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Establishment of an urban agglomeration ecological security pattern taking ecosystem services and human interference factors into consideration

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The assessment of ecological security patterns is one of the hot issues in landscape ecology in recent years. However, ecosystem services and human activities are seldom taken into comprehensive consideration in the assessment of ecological security patterns. Taking the Beijing−Tianjin-Hebei urban agglomeration as the study area, this study uses ecological services to determine ecological sources, divides the importance of ecological sources based on logical coding and functional types of ecological services, combines regional characteristics, synthetically chooses and quantitatively calculates three human disturbance factors (soil erosion sensitivity, geological hazard sensitivity, and night lighting), and modifies the basic resistance surface of land use that identifies ecological corridor by combining these three disturbance factors. The results indicate that water production services, soil and water conservation, and carbon fixation sources are mainly distributed in mountainous areas, recreation sources are mostly distributed in the plains, and the ecological sources improve the recognition of ecological corridors. The modification of resistance surfaces significantly changes the length of ecological corridors in Tianjin, Tangshan, Cangzhou, and Beijing, and the modified resistance surface improves the recognition of ecological corridors. This study provides a new research framework for identifying the ecological security pattern of urban agglomeration and provides scientific guidance for ecological protection and urban planning of the Beijing−Tianjin−Hebei urban agglomeration.

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Abstract

The assessment of ecological security patterns is one of the hot issues in landscape ecology in recent years. However, ecosystem services and human activities are seldom taken into comprehensive consideration in the assessment of ecological security patterns. Taking the Beijing–Tianjin–Hebei urban agglomeration as the study area, this study uses ecological services to determine ecological sources, divides the importance of ecological sources based on logical coding and functional types of ecological services, combines regional characteristics, synthetically chooses and quantitatively calculates three human disturbance factors (soil erosion sensitivity, geological hazard sensitivity, and night lighting), and modifies the basic resistance surface of land use that identifies ecological corridor by combining these three disturbance factors. The results indicate that water production services, soil and water conservation, and carbon fixation sources are mainly distributed in mountainous areas, recreation sources are mostly distributed in the plains, and the ecological sources improve the recognition of ecological corridors. The modification of resistance surfaces significantly changes the length of ecological corridors in Tianjin, Tangshan, Cangzhou, and Beijing, and the modified resistance surface improves the recognition of ecological corridors. This study provides a new research framework for identifying the ecological security pattern of urban agglomeration and provides scientific guidance for ecological protection and urban planning of the Beijing–Tianjin–Hebei urban agglomeration.

Keywords: Beijing–Tianjin–Hebei urban agglomeration; ecosystem service; ecological security pattern; ecological source; ecological corridor

1 Introduction

While urbanization brings fruitful results to modern civilization, it also brings ~~about~~ a series of ecological and environmental problems, such as the loss of ecological land, the decline of ecosystem services, and the aggravation of environmental health risks, which can affect the sustainable development of cities (Han et al., 2015). Therefore, ensuring the stability and functional safety of urban ecosystems and promoting sustainable urban development have become major issues facing the international community (Cumming & Allen, 2017).

Generally speaking, the goal of an ecological security pattern is to achieve regional ecological sustainability through integrating landscape patterns with ecological processes and comparing the importance of different landscape patches on specific ecological processes and ecosystem services (Peng et al., 2018). Constructing ecological security patterns can restrict the expansion of urbanization, regulate the ecological process reasonably, maintain material circulation and energy cycles, strengthen urban ecological health, and promote sustainable urban development (Li et al., 2011).

Since the 1990s, domestic and overseas scholars have carried out extensive research on the construction of ecological security patterns, including theoretical exploration, index construction, and method realization, achieving a series of important results (Ahern, 1995; Zube, 1995; Albanese et al., 2016; Miao et al., 2015). The scope of ecological security pattern research includes species conservation (Dalang et al., 2012), land management (Gaaff et al., 2012), urban planning (Dong et al., 2015), and habitat protection (Kang et al., 2016). At present, the construction of ecological security patterns has formed one research paradigm including the identification of ecological source, and ecological corridor (Teng et al., 2011; Klar et al., 2012). The first step in ecological security patterns construction is to identify ecological source, the ecological source is the origin of species dispersal, maintenance, and landscape component to promote the development of ecological processes (Chen et al., 2008). Ecological sources are identified by quantitative assessment of regional ecological security patterns (Wu et al., 2013). Ecosystem services refers to the environmental conditions and effects on which human beings depend on for survival and development. It includes not only food, fresh water, and raw materials for industrial and agricultural production provided by ecosystems but more importantly, the support and maintenance of ecosystems (Daily, 1997). Therefore, it is of great significance to identify the area with the highest ecological service as the ecological source for maintaining urban ecological security (Peng et al., 2018). However, most of the current research identified the ecological source areas considering the function of ecological services, they did not consider the impact of different types of ecological services on the importance of the same ecological source. In recent years, most studies have shown that clarifying the impact of ecological service categories on the importance of the ecological source areas is helpful in understanding the corresponding relationship between ecological source areas and ecological service functions. And it is very important for fine management of ecological sources. (Raudsepp-Hearne et al., 2010; Kareiva et al., 2007).

The next step in ecological security patterns construction is to identify ecological corridors. In the extraction of ecological corridors, the minimum cumulative resistance model proposed by Knaapen (1992) and improved by Yu (1999), ~~a Chinese scholar,~~ has been widely used in the extraction of ecological corridors. At present, the construction of resistance surfaces is generally based on the resistance coefficient of ecological factors such as land cover type and slope (Fu et al., 2010). The method does not consider the spatial differences caused by specific ecological problems in different regions. The correction of the resistance surface is also based on nighttime lighting data (Zhang et al., 2017) or imperious index(Peng et al., 2018) to enhance the spatial difference of resistance surface. The method considers such differences, but is generally based on qualitative evaluation of the ecological security pattern for a single problem, and the research scale is generally aimed at a province (Peng et al., 2018), city (Li et al.,2010), or county level (Yu Q et al., 2018). As a relatively complex ecosystem, urban agglomeration involves various aspects of ecological security, each of which includes many influencing factors. It is not comprehensive to study ecological security from a single factor (Chen et al., 2018).

The health and sustainable development of the Beijing–Tianjin–Hebei urban agglomeration is an important foundation to guarantee China's national security. However, with the intensification of urbanization, human activities become more frequent, which leads to a series of ecological problems (Gong et al., 2009; Liu et al., 2017). Among them, soil and water conservation are an important ecological safeguards for economic and social development and should play an important role in the Beijing–Tianjin–Hebei coordinated development (Chen et al., 2017). In addition, due to the fragile ecological base, changeable climatic conditions and intense ~~crustal~~ activity of the Beijing-Tianjin-Hebei urban agglomeration, geological disasters occurred frequently(Meng et al.,2017). Soil erosion sensitivity indices and geological hazard sensitivity indices reflect the degree of ecosystem response to human disturbance and natural environment changes ~~and indicate the degree of difficulty and possibility of regional ecological environment problems~~ (Ou Yang et al., 2000). Night light data are widely used in population density, economic development, and urban heat island effect ~~etc.~~ This type of data is a comprehensive characterization of human activity intensity (Mellander et al., 2015). In areas highly sensitive to soil erosion, geological hazards, and nighttime light, the intensity of human activity is relatively high, which has a certain impact on regional species migration. Therefore, setting Beijing–Tianjin–Hebei urban agglomeration as the study area, this study uses ecosystem services and human disturbance factors to construct ecological security patterns, so as to reduce the impact of human activities on the ecological security pattern of Beijing–Tianjin–Hebei urban agglomeration. To this end, three research objectives are proposed as follows: (1) to determine the ecological source through quantitative evaluation of water production services, soil and water conservation, carbon fixation services, leisure and recreation services. (2) This study will determine the importance of dividing ecological sources by combining logical coding and ecological service function types. Finally, (3) using the soil erosion sensitivity, geological hazard sensitivity, and nighttime light indices, we modify ecological resistance surface based on land use to identify ecological corridors.

2 Methodology

2.1 Study area

Beijing–Tianjin–Hebei urban agglomeration is located in the coastal area of Eastern China, with a total area of 218,000 km^2. The Yanshan Mountains are to the north, the North China Plain to the south, the Taihang Mountains to the west, and the Bohai Sea in the east (Figure 1). The climate is cold and snowy in winter, arid and sandy in spring with high wind speeds, and hot and rainy in summer, which is conducive to rock and soil weathering. According to the survey, by 2015, 7255 sudden geological hazards and hidden dangers were found in the study area, including 3526 collapses, 770 landslides, 2288 debris flows and 671 ground collapses (Meng et al.,2017). The population accounts for 7.8% of the total population of China, it belongs to a densely populated area.

Fig.1 Location of the Beijing–Tianjin–Hebei urban agglomeration

2.2 Data acquisition and preprocessing

Meteorological data is derived from the daily data set of basic meteorological elements of China's national surface meteorological stations (V3.0) (http://data.cma.cn/). Land use data come from geospatial data cloud,which were obtained by visual interpretation with a spatial resolution of 80 m (Multi-Spectral Sensor (MSS)), 30 m (Thematic Mapper (TM)) and 15 m (Enhanced Thematic Mapper (ETM)+/ Operational Land Imager (OLI)) using remote sensing and spatial analysis technology (http://www.gscloud.cn/). Soil texture data comes from the Soil Science Data Center of National Earth System Science Data Sharing Service Platform (http://www.geodata.cn/data/) and the Soil Depth Data from the Science Data Center of Cold and Dry Areas (http://westdc.westgis.ac.cn/). Digital Elevation Model(DEM) data comes from a geospatial data cloud with spatial resolution of 30 m. Normalized difference vegetation index (NDVI)(http://www.geodoi.ac.cn/WebCn/doi.aspx?Id=959)and net primary production (NPP) (http://www.geodoi.ac.cn/WebCn/doi.aspx?Id=215)are derived from the publishing system of global change scientific research data. Nighttime light data are derived from the stable night light data generated by OLS (Operational Linescan System) sensors carried by DMSP(Defense Meteorological Satellite Program) (https://ngdc.noaa.gov/eog/download.html).Geological hazard survey data are based on geological hazard general survey data of 1:100,000 and detailed survey data of 1:50,000 geological hazards, as well as geological hazard survey data such as the karst collapse database(Meng et al., 2017). The red line of Beijing ecological protection comes from the Beijing Municipal Environmental Protection Bureau(http://www.bjepb.gov.cn/bjhrb/xxgk/fgwj/qtwj/tzgg/834706/index.html). Tianjin ecological protection red line comes from China Water Network(http://www.h2o-china.com/news/280469.html). Hebei Province ecological protection red line from ZAKER(http://www.myzaker.com/article/5b39d9ca1bc8e0bf3a00022c).

2.3 Ecological sources

2.3.1 Ecological service function assessment

Assessment of the importance of ecosystem services is a basic method to identify regional ecological sources by analyzing the regional service differentiation and identifying the important areas in typical regional ecosystems. Therefore, this study quantitatively identifies and evaluates the water production service, water and soil conservation, carbon fixation service, and leisure and recreation service of the urban agglomeration in combination with the natural environment characteristics of the Beijing–Tianjin–Hebei urban agglomeration.

Especially, the function of water production is based on the water balance principle. Water production is based on the rainfall in a grid unit minus the actual evapotranspiration. In this study, the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) water yield assessment model is used to evaluate service function in the region. The InVEST model is a tool for comprehensive assessment and balance of ecosystem services developed jointly by Stanford University, the Worldwide Fund for Nature (WWF) and the Nature Conservancy (TNC).

The revised universal soil loss equation (RUSLE) model is used to evaluate the soil and water conservation. The universal soil loss equation (USLE) (Universal soil loss equation) model, namely the general soil loss equation, was originally established by Wischmeier and Smith (1965) based on a large number of plot observation data and simulated rainfall experimental data. In 1992, The United States Department of Agriculture-Agricultural Research Service (USDA-ARS) improved the USLE model. The revised RUSLE model for soil erosion analysis was proposed for the first time. The formula is as follows:

$$A_c = A_p - A_r = R \times K \times L \times S \times (1 - C). \quad (1)$$

Formula (1): A_c is the amount of soil and water conservation, $\mathrm{t}/(\mathrm{h}m^2 \cdot \mathrm{a})$; A_p is the potential amount of soil erosion; A_r is the actual amount of soil erosion; R is the factor of rainfall erosivity, $\mathrm{MJ} \cdot \mathrm{mm}/(\mathrm{h}m^2 \cdot \mathrm{h} \cdot \mathrm{a})$; K is the factor of soil erodibility, $\mathrm{t} \cdot \mathrm{h}m^2 \cdot h/(hm^2 \cdot MJ \cdot \mathrm{mm})$; L and S are the topographic factors; L are the factor of slope length. S is the slope factor. C is vegetation cover management factor.

The service of carbon fixation was evaluated by the Carnegie-Ames-Stanford-Approach (CASA) model. The CASA model considers that net primary production (NPP) is determined by plant photosynthesis and its utilization of light energy. Therefore, the estimation of NPP in the CASA model can be expressed by two factors: photosynthetic active radiation (APAR) and actual light energy utilization (ε). The estimation formulas are as follows (Peng et al., 2016):

$$\mathrm{NPP}(x, t) = \mathrm{APAR}(x, t) \times \varepsilon(x, t). \quad (2)$$

In formula (2), APAR (x,t) denotes the photosynthetically active radiation ($\mathrm{g} \cdot \mathrm{c} \cdot m^{-2} \cdot month^{-1}$) the ($\mathrm{g} \cdot \mathrm{c} \cdot MJ^{-1}$).

The leisure and recreation service mainly considers the wetlands of the Beijing–Tianjin–Hebei urban agglomeration. The buffer zones of 25 minutes (min), 20 min, 15 min, 10 min, and 5 min of pedestrian walking distance are analyzed respectively from the wetland, which are included in different levels of leisure and recreation, aiming at emphasizing the impact of human activities.

2.3.2 Ecological source level

On the basis of quantitatively evaluating the ecosystem services and identifying the ecological source area, logical coding is introduced to identify the ecosystem services of different ecological sources. It is used to represent one or more ecosystem service types contained in the ecological source area. The logical coding in this study consists of the numbers "1" and "0", where "1" indicates that the grid has this ecosystem service and "0" indicates that the grid has no such ecosystem service. In this study, the raster computing function of Arcgis10.2 was combined to obtain the spatial pattern of the logical coding of the ecological service category. The calculation formula of logical coding was as follows.

$$T_{ij} = (G1)_{ij} \times 10^{n-1} + (G2)_{ij} \times 10^{n-2} + \cdots + (Gn)_{ij} \times 10^{n-n} \quad , \qquad (3)$$

in which T is the logical coding value of column j of row i in the raster image of logical analysis results, which indicates one or more ecosystem service category. n is the number of ecosystem service. In this study, there are four ecosystem services. Therefore, n=4, $G1_{ij}$, $G2_{ij}$, $G3_{ij}$and $G4_{ij}$ are the logical coding of the corresponding raster types on the raster images of water-producing service, water and soil conservation, carbon fixation service and leisure and recreation service respectively. For example, if the type logical coding is "1101", it means that the ecological source area has the functions of water production service, water and soil conservation service and leisure service, and does not have the functions of carbon fixation service.

According to the number of "1" in the logical coding, the ecological source area is classified, so as to determine the importance of the ecological source area. If the number of "1" in logical coding is 3 or more, it is determined as a primary ecological source, if the number of "1" in logical coding is 2, it is determined as a secondary ecological source, if the number of "1" in logical coding is 1, it is determined as a tertiary ecological source.

2.4 Resistance surface

Ecological resistance surface refers to the degree of impediment to species migration between landscape units. Although the spatial differences of specific ecological problems in small-scale areas can often be solved by constructing ecological resistance surface based on the single-factor correction of land cover types, as a relatively large urban agglomeration, Beijing–Tianjin–Hebei should not only consider the ecological problems in specific areas, but also as a whole. Geological conditions in Beijing–Tianjin–Hebei urban agglomeration are complex and fragile, landslides, debris flows, and serious soil erosion in the region occur frequently. More and more human activities interfere with nature, especially with the development of urbanization. These factors will have a great impact on species migration and regional ecological security and stability. Therefore, in this study, the sensitivity indices of geological hazards, soil erosion, and night light data are introduced to modify the basic ecological resistance surface based on land use. At the same time, we will vectorize the ecological red line corridors in the Beijing Red Line of Ecological Protection, Tianjin Red Line of Ecological Protection, and Hebei Red Line of Ecological Protection in 2018. The ecological resistance is assigned to 0 and finally superimposed on the basic resistance surface and the revised resistance surface to turn it into a raster. Among them, the sensitivity index of soil erosion adopts the evaluation indexes of precipitation erosivity, soil erodibility, slope length and surface vegetation cover, which are proposed in accordance with the red line technical guidelines for ecological protection(Yang et al., 2016). The sensitivity index of geological hazards use nine indicators to calculate the total distribution weight of the layers, as shown in Table 1. The weight of each index is determined by analytic hierarchy process (Saaty, 1987). Since it is impossible to determine which factors have greater impact on the resistance surface of urban agglomeration, the weight of soil and water loss sensitivity index, night lighting and geological hazard sensitivity index is set to 1:1:1. Finally, the three factors are normalized and replaced by the specific ecological resistance surface correction formula as follows:

$$R_i = \left(\frac{NL_i}{NL_a} + \frac{SE_i}{SE_a} + \frac{GS_i}{GS_a}\right) \times \mathrm{R}. \quad (4)$$

Formula (4): R_i is the ecological resistance coefficient of grid i based on water loss sensitivity index, night lighting and geological hazard sensitivity index, NL_i is the night light of grid i, NL_a is the average night light of land use type a corresponding to grid i; SE_i is the water and soil erosion sensitivity index of grid i; SE_a is the average soil erosion sensitivity index of land use type a corresponding to grid i. GS_i is the sensitivity index of geological hazards of grid i and GS_a is the average geohazard sensitivity index of land use type a corresponding to grid i. R is the basic resistance coefficient of land use type corresponding to grid i.

Table 1 Weight of various factors of geological hazard sensitivity

2.5 Ecological corridors

Constructing ecological corridors can solve the problem of fragmentation of ecological sources and enhance the connectivity among ecological sources. With the rapid development of Beijing–Tianjin–Hebei urban agglomeration, the phenomenon of local landscape islanding and fragmentation has become increasingly serious. In this study, the minimum cumulative resistance (MCR) model was first proposed by Knaapen (1992). The model considers three factors, source, distance, and landscape interface, to calculate the cost of species moving from source to destination, and it extracts the resistance trough between the two adjacent "sources" and the most easily connected low-resistance channel as a corridor between ecological safety sources.The basic formulas are as follows:

$$\mathrm{MCR} = f_{min} \sum_{j=n}^{i=m} D_{ij} \times R_i \ . \quad (5)$$

Formula (5): MCR is the minimum cumulative resistance value; D_{ij} is the spatial distance of species from source J to landscape unit i, R_i is the resistance coefficient of landscape unit i; f is the positive correlation between minimum cumulative resistance and ecological process.

3. Results

3.1 Ecological Sources

3.1.1 Spatial pattern of ecological services

The spatial pattern of single ecosystem services can reflect the impacts of different ecological processes on regional ecological security. The assessment results of ecosystem services are divided into five levels from low to high by natural breakpoint method: generally, slightly, moderately, highly and extremely important, as shown in Figure 2, at the same time, the area and area ratio occupied by important areas of various ecosystem service was calculated. The product is shown in Table2.

Table 2 Area and proportion of different levels of ecosystem services

Fig.2 Spatial patterns of ecological services. (A) Spatial patterns of water production service. (B) Spatial patterns soil and water conservation service. (C) Spatial patternsof carbon fixation service (D) Spatial patterns leisure and recreation service.

As shown in A in Figure 2 and Table 2, the water production service of the Beijing–Tianjin–Hebei urban agglomeration in mountainous and hilly areas is generally higher than that of plain and plateau areas; it is also higher in the western and eastern areas than in the central areas. Most of the extremely important areas are located west of Handan and Xingtai, northwest of Baoding, and a few scattered in the eastern coastal areas of Qinhuangdao, Tangshan and Cangzhou. Most of these areas are located in the windward slopes of the Yanshan and Taihang Mountains with large relief and precipitation, so the overall water production capacity is strong. The area of the highly and moderately important areas is not very different; the proportion of the area is 8.26% and 8.37% respectively, mainly distributed in the central plain area. In general, the area of generally important areas is the largest, accounting for 46.97%, indicating that the urban agglomeration belongs to the area of serious water shortage.

As shown in B in Figure 2 and Table 2, the distribution of soil and water conservation of Beijing–Tianjin–Hebei urban agglomeration is gradually decreasing from Yanshan and Taihang Mountains to the surrounding areas. The generally important area is the largest, with an area of 167863.23 km^2, accounting for 78.31% of the total study area. Except for extremely important areas, the proportion of other grades is not very different. The area of the extremely important, highly important, and moderately important regions is 35058.85 km^2, accounting for only 16.36% of the total area, indicating that the overall soil and water conservation capacity of the region is relatively weak. As an important ecological area of soil and water conservation in the Beijing–Tianjin–Hebei urban agglomeration, these areas are rich in precipitation, or the factors of soil erodibility are small, or the vegetation cover has a good ability to regulate and store precipitation, these areas has a strong ability of water and soil conservation.

As shown in C in Figure 2 and Table 2, the carbon fixation service in Beijing–Tianjin–Hebei urban agglomeration is higher in the north and lower in the South and higher in the West and lower in the east. The spatial differences among the important regions are relatively large. The areas of the extremely important regions and the highly important regions are 20117.15 km^2 and 9691.46 km^2, respectively, with the area ratios of 9.31% and 4.48%, respectively. They are mainly distributed in a small part of Handan, Xingtai, Shijiazhuang, Baoding, and Beijing and most of Chengde. Most of the land use types in these areas are forest, with abundant vegetation coverage, a humid climate, and good hydrothermal conditions, which can better meet plant growth requirements. The area of moderately important areas is 77111.86 km^2 which account for 35.67% of the study area. Most of moderately important areas are surrounded by extremely important and highly important areas. The areas of lightly important areas are 79240.88 km^2 which account for 36.66% of the study area and the generally important areas are 30006.56 km^2 which account for 13.88% of the study area. These areas are basically developed unused areas that are mainly distributed in the central, southern, and eastern parts of the region.

As shown in D in Figure 2 and Table 2, the leisure and recreational service of Beijing–Tianjin–Hebei urban agglomeration presents a multi-point distribution pattern as a whole. It mainly distributes in the Bashang area of Zhangjiakou, the eastern area of Beijing, the southeastern area of Tianjin, and the coastal area. The area of the most important area is 8701.79 km^2, accounting for 4.03% of the whole area.

3.1.2 Spatial patterns of ecological sources level

The extremely important areas of each ecosystem service are selected as ecological source areas. The spatial pattern of the logical coding of the ecological service category is shown in figure 3. The area and proportion of logical coding of each ecosystem source type are also calculated as shown in Table 3.

Fig 3. Space patterns of ecological source. (A) Space patterns of logical coding of ecological service categories.(B) Spatial patterns of ecological sources level

Table 3 Area and proportion of logical coding of ecological service categories

As shown in A in Figure 3 and Table 3, there are eight types of ecological source in the Beijing–Tianjin–Hebei urban agglomeration. The area of ecological source is 82605.78 km^2, accounting for 38.21% of the total area. Among them, plain area is the source of leisure and recreation services, and the source logical coding containing this function is 0001, accounting for 0.92% of the area of Beijing–Tianjin–Hebei urban agglomeration. Mountainous area is the source of water production service, soil and water conservation and carbon fixation service. Among the four types of ecological sources, carbon fixation sources account for the largest proportion.

As shown in B in Figure 3, most of the mountain areas are first-level and second-level ecological sources. Plains are a third-level ecological source. The ecological source areas show the spatial distribution characteristics of dense mountains and sparse plains. The number of ecological source at different levels is counted. The primary, secondary and tertiary ecological sources areas is 15, 38 and

97, respectively. The area of ecological source areas is 27999.21 km^2, 25378.32 km^2 and 15505.07 km^2, respectively. The area of ecological source in mountainous areas is first-level and second-level, and the ecological source in plain areas is third-level. The results indicate that the habitat quality of the Beijing–Tianjin–Hebei urban agglomeration is better than that of the plains area, and the source land of plain area is severely fragmented.

3.2 Spatial pattern of ecological corridors and resistance surfaces

Resistance surface modification is the core part of the construction of ecological security pattern. The Beijing–Tianjin–Hebei urban agglomeration has frequent geological disasters, serious soil erosion, and frequent human activities. Therefore, this study uses soil erosion sensitivity, geological hazard sensitivity and night lighting to modify the resistance surface directly based on land use. This study separately calculates the average soil erosion sensitivity index, average nighttime light, average geological disaster sensitivity index and average resistance value of each city in the Beijing-Tianjin-Hebei urban agglomeration as shown in Table 4. At the same time, the average soil erosion sensitivity index, the average nighttime light index and the average geological hazard sensitivity index of various land use types were calculated, as shown in table 5.

Table4 The average soil erosion sensitivity, average nighttime light, average geological disaster sensitivity and average resistance value of each city in the Beijing–Tianjin–Hebei urban agglomeration

Table5 The average soil erosion sensitivity index, average nighttime light index, average geological disaster sensitivity index of various land use

The sensitivity index of soil erosion is shown in A in Figure 4. ~~The sensitivity index of soil erosion~~ is mainly distributed in the Taihang Mountains, the intermountain basins in the northwest portion of the Hebei Province, and the Yanshan Mountains in north China. The average sensitivity index of soil erosion of each land use type is counted independently. As shown in Table4, the average soil and water loss sensitivity index values of Chengde, Beijing, Qinhuangdao, and Zhangjiakou are relatively large, The average soil and water loss sensitivity index values for Tianjin, Hengshui, and Cangzhou are relatively small.As shown in Table5, The sensitivity index of soil erosion of forest land and grassland are relatively large.

As shown in B in Figure 4, the highest values of the night light index is mainly distributed in the economically developed cities. As shown in Table4, the average night light index values of Tianjin, Langfang, Beijing, and Tangshan are relatively large. The average night light of Chengde and Zhangjiakou are relatively small. As shown in Table5, The average night light of construction land is the largest.

The sensitivity index of geological hazards is shown in C in Figure 4. At the regional scale, the distribution of the sensitivity index of geological hazards is highly correlated with the macro-geomorphological gradient and the micro-topographic characteristics.The geological structure has a pattern of NE–SW and NW–SE directions. As shown in Table4, the average geological hazard sensitivity index of Beijing and Chengde are relatively large, while the average geological hazard sensitivity index of Hengshui and Cangzhou are relatively small. As shown in Table5, the high values of geological hazard sensitivity are mainly distributed in forest.

Based on the resistance value of land use in Beijing–Tianjin–Hebei area determined by land use type, methods as described by Xie et al. (2015), the resistance value of land use in Beijing–Tianjin–Hebei urban agglomeration and its corresponding landscape resistance value are determined according to the land use type, and the basic resistance surface is shown in D in Figure 4. Based on the basic resistance surface, night lighting, soil erosion sensitivity index, and geological hazard sensitivity index, the revised resistance surface is shown in E in Figure 4. The revised resistance surface has significant changes within the same category, and has more distinct spatial heterogeneity, which can more accurately characterize the resistance differentiation of biological migration in the Beijing–Tianjin–Hebei urban agglomeration. As shown in Table4, the average resistance values of Langfang, Tianjin and Tangshan are relatively large, while those of Chengde and Zhangjiakou are relatively small.

Ecological corridors are important channels for species exchange between ecological sources. Using the Linkage Mapper plug-in, the ecological source and the modified resistance surface were put into Arcgis 10.2 to obtain the distribution map of ecological corridors, as shown in F in Figure4. At the same time, the length and variation of ecological corridors in each ecological city before and after the resistance surface modification are calculated (Table 6).

Table 6 Changes of ecological corridor length before and after resistance surface correction in Beijing–Tianjin–Hebei urban agglomeration

As can be seen from Table 6, the length of ecological corridors in some cities of Beijing–Tianjin–Hebei has changed significantly. The length of ecological corridors in Tianjin, Tangshan, Cangzhou, and Beijing changed relatively greatly. Among them, Tianjin is greatly affected by night lighting and soil erosion, Tangshan and Beijing are greatly affected by geological hazards and night lighting, and Cangzhou is sensitive to geological hazards and soil erosion. As shown in F in Figure 4, there are 313 ecological corridors in the Beijing–Tianjin–Hebei urban agglomeration, and the total length of ecological corridors is 9399.59 km. In the Yanshan and Taihang Mountains, the density of ecological corridors is relatively high, mainly because of the good quality of the habitats and the strongest correlation between ecological corridors in the region, and the possibility of biological species to overcome resistance to migrate is greater. In the plains area of central and southern Hebei, the distribution of ecological corridors is very sparse. The main reason is that the land use types in this area are mainly farmland and construction land, the habitat quality is relatively poor, and the possibility of biological species to overcome resistance to migrate is relatively small.

3.3 Planning of ecological security pattern

In this study, the area of ecological source determined by ecological services was 68882.81 km^2;

63.16% of the ecological source was within the red line of ecological protection. The area of overlap of primary, secondary and tertiary ecological sources land red line ecological protection was 18580.57 km^2, 14066.25 km^2, and 6723 km^2, respectively. The area where the identified ecological source area overlapped with the existing ecological protection red line gradually decreased with the reduction of the level of ecological source area, indicating the rationality of the identification of ecological source area. As shown in F in Figure 4, it can be seen that the corridors between the plains are longer, the ecological source base is basically the third-level ecological source, and the area of ecological source is less. Therefore, it is suggested to add radiation sources on the basis of the original ecological source. The primary ecological source area is arcuate along yanshan and taihang mountains. Attention should be paid to the protection of habitats here due to the large area and short ecological corridor. The secondary ecological sources are mainly distributed in the northern mountains of hebei province, and the regional habitat restoration should be paid attention to, so as to form the ecological security pattern of the Beijing-Tianjin-Hebei urban agglomeration with reasonable spatial distribution and enhanced ecological service function.

Fig.4 Spatial patterns of resistance surface and ecological corridors (A) Spatial patternsof soil and water loss sensitivity. (B) Spatial patterns of night lighting. (C) Spatial patterns of geological hazard sensitivity index. (D) Spatial patterns of basic resistance surface. (E) Spatial patterns of the corrected resistance surface. (F) Spatial patterns ecological source level and ecological corridors

4. Discussion

4.1 Selection of human interference factors

In recent years, resistance surface modification considering specific ecological problems for specific regions has become a research hotspot in the optimization of ecological security pattern. For example, Zhang et al. (2017) used night light data to modify the ecological resistance surface in Beijing-Tianjin-Hebei urban agglomeration. Peng et al. (2018) used imperious index to modify the ecological resistance surface in Shenzhen, China. The surface wetting index was used to modify the ecological resistance surface for pastoral farming in semi-arid regions (Peng et al., 2018). Above many scholars solved the influence of spatial differences caused by specific ecological problems in different regions on species migration and these factors are collectively referred to as human interference factors, which are used to express the degree of destruction of human activities cause to natural environment. For small regions, the effects of a single factor on species migration can be considered for specific ecological environment problems. However, as a relatively large ecosystem, the Beijing–Tianjin–Hebei urban agglomeration takes into account the protection of biodiversity, the restoration of degraded ecosystems, and the sustainable development of the social economy. The purpose is to systematically solve regional ecological environment problems. The singular problems of environmental pollution or biological resources protection have been extended to the systematic analysis and comprehensive study of regional ecological environment problems (Franklin, 1993). The results show that the areas of high geological hazard and soil erosion sensitivity are concentrated in the mountainous area of urban agglomeration, and the areas of high night light are concentrated in the plains area of the urban agglomeration. The effect of human disturbance factors on species migration in the whole region of Beijing–Tianjin–Hebei urban agglomeration is well explained. It shows that the human interference factors selected in this study are reasonable.

4.2 Contrast with the existing ecological security pattern

The red line of ecological protection refers to the strict control boundary demarcated by law in key ecological functional areas, ecological sensitive areas and vulnerable areas, and it is the bottom line of national and regional ecological security. By geometric correction of the spatial pattern of the red line of ecological protection, the distribution of the red line of ecological protection in the Beijing–Tianjin–Hebei urban agglomeration was obtained by artificial vectorization, as shown in A in Figure 5, the area of ecological protection red line of Beijing–Tianjin–Hebei urban agglomeration is 62329.78 km^2, and the total length of ecological red line corridor is 2670.57 km. Because the ecological red line corridor is relatively small, this study defines the expressway, river and ecological red line corridor as the current corridor. The vector ranges of forest land, grassland and wetland in the ecological red line area, nature reserve, water conservation area, large-scale ecological land use and land use data in the Beijing–Tianjin–Hebei planning outline were regionally vectorized and superimposed. The ecological source area of the study area was extracted, and the area of the ecological source was 4689.72 km^2. Combined with the revised resistance surface, an ecological corridor with human interference factors was generated A in Figure 6 and D in Figure 6, and the ecological corridor considering the ecological service separately is generated by combining the basic resistance surface as shown in B in Figure 6 and E in Figure 6, and the ecological corridor considering the ecological service and human interference factors synthetically is generated by combining the modified resistance surface, as shown in C in Figure 6 and F in Figure 6, respectively. The length of the three ecological corridors and their overlap with the ecological red line corridor and the current corridor are shown in Table 7.

Table 7 Comparison of ecological corridor length

As shown in B in Figure 5 and Table 7, the distribution of ecological corridors is consistent as a whole. Due to the differences of human disturbance and ecological services in some areas, in this study, the overlap length of the ecological corridor identified by ecosystem services and human interference factors and the current corridor became significantly longer, indicating that comprehensive consideration of ecological services and human interference factors can improve the identification effect of the ecological corridor in urban agglomerations.

Fig. 5 Ecological security pattern. (A) The present spatial ecological security pattern of the Beijing–Tianjin–Hebei urban agglomeration. (B) Comprehensive ecological security pattern of the Beijing–Tianjin–Hebei urban agglomeration.

Fig. 6 Comparison of ecological security patterns. (A) Ecological security spatial pattern(human disturbance) of Beijing–Tianjin–Hebei urban agglomeration. (B) Ecological security pattern (ecological services) of the Beijing–Tianjin–Hebei urban agglomeration. (C) Ecological security pattern (ecological services, human disturbance) of the Beijing–Tianjin–Hebei urban agglomeration. (D) The ecological corridor (human disturbance) of Beijing–Tianjin–Hebei urban agglomeration coincides with the current corridor. (E) The ecological corridor (ecological services) of Beijing–Tianjin–Hebei urban agglomeration coincides with the current corridor. (F) Ecological corridor (ecological services, human disturbance) of the Beijing–Tianjin–Hebei urban agglomeration coincides with the current corridor.

5. Conclusion

Based on ecosystem services and human disturbance factors, this study constructs the ecological security pattern of Beijing–Tianjin–Hebei urban agglomeration, which provides a new research framework ~~for the construction of the ecological security pattern of urban agglomeration~~. The main contents of this study include the use of ecosystem services to determine the ecological sources, the establishment of the logical relationship between ecological sources and ecosystem services. Afterwards, ecological corridors were identified using minimum cumulative resistance model based on sources and resistance surface modified through human disturbance factors, the results show that water production , soil and water conservation, and carbon fixation sources are mainly distributed in mountainous regions, recreational sources are mostly distributed in the plains, and the extracted ecological sources improve the recognition of ecological corridors. The modification of resistance surface makes the length of ecological corridors in Tianjin, Tangshan, Cangzhou, and Beijing change significantly, and the modified resistance surface improves the recognition of ecological corridors. According to the importance of the divided ecological sources and the identified ecological corridors, this study puts forward some planning suggestions for the existing ecological security pattern to form a reasonable spatial layout and improve the ecological service function of the urban agglomeration ecological security pattern.

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D.W. and J.H. conceived and designed the research; D.W. and L.Z. performed the experiments; C.J. and Z.C. drafted the article; J.C., Z.S., X.Z. X.W., and W.Z. collected and processed the data; J.C., L.Z. and Z.C. made the data analysis; D.W. and J.C. discussed and modified the original manuscript; and D.W. and J.C. polished the language of the paper. All authors revised the article critically and approved the final manuscript.

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Table 1(on next page)

Table 4 The average soil erosion sensitivity, average nighttime light, average geological disaster sensitivity and average resistance value of each city in the Beijing-Tianjin-Hebei urban agglomeration

Table 4 The average soil erosion sensitivity, average nighttime light, average geological disaster sensitivity and average resistance value of each city in the Beijing-Tianjin-Hebei urban agglomeration

	Average soil erosion sensitivity	Average night light	Average geological hazard sensitivity	Average resistance value
Chengde	0.17	0.04	0.18	109.13
Zhangjiakou	0.12	0.05	0.16	200.72
Qinhuangdao	0.12	0.13	0.17	250.93
Baoding	0.1	0.13	0.16	255.8
Shijiazhuang	0.09	0.18	0.15	301.86
Beijing	0.14	0.33	0.18	311.67
Xingtai	0.08	0.15	0.15	331.7
Hengshui	0.05	0.13	0.14	339.74
Cangzhou	0.05	0.18	0.14	346.57
Handan	0.07	0.2	0.15	358.21
Tangshan	0.08	0.25	0.17	370.29
Tianjian	0.06	0.43	0.16	452.22
Langfang	0.05	0.34	0.16	458.8

Table 2 (on next page)

The average soil erosion sensitivity index, average nighttime light index, average geological disaster sensitivity index of various land use

Table 5 The average soil erosion sensitivity index, average nighttime light index, average geological disaster sensitivity index of various land use

	Average soil erosion sensitivity	Average night light	Average geological hazard sensitivity
Forest land	0.17	0.05	0.19
Wetland	0.04	0.26	0.14
Grassland	0.11	0.07	0.17
Farmland	0.07	0.17	0.15
Unused land	0.08	0.18	0.14
Construction land	0.06	0.42	0.15

Table 3 (on next page)

Changes of ecological corridor length before and after resistance surface correction in Beijing-Tianjin−Hebei urban agglomeration

Table 6 Changes of ecological corridor length before and after resistance surface correction in Beijing—Tianjin—Hebei urban agglomeration

Cities	Ecological corridor length (km)	Ecological corridor length (km) (Ecological services , human disturbance)	Variation of length of ecological corridor (km)
Beijing	451.56	340.51	111.05
Qinhuangdao	194.61	200	5.39
Chengde	581.49	657.57	76.08
Zhangjiakou	961.83	996.24	34.41
Baoding	1088.64	1148.05	59.41
Tianjin	887.56	1145.76	258.2
Tangshan	723.53	966.85	243.32
Langfang	272.36	332.85	60.49
Shijiazhuang	1727.98	1752.52	24.54
Cangzhou	371.11	507.12	136.01
Hengshui	260.15	297.73	37.58
Xingtai	818.62	915.7	97.08
Handan	171.66	137.99	33.67

Table 4(on next page)

Comparison of ecological corridor length

Table 7 Comparison of ecological corridor length

	Ecological Corridor (km)	Ecological Red Corridor Overlap (km)	Current Corridor Overlap (km)
Ecological Service	8515.68	1390.06	4680.62
Human Disturbance	10626.34	1545.83	4751.52
Ecological Service and Human Disturbance	9399.59	1538.76	5458.98

Table 5(on next page)

Weight of various factors of geological hazard sensitivity

Table 1 Weight of various factors of geological hazard sensitivity

Factors	Weight
Density of geological hazards	0.1908
Slope	0.156
Euclidean distance of faults	0.1349
Engineering rock group	0.1109
Earthquake acceleration	0.1099
Waviness	0.0912
Normalized difference vegetation index (NDVI)	0.0743
Precipitation	0.0689
Slope position	0.0632

Table 6 (on next page)

Area and proportion of different levels of ecosystem services

Table 2 Area and proportion of different levels of ecosystem services

	Carbon fixation service		Soil and water conservation service		Water production service		Leisure and recreational service	
	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)
Generally important	30006.56	13.88%	167863.23	78.31%	100565.55	46.97%	4869.16	2.25%
Slightly important	79240.88	36.66%	11425.31	5.33%	64397.39	30.08%	5784.58	2.68%
Moderately important	77111.86	35.67%	9489.43	4.43%	17910.11	8.37%	6724.76	3.11%
Highly important	9691.46	4.48%	7389.25	3.45%	17691.88	8.26%	7697.28	3.56%
Extremely important	20117.15	9.31%	18180.17	8.48%	13528.04	6.32%	8701.79	4.03%

Table 7 (on next page)

Area and proportion of logical coding of ecological service categories

Table 3 Area and proportion of logical coding of ecological service categories

Logical coding of ecological sources type	Area of ecological sources type (km^2)	Area ratio (%)
0000	133585.7	61.79
0001	1978.31	0.92
0010	10434	4.83
0100	25477.83	11.78
0110	20520.31	9.49
1000	11372.3	5.26
1010	1354.78	0.63
1100	4702.49	2.18
1110	6763.19	3.13

Figure 1

Location of the Beijing-Tianjin-Hebei urban agglomeration

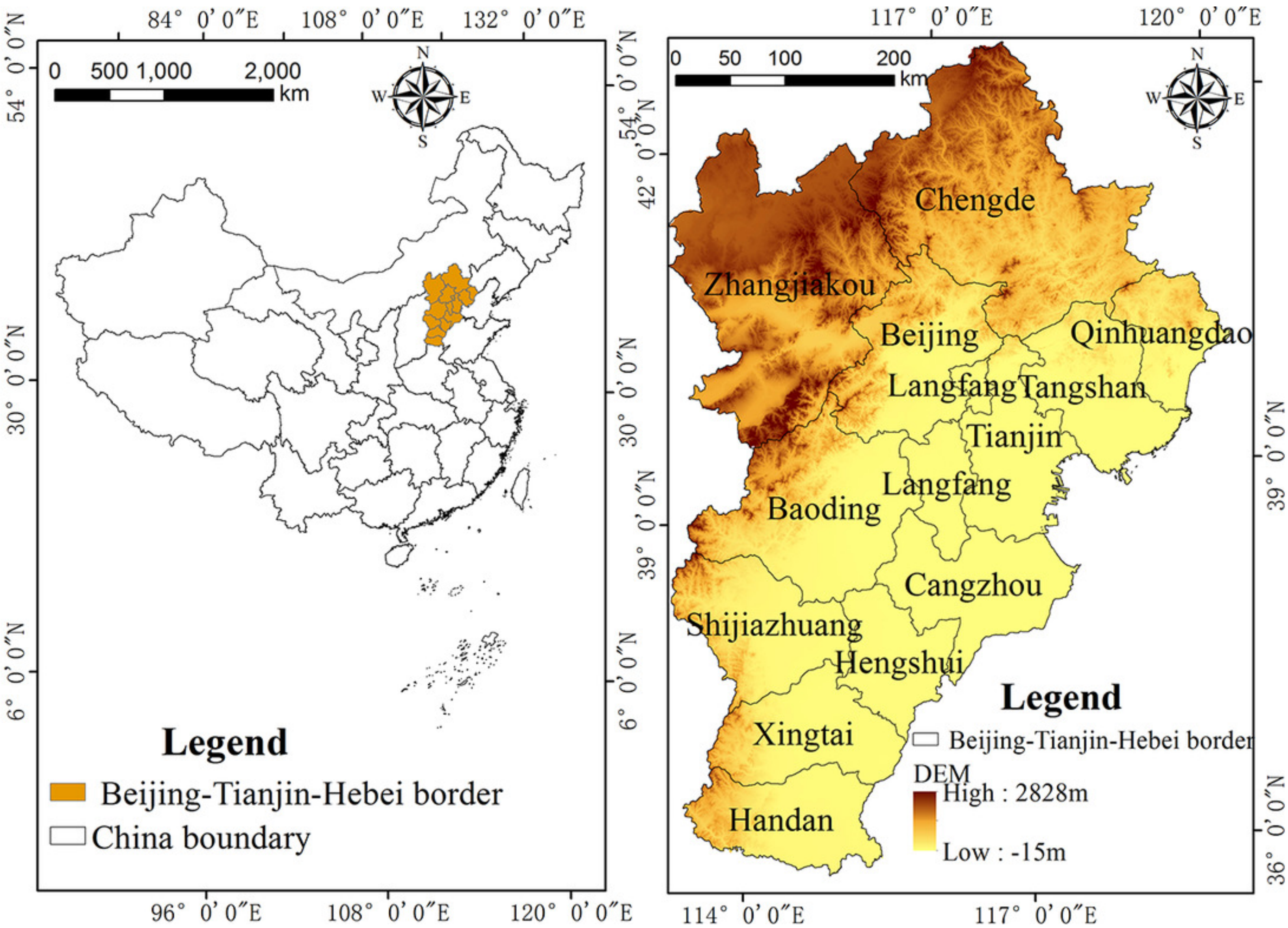
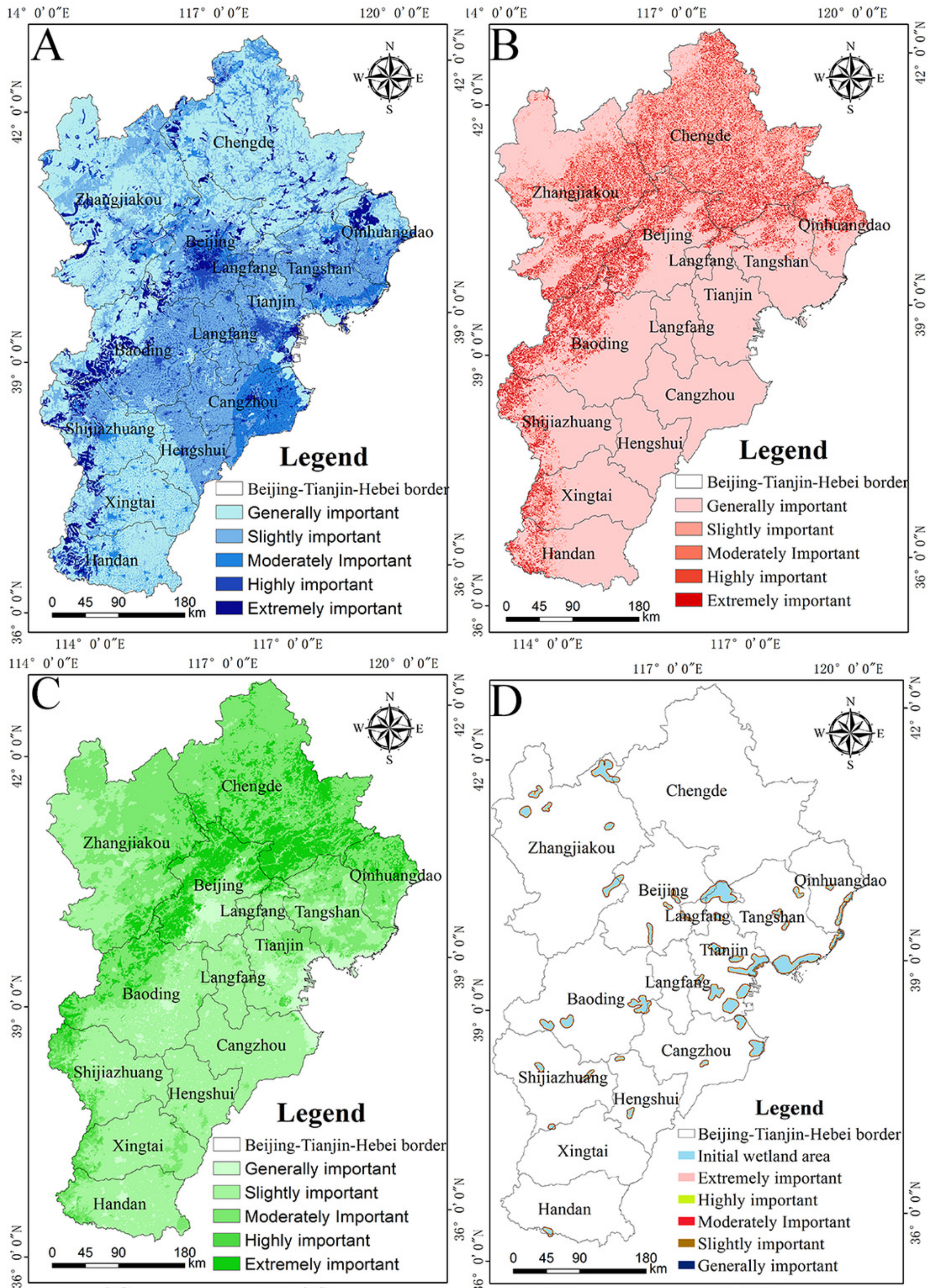


Figure 2

Spatial patterns of ecological services. (A) Spatial patterns of water production service. (B) Spatial patterns soil and water conservation service. (C) Spatial patternsof carbon fixation service (D) Spatial patterns leisure and recreation service.



A
B
C
D
Chengde
Zhangjiakou
Beijing
Qinhuangdao
Langfang
Tangshan
Tianjin
Baoding
Cangzhou
Shijiazhuang
Hengshui
Xingtai
Handan
Legend
Beijing-Tianjin-Hebei border
Generally important
Slightly important
Moderately Important
Highly important
Extremely important
Initial wetland area
0 45 90 180 km

Figure 3

Ecological security pattern.

(A) The present spatial ecological security pattern of the Beijing-Tianjin-Hebei urban agglomeration. (B) Comprehensive ecological security pattern of the Beijing-Tianjin-Hebei urban agglomeration.

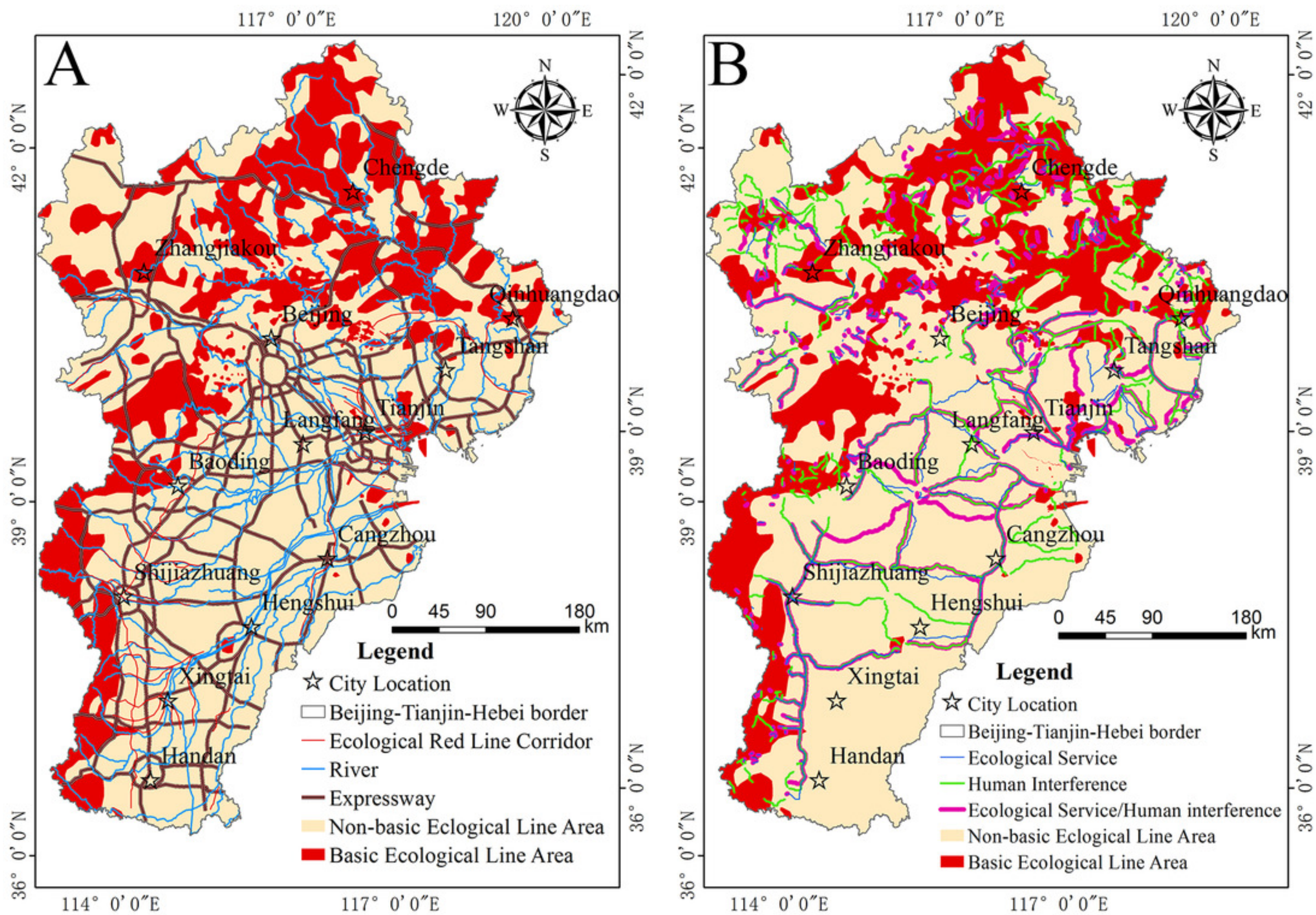


Figure 4

Space patterns of ecological source.

(A) Space patterns of logical coding of ecological service categories.(B) Spatial patterns of ecological sources level.

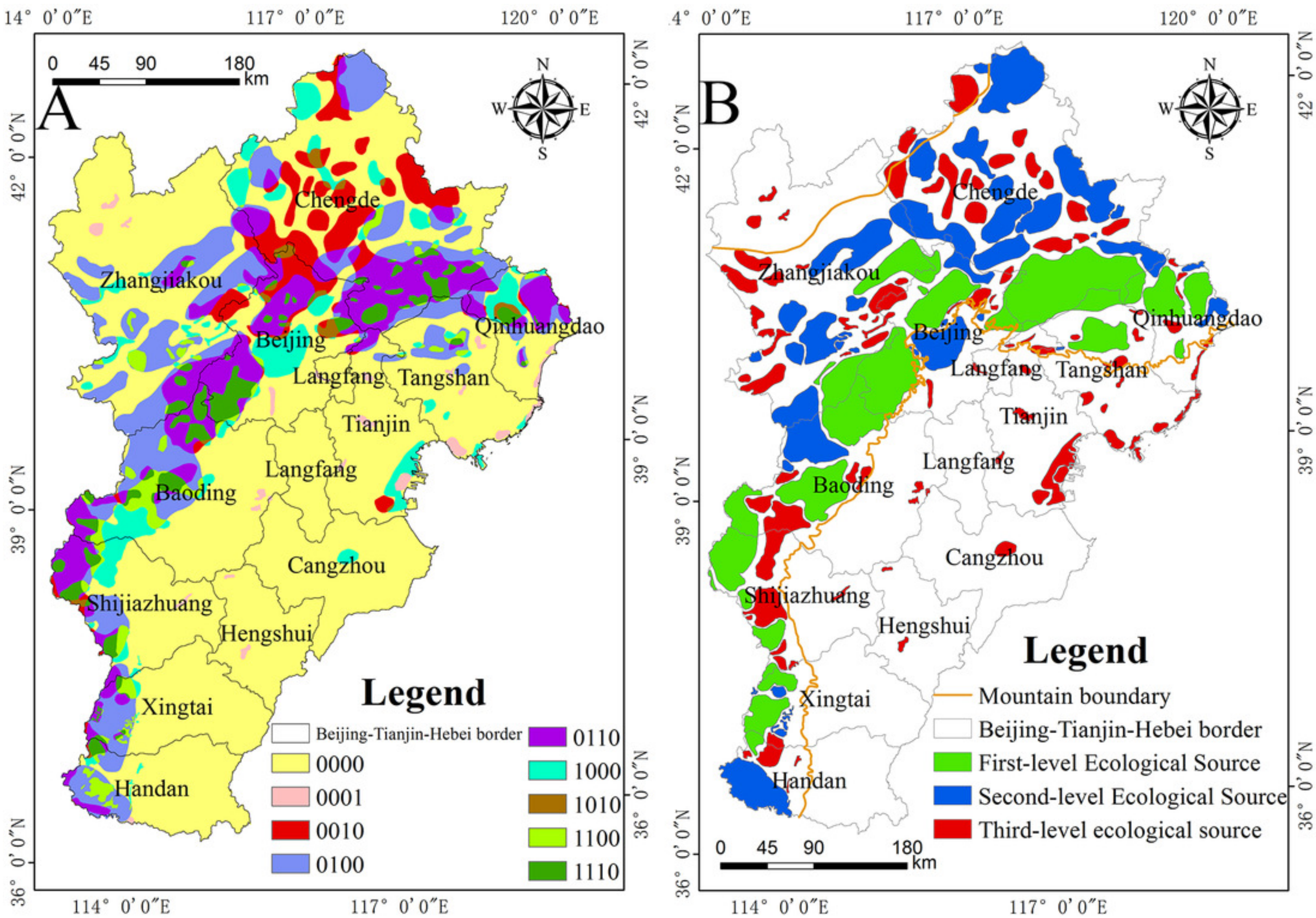
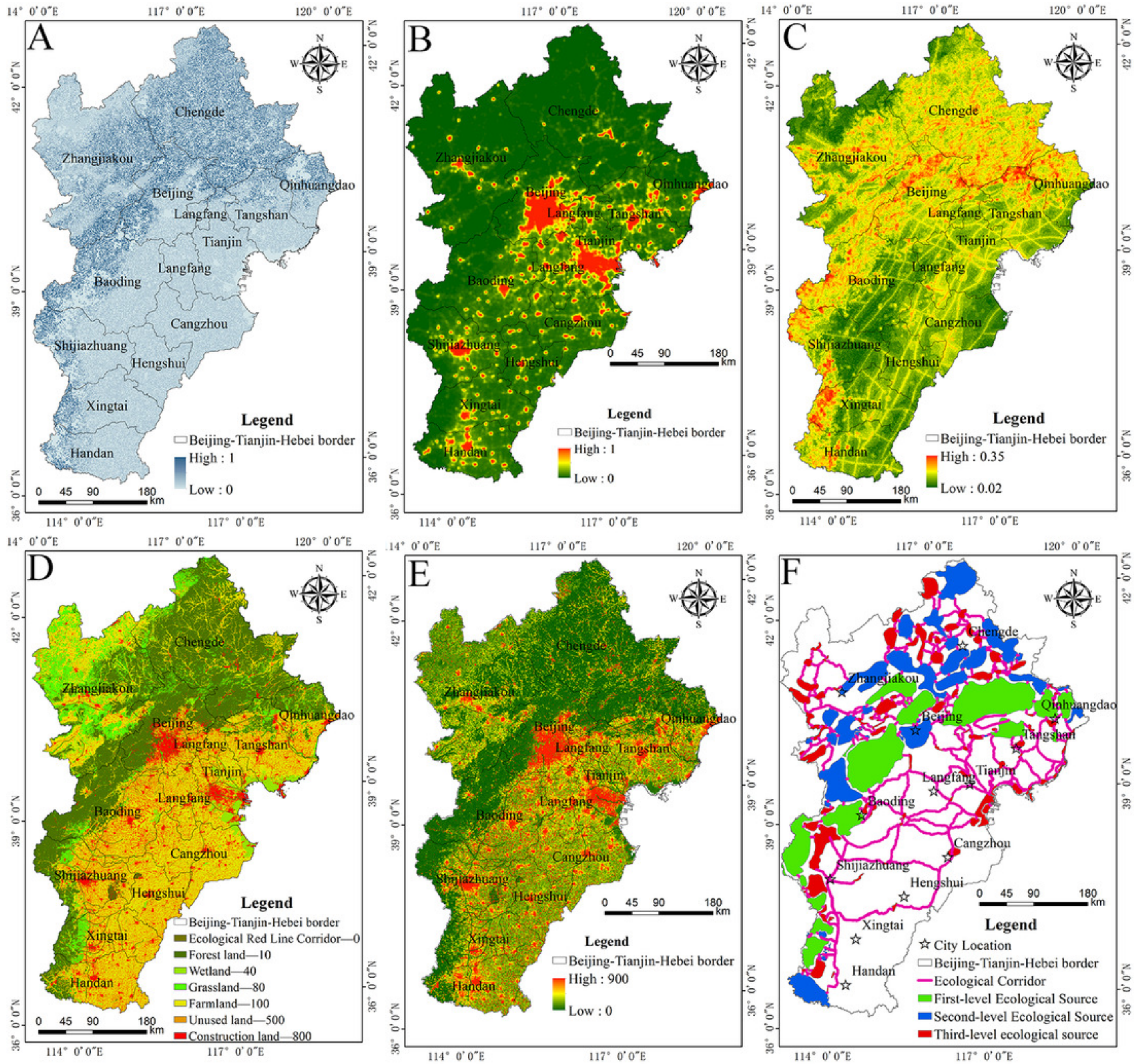


Figure 5

Spatial patterns of resistance surface and ecological corridors

(A) Spatial patternsof soil and water loss sensitivity. (B) Spatial patterns of night lighting. (C) Spatial patterns of geological hazard sensitivity index. (D) Spatial patterns of basic resistance surface. (E) Spatial patterns of the corrected resistance surface. (F) Spatial patterns ecological source level and ecological corridors


A
B
C
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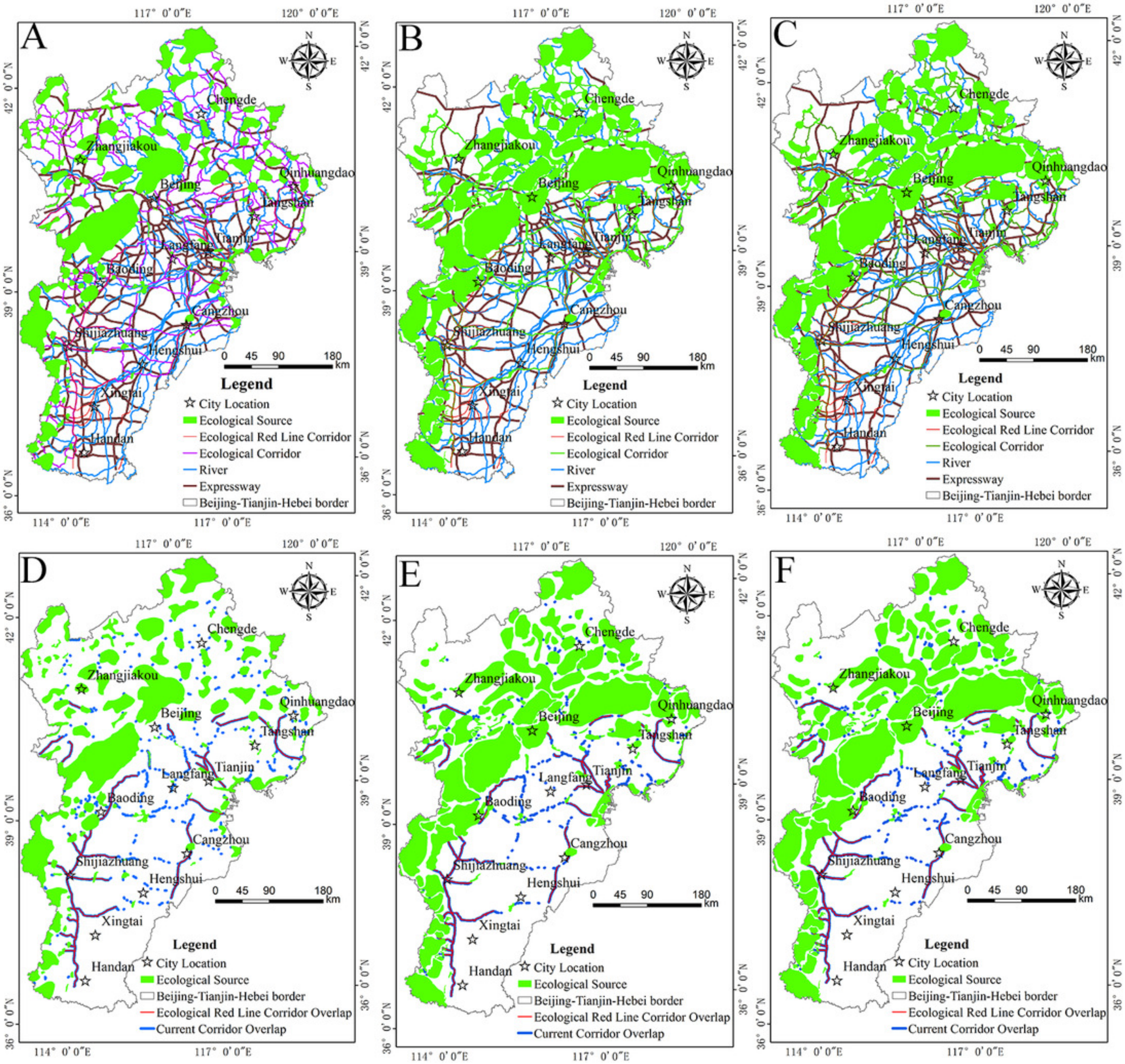
F
Chengde
Zhangjiakou
Beijing
Qinhuangdao
Langfang
Tangshan
Tianjin
Baoding
Cangzhou
Shijiazhuang
Hengshui
Xingtai
Handan
Legend
Beijing-Tianjin-Hebei border
High : 1
Low : 0
High : 0.35
Low : 0.02
Ecological Red Line Corridor—0
Forest land—10
Wetland—40
Grassland—80
Farmland—100
Unused land—500
Construction land—800
High : 900
City Location
Ecological Corridor
First-level Ecological Source
Second-level Ecological Source
Third-level ecological source
0 45 90 180 km
114° 0′0″E
117° 0′0″E
120° 0′0″E
36° 0′0″N
39° 0′0″N
42° 0′0″N

Figure 6

Comparison of ecological security patterns.

(A) Ecological security spatial pattern(human disturbance) of Beijing−Tianjin-Hebei urban agglomeration. (B) Ecological security pattern (ecological services) of the Beijing-Tianjin-Hebei urban agglomeration. (C) Ecological security pattern (ecological services, human disturbance) of the Beijing-Tianjin-Hebei urban agglomeration. (D) The ecological corridor (human disturbance) of Beijing-Tianjin-Hebei urban agglomeration coincides with the current corridor. (E) The ecological corridor (ecological services) of Beijing-Tianjin-Hebei urban agglomeration coincides with the current corridor. (F) Ecological corridor (ecological services, human disturbance) of the Beijing-Tianjin-Hebei urban agglomeration coincides with the current corridor.


A
B
C
D
E
F
Chengde
Zhangjiakou
Qinhuangdao
Beijing
Tangshan
Tianjin
Langfang
Baoding
Cangzhou
Shijiazhuang
Hengshui
Xingtai
Handan
0 45 90 180 km
Legend
City Location
Ecological Source
Ecological Red Line Corridor
Ecological Corridor
River
Expressway
Beijing-Tianjin-Hebei border
Ecological Red Line Corridor Overlap
Current Corridor Overlap
114° 0' 0"E
117° 0' 0"E
120° 0' 0"E
36° 0' 0"N
39° 0' 0"N
42° 0' 0"N