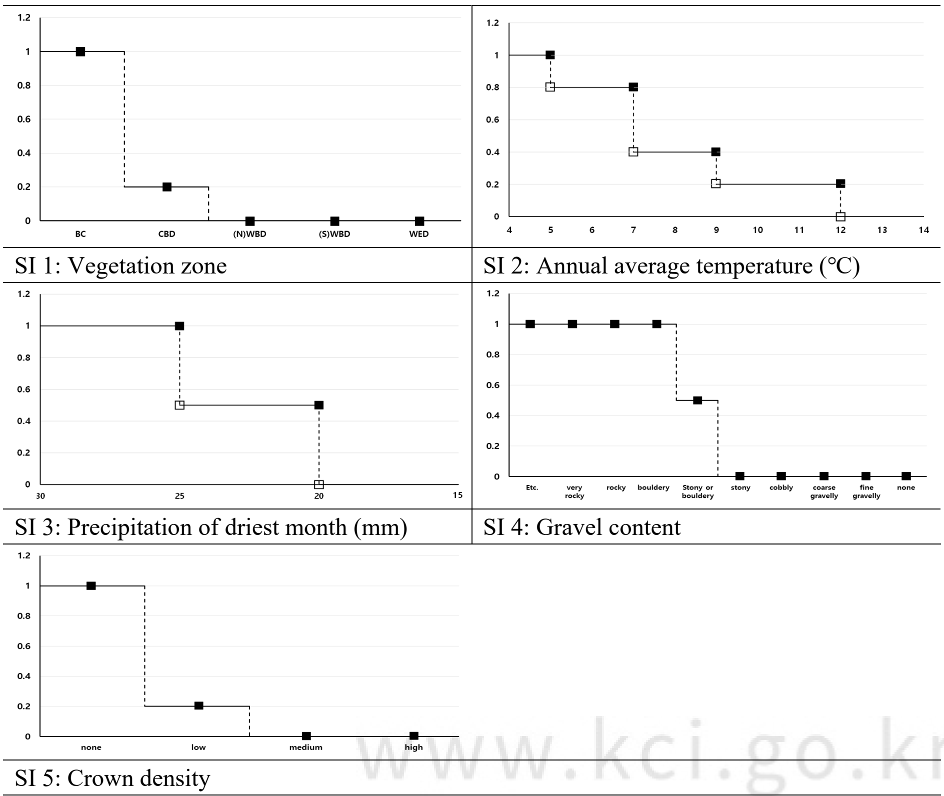

Fig. 3 Suitability index (SI) model for habitat variables of *P. hallaisanensis.*

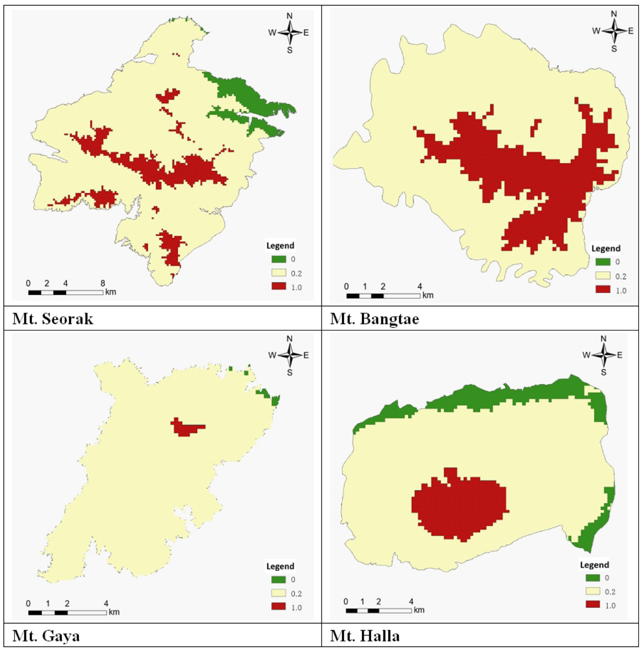

Fig. 4 Vegetation zone (suitability index 1) model map for vegetation zone of *P. hallaisanensis*.

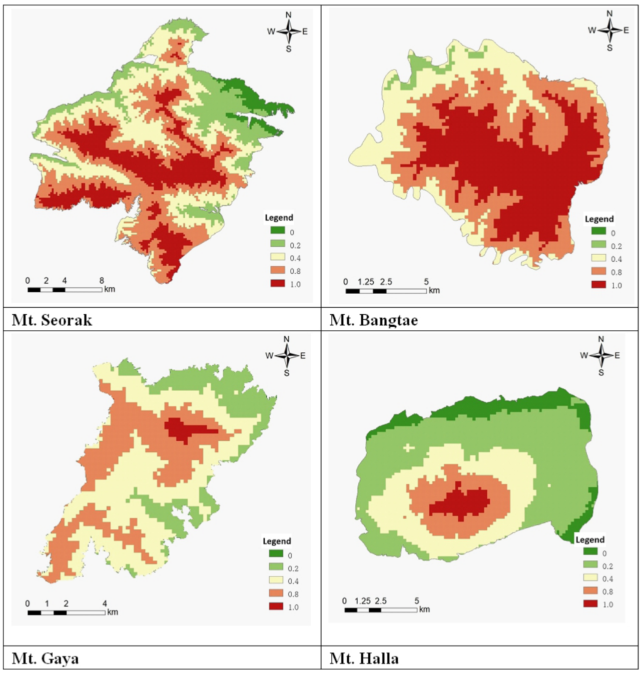

Fig. 5 Annual average temperature (suitability index 2) model map for annual average temperature of *P. hallaisanensis*.

ability of the variable was reviewed through expert consultation (Figs. 3 and 5).

Precipitation of driest month (SI 3)

Results from our review of relevant literature together with environmental monitoring data showed *P. hallaisanensis* to be located in regions with high air humidity. Specifically, Mt. Halla provides suitable growth conditions as the air humidity remains high through the presence of subalpine cloud cover and mist (Korea National Park Service 2013). Regarding fog (cloud and mist), however, the lack of data from a national database on spatial information prevented us from using fog as a variable. As a certain amount of moisture is a prerequisite for plant growth, we selected the precipitation of the driest month as a habitat variable. Within this context, we analyzed the habitat characteristics of 14 locations in South Korea with the precipitation of the driest month above or equal to 25 mm as the most suitable habitats (Figs. 3 and 6).

Gravel content (SI 4)

Results from our literature review and field study indicated that *P. hallaisanensis* are distributed in rocky areas containing a thin layer of soil and in areas with a certain proportion of exposed rocks (NIBR 2018). In addition, the areas marked as “Other” in the spatial analysis (satellite image analysis and field study) consisted of bedrock and watersheds. Thus, to consider the habitat substrate, we selected “gravel content” as a further habitat variable. The gravel content of 14 habitats of *P. hallaisanensis* (Table S2) and related habitat characteristics were analyzed to investigate the respective index (Figs. 3 and 7).

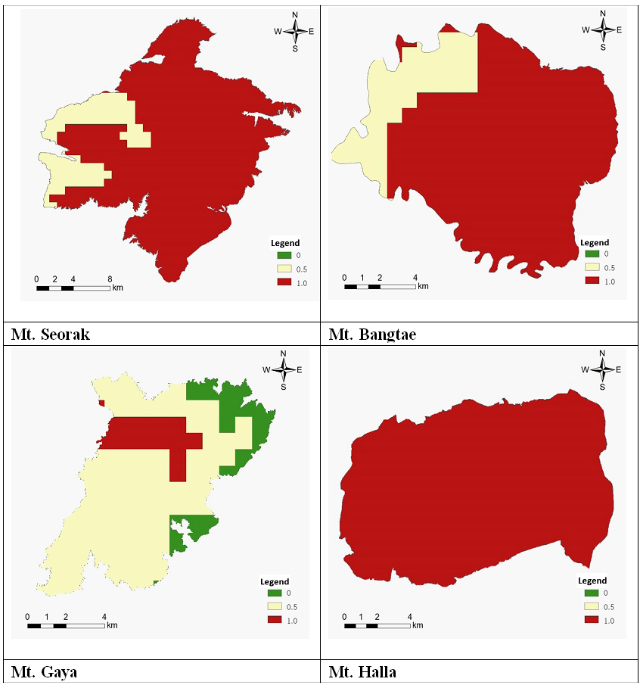

Fig. 6 Precipiation of driest month (suitability index 3) model map for precipitation of driest month of *P. hallaisanensis*.

Crown density (SI 5)

When the crown density is high, the light intensity cannot reach the ground level. However, there was no light intensity information constructed as spatial data, the crown density was replaced with light intensity with reference to expert advice.

P. hallaisanensis growing in full-sun grassland without forest trees or shrub layers require a high light intensity during the growing season (Korea National Park Service 2013; NIBR 2018). In addition, field observations highlighted the presence of *P. hallaisanensis* on mountain peaks and unforested areas, such as on bedrock or cliffs. Taking these conditions into consideration, the unforested areas marked as "Other" were selected as the most suitable habitats, with the respective index (Figs. 3 and 8) based on the potential suitability of certain areas with a high level of rock exposure and a canopy cover of 50% or less (Table S3).

Discussion

Development of the HSI model

The importance of each SI variable was estimated through expert consultation (Table 3), with the weighted value set to define the relationship with the HSI model (Equation 1).

Equation 1. The habitat suitability index (HSI) derivation formula for *P. hallaisanensis*.

P. hallaisanensis HSI = 0.26 (SI 1) + 0.21 (SI 2) + 0.16 (SI 3) + 0.16 (SI 4) + 0.21 (SI 5)

SI: suitability index; SI 1: vegetation zone; SI 2: annual average temperature; SI 3: precipitation of driest month; SI 4: gravel content; SI 5: crown density.

Field study for the *P. hallaisanensis* HSI model

Based on the spatial data of each habitat variable, we constructed HSI maps for *P. hallaisanensis* populations on Mt. Seorak, Mt. Bangtae, Mt. Gaya, and Mt. Halla (Fig. 9). Mt. Seorak had a suitable habitat area of 2.48 km^2 for sites with a score of 1 (0.62% of total area) and 0.01 km^2 for sites with a score of 0.9. Mt. Bangtae had a suitable habitat area of 0.03 km^2 for sites with a score of 1 (0.02% of total area) and 0 km^2 for sites with a score of 0.9. Mt. Gaya showed 0.13 km^2 of suitable habitat for sites with a score of 1 (0.17%

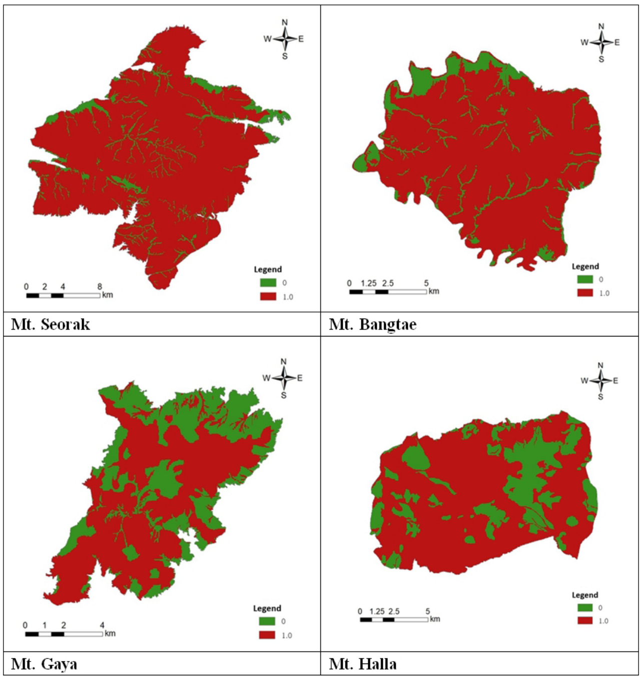

Fig. 7 Gravel content (suitability index 4) model map for gravel content of *P. hallaisanensis*.

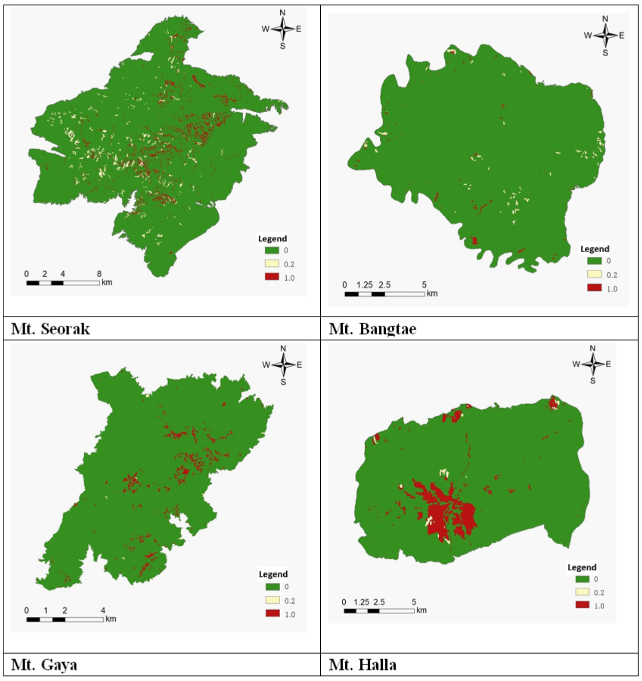

Fig. 8 Crown density (suitability index 5) model map for crown density of *P. hallaisanensis*.

Table 3 Weighted values of selected habitat variables for *P. hallaisanensis*

No.	Habitat variables	Expert									mean
		Kong	LeeⒶ	KimⒶ	Moon	ChoiⒶ	ChoiⒷ	LeeⒷ	KimⒷ	Jang	
1	Vegetation zone (SI 1)	5	5	5	2	5	5	5	5	5	4.67
2	Annual average temperature (SI 2)	-	-	-	-	-	-	4	4	4	4.00
3	Precipitation of driest month (SI 3)	2	4	2	5	3	2	4	2	3	3.00
4	Gravel content (SI 4)	5	2	3	2	2	3	4	3	3	3.00
5	Crown density (SI 5)	5	2	4	5	4	4	5	3	4	4.00

Ⓐ and Ⓑ are used to differentiate 2 experts who have the same surname.
SI: suitability index.

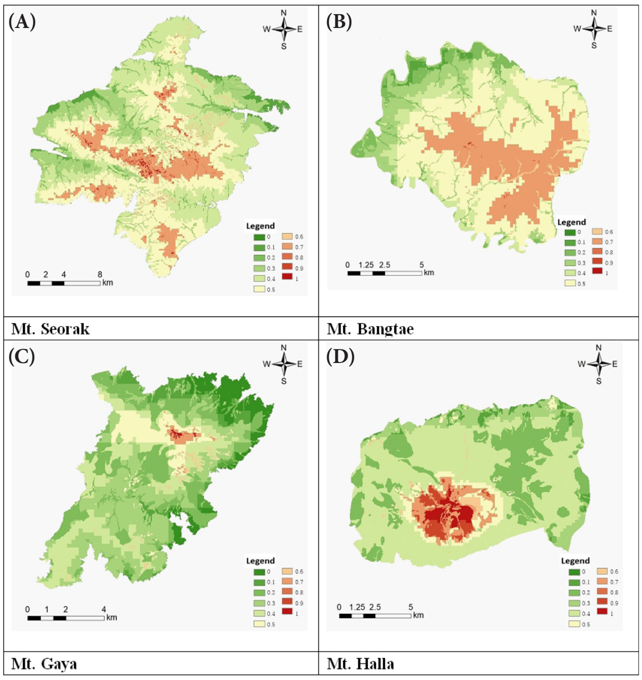

Fig. 9 Habitat suitability index (HSI) map for habitat variables of *P. hallaisanensis* populations of (**A**) Mt. Seorak, (**B**) Mt. Bangtae, (**C**) Mt. Gaya, and (**D**) Mt. Halla.

of total area) and 0 km^2 for sites with a score of 0.9. Lastly, Mt. Halla showed 3.12 km^2 of suitable habitat related to sites with a score of 1 (2.04% of total area) and 4.08 km^2 of sites with a score of 0.9 (2.66% of total area).

To verify our findings, we compared the results from the HSI model with field data from 14 *P. hallaisanensis*, and HSI score of 1 was obtained for all sites, with the exception of four sites. In addition, results of the spatial data analysis indicated that the site with a score of 0.7 located on Mt. Gaya had a lower score as the grid of the respective coordinates was converted to zero (score of 0) during the GIS conversion in the SI 5 score map. Furthermore, results from the field study showed that two sites on Mt. Halla deemed unsuitable for habitation had related scores of 0.7 and 0.5, while the rocky cliff where *P. hallaisanensis* was found had a related score of 0.9 (Table S3). In addition, the area of the sites with an HSI score of 1 (9.85 km^2) accounted for only 1.38% of the total area (768 km^2) of the four study sites (Mt. Seorak, Mt. Bangtae, Mt. Gaya, and Mt. Halla) (Table 4).

Table 4 Comparison of habitat suitability index (HSI) scores with results from a field study of four *P. hallaisanensis* locations

Site	No.	HSI	Remark
Mt. Seorak	1	1	-
	2	1	-
	3	1	-
	4	1	-
Mt. Bangtae	5	1	-
Mt. Gaya	6	1	-
	7	0.7	Limits of changes in clinical density point values due to rasterization
	8	1	-
	9	1	-
Mt. Halla	10	1	-
	11	1	-
	12	0.9	A rock cliff
	13	0.7	Non-habitable area
	14	0.5	Non-habitable area

Conclusions

This study was conducted to suggest the HSI and the core habitats of *Pedicularis hallaisanensis* Hurusawa through the investigation of the current status of ecology and habitat as well as expert consultation.

As a result, the following five habitat variables were selected for *P. hallaisanensis*: vegetation zone, annual average temperature, precipitation of driest month, gravel content, and crown density. These habitat variables were used to develop the SI and HSI models. The resulting HSI was used to analyze the core habitats of *P. hallaisanensis* on Mt. Seorak, Mt. Bangtae, Mt. Gaya, and Mt. Halla.

Mt. Halla accounts for 73.1% of the total core habitat area. Considering the climatic, soil, and forest conditions together with standardized collection sites, our results indicate that Mt. Halla should be viewed as a core habitat of *P. hallaisanensis*.

The findings in this study provide useful data for the identification of core habitat areas and potential alternative habitats to prevent the extinction of the endangered species, *P. hallaisanensis*.

Furthermore, the developed HSI model allows for the prediction of suitable habitats based on the ecological niche of a given species to identify its unique distribution and causal factors. Notably, as the effect of microhabitats, threats, and environmental change fell beyond the scope of our study, If the spatial data on the micro-climate and the long-term monitoring of the *P. hallaisanensis* habitat are constructed through follow-up studies, detailed alternative habitats and core habitats can be suggested by the more precise spatial analysis.

Supplementary Information

Supplementary Information accompanies this paper at https://doi.org/10.5141/jee.22.067.

Table S1. Classification of vegetation zone (Yim, 1977). **Table S2.** Gravel content (SI 4) criteria and differentiation based on the evaluation system used in the soil information system of the National Institute of Agricultural Sciences in Korea. **Table S3.** Classification of crown density using data from the Forest Geospatial Information System (FGIS).

Abbreviations
Not applicable.

Acknowledgements
Not applicable.

Authors' contribution
RHJ did writing-original draft, review & editing, SK did investigation and data curation. JWJ did methodology and writing review, JWT did investigation and data curation. SC did conceptualization and writing-review & editing. YJY did conceptualization, investigation, and writing-review & editing.

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Availability of data and materials
Not applicable.

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The author declares that they have no competing interests.

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