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Forest management can mitigate negative impacts of climate and land-use change on plant biodiversity: Insights from the Republic of Korea

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ABSTRACT

Over the past century, the decline in biodiversity due to climate change and habitat loss has become unprecedentedly serious. Multiple drivers, including climate change, land-use/cover change, and qualitative change in habitat need to be considered in an integrated approach, which has rarely been taken, to create an effective conservation strategy. The purpose of this study is to quantitatively evaluate and map the combined impacts of those multiple drivers on biodiversity in the Republic of Korea (ROK). To this end, biodiversity persistence (BP) was simulated by employing generalized dissimilarity modeling with estimates of habitat conditions. Habitat Condition Index was newly developed based on national survey datasets to represent the changes in habitat quality according to the land cover changes and forest management, especially after the ROK's National Reforestation Programme. The changes in habitat conditions were simulated for a period ranging from the 1960s to the 2010s; additionally, future (2050s) spatial scenarios were constructed. By focusing on the changes in forest habitat quality along with climate and land use, this study quantitatively and spatially analyzed the changes in BP over time and presented the effects of reforestation and forest management. The results revealed that continuous forest management had a positive impact on BP by offsetting the negative effects of past urbanization. Improvements in forest habitat quality also can effectively reduce the negative impacts of climate change. This quantitative analysis of successful forest restoration in Korea proved that economic development and urbanization could be in parallel with biodiversity enhancement. Nevertheless, current forest management practices were found to be insufficient in fully offsetting the decline in future BP caused by climate change. This indicates that there is a need for additional measures along with mitigation of climate change to maintain the current biodiversity level.

1. Introduction

The decline in biodiversity due to climate change and habitat loss is unprecedentedly serious (Dirzo and Raven., 2003; Barnosky et al., 2011; Ceballos et al., 2015; Augustynczik et al., 2019). In order to counter these threats, international organizations have undertaken numerous efforts with the goal of engaging willing signatory countries to protect and sustain plant and animal biodiversity (Aichi Targets for 2020, Parties to the United Nations, Convention on Biological Diversity, and Sustainable Development Goals for 2030 of the United Nations). For governments charged with the responsibility to establish national biodiversity strategies and action plans, it is essential to objectively measure biodiversity change over time and predict future changes for successful biodiversity conservation. However, measuring all species everywhere and over time is an impossible task (Pereira et al., 2013; Branquinho et al., 2019).

To address this need, considerable scientific approaches have attempted to develop quantitative predictions of biodiversity with spatially-explicit scenarios of global change (Botkin et al., 2007). The most common approach has been to project the changes in the

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distribution of individual species according to changes in their habitat conditions (Guisan and Thuiller, 2005; Elith and Leathwick, 2009; Guisan et al., 2017). Although these species-level predictions help in conserving specific species, they are less relevant in establishing conservation strategies for the overall biodiversity (Meyer et al., 2015; Hoskins et al., 2019). Owing to these limitations, the focus is shifting to total (gamma) diversity, encompassing species diversity in sites or habitats (alpha diversity) and variations in species composition within a region of interest (beta diversity) (Fitzpatrick et al., 2011; Blois et al., 2013; Newbold et al., 2016; D'amen et al., 2017; Hoskins et al., 2019).

Biodiversity is affected by not only climate change, but also multiple interacting driving forces, particularly land-use/cover change, which rely heavily on socio-economic constraints and opportunities as well as the physical environment of the region (Mantyka-Pringle et al., 2012; Settele and Wiemers, 2015; Rounsevell et al., 2014; Lambin and Meyfroidt, 2011; Titeux et al., 2016). However, most studies predicting biodiversity changes have dominantly focused on climate change prediction and toto a lesser extent have examined the role of land-use/cover change (Titeux et al., 2016). In addition, habitat destruction and degradation occur not only from the conversion of land cover types but also from changes in the type of vegetation or changes in the way or intensity of human use (Verburg et al., 2013; van Asselen and Verburg, 2013). Nevertheless, most studies have focused primarily on conversion between types of land cover, but little attention has been paid to land-use/cover changes within certain types of land cover (De Chazal and Rounsevell, 2009; Stürck et al., 2014; Titeux et al., 2016). Changes in land management regimes or intensity of use can change habitat quality, which can strongly affect biodiversity (Pe'er et al., 2014). For example, even in forests, which is a good habitat with high biodiversity in general, the habitat condition may vary depending inter alia on the origin, management method, age-class, disease and the surrounding environment (Luque and Vainikainen, 2008). Therefore, in order to more realistically predict biodiversity change, an integrated approach is needed that considers simultaneously climate change, land-use/cover change, and qualitative changes (Titeux et al., 2016).

The Republic of Korea (hereafter, ROK) is a remarkable study area to analyze this integrated effect, as it has achieved rapid economic development with successful reforestation in a short period of time. After the Korean War, a tremendous number of trees were planted throughout the ROK under the National Reforestation Programme (1962–1987) (Kim et al., 2008; Bae et al., 2014). Owing to these efforts, 63% of the ROK is presently covered by forests. Although there has been a decline in the forest cover due to urban expansion and climate change, the quality of forests has improved through continuous forest management (Lee et al., 2015; Cui et al., 2016; Kim et al., 2017). Studies suggest that this large-scale reforestation has led to an increase in species richness (Bae et al., 2014); however, no quantitative and spatial assessment has been done on its impact on biodiversity, especially with respect to community diversity at the national level.

In this study, biodiversity persistence (BP), which indicates the proportion of species expected to persist over the long term (Di Marco et al., 2019a), was simulated for plant species in the ROK, from the 1960sto the 2050s. We applied detailed national survey and environmental datasets to an approach that was established in studies conducted at a global scale to predict global extinction risk (Di Marco et al., 2019a; Hoskins et al., 2019). In order to identify the impacts of past reforestation programs on biodiversity, changes in land use and forest habitat quality were simulated (1960s to present), and spatial scenarios of future changes were constructed. Finally, by analyzing the changes in BP in each scenario and period, the net effect of forest management on biodiversity was also investigated.

2. Materials and methods

2.1. Study area

Fig. 1 demonstrates the study area, which comprises of the entire ROK (33°09′ to 38°45′ N; 124°54′ to 131°06′ E). The ROK is a peninsula located in the mid-latitude, which is influenced by the temperate monsoon climate. Its annual average temperature is 10–15 °C; moreover, its annual precipitation is 1000–1,800m, with 50–60% of the annual precipitation in summer, from June to August (KMA., 2020). The eastern region of Korea consists of mountainous regions, including the Taebaek Mountain Range. From this range, the Sobaek Mountain Range extends from the northeast to the southwest. Below the Korean peninsula lies Jeju Island, which has a distinct climate and unique habitat.

2.2. Biodiversity persistence modeling in plant communities

It is necessary to establish biodiversity conservation strategies by considering both species richness and diversity of species composition, which are attributable to habitat diversity. At the national level, gamma diversity is a useful concept for comparing biodiversity in different regions under different management scenarios (Noss and Cooperrider, 1994). To explore gamma diversity, this study followed the approach described by Allnutt et al. (2008), which applied the concept of BP based on the species-area relationship. The aforementioned approach converts a proportional loss of habitat into an expected loss of species. Moreover, Hoskins et al. (2019) and Di Marco et al. (2019a, 2019b) have applied this approach to global biodiversity assessments to predict changes in the BP under various scenarios of land cover and climate change. The generalized dissimilarity modelling (GDM) was combined with the estimates of global habitat conditions, which represented the proportional species richness - expected to be retained by land-use class. Using detailed national datasets, we reconstructed the models and habitat condition maps to better reflect the domestic environment. Climate change was applied as the input variables for GDM to derive compositional dissimilarity of species. Moreover, changes in land-use and habitat quality were reflected in habitat condition maps by simulating time-series BP (Fig. 2).

GDM statistically analyzes and projects spatial patterns of turnover in community composition (beta diversity) across large regions (Ferrier et al., 2007; Fitzpatrick et al., 2011; Laidlaw et al., 2016; Drielsma et al., 2017; Ware et al., 2018). Moreover, it measures and predicts the dissimilarity in species composition, depending on the differences in environmental variables among sites. It assumes that species turnover rate increases with environmental differences and spatial distances.

A total of 204,218 records of 2,940 plant species, except six exotic species, were obtained from the 3rd national ecosystem survey dataset (2006–2013) and were used to fit the GDM models. Environmental variables consisted of 23 bioclimatic variables, which included four variables that were known to affect the distribution of Korean plants, namely Warmth Index (WI), Minimum Temperature of the Coldest Month Index (MTCI), Precipitation Effectiveness Index (PEI), and Growing Degree Days (GDD) (Choi et al., 2011). Furthermore, the data included 19 bioclimatic variables that were frequently employed in species distribution modeling (Table 1). We used the CHELSA (Climatologies at high resolution for the earth's land surface areas) climate dataset (Karger et al., 2017) at 30 arcsec resolution, which is approximately 1 km. Monthly climate average (monthly minimum, maximum, and mean temperature, and precipitation) was generated over the period from 2004 to 2013 to coincide with the species survey period. In addition, we used a standard Digital Elevation Model (National Environment Information Network System), national soil data (Korean Soil Information System), and level-2 land cover map produced in 2007 by the Ministry of Environment (MoE).

BP was calculated using equation (1), as described in detail by Allnutt et al. (2008) and Di Marco et al. (2019a).

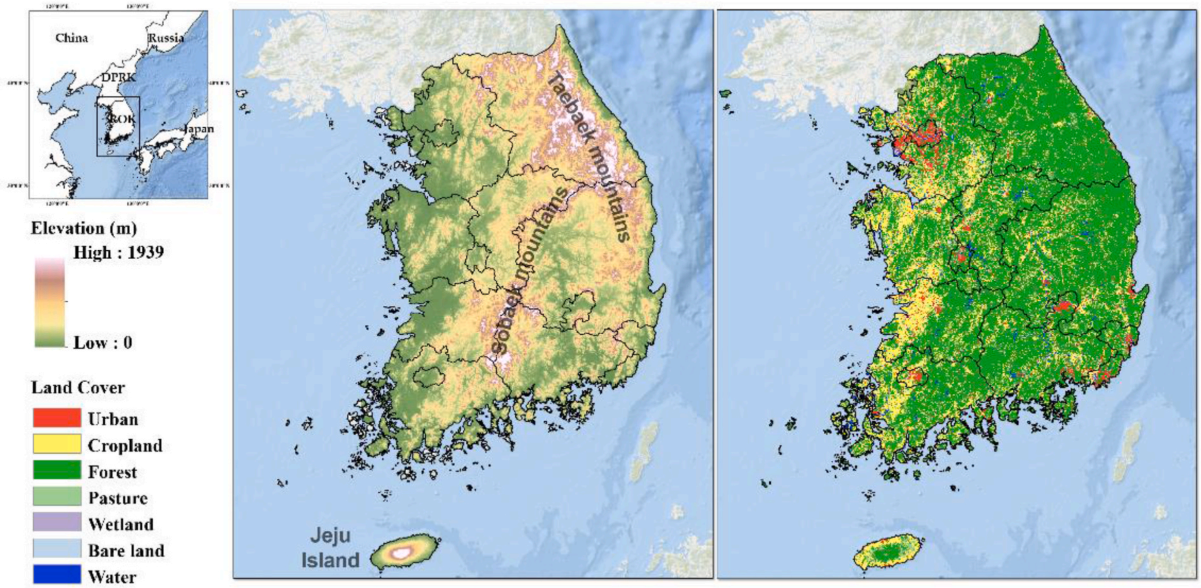

Fig. 1. Basic spatial information on the Republic of Korea: elevation map (left); and land cover map (right).

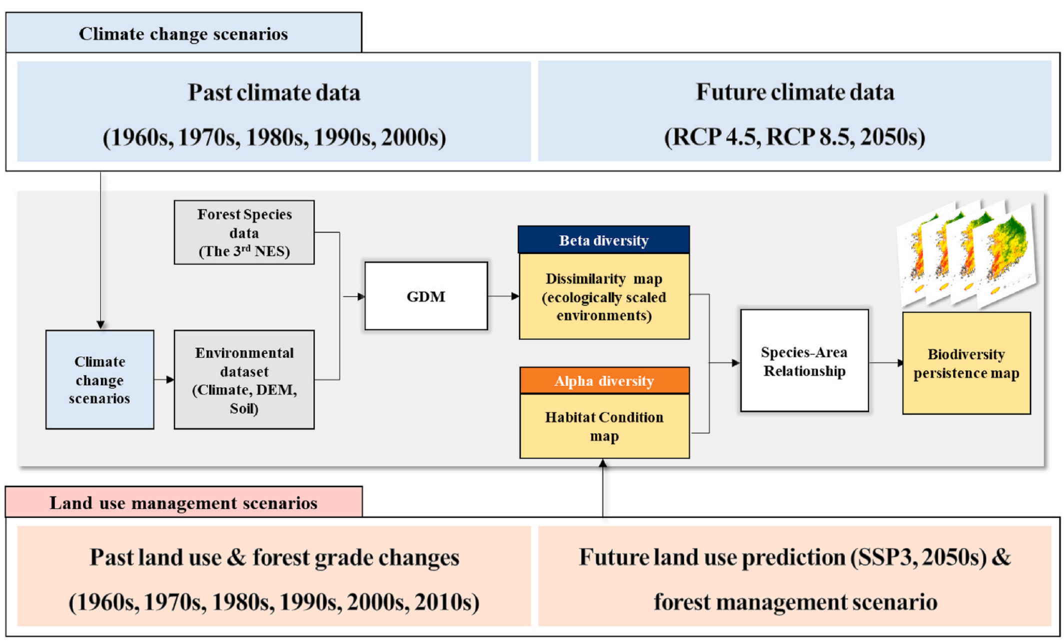

Fig. 2. Research flow for the construction of Biodiversity persistence map in a time-series.

$$p_i = \left[\frac{\sum_{j=1}^{j=n} S_{ij} h_j}{\sum_{j=1}^{j=n} S_{ij}}\right]^{0.25} \tag{1}$$

Here, the denominator represents the potential area of an ecological environment similar to cell i, calculated as the sum of pairwise similarity (s_{ij}) to the all other cells j. By multiplying this similarity (s_{ij}) with the actual habitat condition (h_j) in the numerator, which represents the actual area of similar ecological environments under current environments, we obtain the proportion of species expected to persist (p_i) in the long term. A detailed description of habitat condition (h_j) is provided in the following section 2.3. For a better understanding, BP (p) is translated into extinction rate ($1 - p$), which is the proportion of species expected to become extinct over a long term as a consequence of climate and land-use conditions (Di Marco et al., 2019a). We also report the number of species expected to become extinct using the total number of native plant species in Korea, i.e., 7,833 (National Biodiversity Center, 2019). However, it is important to clarify that this number is not an absolute estimate because the main interest of this study lies in comparing the relative effects of forest management or land use and climate change, rather than accurately predicting the number of endangered species in each scenario.

2.3. *Constructing national habitat condition map*

Habitat conditions that were applied in previous studies on a global scale are based on statistical downscaling, thereby rendering them inadequate in reflecting regional differences. Thus, we developed new coefficients to represent the degree to which species can be supported in each land-use type by using precise national datasets of species distribution and detailed land cover map. Given that better habitat quality

Table 1
Environmental variables for Generalized Dissimilarity Modelling (GDM).

Variable name	Description	Source
Bio1	Annual mean T (°C)	CHELSA (2004–2013)
Bio2	Annual mean diurnal range (°C)	
Bio3	Isothermality (%)	
Bio4	T seasonality (°C)	
Bio5	Maximum T of the warmest month (°C)	
Bio6	Minimum T of the coldest month (°C)	
Bio7	Annual T range	
Bio8	Mean T of wettest quarter (°C)	
Bio9	Mean T of driest quarter (°C)	
Bio10	Mean T of warmest quarter (°C)	
Bio11	Mean T of coldest quarter (°C)	
Bio12	Annual precipitation (mm)	
Bio13	Precipitation of the wettest month (mm)	
Bio14	Precipitation of the driest month (mm)	
Bio15	Precipitation seasonality (%)	
Bio16	Precipitation of wettest quarter (mm)	
Bio17	Precipitation of driest quarter (mm)	
Bio18	Precipitation of warmest quarter (mm)	
Bio19	Precipitation of coldest quarter (mm)	
WI	Warmth Index	
MTCI	Minimum Temperature of the Coldest Month Index	
PEI	Precipitation Effectiveness Index	
GDD	Growing Degree Days	
DEM	Altitude	National Environment Information Network System
LC	Land cover map –level 2 (2007)	Ministry of Environment
Soildepth	Effective soil depth	Korean Soil Information System

leads to greater species diversity and support more individuals, we considered both the number of species and the number of organisms simultaneously. Thus, the Habitat Condition Index (HCI) was created by dividing the product of the total number of species and individuals by the area of each land cover type. (Equation (2)). In this way, the HCI demonstrates that a habitat condition is considered to be better when many species live in the same area, or when the population is large.

$$\text{Habitat Condition Index} = \sqrt{\frac{(\text{number of species})*(\text{number of individuals})}{\text{Area}}} \tag{2}$$

By considering land-use type as a unit, forests were divided into four classes based on their naturalness. Naturalness is a concept characterized by the more natural the ecosystem is if its state is more similar to the expected natural state (Winter 2012; McRoberts et al., 2012). The naturalness of the forests has been used as an important factor in assessing forest biodiversity and the need for natural conservation (Larsson. 2001; ĐAUDYTĖ et al., 2005; Song et al., 2012). Thus, this study employed naturalness to classify the forests based on criteria in the Environmental Conservation Value Assessment Map (ECVAM), which indicates the current environmental values created by MoE. The criteria of naturalness include origin of forests (natural or planted forests), and age-class; this study classified forests into three naturalness grades by applying these criteria (Table 2). Regions that were classified as "forests" on the land cover map but did not have any information on their origin or age were termed as 4th -grade forests. Available occurrence data of plant species were utilized to generate the HCI. A total of 764, 923 records of 4716 plant species were used by compiling a total of 214, 989 records of 4,439 species from the 2nd, 3rd, 4th National Ecosystem

Table 2
Coefficients of conversion of land-use classes into habitat condition values.

Land use class	Explanation	Coefficients
1st-grade forest	Natural forests of more than 50 years old & Planted forests of more than 60 years old	1
2nd-grade forest	Natural forests of more than 40 years old & Planted forests of more than 50 years old	0.920974
3rd-grade forest	Natural forests of less than 30 years old & Planted forests of less than 40 years old	0.824761
4th-grade forest	Forests without origin or age information	0.651241
Semi-natural pasture	Land covered with herbaceous plants in use as farm, golf courses, cemeteries, etc.	0.501153
Farmland	Dry lands for growing grains, fruit trees, vegetables, etc.	0.500167
Natural pasture	Lands naturally covered with herbaceous plants	0.417373
Artificial bare land	Mining area, playgrounds, etc.	0.323916
Rice paddy	Submerged farmland for growing rice	0.323029
Urban	Urbanized area including residential, industrial areas, etc.	0.312521
Other cropland	A house plantation, orchard, and other cultivation areas	0.292475
Natural bare land	A beach, riverbed, and rock	0.098008

Survey datasets, and 550,075 records of 278 species from the 5th National Forest Inventory (Kim et al., 2010, 2013; Park et al., 2016). The level-2 land cover map (2007) and the 5th forest type map (2006–2010) were used as reference land use and forest grade maps to generate coefficients. After calculating the HCI for each land cover type, the coefficients were derived at a proportion that was relative to the highest value of the 1st-grade forests, assuming that it was a pristine environment. The derived coefficients, which reflect the unique habitat environment of the ROK, are provided in Table 2.

2.4. Land cover change modeling for past and future

Land cover for the past 1960s, 1970s and the future 2050s were predicted by using the level 1-land cover maps of the 1980s, 1990s, 2000s, and 2010s that are provided by the MoE. This study applied the machine learning process of the multilayer perceptron (MLP) neural network in the Land Change Modeler (LCM) tool in TerrSet 18.31. The LCM projects changes in the land cover by analyzing historical land cover data (Clark Labs, 2017a). Moreover, it supports the MLP for model development by establishing relationships between two historical land cover layers and a set of potential explanatory variables that cause changes in land cover. The MLP, which is one of the most widely used neural network models (Shade and Kremer. 2019), calculates the transition potential over time using the back-propagation learning algorithm (Clark Labs, 2017b). Using these transition potential models, the LCM predicts the expected quantity of change and the competition in land allocation through the Markov chain analysis in order to determine the land cover at specific time in the future (Clark Labs, 2017b).

In order to simulate land cover in the past 1960s and 1970s, this study constructed a backcast model based on the analysis of changes in the 1980s and 2000s. To predict future land cover, the land cover maps of the 2000s and 2010s were used to construct a forecast model with the predicted change rate of land cover under the Shared Socio-economic Pathways (SSPs). The SSP3 scenario (regional rivalry) was our main scenario, which demonstrated the worst effect on biodiversity due to the expansion in the most prominent urban area as well as forest loss (Song et al., 2018).

We used altitude, slope, aspect, distance to cropland, forests, urban and roads; effective soil depth, and the Environmental Conservation Value Assessment Map (ECVAM) as explanatory variables (Table 3). Legally protected areas were also incorporated as a constraint option. For land cover types except for forests, croplands and urban, which

Table 3
Environmental variables for Land Change Modeler (LCM); which are converted to a raster at 1 km resolution.

Variable name	Description	Source
LC 1980	Level-1 land cover map (1: 50,000)	Ministry of Environment
LC 2000		
LC 2010		
Distance to forests	Derived from each period of LC using the Euclidean distance tool in ArcGIS 10.3	Author
Distance to cropland		
Distance to Urban		
Distance to roads	Derived from the road links using the Euclidean distance tool in ArcGIS 10.3	Standard Node Link from National Transport Information Center
ECVAM	Environmental Conservation Value Assessment Map (1:25,000)	Ministry of Environment
DEM	Altitude	National Environment Information Network System
Slope	Derived from DEM using the slope tool in ArcGIS 10.3	
Aspect	Derived from DEM using the aspect tool in ArcGIS 10.3	
Soil depth	Effective soil depth	Korean Soil Information System
Protected Area	Legally protected areas	KOREA Database on Protected Areas

account for more than 90% of the land area, it was assumed that the status of the 2010s will continue to be maintained in the future because there was no consistent trend of change.

2.5. Forest change scenarios

To simulate past forest change, we used the 1st–5th forest type maps (FTM) of Korea provided by the National Institute of Forest Science (NIoFS). The first FTM was produced in 1972 with a scale of 1:25,000; in 2009, the fifth forest type map was constructed at a scale of 1: 5000 to provide more precise data (NIoFS, 2017). FTMs were constructed based on digital aerial photos and field surveys. They provided a variety of information on forests, including classification of stocked and unstocked, origin, type, tree species, age class, tree diameter at breast height (DBH) classes and crown closure (NIoFS, 2017). The age class structures were grouped into 10-year intervals. Using this information, we divided the forests into four naturalness grades (hereafter, forest grades), based on the criteria presented in Table 2, and analyzed the changes in time series.

Future forest changes were simulated to increase by one age class in 10-year increments (based on the 5th FTM) with logging scenarios for timber production. The final cutting age was applied to the 'timber production forests' which is classified in the national forest function classification (NIoFS, 2004), with the assumption that logging would be carried out only in those. In accordance with the national guidelines for final cutting age by forests, the criteria applied to the final cutting age was, as follows: 60 years for national forests and 40 years for public and private forests. For example, national forests that reached 6th age-class turned into 1st age-class in the timber production forests.

2.6. Integrated land use map with forest habitat quality

In order to create habitat condition maps, the simulated large-scale land cover maps need detailed classification, such as classification of paddy or farmland within the cropland. However, it was difficult to simulate changes through the model due to a variety of land use types with a small area. Thus, detailed land-use types were assumed to be maintained as a level-2 land cover map with a 1: 25,000 scale constructed by MoE. However, only three phases of level-2 land cover maps were provided; land cover maps produced from 2000 to 2004 (hereafter considered as land cover produced in 2002), in 2007, and from 2010 to 2018 (hereafter considered as land cover produced in 2014). Therefore, we uniformly applied the level-2 land cover map produced in 2002 and 2014 to the past and, future respectively.

Forest grade maps made from FTM, whose production period coincided with land cover map, were then applied to the "forests" to create the final habitat condition maps. Table 4 demonstrates the combination of land cover maps and FTM for each period. The level-1 and level-2 land cover maps were provided by the MoE, and the FTMs were provided by the Korea Forest Service. Data marked in blue represent the data that are provided and the others were constructed for this study (Table 4). Thus, habitat condition maps were generated for each study period by combining level-1, level-2, and FTMs in the same row.

To assess the impact of climate change, CHELSA climate datasets were used, that is the CHELSAcruts data for the 1960s and 1970s, the CHELSA Time series data for the 1980s–2010s, and HadGEM2-AO climate model data (RCP 4.5 and RCP 8.5) for the 2050s (Karger et al., 2017). Climate data for each period were calculated as an average of 10 years and were used to produce bioclimatic variables to estimate BP, as listed in Table 1.

2.7. Validation

Although the results of BP are more suitable for evaluating the trend in biodiversity persistence, the values itself cannot be readily detected. Therefore, discrete classifications of plant communities that are deemed to adequately represent the major spatial patterns for the distribution of biodiversity were examined. Accordingly, the grade map of vegetation conservation, which was created based on the national environmental survey (2006–2013) of the MoE, was selected as reference data for validation. This map was considered to contain information most similar to BP, which indicates the degree of vegetation maintenance for a long period of time. The grade of vegetation conservation was evaluated based on human disturbance and natural value of vegetation: The 1st grade is climax forest or natural forest similar to climax forest vegetation with high naturalness; The 2nd grade is forest vegetation in a state that is almost restored close to natural vegetation by secondary succession after

Table 4
A combination of land cover maps and forest type map for each period with climate data.

Lv1 land cover map	Lv2 land cover map	Forest type map	Final Habitats condition map	Climate data
1960s	2002 (2000–2004)	1st (1972–1974)	HCM 1960s	1961–1970
1970s	2002 (2000–2004)	2nd (1978–1980)	HCM 1970s	1971–1980
1980s	2002 (2000–2004)	3rd (1986–1992)	HCM 1980s	1981–1990
1990s	2002 (2000–2004)	4th (1996–2005)	HCM 1990s	1991–2000
2000s	2007	5th (2006–2010)	HCM 2000s	2001–2010
2010s	2014 (2010–2018)	6th (2018)	HCM 2010s	2011–2016
2050s	2014 (2010–2018)	10th (2058)	HCM 2050s	RCP 4.5 2050s
				RCP 8.5 2050s

disturbance; The 3rd grade is forest vegetation in the recovery phase due to secondary succession or in the state still under the disturbance; The 4th grade is artificially afforested vegetation; and the 5th grade is secondary vegetation, orchard, cropland or relatively green residential area. For comparative analysis, the result of BP was also classified into 5 grades based on the distribution ratio of vegetation conservation grade to the same extent.

3. Results and discussion

3.1. Land use and forest habitat quality change from the past to the future (1960s–2050s)

The land cover change from the 1960s to the 2050s are featured in Fig. 3. The most notable aspect was the expansion of urban areas around major hub cities selected by the government policies. In particular, urbanization around the metropolitan area and south-east coast region is expected to increase significantly in the future. It seems to be well simulated by the spread of new urbanized areas along with the wide-area road network. Spatially, a lot of agricultural areas seemed to be urbanized, but it is necessary to take a closer look at the type of land covers that will be converted. There were no noticeable changes in the rest of land covers, such as forests or pastures.

Table 5 summarizes the proportion of land cover for each period, and Fig. 4 displays changes in the proportion of three major land cover types. Urban areas expanded from 1.13% in the 1960s to 5.45% in the 2010s, mainly by utilizing croplands (51% of the expanded area) and forests (30.5% of the expanded area). In contrast, the cropland area continued to decline from 24.66% to in the 1960s 18.75% in the 2010s due to the expansion of urbanization and afforestation. In the case of forests, the area increased from 66.33% in the 1960s to 68.43% in the 2010s; however, the value differed from the national statistics, which showed a

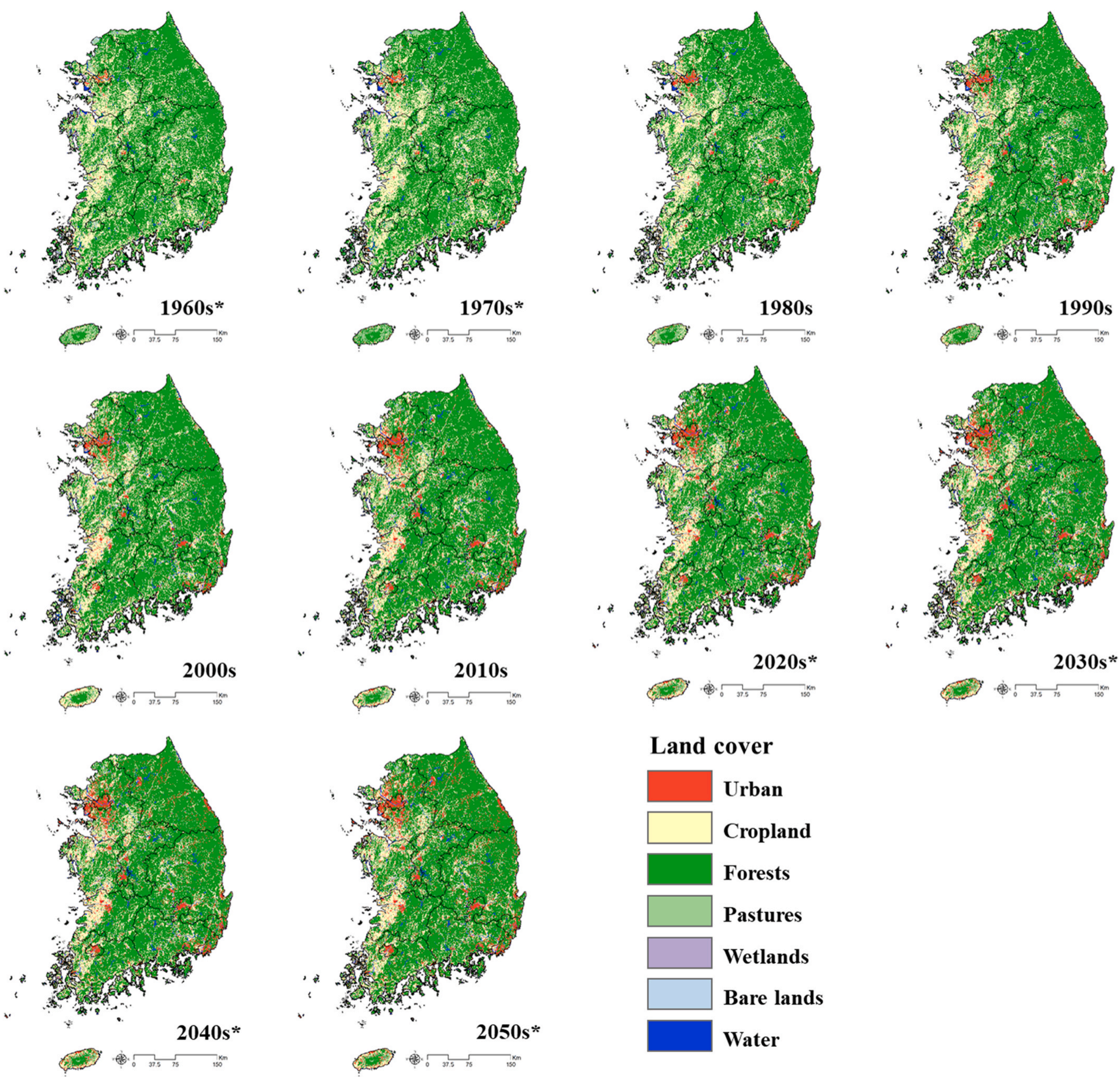

Fig. 3. Land cover changes from past to future (1960–2050). Asterisk indicates predicted results.

Table 5
Proportion of land cover from the past to the future (1960–2050). Asterisk indicates the predicted results (Unit: %).

	1960*	1970*	1980	1990	2000	2010	2020*	2030*	2040*	2050*
Urban	1.13	1.34	2.02	3.48	4.06	5.45	6.20	6.94	7.69	8.44
Croplands	24.66	24.35	23.70	21.52	21.13	18.75	18.36	17.97	17.58	17.19
Forests	66.33	66.47	66.83	66.75	68.21	68.43	68.07	67.71	67.35	67.00
Pastures	4.03	4.04	3.71	4.25	2.77	2.77	2.77	2.77	2.77	2.77
Wetlands	0.92	0.87	0.67	0.39	0.27	0.79	0.79	0.79	0.79	0.79
Bare land	1.15	1.16	1.30	1.66	1.64	1.44	1.44	1.44	1.44	1.44
Water	1.78	1.78	1.78	1.94	1.92	2.38	2.38	2.38	2.38	2.38
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

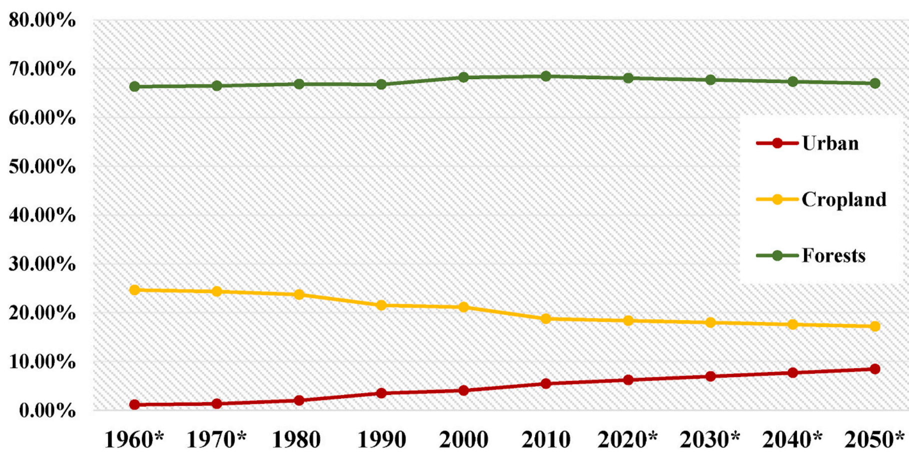

Fig. 4. Changes in proportion of major land cover types: urban, cropland, and forests. Asterisk indicates the predicted results.

decrease from 65,680 km^2 in 1980 to 64,220 km^2 in 2000 (Korea Forest Service, 2016). This variation can be attributed to the difference in the production method between statistical data and land cover maps, which are based on site-survey and satellite images, respectively (Jeon et al., 2013). Meanwhile, pastures saw a reduction due to forestation and urbanization. Furthermore, although bare lands have been partially urbanized, the total area of bare lands has increased as forests and croplands have transformed into bare lands.

Compared to the 2010s, the proportion of urban areas will increase by 2.99% in the 2050s, while croplands and forests will reduce by 1.56% and 1.43%, respectively. The expanded urban areas will be sporadically distributed nationwide. These predictions of future changes in land cover are similar to the results obtained by Song et al. (2018), wherein urban areas account for 7.03% of the entire land, 19.34% are croplands, and 66.42% are forests. These values are based on the SSP3 scenarios in the 2050s.

Fig. 5 demonstrates the changes in forest naturalness grades. Owing to the conservation and reforestation efforts in the 1970s, the proportion of 1st-grade and 2nd-grade forests increased from 27% to 41% in the 1960s to 29% and 45% in the 2000s, respectively. Considering that the forest area did not change significantly, the overall habitat quality of forests has greatly improved. In the future, assuming the scenario of cutting the old trees in the timber production forests which accounts for 33.9% of the total forests, the 1st-grade forests will expand owing to a steady increase in other forests assigned for natural environment conservation, water retention, and such, while the proportion of 2nd-grade forests will remain low.

Fig. 6 comprehensively displays the changes in land use and forest grades. Even though urban areas have continued to expand since the 1960s, the quality of forests in terms of biodiversity has shown improvement. In particular, the grade of conservation areas, including Baekdudaegan (a major mountain range in the ROK), has significantly improved.

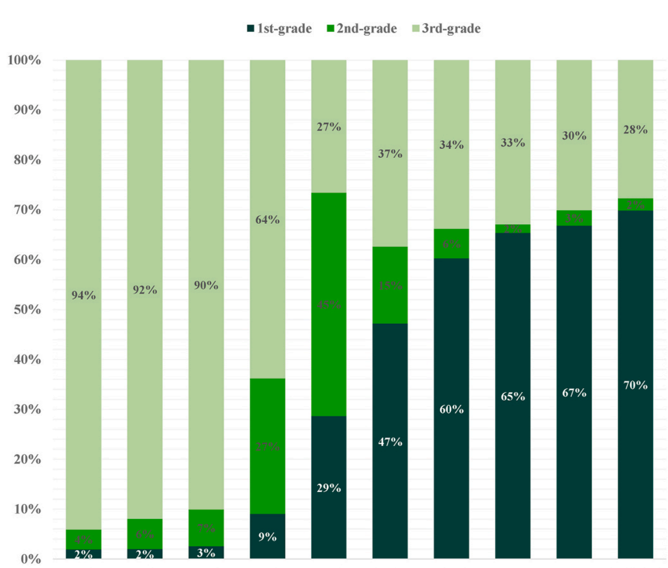

Fig. 5. Changes in the proportion of forest naturalness grades. Asterisk indicates the projected results.

3.2. An analysis of historical biodiversity persistence changes

A dissimilarity map was generated using the dissimilarity matrix that was derived from GDM. This map displayed the relative ecological differences with other regions through the sum of dissimilarity with all the other cells (Fig. 7a). The dissimilarity between cells was mainly affected by geographical distance, Bio10 (Mean Temperature of Warmest Quarter), Bio6 (Min Temperature of Coldest Month) and Bio2 (Mean Diurnal Range). As a result, high-altitude mountain ranges, southern coast, and islands showed high dissimilarities, thereby indicating that

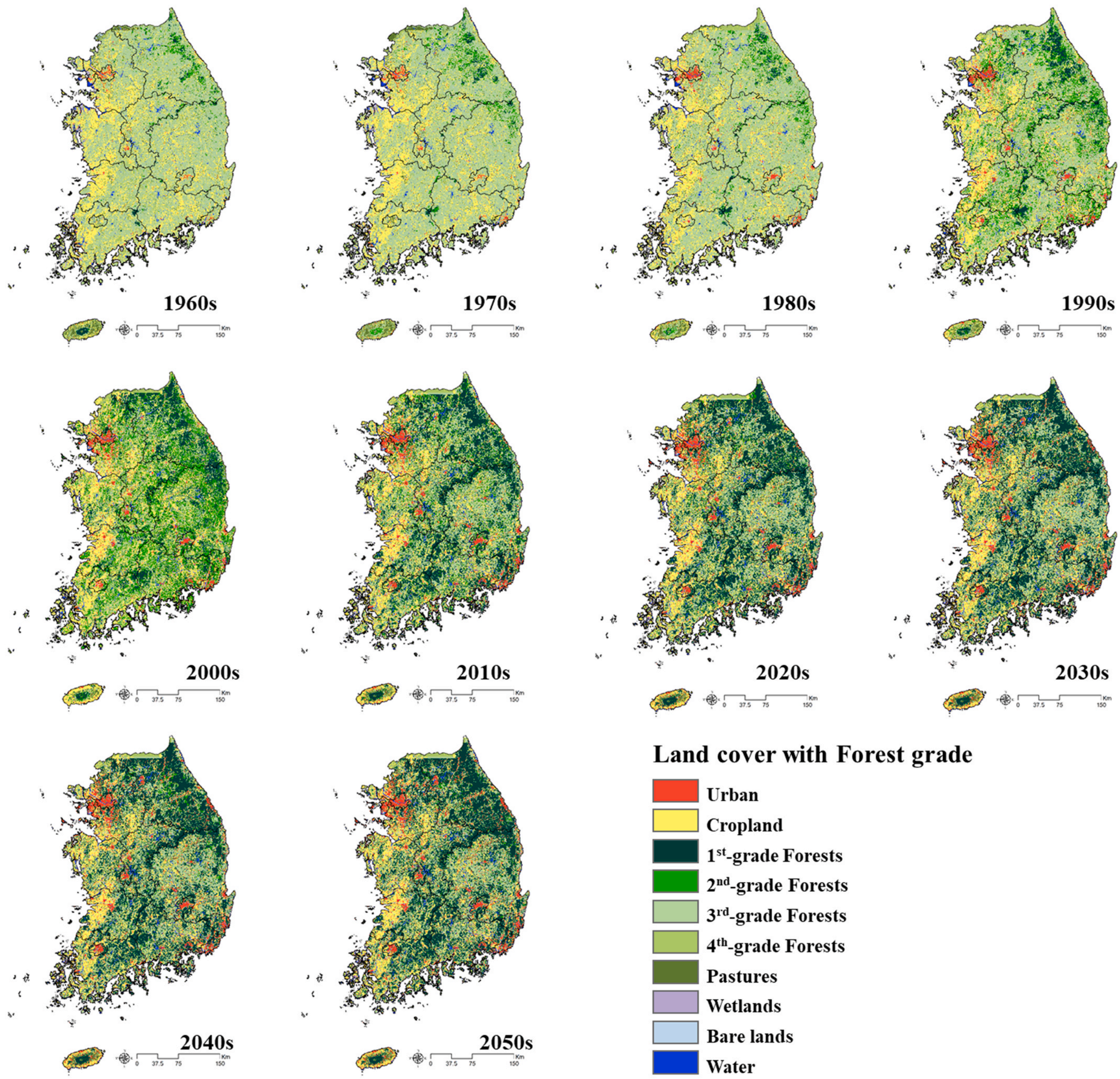

Fig. 6. Land-use changes with forest naturalness grade from the past to the future (1960–2050).

these regions have different species composition compared to the other regions.

These results also reflect the characteristics of Korea's vegetation distribution. Specifically, temperate forests are widespread in most inland areas; coniferous forests and sub-alpine vegetation tend to appear with an increase in altitude. In addition, sub-tropical forests are found only in the southern coastal area, which has a high minimum temperature during the coldest month. Furthermore, unusual vegetation and grassland that are different from the inland, appear in the island region. In particular, Jeju Island, which includes Gotjawal forest, is one of the most unique habitats of Korea. This region has the maximum dissimilarity due to its unique geographical and climatic features.

Important mountain ranges have a high value of habitat condition because species diversity tends to be high in primary forests that are relatively old. On the other hand, urban areas and their surrounding regions show low habitat conditions (Fig. 7b). Thus, using dissimilarity and habitat conditions, BP was calculated to be between 90.7% and 92% (Fig. 7c), which was similar to the global result (Di Marco et al., 2019a). This implies that under the current scenario, about 10% of the plant species are likely to go extinct over time. Considering that the total number of plant species in Korea is 7,833, approximately 689 species are at a risk of extinction. Plant communities that are most likely to suffer are located on the southwest coast of Korea and on Jeju Island. On the other hand, plant communities that are present in major mountain ranges are expected to be more sustainable, assuming that climatic and land cover conditions will remain the same.

3.2.1. Validation of the result

The vegetation conservation-grade map and the BP map, which was reclassified as five grades, were compared (Fig. 8a and b). Both maps

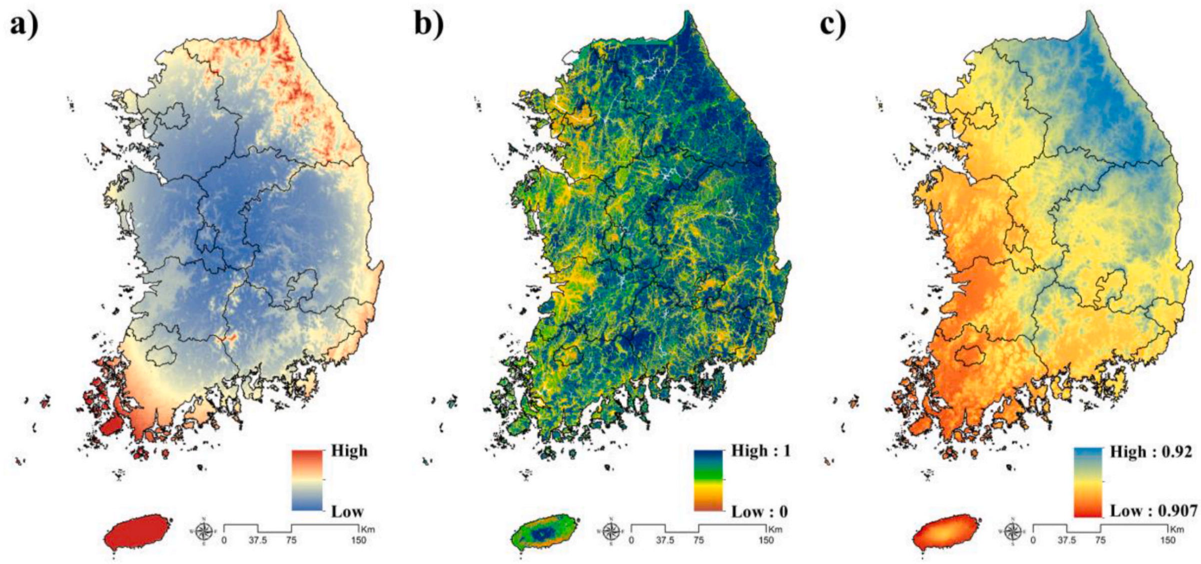

Fig. 7. a) Dissimilarity map b) Habitat condition map c) Biodiversity persistence map of the 2000s.

showed similarity in that the 1st and 2nd grade were distributed near the center of Baekdudaegan and the third grade was widely distributed nationwide. However, in the vegetation conservation-grade, 4th and 5th grade were scattered around the mountain range, while in the BP grade map, the distribution of those grades is prominent in the southwestern coast and Jeju island due to the dissimilarity. To compare these distributions quantitatively, the minimum, maximum and average values of BP for each conservation-grade were analyzed (Fig. 8c). As the vegetation grade decreased from grade 1st to 3rd, the average value of BP was also decreased. In grades 4th and 5th, there was a tendency to increase slightly more than 3rd grade, which is mainly attributable to the differences in the evaluation criteria of these two maps. In particular, BP assumed that the habitat quality improved with age even if it was planted, while all planted vegetation were classified into 4th and 5th in the vegetation conservation map. In other words, BP is high in old-growth planted vegetation, but it was not reflected in vegetation conservation grade. Given these differences, the results of this study can be considered to be somewhat verified through the national official data.

3.2.2. Historical biodiversity persistence changes

Assuming that the current climate is maintained, changes in BP from the 1960s to the 2000s due to land use-forest habitat quality changes are shown in Fig. 9. Overall, the eastern mountains have a high BP, whereas the western plains and island areas have a low BP. However, an increase in BP was noticeable over time due to improvements in the forest naturalness despite the expansion of the urbanized area. In the 1960s, most of the mountainous areas were unstocked forests. During this time, the average BP was 89.95%; however, it continued to improve and rose to 91.43% in the 2010s. In terms of the number of species, this can be interpreted as an increase of 115 species that can be sustained over the long-term. In addition, as the forest naturalness grade improved, the BP range (difference between plain and mountainous regions) is also increased.

3.3. A prediction of future biodiversity persistence changes

The prediction of BP by applying climate change scenarios without land use-forest grade changes is shown in Fig. 10a. The most noticeable change observed in the 2050s scenario was the deterioration of BP in mountainous regions. This was in line with previous research findings that bioclimatic environments which were similar to mountainous area experienced negative effects due to climate change (Choi et al., 2019). On the other hand, coastal areas, southern flat areas, and islands were positively affected by climate change, as areas with similar bioclimatic conditions widens. Thus, there is a reversal in the trend of the spatial distribution of BP compared to the present, with enlarged differences between the maximum and minimum values. Not surprisingly, this phenomenon is exacerbated in the RCP 8.5 scenario. The average BP decreased by 0.47%, and 0.6% in the 2050s under RCP 4.5 and RCP 8.5 scenarios, respectively compared to the 2010s.

In addition to these climate change scenarios, applying future land use and forest management scenarios increased the BP by 0.48% and 0.46% in the RCP 4.5 and RCP 8.5 scenarios, respectively, as compared to applying only the climate change scenario (Fig. 10b). This indicates that despite a reversal in the spatial distribution, the average value would be similar to the current level for RCP 4.5 but would decrease by 0.33% for RCP 8.5. In other words, despite an expansion in urbanized area, the improvement of forest habitat quality has a positive effect on BP as with the past results. Thus, it suggests that the adverse effects of climate change can be mitigated when the forest is managed properly. However, as it does not represent a complete offset, further actions, such as afforestation would be required.

3.4. Time series analysis with various alternative scenarios

By comparing BP from the 1960s to the 2050s in a time series (Fig. 11), the average BP was shown to increase due to continuous forest management. However, in the future, climate change is expected to decrease the BP; although, this will vary for different scenarios. If only land-use changes, such as expansion of urban areas and reduction in forest area, are considered, without changing the quality of the forests, BP will decrease by 0.47% in the RCP 4.5 scenario. In the RCP 8.5 scenario, which assumes a continuation in the emission trends, BP will decrease by 0.6%. This implies an increase in the number of projected species that will be extinction, i.e., an additional 37 and 47 species in RCP 4.5 and RCP 8.5, respectively. However, if forest management scenarios, such increasing forests habitat quality with age, are applied, the effects of climate change could be mitigated. Even in RCP 4.5, the average BP increases by about 0.1%. Meanwhile, RCP 8.5 represents a 0.14% reduction in BP, which is 0.46% less than the scenario that considers only climate change. This is because although BP in the southern regions will increase due to the expansion in the sub-tropical

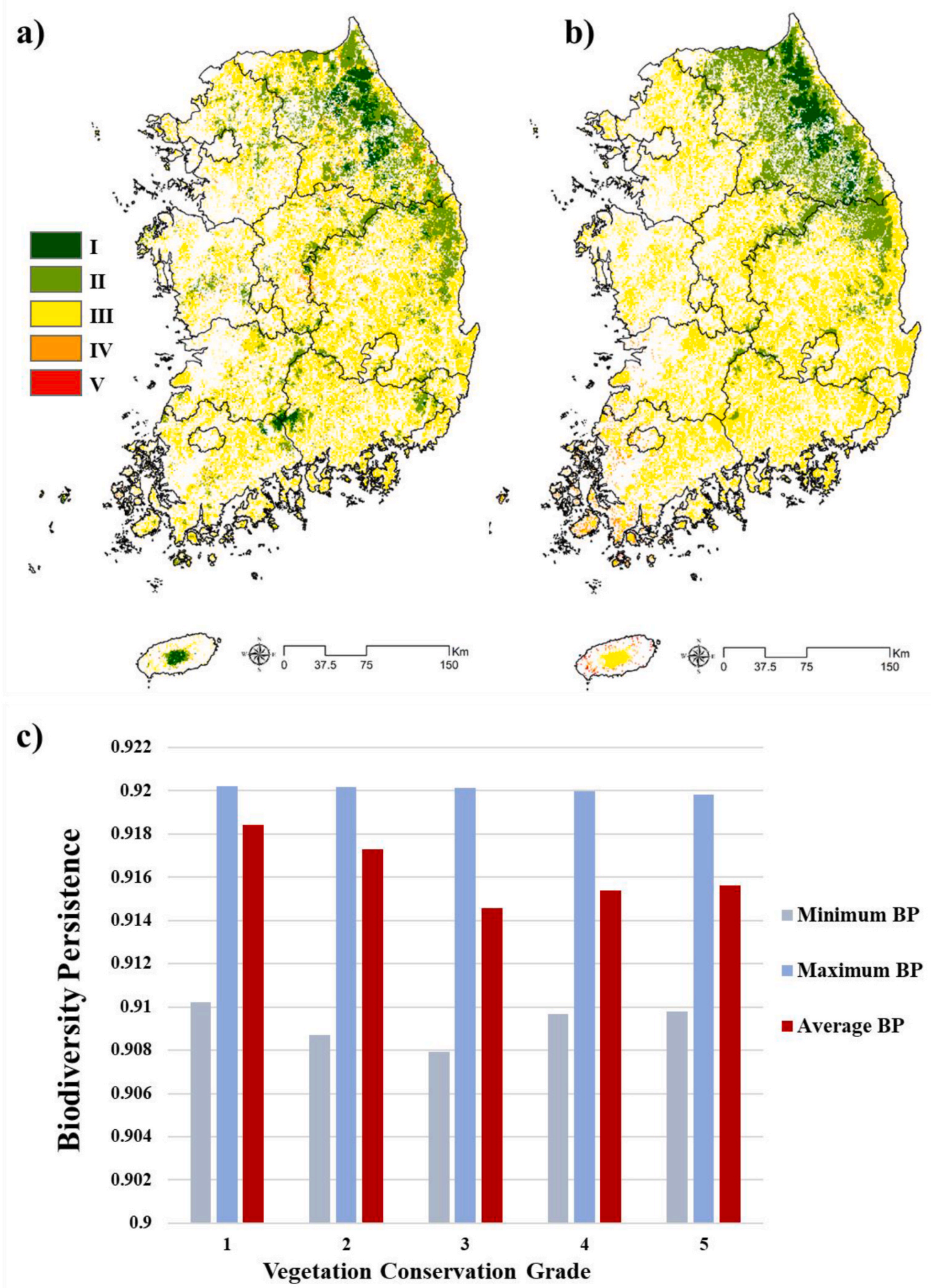

Fig. 8. Comparison of vegetation conservation grade and BP for verification. a) The map of vegetation conservation grades b) The classification map of BP divided into five grades. The color legend is the same for two maps. c) BP value range within each conservation grade. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

climate zone; BP in the mountainous regions will decrease sharply due to the reduction in the cool-temperate climate zone. The problem is that mountainous areas contain numerous rare species. If each species is weighted according to its conservation value, this adverse effect will be greater.

3.5. Evaluation of the effect of forest restoration on BP

What would have happened to the current BP if the damaged forest were not restored in the 1970s under the national reforestation program? To assess the net effect of forest restoration, we simulated BP under the current land cover using the 1960s forest grade (Fig. 12c). In other words, urban areas in the current land cover accounted for 4.06%, which was a 2.93% increase, compared to the 1960s; furthermore, the area of cropland decreased by 3.53%, accounting for 21.13%. On the other hands, forests grades of 1960s are completely maintained with 94% of 3rd grade, 4% of 2nd grade, and 2% of 1st grade (hereafter we term this the "land cover only change scenario).

In this scenario, the BP decreased by 0.18%, as compared to that in the 1960s. This decrease can be seen as an effect of urbanization. However, with land cover and improved forest grades in the 2000s, BP increased by 1.48%, as compared to that in the 1960s. This is the result of an improvement of forest grades (forest habitat quality) by offsetting the negative effect of urbanization, thereby increasing the BP. Therefore,

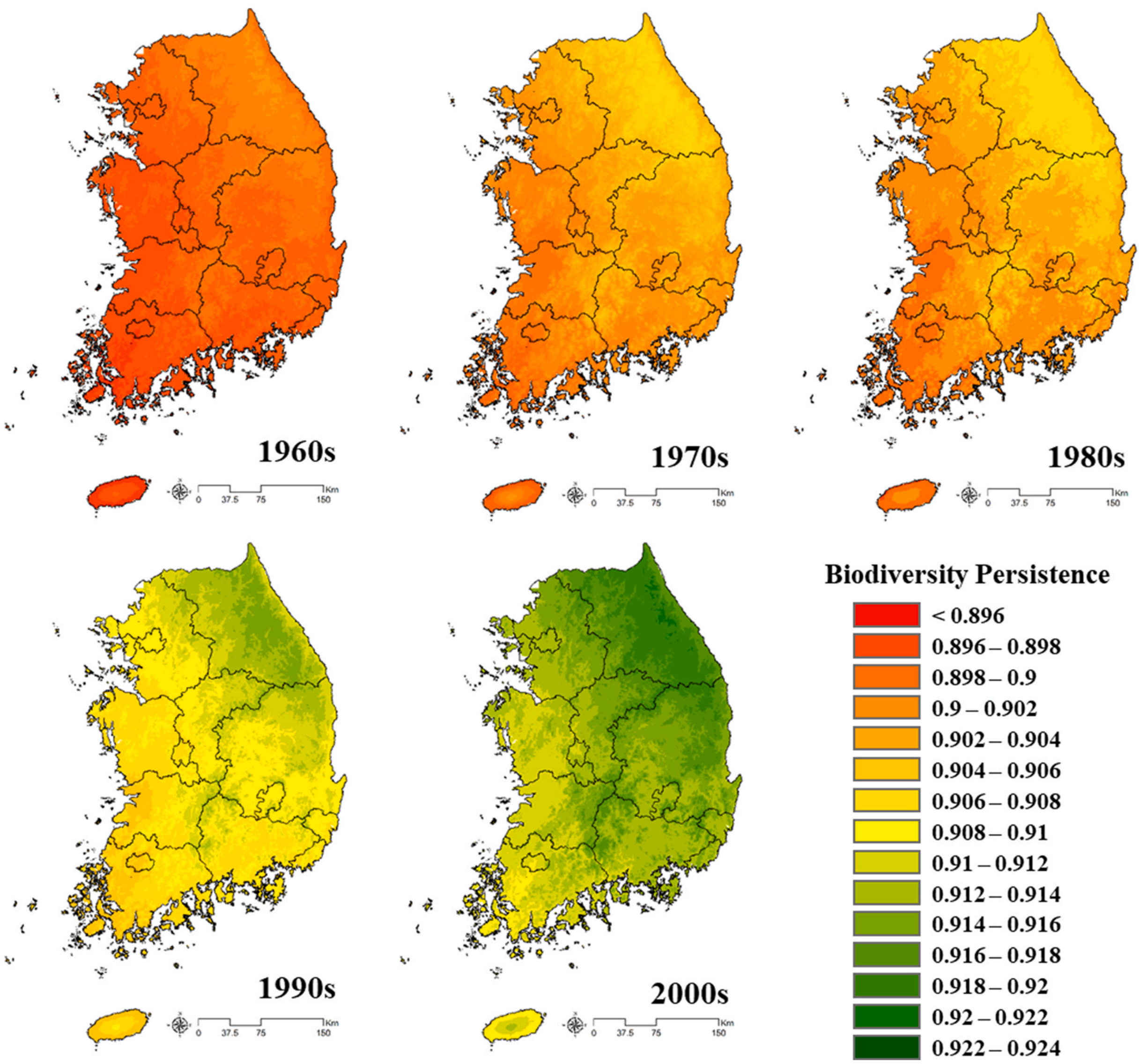

Fig. 9. Historical biodiversity persistence changes from the 1960s to the 2000s due to land use-forest habitat quality changes under current climate. Maps indicate the proportion of species expected to persist over the long term. The color legend is the same for all maps. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the net effect of forest management, is calculated to be about 1.66% (Fig. 13). When converting this value into the number of species, it can be interpreted that the reforestation efforts were able to preserve about 130 additional plant species. This was in line with previous studies that showed that the Korean reforestation program increased the diversity of forest mammals, birds, microorganisms and insects (Bae et al., 2014; Lee et al., 2015). The average BP of this scenario that considered only land cover change was lower than any other historical value, and was even lower than the average value of the 2050s in the RCP 8.5 scenario. Thus, if the forest conditions are maintained as they were in the 1960s, the adverse effects of climate change will be even greater. Therefore, it is observed that Korea's reforestation efforts proved to be effective. This result also suggests that damage/reduction of current forests can have adverse effects on BP in the future and emphasizes the importance of forest management in response to climate change.

3.6. Implications and limitations

Through a spatially explicit methodology established in this study, a time-series biodiversity assessment was conducted for the entire ROK. To this end, a new index was presented to evaluate habitat conditions at the national level. This included the effects of forest habitat quality on biodiversity that were not considered previously. Moreover, realistic land-use and forest change scenarios were established for the future based on the current trend in land-use change and ongoing forest management, which were applied for the prediction of the changes in BP. Consequently, it was observed that qualitative management of forests can aid in overcoming the adverse effects of urbanization in the ROK. Furthermore, vulnerable areas were spatially derived and quantitative evaluations of forest management effects were observed to alleviate the adverse effects of climate change on BP. These results emphasize that forest management, which is one of the most efficient strategies for climate change mitigation and adaption, is also important in combating biodiversity losses.

This study demonstrated that the successful National Reforestation Programme in Korea prompted a significant enhancement of biodiversity even in the midst of development and urbanization. This result suggests that other developing countries where forest degradation is currently underway or has already occurred can achieve economic development without the loss of biodiversity. Moreover, this result also

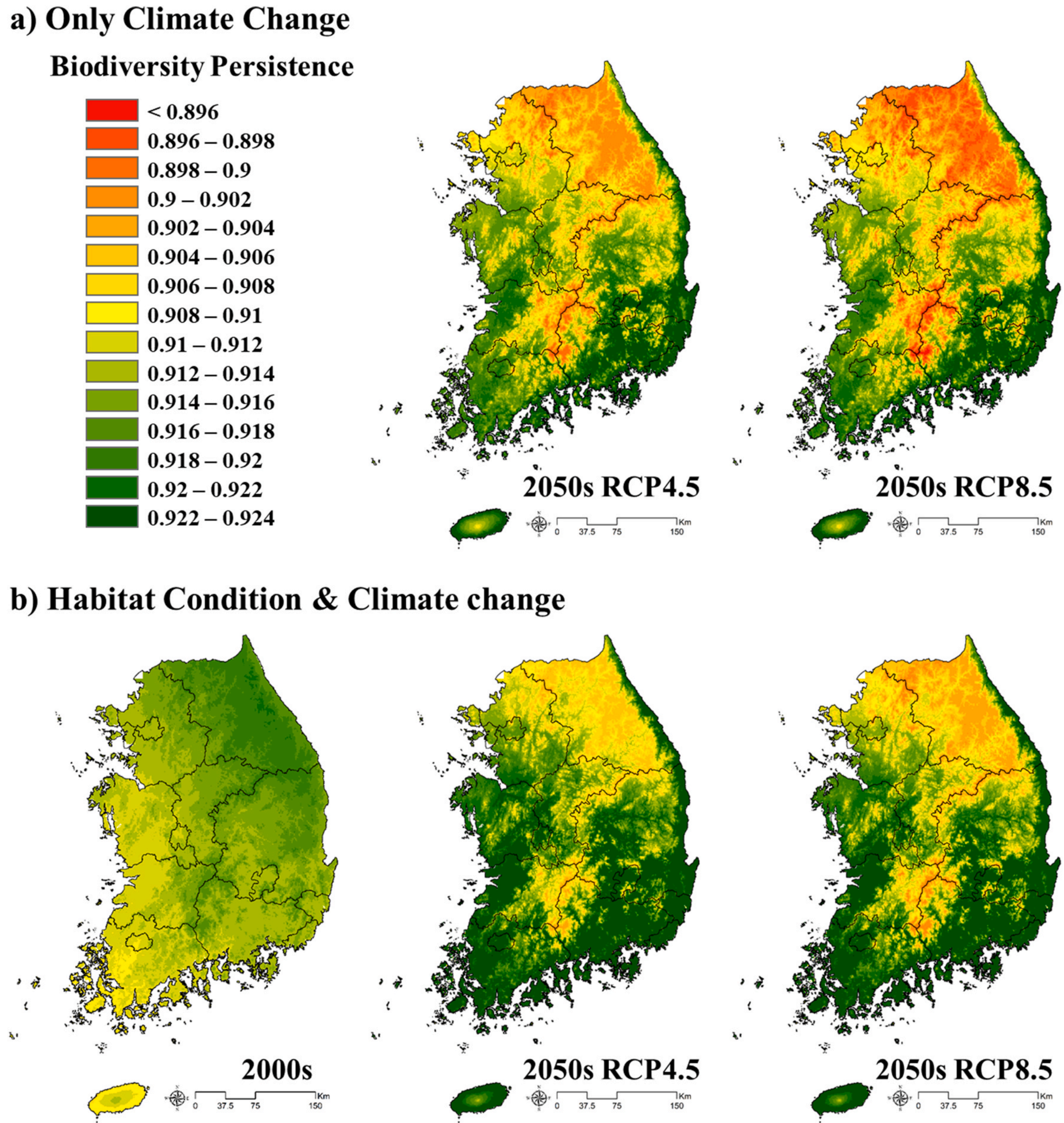

Fig. 10. Future biodiversity persistence changes under two different scenarios: a) only climate change under the current habitat condition, and b) climate change in conjunction with current and improving habitat condition . Maps indicate the proportion of species expected to persist over the long term. The color legend is the same for all maps. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

has significant implications for countries with a high proportion of well-managed forests like ROK. Given the SSP3 scenario or recent trends in land cover change, the decline in natural habitats is expected to be highly probable. In the end, if the expansion of city or urbanized area cannot be controlled, it is necessary to improve sustainability of species through quality enhancement while minimizing the degradation of natural habitats. Therefore, from the perspective of spatial planning, providing a qualitatively superior habitat even in a limited habitat area will contribute to enhancing biodiversity persistence as well as promoting ecosystem services.

However, related long-term assessment has certain limitations in that forest naturalness grade was classified based on forest origin and age class without considering other aspects, such as diversity of tree species or forest structure. Moreover, this study did not explore site-level forest management, such as thinning or pruning; instead, it included only macroscopic forest management, such as reforestation or changes in age class. Furthermore, as the results relied heavily on model-dependent predictions, additional verification is needed with an independent dataset that represents the actual patterns of variation in biological composition in ROK. Regarding these limitations, we suggest following future studies.

- Diversification of Scenarios

Although this study projected changes in land cover based on past changing trends, it is necessary to reflect more diverse scenarios (i.e. combinations of SSP-RCP scenario and forest management). By predicting the impact of future biodiversity under various scenario options, we can provide useful information on the biodiversity declines in the worst-case scenario, which needs to be dealt with. In addition, while this study simulated only the case of 2050s for the future, predicting longer future periods (e.g. 2070s) is also necessary for long-term planning. Based on this analysis, we can minimize the negative impacts of environmental changes and maximize the potential benefits of forest

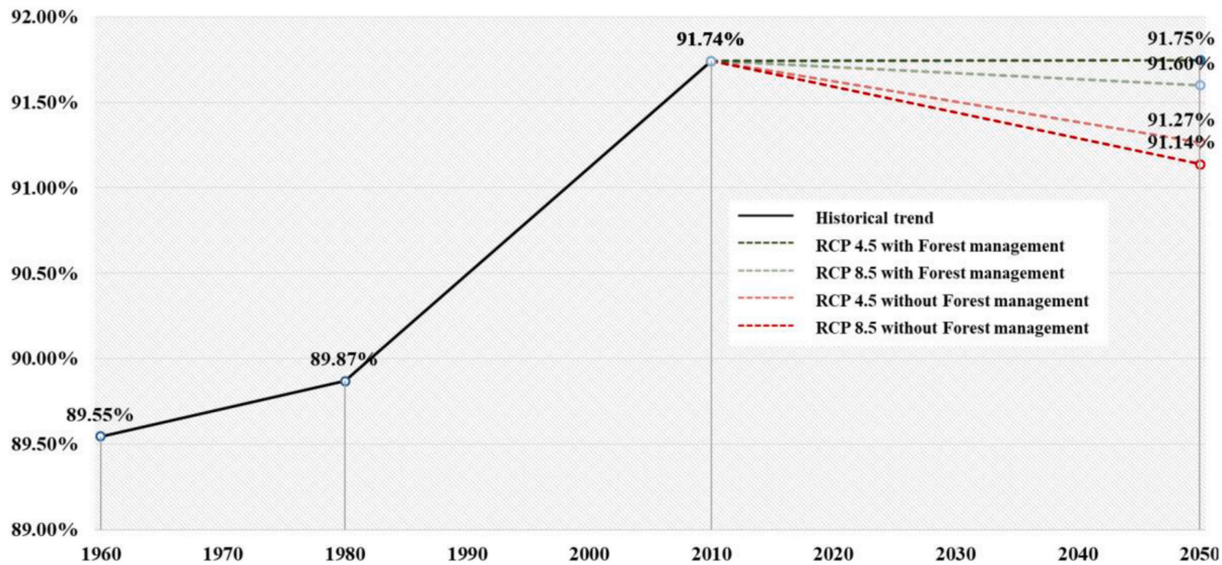

Fig. 11. Trends the average biodiversity persistence from the past to the future (1960–2050). The y-axis reports the percentage of species expected to persist. Future projection represents four alternative scenarios according to the combination of climate change (RCP 4.5 and RCP 8.5) with/without forest management scenario.

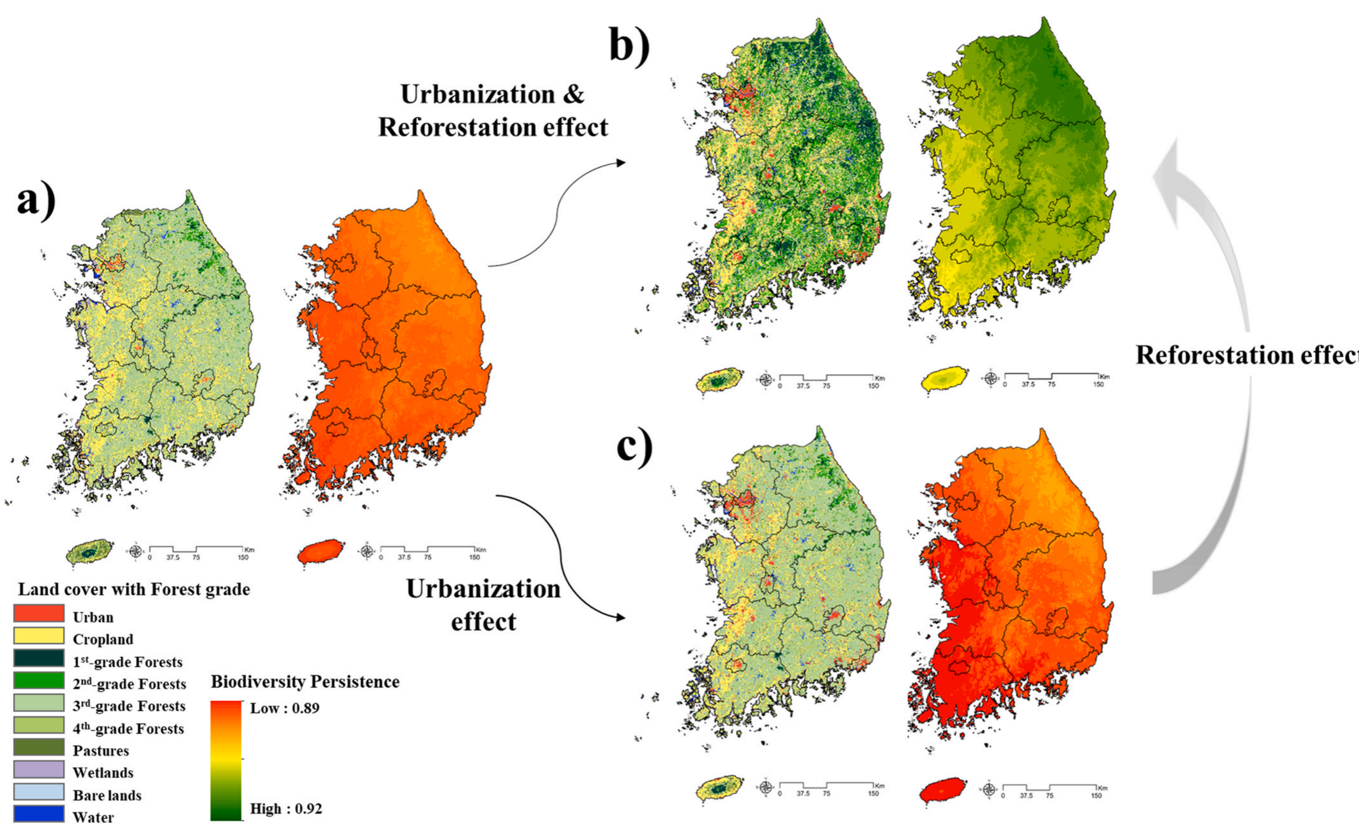

Fig. 12. Scenario comparison diagram to assess the effect of forest restoration on BP: a) land cover map in the 1960s with forest naturalness grades in the 1960s, b) land cover in the 2000s with forest naturalness grades in the 2000s, and c) land cover in the 2000s with forest naturalness grades in the 1960s.

management.

- Subdivision of habitat types

Although this study employed land cover types with forest naturalness grades as habitat types, they could be refined by considering various factors such as the intensity of use or surrounding environment. For example, in the protected forests and timber production forests, there might be a difference in forest quality even if the forests consist of the same grades. Or even in forests managed for the same purpose e.g. timber production, the conditions could vary depending on the interval of wood harvesting, the types of machinery used for harvest, or distance to roads. These qualitative differences affect the distribution of species, namely biodiversity. Therefore, habitat types should be subdivided in consideration of various aspects. Furthermore, if detailed coefficients for each type are constructed, the impact of biodiversity can be evaluated

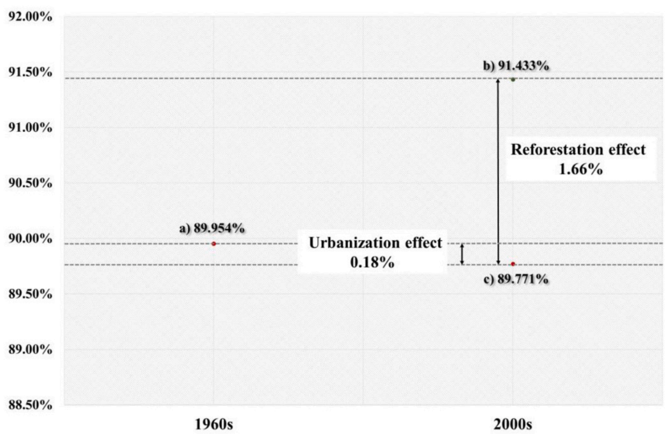

Fig. 13. Quantitative evaluation of restoration effect through comparison of three scenarios. Graph represents the average BP value of Fig. 12 scenarios to quantify the urbanization and reforestation effect. a-c) is the same in Fig. 12.

more reliably.

- Beyond flora

This study focused only on flora because plants sustain life on Earth, making up the largest part (~80%) of terrestrial biomass (Bar-On et al., 2018) and the availability and reliability of location records are higher than those of mobile animals. However, in order to comprehensively understand biodiversity, other taxa should be considered as well as plant species. Although a positive association between the number of plant species and animal species has been found in experimental and observation studies (Zhao et al., 2006; Santi et al., 2010; Castagneyrol and Jactel, 2012), there were also contrary results on the premise that plant diversity drives animal diversity (Boone and Krohn, 2000; Andrews and O'Brien 2000; Hawkins and Pausas; 2004). Moreover, since each taxonomic group is differently affected by climate and land-use change, it is necessary to make predictions for each taxa considering the characteristics of each taxonomic group. If the prediction results by taxa are combined and provided as public environmental information such as a thematic map, it can support future environmental planning.

4. Conclusion

In this study, the changes in biodiversity persistence were simulated from the past to the future (1960s–2050s) employing the global model with detailed national datasets. To this end, a habitat condition map was constructed to properly represent the Korean environment by creating a new index that indicated the degree to which biodiversity can be supported for each land cover. Spatial scenarios integrating land cover with forest habitat quality were also constructed for the periods from the 1960s–2050s, using a variety of spatial data and models. From these scenarios, we quantitatively and spatially presented the effect of reforestation and forest management by analyzing the changes in BP over time. The results demonstrated that these scenarios had a fairly positive impact on BP by offsetting the negative effects of urbanization in the past, and mitigating the serious consequences expected from climate change. However, as current forest management practice are insufficient to fully offset the decline in BP attributable to climate change, further studies, such as suggested in the aforementioned section *3.6* are needed to develop optimal strategies to minimize the decline in BP and maintain the current biodiversity level.

CRediT authorship contribution statement

Yuyoung Choi: Methodology, Writing – original draft, Visualization. **Chul-Hee Lim:** Conceptualization, Methodology. **Hye In Chung:** Validation. **Yoonji Kim:** Writing – review & editing. **Hyo Jin Cho:** Software. **Jinhoo Hwang:** Resources. **Florian Kraxner:** Supervision, Writing – review & editing. **Gregory S. Biging:** Supervision, Writing – review & editing. **Woo-Kyun Lee:** Supervision, Writing – review & editing. **Jinhyung Chon:** Supervision, Writing – review & editing. **Seong Woo Jeon:** Conceptualization, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Allnutt, T.F., Ferrier, S., Manion, G., Powell, G.V., Ricketts, T.H., Fisher, B.L., Lees, D.C., 2008. A method for quantifying biodiversity loss and its application to a 50-year record of deforestation across Madagascar. Conservation Letters 1 (4), 173–181.
Andrews, P., O'Brien, E.M., 2000. Climate, vegetation, and predictable gradients in mammal species richness in southern Africa. J. Zool. 251, 205–231.
Augustynczik, A.L.D., Yousefpour, R., Hanewinkel, M., 2019. Climate change and the provision of biodiversity in public temperate forests–A mechanism design approach for the implementation of biodiversity conservation policies. J. Environ. Manag. 246, 706–716.
Bae, J.S., Lee, K.H., Lee, Y.G., Youn, H.J., Park, C.R., Choi, H.T., Kim, T.G., 2014. Lessons Learned from the Republic of Korea's National Reforestation Programme. Korea Forest Service, Daejeon, Republic of Korea https://www. cbd. int/ecorestoration/doc/Korean-Study_Final-Version-20150106. pdf.
Bar-On, Y.M., Phillips, R., Milo, R., 2018. The biomass distribution on Earth. Proc. Natl. Acad. Sci. U.S.A. 115, 6506–6511.
Barnosky, A.D., Matzke, N., Tomiya, S., Wogan, G.O., Swartz, B., Quental, T.B., Mersey, B., 2011. Has the Earth's sixth mass extinction already arrived? Nature 471 (7336), 51–57.
Blois, J.L., Williams, J.W., Fitzpatrick, M.C., Ferrier, S., Veloz, S.D., He, F., Liu, Z.Y., Manion, G., OttoBliesner, B., 2013. Modeling the climatic drivers of spatial patterns in vegetation composition since the Last Glacial Maximum. Ecography 36, 460–473.
Botkin, D.B., Saxe, H., Araujo, M.B., Betts, R., Bradshaw, R.H., Cedhagen, T., Ferrier, S., 2007. Forecasting the effects of global warming on biodiversity. Bioscience 57 (3), 227–236.
Boone, R.B., Krohn, W.B., 2000. Partitioning sources of variation in vertebrate species richness. J. Biogeogr. 27, 457–470.
Branquinho, C., Serrano, H.C., Nunes, A., Pinho, P., Matos, P., 2019. Essential biodiversity change indicators for evaluating the effects of Anthropocene in ecosystems at a global scale. In: From Assessing to Conserving Biodiversity. Springer, Cham, pp. 137–163.
Castagneyrol, B., Jactel, H., 2012. Unraveling plant–animal diversity relationships: a meta-regression analysis. Ecology 93 (9), 2115–2124.
Ceballos, G., Ehrlich, P.R., Barnosky, A.D., García, A., Pringle, R.M., Palmer, T.M., 2015. Accelerated modern human–induced species losses: entering the sixth mass extinction. Sci. Adv. 1 (5), e1400253.
Choi, S., Lee, W.K., Kwak, D.A., Lee, S., Son, Y., Lim, J.H., Saborowski, J., 2011. Predicting forest cover changes in future climate using hydrological and thermal indices in South Korea. Clim. Res. 49 (3), 229–245.
Choi, Y., Lim, C.H., Chung, H.I., Ryu, J., Jeon, S.W., 2019. Novel Index for bioclimatic zone-based biodiversity conservation strategies under climate change in Northeast Asia. Environ. Res. Lett. 14 (12), 124048.
Clark Labs, 2017b. TerrSet (18.3) [Help System]. Clark University, Worcester, MA, USA.
Clark Labs, 2017a. TerrSet (18.3) [Software]. Clark University, Worcester, MA, USA.
Cui, G., Kwak, H., Choi, S., Kim, M., Lim, C.H., Lee, W.K., Chae, Y., 2016. Assessing vulnerability of forests to climate change in South Korea. J. For. Res. 27 (3), 489–503.
D'amen, M., Rahbek, C., Zimmermann, N.E., Guisan, A., 2017. Spatial predictions at the community level: from current approaches to future frameworks. Biol. Rev. 92 (1), 169–187.
ĐAUDYTË, S., KARAZIJA, S., BELOVA, O., 2005. An Approach to Assessment of Naturalness for Forest Stands in Lithuania.

De Chazal, J., Rounsevell, M.D., 2009. Land-use and climate change within assessments of biodiversity change: a review. Global Environ. Change 19 (2), 306–315.
Di Marco, M., Ferrier, S., Harwood, T.D., Hoskins, A.J., Watson, J.E., 2019b. Wilderness areas halve the extinction risk of terrestrial biodiversity. Nature 573 (7775), 582–585.
Di Marco, M., Harwood, T.D., Hoskins, A.J., Ware, C., Hill, S.L., Ferrier, S., 2019a. Projecting impacts of global climate and land-use scenarios on plant biodiversity using compositional-turnover modelling. Global Change Biol. 25 (8), 2763–2778.
Dirzo, R., Raven, P.H., 2003. Global state of biodiversity and loss. Annu. Rev. Environ. Resour. 28.
Drielsma, M.J., Love, J., Williams, K.J., Manion, G., Saremi, H., Harwood, T., Robb, J., 2017. Bridging the gap between climate science and regional-scale biodiversity conservation in south-eastern Australia. Ecol. Model. 360, 343–362.
Elith, J., Leathwick, J.R., 2009. Species distribution models: ecological explanation and prediction across space and time. Annu. Rev. Ecol. Evol. Syst. 40, 677–697.
Ferrier, S., Manion, G., Elith, J., Richardson, K., 2007. Using generalized dissimilarity modelling to analyse and predict patterns of beta diversity in regional biodiversity assessment. Divers. Distrib. 13, 252–264.
Fitzpatrick, M.C., Sanders, N.J., Ferrier, S., Longino, J.T., Weiser, M.D., Dunn, R., 2011. Forecasting the future of biodiversity: a test of single- and multi-species models for ants in North America. Ecography 34, 836–847.
Guisan, A., Thuiller, W., 2005. Predicting species distribution: offering more than simple habitat models. Ecol. Lett. 8, 993–1009.
Guisan, A., Thuiller, W., Zimmermann, N.E., 2017. Habitat Suitability and Distribution Models: with Applications in R. Cambridge University Press.
Hawkins, B.A., Pausas, J.G., 2004. Does plant richness influence animal richness?: the mammals of Catalonia (NE Spain). Divers. Distrib. 10 (4), 247–252.
Hoskins, A.J., Harwood, T.D., Ware, C., Williams, K.J., Perry, J.J., Ota, N., Purvis, A., 2019. Supporting Global Biodiversity Assessment through High-Resolution Macroecological Modelling: Methodological Underpinnings of the BILBI Framework. BioRxiv, 309377.
Karger, D.N., Conrad, O., Böhner, J., Kawohl, T., Kreft, H., Soria-Auza, R.W., Kessler, M., 2017. Climatologies at high resolution for the earth's land surface areas. Scientific data 4, 170122.
Kim, C.H., Kang, J.H., Kim, M., 2013. Status and development of national ecosystem survey in korea. J. Environ. Impact Assess. 22 (6), 725–738.
Kim, J.S., Kwoun, Y.M., Son, Y., Lee, S.K., 2008. The History of Deforestation and Forest Rehabilitation in Korea. Division of Environmental Science and Ecological Engineering, Korea University, Seoul.
Kim, M., Lee, W.K., Son, Y., Yoo, S., Choi, G.M., Chung, D.J., 2017. Assessing the impacts of topographic and climatic factors on radial growth of major forest forming tree species of South Korea. For. Ecol. Manag. 404, 269–279.
Kim, S.H., Shin, M.Y., Jeong, J.H., 2010. The republic of Korea. National Forest Inventories À Pathways for Common Reporting. Springer, Heidelberg, 465À471.
Korea Meteorological Administration (KMA). Available online. http://www.kma.go.kr/weather/climate/average_south.jsp. (Accessed 15 January 2020).
Laidlaw, M.J., Richardson, K.S., Yeates, A.G., McDonald, W.J.F., Hunter, R.J., 2016. Modelling the spatial distribution of beta diversity in Australian subtropical rainforest. Austral Ecol. 41, 189–196.
Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. Proc. Natl. Acad. Sci. U.S.A. 108, 3465–3472, 3.
Larsson, T.B., 2001. Biodiversity Evaluation Tools for European Forests, vol. 75. Criteria and Indicators for Sustainable Forest Management at the Forest Management Unit Level.
Lee, D.K., Park, P.S., Park, Y.D., 2015. Forest Restoration and Rehabilitation in the Republic of Korea. Restoration of Boreal and Temperate Forests, second ed. CRC Lewis, Boca Raton, Florida, USA, pp. 217–231.
Luque, S., Vainikainen, N., 2008. Habitat quality assessment and modelling for forest biodiversity and sustainability. In: Patterns and Processes in Forest Landscapes. Springer, Dordrecht, pp. 241–264.
Mantyka-pringle, C.S., Martin, T.G., Rhodes, J.R., 2012. Interactions between climate and habitat loss effects on biodiversity: a systematic review and meta-analysis. Global Change Biol. 18 (4), 1239–1252.
McRoberts, R.E., Winter, S., Chirici, G., LaPoint, E., 2012. Assessing forest naturalness. For. Sci. 58 (3), 294–309.
Meyer, C., Kreft, H., Guralnick, R., Jetz, W., 2015. Global priorities for an effective information basis of biodiversity distributions. Nat. Commun. 6, 8221.
National Biodiversity Center, 2019. Biodiversity Statistics of Korea (2018). National Institute of Biological Resources, Incheon. Designzip, 272pp.
National Institute of Forest Science (NIoFS), 2004. Development of Forest Functional Classification Map. Research Report 04-03 (Seoul, Korea).
National Institute of Forest Science (NIoFS), 2017. Forest Type Map of south korea. National Institute of Forest Science.
Newbold, T., Hudson, L.N., Arnell, A.P., Contu, S., De Palma, A., Ferrier, S., Burton, V.J., 2016. Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. Science 353 (6296), 288–291.
Noss, R.F., Cooperrider, A., 1994. Saving Nature's Legacy: Protecting and Restoring Biodiversity. Island Press.
Park, B.B., Han, S.H., Rahman, A., Am Choi, B., Im, Y.S., Bang, H.S., Shin, M.Y., 2016. Brief history of Korean national forest inventory and academic usage. Kor. J. Anim. Sci. 43 (3), 299–319.
Pe'er, G., Dicks, L.V., Visconti, P., Arlettaz, R., Báldi, A., Benton, T.G., Henle, K., 2014. EU agricultural reform fails on biodiversity. Science 344 (6188), 1090–1092.
Pereira, H.M., Ferrier, S., Walters, M., Geller, G.N., Jongman, R.H.G., Scholes, R.J., Coops, N.C., 2013. Essential biodiversity variables. Science 339 (6117), 277–278.
Rounsevell, M.D.A., Arneth, A., Alexander, P., et al., 2014. Towards decision-based global land use models for improved understanding of the Earth system. Earth Syst. Dynam. 5, 117–137.
Santi, E., Mari, E., Piazzini, S., Renzi, M., Bacaro, G., Maccherini, S., 2010. Dependence of animal diversity on plant diversity and environmental factors in farmland ponds. Community Ecol. 11 (2), 232–241.
Settele, J., Wiemers, M., 2015. Interacting global change drivers. Nat. Clim. Change 5 (10), 913–914.
Shade, C., Kremer, P., 2019. Predicting land use changes in philadelphia following green infrastructure policies. Land 8 (2), 28.
Song, C., Yoo, S., Kim, M., Lim, C.H., Kim, J., Kim, S.J., Kim, G.S., Lee, W.K., 2018. Estimation of future land cover considering shared socioeconomic Pathways using scenario generators. J. Adv. Clim. Change Res. 9 (3), 223–234 ([Korean Literature]).
Song, W., Kim, E., Jeon, S.W., Park, S., Lee, J., 2012. Improvement of the criteria on naturalness of the environmental conservation value assessment map (ECVAM). J. Korea Soc. Environ. Restor. Technol. 15 (2), 31–40.
Stürck, M.D.A., Arneth, A., Alexander, P., et al., 2014. Towards decision-based global land use models for improved understanding of the Earth system. Earth Syst. Dynam. 5, 117–137.
Titeux, N., Henle, K., Mihoub, J.B., Regos, A., Geijzendorffer, I.R., Cramer, W., Brotons, L., 2016. Biodiversity scenarios neglect future land-use changes. Global Change Biol. 22 (7), 2505–2515.
Van Asselen, S., Verburg, P.H., 2013. Land cover change or land-use intensification: simulating land system change with a global-scale land change model. Global Change Biol. 19 (12), 3648–3667.
Verburg, P.H., van Asselen, S., van der Zanden, E.H., Stehfest, E., 2013. The representation of landscapes in global scale assessments of environmental change. Landsc. Ecol. 28 (6), 1067–1080.
Ware, C., Williams, K.J., Harding, J., Hawkins, B., Harwood, T., Manion, G., Ferrier, S., 2018. Improving biodiversity surrogates for conservation assessment: a test of methods and the value of targeted biological surveys. Divers. Distrib. 24 (9), 1333–1346.
Winter, S., 2012. Forest naturalness assessment as a component of biodiversity monitoring and conservation management. Forestry 85 (2), 293–304.
Zhao, S., Fang, J., Peng, C., Tang, Z., 2006. Relationships between species richness of vascular plants and terrestrial vertebrates in China: analyses based on data of nature reserves. Divers. Distrib. 12 (2), 189–194.