APPLIED ECOLOGY

Spatial variation in biodiversity loss across China under multiple environmental stressors

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Biodiversity is essential for the maintenance of ecosystem health and delivery of the Sustainable Development Goals. However, the drivers of biodiversity loss and the spatial variation in their impacts are poorly understood. Here, we explore the spatial-temporal distributions of threatened and declining ("biodiversity-loss") species and find that these species are affected by multiple stressors, with climate and human activities being the fundamental shaping forces. There has been large spatial variation in the distribution of threatened species over China's provinces, with the biodiversity of Gansu, Guangdong, Hainan, and Shaanxi provinces severely reduced. With increasing urbanization and industrialization, the expansion of construction and worsening pollution has led to habitat retreat or degradation, and high proportions of amphibians, mammals, and reptiles are threatened. Because distributions of species and stressors vary widely across different climate zones and geographical areas, specific policies and measures are needed for preventing biodiversity loss in different regions.

INTRODUCTION

Biodiversity loss disrupts many ecosystem processes, such as community structure and interactions, and can cause ecosystem malfunctioning, ranging from reduced biomass productivity to weakening ecosystem resilience (*1*, *2*). The current loss of global biodiversity is much faster than in the paleorecord (*3*), and it has been estimated that more than 1 million species are threatened with extinction worldwide (*4*). There is strong evidence that the biodiversity loss is degrading ecosystem health and human well-being (*5*–*8*). For example, loss of marine biodiversity reduces the ocean's ability to provide food and maintain ecosystem stability (*9*). Biodiversity loss is relevant to each of the United Nations' Sustainable Development Goals (*6*, *10*). Governments have committed to international agreements such as the Convention on Biological Diversity (CBD) to reduce biodiversity loss. However, most of the targets in these agreements are proving difficult to achieve on schedule (*11*), because they have not been put into practical implementation at the subnational level.

The causes of biodiversity loss generally include climate change (*12*), habitat loss, and environmental pollution (*13*, *14*), as well as a number of other drivers (*15*, *16*). The responses of biodiversity to single drivers are gradually becoming understood. Climate change has received the most attention, and it can change the composition (*17*, *18*), structure, and function of ecosystems (*19*, *20*) and reshape the distribution of biodiversity (*5*, *12*). However, many species and ecosystems are subject to multiple, interacting threats (*21*) so that climate change impacts on biodiversity will change in relation to other threats in any particular location. For example, in mountain ecosystems, climate change and land use together explain 54% of changes in species richness, ecosystem composition, and ecosystem functions, while, as single factors, they explain only 30% (*22*). The same argument applies to individual species; the Chinese paddlefish was declared extinct in December 2019, as a result of multiple threats (*23*), including overfishing and habitat fragmentation. At present, an integrated policy mechanism for addressing multiple threats to biodiversity is lacking, despite being very important for the conservation and restoration of biodiversity.

China is very rich in biodiversity and also has a large number of threatened species (~22% of vertebrates and ~11% of higher plants) (*24*, *25*). On a global scale, south-central China is one of 25 biodiversity hot spots (*26*). At the national level, China had established a total of 2750 nature reserves by the end of 2018 and the 35 biodiversity conservation priority areas delineated in the "China Biodiversity Conservation Strategy and Action Plan (2011–2030)" basically cover China's biodiversity hot spot areas (*27*–*30*). However, the acceleration of environmental change is putting biodiversity under multiple stresses (*21*, *31*). The multiple combinations of these stresses at the provincial level bring previously unidentified challenges to biodiversity conservation because the topography, climate conditions, population, economic development level, and external stressors are different from one province to another, and these provinces also need to integrate biodiversity protection and social development. This also provides a suitable laboratory for studying biodiversity protection under multiple stresses, while very little literature has discussed it at such a large scale. These considerations call for new knowledge and an integrated framework when setting conservation policies for the next 10 years.

To fill this gap, here, we analyze quantitatively the spatiotemporal effects of multiple stressors on biodiversity and the distribution of threatened species in the past century over the large land area of China based on statistical, sampling, and survey data for 31 provinces excluding Hong Kong, Macao, and Taiwan (Extended data, Supplementary Materials), including 2,749,608 records from the National Specimen Information Infrastructure (http://www.nsii.org.cn/) and 1,049,022 occurrence records from Global Biodiversity Information

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Facility (GBIF) (https://www.gbif.org/) on mammals, birds, amphibians, and higher plants, except for the data from International Union for Conservation of Nature (IUCN) Red List. For sustainable biodiversity conservation, we should set up targets not only at the national level but also at provincial or state levels to ensure the practical and effective implementation of the national targets. Therefore, the analysis at the provincial level is notable for the provincial allocation of national targets and to enhance our understanding of which provinces contain the most endangered and threatened species to find out the reasons and take actions. This will provide a new insight for setting the 2030 global biodiversity target in the 15th meeting of Conference of Parties (COP15) to the CBD and reconciling the relationship between multiple stressors and biodiversity in the long term.

RESULTS AND DISCUSSION

Spatial variation in the distribution of threatened species

Threatened species, comprising the "Critically Endangered" (CR), "Endangered" (EN), and "Vulnerable" (VU) Red List categories, are mainly found in southwest and south China, including Yunnan, Sichuan, Guangxi, and Guangdong provinces, while the number of threatened species in central and northeastern China is relatively low. The distribution pattern of endangered species is similar with that of broader biodiversity distribution in China (*32*), which has latitudinal gradients. The highest proportion of threatened species is also mainly found in southwest China. There is a high correlation between the number of threatened species and species richness, but there are certain differences between different taxa (Fig. 1, A and B). This disparity suggests that the threatened species are affected by multiple stressors, and threat factors have different impacts on different taxa. Amphibians, mammals, and reptiles are threatened at higher proportions, and the average threatened proportions are 11.05, 11.64, and 10.72%, respectively. These are followed by higher plants (~7.71%) and birds (4.08%).

The distribution records of threatened species were divided into three periods (1901–1980, 1981–2005, and 2006–2018) to analyze better spatial variation in regional biodiversity losses. The number of threatened species in Gansu (northwest China), Guangxi (south China), Fujian (southeast China), and Hubei (central China) decreased by more than 20 species in 1981–2005 compared with numbers in 1901–1980 (table S1). By contrast, more than 20 most threatened species colonized (i.e., were newly reported) in the Guizhou and Yunnan provinces over this time period. The number of threatened species decreased by more than 20 from 1981–2005 to 2006–2018 in Hainan and Guizhou, while more than 20 species colonized (i.e., were newly reported) in Shandong, Shanghai, Jiangxi, Hunan, and Guangxi. In summary, there has been large spatial variation in the distribution of threatened species over China's provinces, and these patterns have changed over time. In general, the biodiversity of Gansu, Guangdong, Hainan, and Shaanxi provinces has been severely reduced. The degree of the economic development in these provinces has been at different levels, which suggests the drivers of biodiversity reduction in these provinces may be different.

The number of provinces with threatened species was used to represent changes in the species distributions. The average number of provinces with threatened species during 1901–1980 was significantly greater than during 2006–2018 ($P < 0.05$) (Fig. 1C), implying that threatened species had been lost from some provinces in later time periods. Compared with 1981–2005, the distribution areas of 74 species expanded during 2006–2018 (fig. S1, A and B), which may indicate benefits from the implementation of China's Biodiversity Conservation Strategy and Action Plan (2011–2030) and a series of policies for ecological preservation (*33*). However, for threatened species that were found in more than four provinces, their distribution areas (i.e., the number of provinces in which they were found)

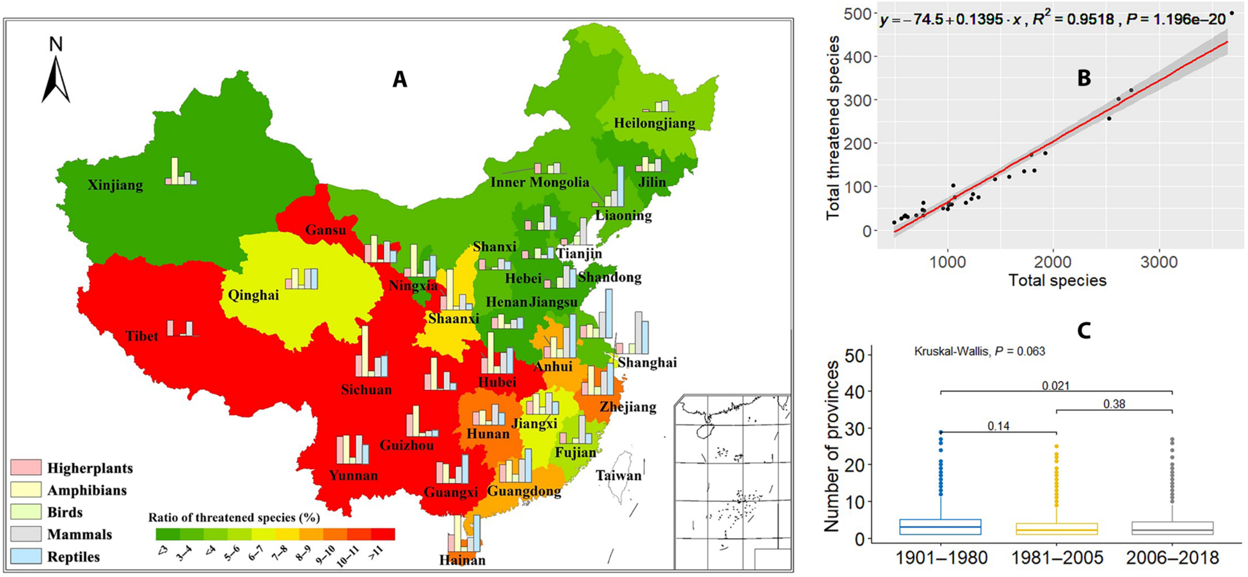

Fig. 1. Spatial variation in biodiversity loss. (**A**) Ratio of threatened species, encompassing IUCN Red List categories: Critically Endangered (CR), Endangered (EN), and Vulnerable (VU). Provinces with a high proportion of threatened species are mainly found in southwest China, including Tibet, Yunnan, Sichuan, Guangxi, and Guizhou provinces. (**B**) Correlation between total number of species and total number of threatened species. There is a significant positive correlation between the number of threatened species and richness in different provinces. (**C**) Distribution range of threatened species significantly reduced during 2006–2018 compared with 1901–1980.

declined significantly over all three periods (fig. S1, C and D), which means that threats to biodiversity are still widespread (*34*), while the distribution areas of species found in fewer than four provinces increased during 1981–2010 but declined in 2011–2018 (fig. S1E).

Spatial relationships between biodiversity loss and multiple environmental stresses

Because of China's biodiversity conservation and environmental protection programs, many species are actually recovering at scale; thus, we have paid more attention to key "biodiversity-loss" species defined as those for whom the overall population is decreasing. We used bivariate Moran's I (BMI) to analyze the spatial autoregression between a particular environmental stressor and biodiversity, in terms of numbers of biodiversity-loss species, at the provincial level, with the primary purpose of assessing the spatial relationships between each environmental stressor and biodiversity (Table 1).

Average precipitation, average temperature, and climate zone all show positive effects on numbers of biodiversity-loss species, which implies that a tropical or subtropical climate has a positive effect on many species, possibly reflecting the well-known global pattern that the lower latitudes have more species (*35*). CO_2 and NO_x emissions have had effects on species locally, and we explore them in the next section. Nighttime light, construction land, cultivated land, electricity consumption, and gross domestic product (GDP) separately represent changes in industrial land use and the intensity of human activities, both of which adversely affect species numbers. Forest coverage and economic losses caused by geological disasters have positive relationship with species distribution. Forest coverage and frequencies of geological disasters are high in the southwest area, where there are high numbers of biodiversity-loss species. In addition, geological disasters often cause habitat destruction and isolation, which decreases population densities. Eco-water supplies have negative effects due to the relationship with the expansion of geographic range affected by drought, and droughts can degrade habitat.

We find that multiple environmental stresses and biodiversity reduction are spatially related, and climate change and human activities are likely the fundamental shaping forces.

Table 1. Multiple environmental stressors and their bivariate Moran's I values. Positive or negative values of the BMI for biodiversity-loss species reflect how closely variables are correlated in space. A positive value indicates driving positive effect of a stressor on numbers of key biodiversity-loss species in the surrounding area, while a negative value indicates the corresponding adverse effect. A total of 1499 key biodiversity-loss species are found in China, and the overall population is decreasing. Refer to table S5 for the definitions and sources of these stressors. These data were collected at the provincial level and mainly cover recent years.

Stressor category	Specific stressor	Bivariate Moran's I (BMI) with threatened species	*P*
Climate factors	Climate zone	0.239	0.002
	Average precipitation	0.278	0.003
	Average temperature	0.31	0.001
	Longitude	−0.239	0.003
	Latitude	−0.395	0.001
Climate change	NO_x emissions	−0.211	0.003
	CO_2 emissions	−0.228	0.001
	Long-term precipitation change	0.106	0.051
	Long-term temperature change	−0.101	0.054
Pollution	SO_2 emissions	−0.134	0.028
	Industrial solid waste emissions	−0.211	0.001
	Waste water emissions	−0.038	0.324
	Emergent environmental accidents	−0.046	0.223
Human activities	Gross domestic product (GDP)	−0.087	0.094
	Electricity consumption	−0.105	0.053
	Nighttime lights	−0.154	0.007
	Cultivated land	−0.106	0.014
	Construction land	−0.133	0.029
Natural factors	Forest coverage	0.211	0.005
	Economic losses caused by geological disasters	0.142	0.027
	Soil erosion	0.042	0.184
	Eco-water supplies	−0.226	0.001

Relationships between biodiversity and climate change–related stressors

We constructed local Geary's statistics for CO_2 and NO_x at the provincial level to assess the local impacts of greenhouse gas (GHG) emissions (Fig. 2A). CO_2 and NO_x emissions are positively spatially correlated in Shandong, Hebei, Jiangsu, Sichuan, Yunnan, and Guangxi, while they are negatively correlated in Beijing, Tianjin, Shanghai, and Xinjiang mostly because of the different industrial activities in each region. Shandong, Hebei, and Jiangsu are all significantly engaged in iron and steel manufacturing, accounting for 25.22, 9.19, and 9.99% of total raw iron production of China in 2017 (table S2). SO_2, NO_x, and dust particles are the primary pollutants in the production process of iron and steel enterprises. Moreover, the transportation of iron and steel mainly relies on trucks or railway traveling on intercity roads, which also discharge CO_2 and NO_x (*36*). Sichuan province is a leading producer of natural gas and electric power in China, with the production and combustion of natural gas strongly related to CO_2 and NO_x emissions. Yunnan is the China's largest cigarette manufacturing base, producing 15% of the country's cigarettes (table S2). The boiler exhaust gas of the cigarette factory contains a great amount of nitrogen oxides according to the disclosure of environmental information of Chinese tobacco factories, and according to the World Trade Organization (WTO), the flue gas of the cigarette factory contains a considerable amount of

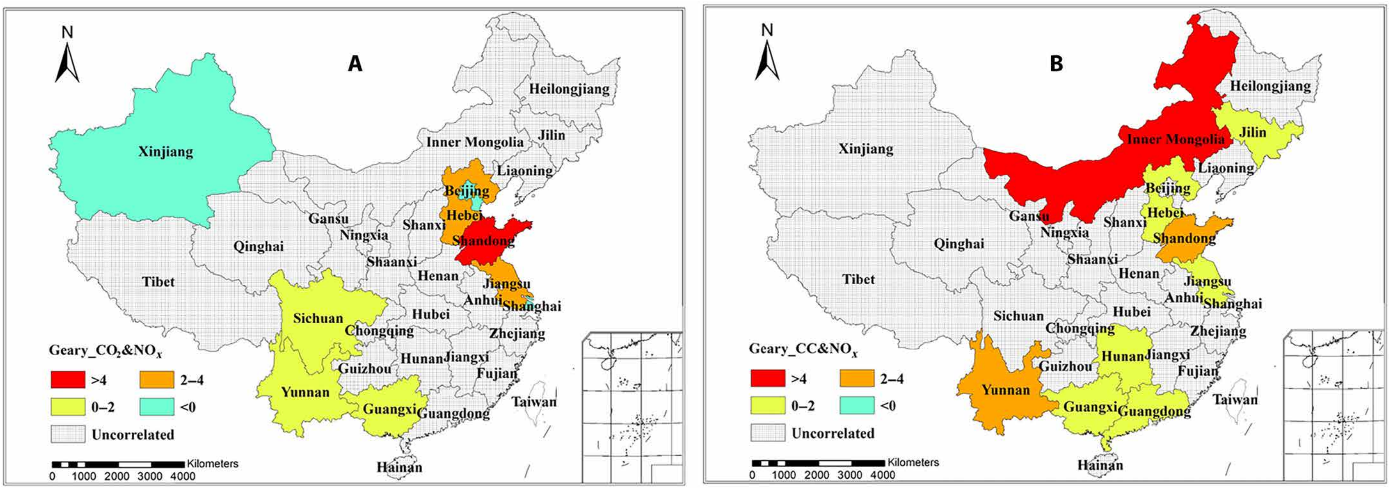

Fig. 2. Climate change and human activities represented by local Geary cluster maps. (**A**) Local Geary cluster map of CO$_2$ and NO$_x$ emissions. (**B**) Local Geary cluster map of eco-water, green gas emissions, and biodiversity-loss species.

carbon dioxide, methane, and nitrogen oxides and deforestation also affects tobacco crops' ability to absorb carbon (*37*). Car production in Guangxi province is significantly higher than in other provinces (table S2), and its vehicle emissions produce more GHGs. The main reason for the negative relationship in Beijing, Tianjin, and Shanghai may be that the three cities all have a high level of development, and the service industry dominates their industrial structure. Xinjiang is negative mainly because its nitrogen oxide emissions have greatly exceeded the emission control target issued by the state (*38*). A more interesting finding is about the relationship between climate change, GHG emissions, and biodiversity-loss species. Because the positive relationship between CO$_2$ and NO$_x$ is apparent, here, we only compare eco-water supplies (as an instrument valuable for climate change–related factors) and NO$_x$ with biodiversity-loss species. We find that nine provinces with positive correlations (Fig. 2B) are Inner Mongolia, Yunnan, Shandong, Hebei, Guangdong, Jiangsu, Guangxi, Hunan, and Jilin. Inner Mongolia (*39*, *40*) is famous for its mining industry, desertification, and fragile ecological conditions; Yunnan boasts the highest species richness but suffers from geo-disasters and soil erosion brought about by climate change; and Shandong is a traditional heavy industry province and GHG emissions producer (*41*), which makes it vulnerable to climate change.

Spatial variation of biodiversity reduction in different climate zones

The drivers of biodiversity-loss species numbers are mostly related to the climate zone (fig. S2). Precipitation and temperature are fundamental indicators of local climate, and geological disasters are also inseparable from local precipitation, temperature, humidity, and extreme weather because geological disasters mainly include landslides, debris flows, ground collapse, and those disasters closely related to local precipitation. Local climatic conditions (*32*) are one of the most critical factors determining the distribution of species, climate directly affects local heat and precipitation, and the distribution of species is seriously influenced by atmosphere and precipitation. Disasters caused by climate change can have marked effects on local species distribution and population size.

As shown in Table 2 (also in table S3), biological richness varies in different climate zones. South and southwest China are located in either the tropical monsoon climate (TRMC) zone or subtropical monsoon climate (SMC) zone, which have very high biological richness. Species numbers decrease significantly from subtropical to temperate zones, which implies the significant influences of climatic conditions on biodiversity.

The SMC zone has more biodiversity-loss species than other climate zones. The largest biodiversity-loss family in plateau mountain climate (PMC), SMC, temperate continental climate (TCC), and temperate monsoon climate (TEMC) zones is simultaneously Orchidaceae because species of the Orchidaceae (*42*) tend to be found in warm climates and are widely distributed, and many are drought resistant. Orchids often need specialized symbiotic fungi to ensure germination and early survival. Moreover, Orchidaceae plants are overexploited because of their high ornamental and medicinal value. The other large families of biodiversity-loss species in the SMC zone in order are Magnoliaceae, which tend to live in warm, humid climates and need open, well-lighted conditions at early life stages [magnolias also produce few seeds and are not easy to germinate, and their habitat is severely fragmented (*43*)], Cyprinidae [threatened by interbreeding with artificially bred carp, also by industrial pollution and habitat degradation (*44*)], and Pinaceae [widely distributed; wild species have sparse growth, have low individual and population numbers, and are distributed over a narrow range (*45*)]. The major biodiversity-loss family in the TRMC zone is Fabaceae, which is extraordinarily cold resistant and is widely distributed in tropical regions. Some species like *Dalbergia hainanensis* and *Dalbergia cochinchinensis* are very precious in China and are often unlawfully harvested.

Impacts of industrial activities on habitat degradation

By-products of industrial activities can damage ecosystems. For example, industrial solid waste, mainly including coal gangue, tailings, slag, pulverized coal, and chemical waste residues, often ends up in poorly operated landfill sites or is dumped (*46*), causing severe pollution of natural habitats.

Through the local Geary cluster analysis (Fig. 3A), we found that the major overlapping areas of industrial solid waste and biodiversity-loss

Table 2. The numbers of biodiversity-loss species and families in different climate zones. "Major family" represents a family with more species number in the relevant climate zone as shown in table S3.

Climate zone	Average precipitation (mm)	Average temperature (°C)	Main distribution area	Name of the major family	Corresponding species number	Percentage of total zone
Tropical monsoon climate (TRMC)	1500–2000	Above 20	Hainan Island, southern Yunnan, etc.	Fabaceae	6	7.8%
				Orchidaceae	5	6.5%
				Theaceae	5	6.5%
				Annonaceae	4	5.2%
Subtropical monsoon climate (SMC)	1000–1600	14–20	25°–35° north latitude, widely distributed in south China	Orchidaceae	113	15.8%
				Theaceae	37	5.2%
				Magnoliaceae	31	4.3%
				Cyprinidae	30	4.2%
				Pinaceae	21	2.9%
				Aquifoliaceae	17	2.4%
				Atyidae	17	2.4%
				Berberidaceae	16	2.2%
				Araliaceae	15	2.1%
				Cycadaceae	12	1.7%
				Apocynaceae	11	1.5%
				Aristolochiaceae	11	1.5%
				Cupressaceae	11	1.5%
				Taxaceae	11	1.5%
				Annonaceae	10	1.4%
Temperate monsoon climate (TEMC)	400–800	5–12	Widely in north and northeast China	Orchidaceae	14	13.2%
				Anatidae	5	4.7%
				Pinaceae	5	4.7%
Plateau mountain climate (PMC)	300–500	1–5	Mainly Qinghai-Tibetan plateau	Orchidaceae	21	31.8%
				Pinaceae	6	9.1%
				Berberidaceae	4	6.1%
				Taxaceae	4	6.1%
Temperate continental climate (TCC)	100–400	3–9	Northwest China	Orchidaceae	16	19.3%
				Gruidae	5	6.0%
				Pinaceae	5	6.0%

species are in northern China (Shandong, Hebei, Shanxi, and Inner Mongolia) and southern China (Jiangxi, Fujian, Guangdong, Guangxi, and Yunnan). For example, Shanxi is one of the largest coal-producing provinces in China (table S2) with considerable coal gangue discharge. Hebei is the largest iron- and steel-producing province, which inevitably generates slag, dust, and tailings. Guangdong, as a large economic province, has many industrial categories producing a large amount of industrial solid waste. Inner Mongolia has a well-developed mining industry, and Jiangxi is a major nonferrous metal mining province, with mining wastewater and solid waste discharged in large quantities, which poses a severe risk to wildlife. It has to be noted that Yunnan, a province with high species richness, is also experiencing a threat of solid waste to habitats (*47*).

Industrial production requires the expansion of construction land, which causes loss of ecological habitats and habitat degradation. For instance, nighttime light, as a significant indicator of industrial production, urban expansion, and human activities, has a BMI of −0.154, which implies a strong correlation between industrial development with the increasing number of biodiversity-loss species (Fig. 3B). The major overlapping areas of construction land and biodiversity-loss species are in Yunnan, Shandong, Guangdong, Jiangsu, Guangxi, Hebei, Anhui, Hunan, and Heilongjiang provinces. Hebei, Shandong, Jiangsu, and Guangdong (*48*–*50*) (table S2) are China's major industrial provinces. Heilongjiang is a traditional heavy industrial base, and recently, it has been restructuring the old industries. Anhui and Hunan are emerging industrial provinces in central and eastern China. Yunnan's GDP has grown, and its demand for construction land has been relatively stable (*51*), which has the potential for contradiction between its industrial development and the protection of biodiversity-loss species, as Yunnan is the province with the richest biodiversity in China.

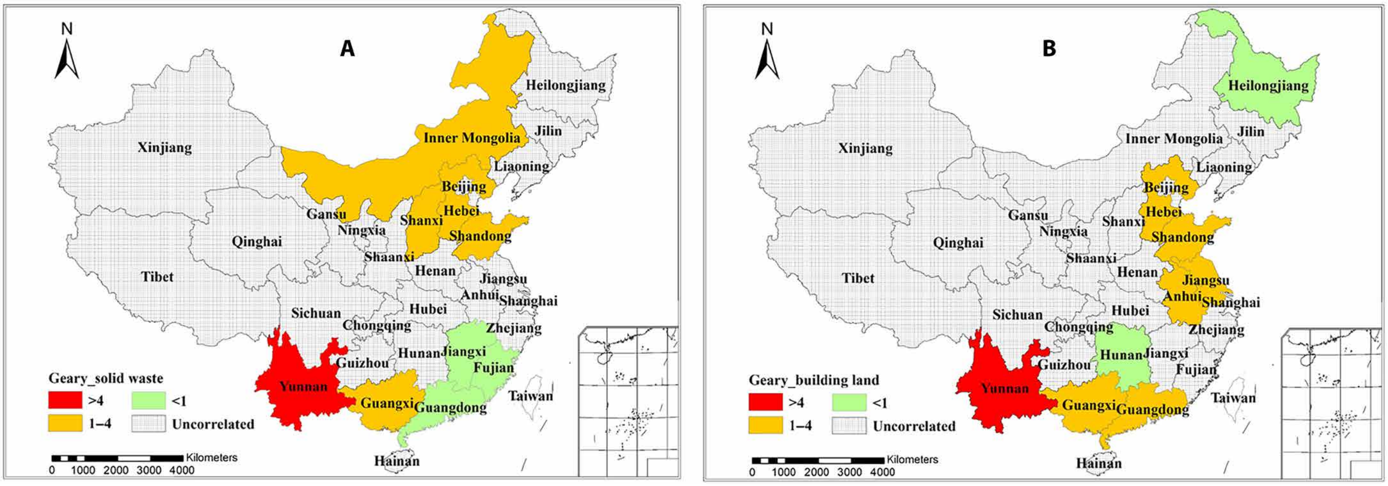

Fig. 3. Human activities represented by local Geary cluster maps. (**A**) Local Geary cluster map of solid waste and biodiversity-loss species. (**B**) Local Geary cluster map of construction land and biodiversity-loss species.

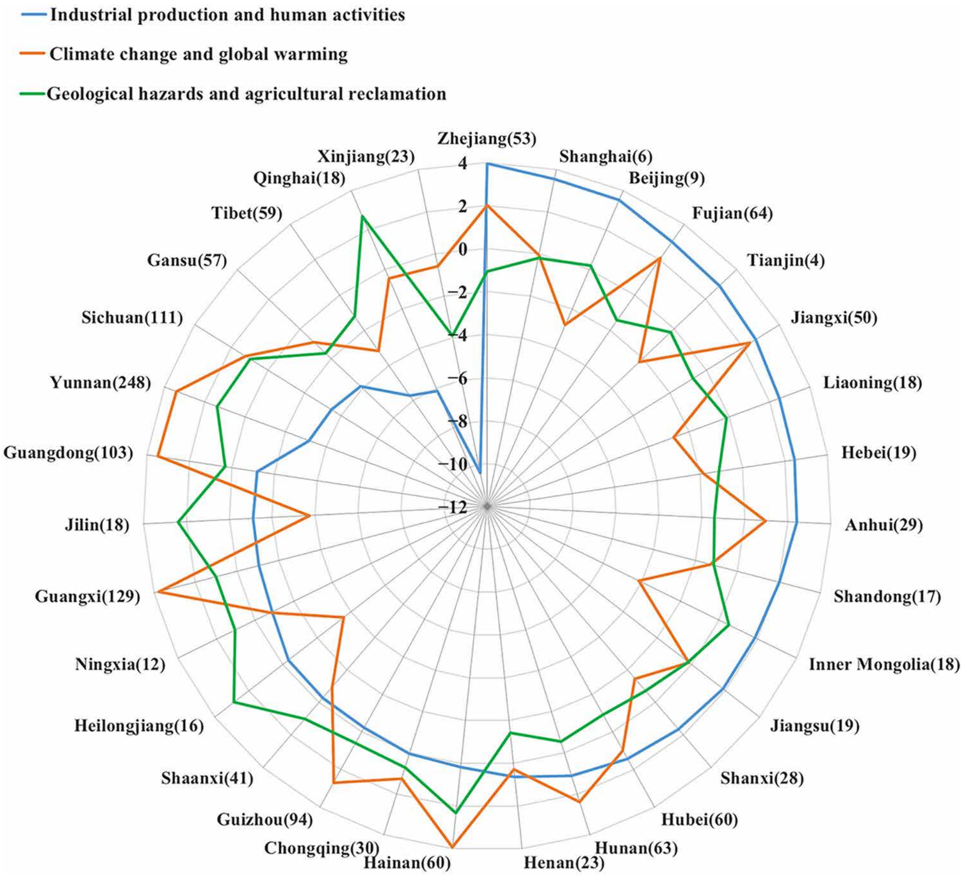

Fig. 4. Main influencing factors of provincial biodiversity levels. The bracket after the province name is the number of biodiversity-loss species in that province. Positive or negative values indicate the relative deviation from the average.

Main threats to biodiversity in each province

Through principal components analysis (PCA) (Fig. 4 and table S4), we found that the "industrial production and human activities" are the most significant threat factors for Zhejiang, Shanghai, Beijing, Fujian, and Tianjin, which are among the China's largest industrial and densely populated provinces. The "climate change and global warming" threat factors are compelling for Hainan, Guangxi, Guangdong, Yunnan, and Guizhou, which are mainly located in the south and southwest of China with rich biodiversity (fig. S2B) but suffer frequently from disasters due to climate change (*52*–*55*). The "geological disasters, soil erosion, and agricultural reclamation" threat factors are severe in Heilongjiang, Qinghai, Jilin, Hainan, and Yunnan. Therefore, there is variation from province to province in terms of key threats to biodiversity. Furthermore, it can be found from the loadings of principal component 1 (PC1) that industrialization releases a large amount of GHGs, including nitrogen oxides and carbon dioxide. Irrational changes in land use also reduce the ability of forests to absorb carbon emissions. Considering that GHG emission–related variables account for a significant molecular load of PC1 (i.e., industrialization and GHG emissions are simultaneous processes), climate change should be the most noticeable threatening factor for species.

In the four biodiversity hot spots of Yunnan, Sichuan, Guangxi, and Guangdong, biodiversity is mostly threatened by both "climate change and global warming" and "geological disasters, soil erosion, and agricultural reclamation," as other studies also show that human-induced climate and atmospheric change are the most compelling factors for diversity change (*56*). Because there are various mountains, valleys, and slopes with fragile geological structures in these provinces, they are more vulnerable to geological disasters and soil erosion (fig. S3), and studies have also demonstrated that montane species are more vulnerable to climate change (*56*). Geological disasters change resource and habitat availability for some organisms, leading directly to a reduction in their density and biomass and ultimately a decline in ecological functions. Physical changes, such as landslides, ground fissures, depressions, and river blocking caused by geological disasters, have long-term adverse effects on the migration and reproduction of some rare animal species, such as rare fish, and pollen exchange in plants (*57*). Because of increasing human activities, complex terrain and geological structure, and fragmentation of rock and soil in the southwestern region, coupled with intense precipitation and also frequent droughts brought about by climate change, the degradation and fragmentation of habitats are severe. Soil and water loss (*58*) lead to the fragmentation of habitats, loss of soil nutrients, and disruption of food webs. Therefore, region-specific actions are important to target these provinces for the preservation of local biodiversity.

Uncertainties and outlook

This article has discussed the loss of biodiversity and its causes in the context of global warming, rapid economic development, frequent natural disasters, and intensive human activities and found that biodiversity loss is linked to multiple environmental stresses. Climate change, human activities, and natural factors all seem to have a significant impact on biodiversity loss, while human activities and climate change–related factors are the most significant drivers of biodiversity loss. The distributions of species and stressors vary widely across different regions, which suggests the need for specific policies and measures for preventing biodiversity loss in different locations.

However, there are still some uncertainties that deserve further investigation and attention. For example, we used the IUCN Red List representative of threatened species in China; these species are likely affected by local human activities, and some taxa may have not been evaluated by IUCN. Although this bias may lead to a slightly higher impact of human factors on the reduction of biodiversity, the pattern of spatial variation in biodiversity loss can still be accurately revealed. There is a shortage of highly spatially and temporarily resolved data on species, population, and ecosystems for different time periods, and even the data about different areas in the same period of time. Therefore, it is challenging to conduct time series analysis to explore the evolution of biodiversity over time. High-resolution data could provide stronger evidence that not only climate change has had negative impacts on biodiversity but also global warming is conducive to promote biodiversity in cold regions, if considered only in terms of species richness (*59*). Therefore, an in-depth analysis based on more observational data is necessary to study the impacts of different climate zones on biodiversity-loss species. Effects of human activities on ecosystem change and habitats are a crucial cause of biodiversity loss, which deserves future attention. The impacts of natural disasters on biodiversity may not be entirely negative, as the migration of people and the improvement of animal and plant habitats are valuable to biodiversity conservation. For example, certain plant functional groups may depend on wildfire to complete their life cycle (*60*).

It is evident that biodiversity conservation is strongly related to social and economic conditions. Those regions with rich biodiversity or highly sensitive to biodiversity loss are usually less developed in China. How to make balance between economic development and biodiversity is a challenging issue for policy makers. To set up an achievable biodiversity conservation plan and roadmap, target setting for biodiversity conservation has to be incorporated into regional sustainable development plans.

MATERIALS AND METHODS

Data on species and environmental stressors were collected from different types of databases, including the China Statistical Yearbook, China Statistical Yearbook on Environment, China Bulletin of Soil and Water Conservation, China Forest Resources Report (2009–2013), and others (table S5). Spatial mapping was performed for 31 provinces excluding Hong Kong, Macao, and Taiwan due to data unavailability, using ArcMap software in ArcGIS version 10.3.

Data mining

The 9200 species found in China that are on the IUCN Red List were used to represent the species list for this study (https://www.iucnredlist.org/) (table S6). The spatiotemporal distribution data for the species list were based on three sources. First, we extracted the current provincial-level distribution from the IUCN Red List, obtaining 3407 species with distribution information at the provincial level. Second, we trawled 2,749,608 records by using the scientific names listed in table S6 from the National Specimen Information Infrastructure (http://www.nsii.org.cn/) and by obtaining sample collection time and location from specimen details. By comparison with the taxonomy table in the IUCN Red List, 1,815,873 valid records were obtained. Third, we obtained 1,049,022 occurrence records that contained geographic information from GBIF using the species names in table S6 (https://www.gbif.org/). Using the latitude and longitude information, species distribution information was obtained by the Baidu reverse geocoding service (http://lbsyun.baidu.com/index.php?title=webapi/guide/webservice-geocoding-abroad). Ultimately, the data from the three sources were merged and formed the dataset for this study (Extended data, Supplementary Materials). Data trawling and data processing were performed with Python software (Python 3.7.3, https://www.python.org/).

Spatial statistics

To characterize the spatial correlation of two variables and avoid statistical errors caused by spatial dependence, a spatial autocorrelation analysis and other spatial analyses were performed for the 31 provinces with GeoDa 1.14. GeoDa (*61*) provides methods of exploratory spatial data analysis, such as spatial autocorrelation statistics for aggregate data, and fundamental spatial regression analysis. GeoDa also provides its workbook annually on its website (https://geodacenter.github.io/documentation.html).

All algorithms and interpretations were implemented in GeoDa, except that the PCA was conducted in Stata 16.1. GeoDa gives a list of references for algorithms on its website homepage. Introduction to the spatial statistical methods can be found in the Supplementary Materials.

Bivariate Moran's I

A calculation formula of BMI (*62*, *63*) could be as follows

$$I_B = \frac{\sum_i \left(\sum_j w_{ij} y_j \times x_i\right)}{\sum_i x_i^2}$$

The concept of bivariate spatial correlation does not directly consider the inherent correlation between the two variables due to the existence of spatial dependence. The bivariate spatial correlation is between x_i and $\Sigma j W_{ij}{}^* y_j$ but does directly consider the correlation between x_i and y_i while using a simulation: $y_i \approx \Sigma j W_{ij}{}^* y_j$.

We use BMI to explore the spatial correlation and impacts of stressors on biodiversity. The significant relationship of spatial autoregression between the two variables can only indicate that the two variables are spatially dependent. The absence of spatial dependence of the two variables does not mean that there is no other correlation, nor does it mean that the two variables do not have a causal relationship.

Local Geary statistics

The multivariate local Geary statistic (*64*) could provide an additional perspective to measure the tension between attribute similarity and locational similarity; thus, we used it to measure the spatial relationship between biodiversity loss and different stressors.

The multivariate local Geary statistic is calculated as

$$c_i = \sum_{h=1}^{m} \sum_j w_{ij} (x_{hi} - x_{hj})^2$$

where m variables, indexed by h, are given by geographic location i and its geographic neighbor j.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/6/47/eabd0952/DC1

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