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Impacts of future climate change on species richness of land vertebrates and critical areas in South Korea

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ABSTRACT: Climate change has extensive impacts on abundance, distribution, and conservation of species and ecosystems. The purpose of this study was to investigate impacts of future climate change on the species richness of land vertebrates, and to assess critical areas that might be continuously threatened by climate change in order to maintain high species richness in South Korea. The Climate Change Severity Index (CCSI) was calculated based on representative concentration pathway (RCP) scenarios to determine the climatic space (also known as comfort zone) of species and ecosystems under historic and future climate conditions. Regions with high species richness were then identified using survey results of species abundance and distribution. Finally, we identified critical areas with high CCSI values and high levels of species richness. These are areas where species and ecosystems are threatened the most by climate change. The number of critical areas is predicted to increase towards the late 2000s, and this increase is greater under RCP 8.5 than under RCP 4.5. Furthermore, the number of critical areas will increase more in coastal and wide plain areas than in inland mountainous areas. This study provides information useful for the conservation of species and their habitats in South Korea. It also indicates opportunities for launching protection measures and actions in highly vulnerable areas.

KEY WORDS: Climate Change Severity Index · Species richness · Critical area · RCP scenarios

1. INTRODUCTION

Climate change affects various climatic factors such as global temperature, precipitation, sunshine, and potential evapotranspiration (Hulme & Jenkins 1998). Climate departure represented by extreme weather events has profound impacts on ecosystems, leading to rapid changes in habitat conditions and species diversity (Gitay et al. 2002). Thus, climate change has diverse impacts on habitat distribution, migration time, survival, reproductive success, emergence of exotic species, environmental adaptation, and extinction at individual and population levels (Davis & Shaw 2001, Hannah et al. 2005, Levinsky et al. 2007, McMenamin et al. 2008, Mawdsley et al. 2009, Sinervo et al. 2010, Ryan et al. 2014, Princé & Zuckerberg 2015). A recent study on biodiversity status by Pimm et al. (2014) has suggested that the extinction rate is proceeding 1000 times faster than that shown in past fossil records, while vertebrate extinction rates are proceeding about 10 000 times faster than in the past. Anthropogenic impacts on the environment such as habitat loss and modification, human activities, and global warming are the most common causes of biological extinction (Bakkenes et al. 2002, Erasmus et al. 2002, Midgley et al. 2002, Thomas et al. 2004, 2006). Since the average temperature of Earth is expected to increase by 1.4 to 5.8°C by 2100 (IPCC 2001), rapid declines in biodiversity and habitats are expected (Thomas et al. 2006, Mayhew et al. 2008, Di Febbraro et al. 2016).

The Climate Change Severity Index (CCSI) determines the climatic space (also known as the comfort zone) of species and ecosystems. It uses historical and

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future temperature and precipitation data to represent climate change severity (Anderson et al. 2008a,b). Anderson et al. (2008a,b) introduced the CCSI in order to identify comfort zones and critical areas to assess the future impacts of climate change on biodiversity in Central America and the Caribbean. The comfort zone represents the specific temperature and precipitation regimes along with elevation and geology that current species and ecosystems have adapted to (Anderson et al. 2008a,b, Mesquita & Sousa 2009). A decrease in comfort zones due to climate change will affect food sources and breeding success of fauna, which can lead to decreased species richness (Levinsky et al. 2007, Anderson et al. 2008a,b). Such areas in which species richness is high but where climate change may cause a rapid decrease in species richness in the future are referred to as critical areas. Thus, the CCSI can reveal critical areas where species and habitat vulnerabilities are high.

South Korea is making great efforts to maintain stable ecosystems and protect biodiversity, although the country is experiencing rapid land development with high human population density and environmental change due to industrial development. According to the Environmental Performance Index score surveyed by the World Economic Forum in 2008, Korea was ranked 126th for biodiversity and habitat and 147th for air pollution among 149 countries. This indicates that efforts to conserve species and habitats in South Korea are urgent. Amphibians, reptiles, and long-lived species might be under the greatest threat due to climate change. Nevertheless, few studies have been conducted to predict the future status of these species or their ecosystems in South Korea. Although the distribution and abundance of a wintering population of cranes in the Cheolwon area (Yoo et al. 2015) and the influence of short-term climate change on bird populations in national parks have been investigated (Kim 2015), these studies have only explained the distribution of species from past to present. They are insufficient for predicting future trends or developing species protection and adaptation strategies under long-term climate change.

Therefore, the objective of this study was to calculate the CCSI based on a 200 yr control integrated representative concentration pathway (RCP) climate change scenario and predict how the CCSI will change from 2011 to 2100 in the Korean Peninsula. Vulnerable areas (critical areas) predicted to significantly decrease in species richness due to climate change during the same time period were also selected based on results of the third National Natural Environment Survey conducted in South Korea (National Institute of Environmental Research 2012). Finally, we aimed to identify future conservation areas where there were high levels of species richness and CCSI values in South Korea. We did not consider other perspectives critical to specific areas such as coastal conservation and size of islands affected by sea level rise, migration, or life history of each species. The results of this study provide detailed information for planning research, management, and conservation of species diversity and ecosystems.

2. MATERIALS AND METHODS

2.1. Climatological data for the CCSI

To obtain climate data for calculating the CCSI, we utilized monthly average temperature and precipitation from the RCP scenario provided by the Korea Meteorological Administration (KMA). The KMA has introduced and installed HadGEM2-AO, a global climate change prediction model developed by the Hadley Centre of the United Kingdom Meteorological Agency that has a horizontal resolution of 135 km. In addition, a regional climate model (HadGEM3-RA), obtained through dynamic refinement of the global climate change scenario, was used. This model was constructed for South Korea with 12.5 km resolution. Lastly, we used past climate observation data with a 1 km resolution grid (Kim et al. 2012, 2013, KMA GAW 2018). In this study, we used 200 yr integrated RCP 4.5 and RCP 8.5 scenarios provided by the KMA and future climate change data from 2011 to 2100. For spatial data, converted 1:25 000 grid data were used with the help of the Institute of Mathematical Sciences, Pusan National University.

The CCSI was obtained using the method of Anderson et al. (2008a,b), based on the concept of change in a climatically suitable range (Levinsky et al. 2007). The CCSI indicates the severity of change in a future climate zone compared to the current comfort zone. To determine the CCSI, historic (or baseline) climate data such as average monthly temperatures and precipitation were obtained for the 10 years from 2000 to 2010. To characterize climate zones under future climate change scenarios, 3 separate periods between 2000 and 2100 were examined: early (2011–2040), middle (2041–2070), and late (2071–2100). The CCSI was calculated with 2 severity indexes: Temperature Change Severity Index ($CCSI_t$) and Precipitation Change Severity Index ($CCSI_p$). These 2 indexes

Table 1. Climate Change Severity Index values and severity levels related to comfort zone

Values	Severity	Relevance to comfort zone
≤0.24	Marginal	Average temperature/precipitation within historical range
0.25–0.49	Low	Average temperature/precipitation within historical range
0.50–0.74	Medium	Average temperature/precipitation within historical range
0.75–0.99	High	Average temperature/precipitation reaching the limits of historical range
1.00–1.49	Very High I	Movement of average temperature/precipitation outside historical range
1.50–1.99	Very High II	Movement of average temperature/precipitation far outside historical range
2.00+	Extreme	Movement of average temperature/precipitation very far outside historical range

were considered equally and combined as follows (Anderson et al. 2008a,b):

$$CCSI_t = \frac{T_{future} - T_{historic}}{T_{range}} \quad (1)$$

$$CCSI_p = \frac{P_{future} - P_{historic}}{P_{range}} \quad (2)$$

$$CCSI = \frac{CCSI_t + CCSI_p}{2} \quad (3)$$

where T_{future} and P_{future} are annual mean scenario temperature and precipitation, $T_{historic}$ and $P_{historic}$ are annual mean baseline temperature and precipitation (2000–2010), and T_{range} and P_{range} are baseline temperature and precipitation ranges ($T_{max} - T_{min}$; $P_{max} - P_{min}$) based on historic mean values for the maximum (T_{max}; P_{max}) and minimum (T_{min}; P_{min}) quarters in 2000 to 2010.

The CCSI values were divided into 7 severity levels (Marginal, Low, Medium, High, Very High I, Very High II, Extreme; Table 1) based on the range of values provided by Anderson et al. (2008a,b). Values between 0 and 0.99 reflect future increases in the CCSI index that remain within the historical range.

2.2. Estimation of species richness

The Ministry of Environment of the Republic of Korea has conducted nationwide natural environment surveys since 1986 to systematically preserve and manage natural resources in Korea. These survey results have been used to promote national biodiversity and conserve natural ecological conditions (Ministry of Environment 2006). In this study, we used survey results describing species richness of amphibians, reptiles, mammals, and birds from the third National Natural Environment Survey (2006 to 2012). As the total number of bird species was much larger than those of amphibian, reptile, and mammal species, we used proportional species richness (Winkler et al. 2016), summing the ratios of species number in each grid to total number of species found in all grids per taxonomic group, instead of absolute species numbers (Fig. 1).

2.3. Selecting critical areas

We analyzed the relationship between the CCSI and the distribution of current species in each grid to determine which areas might be more likely to be influenced by climate change. Critical areas are those where a severe decrease in species richness is anticipated due to future climate change. In these areas, both the CCSI and species richness are high. An increase in CCSI values increases the number of critical areas and decreases the number of climatic comfort zones. Our aim was to prioritize areas for climate change adaptation and conservation based on geographic overlaps between high climate change severity and high species richness. Therefore, we selected climate risk zones with High and Extreme CCSI levels and high species richness with values of ≥0.24 (>50% of proportional

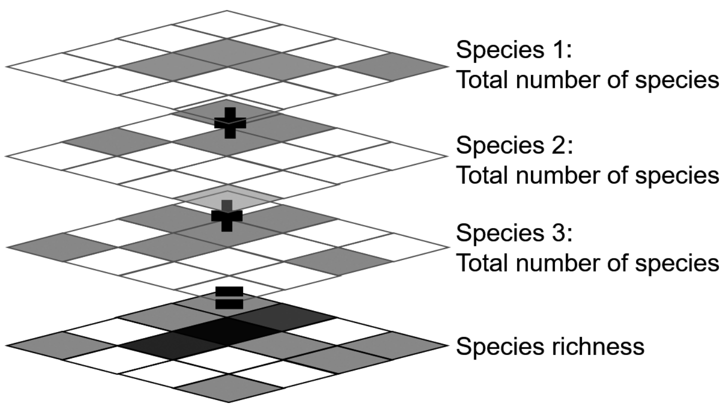

Fig. 1. Habitat range and species richness on a 1:25 000 scale map. Richness was obtained by adding ratios of detected individual species to total number of species of each taxonomic group (amphibians, reptiles, birds, and mammals). Darker grids indicate higher richness due to more species inhabiting that area

species richness). Areas where these 2 criteria overlapped were selected as critical areas. Areas with Very High CCSI values (including Very High I and II values) that overlapped with high species richness areas were designated as second class critical areas, while those with Extreme CCSI values were designated as first class critical areas.

3. RESULTS

3.1. Future impacts of climate change on CCSI and species richness in South Korea

From 2011 to 2100, CCSI values were predicted to be in the range of 0.25 to 2.12 (Low to Extreme) under RCP 4.5 and in the range of 0.29 to 4.01 (Low to Extreme) under RCP 8.5 (Fig. 2). The changes in the severity index measured in coastal areas and partial inland regions were larger than those in inland mountain areas. Towards the late 2000s, both scenarios tended to show higher index values. The magnitude of climate change severity under RCP 8.5 was much greater than that under RCP 4.5 (Table 2). In the early 2000s, most severity levels were Low and Medium (RCP 4.5: 97.96 %; RCP 8.5: 96.28 %). However, in the mid 2000s, High and Very High levels (including Very High I and II) accounted for 89.07 % and 98.80 % under RCP 4.5 and RCP 8.5, respectively. In the late 2000s, levels exceeding Extreme accounted for 0.12 % and 84.03 % under RCP 4.5 and RCP 8.5, respectively.

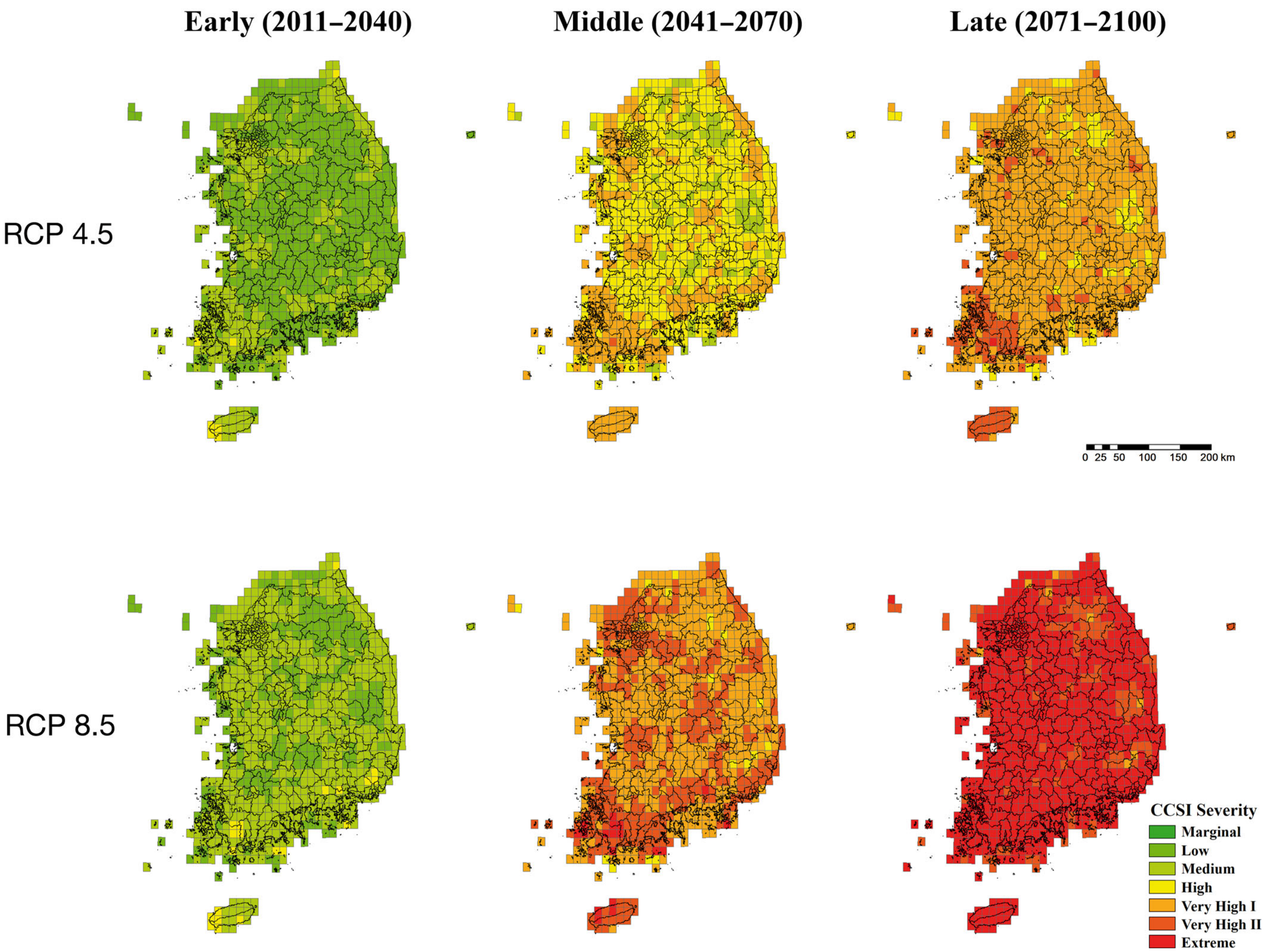

Fig. 2. Comparison of climate change severity among 3 time periods in the 2000s according to representative concentration pathway (RCP 4.5 and RCP 8.5) scenarios in South Korea

Table 2. Comparison of grid numbers allocated to each severity level of the Climate Change Severity Index in South Korea under the representative concentration pathway (RCP) 4.5 and RCP 8.5 scenarios (833 grids total). Early: 2011–2040; Middle: 2041–2070; Late: 2071–2100

RCP scenario classification	RCP 4.5						RCP 8.5					
	Early		Middle		Late		Early		Middle		Late	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Marginal	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Low	535	64.23	0	0.00	0	0.00	242	29.05	0	0.00	0	0.00
Medium	281	33.73	81	9.72	0	0.00	560	67.23	0	0.00	0	0.00
High	7	0.84	488	58.58	68	8.16	21	2.52	18	2.16	0	0.00
Very High I	0	0.00	253	30.37	652	78.27	0	0.00	462	55.46	8	0.96
Very High II	0	0.00	1	0.12	102	12.24	0	0.00	343	41.18	115	13.81
Extreme	0	0.00	0	0.00	1	0.12	0	0.00	18	2.16	700	84.03

Results of the third National Natural Environment Survey showed that species richness varied in grids. Among them, regions with high species richness were sub-divided into regions with the highest (≥0.29) and the second highest (0.24 to 0.28) proportions, estimated based on regions with species richness greater than 0.24. Among a total of 833 grids, 396 (47.54 %) grids were classified as regions with a high proportion of species richness (Fig. 3).

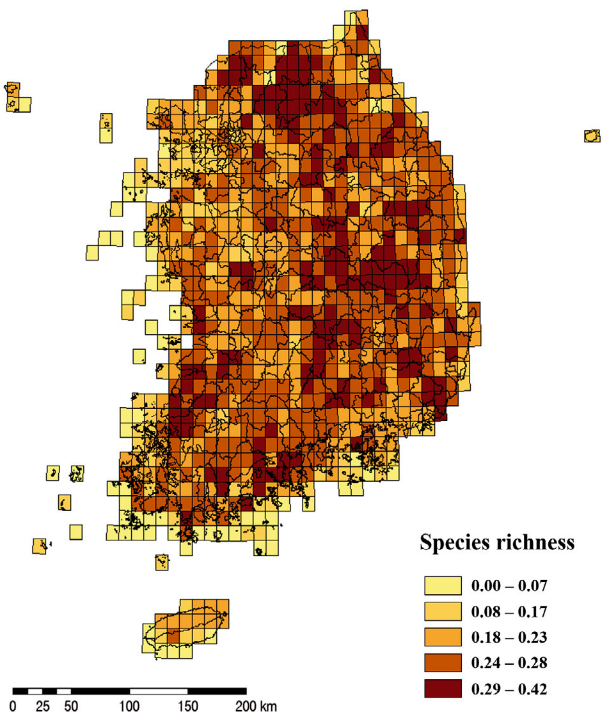

Fig. 3. Overall proportional species richness of amphibians, reptiles, birds, and mammals in South Korea. Richness was obtained by summing ratios of the number of species to total numbers found in all grids per grid per taxonomic group

3.2. Changes in critical areas

The number of critical areas (major conservation areas) combining high CCSI and high species richness increased more under RCP 8.5 than under RCP 4.5 (Table 3, Fig. 4). Under RCP 4.5, the number of critical areas did not change markedly until the mid 2000s. However, in the late 2000s, an extensive increase in second-class critical areas occurred all over the country except in some inland mountainous regions. Under RCP 8.5, the number of second-class critical areas also increased in the mid 2000s but to a greater extent compared to that observed in the late 2000s under RCP 4.5. In addition, some first-class critical areas appeared in southwestern areas. In the late 2000s, the first-class critical areas expanded more extensively nationwide, while second-class critical areas remained along the inland mountainous region.

4. DISCUSSION

Our results show that the CCSI will steadily increase during the 21st century in South Korea, and that most regions will be classified as 'high climate change severity' in the latter half of the 2000s. Such an increase in the CCSI causes conservation concerns regarding the maintenance of high species richness in ecosystems in response to climate change. Similar results have been reported by Anderson et al. (2008a,b), showing a significant increase in the CCSI in Central America towards the late 2000s to the point where climate change threatens ecosystems and species. These results imply that greenhouse gas emissions caused by human activities need to be reduced. Such results also highlight common considerations for conservation and management efforts of species and their habitats in the future.

Table 3. Comparison of grid numbers representing critical areas over 3 time periods in the 2000s under representative concentration pathway (RCP) 4.5 and RCP 8.5 scenarios. Early: 2011–2040; Middle: 2041–2070; Late: 2071–2100

	Early		Middle		Late	
	No.	%	No.	%	No.	%
RCP 4.5						
Second-class critical area	0	0.00	104	12.48	355	42.62
First-class critical area	0	0.00	0	0.00	0	0.00
RCP 8.5						
Second-class critical area	0	0.00	384	46.10	65	7.80
First-class critical area	0	0.00	3	0.36	331	39.74

In this study, the CCSI was determined from 2 climatic factors, namely temperature and precipitation. The CCSI has an impact on future critical areas that are known to play an important role in breeding, migration, and dispersal of species. It also affects the survival and reproductive success of species in South Korea. An increase in the CCSI would directly or indirectly affect the distribution of species and their habitats (Levinsky et al. 2007, Laurance 2008, Morganti et al. 2017). For instance, the breeding and wintering sites of lesser kestrel in Europe are expected to change due to the severity of climate change predicted by the RCP scenario, and changes in temperature and precipitation are predicted to have the greatest impact. A gradual decrease in populations due to a reduction in habitat caused by climate change is also anticipated (Brooks et al. 1999). Genetic drift and reduced genetic diversity due to reduced habitat ranges might lead to population extinctions (McCarty 2001). Thus, a future increase in the CCSI in South Korea may induce changes in the climatic environment of species, which in turn might adversely affect their survival and reproduction.

Future CCSI values in South Korea in coastal areas appeared to be higher than those in inland areas. The CCSI was particularly high in western coastal regions (Geum River Estuary, Seocheon-gun, Chungnam; and

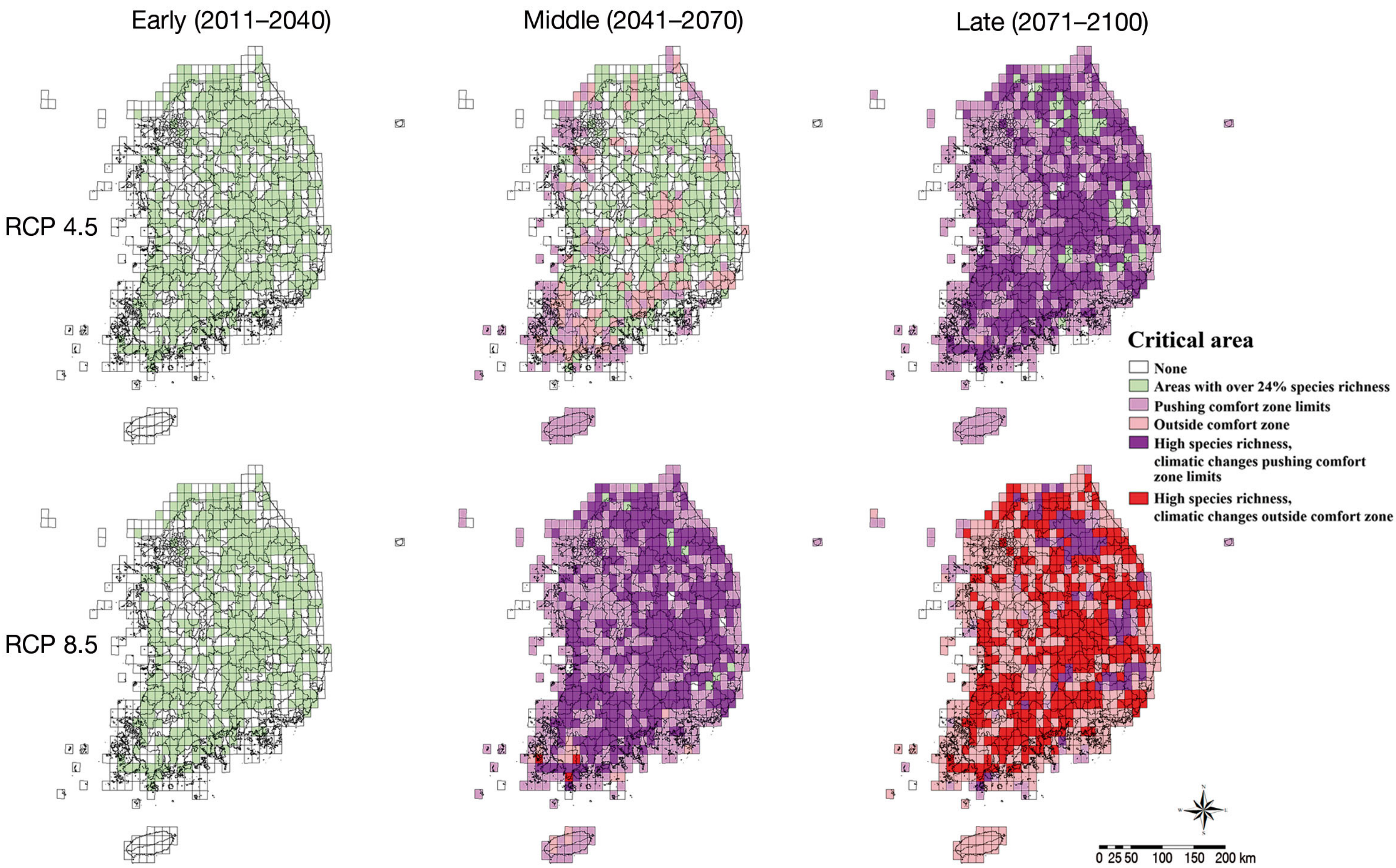

Fig. 4. Critical areas over 3 time periods in the 2000s according to representative concentration pathway (RCP) 4.5 or RCP 8.5 scenarios showing high species richness and climate change severity in South Korea

Gunsan-si, Jeonbuk) and northeastern coastal regions (Goseong and Sokcho, Gangwon). According to the distribution pattern of species richness in South Korea based on the third National Natural Environment Survey, the main regions with high species richness are located in inland mountainous regions and on western coasts. Overall, western and northeastern coastal areas showed increases in the CCSI, while inland mountainous regions and western coastal regions showed high species richness. These results indicate that a high number of species in coastal areas will be exposed to severe climate change. They may face the most difficult challenges in adapting to changing temperature and precipitation (Fig. 3). In particular, the west coast including the Geum River Estuary with tidal flats and wide plains was recognized as a critical area in the future climatic environment of South Korea, because it serves as a stopover area for large migratory birds. In addition, severe changes in habitat and climate are expected to rapidly decrease species richness. Thus, an increase in areas with high CCSI values is likely to adversely affect the distribution of species and their optimal habitats, which may lead to changes in biodiversity and species richness (Parmesan & Yohe 2003, Root et al. 2003, Sinervo et al. 2010). These results suggest that the coastal region is under the greatest threat regarding species richness in the future climatic environment of South Korea. Thus, conservation policies should be implemented as a priority to conserve and manage species and their habitats under climate change.

In contrast, the number of critical areas and the CCSI were low along grids in the mountain ranges extending north and south, and covering a length of approximately 700 km and an area of 2700 km^2. Similarly, Anderson et al. (2008a,b) reported that the higher the altitude, the lower the impact on species richness because species that inhabit high altitudes are more adapted to greater ranges in temperature. Thus, as comfort zones have a broader range in high altitude areas, any climate-induced change is less likely to push grid cells out of historic comfort zones, while lowland species and invasive species can move uphill. In addition, since most inland mountains in South Korea are forested, these forests may help buffer the effects of climate change on species richness because the forest ecosystem shows resilience to changing environmental conditions (Thompson et al. 2009; our Fig. 4).

The magnitude of the increase in CCSI values under RCP 8.5 was larger than that under RCP 4.5. Critical areas are predicted to occupy 42.62% (all second-class areas) of South Korea in the latter half of the 21st century under RCP 4.5 and 47.54% (first-class areas; 39.74%) under RCP 8.5. Therefore, the future status of species is likely to be worse under the RCP 8.5 scenario in the late 2000s. Since the difference between the RCP 8.5 and 4.5 scenarios depends on enforcement of climate change mitigation policy on greenhouse gas emissions, the higher CCSI values under RCP 8.5 indicate the importance of implementing greenhouse gas mitigation measures to protect species and maintain species richness.

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