Research Article

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Analyzing Priority for Protected Area Expansion Based on Predicting Mammals' Habitat Distribution Using SSP Scenarios.

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ABSTRACT

Protected areas play a crucial role in mitigating the impact of climate change on biodiversity. However, traditional methods of expanding protected areas have focused solely on increasing area size to meet the Convention on Biological Diversity (CBD) objectives, without considering the effects of climate change. This study aims to address the limitations of previous research by analyzing the impact of climate change on biodiversity. It prioritizes protected areas by examining changes in key habitats for 10 South Korean mammal species across three periods: A (2011-2040), B (2041-2070), and C (2071-2100). Two scenarios were used: SSP1-2.6 (active mitigation) and SSP3-7.0 (passive mitigation). In the SSP1-2.6 scenario, key habitat areas decreased in period B but gradually recovered in period C, while in SSP3-7.0, habitat areas slightly increased in period B but decreased again in period C. The findings suggest that climate change mitigation policies significantly affect habitat area changes. Based on this analysis, the study recommends prioritizing southern Gangwon-do and northern Gyeongsangbuk-do as first-priority protected areas, with Demilitarized Zone (DMZ)-adjacent regions, eastern Gyeonggi-do, and western Gangwon-do as second priorities for future conservation efforts. It is expected that the proposed key habitat areas will be a useful reference for future mid- to long-term expansion of protected areas.

Keywords : climate change; key habitat area; MaxEnt; potential habitat.

INTRODUCTION

Protected areas are considered the most effective means of conserving biodiversity, protecting species, habitats, and ecosystems, while also mitigating the impacts of climate change (Barr et al. 2021). Recognizing the global need for such areas, the 15th Conference of the Parties to the Convention on Biological Diversity (CBD COP15) set a target to protect at least 30% of terrestrial and marine ecosystems by 2030. South Korea, as a signatory to this convention, has expanded its protected areas by approximately 28% since the 2000s. However, despite this increase in protected areas worldwide, internal biodiversity loss continues unabated (Negacz et al. 2022). This issue arises because the focus has been on expanding the quantity of protected areas without adequately addressing their internal ecological effects (Terraube et al. 2020), which overlooks their impact on other sustainability goals and obscures their efficiency and importance. The Protected Planet Report 2020 highlights the need to address biodiversity loss to ensure the survival of species, ecosystems, and human societies. This problem suggests that expanding protected areas has not been adequately achieved, and selection criteria must be established when expanding protected areas.

Climate change and greenhouse gas emissions pose significant threats to natural ecosystems and the societies that depend on them (Malhi et al. 2020). Forest ecosystems, in particular, are expected to undergo gradual changes due to climate change, which will affect both the extent of protected areas and the habitats of species within them. Therefore, future strategies for expanding and conserving protected areas must take climate change into account.

Previous studies have used Representative Concentration Pathway (RCP) scenarios to estimate the impact of climate change on specific species or predict the distribution of endangered plant species under current and future climate scenarios (Martínez-López et al. 2021; Hoveka et al. 2022). However, these studies often fail to consider ecological characteristics and the extent of protected areas. The Intergovernmental Panel on Climate Change's Sixth Assessment Report (AR6) introduced Shared Socioeconomic Pathways (SSPs), which provide a more comprehensive analysis of future climate responses compared to RCPs by incorporating social and economic factors such as population growth, income levels, agricultural production, and land use patterns (Popp et al. 2017; Chaudhary and Mooers 2018). The SSP scenarios offer a more sophisticated approach than RCPs by considering societal and economic changes alongside climate projections.

Korea's forests cover approximately 70% of its land area and provide crucial habitats for various mammal species. Mammals serve as important indicators for assessing ecosystem stability and planning conservation efforts. In particular, umbrella species—often top predators or consumers—are frequently studied in Korea due to their significant role in maintaining ecosystem balance (Kim et al. 2012; Lee et al. 2017). However, accelerated climate change may prevent some mammals from adapting quickly enough to survive (He et al. 2023). According to IPCC estimates, between 32% and 46% of free-ranging mammals could lose up to 30% of their current habitat range due to climate change (He et al. 2023). Understanding mammal distribution is therefore essential for evaluating ecosystem stability and identifying priority areas for conservation.

Conducting nationwide surveys of mammal populations is challenging due to time and resource constraints. To address this issue, South Korea's Ministry of Environment has been conducting surveys on terrestrial and freshwater ecosystems since 1986, collecting data on various taxonomic groups including plants, mammals, birds, amphibians/reptiles, insects, and fish (Kim et al. 2012). This data can be used to derive potential habitats for mammals and guide conservation planning.

This study conducted a literature review on the application of climate change scenarios in conservation research. It was found that previous studies often used RCP scenarios and species distribution models (SDMs) to estimate the potential impact of climate change on various species within protected areas (Pomoim et al. 2022). The SDM approach is useful for identifying potential mammal habitats under changing climate conditions and provides a scientific basis for selecting protected areas. Existing protected areas have primarily focused on quantitative expansion without sufficient strategic or organizational planning (Bax and Francesconi 2019), which has limited their effectiveness in conserving biodiversity. Additionally, animal habitat shifts due to climate change are emerging as critical factors that must be considered when selecting new protected areas.

After conducting a literature review, it was found that while numerous studies have explored the impact of climate change on potential habitats, there is a significant gap in research focused on identifying specific protected areas based on these changes. Additionally, few studies have applied climate change scenarios specifically to mammals, making this study distinctive. The research centers on umbrella and endangered species, which play a crucial role in biodiversity conservation. The aim of this study is to establish a foundational strategy for determining priority conservation areas by analyzing habitat changes driven by climate change.

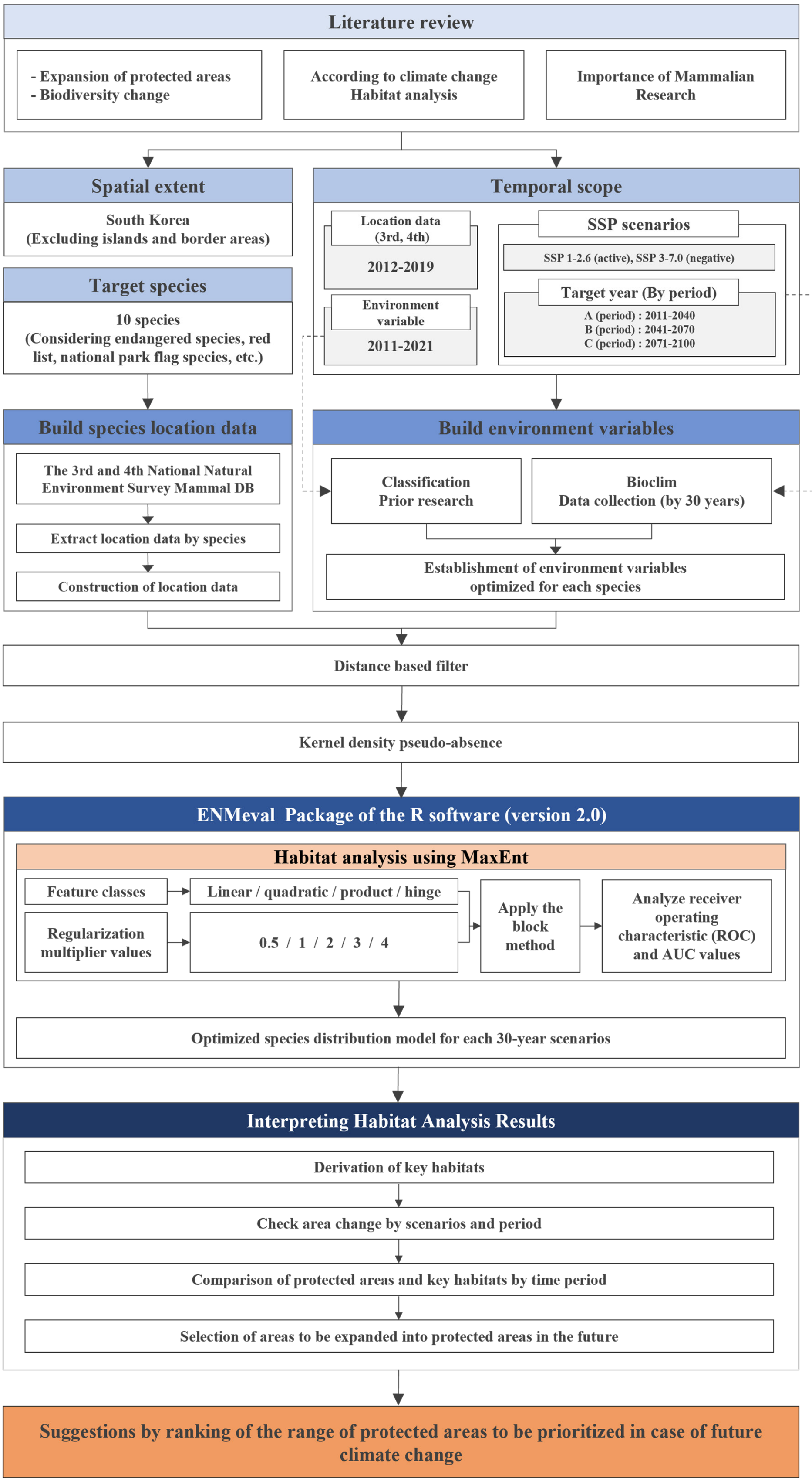
The primary goal of this research is to identify critical mammal habitats and propose these areas as top priorities for protection. The essential habitat data provide an estimate of where target species are most likely to reside, which serves as the basis for prioritizing the selection of protected areas. To assess biodiversity within these areas, the study adopted two Shared Socioeconomic Pathways (SSP) scenarios: SSP1-2.6, representing a positive scenario with successful climate change mitigation policies, and SSP3-7.0, representing a more negative outcome. Species distribution models (SDMs) were then developed for ten target mammal species to qualitatively assess biodiversity within existing protected areas.

2. METHODS

2.1. Flow Chart of Research

To do this research, a literature survey was conducted on important mammals in Korea, biodiversity changes due to the expansion of protected areas, and habitat analysis models affected by climate change. Next, this study created bioclimatic variables based on species location data and environmental variables using SSP1-2.6 and SSP3-7.0 scenarios. This study evaluated the predictive performance of a species distribution model using the ENMeval package (version 2.0) in R software. To do this, the "MaxEnt" model was selected from among SDM models and habitat analysis was conducted based on it. First, a distance-based filter was applied to include only data within a certain distance in the spatial data. Next, a kernel density imputation method was applied to replace missing data with virtual data. Feature classes were classified into four types: linear, quadratic, product, and hinge. The regularization multiplier values were set to 0.5, 1, 2, 3 and 4. Then, block analysis was applied and the receiver operating characteristic (ROC) and area under the curve (AUC) values were evaluated. The species distribution model was optimized for each 30-year scenario through this process. Then, the habitat map was evaluated by dividing it into five grades (grade 1: 9-10, grade 2: 7-8, grade 3: 5-6, grade 4: 3-4, grade 5: 0-2) to distinguish importance. This study hypothesized a double first magnitude (9, 10) as an essential habitat. Finally, based on these results, the areas that require priority selection of protected areas were examined by comparing key and protected areas according to future changes in habitat areas.

Figure 1: Flow chart of research.



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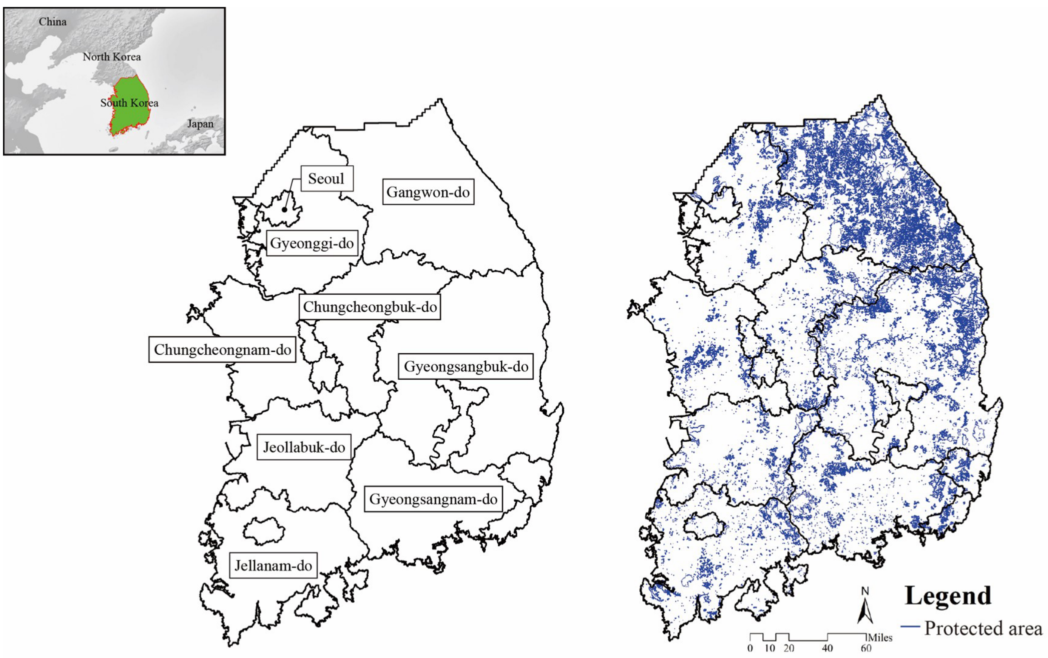
2.2. Spatial Scope

This study aims to examine the entire Korean Peninsula, which lies at 127 degrees east longitude and 37 degrees north latitude. Its total area is 9,994,754 hectares, accounting for about 45% of the Korean Peninsula's overall land area of 22,234,030 hectares (Yi 2021). Due to the geographical influence of the Eurasian continent and the Pacific Ocean, the Korean Peninsula's climate is characterized by continental and monsoon temperatures. Although its altitude is not high, the Korean Peninsula's complex topographic structural features result in relatively steep slopes and diverse topography, making the boundary between mountains and plains unclear compared to other regions. In this study, island regions and border regions with North Korea were excluded from the analysis due to the limited data available, which may result in overestimating or underestimating habitats.

This study selected key protected areas in Korea, including national parks, Baekdudaegan, and ecological natural grade, and compared them with critical habitats. According to the Korea Forest Service, the Baekdudaegan range is a central mountain range of the Korean Peninsula that runs through the major mountain ranges of the Korean Peninsula to Jirisan and is a protected area with important value in various aspects as it forms the core axis of the natural ecosystem. According to the National Institute of Ecology, the ecological and natural grade is a map that classifies the natural environment of mountains, rivers, inland wetlands, lakes, farmlands, and cities throughout the country according to ecological value, naturalness, and scenic value (**Fig 2**).

Figure 2: Site of research.



2.3. Temporal Scope

The temporal scope of this study was determined based on the time when the 3rd and 4th National Natural Environment Surveys, which were used in this research, were conducted. The data from the emergence points of the 3rd and 4th Surveys were used together because the 3rd data can supplement the 4th data, and the entire country was surveyed at equal intervals in a grid unit, ensuring consistency with the 4th data. Moreover, the 3rd survey data allowed this study to select a more uniform survey area than the 2nd survey, providing more appropriate primary data for the wildlife species distribution model. Additionally, the land cover intermediate classification data (2019) used in the analysis was produced closest to completing the 4th National Environmental Survey in 2018, which helped compensate for bias. By setting the temporal range from 2012 to 2019, this study established environmental spatial information to produce ecological variables.

2.4. Target Species and Appearance Location Data

The appearance data for target species were obtained from the 3rd and 4th National Natural Environment Surveys. Species with at least 50 occurrence records were selected to ensure sufficient data, with additional consideration given to endangered wildlife (Class I·II), IUCN Red List Vulnerable (VU) species, and national park flagship species. Based on previous biodiversity and habitat analysis research, 10 target mammals were identified: wild boar (*Sus scrofa*), water deer (*Hydropotes inermis*), wild cat

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(*Prionailurus bengalensis*), badger (*Meles leucurus*), otter (*Lutra lutra*), marten (*Martes flavigula*), goat (*Naemorhedus caudatus*), flying squirrel (*Pteromys volans*), roe deer (*Capreolus pygargus*), and Manchurian weasel (*Musan Mustela nivalis*). Although *Sus scrofa* and *Capreolus pygargus* did not meet the selection criteria, they were included due to their wide distribution in Korea. Additional data were added to reduce bias in creating the binomial map.

The location data of the 10 target mammal species were extracted from data collected during the 3rd and 4th National Natural Environment Surveys. During the 3rd survey, species located in urban areas (residential, commercial, industrial, recreational, public facilities, and transportation) were excluded from the land cover intermediate classification data (2019) due to temporal changes.

Spatial autocorrelation occurs when sampling sites are not independent due to proximity, leading to inaccurate model predictions and evaluations even without other biases (F. Dormann et al. 2007). The sgeostat package in the R software (R Development Core Team, 2008) was used to evaluate the spatial autocorrelation of niche model errors by calculating semivariograms. Semivariograms measured the variance between pairs of points as a function of their spatial separation distance. The end at which the semivariance reached a plateau was known as the "range," beyond which the semivariance between pairs of points was considered spatially independent. We used the ditance-based semivariogram technique to remove spatial autocorrelation. The number of occurrence points decreased from 29,090 to 17,875 after the filtering process (**Table 1**, See **Appendix 1**).

MaxEnt models often use occurrence records with spatial bias towards accessible or well-surveyed areas. Bias files help select background data with similar bias, improving SDM performance and prediction accuracy for species datasets (Phillips et al. 2009). The study used Gaussian kernel density estimation to create a bias file, transforming points into a continuous probability surface. Bias values of 1 indicate no sampling bias, while higher values reflect increased sampling bias during background point selection (Brown 2014).

To ensure the independence between training and test data, it is crucial to prevent spatial autocorrelation between them (Sillero and Barbosa 2021). The study used the ENMevaluate function from the ENMeval package for spatially independent cross-validation with background masking. The block method was useful for analyzing model transfer across space or time under non-analog conditions (Wenger and Olden 2012).

Table 1: Selection criteria for target species.

Scientific Name	Count (Before filter)	Count (After filter)	Endangered Wildlife Rating	National Park Flagship Species	Red List Vulnerability Level
Sus scrofa	5,551	3,625	-	-	-
Hydropotes inermis	11,207	6,917	-	-	VU
Prionailurus bengalensis	4,313	2,856	I I	O	VU
Meles leucurus	2,932	1,898	-	-	NT
Lutra lutra	1,876	126	I	O	VU
Martes flavigula	954	706	I I	-	VU
Naemorhedus caudatus	140	30	I	O	VU
Pteromys Volans	277	254	I I	O	VU
Capreolus pygargus	1,818	1,456	-	-	-
Musan Mustela nivalis	22	7	I I	-	VU
※ Legend: VU (Weak), NT(Quasi-Threat)					

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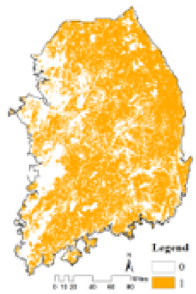
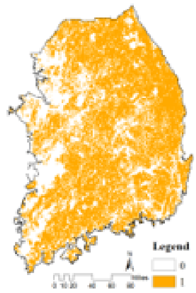
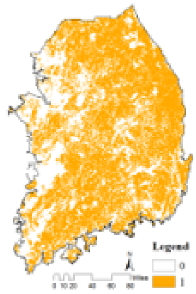
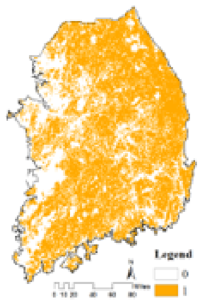
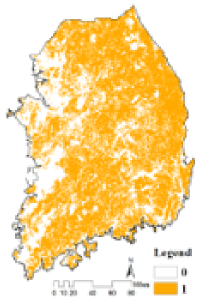
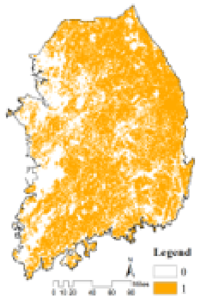
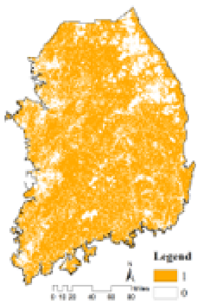
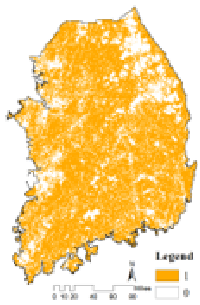
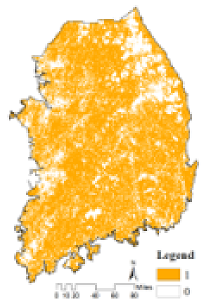
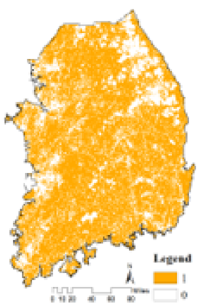
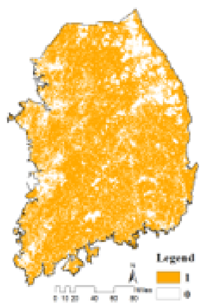
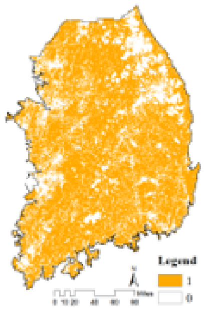
Appendix 1: Individual species results (ongoing)

1. *Sus scrofa*		
		
A SSP 1-2.6 (2011-2040)	B SSP 1-2.6 (2041-2070)	C SSP 1-2.6 (2071-2100)
		
A SSP 3-7.0 (2011-2040)	B SSP 3-7.0 (2041-2070)	C SSP 3-7.0 (2071-2100)
2. *Hydropotes inermis*		
		
A SSP 1-2.6 (2011-2040)	B SSP 1-2.6 (2041-2070)	C SSP 1-2.6 (2071-2100)
		
A SSP 3-7.0 (2011-2040)	B SSP 3-7.0 (2041-2070)	C SSP 3-7.0 (2071-2100)

2.5. Method for Constructing Environmental Variables

To evaluate the habitat suitability of the target species, a comprehensive literature review was conducted based on 22 preferred habitat environments for each species. A list of applicable environmental variables for each species was generated from the reviewed literature. To determine the importance of each variable, the jackknife method was employed, and the impact of quantitative environmental factors was assessed (Zhao et al. 2021). The final list of variables included land use (15 items), Topographic (5 items), forests (6 items), protected area (1 item) and climate (21 items). The types and sources of environmental

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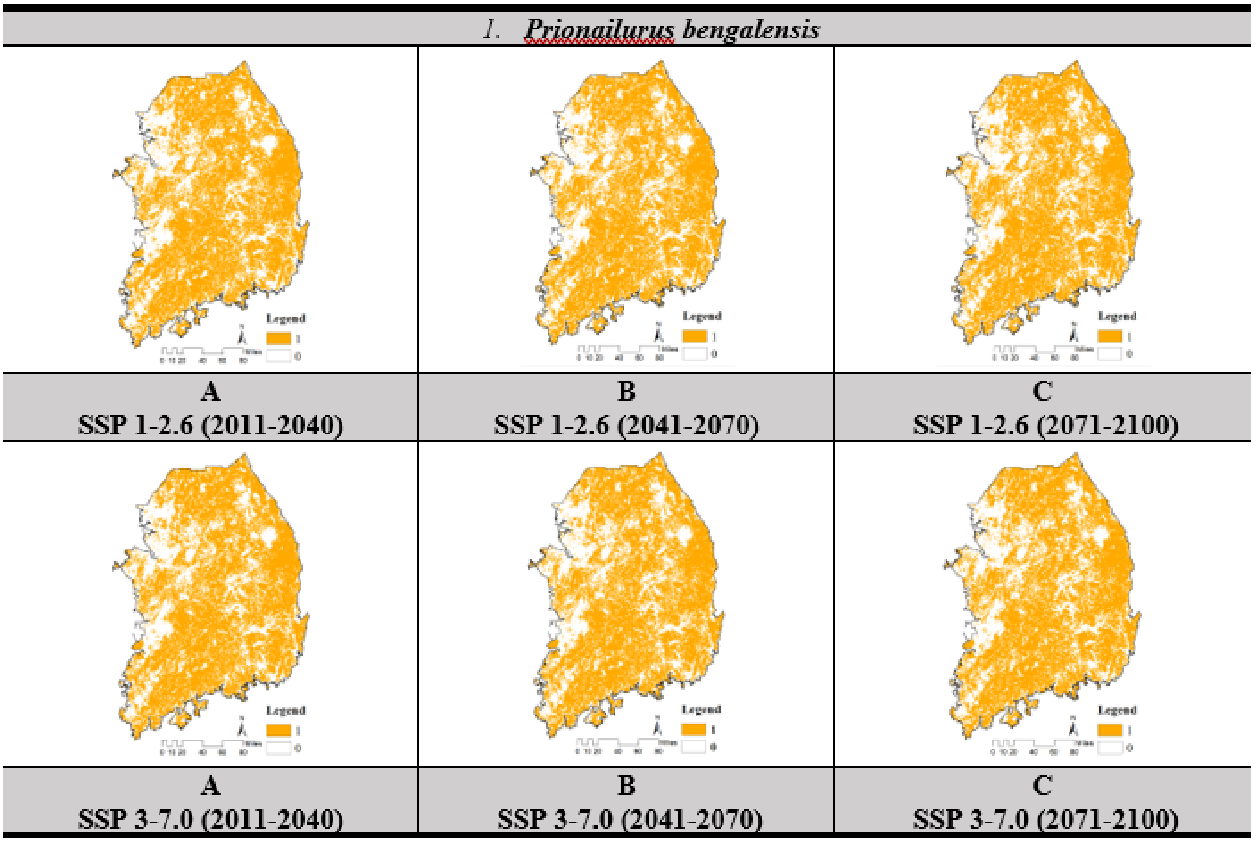
variables can be found in **Appendix 2**, while **Appendix 3** provides a detailed list of environmental variables applied to each species.

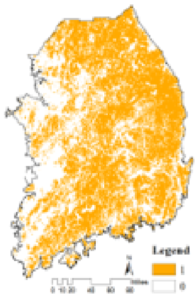
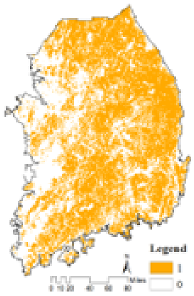
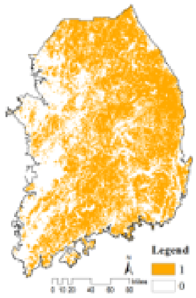
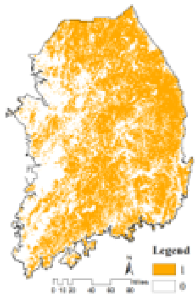
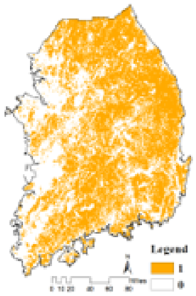
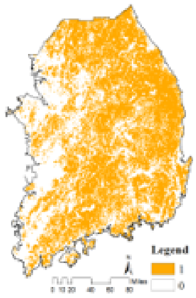
The final list of environmental variables used in this study included land use (15 items), topography (5 items), forests (6 items), protected areas (1 item), and climate (21 items). Data sources and types are detailed in Appendix 2, while Appendix 3 lists the variables applied to each species. The study collected data on land cover classifications (13 items, 2019), Digital Elevation Models (4 items, 2012), national forest maps (4 items, 2019), forest road networks (1 item, 2020), hiking trails (1 item, 2020), protected areas (1 item, 2019), river networks (1 item, 2011), minimum temperature maps (1 item, 2021), NDVI maps (1 item, 2020), and bioclimatic variables (20 items, 2022). Environmental variable surveys were aligned with species distribution data from the fourth national natural environment survey, conducted until 2018. Data from 2011-2021 were selected for their high resolution and reliability, with LULC having the highest resolution at 1m. Distance-based variables were aligned to the lowest resolution variable (climate data at 1km). ArcGIS's "Euclidean distance" method was used for distance calculations related to hiking trails, roads, land cover types, and forest road networks. All collected data were converted to ASCII files for species distribution analysis.

This study utilized the recently adopted greenhouse gas emission scenarios of SSP, encompassing SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, featured in the IPCC Sixth Assessment Report to predict the future habitat changes of ten target mammalian species. We selected SSP1-2.6 and SSP3-7.0 as they represent the standard pathways of the SSP scenarios. SSP1-2.6 assumes a proactive approach to climate change mitigation, with reduced reliance on fossil fuels and environmentally sustainable economic growth by developing renewable energy technologies. In contrast, SSP3-7.0 predicts a vulnerable social structure due to delayed technological development in climate change, taking a passive approach to mitigation. The selected scenarios consider the potential for diverse social and economic developments while incorporating environmental constraints, such as reducing carbon dioxide emissions. Consequently, SSP1-2.6 and SSP3-7.0 were regarded as the most suitable scenarios for predicting future climate change responses and analyses and were thus chosen for this study (NIBR 2022).

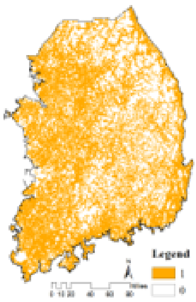
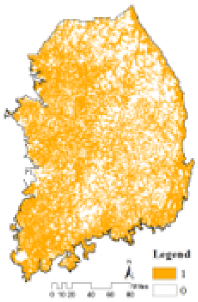
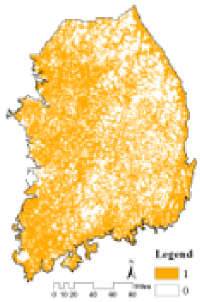
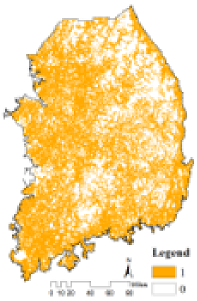
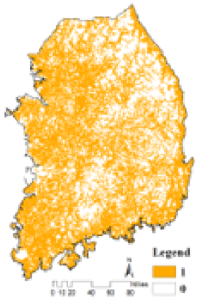
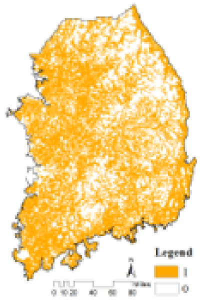
For the bioclim period, the CIMP6's past reproductive period was set to end in 2014 and forecast data for each SSP scenario were available for the period after 2015. In this study, a period of 30 years, including the present (Period A: 2011-2040), the future (Period B: 2041-2070), and a further future period (Period C: 2071-2100), were defined for analysis. Nineteen variables were converted and analyzed from the present to the future in 30-year intervals, using the same method as the general environmental variables (NIBR 2022).

Appendix 2: Individual species results (ongoing).

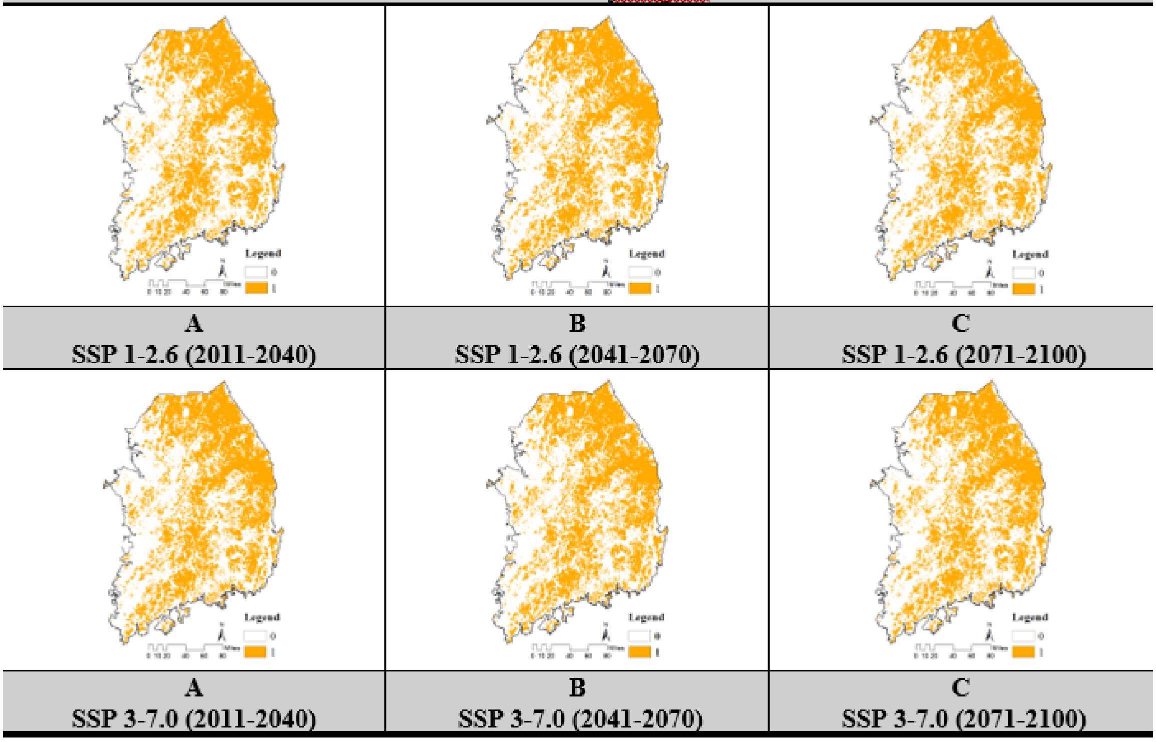


2. *Meles leucurus*		
		
A **SSP 1-2.6 (2011-2040)**	**B** **SSP 1-2.6 (2041-2070)**	**C** **SSP 1-2.6 (2071-2100)**
		
A **SSP 3-7.0 (2011-2040)**	**B** **SSP 3-7.0 (2041-2070)**	**C** **SSP 3-7.0 (2071-2100)**

Appendix 3: Individual species results (ongoing)

1. *Lutra lutra*		
		
A **SSP 1-2.6 (2011-2040)**	**B** **SSP 1-2.6 (2041-2070)**	**C** **SSP 1-2.6 (2071-2100)**
		
A **SSP 3-7.0 (2011-2040)**	**B** **SSP 3-7.0 (2041-2070)**	**C** **SSP 3-7.0 (2071-2100)**

2. *Martes flavigula*



A SSP 1-2.6 (2011-2040) | B SSP 1-2.6 (2041-2070) | C SSP 1-2.6 (2071-2100)

A SSP 3-7.0 (2011-2040) | B SSP 3-7.0 (2041-2070) | C SSP 3-7.0 (2071-2100)

Table 2: Environmental variable list.

No.	Category	Year	Name	Type	Sources
1			Distance from resident	Continuous	
2			Distance from industry	Continuous	
3			Distance from commerce	Continuous	
4			Distance from paddy	Continuous	
5			Distance from farm	Continuous	
6			Distance from orchard	Continuous	
7			Distance from river	Continuous	
8	Land Cover	2019	Distance from forest	Continuous	(Ministry of Environment 2019)
9			Distance from softwood	Continuous	
10			Distance from broadleaf	Continuous	
11			Distance from mixed	Continuous	
12			Distance from bare	Continuous	
13			LULC	Categorical	
14			Distance from trail	Continuous	(Service 2020)
15			Distance from road	Continuous	(Ministry of Land 2020)
16			Altitude	Continuous	
17			Slope	Continuous	
18	Topographic	2012	Aspect	Continuous	(Market 2012)
19			Hillshade	Continuous	
20			Stream order	Categorical	(Wamis 2011)
21			Density	Categorical	
22			Year	Categorical	
23		2019	Diameter	Categorical	(Service 2019)
24	Forests		Forests & Grasslands type	Categorical	
25			Distance from forest road	Continuous	(Service 2020)
26		2020	NDVI	Continuous	(MODIS 2020)

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27	Protected area	2019	The presence or absence of protected areas	Continuous	(KDPA 2019)
28	Climate	2021	Temperature range	Continuous	(Administration 2021)
29		2022	bio01~bio19	Continuous	(NIBR 2022)

2.6. Key Habitat Analysis Model (MaxEnt)

As an illustration of species distribution modeling (SDM) for the research and conservation of target species (Feijó et al. 2022), MaxEnt was used as a probability model to identify priority areas for protected areas. MaxEnt, or Maximum Entropy Modeling, is a machine learning method commonly employed in SDM that utilizes species' occurrence data to generate model predictions (Stolar and Nielsen 2015). To create ecological niche models (ENMs) for a target species, this study employed Maxent, one of the most commonly used presence-only methods available in the ENMeval Package of the R software (version 2.0) (Valavi et al. 2019). In this study, the output format of MaxEnt was set to "cloglog" after refining the occurrence data and environmental variables for each of the 10 target mammal species. The cloglog setting is used because it offers greater accuracy in predicting areas with high occurrence probability and generates stronger predictions for identifying key habitat areas (Phillips et al. 2017).

To attain a balance between goodness-of-fit and model complexity, this study conducted a series of model runs with varying settings for feature classes ("L", "LQ", "LQH", "LQHP") and regularization multiplier values (0.5, 1, 2, 3, 4). To assess the performance of the ecological niche models (ENMs), AUCtest, AUCdiff, and Continuous Boyce Index (CBI) were calculated. AUCtest was computed using the complete set of background locations across all k bins to allow for comparison among k-fold iterations. The final model prediction was generated by performing cross-validation four times, analyzing Receiver Operating Characteristic (ROC) and Area Under the Curve(AUC) values for high reliability (Phillips et al. 2017).

The AUC values ranged from 0.6-0.7 (low confidence), 0.7-0.8 (moderate confidence), 0.8-0.9 (high confidence), and 0.9-1.0 (very high confidence), and this confidence range of the model output was checked. AUCdiff was derived by subtracting the testing AUC from the training AUC. Models with high AUCdiff values were considered to be overfit. In addition, CBI was utilized to evaluate the transferability of MAXENT models to predicted geographic areas. The Boyce Index produces continuous values ranging from -1 to +1, where positive values indicate good model performance with consistent predictions of actual presence data. CBI assessed model transferability, with positive values indicating good performance and negative values showing counter-predictions. The importance of environmental variables was measured using Percentage contribution and Permutation importance methods. Spearman analysis was used to exclude variables with a correlation coefficient above 0.7 to avoid multicollinearity.

In this study, we evaluated the performance of the MaxEnt model using probabilistic analysis. To evaluate the performance of the model, we used sensitivity, specificity, overall accuracy, and Cohen's kappa statistic. These measures indicate how well the model predicts the actual value. The kappa statistic value is between -1 and +1, with a value closer to 1 indicating better model performance. We extracted the spatial distribution of hotspots by performing overlay analysis on the results of all probability outputs with equal weights, in order to reduce the overfitting error that can occur in binary maps (Gilani et al. 2020).

The study categorized the future into three 30-year periods (A, B, C) and created habitat maps ranked from grade 1 (most critical) to grade 5. Grade 1 areas were extracted to identify key habitats under SSP1-2.6 and SSP3-7.0 scenarios. These areas were compared with existing protected regions to assess their future value as critical habitats.

3. RESULTS

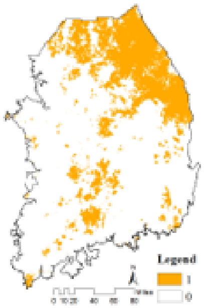
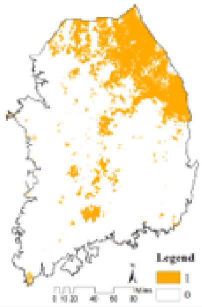
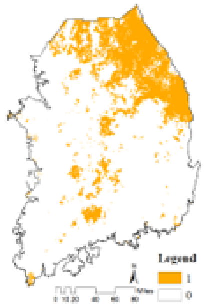
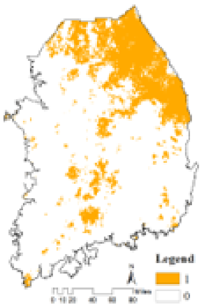
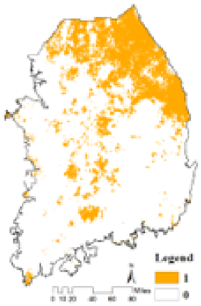
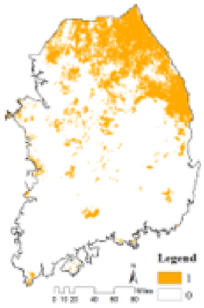
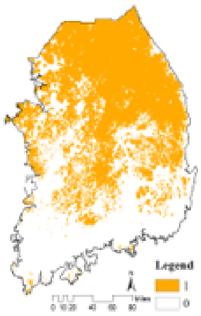
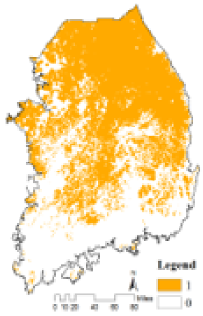
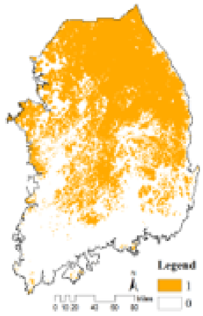
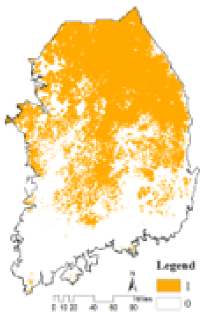
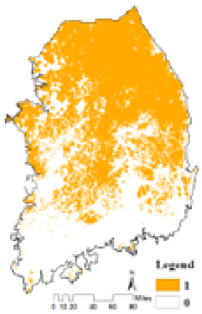
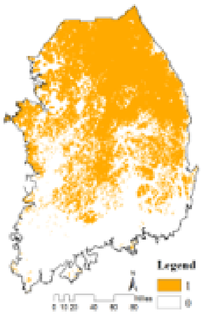
3.1. Individual Mammalian Habitat Analysis Model

After running MaxEnt for each SSP scenario, it has been confirmed that the most impactful environmental variables are "distance from forest," "distance from paddy," "LULC," "stream order," "altitude," "distance from orchard," and "bio08" (See Appendix 4).

The study found that "distance from forest" was the most influential variable for *Musan Mustela nivalis* (47.16%), consistent across all periods. For *Hydropotes inermis*, "distance from paddy" was most important (37.59%) in period A of SSP 1-2.6, while *Prionailurus bengalensis* was most affected by "LULC" (26.54%) in period C of SSP 3-7.0. *Lutra lutra* was influenced by "stream order" (47.07%), and *Martes flavigula* by "altitude" (37.55%) in period C of SSP 1-2.6. *Naemorhedus caudatus* was most affected by "distance from orchard" (45.81%) in period A of SSP 3-7.0, and for *Pteromys volans*, "bio08" had the highest contribution (35.89%) in period B of SSP 1-2.6. For *Capreolus pygargus*, the most influential variable differed: "bio08" in SSP 1-2.6 and "distance from forest" in SSP 3-7.0 (See **Appendix 4**).

This study assessed the reliability of habitat change for 10 target mammals by averaging AUC values across three periods (A, B, C) under SSP 1-2.6 and SSP 3-7.0. The AUC values ranged from 0.7 to 0.8, indicating adequate reliability. *Musan Mustela nivalis* had the lowest AUC (0.747), while *Sus scrofa, Hydropotes* *inermis, Prionailurus bengalensis, Meles leucurus*, and *Capreolus pygargus* had the highest AUC (0.784). The remaining species had AUC values between 0.764 and 0.774 (See **Appendix 5**).

Appendix 4: Individual species results (ongoing)

1. *Naemorhedus caudatus*		
		
A **SSP 1-2.6 (2011-2040)**	**B** **SSP 1-2.6 (2041-2070)**	**C** **SSP 1-2.6 (2071-2100)**
		
A **SSP 3-7.0 (2011-2040)**	**B** **SSP 3-7.0 (2041-2070)**	**C** **SSP 3-7.0 (2071-2100)**
8. *Pteromys volans*		
		
A **SSP 1-2.6 (2011-2040)**	**B** **SSP 1-2.6 (2041-2070)**	**C** **SSP 1-2.6 (2071-2100)**
		
A **SSP 3-7.0 (2011-2040)**	**B** **SSP 3-7.0 (2041-2070)**	**C** **SSP 3-7.0 (2071-2100)**

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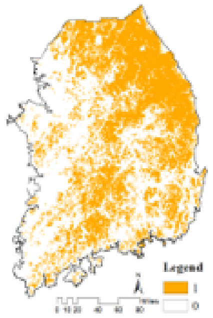
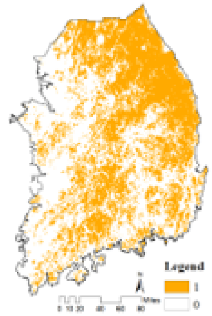
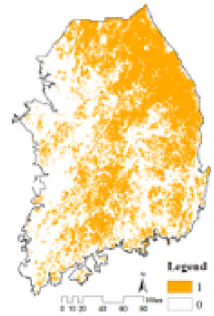
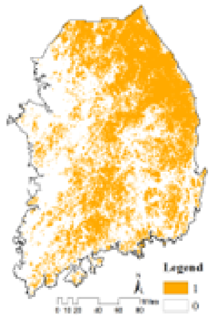
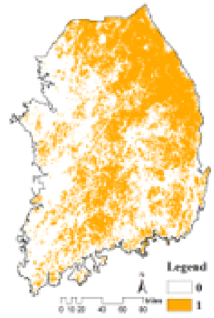
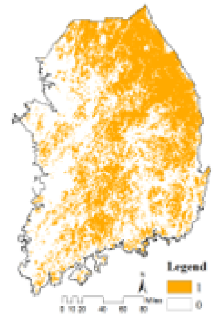
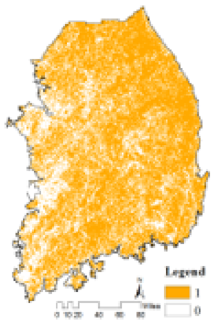
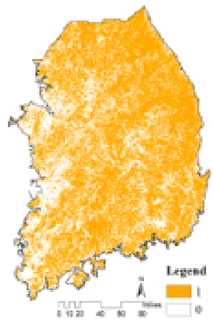
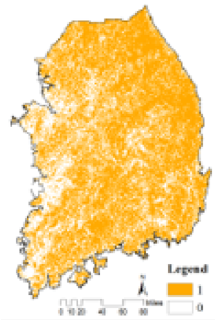
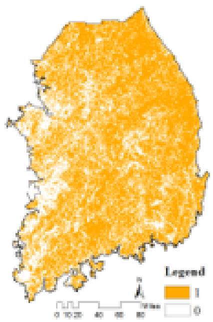
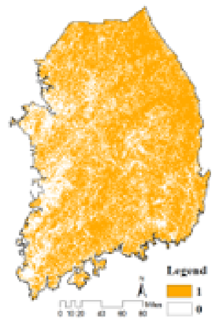
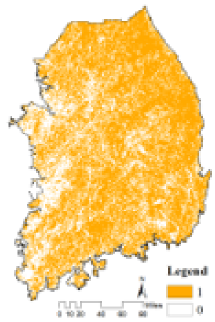
Appendix 5: Individual species results

3. *Capreolus pygargus*		
		
A **SSP 1-2.6 (2011-2040)**	**B** **SSP 1-2.6 (2041-2070)**	**C** **SSP 1-2.6 (2071-2100)**
		
A **SSP 3-7.0 (2011-2040)**	**B** **SSP 3-7.0 (2041-2070)**	**C** **SSP 3-7.0 (2071-2100)**

4. *Musan Mustela nivalis*		
		
A **SSP 1-2.6 (2011-2040)**	**B** **SSP 1-2.6 (2041-2070)**	**C** **SSP 1-2.6 (2071-2100)**
		
A **SSP 3-7.0 (2011-2040)**	**B** **SSP 3-7.0 (2041-2070)**	**C** **SSP 3-7.0 (2071-2100)**

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3.2. Characteristics of individual mammalian habitat distribution in period A (2011-2040)

This study investigated the habitat distribution characteristics of individual mammals for different scenarios and periods. The analysis results, focusing on period A, are as follows. *Musan Mustela nivalis* is found to be able to inhabit all of South Korea. *Sus scrofas, Prionailurus bengalensis*, and *Meles leucurus* are likely to inhabit most areas of South Korea, excluding the western region. *Hydropotes inermis* are found in all regions of Korea except for the mountainous areas of Gangwon-do. *Martes flavigula* and *Capreolus pygargus* have similar habitat distribution patterns, and they are likely to inhabit areas, excluding the western region and some areas of Gyeongsangnam-do. The habitats of *Lutra lutra* and *Naemorhedus caudatus* are distributed according to the habitat characteristics of each species. *Pteromys volans* is found to inhabit the remaining areas of South Korea, excluding the southern region.

Lutra lutra is likely to inhabit areas near rivers, as is its habitat characteristic. *Naemorhedus caudatus* is a species that inhabits steep cliffs, and it is most likely to inhabit areas in Gangwon-do and some areas of Gyeongsangbuk-do, which are the most rugged mountainous regions in South Korea (See Appendix 6).

3.3. Characteristics of individual mammalian habitat distribution in period B (2041-2070) and C (2071-2100)

A study of habitat distribution changes for future periods B and C found that *Naemorhedus caudatus* had the most significant shift in habitat area. In the period B of SSP 1-2.6, the habitat area decreased but gradually recovered in the period C. On the other hand, in the case of SSP 3-7.0, it was confirmed that the habitat area decreased significantly as the period C progressed. *Pteromys volans* also showed changes in habitat area depending on the scenario. In SSP 1-2.6, the area increased as the period C progressed, but in SSP 3-7.0, it decreased as the period C progressed. *Meles leucurus* slightly decreased in habitat area in the period B of SSP 1-2.6 but recovered in the period C. On the other hand, it was confirmed that the habitat area decreased as the period C progressed in SSP 3-7.0. *Lutra lutra* showed increased habitat area as the period C progressed in SSP 1-2.6. However, in SSP 3-7.0, the area slightly increased in the period B but decreased again as the period C progressed. *Sus scrofa, Hydropotes inermis, Prionailurus bengalensis, Martes flavigula, Capreolus pygargus*, and *Musan Mustela nivalis* showed insignificant changes in both scenarios, compared to the four species mentioned above (See Appendix 6).

3.4. Key Habitat Coverage

The change in the area of key habitats was derived from the results of the habitat map evaluation for the periods A and C (Fig 3). The study compared changes in key habitat areas between SSP 1-2.6 and SSP 3-7.0 scenarios. In SSP 1-2.6, key habitats increased by 689 km² from period A to C, then decreased by 930 km². In SSP 3-7.0, key habitats grew by 890 km² but later declined by 974 km². The larger area change in SSP 3-7.0 suggests that passive climate change mitigation could reduce ecological stability due to environmental impacts. In this study, grade 1 of the habitat map was considered key habitat. Under the SSP 1-2.6 scenario, key habitats in period A covered 16,436 km², mainly in Gangwon-do, Gyeongsangbuk-do, Chungcheongbuk-do, and the DMZ. In period B, the area decreased to 12,128 km², a reduction of 1,308 km². By period C, the area slightly recovered to 12,344 km². The distribution of key habitats remained consistent across all periods (Fig 4a). In the SSP 3-7.0 scenario, key habitats in period A covered 13,168 km², concentrated in mountainous regions and the DMZ. The area increased to 13,355 km² in period B but decreased to 12,250 km² in period C, reversing the trend of growth from period A to B (Fig 4b).

This study analyzed changes in key habitats within protected areas. In the SSP 1-2.6 scenario, the habitat area decreased in period B but showed recovery in period C, similar to the overall study area. In contrast, the SSP 3-7.0 scenario showed an increase in grade 1 areas in period B and a decrease in period C. However, key habitats within protected areas continuously decreased from period A to C (Fig 4d).

The most striking difference between the maps of the entire study area and the habitat within the protected area is that in the period B, the area of the key habitat in the SSP 3-7.0 scenario was larger than that of the SSP 1-2.6 scenario, but in the period C, the area of the key habitat in the SSP 1-2.6 scenario was larger than that of the SSP 3-7.0 scenario.

In the case of the SSP 3-7.0 scenario, the total habitat area decreased by 6.97% in the period C, while in the SSP 1-2.6 scenario, the total habitat area decreased by 9.74% in the period B but recovered by 1.78% in the period C. In addition, it was confirmed that the area of habitats with grades 2 to 5 showed a similar pattern.

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Figure 3.

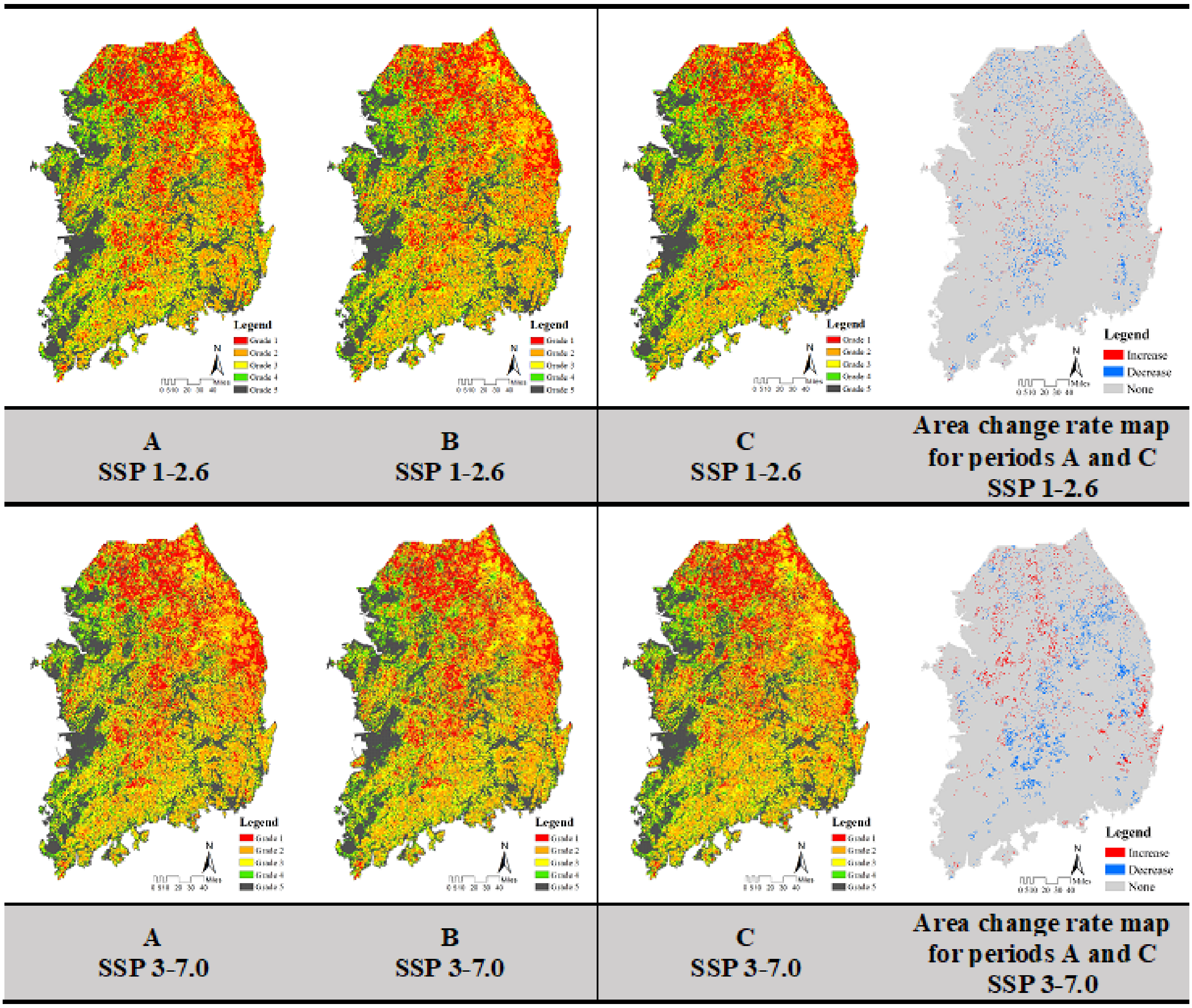

Figure 3: Map of key habitats according to SSP 1-2.6 and SSP 3-7.0 scenarios. A (2011-2040), B (2041-2070), and C (2071-2100) represent periods of 30 years each in both scenarios. Legends 1-5 indicate the relative importance of suitable habitats. Grade 1 represented the most critical areas for key habitats, whereas grade 5 indicates areas less likely to be considered vital habitats. The area change rate map for periods A and C is a map that shows the area change rate for periods A and C. Red indicates areas where the area has increased, and blue indicates areas where the site has decreased

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Figure 4.

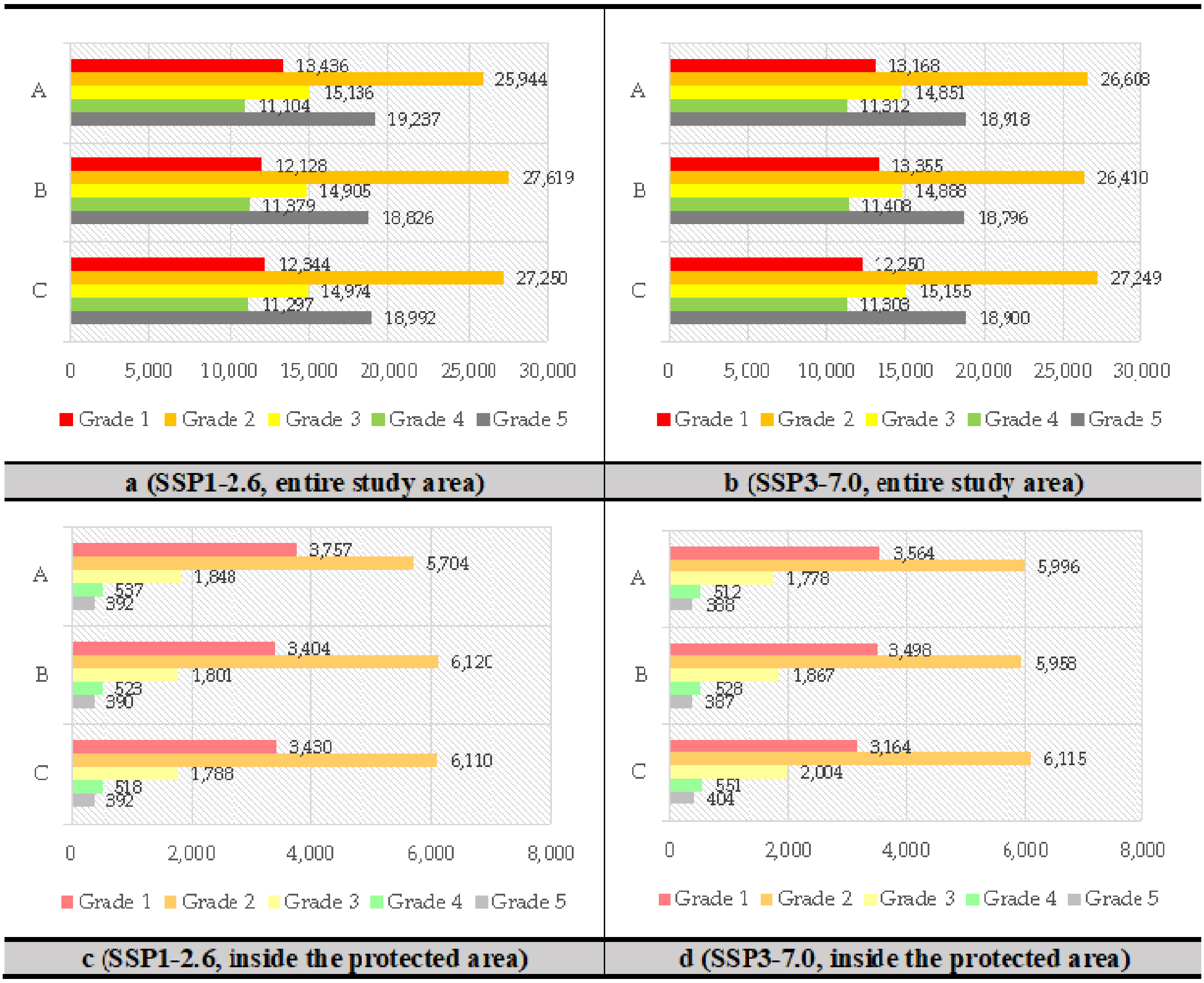

Figure 4: Changes in key habitat area and key habitat grade by target period in SSP 1-2.6 and SSP 3-7.0 scenarios. A (2011-2040), B (2041-2070), and C (2071-2100) represent periods of 30 years each in both scenarios. Legends 1-5 indicate the relative importance of suitable habitats. Grade 1 represents the most critical areas for key habitats, whereas grade 5 indicates areas less likely to be considered vital habitats. The table above shows the location of each grade in the entire research area, and the table below shows the size of each grade in the protected area. The units of all tables are square kilometers (km^2).

3.5. Comparison of Key Habitats and Protected Areas

This study compared key habitats with Korea's terrestrial protected areas using data from the Korea Protected Areas Integrated Database (KDPA) and the National Park Service. National parks and the Baekdudaegan mountain range were selected for comparison, along with Grade 1 ecological naturalness areas, which hold the highest ecological value. The analysis focused on protected areas with the greatest overlap with key habitats to assess their ecological significance and conservation potential. The protected area area ratio (%) was calculated by dividing the protected area area by the total area of the country (in the case of ecological naturalness, the total area of ecological naturalness was set as the total area of the country). The following table includes some areas of marine protected areas, but Hallasan National Park located in Jeju Island was excluded from this table as it is classified as a remote island region (Table 3).

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Table 3: This study analyzed a subset of terrestrial protected areas in South Korea. The analysis was conducted across the entire range of protected areas without being divided by type. Data on ecological naturalness were obtained from the National Institute of Ecology, and data on Baekdudaegan and national parks were obtained from the Korea Data Portal Agency (KDPA)

Category	Name			Area (km^2)	Count	Area Ratio (%)
Ministry of Environment	National Park	Mountain type	Bukhansan	3,257.5	22	16.85
			Byeonsanbando			
			Chiaksan			
			Deogyusan			
			Gayasan			
			Gyeryongsan			
			Jirisan			
			Juwangsan			
			Mudeungsan			
			Naejangsan			
			Odaesan			
			Seoraksan			
			Sobaeksan			
			Sokrisan			
			Taebaeksan			
			Wolchulsan			
			Woraksan			
		Coastal type	Hallyeohaesang	1,212.16		
			Dadohaehaesang			
			Taeanhaean			
			Byeonsanbando			
		Historical type	Gyeongju National Park	136.55		
Forest Service	Baekdudaegan Protected Area			2,646	1	6.56
National Institute of Ecology	Ecological Natural Map Grade 1			8,056.60	-	8.1
	Ecological Natural Map Grade 2			39,008.10	-	39.3
	Ecological Natural Map Grade 3			41,125.50	-	41.5
	Separate management area			10,948.40	-	11.0
※ Source: KOREA Database on Protected Areas (KDPA), National Institute of Ecology						

A comparison of the selected protected areas with the key habitats of each scenario and time period showed that grade 1 areas were primarily concentrated near protected areas in the forests of Gangwon and Gyeongsangbuk-do provinces. In the period A, both scenarios had a relatively even distribution of key habitats, but in the periods B and C, grade 1 areas in SSP 3-7.0 decreased noticeably compared to SSP 1-2.6, transitioning to grades 2-3 (Fig 5).

Next, we found that grade 1 areas were also concentrated near protected areas located in the DMZ, some areas of Gyeonggi Province, and some forest areas of Gangwon Province. In these areas, the area of grade 1 habitats decreased slightly in the period B under the SSP 1-2.6 scenario, but it recovered in the period C as grades 2-4 areas transitioned to grade 1. Under the SSP 3-7.0 scenario, the area of key habitats slightly increased in the period B as some grades 2-3 areas transitioned to grade 1. However, this increase was short-lived, as these areas fell back to grades 2-4 in the period C, leading to a decrease in the overall area of key habitats (Fig 6).

Figure 5.

Figure 5: Comparison of critical habitats and protected areas by period (A: 2011-2040, B: 2041-2070, and C: 2071-2100). The area in question is a forest area located between Gangwon-do and Gyeongsangbuk-do. The three small maps below represent grades 1, 2, and 3 from left to right.

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Figure 6.

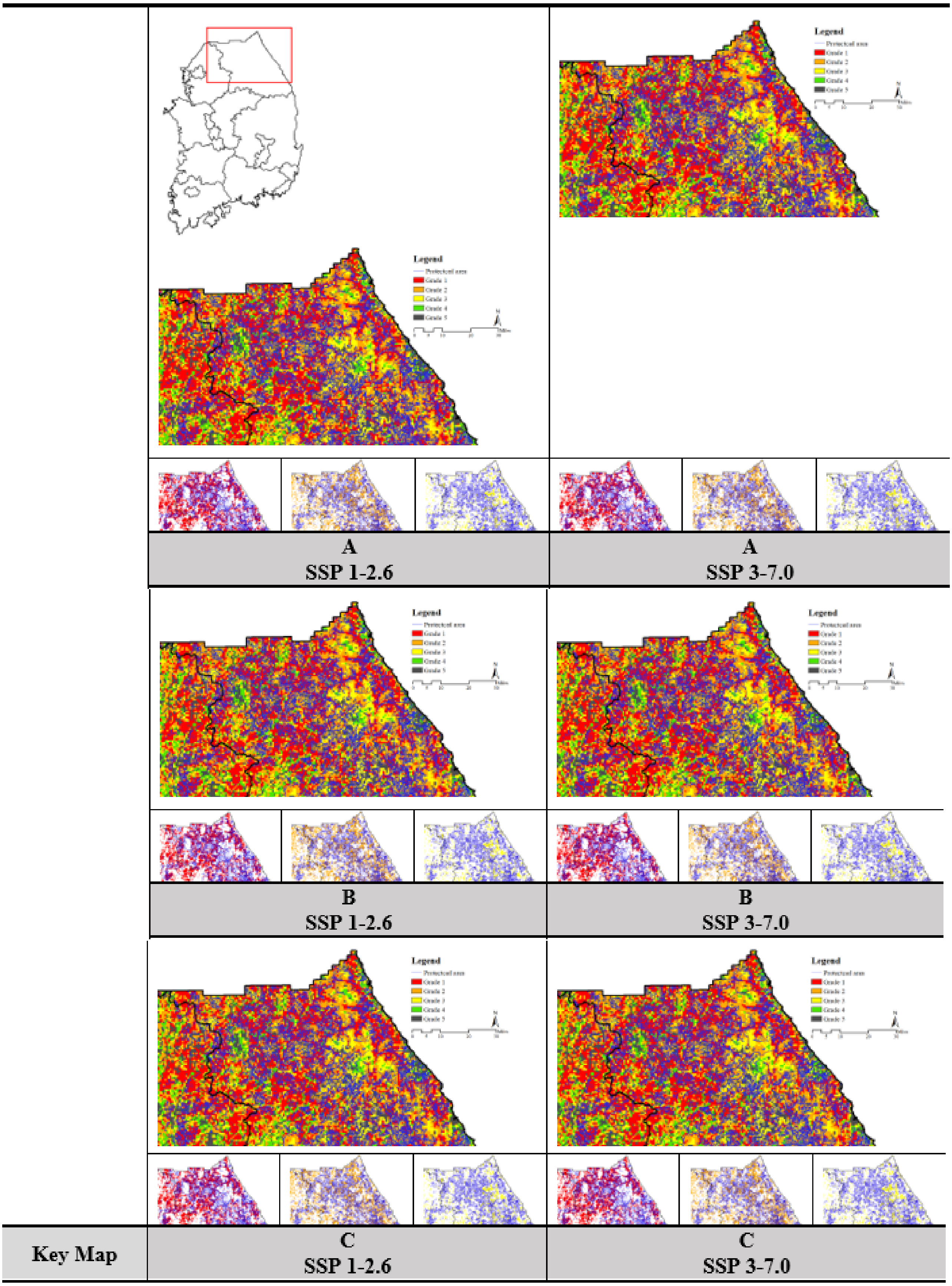

Figure 6: Comparison of critical habitats and protected areas by period (A: 2011-2040, B: 2041-2070, and C: 2071-2100). The area is a combination of the DMZ, eastern Gyeonggi Province, and some forest areas in Gangwon Province. The three small maps below represent grades 1, 2, and 3 from left to right.

4. DISCUSSION

This study analyzed critical habitats under SSP 1-2.6 and SSP 3-7.0 scenarios, representing active and passive climate change mitigation policies, respectively. The total overlapping area of grade 1 regions was larger for SSP 1-2.6 (1,741 km²) compared to SSP 3-7.0 (1,043 km²). The overall overlapping key habitat area between the two scenarios was 9,131 km², with a projected 6.3% reduction in key habitats under SSP 3-7.0, highlighting the importance of active climate change mitigation to prevent habitat loss.

Protected areas are essential for conserving mammal habitats, enhancing connectivity, and buffering environmental disturbances. As climate change shifts habitat distributions, expanding protected areas becomes crucial for maintaining biodiversity. The study identified southern Gangwon-do and northern Gyeongsangbuk-do as top priority regions for expanding protected areas due to their concentration of target species and resilience to climate change (Fig 7a).

The second priority regions include areas near the DMZ and eastern Gyeonggi Province (Fig 7b), where many critical habitats lie outside current protected areas. Expanding protected areas in these regions would enhance connectivity and help preserve mammal habitats as they shift due to climate change. These identified critical habitats should be prioritized for future conservation efforts to ensure long-term biodiversity protection.

Figure 7.

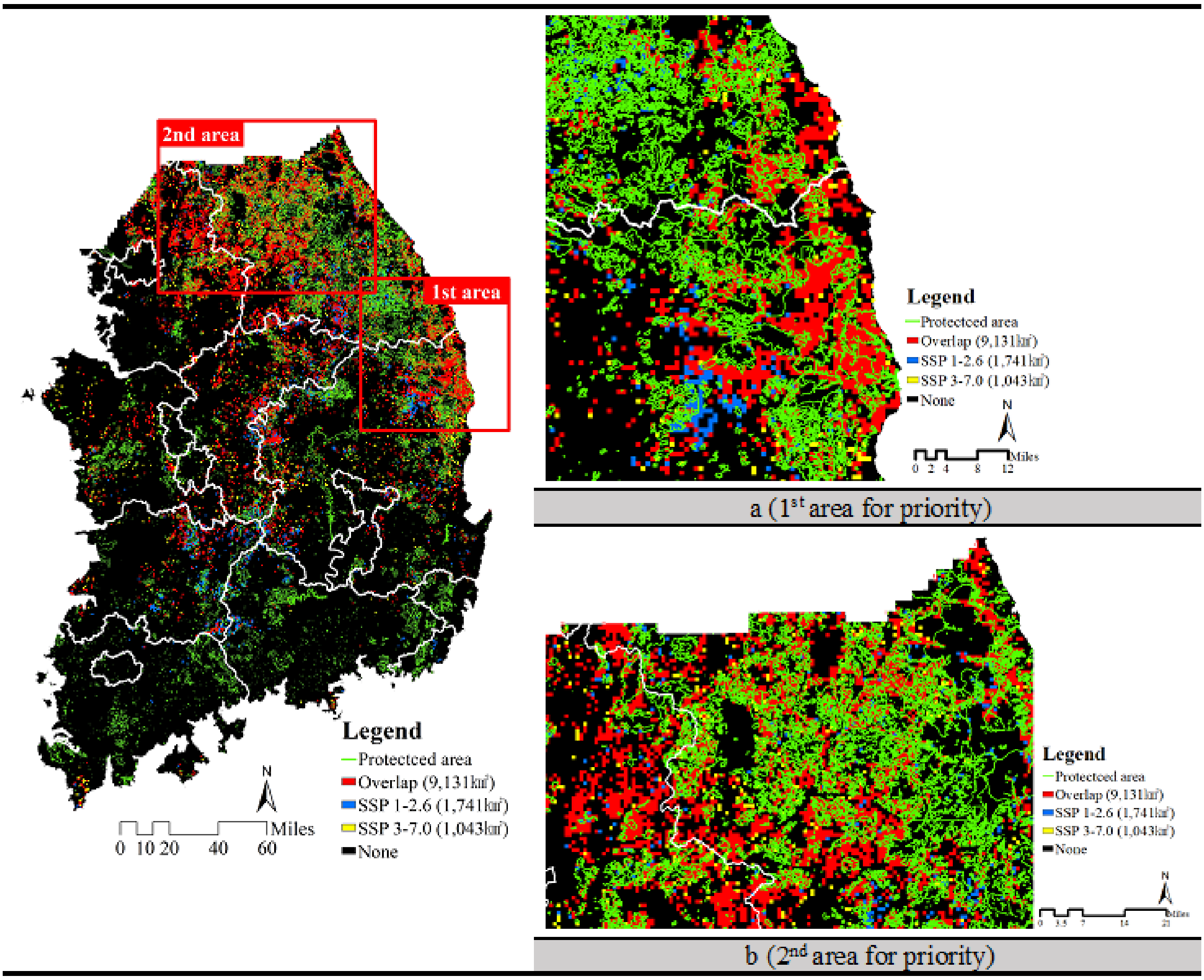

Figure 7: Areas to consider for expanding protected areas based on overlapping key habitat grade 1 places by SSP scenario. The red represents the combined results of critical habitat areas for all periods (A, B, and C) under SSP 1-2.6 and SSP 3-7.0 scenarios. The blue and yellow represent the key habitat areas of each scenario. In addition, the area values of the two SSP scenarios in the legend indicate the area values of the overlapping regions. The 1st area for priority is forest areas located between Gangwon-do and Gyeongsangbuk-do. The 2nd area for focus is regions near the DMZ, the eastern part of Gyeonggi Province, and the western part of Gangwon Province.

CONCLUSION

This study used the MaxEnt model to identify critical habitats for 10 target mammal species and compared them with existing protected areas to prioritize future conservation efforts. Southern Gangwon-do and Gyeongsangbuk-do forests were identified as top priority areas due to their high concentration of grade 1 habitats, which are expected to remain stable. Regions near the DMZ, eastern Gyeonggi Province, and western Gangwon Province were identified as second priority areas, as expanding protected areas here would enhance habitat connectivity and mitigate climate change impacts. Under the SSP 1-2.6 scenario, representing active climate change mitigation, grade 1 habitats decreased in period B but recovered in period C, suggesting stability. However, in the SSP 3-7.0 scenario, which assumes passive mitigation, grade 1 areas increased in period B but declined in period C, indicating that active policies are crucial for long-term habitat preservation.

The study highlights the importance of considering SSP scenarios, which account for social and economic factors alongside climate projections. However, it acknowledges limitations due to the uncertainty of these scenarios and the exclusion of other taxa such as plants and amphibians. Future research should incorporate these elements to improve prediction accuracy and expand the scope of conservation efforts. The AUC values for all species ranged from 0.7-0.8, indicating moderate reliability, but further refinement of environmental variables is needed to enhance model performance and guide long-term protected area designation. A detailed investigation of the ecological environment within the proposed key habitat area and addressing the study's limitations will enhance its usefulness as primary data for the designation of a mid-term to long-term protected area.

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