Prioritizing ecological conservation strategies to enhance national ecological connectivity in China

Meirong Tian [a], Jixi Gao [b,*], Guobao Song [c], Chaoyang Feng [a]

[a] State Environmental Protection Key Laboratory of Regional Eco-process and Function Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China
[b] Ministry of Ecology and Environment Center for Satellite Application on Ecology and Environment, Beijing 100094, China
[c] Key Laboratory of Industrial Ecology and Environmental Engineering (MOE), School of Environmental Science and Technology, Dalian University of Technology, Dalian 116024, China

A B S T R A C T

The decline of ecological connectivity poses a challenge for China as it faces a continuous loss of biodiversity. However, this phenomenon also increases the country's natural reserves and afforestation area. With the approval of the national plan for combating climate change and the implementation of the "ecological redline" policy, there is an opportunity to improve China's eco-connectivity with significant investments available for a continuous ecological restoration. However, little research has been conducted with respect to ecological connectivity, thus preventing policy makers from allocating a central investment between provinces for ecological restoration. This study modelled the resistance map against connectivity conservation by quantifying indicators of human disturbance and subsequently derived the national eco-corridor network by using least-cost path methods. A total of 2790 potential eco-corridors, connecting 97% of the protected areas in continental China were extracted. The paper ranked the importance of each eco-corridor for maintaining national ecological connectivity and identified the pinch points with high resistance. Based on the national eco-corridor framework, this paper proposed a two-dimensional coded table to help policy makers conduct effective management. The table also develops scenarios to aid decision makers in allocating central investments in provinces. By prioritizing ecological restoration to enhance ecological connectivity, the established eco-corridor network and scenario analysis will contribute to biodiversity conservation in China. This paper gives policy suggestions on cross-border management and plan implementation of eco-corridors, which helps decision makers in working towards ecological protection in China.

1. Introduction

Due to landscape fragmentation and habitat loss (Rands et al., 2010; Laurance et al., 2014), the past several decades have witnessed a global decline in biodiversity indicators (Butchart et al., 2010a; Green et al., 2019). Climate change has only further exacerbated the situation driving fauna to northern and higher locations in search of low temperature (Dawson et al., 2011; Burrows et al., 2014). A reduced ecological connectivity prevents species from climate adaptation and richness improvement (Damschen et al., 2006; Rudnick et al., 2012). Therefore, to improve ecological connectivity, it is pivotal to identify, promote, and preserve strategically planned green networks (Liquete et al., 2015; Morandi et al., 2020). China, one of the 12 mega-biodiverse

countries in the world faces a serious issue in biodiversity loss caused by lowered ecological connectivity (Butchart et al., 2010b; Liu et al., 2020). Even so, certain indicators, such as increased areas of artificial forests and natural reserves seem to be achieved (Xu et al., 2009; Xu et al., 2010).

In recent, China has experienced an unexpected rate of urbanization (Bai et al., 2014), with the proportion of urban residents rising from 17.9% in 1978 to 63.8% in 2020. The country's urban expansion has consumed farmland, while new farmland is reclaimed by wilderness to keep the urbanization rate balanced. Mountain cities with insufficient space for development have managed to create flat land by leveling hills and filling valleys (Li et al., 2014). Moreover, economic development zones (EDZs) have thrived since 1984, with new policy for upgrading

EDZs being issued in order to promote China's policy of reformation and openness (Ministry of Commerce of China, 2014). Unfortunately, these policies have also resulted in further land occupation. In addition, by constructing 161,000 km of roads until 2020 (Ministry of Transport of China, 2021), China has become a global leader in highway development, thus further fragmenting its landscape(Li et al., 2010; Laurance et al., 2014; Liu et al., 2014).

In recent years, China has actively promoted the establishment of protected areas which encompass national parks, nature reserves, and various other natural parks. The country has established close to 10,000 protected areas, which account for about 18% of China's total land area. The country's nature reserves account for 15% of these protected areas, while national parks accounts for 2.3% (The State Council Information Office, China, 2021). These areas are devoted to protecting natural habitats and combating the trend of biodiversity loss. However, due limited enforcement of existing laws, scarce local participation (Quan et al., 2011), disagreement between multi-departmental administrators (Xu et al., 2012, Liang et al., 2018) and even contradictory policies (Zheng and Cao, 2015), these areas are face a wide array of problems. Many natural reserves ultimately become isolated because the issue of ecological connectivity is not considered when these systems are designed at the national level. As they are biologically separated from their neighboring protected areas, these reserves face the risk of landscape fragmentation, as well as the growing challenge of climate change that forces animals to migrate in search of areas with lower temperatures.

The country's State Council Information Office has recently approved white paper on biodiversity conservation in China (The State Council Information Office, China, 2021). The Ecological Redline policy, which has been added to China's newly revised Environmental Protection Law (The National People's Congress of China, 2014) has been designed to enhance ecological restoration. A large budget for ecological restoration will be available in the foreseeable decades. However, central policy makers are faced with the challenge of how to allocate investments for ecological connectivity between the provinces, as well as the issue of managing cross-boundary eco-corridors. In addition, local regulators are still uncertain about which areas should be given priority with respect to ecological connectivity, while the effective implementation of the eco-corridors plan at the national level has still not been comprehensively researched.

Therefore, this study has three main objectives. Firstly, based on the national natural reserves and spatial pattern of resistance surface of human footprint, this paper aimed to identify China's eco-corridor network by the least-cost method. Secondly, it wished to rank the eco-corridors by importance and identify their key points (i.e., bottlenecks). Finally, through scenario analysis, this paper aims to help policy makers decide on which areas should receive investments for ecological restoration. It also aids the discussion on enhancing ecological connectivity to conserve biodiversity. Fig. 1 illustrates the flow chart of the study.

2. Materials and methods

2.1. Construction of resistance surface

The Minimum Cumulative Resistance model (MCR) to identify the ecological corridor with the minimum cost. Changes in landscape structure affect the cost of material and energy migration, and human activities change the type of land use, thereby affecting the landscape structure. This study based on the hemeroby theory(Sukopp,1969) which believes that the types of land use under the influence of human activities, the interference of human economic and social development on landscape patterns. Besides, human disturbance on the natural ecosystem differs heterogeneously even though at the same land use type. This is why we covered the three metrics of GDP, population density, and nighttime light to quantitatively reflect the density of human distance. The linear barriers between roads and rivers that divide natural landscape patches can all hinder the direct material and energy exchange and migration movement of species or certain ecological processes between the patch landscape elements. So, we choose anthropogenic land use, density of human disturbance and linear barriers as a three-level indicator system of resistance surfaces to map China's eco-corridor. The study covered eleven indicator layers in the Esri raster format. We used expert experience method to determine the weight of indicators due to its simple and intuitive use (Zeller et al., 2012). In the study, multiple experts in landscape ecology, animal and plant conservation, geographic information systems, and other disciplines were invited to evaluate the ecological corridor resistance surface indicators. For each province in China, three experts were invited to give the score on the uniformly designed questionnaire. The weight of the factors is designed between 0 and 1. By analyzing and summarizing the results of indicators provided by experts, the average value of the weight is adopted as the indicator weight. The weight (w1, w2, and w3) of the resistance factors was measured using the above method (Table 1).

2.1.1. Anthropogenic land use

Developed land and agricultural land are land use types generated under human production and living activities, which change the original land use cover and landscape composition, and will have an impact on the material and energy flow of natural ecosystems. Developed and agricultural land data which resolution is 1 km obtained from National Earth System Science Data Center (NESSDC, 2020a) function as the components of anthropogenic land. Developed land includes urban and rural settlements and other developed areas, including manufacturing
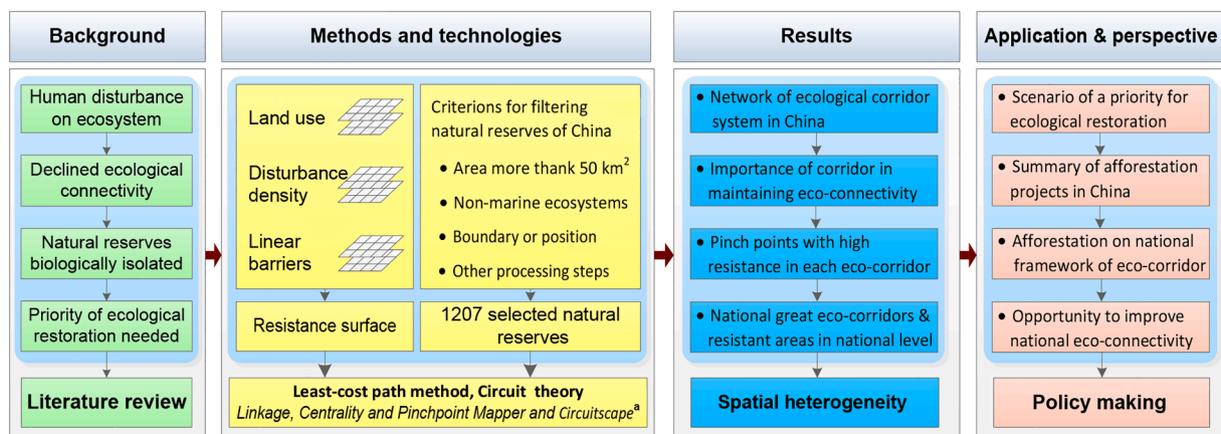

Fig. 1. Flow chart of ecological connectivity study and its application helping policy makers to prioritize the central investment for ecological restoration.

Table 1
Three-level indicators for quantifying human footprints as resistance surfaces to map China's eco-corridor.

First level	w1	Second level	w2	Third level	w3
Anthropogenic land use	0.4	Developed land	0.6	Urban development land	0.4
				Rural development land	0.3
				Other development land	0.3
		Agricultural land	0.4	Dry farmland	0.4
				Paddy field	0.3
				Other agricultural land	0.3
Disturbance density	0.3	GDP	0.3	–	–
		Population density	0.3	–	–
		Nighttime light	0.4	–	–
Linear barrier	0.3	Road density	0.6	–	–
		River density	0.4	–	–

districts, factories, mining areas, oil fields, and quarries. On the other hand, agricultural land comprises dry farmland, paddy fields and other agricultural areas of orchards, tea plantations, and nursery gardens. Due to their small human footprints resisting, native grassland, forest, wetland and barren land were excluded from analysis.

2.1.2. Disturbance density

The disturbance of human economic and social development to the ecological landscape is mainly considered in Disturbance Density. There is a strong positive correlation between nighttime light intensity and the level of economic activity. Lightscapes also prevent the change of migration path among habitat patches (Jonathan et al., 2014; Kevin and Jonathan, 2014). Gross Domestic Product (GDP) and population density are important indicators to measure the economic situation and development level of a country or region. The stronger the nighttime light intensity, the higher GDP and population density, indicates the higher the level of human activity, and the bigger intensity of interference with natural landscapes. Therefore, GDP, population density, and nighttime light are selected as the specific indicators of disturbance density. The data of gridded gross domestic productivity which resolution is 1 km retrieved from China's GDP spatial distribution kilometer grid dataset (Xu, 2020a). The data of gridded population density which resolution is 1 km retrieved from China population spatial distribution kilometre grid dataset (Xu, 2020b).The data of nightlight brightness with a spatial resolution of 30 arc second come from annual dataset of night lighting in China (Xu, 2022), In order to eliminate the influence of brightness variations between years, the brightest image was first composited from the stable time-series images for 2012–2019 and then used to establish the resistance surface.

2.1.3. Linear barriers

Linear barriers mainly include roads and rivers, which divide natural landscape patches and reduce the connectivity of natural landscapes. The higher the density of roads and rivers, the higher the resistance to material and energy flow between natural landscape patches. Therefore, road density and river density are selected as the specific indicators of linear barrier. A 5-level river system obtained from National Earth System Science Data Center (NESSDC, 2020b) and a 3-level road system obtained from Resource and Environment Science and Data Center (RESDC, 2020) in a scale of 1:250 000 were taken to be spatial barriers. The range of values to the linear ground feature is set between 1 and 10 based on relevant literature (Niu et al., 2019), through similar process of indicators weight, the average value of the assignment is taken as the resistance value of the linear ground object. For the river system, 1st level rivers were assigned a value of 7 to enhance the barrier effect of main streams, while 2nd and 3rd level tributaries were assigned a value

of 5, and 4th and 5th level tributaries were assigned a value of 1 to quantitatively reduce the resistance effect. With respect to the road system, highways were assigned a value of 7, while national and provincial back roads were assigned a value of 5. In order to map the linear barriers into pixels with the resolution is 1Km, a kernel density analysis was then conducted in ArcGIS by using the assigned values as weights.

2.1.4. Spatial overlay

Most indicators raster with 1 km resolution which can capture landscape changes without dramatically increasing processing time in national scale. Therefore, we resampled each dataset to 1 km resolution using the cubic convolution method in ArcGIS. The pixel values for all indicators were standardized within a range from 1 to 100 by linear stretching to standard for the relative magnitude of resistance against connectivity. By using ArcGIS, the paper conducted a spatial overlaying to calculate the national human disturbance on the ecosystem.

2.2. Natural reserve selecting

The Nanjing Institute of Environmental Science provided the study with a total of 2790 natural reserves in their national spatial database. Errors and small or marine natural reserves were eliminated from the analysis by applying three filtering criterions: having either a spatial boundary or a spatial position, constituting an area of more than 50 km^2, and being a non-marine ecosystem. After applying this criteria, 1207 natural reserves, covering 1 357 089 km^2 (i.e., 91% of all natural reserves or 97% of continental reserves) had met the criteria for further analysis. Three zones from each reserve (a core area, a buffer zone, and a transition zone) were then merged and assigned a value of 1, which represented minimum resistance and entailed no obstruction between the buffer-transition or buffer-core zones. Natural reserves that shared a boundary were treated as one patch. In the case that a reserve had two nonadjacent patches, it was examined as two patches.

2.3. Eco-corridors, importance ranking and pinch points

In order to connect China's natural reserves, the eco-corridors were first identified by the model of minimum cumulative resistance (MCR) which widely used in corridor construction (Dai et al., 2021). Then, the study calculated the centrality of the least-cost path (LCP) to determine the contribution of each to China's ecological connectivity (Carroll et al., 2012). In order to identify the bottlenecks with high resistance in each LCP, the high-volume pinch points between adjacent natural reserves were mapped based on circuit theory (McRae et al., 2008). These analyses used both Linkage Mapper (McRae and Kavanagh, 2012) and Circuitscape (McRae and Shah, 2009).

2.4. Comprehensive priority of ecological restoration for pixels in eco-corridor

All vector corridors that were based on the calculated centrality values were first reclassified into 10 levels by the natural breaking method. They were then converted into a raster with pixels coded by four digits, ranging from 1100 to 2000 in intervals of 100. Pixels with a higher value contributed more to the corridor to China's ecological connectivity at the national level (Fig. 2A). Similarly, the pixel values of current layers for identifying pinch points were ranked in 10 levels. They were coded by two digits, ranging from 01 to 10, thus representing bottlenecks at the local level. A higher value indicated a more important pinch point more important (Fig. 2B). The two layers were then combined to form a 100-level corridor image. Each pixel in the image consisted of four digits, which descended from 2010 to 1101 throughout Chinese territory (Fig. 2C and 2D). The first two digits denote the connectivity at the national level, while the last two indicate the current magnitude at the local level. The methods used to calculate each pixel were also able to determine the priority of ecological connectivity,
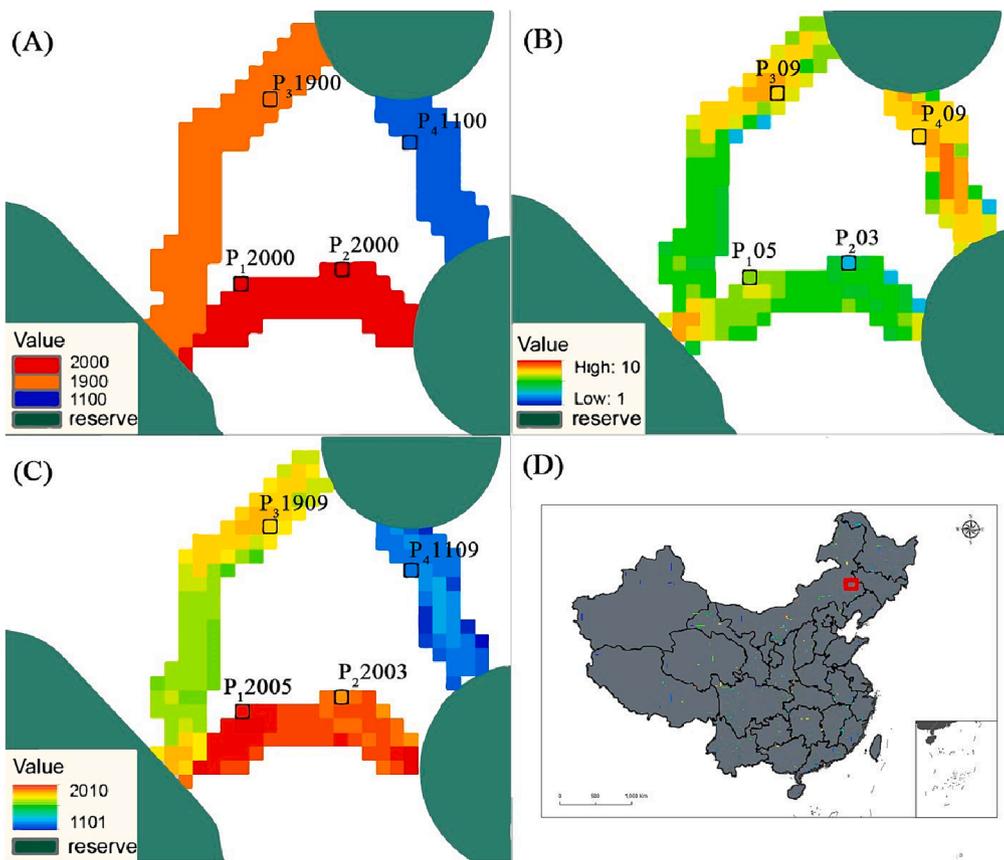
Fig. 2. Combined rankings of corridor pixels for priority of ecological restoration. (A) Centrality rankings and (B) current magnitude rankings of each corridor. (C) The priority of the four sample points for ecological restoration is P1 > P2 > P3 > P4, based on the combined rankings of both centrality and current magnitude. (D) the combined ranking of national corridor pixels with red box representing the spatial range of (A), (B) and (C). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

which in turn guides the investment to key area in need. However, individual provinces (or other local areas) should refine these analyses at a finer scale before taking further local actions.

3. Results

3.1. National eco-corridor network

The national eco-corridor network was established in this study and illustrated in Fig. 3. The paper identified a total of 2790 least-cost paths
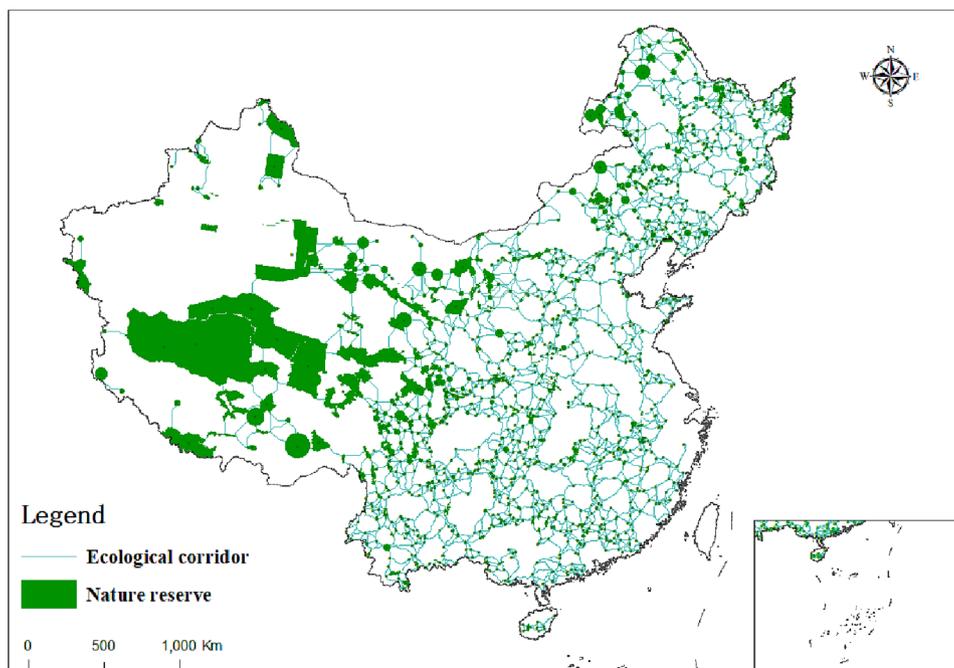

Fig. 3. Spatial pattern of potential eco-corridors in China.

(LCPs), with a total length of 158 435 km that connects 97% of continental protected areas.

3.2. Difference in importance of eco-corridor and pinch points

Each eco-corridor has a separate and unequal role in the national network of ecological connectivity. Connectivity resistance even varies along an individual LCP. The present study used the Centrality Mapper to identify the importance of each LCP according to its quantitative contribution to the maintenance of ecological connectivity at the national level (Fig. 4A). Furthermore, the intensity of human interference and the resistance to the biological migration process vary between different positions of the same eco-corridor. Pinch points with a high resistance to connectivity in a limited space were further identified by using the Pinch-point Mapper (Fig. 4B).

Identifying the pinch points could guide environmental management and conservation actions (McRae et al. 2012). Centrality rankings and resistance of pinch points along different eco-corridors will be most beneficial for ensuring corridor connectivity, maintaining biodiversity, and guiding management departments to carry out ecological restoration through accurate spatial positioning.

Based on the centrality rankings, this study has identified the importance of eco-corridors into 5 levels: "important", "fairly important", "very important", "specially important" and "extremely important" (Fig. 5); in which, the latter three levels that contain 503 corridors are recommended to be prioritized in practical construction.

3.3. Scenario of priority protection

Due to a lack of funds, it is impossible to ecologically restore all the eco-corridors at the same time. Because of this, policy makers need to be aware of the restoration potential when developing their annual central budgets. This study has calculated the centrality and current resistance rankings of China's eco-corridors in a two-dimensional color-coded table (Fig. 6A). In order to facilitate the allocation of funds among the provinces, the study has developed scenarios by combining the descending centrality rankings and current resistance (Fig. 6B-6D).

The allocation of funds is dependent on the availability of the central budget. The policy scenarios in Fig. 6B and 6C show that Hebei receives the maximum share of investment, while the coastal and northwestern provinces receive no funds when the budget is insufficient. Shanxi, Shaanxi, and Hubei are recognized as investment targets in Scenario 2. In Scenario 3, the focus transfers to Yunnan, while Hainan and the Xinjiang Uygur Autonomous Region are not considered due to their lower contribution in maintaining China's ecological connectivity (Fig. 6D). Detailed information is provided in Table 2.

4. Discussion

4.1. Resistance factors and widths of eco-corridors

The first step in constructing eco-corridors is identifying resistance surface. However, there is no unified standard for the selection and assignment of resistance factors to resistance surface (Tian et al., 2022). This paper chose 11 resistance factors from anthropogenic land use, disturbance density, and linear barrier. In order to normalize the resistance value, all pixel values were standardized within a range between 1 and 100. Resistance factors and their values may often be affected by different research purposes, diffusion behaviors and site conditions within the study area. This paper's main purpose is to create the first national eco-corridor map. With the acquisition of a large number of experimental data on the diffusion behavior (Chen et al., 2015; Puri et al., 2022), the method of choosing resistance factors and standardizing resistance layers will be improved in the future and the results of eco-corridor will be more likely reflect reality. As reviewed by the Zeller et al. (2012), we all understood the risk or uncertainties of fully depending on the expert's opinion when developing the resistance surface. However, there still lacks a holistic method currently to address this issue. The topic on the specified weighting factors deserves in-depth investigation in the next-step. The issue of reasonably setting the length and width of the eco-corridor has always been the focus of management department and scientist. If the design of the eco-corridor is too large and the protected patches more than 80 km apart, wild animal migrations within the eco-corridor will be threatened by land use conversion (Clevenger and Huijser, 2009). Thus, when the distance between two protected areas is greater than 80 km, the corridor is designed to include one or more large habitat patches based on the ecological steppingstone principle. This way, the animals are able to stay for a time during the migration season as a form of transition, while this practice also reduces the migration risk of the corridor caused by climate change. If the corridor is too narrow, it will be able protect biodiversity, thus wasting the protection investment. On the other hand, if is too wide, it will expand faster and will not be able to connect the protected area (Beier, 2019). The suitable eco-corridor width should thus be determined by the size of the protected area and the distance between two protected areas. For instance, when the size of the protected area exceeds 50 km^2 and the distance is between 8 and 80 km, the width should be at least 2 km (Beier, 2019). As the distance and area decrease, the corridor width will become smaller.

The purpose of this study is to build a national large-scale eco-corridor. Implementing each fine-scale individual corridor will require further cooperation with scientists and ecological conservation planners. The width of the ecological corridor should consider the impact of
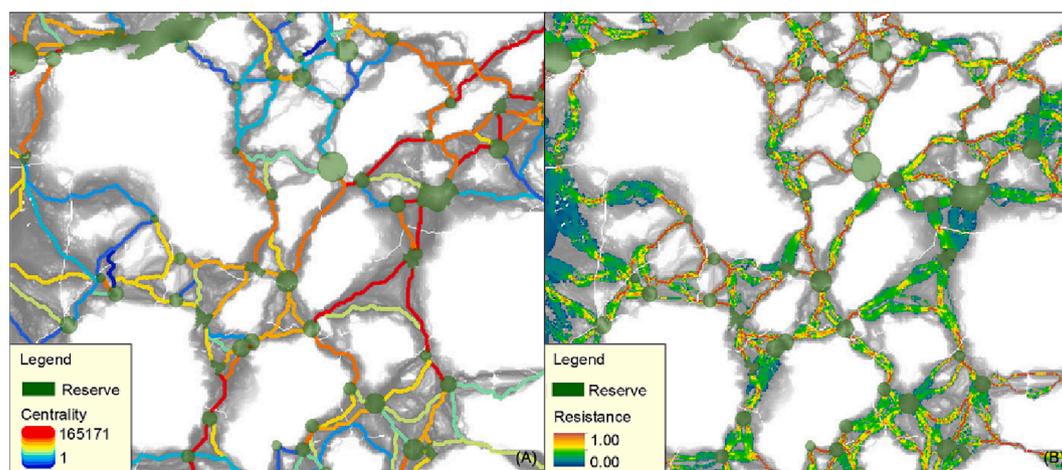

Fig. 4. Centrality rankings and resistance of pinch points along different eco-corridors. (A) Centrality rankings and (B) pinch points of each corridor.
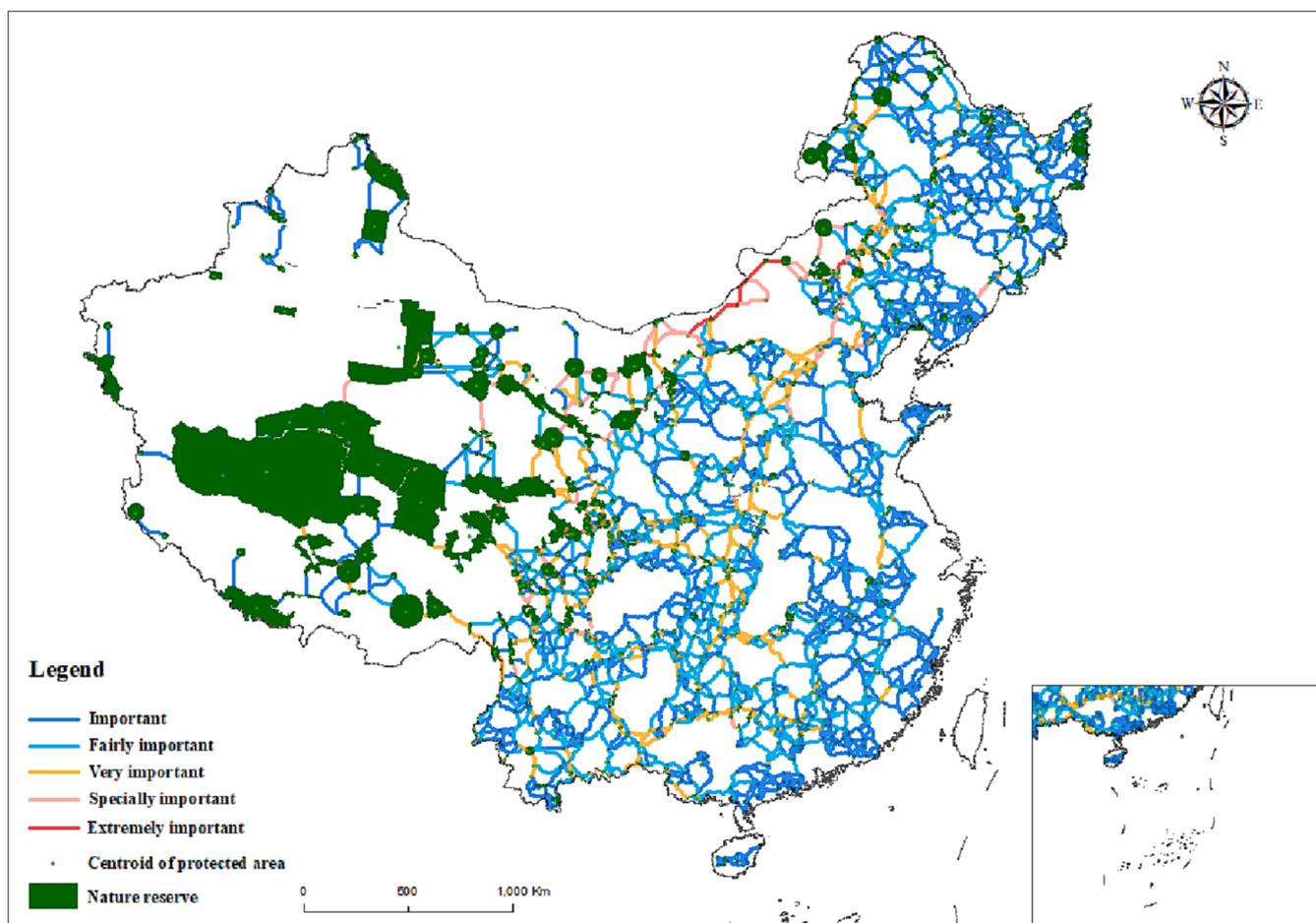
Fig. 5. Five importance levels of national eco-corridors in China.

protection objectives, species diffusion behavior, corridor vegetation composition, corridor matrix, and several other factors. The suitable eco-corridor could aid plants and animals in shifting their ranges in response to climate change (Beier, 2019).

4.2. Cross-boundary eco-corridor management and biodiversity conservation

Large-scale ecological corridors often cross boundaries. Among the identified eco-corridors, 572 connect two provinces and intersect with administrative boundaries, generating a total of 1346 crossing points (Table 3). Inner Mongolia and the Hebei and Sichuan provinces have the most intersection points, while Xinjiang Uygur, Tibet autonomous regions and Qinghai province have the least.

Ecological connectivity should not be restricted by administrative boundaries. In general, the Chinese Environmental protection department executes polices through a top-down approach that includes multiple levels, including the central ministry, provincial, prefectural or county administrations. However, the design of eco-corridors should not be conducted on the provincial level independently, as the 1300 eco-corridor crossing points with provincial boundaries would otherwise be neglected.

Governing eco-corridors requires coordination between governmental organizations that spans beyond jurisdictional boundaries (Fremier et al. 2015). Thus, establishing social connectivity and network governance are pivotal to managing the cross-boundary eco-corridor. These measures will bring about responses and better adaptation to environmental change across administrative boundaries and enhance coordinated planning, funding and actions among governing bodies

(Keeley et al., 2022).

The mode of construction and management for cross-boundary eco-corridor network should be developed. Government policy makers, non-governmental organizations, and individuals from different cultural backgrounds should work on enhancing eco-corridor protection awareness and coordination capacity. All these groups should also participate in the formulation of cross-boundary management models.

It is important to evaluate the effectiveness of the network of cross-boundary protected areas (Agrawal,2003). Setting evaluation indicators and monitoring their changes, evaluating the effectiveness of the infrastructure, legal system construction, capital investment and community participation in the reserve, identifying gaps in coordination, investment, and training, that would guide the efficient implementation of cross-boundary management and ensure animal migration and improve biodiversity.

However, most cross-boundary protection still lacks well thought out policies, restricting the development of a cross-boundary protection area network. Because of this, it is necessary to further study and establish better cross-boundary protection laws, policies, special management departments, supervision and operation institutions. It is also crucial to strengthen the role of non-governmental organizations in cross-boundary protection, establish departmental communication and coordination, and enhance the management of natural resources.

4.3. Implementation eco-corridor plan for biodiversity

On the global level, China has invested the most for ecological restoration. In 2001, the Chinese State Council approved a six-project clustered forestry program, proposed by the State Forestry
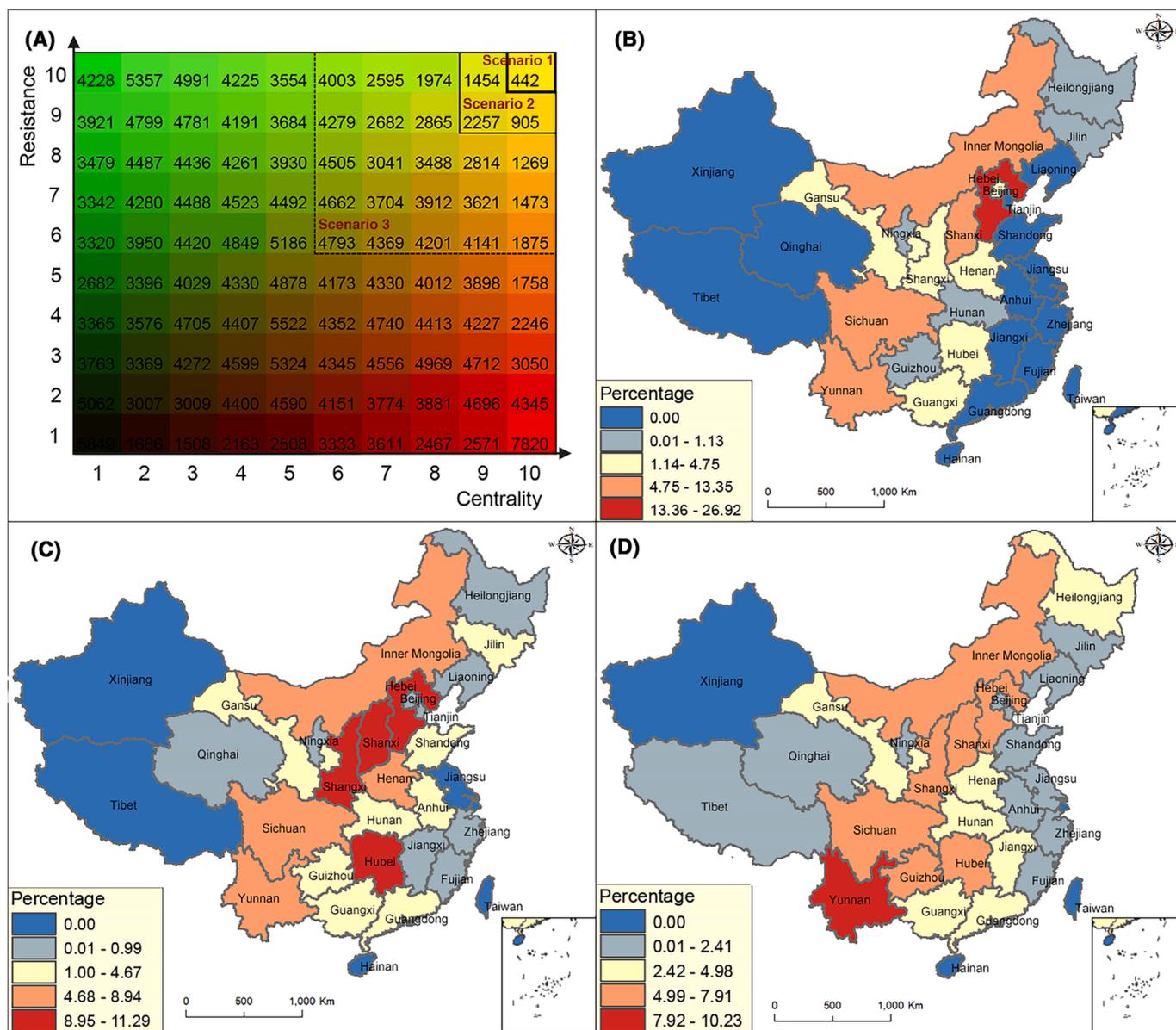
Fig. 6. Policy scenarios of allocating central funds for ecological restoration among the provinces in China. (A) Tabulated areas (km²) of eco-corridors based on combined rankings of centrality and current resistance. Three scenarios for the allocation of funds for ecological restoration are indicated. (B) Scenario 1: percentage of funds allocated to areas with both the highest centrality and resistance levels. (C) Scenario 2: percentage of funds allocated to areas with the two highest centrality and resistance levels. (D) Scenario 3: percentage of funds allocated to areas with the five highest centrality and resistance levels.

Administration. Four of the projects involve massive revegetation: the Natural Forest Protection Project, the Cropland Conversion to Forest Project (i.e., Grain for Green), the Three North Shelter and Yangtze River Basin Shelter Forest Project and the Project of Sandstorm Sources Treatment in Beijing and Tianjin. This clustered program was a milestone in the process of national ecological restoration, with 362 billion CNY (ca. 52.14 billion US$) of investment funds being distributed between the provinces (Fig. 7A, Fig. 7B). Unintended results such as overemphasis on the economic function of mono-culturing can occur (Xu et al., 2000; Xu, 2011). China's afforestation projects produced 40.24 million ha of new forest land between 2003 and 2012 (Fig. 7C, Fig. 7D). Consequently, while the number of Net Primary Production (NPP) and vegetation-covered areas increased, the number of species planted in the afforestation plan was fewer than in natural forests resulting in poor biodiversity and a weak self-regulation ability of the ecosystem (Feng et al., 2021).

Even though the country has allocated a significant amount of funds for domestic ecological restoration, the protection network is yet to been formed. Due to previous research gaps related to spatial patterns of both centrality and the pinch points of the eco-corridor network, the contribution of massive afforestation to ecological connectivity has been compromised in the past. Various ecological projects sponsored by the central government have often been conducted independently of each other, thus highlighting only their own singular purpose. As a result, the commonly shared purpose of connecting natural reserves through ecocorridors was never fully considered. The failure to link the conservation of biodiversity with afforestation projects has weakened the efficiency of central investments intended for in mitigating the increasing threat of climate change and anthropogenic activities. Similarly, due to the impact of human grazing and human activity, the protection effect of the existing international ecological network is performing as well as expected. For example, site covers only the minority of national species of community interest, with birds making up a maximum of 2% in Natura 2000 network (Zisenis, 2017). Thus, the eco-corridors network

Table 2
Areas of pixels in eco-corridor for priori ecological restoration in various provinces.

Province	Area of S_1[a] (km^2)	Percentage of S_1[a] (%)	Area of S_2[a] (km^2)	Percentage of S_2[a] (%)	Area of S_3[a] (km^2)	Percentage of S_3[a] (%)
Heilongjiang	1	0	50	1	2415	3
Inner Mongolia	54	12	398	8	5391	7
Xinjiang	0	0	0	0	0	0
Jilin	3	1	102	2	1520	2
Liaoning	0	0	41	1	1796	2
Gansu	21	5	155	3	2871	4
Hebei	119	27	571	11	4646	6
Beijing	21	5	50	1	587	1
Shanxi	46	10	478	9	5472	7
Tianjin	0	0	24	0	147	0
Qinghai	0	0	4	0	107	0
Shaanxi	20	5	493	10	5101	7
Ningxia	5	1	9	0	1252	2
Tibet	0	0	0	0	20	0
Shandong	0	0	197	4	1815	2
Henan	17	4	301	6	2931	4
Jiangsu	0	0	0	0	673	1
Anhui	0	0	236	5	1601	2
Sichuan	59	13	435	9	5957	8
Hubei	1	0	129	3	2363	3
Shanghai	0	0	0	0	0	0
Zhejiang	0	0	8	0	88	0
Jiangxi	0	0	26	1	2745	4
Hunan	16	4	519	10	5151	7
Yunnan	41	9	452	9	7708	10
Guizhou	5	1	105	2	5068	7
Fujian	0	0	3	0	944	1
Guangxi	13	3	154	3	3753	5
Taiwan	0	0	0	0	0	0
Guangdong	0	0	117	2	3202	4
Xianggang	0	0	0	0	0	0
Hainan	0	0	0	0	0	0
Total	442	100	5057	100	75,324	100

[a] S1, Scenario 1: pixels in the 10th centrality and current resistance levels are considered for ecological restoration; S2, Scenario 2: the 9th and 10th centrality and current resistance levels are considered for ecological restoration and S3, Scenario 3: the 6th-10th centrality and current resistance levels are considered for ecological restoration.

Table 3
Total number of crossing points between administrative boundaries and eco-corridors in various provinces.

Province	Number	Province	Number	Province	Number	Province	Number
Inner Mongolia	96	Anhui	61	Shanxi	47	Liaoning	24
Hebei	94	Heilongjiang	61	Beijing	45	Shandong	18
Sichuan	89	Gansu	59	Henan	45	Ningxia	17
Guangxi	83	Guizhou	59	Guangdong	44	Tianjin	17
Jiangxi	74	Yunnan	57	Jiangsu	29	Qinghai	16
Hubei	73	Shaanxi	55	Zhejiang	26	Xizang	7
Hunan	73	Jilin	50	Fujian	25	Xinjiang	2

should also include endemic species, endangered species, as well as habitats suitable for them. In addition, the corridor should also take into account the current potential threats and protection measures to achieve the protection objectives at the minimum cost (Sanderson et al., 2003).

Research has shown that partnership among stakeholders, continuity of leadership, sufficient funds and public outreach are important for encouraging the implementation of ecological corridors (Keeley et al., 2019). Designing mechanisms for stakeholder engagement and building an eco-corridor management platform with government leadership and multi-party participation will ensure corridor construction. Based on the government funds allocated for this project and the need for attracting multi-channel investment, it is necessary to establish a multi-level and multi-channel investment mechanism for nature reserves that will envelop both the state and local level. The country needs to assess the reconstruction cost for the damaged corridor through land use adjustment. This will provide a basis for the budget needed for practical land use adjustment and will solve the issues of ecological suitability and economic rationality (Li et al., 2022). In addition, public outreach is also able to support connectivity implementation actions. Namely, under

public pressure, institutions may be more likely to take protective actions.

4.4. Natural block conservation

Habitat loss due to anthropogenic influences, such as urbanization and infrastructure development, is one of the main causes behind biodiversity decline (Fletcher et al., 2018). Even though the National Nature Reserve policy facilitates conditions for the development of natural vegetation without negative human interference (Feng et al., 2021), misleading policies such as eco-corridor scale reduction and natural blocks may negatively impact the environment and biodiversity (Conceicao et al., 2022). Therefore, it is crucial to strengthen the protection and management of ecological blocks which are connected with the construction of natural reserve system.

Land use change is the primary cause of ecological degradation, which has directly affected China's biodiversity since 1970 which reported by Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019). Habitats and natural blocks
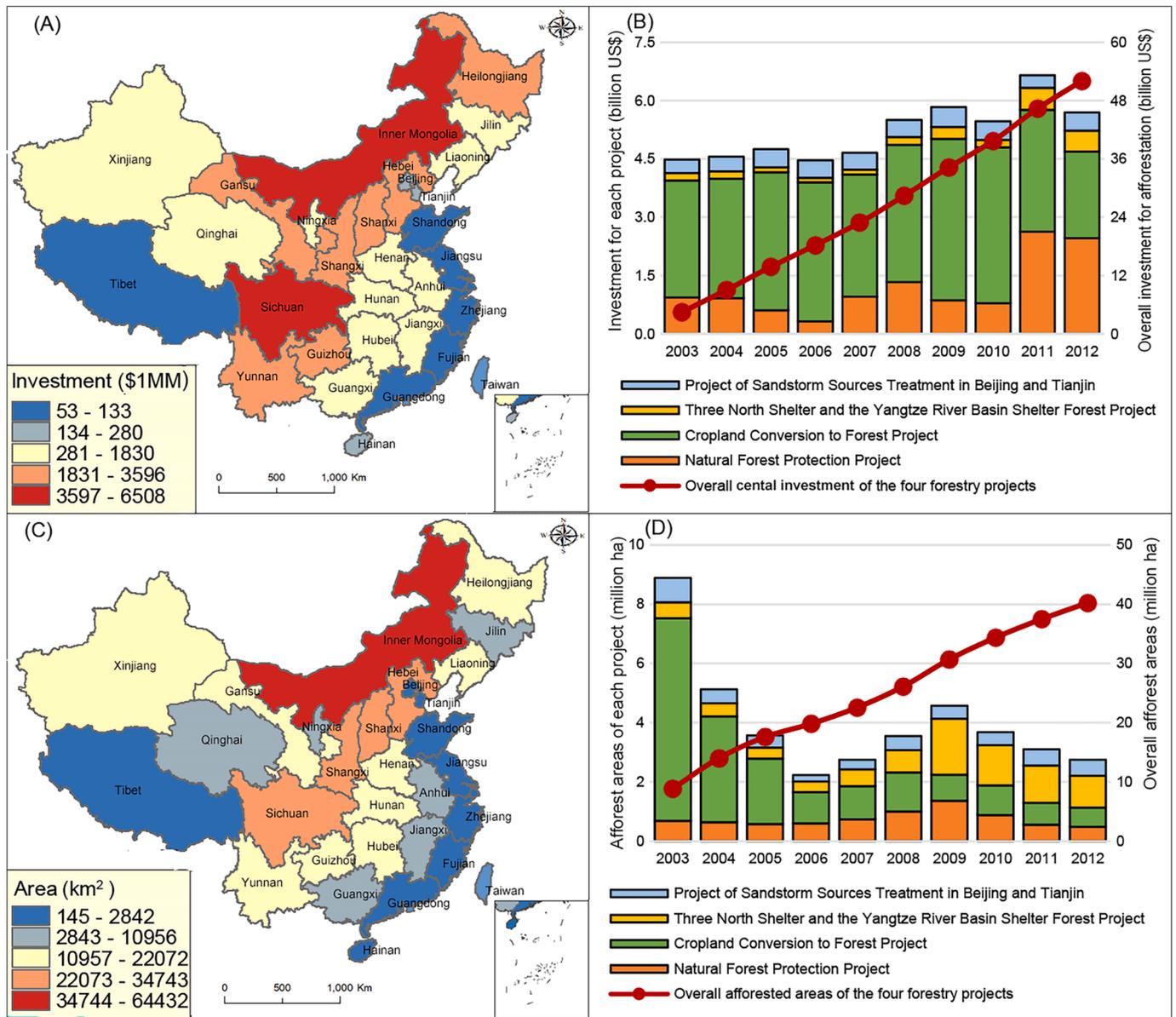
Fig. 7. Spatial pattern of (A) central investment distributed among the provinces, (B) accumulated central investment of the four major forestry projects between 2003 and 2012, (C) afforest areas distributed among the provinces, and (D) overall afforestation areas of the four major forestry projects between 2003 and 2012.

situated outside national natural reserves are vulnerable to incompatible land-use change and decisions made by local governments. Recent scientific evidence suggests that municipal actions regarding land use change are a critical for biodiversity conservation (Allred et al., 2021). Individuals involved in land use and protection planning programs should thus actively cooperate with municipal officials providing continuous assistance (Allred et al., 2021). In the future, these practices may be further developed to help municipal decision makers improve their biodiversity protection capacity.

Habitate protection shall be included in both spatial planning and operational policies, such as the land protection fund and the biodiversity conservation fund. Furthermore, biodiversity offsets are also being implemented as part of the No Net Loss (NNL) policies around the world. These policies have managed to compensate for the impact of human intervention on natural habitats in many countries (Sponagel et al., 2022). In China, a biodiversity offets is visible through allocating a budget for key ecological functional areas for 15 years, with the budget set to increase to 98.204 billion CNY by 2022. However, there is still a lack of research on the effect of biodiversity compensation. Because of

this, policy makers, stakeholders, and scientists need to cooperate and evaluate the economic and ecological impact under different compensation scenarios. After, they will be able to select the most appropriate compensation scheme. Finally, in order to encourage people to donate to biodiversity funds, one suggested strategy is to take flagship species as a protection target and attract public action and investment for habitat connection (Walpole and Leader-Williams, 2002).

5. Conclusions

Connectivity is a pivotal for conserving biodiversity (Dupras et al., 2016; Montis et al., 2019). The aim of eco-corridor research is to protect biodiversity and promote the material and energy flow of "ecological isolated islands". Because of this, eco-corridors will play a crucial role in future ecological research. In China, declined ecological connectivity threatens the country's biodiversity. Forestry projects should be continue, and new policies for increasing the carbon sink and demarcating ecological limits (redline) will soon be introduced. Based on the eco-corridor framework, this study has highlighted the importance of

ranking and identifying the pinch points with high resistance. Thus, policy makers must work to include eco-corridors in their plans for ecological restoration. By including them into ecological restauration plans, two goals could be achieved. There would be revegetating at the local level, while ecological connectivity would be enhanced at the national level. Furthermore, connectivity conservation should also seek to restore ecological connectivity at a national scale through collaborative conservation (Wyborn, 2015), government management, and increased public interest.

CRediT authorship contribution statement

Meirong Tian: Writing – original draft, Writing – review & editing. **Jixi Gao:** Supervision, Writing – review & editing. **Guobao Song:** Data curation, Writing – original draft. **Chaoyang Feng:** Investigation.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgement

References

Agrawal, A., 2003. Transboundary Protected Areas and Adaptive Management. IUCN-The World Conservation Union, Gland, Switzerland.

Allred, S., Stedman, R., Heady, L., Strong, K., 2021. Incorporating biodiversity in municipal land-use planning: An assessment of technical assistance, policy capacity, and conservation outcomes in New York's Hudson Valley. Land Use Policy 104. https://doi.org/10.1016/j.landusepol.2021.105344.

Bai, X.M., Shi, P.J., Liu, Y.S., 2014. Realizing China's urban dream. Nature 509, 158–160.

Beier, P., 2019. A rule of thumb for widths of conservation corridors. Conserv. Biol. https://doi.org/10.1111/cobi.13256.

Burrows, M.T., Schoeman, D.S., Richardson, A.J., Molinos, J.G., Hoffmann, A., Buckley, L.B., Moore, P.J., Brown, C.J., Bruno, J.F., Duarte, C.M., Halpern, B.S., Hoegh-Guldberg, O., Kappel, C.V., Kiessling, W., O'Connor, M.I., Pandolfi, J.M., Parmesan, C., Sydeman, W., Ferrier, S., Williams, K.J., Poloczanska, E.S., 2014. Geographical limits to species-range shifts are suggested by climate velocity. Nature 507, 492–495. https://doi.org/10.1038/nature 12976.

Butchart, S.H.M., Baillie, J.E.M., Chenery, A.M., Collen, B., Gregory, R.D., Revenga, C., Walpole, M., 2010a. National indicators show biodiversity progress—response. Science 329, 900–901. https://doi.org/10.1126/science.329.5994.900-c.

Butchart, S.H.M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J.P.W., Almond, R.E.A., Baillie, J.E.M., Bomhard, B., Brown, C., Bruno, J., Carpenter, K.E., Carr, G.M., Chanson, J., Chenery, A.M., Csirke, J., Davidson, N.C., Dentener, F., Foster, M., Galli, A., Galloway, J.N., Genovesi, P., Gregory, R.D., Hockings, M., Kapos, V., Lamarque, J.-F., Leverington, F., Loh, J., McGeoch, M.A., McRae, L., Minasyan, A., Morcillo, M. H., Oldfield, T.E.E., Pauly, D., Quader, S., Revenga, C., Sauer, J.R., Skolnik, B., Spear, D., Stanwell-Smith, D., Stuart, S.N., Symes, A., Tierney, M., Tyrrell, T.D., Vié, J.-C., Watson, R., 2010b. Global biodiversity: Indicators of recent declines. Science. 328, 1164-1168. 10.1126/science.1187512.

Carroll, C., McRae, B.H., Brookes, A., 2012. Use of linkage mapping and centrality analysis across habitat gradients to conserve connectivity of gray wolf populations in western north America. Conserv. Biol. 26, 78–87. https://doi.org/10.1111/j.1523-1739.2011.01753.x.

Chen, C.D., Wu, S.J., Meurk Colin, D., Lu, M.Q., Wen, Z.F., Jiang, Y., Chen, J.L., 2015. Effects of changing cost values on landscape connectivity simulation. Acta Ecol. Sin. 35, 7367–7376. https://doi.org/10.5846/stxb201404010611.

Clevenger, A.P., Huijser, M.P., 2009. Handbook for Design and Evaluation of Wildlife Crossing Structures. Western Transportation Institute, Bozeman, Montana.

Conceicao, E.O., Garcia, J.M., Alves, G.H.Z., Delanira-Santos, D., Corbetta, D.D., Betiol, T.C.C., Pacifico, R., Romagnolo, M.B., Batista-Silva, V.F., Bailly, D., Ferreira, J.H.D., do Couto, E.V., 2022. The impact of downsizing protected areas: how a misguided policy may enhance landscape fragmentation and biodiversity loss. Land Use Policy 112. https://doi.org/10.1016/j.landusepol.2021.105835.

Dai, L., Liu, Y.B., Luo, X.Y., 2021. Integrating the MCR and DOI models to construct an ecological security network for the urban agglomeration around Poyang Lake, China. Sci. Total Environ. 754, 141868 https://doi.org/10.1016/j.scitotenv.2020.141868.

Damschen, E.I., Haddad, N.M., Orrock, J.L., Tewksbury, J.J., Levey, D.J., 2006. Corridors increase plant species richness at large scales. Science 313, 1284–1286. https://doi.org/10.1126/science.1130098.

Dawson, T.P., 2011. Beyond predictions: biodiversity conservation in a changing climate. Science 332, 664. https://doi.org/10.1126/science.1200303.

Dupras, J., Marull, J., Parcerisas, L., Coll, E., Gonzalez, A., Girard, M., Tello, E., 2016. The impacts of urban sprawl on ecological connectivity in the Montreal Metropolitan Region. Environ. Sci. Policy 58, 61–73.

Feng, D.R., Bao, W.K., Yang, Y.Y., Fu, M.C., 2021. How do government policies promote greening? Evidence from China. Land Use Policy, 104.10.1016/j.landusepol.2021.105389.

Fletcher, R.J., Didham, R.K., Banks-Leite, C., Barlow, J., Ewers, R.M., Rosindell, J., Ewers, R.M., Rosindell, J., Holt, R.D., Gonzalez, A., Pardini, R., Damschen, E.I., Melo, F.P.L., Ries, L., Prevedello, J.A., Tscharntke, T., Laurance, W.F., Lovejoy, T., Haddad, N.M., 2018. Is habitat fragmentation good for biodiversity? Biol. Conserv. 226, 9–15. https://doi.org/10.1016/j.biocon.2018.07.022.

Fremier, A.K., Kiparsky, M., Gmur, S., Aycrigg, J., Craig, R.K., Svancara, L.K., Goble, D. D., Cosens, B., Davis, F.W., Scott, J.M., 2015. A riparian conservation network for ecological resilience. Biol. Conserv. 191, 29–37. https://doi.org/10.1016/j.biocon.2015.06.029.

Green, E.J., Buchanan, G.M., Butchart, S., Chandler, G.M., Burgess, N.D., Hill, S., Gregory, R.D., 2019. Relating characteristics of global biodiversity targets to reported progress. Conserv. Biol. 33, 1360–1369. https://doi.org/10.1111/cobi.13322.

Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2019. In: Brondizio, E.S., Settele, J., Díaz, S., Ngo, H.T. (Eds.), Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services. IPBES Secretariat, Bonn, Germany.

Jonathan, B., Thomas, D., Richard, I., Kevin, G., 2014. Mapping artificial lightscapes for ecological studies. Methods Ecol. Evol. 5, 534–540. https://doi.org/10.1111/2041-210X.12182.

Keeley, A.T.H., Beier, P., Creech, T., Jones, K., Jongman, R.H.G., 2019. Grace Stonecipher3 and Gary M TaborThirty years of connectivity conservation planning: an assessment of factors influencing plan implementation. Environ. Res. Lett. 14, 103001 https://doi.org/10.1088/1748-9326/ab3234.

Keeley, A.T.H., Fremier, A.K., Goertler, P.A.L., Huber, P.R., Sturrock, A.M., Bashevkin, S. M., Barbaree, B.A., Grenier, J.L., Dilts, T.E., Gogol-Prokurat, M., Colombano, D.D., Bush, E.E., Laws, A., Gallo, J.A., Kondolf, M., Stahl, A.T., 2022. Governing ecological connectivity in cross-scale dependent systems. Bioscience 72, 372–386. https://doi.org/10.1093/biosci/biab140.

Kevin, G., Jonathan, B., 2014. Demographic effects of artificial nighttime lighting on animal populations. Environ. Rev. 22, 1–8. https://doi.org/10.1139/er-2014-0005.

Laurance, W.F., Clements, G.R., Sloan, S., O'Connell, C.S., Mueller, N.D., Goosem, M., Venter, O., Edwards, D.P., Phalan, B., Balmford, A., Van Der Ree, R., Arrea, I.B., 2014. A global strategy for road building. Nature 513, 229–237. https://doi.org/10.1038/nature13717.

Li, P.X., Cao, H., Sun, W., Chen, X.Y., 2022. Quantitative evaluation of the rebuilding costs of ecological corridors in a highly urbanized city: The perspective of land use adjustment. Ecol. Ind. 141, 109–130. https://doi.org/10.1016/j.ecolind.2022.109130.

Li, P.Y., Qian, H., Wu, J.H., 2014. Environment: accelerate research on land creation. Nature 510, 29–31. https://doi.org/10.1038/510029a.

Li, T.A., Shilling, F., Thorne, J., Li, F.M., Schott, H., Boynton, R., Berry, A.M., 2010. Fragmentation of China's landscape by roads and urban areas. Landsc. Ecol. 25, 839–853. https://doi.org/10.1007/s10980-010-9461-6.

Liang, J., He, X.Y., Zeng, G.M., Zhong, M.Z., Gao, X., Li, X., Li, X.D., Wu, H.P., Feng, C.T., Xing, W.L., Fang, Y.L., Mo, D., 2018. Integrating priority areas and ecological corridors into national network for conservation planning in China. Sci. Total Environ. 626, 22–29. https://doi.org/10.1016/j.scitotenv.2018.01.086.

Liquete, C., Kleeschulte, S., Dige, G., Maes, J., Grizzetti, B., Olah, B., Zulia, G., 2015. Mapping green infrastructure based on ecosystem services and ecological networks: a Pan-European case study. Environ Sci Policy 54, 268–280. https://doi.org/10.1016/j.envsci.2015.07.009.

Liu, S.L., Deng, L., Chen, L.D., Li, J.R., Dong, S.K., Zhao, H.D., 2014. Landscape network approach to assess ecological impacts of road projects on biological conservation. Chin. Geogr. Sci. 24, 5–14. https://doi.org/10.1007/s11769-014-0651-z.

Liu, J.J., Yong, D.L., Choi, C.Y., Gibson, L., 2020. Transboundary frontiers: an emerging priority for biodiversity conservation. Trends Ecol. Evol. 35, 679–690. https://doi.org/10.1016/j.tree.2020.03.004.

McRae, B.H., Kavanagh, D.M. Linkage mapper connectivity analysis software. 2012. Available at: <http://www.circuitscape.org/linkagemapper> (accessed on Jul 7, 2012).

McRae, B.H., Shah, V.B. Circuitscape user's guide, 2009. Available at: <http://www.circuitscape.org.> (accessed on Nov 1, 2009).

McRae, B.H., Dickson, B.G., Keitt, T.H., Shah, V.B., 2008. Using circuit theory to model connectivity in ecology, evolution and conservation. Ecology 89, 2712–2724. https://doi.org/10.1890/07-1861.1.

McRae, B.H., Hall, S.A., Beier, P., Theobald, D.M., 2012. Where to restore ecological connectivity? Detecting barriers and quantifying restoration benefits. PLoS One 7. https://doi.org/10.1371/journal.pone.0052604.

Ministry of Commerce of China, 2014. Promoting transformation, upgrading, innovation of national development zones. Available at: ⟨http://english.mofcom.gov.cn/article/newsrelease/policyreleasing/201412/20141200828595.shtml⟩(accessed on Nov 21, 2015).

Ministry of Transport of China, 2021. Chinese highway development. Available at: <https://www.thepaper.cn/newsDetail_forward_14183486> (accessed on Aug 24, 2021) (in Chinese).

Montis, A.D., Ganciu, A., Cabras, M., Bardi, A., Mulas, M., 2019. Resilient ecological networks: a comparative approach. Land Use Policy 89, 104207. https://doi.org/10.1016/j.landusepol.2019.104207.

Morandi, D.T., Frana, L.C.J.D., Menezes, E.S., Machado, E.L.M., Piuzana, D., 2020. Delimitation of eco-corridors between conservation units in the brazilian cerrado using a gis and ahp approach. Ecol. Ind. 115, 10. https://doi.org/10.1016/j.ecolind.2020.106440.

National Earth System Science Data Center (NESSDC), 2020a. China land use dataset. DOI:10.12041/geodata.122535017095134.ver1.db <http://www.geodata.cn/data/datadetails.html?dataguid=122535017095134&docid=8439>.

National Earth System Science Data Center (NESSDC), 2020b. Lake-Watershed Science SubCenter, National Science & Technology Infrastructure of China. Water system distribution dataset . DOI: 10.12041/geodata.49919573122702.ver1.db <http://lake.geodata.cn/data/datadetails.html?dataguid=49919573122702&docid=427>.

Niu, T., Yue, D.P., Zhang, Q.B., Yu, Q., Yu, J.X., Yu, K., 2019. Spatial structure and characteristics of potential ecological networks. J. Agric. Machinery. 50(8):165-175. 10.6041 / j. issn.1000-1298.2019. 08. 019.

Puri, M., Srivathsa, A., Karanth, K.K., Patel, I., Kumar, N.S., 2022. Links in a sink: Interplay between habitat structure, ecological constraints and interactions with humans can influence connectivity conservation for tigers in forest corridors. Sci. Total Environ. 809, 151106 https://doi.org/10.1016/j.scitotenv.2021.151106.

Quan, J., Ouyang, Z.Y., Xu, W.H., Miao, H., 2011. Assessment of the effectiveness of nature reserve management in China. Biodivers. Conserv. 20, 779–792. https://doi.org/10.1007/s10531-010-9978-7.

Rands, M.R.W., Adams, W.M., Bennun, L., Butchart, S.H.M., Clements, A., Coomes, D., Entwistle, A., Hodge, I., Kapos, V., Scharlemann, J.P.W., 2010. Biodiversity conservation: challenges beyond 2010. Science 329, 1298–1303. https://doi.org/10.1126/science.1189138.

Resource and environmental science data center (RESDC).2020. China's roads spatial distribution kilometer grid data. <https://www.resdc.cn/data.aspx?DATAID=237>.

Rudnick, D.A., Ryan, S.J., Beier, P., Cushman, S.A., Dieffenbach, F., Epps, C.W., Gerber, L.R., Hartter, J., Jenness, J.S., Kintsch, J., Merenlender, A.M., Perkl, R.M., Preziosi, D.V., Trombulak, S.C., 2012. The role of landscape connectivity in planning and implementing conservation and restoration priorities. Issues in Ecol. 1–19 https://doi.org/10.1095/biolreprod46.1.155.

Sanderson, J., Alger, K., De Fonseca, G.A.B., Galindo-Leal, C., Inchausty, V.H., Morrison, K., 2003. Biodiversity Conservation Corridors: Planning, Implementing, and Monitoring Sustainable Landscapes. Conservation International, Center for Applied Biodiversity Science, Washington, DC.

Sponagel, C., Bendel, D., Angenendt, E., Weber, T.K.D., Gayler, S., Streck, T., Bahrs, E., 2022. Integrated assessment of regional approaches for biodiversity offsetting in urban-rural areas – A future based case study from Germany using arable land as an example. Land Use Policy 117. https://doi.org/10.1016/j.landusepol.2022.106085.

Sukopp, H., 1969. Der Einfluss des Menschen auf die Vegetation. Plant Ecol. 17, 360–371.

The National People's Congress of China. Environmental protection law revision. 2014. Available at: <http://www.gov.cn/zhengce/2014-04/25/content_2666434.htm> (accessed on Apr 24, 2014) (in Chinese).

The State Council Information Office of the People's Republic of China, 2021. Biodiversity Conservation in China, Available at: <http://www.gov.cn/zhengce/2021-10/08/content_5641289.htm> (accessed on 8th Oct 2021).

Tian, M.R., Chen, X.L., Gao, J.X., Tian, Y.X., 2022. Identifying ecological corridors for the Chinese ecological conservation redline. PLoS One 17 (7), e0271076.

Walpole, M.J., Leader-Williams, N., 2002. Tourism and flagship species in conservation. Biodivers. Conserv. 11, 543–547. https://doi.org/10.1023/A:1014864708777.

Wyborn, C., 2015. Connectivity conservation: Boundary objects, science narratives and the co-production of science and practice. Environ Sci Policy 51, 292–303. https://doi.org/10.1016/j.envsci.2015.04.019.

Xu, J.C., 2011. China's new forests aren't as green as they seem. Nature 477, 371. https://doi.org/10.1038/477371a.

Xu, H.G., Ding, H., Wu, J., 2010. National indicators show biodiversity progress. Science 329, 900. https://doi.org/10.1126/science.329.5994.900-b.

Xu, M., Qi, Y., Gong, P., 2000. China's new forest policy. Science 289, 2049–2050. https://doi.org/10.1126/science.289.5487.2049b.

Xu, H.G., Tang, X.P., Liu, J.Y., Ding, H., Wu, J., Zhang, M., Yang, Q.W., Cai, L., Zhao, H. J., Liu, Y., 2009. China's progress toward the significant reduction of the rate of biodiversity loss. Bioscience 59, 843–852. https://doi.org/10.1525/bio.2009.59.10.6.

Xu, J.L., Zhang, Z.W., Liu, W.J., McGowan, P.J.K., 2012. A review and assessment of nature reserve policy in China: advances, challenges and opportunities. Oryx 46, 554–562. https://doi.org/10.1017/S0030605311000810.

Xu, X.L., 2020a. China's GDP spatial distribution kilometer grid dataset. Resource and environmental science data registration and publishing system. doi: 10.12078/2017121102 <https://www.resdc.cn/DOI/doi.aspx?DOIid=33>.

Xu, X.L., 2020b. China Population Spatial Distribution Kilometre Grid Dataset. Resource and environmental science data registration and publishing system. doi: 10.12078/2017121101 <https://www.resdc.cn/DOI/doi.aspx?DOIid=32>.

Xu, X.L., 2022. Annual dataset of night lighting in China. Resource and environmental science data registration and publishing system. doi: 10.12078/2022090902 <https://www.resdc.cn/DOI/DOI.aspx?DOIID=105>.

Zeller, K.A., McGarigal, K., Whiteley, A.R., 2012. Estimating landscape resistance to movement: a review. Landsc. Ecol. 27, 777–797. https://doi.org/10.1007/s10980-012-9737-0.

Zheng, H.R., Cao, S.X., 2015. Threats to china's biodiversity by contradictions policy. Ambio 44, 23–33. https://doi.org/10.1007/s13280-014-0526-7.

Zisenis, M., 2000. Is the Natura 2000 network of the European Union the key land use policy tool for preserving Europe's biodiversity heritage? Land Use Policy 69, 408–416. https://doi.org/10.1016/j.landusepol.2017.09.045.