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Novel Index for bioclimatic zone-based biodiversity conservation strategies under climate change in Northeast Asia

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Abstract

Biodiversity is rapidly declining globally and targeted efforts are needed to mitigate the loss of species. Conventional conservation efforts have focused on establishing protected areas and restoring degraded lands in order to maintain current conditions or restore ecosystems to a pre-damaged state. However, as the climate changes, the current bioclimatic zones will be re-distributed globally. Historical distribution patterns may no longer serve as an effective guide for supporting biodiversity under climate change. In response to these challenges, this study proposes a spatially explicit strategy for biodiversity conservation that takes climate change into account using bioclimatic classification. The bioclimatic classification maps of Northeast Asia (NEA) were constructed for three historical time periods (the 1980s, 1990s, and 2000s) and two future time periods (the 2050s and 2070s) using five general circulation models (GCMs) in representative concentration pathway (RCP 8.5) scenarios. It was predicted that, in general, zones are shifting north, and some zones are expanding or shrinking rapidly. Based on an analysis of latitudinal and areal change for each zone, the bioclimate vulnerability index (BVI) and naturality index (NI) were developed to quantify the impact of environmental change. As a result of the BVI analysis, the distribution of vulnerable zones is expected to shift northward and expand. As is evident with the increased vulnerability of the subarctic region caused by the expansion of the temperate climate, the extent of vulnerable zones will increase. Also, the southern regions of NEA are becoming vulnerable due to the transformation of the temperate zone to a more subtropical zone. Quadrant graphs based on the BVI and NI were created to present appropriate strategies for each zone. Our proposed framework shows that conservation strategies should be modified based on the changes in the relative position of each zone over time.

1. Introduction

Climate change is one of the most important factors affecting biodiversity, which is the most important foundation of ecosystem resilience and ecosystem services [1–4]. As climates change, some species are expected to maintain their original distribution, adapting quickly to environmental change by utilizing suitable habitats near or within their historical distributions, or through increasing genetic diversity within their gene pools [5–10]. However, many habitats, particularly those dependent on cool and humid climates, are expected to shrink and in some cases completely disappear, which could lead to a decrease in biodiversity [11–13]. In response, there has been an increasing effort to halt, and eventually reverse, the loss of biodiversity through international cooperation [14, 15].

Conservation efforts have traditionally included habitat management, such as land protection and restoration of degraded land, and direct species management [16–18]. Habitat management aims to maintain current conditions or restore the habitat conditions to a pre-damaged state. However, as the
climate changes, the current distribution of environmental conditions across the globe will change [19, 20]. This means that the restoration of historical habitat conditions may no longer be effective, as the climatic conditions are no longer suitable for that habitat [21–23]. Accordingly, many researchers have begun to reconsider the use of targets based on conditions and are instead proposing climate-adapted interventions or advanced, proactive planning approaches [24–27].

Ecosystem classifications, including ecoregions, and climate classifications are commonly used as a basis for conservation planning, with the assumption that environmental change is reflected in changes in biodiversity patterns [25, 28–30]. For instance, using the concept of ecoregions, researchers have proposed the prioritization of conservation [31], carried out climate change vulnerability analysis [29], and evaluated protected areas [32], e.g. WWF’s Global200 Ecoregions [33]. Further, bioclimatic classification is used for studies visualizing the impact of climate change [20, 34], and predicting the regional impacts on land-use change [35] or biodiversity and industry [36]. These studies are conducted on the premise that the distribution of species is affected when bioclimatic changes occur. However, most of the previous studies use these bioclimatic and ecoregional classifications as evaluation units and have not considered the changes within the zones in their conservation strategies.

The purpose of this study is to propose a spatially explicit strategy for biodiversity conservation that takes climate change into account using bioclimatic classification. In order to achieve this, bioclimatic classification maps of Northeast Asia (NEA) are constructed for the past and the future, and new indices are produced to quantify the impact of environmental change. Using the newly proposed indices, a framework for selecting a priority conservation strategy is suggested and examples of its utilization are presented.

2. Study area and data

2.1. Northeast Asia

The study area is shown in figure 1. The latitudes of the plot range from 18°58′57″ to 57°17′15″ and the longitudes of the plot range from 111°0′56″ to 147°17′12″. This includes some parts of Russia, the eastern part of Mongolia and China, the Korean Peninsula, Japan, and Taiwan. The eastern part of China is mainly a plateau, and the Gobi Desert, whose climate is generally characterized by extreme dryness, combined with cold in northern areas making it unable to support much plant growth, covers part of northeastern China and southern Mongolia. Korea and Japan, which are mostly mountainous and close to the ocean, have a temperate monsoon climate [37]. Taiwan, on the other hand, is surrounded by the ocean and has a hot and humid tropical climate. Because of these climatic and geographical features, the study area includes a variety of land cover types, such as desert, grassland, cropland, and diverse types of forest [38].

2.2. Climate data

We used the Climatologies at high resolution for the earth’s land surface areas (CHELSA) climate dataset [39] at 30 arcsec resolution, which dates from 2016 and has a higher predictive capability than other global climate data sets [40]. A monthly minimum, maximum, and mean temperature and precipitation for the years 1981–2010 were extracted and processed. In order to understand historical climate conditions, monthly climate averages over 1981–1990, 1991–2000, and 2001–2010 were generated for the 1980s, 1990s and 2000s, respectively. For future prediction, five general circulation models (GCMs) under the representative concentration pathway (RCP) 8.5 scenarios for the periods of the 2050s (2041–2060) and 2070s (2061–2080) were utilized to reduce the uncertainty. The five GCMs used in this study were CESM1-BGC, MPI-ESM-MR, MIROC5, CMCC-CM, and CESM1-
CAM5, which show the lowest amount of interdependence [41], except for ACCESS1-3 which was not provided by CHELSA.

2.3. Land cover data
Land cover data were obtained from the European Space Agency Climate Change Initiative (ESA CCI), which provides comprehensive land cover datasets. The annual ESA CCI land cover maps cover a period of 24 years from 1992 to 2015, a unique long-term time series, at 300 m spatial resolution [42]. These maps depict the geographical distribution of global land cover in 37 classes based on the United Nations Land Cover Classification System (UN-LCCS; [43]). In this study, four land cover maps were used from 1992 representing the 1980s, which is the closest available data to the 1980s, 1995 for the 1990s, 2005 for the 2000s, and 2015 for the future.

3. Methodology
This study suggests a framework for deriving conservation strategies that should be prioritized in each bioclimatic zone, which represent the spatial range in which the climatic conditions affecting potential habitat distribution are homogenous [20, 44]. In order to do this, we first developed two indices that can quantify the impact of climate change and the natural habitat of each zone. We then suggest a methodology for selecting strategies through comparing the two indices of the bioclimatic zones.

3.1. Construction of bioclimatic classification
To produce bioclimatic maps in NEA, this study applied the bioclimatic variables and methods of [45], which have been used for estimating the climate change impacts on terrestrial ecosystems and have been validated through various studies ([46], [35, 47], [36], [20]). Reference [45] derived four significant bioclimatic variables from the global climate dataset using statistical screening, including correlation analysis, principal component analysis, aridity index, growing degree-days on a 0 °C base (GDD), potential evapotranspiration seasonality, and temperature seasonality. A detailed description and equations for each variable can be found in [48] and [34]. These four bioclimatic variables for each period were constructed with a spatial resolution of 30 arcsec (equivalent to 0.86 km² at the equator) and as for the input bands to the Iterative Self-Organizing Data Analysis Techniques (ISODATA), the variables of the 1980s were used to classify the 1980s bioclimatic zones in NEA. The ISODATA method is an iterative procedure for clustering multivariate data using minimum Euclidean distance in the multidimensional feature space of the input variables [49], which can also create the statistics of each class including mean vector and the covariance matrix as a signature profile. The number of zones was empirically determined based on the previous study [34], which also classified bioclimatic zones in the same way and identified the environmental characteristics of each zone in Northeast Asia. With the signature profile of the 1980s bioclimatic zone, the maximum likelihood classification algorithm, which computes the statistical probability of the cells for each class to determine the membership, was used to assign the bioclimatic zones in the 1990s and 2000s, and the future (the 2050s and 2070s). Using each of the five GCMs with RCP 8.5 scenarios, which best represents the current emission trend linked to climate change [50], the future bioclimatic zones were determined through collating the results of five models, assigning the class with the majority occurrence within any particular grid cell. All calculations and analyses were performed using ArcGIS 10.3 (ESRI, Redlands, CA, USA) and R version 3.5.1 (R Foundation for Statistical Computing, Vienna, Austria).

3.2. Change analysis of bioclimatic zones
The change in the distribution of each zone was analyzed in terms of two aspects i.e. latitudinal and areal change. Since zones generally shift northward [20, 34, 35, 51], we examined the latitudinal density of each zone using a violin plot. We derived the maximum, minimum, and average latitude values of each zone and calculated the moving speed by the change in average position over time (km yr⁻¹). The moving speed is considered as a relative index measure, rather than the calibrated value of migration rates, which estimates the geographic distance species move to keep pace with climate shifts. In addition, the distribution area changes in each zone were derived. The 2000s was set as the baseline, and all analyses were conducted by comparing with this baseline. Accordingly, the analysis was conducted considering the comparison with the 1980s as the past, the comparison with the 2050s as the mid-term future, and the comparison with the 2070s as the long-term future.

3.3. New indices for biodiversity conservation strategies
3.3.1. Bioclimate vulnerability index (BVI)
While the response to climate change can vary, species living in areas with significant changes, where more effort is required for adapting, are more exposed to climate change. In terms of the bioclimatic zone, the faster the zone’s moving speed or the smaller the area of the future bioclimatic zone, the more likely it is that species in that bioclimatic zone will lose their suitable climate habitat in the future. Based on this assumption, we developed the BVI to quantitatively assess the degree of impact in each zone because of climate change. In other words, the zones with higher BVI could be considered more vulnerable area to climate change impacts on biodiversity. The index consists of moving speed and the area change rate (equation (1)).
The moving speed is defined as the distance traveled by the distribution density center of each zone over time. The area change rate was calculated as the distribution area of each zone in each period relative to the area in the base period (2000s)

\[
BVI = \frac{\text{Moving speed}}{\text{Future distribution area} / \text{Current distribution area}} \tag{1}
\]

The BVI was derived for three periods: the past (1980–2000), mid-term future (2000–2050), and long-term future (2000–2070). They were standardized using the overall mean and standard deviation for a fair comparison between all periods and evaluating the criticalness of the values. We define a value >1 as Highly Vulnerable, 0–1 as Vulnerable, −1–0 as Stable, and <−1 as Highly Stable.

3.3.2. Naturality index (NI)

In addition, since species are affected not only by the impact of climate change but also by the loss of habitat owing to other factors, considering the quantity of natural habitat is also important for an effective conservation strategy [52–54]. There are several studies that have used vegetation intactness, which quantifies the proportion of areas where native vegetation has been totally transformed, as a proxy for adaptive capacity [29, 55]. However, since this study used different land cover classifications, we introduced a new index called the NI. The NI is defined as the total proportion of natural area in each bioclimatic zone (equation (2)), which takes into account the degradation of natural habitats, and is a broader concept than vegetation intactness. When calculating the area of natural habitat, the land cover was reclassified as natural areas for various types of forests (e.g. broad-leaved evergreen, broad-leaved deciduous, needle-leaved evergreen, needle-leaved deciduous and mixed leaf type), shrubland, grassland, and waters, and non-natural areas for urban areas and cropland

\[
NI = \frac{\text{Area of natural habitat}}{\text{Total area of each bioclimatic zone}} \tag{2}
\]

Changes in NI account for not only changes in land cover resulting from an expansion of agricultural land or urban areas but also shifts in the bioclimatic zones. Thus, a decline in NI cannot be interpreted only as the destruction of natural areas, and an increase in NI also cannot be interpreted only as restoration of natural areas. The NI indicates the present extent of natural habitat in each zone, which can provide useful information on planning conservation strategies. The NI was derived for the three periods (the 1980s, 1990s, and 2000s) using land cover data from 1992, 1995, and 2005, respectively. For the future NI (the 2050s and 2070s), we used the latest available 2015 land cover data with the assumption that the land cover would be maintained. Though the NI values have inherent meanings, they were also standardized just as BVIs to construct a framework in the same range.

3.4. Bioclimatic zone-based framework for biodiversity conservation strategies

We developed a framework to support effective biodiversity strategies by undertaking a bioclimatic assessment that integrates BVI and NI to provide spatially explicit adaptation guidance for broad-scale management or planning. The vulnerability of each bioclimatic zone was evaluated by using the standardized BVI and NI. Quadrants graphs with two axes for BVI and NI were created, and appropriate strategies were presented for each quadrant based on the literature review. For each quadrant, a specific example was presented for one of the bioclimatic zones. In addition, by identifying the changes in the relative position within the quadrants in which each zone is located, a reprioritization of alternative options was suggested.

4. Results and discussion

4.1. Construction and change analysis of bioclimatic zones

The study area is classified into 15 bioclimatic zones that represent the climate and environmental characteristics of NEA [34, 56]. Five bioclimatic classification maps were constructed for three time periods (the 1980s, 1990s, and 2000s) and two future time periods (2050s and 2070s) for RCP 8.5 scenarios (figure 2). The changes in the bioclimatic maps for the different time periods indicate how each zone changes in response to climate change, including the direction of the shift and the extent of change. There were no major changes between the 1980s and 2000s, but since the 2000s, there have been significant changes in the zones. In figure 2, the reduction of Zones 1 and 2, the expansion of Zones 5–11 in the central inland region, and the expansion of Zones 14 and 15 in the southern marine region is evident. Meanwhile, with climate change, most of the bioclimatic zones shifted northwards conspicuously, in line with the findings of other climate change studies [20, 35, 51, 57].

4.1.1. Area change analysis

Species living in bioclimatic zones where the future distribution area decreases significantly with climate change are more likely to be affected [36, 48]. On this basis, an analysis of the change in area was conducted, and table 1 shows the area change ratio compared to the base period (i.e. the 2000s). As a result, the zones could be divided into three categories; the decreasing zones, the increasing zones, and the fluctuating zones e.g. decreasing until the 2000s but predicted to increase in the future or vice versa. It was found that the expansion and reduction of the areas are closely
Figure 2. Time series maps for 13 bioclimatic zones and elevation map in NEA.

Table 1. Area change rate, average altitude in the 1980s and altitude change rate of each bioclimatic zone. The decreasing zones are indicated in orange and yellow, the increasing zones in blue, and the fluctuating zones in green.

| Bioclimatic zone | Area change rate (%) | Average altitude in 1980s (m) | Altitude change rate (%) |
|------------------|-----------------------|-------------------------------|--------------------------|
|                  | 2000 compared to 1980 | 2050 compared to 2000 | 2070 compared to 2000 | 2000 compared to 1980 | 2050 compared to 2000 | 2070 compared to 2000 |
| 1                | -30                   | -72                           | -89                      | 1215                   | 5                   | 23                           | 35                       |
| 2                | 2                     | -36                           | -65                      | 791                    | 7                   | 24                           | 47                       |
| 3                | -18                   | -41                           | -43                      | 627                    | 4                   | 22                           | 39                       |
| 4                | -29                   | 8                             | -38                      | 752                    | -12                 | 15                           | 35                       |
| 5                | 7                     | -14                           | -12                      | 684                    | 0                   | -5                           | 6                        |
| 6                | 13                    | 14                            | 3                        | 545                    | 11                  | 11                           | 3                        |
| 7                | 44                    | 42                            | 50                       | 557                    | 6                   | -9                           | 5                        |
| 8                | 12                    | 14                            | 49                       | 856                    | -10                 | -2                           | 4                        |
| 9                | -18                   | 21                            | 38                       | 824                    | 8                   | -23                          | -15                      |
| 10               | 13                    | 87                            | 122                      | 380                    | 53                  | 18                           | 4                        |
| 11               | 4                     | -15                           | 58                       | 326                    | 41                  | 48                           | 60                       |
| 12               | -9                    | -26                           | -37                      | 401                    | -2                  | 36                           | 81                       |
| 13               | -15                   | -34                           | -52                      | 278                    | 13                  | 33                           | 89                       |
| 14               | 29                    | 35                            | 33                       | 274                    | -4                  | -3                           | -1                       |
| 15               | 19                    | 61                            | 122                      | 160                    | 16                  | 26                           | 38                       |
related to the present altitude of the zone and the altitudinal changes during the shift.

Zones with a constantly decreasing area tend to show an increasing change rate of altitude, while zones with increasing area generally tend to show little change or a decreasing change rate of altitude (table 1). Zones 1, 3, 12, and 13 are decreasing zones, but can be classified into two different types according to their distribution positions. Zones 1, and 3 are located in the north with low temperatures and high altitudes (>600 m) and will gradually shift up to higher altitudes with a reduction in area. Zones 2 and 4 increase slightly in 2000 and 2050 respectively but overall show a declining trend for the same reasons as Zones 1 and 3. On the other hand, Zones 12 and 13 with low altitudes (<400 m) are shrinking as they are limited to the plains, and cannot expand further into the high-altitude mountainous areas towards the north. Though Zone 5 is relatively high at an average altitude of 684 m, because it includes some of Mongolia’s highlands, examining its movement pattern shows it will be limited by high mountains such as Zones 12 and 13. In contrast, increasing Zones 6, 7, 8, and 10 of the central inland, and Zones 14 and 15 of the southern subtropical regions, continue to shift northward and expand into the plain. Zone 15 is exceptionally high in altitude, but it is difficult to interpret owing to limitations of the methodology, in which new climates cannot emerge. The other zones showing fluctuation tend to decrease in the current location but expand into new regions. Zone 9, located in the mountainous region of the Korean Peninsula, reduced during the 2000s by shifting to higher altitudes, but by the 2050s it is expected to expand into the plains of China. Zone 11, located in the region near the Shandong Peninsula in China and south-central Korean Peninsula, would be almost extinguished in these regions in the 2050s but will expand its distribution into the northern part of the Korean Peninsula and into Liaoning province in the north eastern part of China. In general, the interpretation of these changes in bioclimatic zones show a reduction in the boreal climate zone in the northern region and an extension of the hot and humid subtropical climate.

4.1.2. Moving speed analysis

To analyze the vulnerability of bioclimatic zones, it is necessary to consider not only the area change but also the relative change in future latitudinal distribution. This is because species inhabiting expanding zones with the significant difference between the current and the future location may have difficulty in following the shift. Latitudinal distribution analysis was undertaken (figure 3). The violin plot represents the distribution of

![Violin plots of the latitudinal distribution of the 15 bioclimatic zones for each time period. The violin lines represent the distribution of each zone against latitude. Three points in the plot are plotted to indicate the highest, lowest, and average latitude value of the distribution.](image)
each zone in terms of change in latitude over time with three points plotted to indicate the highest, lowest, and the average value of the distribution. Through this, we could identify the change in the distribution pattern during a northward shift.

The movement speed of each zone is expressed as the distance in the shift of the density center over time. In general, the centers of distribution density in the northern zones are higher than those in the south. Through examining the change in the relative position of the distribution density center, the northern limit of distribution rises to the north first, and the center of the density distribution gradually shifts to the north under climate change. Zones 1 and 2 are excluded from this interpretation because they deviate from the study area as they shift northwards.

Table 2 shows the average moving speed calculated in terms of the change in position of the density average centers in each period. The historical average moving speed, except for Zones 1 and 2, was 4.63 km yr$^{-1}$, but will gradually increase to 5.14 km yr$^{-1}$ by 2050 and 5.9 km yr$^{-1}$ by 2070, which provides further evidence that the pace of climate change is accelerating. Between 1980 and 2000, Zone 5 showed the fastest moving speed at 7.80 km yr$^{-1}$, followed by Zone 8 at 7.4 km yr$^{-1}$ and Zone 4 at 6.79 km yr$^{-1}$. The moving speed of Zones 6, 12, 13, and 14 was more than 5 km yr$^{-1}$, and the rest of the zones moved less than 5 km yr$^{-1}$. From 2000 to 2050, only Zones 5 and 9 will show moving speeds of over 7 km yr$^{-1}$, while the other zones are expected to move at speeds of less than 6 km yr$^{-1}$, with the majority of zones to exceed 5 km yr$^{-1}$. By 2070, the majority of zones would have moving speeds above 5 km yr$^{-1}$, with seven zones moving at over 6 km yr$^{-1}$; Zone 5 maintains a rapid pace, and the speeds of the zones around Zone 5, e.g. Zone 3–10 in the central inland area are generally accelerated. From 1980, Zone 14, located in a subtropical climate, has also maintained a rapid northward moving speed.

4.2. Evaluation results of BVI and NI
As a result of evaluating each zone using BVI, which reflects both the changes in speed and area, the vulnerable zones for each period can be identified. Owing to their fast-moving speed and a significant reduction in area in the past, Zone 4 was evaluated as Highly Vulnerable, which is located on the border of grassland in eastern Mongolia and northeastern China and Russia’s mountain range including Yablonovyy, Greater Khingan and Sikhote Alin range in the 1980s. Zones 5, 8, 9, 12 and 13 as Vulnerable, and the remaining zones as Stable. Of the Vulnerable zones, Zones 5 and 8 were evaluated as such because of their rapid moving speed despite an increase in area, while Zones 9, 12 and 13 were mainly affected by a decrease in area. In terms of geographic location, Zone 5 is widely distributed in the middle altitude region, which extends from the border of Mongolia and China near the Gobi desert to the border between China and Russia. As located in the middle of the study area, Zones 8 and 9 cover the Taihang Mountains in eastern China and Baekdudaegan, the main mountain range of the Korean Peninsula. Zones 12 and 13 include the North China Plain, the southern coast of the Korean Peninsula, and most of the mountainous areas in Japan. In the mid-term future, Zones 3 and 5, which are to be replacing the location of Zone 4 in the 1980s, are predicted to be Highly Vulnerable owing to their significant decrease in area and rapid moving speed, respectively. In the long-term future, it was predicted that Zones 4 and 13 would be Highly Vulnerable, and there would be a greater number of Vulnerable zones due to the overall reduction in area and increasing moving speeds in the 2070s.

When comparing the BVI over the three periods, it was predicted that the distribution of the Vulnerable zones would shift northward and expand (figure 4). The Vulnerable zones indicate areas where relatively rapid environmental changes occur within the boundary of the study area, but cannot be construed as absolutely vulnerable areas because species responses to the changes would differ. However, this result is consistent with the findings of other previous studies that predict changes in biomes or terrestrial vegetation because of climate change [29, 58–60]. In particular, [60] predicted a significant increase in net primary productivity (NPP) in tropical forests and temperate forests, but a decrease in NPP in sub-tropical forests and south temperate forests. In general, they conclude that ecosystems in the mid to high latitudes would be more vulnerable to future climate change in terms of distribution ranges and NPP. The BVI results correspond with findings that the subarctic region is

| Bioclimatic zones | 1980–2000 | 2000–2050 | 2000–2070 |
|-------------------|-----------|-----------|-----------|
| 1                 | 1.69      | −0.44     | −0.24     |
| 2                 | 2.28      | 2.87      | 2.31      |
| 3                 | 2.81      | 5.78      | 6.50      |
| 4                 | 6.79      | 5.99      | 5.93      |
| 5                 | 7.80      | 7.20      | 7.87      |
| 6                 | 5.02      | 5.54      | 7.70      |
| 7                 | 4.84      | 4.66      | 5.87      |
| 8                 | 7.41      | 4.73      | 5.45      |
| 9                 | 4.29      | 7.13      | 7.19      |
| 10                | 0.44      | 5.26      | 6.64      |
| 11                | 1.91      | 3.13      | 4.98      |
| 12                | 5.41      | 3.34      | 3.24      |
| 13                | 5.36      | 5.05      | 4.55      |
| 14                | 5.72      | 5.86      | 6.74      |
| 15                | 2.21      | 3.13      | 4.02      |
| Average           | 4.28      | 4.61      | 5.25      |
| Average excluding Zone 1 and 2 | 4.63 | 5.14 | 5.90 |
vulnerable to the expansion of the temperate climate, and in the future, Vulnerable areas will expand to the north as the temperate climate expands. Moreover, the southern zone will become Vulnerable due to the transformation of the temperate zone into a subtropical zone.

The NI indicates the extent of natural areas in each zone to inform conservation strategies. The proportion of natural areas in NEA has not changed much, with a 1.4% decrease in 2015 compared to 1992, mainly due to the expansion of urban areas and croplands. However, considering the shifts in the zones and the changes in the area due to climate change, the NI of each zone would generally increase. In NEA, the zones in the north have a high NI since many forests are located in the north, while the zones in the south-central part, where the agricultural and urban areas are located, have a low NI. As the zones shift northward, the NI of the central zones would increase and the NI of southern zones would remain constant or decrease (table 3).

### 4.3. Bioclimatic zone-based framework for biodiversity conservation strategies

In addition to predicting the future vulnerability of bioclimatic zones, the approach outlined in this analysis can assist in adaptation planning with a spatially explicit framework for broad-scale management strategies and interventions. Through combining BVI and NI results, we suggest frameworks that prioritize conservation strategies under a changing climate (figure 5(a)).

In figure 5(a), relative values of BVI and NI for each zone are expressed as #.1, #.2, and #.3 in three periods, e.g. the past 20 years, mid-term future, and long-term future, respectively. In other words, Zone 1.1–15.1 represent the index based on changes from 1980 to 2000, Zone 1.2–15.2 from 2000 to 2050, and
Zone 1.3–15.3 from 2000 to 2070. Figure 5(b) shows, as an example, in which quadrant each zone is located based on the changes between the 2000s and 2050s bioclimatic classification, e.g. using the value 1.2–15.2.

We suggest priority conservation strategies and specific examples for one representative zone in each quadrant. In addition, the framework indicates that conservation strategies should be modified based on the change in the relative position of each zone over time.

4.3.1. High BVI, high NI (first quadrant)
Within zones with high BVI and high NI, species living in natural habitats may be highly affected by climate change. Therefore, we recommend active management interventions in these zones, while maintaining areas of natural habitat. There should also be close monitoring of species and more aggressive adaptive actions should be taken for vulnerable species that are unlikely to adapt to the changes [29, 61]. The aggressive actions include managing direct threats other than climate change, such as habitat destruction, and ensuring that remaining species are relocated to more favorable climate environment through translocation or ex situ conservation [62, 63]. In addition, proactive measures include identification of species that could invade habitats owing to climate change and assessments of their potential threat to ecosystems [64]. However, managers should remain cognizant of the potential for the ecosystem to adjust naturally to climate change without any interventions [65, 66].

In Zone 3, for example, NI is maintained over time, but the BVI increases as the moving speed...
gradually increases. Historically, preservation was a priority in this zone (located in the fourth quadrant in the 1990s); however, as the bioclimate becomes progressively Unstable (located in the third quadrant in the mid-term and long-term future), active management taking climate change into consideration has become necessary. As Zone 3 is gradually replaced by Zones 4 and 5, it is necessary to monitor whether species can adapt to the changes or whether they can move with Zone 3. If not, managers should consider artificial interventions including translocation.

4.3.2. High BVI, low NI (second quadrant)
In the second quadrant, zones are affected by climate change as in other high BVI areas (first quadrant). Monitoring programs and measures such as securing climate refuges or migration corridors for the existing species should be implemented. However, these zones require greater ecological restoration efforts due to the low extent of natural habitat, in order to maintain important native species pools [67]. Ecological restoration efforts should go further than simply maintaining current conditions or returning conditions to the pre-damaged state, and should consider the introduction of species suitable for future climate zones [68, 69]. Nevertheless, managers should be cautious of introducing exotic species [70, 71].

In the case of Zone 13, most of the land cover is cropland, so the restoration of natural areas may be needed for biodiversity conservation if the changes in BVI are considered. For example, in China, restoration strategies should focus on species in Zone 14, which will replace Zone 13 over time. On the other hand, in the Korean Peninsula and Japan, where Zone 13 will expand, conservation strategies should consider the likelihood of the spread of invasive species.

4.3.3. Low BVI, low NI (third quadrant)
Zones with low NI will require greater restorative interventions, unlike the zones in the second quadrant, since these zones have a stable bioclimate, and historical species compositions and processes can be restored in these areas [69]. At present, these zones have a low density of natural areas but if they are protected from further degradation, they could serve as a shelter for species in the future owing to their relatively stable climate [25]. As Zone 10 has low NI and climate change is relatively slow, the historical distribution of ecosystems and species can be used as a guide in the restoration of damaged areas.

4.3.4. Low BVI, high NI (fourth quadrant)
Zones with stable BVI and high NI need to be preserved while minimizing other threats: aggressive conservation interventions should be avoided, since there is a risk of unintended effects [71]. These zones may be the best candidates for the establishment of protected areas, which are essential for biodiversity conservation [72, 73]. Zones 1 and 2 are located in the fourth quadrant but are shifting out of the study area.

4.4. Implications and limitations
The results of this study can be used for monitoring and managing biodiversity. Through the new indices BVI and NI, we have suggested where, why and what conservation strategies are required by quantitatively analyzing and visualizing the impacts of climate change on the bioclimatic environment. This study indicates priority areas for monitoring and management, which could be used for international cooperation for biodiversity conservation in Northeast Asia. Moreover, since this framework presents region-centric results not species-centric results, it can provide an opportunity to scrutinize species that may be threatened by climate change, but were not previously recognized. Furthermore, if the same methodology and framework are applied at the local level, it may be used to establish practical environmental planning. Specifically, the time-series bioclimatic maps delineate the pathway of the bioclimatic zones so that they can be used as a reference when considering the introduction of new species or migration locations when establishing restoration strategies.

However, the BVI method is limited by its equal weightages of changes in moving speed and area. This method could be improved if changes in bioclimatic zones and the corresponding impacts on species are more clearly identified through future monitoring. In addition, since BVI is an index showing the relative vulnerability among bioclimatic zones, different values and strategies can be derived depending on the scope of the target area. It is meaningful to prioritize interventions based on their relative importance within the scope of planning. On the other hand, NI has a limitation in the assumption that current land cover will be maintained in the future. This is because high resolution open source data for future land cover predictions is not available, and we believed that this would not significantly affect the results. However, more realistic results could be produced if we reflect the predicted future land cover changes. Other methodological limitations include the limited scope of the study area, and the fact that the bioclimatic zones are based on the current climate. The method does not allow interpretation for zones north of the study area and the emergence of hotter and drier zones in the future. This could be addressed in future studies by broadening the study area globally or by exploring new methodologies. Furthermore, in this study, we focused on presenting the general conservation strategies in a spatial and macroscopic perspective, but if information on species in each zone is constructed, more specific conservation strategies can be established including for species inhabiting zone boundaries.
5. Conclusion

In this study, we have developed new indices i.e. BVI and NI, to identify bioclimatically vulnerable regions under climate change through the analysis of changes in bioclimatic zones, which can provide useful information to prioritize conservation strategies. We constructed the bioclimatic zones of NEA and analyzed changes in the latitudinal moving speed and area of each zone. The results, which are consistent with previous studies using different methods, demonstrated that the rate of climate change gradually increases and vulnerable bioclimatic areas are expanding. This study presents a novel index to quantify the impact of climate change and to provide spatially explicit adaptation guidance for broad-scale management or planning, reflecting the predicted changes in bioclimatic zones, rather than simply using the existing zones as a unit of evaluation.

This study highlights the fact that different conservation priorities are needed for different regions and times depending on the current and future degree of change. However, for more detailed conservation strategies, ecosystem surveys and identification of specific vulnerable species in each zone should be undertaken and a better information exchange system between countries will be necessary.

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Data availability statement

Any data that support the findings of this study are included within the article.

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