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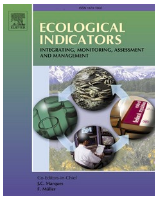

Constructing a multi-leveled ecological security pattern for improving ecosystem connectivity in the Asian water Tower region

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ABSTRACT

Serious ecological crises have emerged in the Asian Water Tower region (17 countries centered on the Qinghai-Tibetan Plateau), making it a major priority and challenge for Asian and even global ecological conservation efforts. Constructing a multi-leveled ecological security pattern (ESP) based on the synergies among multiple ecosystem services (ESs) for this region can enhance the structural integrity, functional stability, and spatial connectivity of ecosystems. Therefore, based on a series of GIS spatial analysis methods, the minimum cumulative resistance model, and the analytic hierarchy process, this study measured the importance of five key ESs focused by Sustainable Development Goal 15 (including water conservation, carbon sequestration, sand fixation, soil conservation, and biodiversity conservation); and took fishnet scale as data calculation unit to construct a hierarchical ESP (including three levels of ecological sources and corridors) to provide evidence-based support for identifying and prioritizing synergistic conservation actions across scales (regions, nations, and basins). Overall, the ESP included a total of 534 sources and 656 corridors. Some key conservation obstacles in the region (e.g., edge effects and several human activities) and corresponding priority actions are provided, such as integrating the ESPs into long-term planning, enhancing the conservation and the restoration of both the extent and the quality of forests (e.g., increasing tree species richness), and increasing collaboration across scales for resource mobilization and synergistic land use.

1. Introduction

Ecological security refers to the ecosystem integrity and health, and is the basis of maintaining sustainable development and human well-being (Liu et al., 2022a). However, Asia has faced multiple serious ecological crises as a result of human activities affecting large tracts of land, wetlands, and oceans (Reyers and Selig, 2020). To promote progress toward the Sustainable Development Goals (SDGs), and to achieve the targets of the Kunming-Montreal Global Biodiversity Framework (Zhu et al., 2021), it is vital and urgent to identify across-scale conservation strategies and actions for Asia to maintain ecosystem structural and functional stability and enhance its integrity and connectivity (i.e., address ecosystem fragmentation). In particular, the Asian Water Tower (AWT) region (containing 17 countries centered on the Qinghai-Tibetan Plateau) represents a major priority for Asian ecological conservation. However, most studies have focused only on the Qinghai-Tibetan Plateau, ignoring the regional spatial correlations when identifying priority conservation areas and actions.

Constructing ecological security patterns (ESPs) based on the analysis of multiple ESs can be a critical and mainstream solution to identify and prioritize ecological conservation actions (Peng et al, 2018). As the Kunming-Montreal Global Biodiversity Framework emphasized, increasing the area, connectivity, and integrity of ecosystems is one of the most important goals for measuring progress toward global conservation (Hansen et al, 2021). ESPs, seeking solutions for ecosystem fragmentation from a holistic perspective, can be an effective way to

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achieve that goal (Zhang et al., 2022). Specifically, ESPs aim to promote species migration and the regional circulation, address ecosystem fragmentation, and enhance ecosystem integrity and connectivity by identifying and regulating ecological sources and corridors (Dai et al., 2021; Liu et al., 2022b).

The ecological sources are key ecological patches that promote ecological processes, maintain ecosystem integrity, and supply ESs (Xiao et al., 2020). Some studies directly identified existing natural reserves or ecological land meeting a certain area threshold as ecological sources, which could not guarantee the full play of ecosystem functions or services (Li et al., 2020). Thus, a method of identifying areas with a high importance of ESs as sources has been widely adopted (Dong et al., 2021). However, the ES evaluation results generally contain many fragmented patches and obvious edge effects. The lack of further analysis (e.g., removing these patches) will disturb ESP construction.

Ecological corridors connect different ecological patches and provide channels for the migration of species and ecological flow between sources (Peng et al, 2018). Ecological corridors are usually constructed by using the minimum cumulative resistance (MCR) model (Dong et al., 2021), patch gravity model (Kong et al., 2010), or circuit theory (Li et al., 2020), which are based on the measurement of the ecological resistance surface. Most studies have measured the scores of surfaces through expert elicitation based on land-use types; however, the spatial differences of the same land-use type were not considered. Although many studies aimed to address this issue by using the elements (e.g., nightlight and slope) affecting species migration in ecological corridors, most of the elements were missed (e.g., vegetation cover and traffic impacts). Therefore, a more integrated consideration of multiple ESs and of elements affecting ecological flows is urgently needed to construct ESPs.

Previous global targets for the environment, such as the Aichi Biodiversity Targets that ended in 2020, were not achieved at the global scale (Hansen et al., 2021), representing the limitations of existing actions (Zhu et al., 2021). Thus, more specific, proactive, and collaborative actions are urgently needed. ESPs can be seen as a critical practice of the core concept of “pattern-process-scale” in landscape ecology (Dong et al., 2021). They emphasize the interactions among landscape patterns and ecological processes, which can manifest as intra-coupling, neighborhood coupling, or telecoupling at different scales (Bird and Nimmo, 2018). For example, some ESs are delivered at the local or national scale, and their supply can be affected by regional- or global-scale processes (Carpenter et al., 2006). Studies have argued that multilevel analysis is a tool that can be used to combine the advantages of both fine-scale and coarse-scale modeling without losing detail (Larondelle and Lauf, 2016). Thus, it is critical to construct hierarchical (multilevel) ESPs at a large scale (e.g., the AWT regional scale) to promote synergistic across-scale (regional, national, and basin) actions to achieve regional- and global-based frameworks. However, such studies are still rare.

Overall, this study aimed to construct the ESPs for the AWT region, including the identification of hierarchical ecological sources and corridors based on the synergies among five ESs focused by SDG 15 (life on land), to enhance the structural integrity, functional stability, and spatial connectivity of ecosystems and provide evidence-based support for prioritizing the actions of regional ecological conservation. To do so, an integrated methodological framework was constructed (Section 2). Based on the results (Section 3), we discussed in detail the key conservation obstacles, possible conservation priority actions, and limitations and uncertainties of the framework we adopted (Section 4).

2. Materials and methods

2.1. Study area

The Qinghai-Tibetan Plateau is a crucial ecological barrier and gene pool of biological species in many Asian countries (Lin et al., 2021), and involves multiple significant transboundary river basins (Yao, 2018), which make the 17 countries centered on it have close and complex interrelationships (Wang et al., 2021; Lin et al., 2021). Thus, we recognized these 17 countries as the AWT region (Fig. 1) (Huan et al., 2023). The terrain of AWT region is extremely complex, with multiple types of landforms including plateaus, mountains, hills, plains, and basins. The Himalayas and the Qinghai Tibet Plateau are the highest mountain ranges and plateaus in the world, respectively. The climate types are diverse, with typical monsoon climate in East Asia, Southeast Asia, and South Asia, and with continental climate in Central Asia and West Asia. The diverse climate and terrain have formed rich natural resources and diverse ecosystems, including artificial ecosystems (29.9%), grassland ecosystems (26.5%), forest ecosystems (21.2%), desert ecosystems (19.0%), and water ecosystems (3.3%). Due to high-intensity human interference in the process of rapid urbanization, the AWT region has experienced multiple severe ecological crises, including serious ecosystem conversion, degradation, and fragmentation (Rosa et al., 2016; Gray et al., 2020). The AWT region stands out as a major priority and challenge for ecological conservation in Asia and globally. Thus, this study aimed to focus on the AWT region and support its regional ecological conservation actions.

2.2. Data sources

The main data and their sources and other key information are shown in in the Supplementary Information.

2.3. Methods

Compared with the conservation of point or polygon ecological functional areas, the ecological security in this study highlighted more on networked ecological spaces, that is, in addition to focusing on the conservation of critical ecological sources, strengthening the connectivity and integrity of ecosystems is equally important for maintaining ecological security (Gao et al., 2021). Therefore, based on the “source-sink” theory of landscape ecology (Dai et al., 2021), a methodological framework for building a multi-leveled ESP was proposed. The framework was outlined in three steps (Fig. 2). First, multiple models were used to measure the values of five ESs and identify the ecologically important areas, the initial ecological sources, and the core ecological sources (Section 2.1). We then adopted the central feature method, hotspot analysis, and kernel density estimation to identify three levels of ecological sources (Section 2.2). Last, the MCR model and analytic hierarchy process (AHP) were used to construct three levels of ecological corridors (Section 2.3).

2.3.1. Identifying core ecological sources

We first measured the values of each of the five ESs based on a series of GIS spatial analysis models (see details of the models in the Supplementary Information). Water conservation, sand fixation, soil conservation, carbon sequestration and biodiversity conservation were measured by adopting the water balance model (WBQ model) (Wu et al., 2020), the revised wind erosion equation model (RWEQ model) (Jarrah et al., 2020), the revised universal soil loss equation model (RUSLE model) (Lin et al., 2021), the habitat quality module and the carbon storage and sequestration module of the InVEST model (Ouyang et al., 2016), respectively, to obtain a raster map for the value of each ES. The values were further divided into five levels, including high, relatively high, medium, relatively low, and low. The areas with high and relatively high levels of ESs were identified as important areas for ESs.

We then superimposed the important areas of five ESs as initial ecological sources. To remove many fragmented patches in ecological sources and reduce their edge effects, distance effects, and islet effects, we further extracted ecological land (including forestland, grassland, water, wetland, and unused land) from the initial ecological sources and applied morphological spatial pattern analysis (MSPA) to identify core ecological sources ($\geq$50 km^2) (Wickham et al., 2010). MSPA can

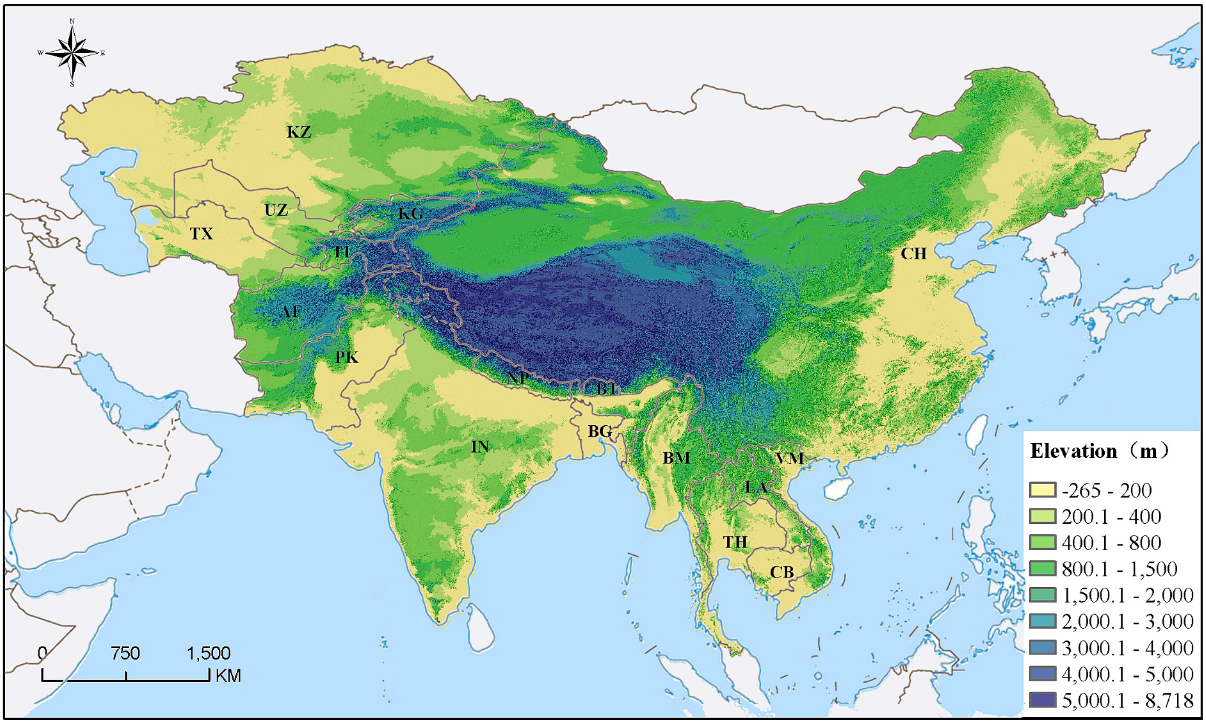

Fig. 1. Location of the study area. Note: the region includes Cambodia (CB), Laos (LA), Myanmar (BM), Thailand (TH), Vietnam (VM), China (CH), Bangladesh (BG), Bhutan (BT), India (IN), Nepal (NP), Pakistan (PK), Afghanistan (AF), Kazakhstan (KZ), Kyrgyzstan (KG), Tajikistan (TI), Turkmenistan (TX), and Uzbekistan (UZ); and we did not include Hainan and Taiwan of China in the study region because they are islands that are not connected to the mainland.

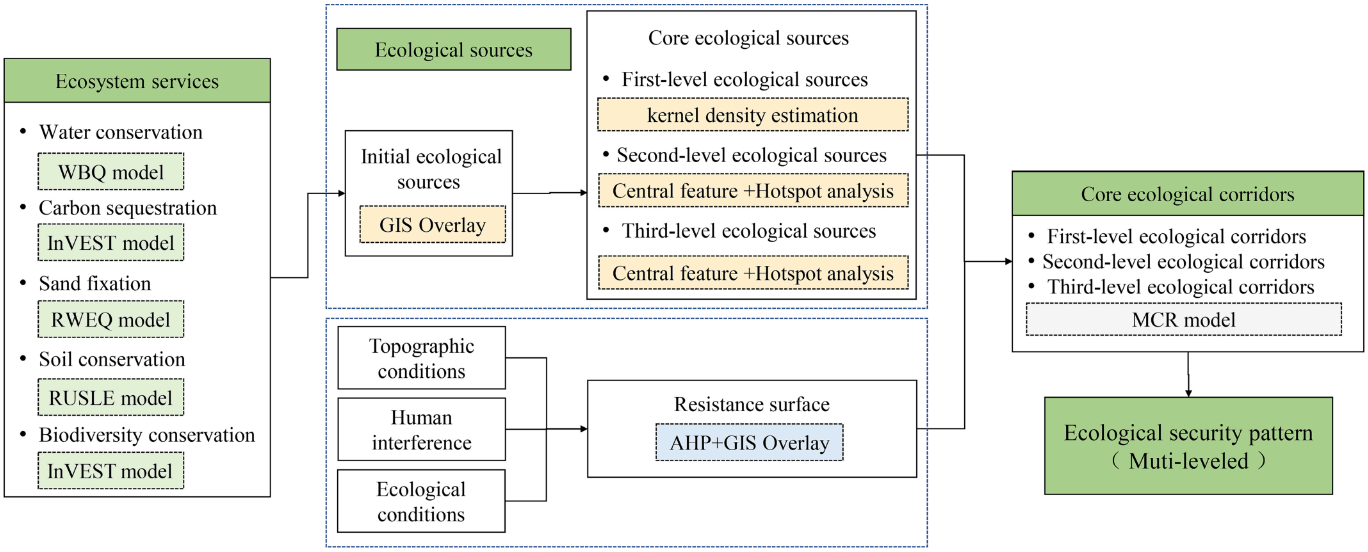

Fig. 2. Assessment framework adopted in this study.

distinguish the type and structure of the landscape more precisely than other approaches (e.g., extracting the existing conservation areas as sources) (Ye et al., 2020; Hu et al., 2022). Specifically, MSPA uses a series of image processing routines to identify seven main categories with different functions, including core, islet, bridge, loop, branch, edge, and perforation (Soille and Vogt, 2009; Wickham et al., 2010). The ecological sources obtained in this way has the characteristics of important ESs and sustainability.

2.3.2. Grading extraction of ecological sources

The central feature method identifies the most central element in the data set (i.e., the one with the smallest cumulative distance from all other elements in the data set) to characterize the most convenient location in the ecological network for animals' movement. We transformed the core sources from polygons to points, built a spatial evaluation unit (considering the similarity of spatial scales, the spatial evaluation unit adopts the boundaries of prefecture-level cities in China and provincial boundaries in other countries), and extracted the central element of each unit from these points as the third-level ecological sources. We further created a 500 km × 500 km fishnet and extracted the central elements of each 500 km fishnet unit from all third-level sources as the second-level ecological sources.

Using the central feature method to extract the first-level ecological sources requires the establishment of larger fishnet units, but such oversized fishnet units are often poorly matched with geomorphological units, which can cause the artificial fragmentation of ecosystems and affect the accuracy of core source extraction. Therefore, we used hotspot analysis and kernel density estimation to identify the first-level ecological sources.

Hotspot areas are areas with aggregations of high-value distributions of each service (Cai et al., 2017). We built a 20 km × 20 km fishnet and measured the areas of core ecological sources in each fishnet; then, we used the hotspot analysis tool in ArcGIS to identify where the high values of each ES in each fishnet unit were clustered spatially. Finally, we extracted the hotspots of ESs at three confidence levels from low to high (Li et al., 2022).

We further performed kernel density estimation (i.e., calculating the density of elements in their surrounding neighborhoods) for the hotspots. The kernel density distribution map included the core location, morphological characteristics, and extension of the regional ES aggregation. In the map, the larger the kernel density value of a fishnet unit was, the denser the ES hotspot, that is, the higher the importance of the ecological source. The geometric center of the results of kernel density estimation was eventually identified as the first-level ecological sources (i.e., the areas with the most important ecosystem functions) (Li et al., 2020).

2.3.3. *Constructing ecological corridors*

Ecological corridors are great pathways for interconnecting high-quality ecological sources in a region and are key vehicles for maintaining the effective stability and flow of ESs and ecological processes between different sources (Peng et al., 2018). Various methods have been developed for the identification of ecological corridors (see the review in Liu et al. (2022a), among which the MCR model proposed by Knaapen et al. (1992) has been widely used (e.g., Hansen et al. (2021); Ding et al. (2022)). Based on the MCR (Eq. (1), we identified the corresponding levels of ecological corridors for three levels of ecological sources.

$$MCR = fmin \sum_{j=n}^{i=m} (D_{ij} \times R_i) \tag{1}$$

In Eq. (1), MCR is the cumulative minimum resistance value; $fmin$ is a positive function reflecting the positive correlation between the MCR and ecological processes from a point to the basal plane; D_{ij} is the spatial distance from source j to a source i; and R_i is the resistance coefficient of landscape i to a certain ecological process, indicating the degree to which species are hindered from moving through different landscape units or habitat patches (Peng et al., 2018). The method of considering land-use types to assign the ecological resistance coefficient value has been widely used (Dong et al., 2021). However, simulations based on land-use type assumptions, to some extent, ignore the differentiated land-use patterns and intensities under the same land cover type (Liu et al., 2022a). In general, in addition to land cover, ecological resistance coefficients are closely related to topographic conditions (e.g., elevation and slope), human interference (e.g., distance from towns, villages, traffic proximity, and nighttime lighting), and ecological conditions (e.g., vegetation cover). An integrated consideration of these factors can better simulate ecological processes of animals' movement among ecosystems (Wang and Pan, 2019). We adopted the AHP (Sun et al., 2016; Li et al., 2020; Wu and Hu, 2020) to construct the indicator framework with three categories of 10 elements and set the weights (Table 1) (see details in Supplementary Information), and used Eq. (2) to acquire resistance coefficients among all three-level ecological sources.

$$R_i = \sum_{i=1}^{n} r_i \times w_i \tag{2}$$

In Eq. (2), R_i is the resistance coefficient; r_i is the resistance index value of the ith factor; w_i is the weight of the ith factor; and n is the total number of factors.

3. Results

3.1. *Initial and core ecological sources*

The initial ecological sources were obtained by superimposing the important areas of five ESs, totaling 5,193,000 km^2 (4,523,000 km^2 of ecological land and 670,000 km^2 of non-ecological land), accounting for 30.0% of the study region (Fig. 3A). The initial ecological sources showed spatial distribution characteristics of more in the southeast and fewer in the northwest and more along the coast and fewer inland. This result is mainly due to the strong environmental dependence of ESs; that is, the southeastern and coastal areas have more abundant precipitation, better light and heat conditions, and lush vegetation growth, forming rich and diverse ecosystem types that play a critical role in regulating climate, maintaining habitat, conserving soil and water, intercepting rainfall, and mitigating surface runoff. In addition, these areas are dominated by mountains, hills, and plateaus. The complex topography reduces the degree of exposure to human interference, and the higher surface roughness is crucial for wind speed abatement and sand control. Notably, the initial ecological sources had significant spatial heterogeneity, with East Asia accounting for 51.8%, followed by Southeast Asia and South Asia (23.6% and 18%, respectively), while Central Asia and West Asia accounted for only 6.7% (Fig. 3A).

We then extracted the ecological land in the initial ecological sources and further identified core ecological sources by adopting MSPA, whose total area was 2,758,000 km^2 (61% of the total areas of initial ecological sources) (Fig. 3B). Among them, East Asia accounted for 43.6%, followed by Southeast Asia and South Asia (34.4% and 18%, respectively), while Central Asia and West Asia accounted for only 4.0%. Furthermore, among the initial ecological sources, we identified 744,000 km^2 of edge (16.4%) and 1,021,000 km^2 of other areas (22.6%), including islet, loop, perforation, bridge, and branch.

Table 1
Grading values and weights of resistance factors for the construction of an ecological resistance surface.

Index system		Score assignment				
Rule layer (weights)	Scheme layer	1	2	3	4	5
Topographic conditions (0.17)	Dem (m)	<2500	2500–3500	3500–4500	4500–5500	≥5500
	Slope (°)	<10	10–30	30–50	50–70	≥70
Human interference (0.5)	Nightlight	<3	3–11	10–25	25–45	≥45
	Distance from road (m)	≥2000	1500–2000	1000–1500	500–1000	<500
	Distance from railway (m)	≥2000	1500–2000	1000–1500	500–1000	<500
	Distance from Urban (m)	≥5000	3000–5000	2000–3000	1000–2000	<1000
	Distance from Rural (m)	≥2000	1500–2000	1000–1500	500–1000	<500
	Distance from Cultivated land (m)	≥1000	600–1000	400–600	200–400	<200
Ecological conditions (0.33)	Land use type	Forest and Water body	Shrublands	Grasslands	Croplands and bare	Artificial area
	Vegetation cover	≥0.8	0.6–0.8	0.4–0.6	0.2–0.4	<0.2

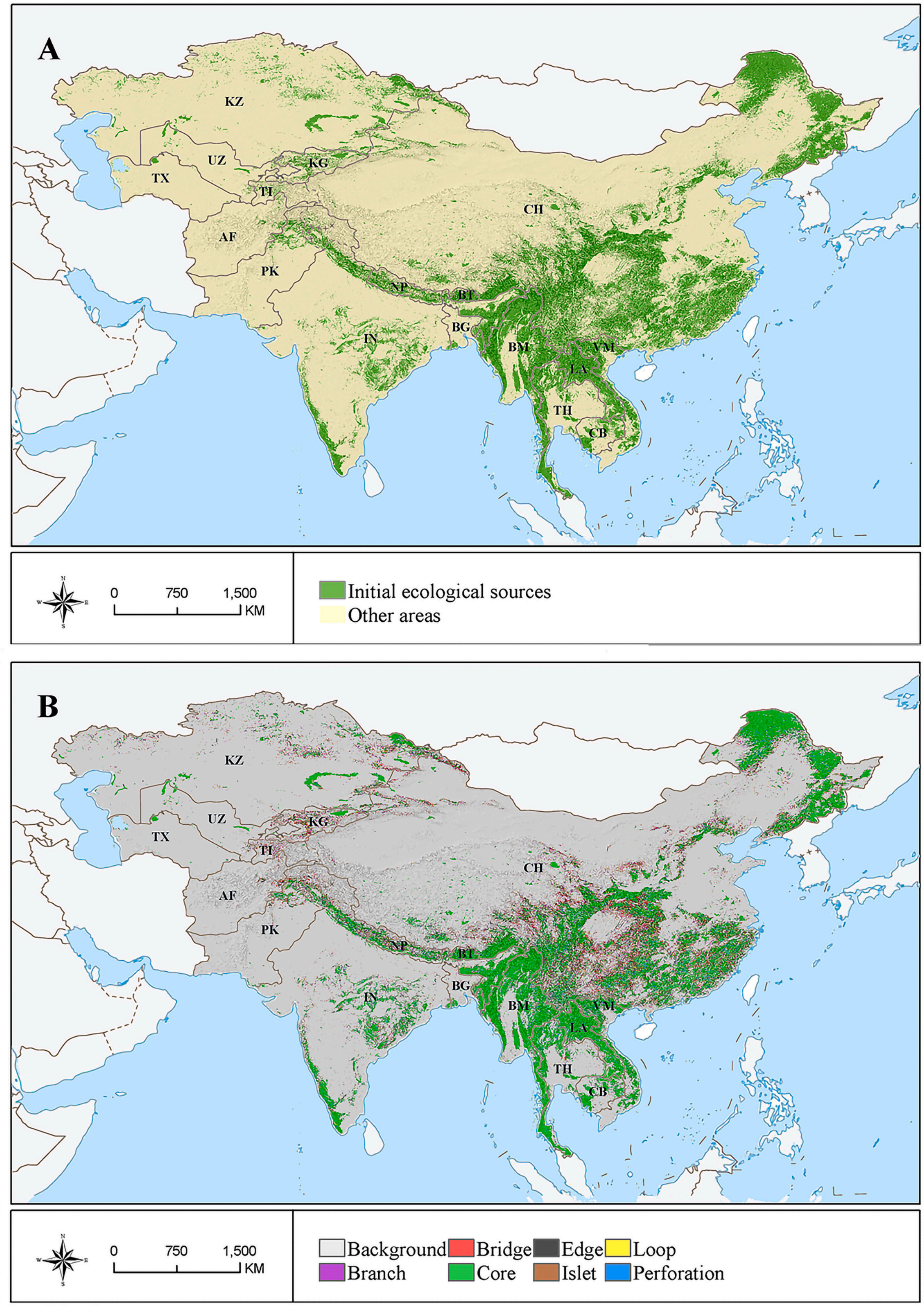

Fig. 3. Identification of ecological sources. A. Initial ecological sources; B. Core ecological sources and other areas in initial ecological sources. Note: The abbreviations are the same as those shown in Fig. 1.

After mapping the correspondences among the core ecological sources and land use, the results showed that the habitat quality of the core ecological sources was good. Among the five land-use types, forests were the most dominant ecosystem type (84.69%), followed by grasslands (approximately 9.41%), water (4.94%), wetlands (0.93%), and glaciers and permanent snow (0.04%).

3.2. *Three levels of ecological sources*

We extracted 419 third-level ecological sources (Fig. 4A). Among them, there were 210 in East Asia, 47 in South Asia, 17 in Central Asia, 144 in Southeast Asia, and 1 in West Asia. We extracted the central elements of the third-level ecological sources within each fishnet unit by using 500 km × 500 km as the evaluation unit to identify second-level ecological sources, of which there were 78 in total (Fig. 4B). Among them, 32 were in East Asia, 17 were in South Asia, 18 were in Southeast Asia, 10 were in Central Asia, and 1 was in West Asia.

We used a 20 km × 20 km fishnet as the evaluation unit, measured the area of core ecological sources within each fishnet (Fig. 4B), and then used hotspot analysis to identify 10,063 hotspots in core ecological sources (Fig. 4C). We further performed kernel density estimation on these hotspots to identify the first-level ecological sources, totaling 37 (Fig. 4D). They were the most significant spaces that maintained the ESs in the study region. Among them, 16 were in East Asia, 9 were in South Asia, 7 were in Southeast Asia, 5 were in Central Asia, and 0 was in West Asia (Fig. 4D).

3.3. *Ecological corridors*

We assessed the resistance coefficients of animals' movement between different ecological sources (Fig. 5A-5J). After superimposing them in a weighted manner, the integrated resistance coefficients were obtained (0–4.7) (Fig. 5K). In terms of spatial distribution, the areas with low integrated resistance coefficients were mainly located in Southeast Asia, the eastern Qinghai-Tibet Plateau, and northeastern China. Most of them were mountainous. Although the complex topography had a great impact on ecological processes (e.g., affecting species migration and increasing the difficulty of soil conservation), they still had low resistance to ecosystem animals' movement due to the good natural conditions and less human interference.

In addition, the areas with high integrated resistance coefficients were mainly located in central and eastern China, peninsular India, and peninsular South Asia. These areas were mainly plain areas, which were the gathering areas for town development, transportation construction, and agricultural production; that is, the fragmentation degree of ecological sources by human activities was greater, indicating the weaker connection between sources and the harder construction of ecological flow paths of animals' movement.

We further identified potential ecological corridors for three levels of ecological sources with corresponding levels. The first-level ecological corridors (Fig. 6A), 42 in total, had a total length of 32,828.8 km. Among them, the length of the first-level ecological corridors in East Asia was 13,498.3 km (41.12% of the total length), followed by that in South Asia and Southeast Asia (25.26% and 22.2%, respectively), while Central

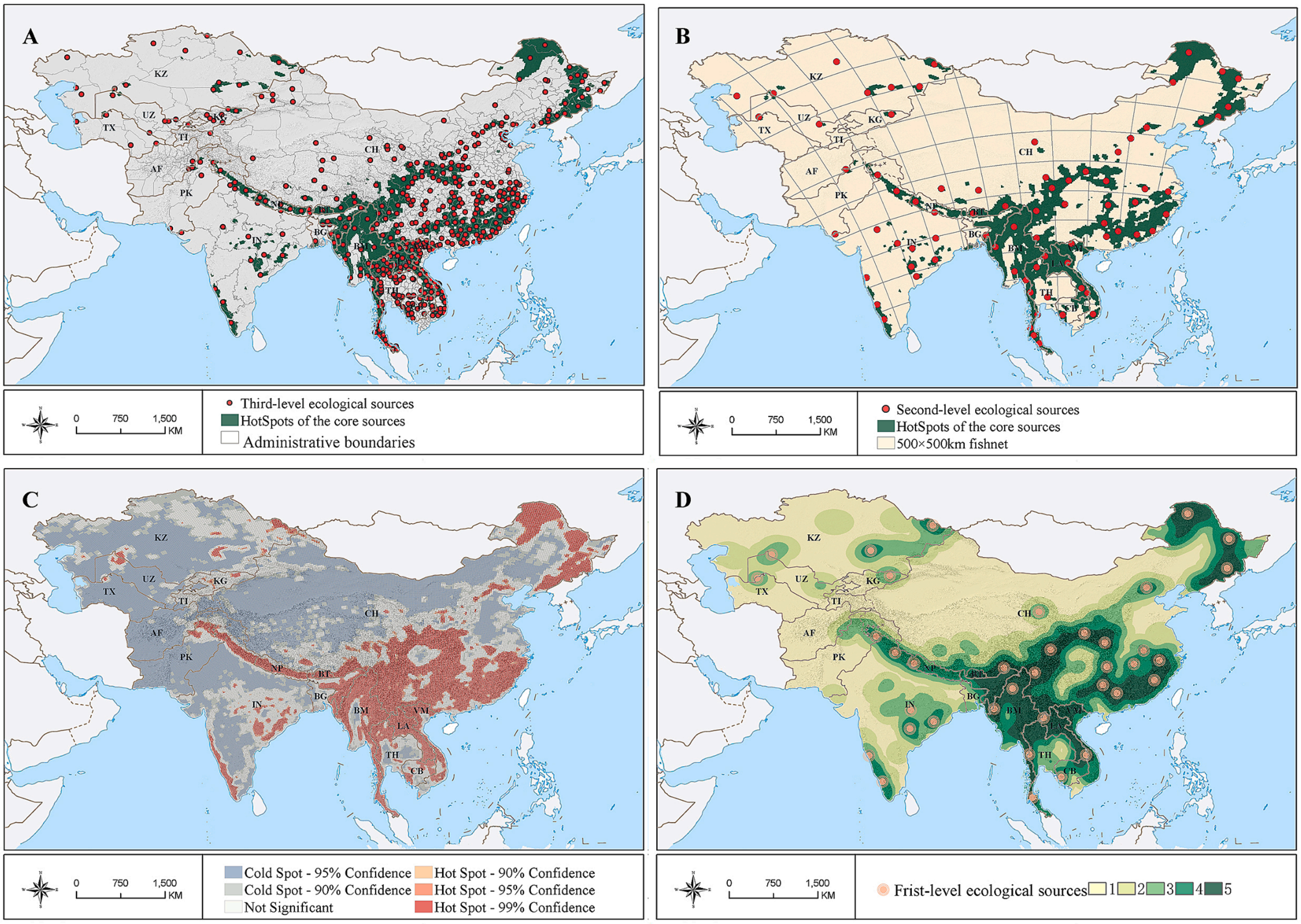

Fig. 4. Different levels of ecological sources. A. Third-level ecological sources; B. Second-level ecological sources; C. Hotspots of ecosystem services; D. First-level ecological sources. Note: The abbreviations are the same as those shown in Fig. 1.

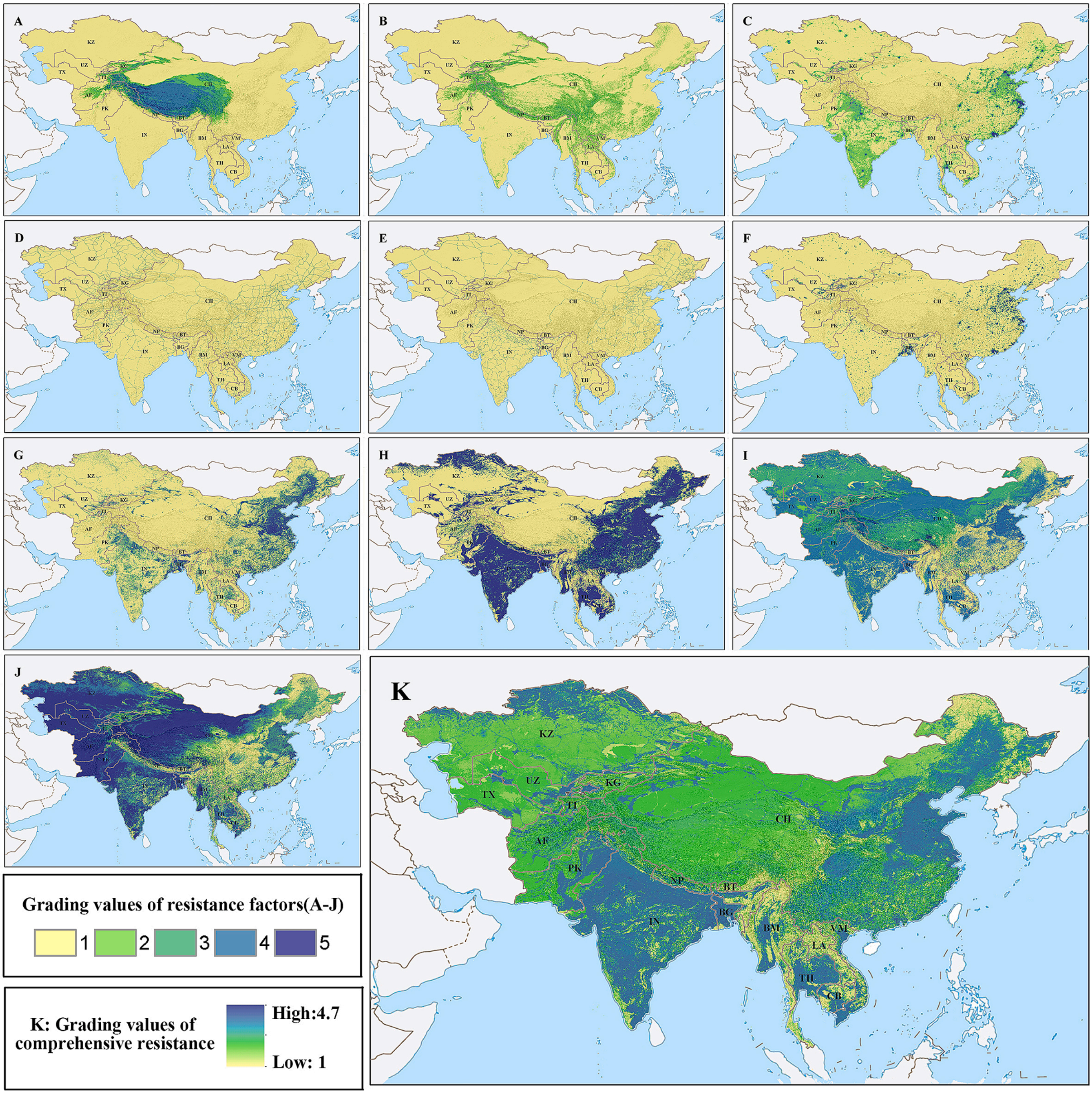

Fig. 5. Ecological resistance coefficient. A. elevation factor; B. slope factor; C. nighttime lighting factor; D. road factor; E. railway factor; F. town factor; G. rural settlement factor; H. farmland factor; I. ecosystem type factor; J. vegetation cover factor; K. integrated resistance factor. Note: The abbreviations are the same as those shown in Fig. 1.

Asia and West Asia had the shortest corridors (11.4% and 0.04%, respectively). The second-level ecological corridors (Fig. 6B), totaling 129, had a total length of 53,834.3 km. Among them, the length of the second-level ecological corridors in East Asia was 20,842.9 km (38.7% of the total length), followed by that in South Asia (28.4%), Southeast and Central Asia (16.8% and 15.4%), and the lowest was in West Asia (0.7%). The third-level ecological corridors (Fig. 6C), 485 in total, had a total length of 81,654.2 km, which was approximately 1.5 times more than that of the second-level corridors. Among them, East Asia had35,805.3 km (nearly half of the total length), followed by South Asia (22%), Southeast Asia (18.5%), and Central Asia (14.4%), while West Asia continued to account for the shortest length (only 1.2%).

4. Discussion

4.1. Making multi-scale ecological security pattern work

With the worsening of the global ecological crisis (e.g., sharp decline in biodiversity and ESs), ecological security plays a vital role in sustainable development and has become a worldwide topic of concern in the 21st century (Liu et al., 2022a). By identifying important areas of ES provision, constructing multi-scale ESPs, our study aimed to contribute to the implementation of the Kunming Montreal Global Biodiversity Framework. First, effective conservation and management of at least 30% of the world’s lands by 2030 is one of the main conservation goals

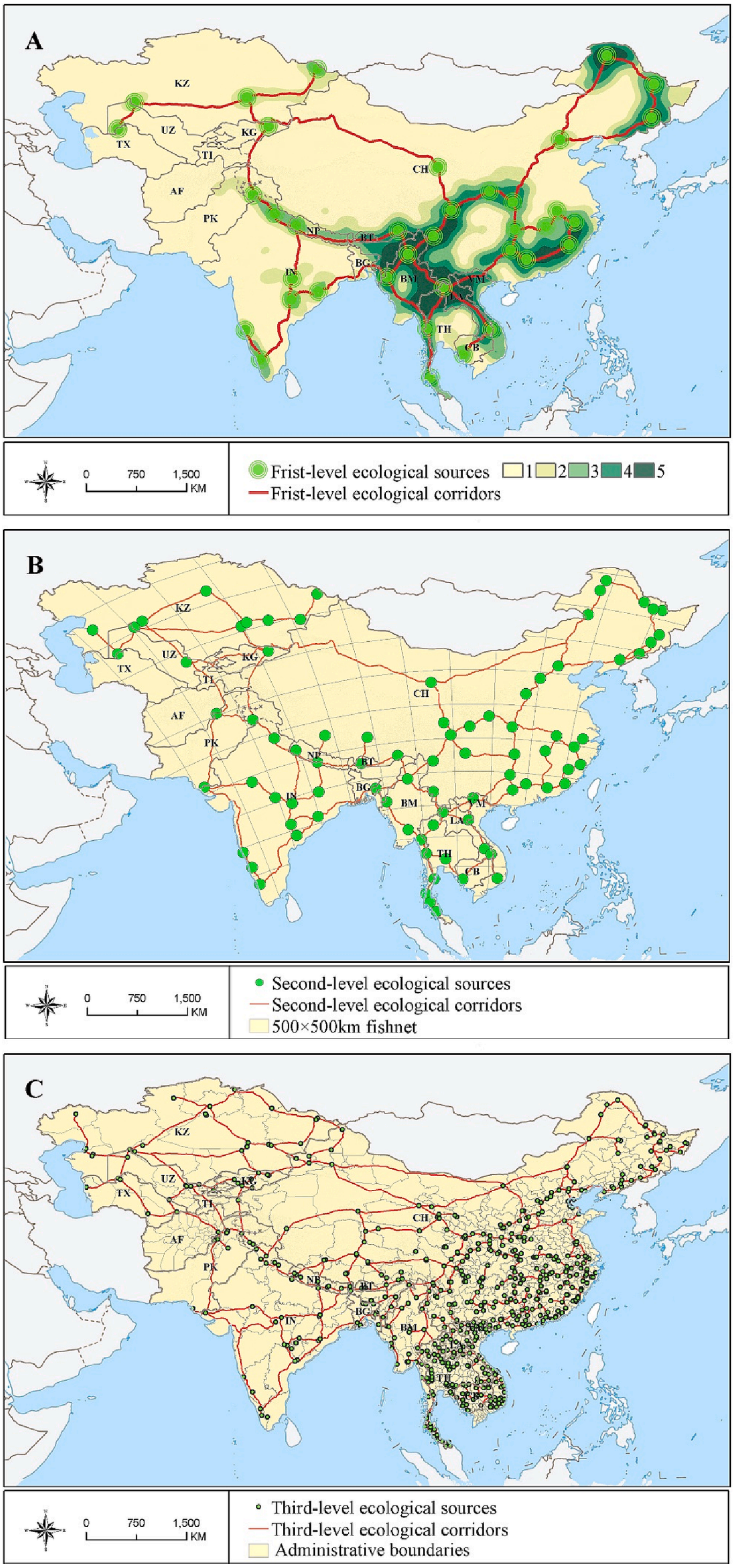

Fig. 6. Different levels of ecological corridors. A. First-level ecological corridors; B. Second-level ecological corridors; C. Third-level ecological corridors. Note: The abbreviations are the same as those shown in Fig. 1.

proposed by the Kunming-Montreal Global Biodiversity Framework (Hansen et al, 2021). To achieve it, the ecological sources (2,758,000 km^2) identified in this study can be prioritized, given that they are important carrying spaces for various ESs. Second, ecosystem fragmentation is one of the main reasons for the sharp decrease in ESs (e.g., biodiversity), and simply increasing the conservation area may not be effective in addressing ecosystem fragmentation and insulation at the regional scale (Gao et al., 2022). We should strengthen the construction of ecological corridors to promote connectivity, and avoid that the layout of industries, transportation, and agriculture hinders the connectivity of these main ecological corridors. Third, ecological conservation actions are generally carried out at different scales, such as regions, countries, and basins. The aim of this study is to promote the synergies among these actions by constructing a "tree like" ecological network. The first-level ecological corridors are equivalent to a tree trunk (i.e., supporting the regional conservation goals and actions); the second-level ecological corridors are the main branches (i.e., supporting the national conservation goals and actions); and the third-level ecological corridors are the side branches (i.e., supporting the conservation goals and actions of the basins). The three levels of ecological sources and corridors we identified can be used as conservation priorities at different scales, and these areas can promote the animals' movement between ecological sources and enhance the structural integrity, functional stability, and spatial connectivity of ecosystems (Roberts et al., 2020; Zhang et al., 2022).

4.2. Key conservation obstacles

The ESs of the study region have faced unprecedented pressures, and several key conservation obstacles must be considered and addressed. Among the initial ecological sources (5,193,000 km^2) identified according to the importance of the five ESs, non-ecological land uses (e.g., arable land and construction land) accounted for 12.9%. These land uses pose a great risk to the degradation of ESs, such as habitat quality degradation, soil erosion, and vegetation degradation (Wang and Pan, 2019). Although construction land poses a greater risk to ecological sources than other human activities, it is generally relatively concentrated in areas with flatter terrain, and these areas have less overlap with ecological sources (mostly distributed in mountainous areas with high vegetation cover and complex topography, without the transportation conditions and land resources for urban development). Rural settlements and arable land tend to be scattered in various areas, interspersed with ES areas, resulting in a wider range of disturbance to ecosystems (Zhang et al., 2022). Notably, low-slope hills tend to become the space for arable land expansion and are usually ecologically fragile; thus, they easily cause the deterioration of ecological problems and the degradation of ecological functions (Peng et al., 2018).

Fragmentation has transformed more than 50% of the planet's landscapes through the impacts of agriculture, urbanization, grazing, industrial activity, and linear barriers, such as roads, railways, pipelines, fences, and canals. In the initial ecological sources we identified, many edge, islet, loop, perforation, bridge, and branch were included, totaling 1,765,000 km^2 (Fig. 3B). The ecologically important areas in the study region face serious edge effects, distance effects, and islet effects. For example, East Asia (China) has experienced severe ecological fragmentation, and its share of core ecological sources decreased by 8.2% compared to the share of initial ecological sources. Notably, the abovementioned increase in human activities, the impacts of COVID-19 (e.g., the lengthy lockdowns and the transfer of financial resources for ecological conservation), and global conflicts (e.g., the war in Ukraine in 2022) will further exacerbate these negative effects (Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services, 2019; Ranjbari et al., 2021). We are approaching a tipping point where, without immediate and substantial actions, ecosystem degradation and biodiversity loss will become increasingly severe, further affecting regional livelihoods, quality of life, and public health (Dinerstein et al., 2019).

4.3. Possible conservation priority actions

Several conservation priority actions can be considered based on our results. First, ecological sources and ecological corridors can be integrated into long-term ecological conservation planning. The ecological sources in the study region had severe fragmentation and edge effects. The future rate, scale, and spatial distribution of decline in biodiversity and ESs depend on specific development pathways chosen by humans (Li et al., 2022). There is an urgent need for the region to prioritize the conservation of ecological land (4,523,000 km^2) in ecological sources to avoid the further expansion of ecological risks; meanwhile, areas in ecological sources that are severely degraded and difficult to restore with the self-healing capacity of ecosystems should be restored in a planned and step-by-step manner through artificial restoration or reconstruction works.

Enhancing the conservation of integrated forest ecosystems is essential to maintain ecosystem stability and enhance ESs in the study region. Among the core ecological sources, forests were the most dominant ecosystem type (up to 83.9%), covering 9 and 14 times more areas than grassland and water ecosystems, respectively. Intact forests, especially tropical forests, sequester twice as much carbon as planted monocultures (Dinerstein et al., 2019), and it can enhance biodiversity by 15–84% and vegetation structure by 36–77% compared with degraded ecosystems (Crouzeilles et al., 2016). Therefore, forest restoration is considered a key strategy for global biodiversity conservation, soil conservation and climate change mitigation (Erbaugh et al., 2020). However, for protecting and restoring forests, only forest extent is typically considered, and forest quality is ignored (Hansen et al., 2020). While a range of actions (e.g., from restoring natural forests to planting monocultures) have led to forest expansion, the impact of these actions on biodiversity and contribution to people varies considerably. Increasing tree species richness can enhance the supply of multiple ESs. For example, biomass production was approximately 50% greater with five than with one tree species (Gamfeldt et al., 2013).

The southeastern part of the study region was the most important area providing the five ESs; more than 40% of its core ecological sources and corridors were located in China (especially in the mountainous region of southern China), and the countries in Southeast Asia had the most densely distributed ecological sources and corridors per national unit of land area. Therefore, to maintain the ecological security of the entire study region and avoid the risk of ecological degradation due to the conversion of native ecosystems (e.g., forests or grasslands) into agricultural systems or other artificial ecosystems (Chuai et al., 2013), these areas may need to assume a larger scale of conservation objectives, such as protecting 30–50% of the land (Dinerstein et al., 2019; Zhu et al., 2021). However, it may impose many constraints on the industry, economy, and livelihood development of these countries. The economies of these areas are often less developed to provide costly resources (e.g., funding) related to ecosystem conservation. Therefore, there is an urgent need for greater collaboration across scales to develop strategies and actions for effective resource mobilization, as well as synergistic land use and conservation goals and plans (Li et al., 2022).

4.4. Comparison with other studies

The ESP (i.e., constructing the ecological networks) has been widely applied in improving ecosystem connectivity (Peng et al., 2018). However, most related studies were conducted at national and local scales, or used watersheds and urban clusters as the study area (e.g., Liang et al., 2018; Tian et al., 2022). Constructing large-scale (regional and global) ESP are extremely rare (e.g., Wang and Liu, 2020; Fnukalova et al., 2021), representing a major research gap. Therefore, it Is difficult to find similar regional scale ESP to compare with ours. However, judging from the current research, ecological source identification and corridor extraction are key steps in ESP construction, and the most common models adopted are the MCR model and circuit theory (Liu et al., 2022a). As for their results, taking Liang et al. (2018) as an example, the ESPs we and they constructed for China are mostly similar, but with slight differences, such as the ecological corridor of Taihang mountain-Yanshan mountain that linked Qinling Mountains and northeastern China, which we identified mainly due to the consideration of synergies among multiple ESs.

Moreover, for transboundary ecosystem (e.g., the AWT region), one of the biggest challenges is how to form an effective management system to preserve the biodiversity and ecological sustainability that are divided in different countries and different scales (Wang and Liu, 2020). Therefore, constructing a multi-scale (multi-level) ESP is critical for synergizing conservation at the regional and global scale. However, there is no uniform standard for the numbers of levels, which can be multiple. Overall, identifying major ecological conservation frameworks is the primary goal, and too many levels may blur major ESP. The AWT region contains multiple river basins, which are ecological units that characterize the integrity of biological communities and inorganic environments at certain spatial scales. Thus, we only constructed a three-level ESP to synergize the conservation actions at the regional, national and river basin scales.

4.5. Limitations and uncertainties

Despite these strengths, some limitations, uncertainties, and unaddressed issues in this study are noteworthy. The identification of ecological sources is a key step in constructing the ESP. However, ecological sources vary depending on the choices of ESs and their assessment methods (Dong et al., 2021). In general, comparing to other types of ecosystems, forest ecosystems can always achieve a higher value of water conservation, sand fixation, and carbon sequestration. Thus, the distribution of ecological sources (Fig. 3) in this study mainly located in forest ecosystems, and some key ecological functional areas (e.g., special species habitats, the sources of some important rivers, and some grassland ecosystems) were omitted. Comprehensiveness and representativeness have always been the goals of ecological source identification. It is necessary to include key ecological functional areas in ecological sources. However, similar to many existed studies, data availability can impose major challenges and uncertainties for the importance assessment of ESs at large scale (Li et al., 2020; Hochkirch et al., 2021). This study did not collect data on each country's key ecological functional areas, and there may be some shortcomings in determining the ecological sources. Also, more ESs can be introduced for the assessment in the future.

The representative points for the ecological source polygons with large area should be carefully selected for different research aims when extracting the ecological corridors. For large-scale research, identifying the framework for ecological conservation is the primary goal. Using the geometric center of the ecological sources as the representative point to extract ecological corridors is beneficial for identifying the framework and structure of ESP (e.g., Li et al., 2020; Dong et al., 2021). In addition, for large ecological source polygons, there are also more suitable or easily accessible potential corridors within them, and using the geometric center to extract ecological corridors is also beneficial for identifying those potential corridors. However, for medium- and small-scale research, using the boundary point of the ecological sources as the representative point to extract ecological corridors may be more appropriate, which can identify the least-cost paths (e.g., Peng et al., 2018; Zhou et al., 2023). In reality, species lack knowledge about the landscapes they pass through and do not necessarily choose the optimal path (Zhou et al.,2023). In an ideal situation, multiple ecological corridors identified by the above two methods should be considered. Regardless of the extraction methods, only a preliminary plan for ecological corridors can be provided. More factors (e.g., surrounding land-uses, financial investment, transportation or other obstacles, and target species) need to be considered in the specific implementation.

5. Conclusion

Various ambitious global ecological conservation targets have been proposed, and countries should take more specific, proactive, and collaborative actions to achieve them. Identifying a holistic multi-leveled ecological security pattern based on the synergies among multiple ESs can provide effective evidence-based support for identifying and prioritizing such actions across scales (region, nation, and basin), and this approach is critical for large-scale ecological conservation. For the AWT region, by adopting a series of GIS spatial analysis methods, the MCR model, and the AHP, this study 1. measured the importance of five ESs (including water conservation, sand fixation, soil conservation, carbon sequestration and biodiversity conservation); 2. identified initial, core, and three different levels of ecological sources; and 3. constructed three different levels of ecological corridors. Overall, a total of 534 ecological sources were identified, and 656 ecological corridors were constructed. Several key conservation obstacles in the region and corresponding priority actions for policy-makers, research communities, and other stakeholders were provided, which can provide across-scale support for strengthening the continuity of ecological functions and ecological processes, balancing ecological conservation and economic development, and promoting progress toward several global targets, such as those proposed by the Kunming-Montreal Global Biodiversity Framework and SDG 15 (life on land).

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CRediT authorship contribution statement

Guangjin Zhou: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Yizhong Huan:** Conceptualization, Writing – original draft, Supervision. **Lingqing Wang:** Writing – review & editing. **Riqi Zhang:** Writing – original draft. **Tao Liang:** Writing – review & editing, Supervision. **Xiaoxiao Han:** Writing – review & editing. **Zhaohui Feng:** Writing – review & editing.

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

I have shared the data in the Supplementary Information.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.110597.

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