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Coupling ecosystem services supply and human ecological demand to identify landscape ecological security pattern: A case study in Beijing–Tianjin–Hebei region, China

Liqing Zhang [1,2] · **Jian Peng** [1] · **Yanxu Liu** [1] · **Jiansheng Wu** [1,3]

Abstract Landscape ecological security pattern (LESP) can effectively safeguard urban ecological security, which is vital for urban sustainable development. Previous studies have not adequately considered the ability to fulfill people's demand for ecosystem services when identifying sources of LESP. To address this gap, we sought to develop a more comprehensive approach coupling ecosystem services supply and human ecological demand to construct LESP for Beijing–Tianjin–Hebei region. We proposed a new evaluation framework integrating ecosystem services importance assessment and landscape connectivity analysis with human ecological demand importance assessment to identify ecological sources. Afterwards, ecological corridors were identified using Minimum Cumulative Resistance model based on sources and resistance surface modified through nighttime light data. Combined with ecological sources and corridors, LESP for Beijing–Tianjin–Hebei region can be constructed. The ecological sources are mainly located in western Beijing and southwestern Chengde. The ecological source area totals 36,245.50 km^2, accounting for 21.26% of the ecological land in Beijing–Tianjin–Hebei region. The ecological corridors cross the whole region, from northeast to southwest, similar to the direction of the Yanshan–Taihang Mountain Chain. All the national nature reserves and 91.4% of the provincial nature reserves are distributed within the LESP. The validity of our methodology is confirmed by the distribution of the nature reserves. This study adds new insights into the methodology of LESP construction, and its results provide information about local ecological characteristics that can provide an important reference for decision-making concerning urban planning and ecological conservation.

Keywords Landscape ecological security pattern · Human ecological demand · Ecosystem services · Ecological source · Ecological corridor · Beijing–Tianjin–Hebei region

Introduction

The world is undergoing massive urbanization, with the United Nations (2014) predicting that 66% of the global population will reside in urban areas by 2050. Urbanization, as the key driver of land use/land cover change, has transformed landscape patterns and the structure and function of urban ecosystems, resulting in a transition from natural ecosystems to social–ecological coupling systems (Gunawardhana et al. 2011; Li et al. 2012; Zhou et al. 2010, 2011). A growing number of ecological and environmental problems such as habitat fragmentation, biodiversity loss, and air and water pollution caused by urbanization have been widely recognized (Asgarian et al. 2015; Faulkner 2004; Grimm et al. 2008; Jenerette and Potere 2010). How to reduce the effects of urbanization on the ecological environment and achieve urban sustainability has become an important question in the field of landscape ecology (Breuste and Qureshi 2011; Breuste et al. 2013; Taylor and Hochuli 2015; Wu 2010).

✉ Jian Peng
jianpeng@urban.pku.edu.cn

[1] Laboratory for Earth Surface Processes, Ministry of Education, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China

[2] Department of Architecture, School of Design and Environment, National University of Singapore, Singapore 117566, Singapore

[3] Key Laboratory for Environmental and Urban Sciences, School of Urban Planning & Design, Shenzhen Graduate School, Peking University, Shenzhen 518055, China

Constructing a landscape ecological security pattern (LESP) through an understanding of the interaction between ecological processes and landscape patterns to effectively safeguard urban ecological security is one important way to maintain sustainability (Teng et al. 2011; Wu et al. 2013; Yu et al. 2006). The LESP concept was proposed by Yu (1996), who sought to understand ecological security from the perspective of landscape ecology and to identify the key landscape pattern most useful in maintaining ecological processes (Yu 1995, 1996). Yu (1996) described a potential spatial pattern as a security pattern composed of strategic portions and positions of the landscape that are critical for safeguarding and controlling certain ecological processes. The components of a LESP are correspond to the "patch-corridor-matrix" paradigm of landscape patterns. The traditional identification method for LESP can be divided into three main steps: source recognition, resistance surface creation, and corridor identification. A basic LESP can be developed by combining the outcomes of these three steps.

Source recognition, the first and most fundamental step in building a LESP, affects all subsequent steps; thus, the source area recognition method should be designed carefully. Previous studies identify two main recognition methods. The first is direct recognition, done by simply selecting nature reserves, natural scenic spots, and habitats for focal species (Aminzadeh and Khansefid 2010; Vergnes et al. 2013). The second is based on importance assessment of ecological patches using different indicator systems from multiple perspectives. The most common evaluation perspectives include ecological risk evaluation, biodiversity conservation, and resilience assessment (Li et al. 2014; Peng et al. 2015). Recently, several new indicators have been developed. Only the intrinsic functions of patches, such as land cover type, patch area, and location (Teng et al. 2011) and ecological importance (Xie et al. 2015), are typically considered as indicators. In some studies, the spatiotemporal dynamic of patches has been included into the indicator system (Deckers et al. 2005; Du et al. 2013), and one study has included the structural importance of patches in the whole landscape in the evaluation framework (Wu et al. 2013).

Despite the recent development of source recognition approaches, most studies still focus on the ecological dimension of patches as the supplier of ecosystem services, ignoring the interaction between ecosystem and human socioeconomic systems. To achieve sustainable human and natural development, the services supplied by ecosystems should match human demand (Burkhard et al. 2012). Thus, aside from the ability of ecological patches to provide ecosystem services, their ability to fulfill human demand for ecosystem services is also essential for evaluating the capacity of the patches to be one part of source area.

The importance of considering demand for ecosystem services has received increasing attention over the past decade (Gutman 2007; McDonald 2009; Van Jaarsveld et al. 2005). A recent review of ecosystem services demand indicates that studies are increasingly mapping ecosystem services supply–demand relationships and integrating human demand into ecosystem services evaluation (Wolff et al. 2015). However, supply–demand analysis has rarely been applied to importance assessment for source recognition.

This study addresses the gaps described above by establishing a new approach to identifying LESP in order to safeguard ecological security in urban areas. Specifically, the main objectives of this study are to identify (1) ecological sources using a new methodology that considers the ability of ecological patches to both provide ecosystem services and fulfill demand for ecosystem services and connectivity; and (2) ecological corridors based on resistance surface construction, allowing the construction of LESP for Beijing–Tianjin–Hebei region.

Materials and methodology

Study area

The study area is Beijing–Tianjin–Hebei region (113°46′-119°79'E, 36°07′-42°65'N), northern China's economic development center. It covers an area of 201,680 km^2, and contains two municipalities (Beijing and Tianjin) and one province (Hebei) with 11 prefecture-level cities (see Fig. 1). Beijing's population density was 1284.58/km^2, Tianjin's was 1183.66/km^2, and Hebei's was 410.18/km^2 in 2010, indicating obvious differences in population aggregation. This great disparity also exists among economic development levels. The per capita GDP of Beijing, Tianjin, and Hebei in 2010 is 71,198, 71,123, and 28,349 RMB respectively. The study area is a complete regional ecological system regarding geology, landform, climate, and biomes. The terrain of Beijing–Tianjin–Hebei region slopes downwards from the northwest to the southeast. The area has abundant representative tectonic landforms, including plateaus, plains, mountains, hills, and basins. The area has both a temperate semi-humid and semi-arid continental monsoon climate, with four distinct seasons.

Data sources

Eight main datasets were used in this research: (1) SPOT_Vegetation long sequence Normalized Difference Vegetation Index (NDVI) datasets downloaded from the Cold and Arid Regions Science Data Center, China; (2) vegetation type data downloaded from the MODIS International Geosphere Biosphere Programme (IGBP) Land Cover database, which has been reclassified into seven land use types (forest land, grassland, farmland, wetland, water bodies, unused land, and construction land; see Fig. 1); (3) Digital Elevation Model (DEM) data downloaded from the Cold and Arid Regions Science Data Center, China; (4) population density data

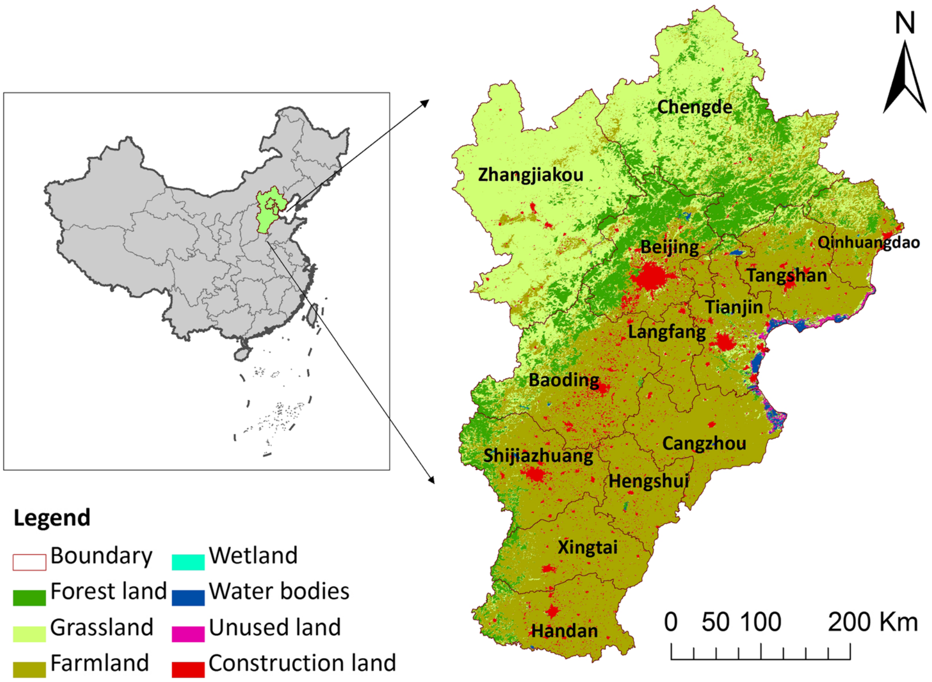


Fig. 1 Location of Beijing-Tianjin-Hebei region and its land use distribution in 2010

downloaded from Land Scan dataset; (5) monthly average meteorological data collected from the China Meteorological Science Data Sharing Service System; (6) Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) nighttime light data using invariable-object methods (Wu et al. 2013a); (7) data on the spatial distribution of roads and rivers provided by the Institute of Geographic Sciences and Natural Resources Research, China; and (8) nature reserves distribution data downloaded from the World Database on Protected Areas. All the data sources reflected the situation in 2010.

Methodology framework

The methodology framework is shown in Fig. 2. A detailed explanation of each research process is provided in the following sections.

Ecological source recognition

In the first step of identifying LESP, a multilevel evaluation framework is developed based on the hypothesis that feasible source area must satisfy three conditions simultaneously. (1) It should ensure a sustainable supply of ecosystem services. The services to be considered differ according to the specific eco-environmental characteristics of the area. Since estuary ecosystem degradation, soil erosion in northern rocky mountainous areas, and water resource shortages are the three main environmental problems in Beijing–Tianjin–Hebei region, the biodiversity, soil conservation, and water resource security services will be considered in identifying the area with a high degree of habitat importance (the detailed method of evaluating each ecological process is explained below). (2) It should maintain the integrity of the ecological process. An ecological patch with high connectivity can perform its ecological functions more efficiently (Kang et al. 2015; Matlack and Monde

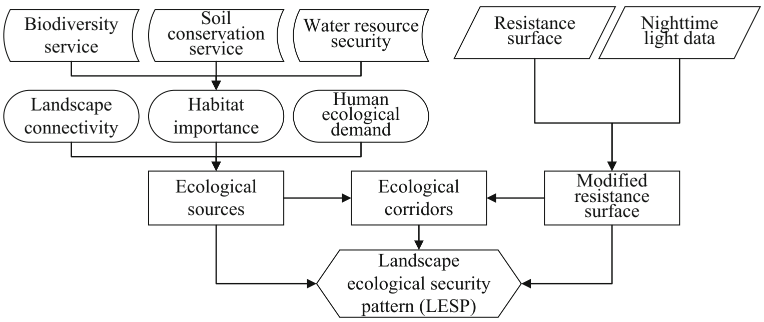


Fig. 2 Framework of landscape ecological security pattern (LESP) construction

2004); thus, the patches' landscape connectivity indexes will be used as criteria. (3) Finally, it should be effective in fulfilling human demand for ecosystem services.

The results of the ecosystem services importance analysis and connectivity analysis reflect the importance of patches in providing ecosystem services and delivering services flow effectively. The outcome of demand analysis reflects the patches' ability to meet ecological demand. Therefore, we introduced the protection index (PI) of ecological land based on the standard ecological importance index (EI) and standard ecological demand index (DI). The proposed formula for calculating the importance of ecological patches is as follows:

$$PI_i = EI_i + DI_i = \frac{(HI + CI)_i - (HI + CI)_{\min}}{(HI + CI)_{\max} - (HI + CI)_{\min}} + \frac{NI_i - NI_{min}}{NI_{max} - NI_{min}} \quad (1)$$

where PI_i is the protection index of grid i, EI_i is the normalized value of ecological importance degree, DI_i is the normalized value of ecological demand importance degree, HI and CI represent the degree value of habitat importance and connectivity importance respectively, $(HI+CI)_i$ is the sum of habitat importance degree and connectivity importance degree of grid i, $(HI+CI)_{\max}$ and $(HI+CI)_{\min}$ represent the maximum and minimum values of the sum among all the grids, and NI_i, NI_{max}, and NI_{min} represent grid i's ecological demand importance and the maximum and minimum values of ecological demand importance among all the grids, respectively.

After calculating the protection index for all the grids, the final assessment result is classified into five grades using quantile classification method, which is useful for showing rankings and ordinal data without depending on data value distribution (Razandi et al. 2015). These five degrees are defined as "most important", "very important", "important", "general", and "unimportant". The most important patches among them are considered as the ecological sources.

Habitat importance assessment

Based on the local context and previous studies (Crossman et al. 2013; Gao et al. 2012; Peng et al. 2016), three types of ecosystem services are considered in the habitat importance assessment: biodiversity service, soil conservation service, and water resource security. In each service assessment, each grid receives an importance value. The final assessment result will be the highest importance value among these three evaluation outcomes.

Biodiversity service The ability to maintain biological resources differs among different land use types. Based on the equivalent quantum of biodiversity service established by Xie et al. (2015) and the ecosystem services study conducted in Beijing–Tianjin–Hebei region by Ma et al. (2013), we calculated the basic equivalent value per unit area of the biodiversity service. The values for forest land, grassland, farmland, wetland, water bodies, and unused land are 9.59, 3.21, 2.09, 7.35, 7.32, and 1, respectively. However, ecosystem services values can differ within a single land use type. Many studies utilize the Normalized Difference Vegetation Index (NDVI) to evaluate biodiversity service (Martínez-Harms and Balvanera 2012; Zurlini et al. 2014). We use the NDVI as the revising factor to modify the basic equivalent value. Based on the weather features in Beijing–Tianjin–Hebei region, NDVI data from April to November (three records for each month, for a total of 24) have been selected. The average of these 24 NDVI records was used as the annual mean value. Formula 2 was used to calculate the modified equivalent value per unit area of the biodiversity service based on NDVI:

$$EV' = \frac{NDVI_i}{NDVI_t} \times EV_0 \quad (2)$$

where EV' is the modified equivalent value based on the NDVI of grid i belonging to land use type t, EV_0 is the basic equivalent value of land use type t, $NDVI_i$ represents the annual average NDVI of grid i and $NDVI_t$ represents the average NDVI of land use type t.

The EV' value of each grid is calculated to demonstrate the importance degree of the biodiversity service. The importance is then classified into such five grades as "most important," "very important," "important," "general," and "unimportant" using quantile classification method, with corresponding values of 5, 4, 3, 2, and 1.

Soil conservation service The development of quantification methods for soil erosion risk assessment provides a good pathway for evaluating the soil conservation service. The Revised Universal Soil Loss Equation (RUSLE) model is widely used (Ibrahim and Musa 2015; Van Oost et al. 2000). In this paper, the difference between potential soil loss and actual soil erosion was calculated using the RUSLE model in order to identify soil conservation service. According to RUSLE model, both the potential soil loss (A_0) and the actual soil erosion (A) are conditioned by five factors: rainfall erosive factor (R), soil erosivity factor (K), slope length and steepness factor (LS), the factor of vegetation coverage (C) and the factor of engineering measures (P). The formula for the soil conservation amount (A_1) is as follows:

$$A_1 = A_0 - A = R \times K \times LS - R \times K \times LS \times C \times P = R \times K \times LS \times (1 - C \times P) \quad (3)$$

The values of R, K, LS, and C can be calculated via the RUSLE model. For P, different P values were assigned for different land use types based on previous studies on northern China. The value (1) is the same for forest land, grassland, and unused land; the P for farmland is 0.75. Water bodies, wetland, and constructed land all have the same value (0). The A_1 value of each grid represents the importance degree of the soil conservation service. The classification method used for the biodiversity service importance assessment is used to classify soil conservation service importance into five degrees.

Water resource security Water resource security is evaluated in terms of two dimensions. The first is security from flooding, and the other is water resource conservation. The former is assessed by measuring the distance from rivers; the latter is evaluated by assessing the distribution of water bodies and the water conservation ability of different vegetation cover. As shown in Table 1, different importance values are assigned to different objects.

Landscape connectivity assessment

The most commonly used index for landscape connectivity assessment is the Probability of Connectivity index (PC) (Carranza et al. 2012), a graph-based index proposed by Pascual-Hortal and Saura (2006). The PC is based on the possibility model, and the possibility of connectivity is related to the distance between patches. The PC index is used to measure landscape connectivity. The formula for the PC index is as follows (Saura and Torne 2009):

$$I_{\mathrm{PC}} = \frac{\sum_{i=0}^{n}\sum_{j=0}^{n} a_i \cdot a_j \cdot P_{ij}^{*}}{A_L^2} \tag{4}$$

where n is the total number of patches in the landscape, a_i and a_j represent the area of patch i and patch j respectively, A_L is the total landscape area, P_{ij}^{*} is the maximum product of dispersal probabilities along the links of all possible paths between patches i and j (Carranza et al. 2012), and the value of I_{PC} lies between 0 and 1.

The delta values for each index (*dI*) were used to represent the importance of each patch. Formula 5 shows the calculation method:

$$dI(\%) = 100 \times \frac{I - I_{\mathrm{remove}}}{I} \tag{5}$$

where I is the index value before the change, and I_{remove} is the value of the same index after the change (e.g. after a certain patch loss) (Pascual-Hortal and Saura 2006). When dI is higher, the connectivity importance of the patch is higher.

In this study, *dPC* is used to evaluate the structural importance of terrestrial ecological patches (forest land patches, farmland patches, and grassland patches) using Conefor Sensinode 2.5.8 and GIS. The importance is then classified into five grades using quantile classification method. These five degrees are defined as “most important”, “very important”, “important”, “general”, and “unimportant” with corresponding values of 5, 4, 3, 2, and 1.

Human ecological demand assessment

Normally, ecological demand refers to the amount of ecosystem services consumed/used or required/desired by humans (Burkhard et al. 2012; Villamagna et al. 2013). The most common indicators used to measure human demand include the actual usage or consumption of ecosystem services, the nonmonetary or monetary benefits from risk reduction services, and the preference and values of cultural services (Wolff et al. 2015). This study uses human demand as an indicator to select the ecological patches most important to humans. Therefore, we consider ecosystem services demand using the reverse process: we define human ecosystem services demand from the perspective of ecological patches rather than of humans. Specifically, the potential of ecological patches to fulfill human demand for ecosystem services is used to represent human ecological demand.

Thus, the assessment of human ecological demand importance is based on how easily and how many ecosystem services can be delivered to people by ecological patches. Previous studies (Ala-Hulkko et al. 2016; Baró et al. 2016; Paracchini et al. 2014) show that the combination of population density and accessibility can be used to evaluate this demand. We distinguished the utilization of ecological land among three time scales: daily relaxation on weekdays, short trips on the weekends, and long journeys during public holidays. Different criteria are used for each measurement

Table 1 Evaluation system of water resource security

Influence object	Influence range	Importance	Value
River	1 km away from the river	Most important	5
	2 km away from the river	Very important	4
	3 km away from the river	Important	3
Wetland, lake, and reservoir		Most important	5
Vegetation	Deciduous broadleaf forest and mixed forest	Most important	5
	Evergreen coniferous forest, deciduous needle-leaf forest, shrub, and savanna	Very important	4
	Meadow	Important	3
	Farmland, mosaics of farmland, and other natural vegetation	General	2
Others		Unimportant	1

method. Concerning daily activities on weekdays, we assume that, as the distance from ecological land to the nearest community becomes shorter, the utilization frequency increases, and the fulfillment of ecological demand also increases. For trips on weekends and holidays, the beneficiary population is used to represent the fulfillment of demand: as the population density within the service radius increases, the size of the beneficiary population also increases.

Based on the above consideration, a measurement model for human ecological demand importance has been created. The Euclidean distance from the ecological land to the nearby residential area was used to represent ecological demand importance on weekdays, and the population agglomeration strengths in circles with radii of 10 km and 100 km were used to represent ecological demand importance on weekends and holidays respectively. The total ecological demand importance is the combination of these three demands at different time scales:

$$NI_i = \frac{0.5 \times PD_i^1 + 0.5 \times PD_i^2}{ED} \tag{6}$$

where NI_i is the ecological demand importance for grid i, PD_i^1 and PD_i^2 represent the kernel density of the population density in circles with radii of 10 km and 100 km respectively, and ED is the shortest distance from grid i to its nearby residential area.

The classification method used in the biodiversity service importance assessment is used to classify human ecological demand importance into five degrees.

Potential ecological corridor identification

Resistance surface construction using nighttime light data

The second step is the creation of the ecological resistance surface, hampered degree of species' migration among different landscape units. Species' utilization of landscape can be seen as a competitive control and coverage of space; thus, surface resistance is the basis from which to build diffusion path to overcome that resistance (Mörtberg et al. 2013). The most commonly used method of creating a resistance surface is assigning resistance values according to land use type based on the notion that different land use types exert different levels of resistance to the flow of material and energy (Gurrutxaga et al. 2011; Kong et al. 2010; Teng et al. 2011).

However, this method's strong subjectivity and lack of sufficient theoretical support have been criticized. Some studies have modified it by considering topography to increase its objectivity (Li et al. 2010b). Using topography might help to describe geographical resistance to some extent, but explaining the disturbance caused by human activities remains difficult; using impervious surface might illustrate the internal disparity within the same land use type, improving evaluation precision, but the impervious surface represents only the land cover pattern and has a limited ability to explain the strength of human disturbance (for example, the difference between a high-rise building and an open square would not be recognized).

Obtaining a better outcome requires a better indicator. A great number of studies reveal that Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) nighttime light data can accurately reflect the economic development situation, energy consumption, urbanization level, and other human activity factors (Elvidge et al. 2009; Ghosh et al. 2010; Zhang and Seto 2011). These data have been used in other studies for Beijing–Tianjin–Hebei region (Peng et al. 2016; Xie et al. 2016). Therefore, this study uses nighttime light data to determine the spatial pattern of human activity intensity levels.

Following previous studies (Gurrutxaga et al. 2011; Kong et al. 2010), different basic ecological resistance values are assigned to different land use types. The resistance coefficient increases as the anthropogenic disturbance increases. The basic ecological resistance coefficients for forest land, grassland, farmland, wetland, water bodies, unused land, and construction land are 1, 10, 30, 50, 50, 300, and 500 respectively. The DMSP-OLS nighttime light data is introduced as revising factor to reflect disparities within the same land use type. Formula 7 shows the calculating method for the modified resistance coefficients based on the total light index:

$$R' = \frac{TLI_i}{TLIa} \times R \tag{7}$$

where R' is the modified resistance coefficient, TLI_i is the total light index of patch i which is belonging to land use type a , TLI_a is the average total light index of land use type a, and R is the basic resistance coefficient of land use type a.

Ecological corridor identification using MCR model

In the third step of LESP identification, Minimum Cumulative Resistance (MCR) model is used to identify the corridors between source patches, which has been applied in many studies (Baudry et al. 2003; Li et al. 2015, 2010a). The MCR model, proposed by Knaapen et al. (1992), considers the source, distance, and landscape matrix to calculate the cost in the movement process. The formula used to calculate the MCR is:

$$MCR = f \ \min \Sigma_{j=n}^{i=m} D_{ij} \times R_i \tag{8}$$

where f is the positive correlation coefficient for minimum cumulative resistance and ecological processes, D_{ij} is the spatial distance from source j to landscape unit i and R_i is the resistance coefficient of i for species dispersal.

Corridor identification based on the MCR model can be achieved via the GIS distance model by setting ecological sources as source data and ecological resistance surface as cost data. In this study, two types of corridors are extracted. The first type is potential corridors, based on which one least-cost path occurs from every source to every destination. The second type is key corridors, based on which only one least-cost path occurs from every source to all the destinations. Obviously, the key corridors are belong to potential corridors.

Results

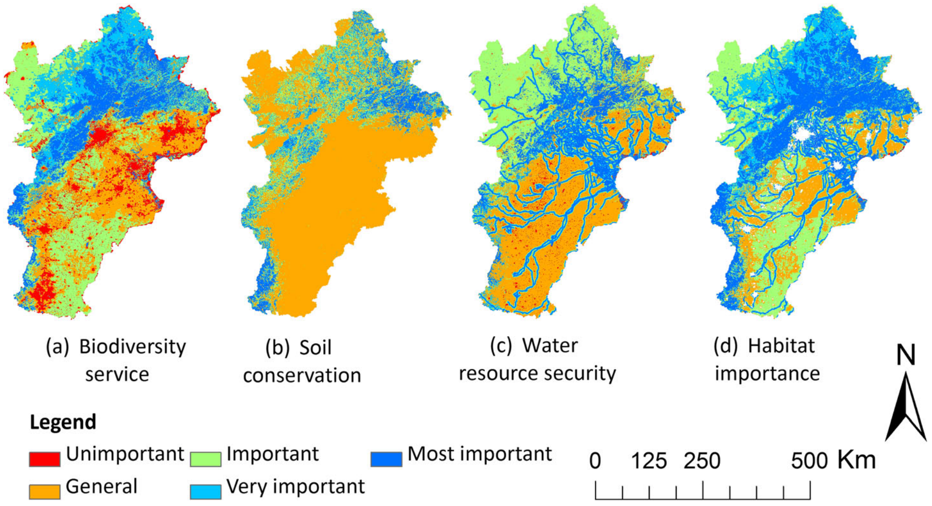
Habitat importance

An area calculation indicates that farmland, grassland, and forestland are the main land use types in the study area. Farmland area takes up 102,759.75 km^2 (50.95%) of the total area, mainly distributed across the plains area in the southeast. Grassland area takes up 62,743.75 km^2 (31.11%) of the total area and is mainly located in the northwest. Forest land, construction land, water bodies, unused land, and wetland represent 13.12%, 3.95%, 0.43%, 0.38%, and 0.06% of the total areas respectively. Except construction land, all the other land use types consist of ecological land. Ecological land takes up 193,704.25 km^2 (96.05%) of the total area.

The spatial distribution of biodiversity service importance is shown in Fig. 3a. The most important patches cover an area of 37,621.00 km^2, or 18.65% of the region. The distribution of the most important patches is similar to forest land. The very important patches cover 30,795.75 km^2, or 15.27% of the region. These patches are mainly distributed along the northern region of the most important patches. Important patches cover 58,930.00 km^2, or 29.22% of the region. These patches are mainly distributed in the Bashang plateau region of Zhangjiakou, Hengshui, Xingtai, and Handan. As shown in Fig. 3b, the most important, very important, and important patches in terms of soil conservation importance are mainly distributed in the northern and western mountainous areas. The most important, very important, and important patches cover 8.73%, 9.74%, and 13.52% of the region respectively. The spatial distribution of water resource security importance is shown in Fig. 3c. The most important and very important patches are mainly distributed in Beijing, Chengde, and the tidal flats of the Bohai Sea coast. The important patches are mainly distributed in the northwest of Hebei, similar to the distribution of grassland. The most important, very important, and important patches cover 21.25%, 11.42%, and 30.93% of the region respectively.

The result of the habitat importance assessment based on the above three ecosystem services importance assessments is shown in Fig. 3d. The most important patches cover 65,505.75 km^2, or 33.80% of the total ecological land area in Beijing–Tianjin–Hebei region. These patches are mainly distributed in the northern mountainous area. Over 30% of the most important patches are located in Chengde, and over 15% of these patches are located in Beijing. Very important patches and important patches cover 40,606.25 km^2 and 53,191.75 km^2, or 20.95% and 27.44% of the total ecological land area respectively. The very important patches are mainly located in the northwest part of Hebei, and the important patches are mainly located in Hebei Plain area.

Beijing has the largest proportion of most important patches, covering nearly 75% of its area. Chengde has the second-largest proportion of most important patches, covering 56.67% of its area. Thus, the northern part of Beijing–Tianjin–Hebei region, especially Chengde and Beijing, are hotspots of important habitats. Among land use types, forest land has the largest proportion (97%) of the most important patches. Water bodies and wetland has the second and third largest proportions of the most important patches (95% and 84.55% respectively). As for grassland, the proportion of the most important patches is 41.47%.



(a) Biodiversity service (b) Soil conservation (c) Water resource security (d) Habitat importance

Fig. 3 Evaluation results of ecosystem services importance and habitat importance

Ecological sources

Combining the results for forest land, grassland, and farmland produces the connectivity importance distribution shown in Fig. 4a. As shown, 85.32% of the ecological land has high connectivity importance, but differences appear among land use types. The average *dPC* value for grassland is the highest (1.35), and that of forest land and farmland is 0.85 and 1.13 respectively. Farmland has the highest maximum value (82.31), while grassland has the smallest minimum value (0.005). Concerning the land use distribution of the most important patches, 94.25% of farmland, 84.69% of grassland, and 46.18% of forest land are among the most important patches.

The spatial distribution of human ecological demand importance is shown in Fig. 4b. Ecological demand importance tends to be higher in the east and lower in the west. Most of the important patches are located around construction land. By calculating the average value of ecological demand importance for each city, Langfang was found to have the highest value (0.38). The mean values for Handan, Shijiazhuang, Tianjin, Xingtai, Beijing, Hengshui, Baoding, Tangshan, Cangzhou, Qinhuangdao, Zhangjiakou, and Chengde are 0.30, 0.27, 0.26, 0.25, 0.25, 0.24, 0.23, 0.20, 0.20, 0.09, 0.03, and 0.02 respectively.

The spatial distribution of ecological land protection importance is shown in Fig. 4c. The most important patches cover 36,245.50 km^2, or 21.26% of the total ecological land. Very important and important patches cover 33,571.50 km^2 and 50,302.25 km^2 respectively. The most important patches are mainly located in western Beijing and the southwest of Chengde, with others distributed in western mountainous areas and the tidal flats of the Bohai Sea coast. The very important patches are mainly distributed in the northwest of Hebei, while the important patches are mainly located in the Hebei Plain area.

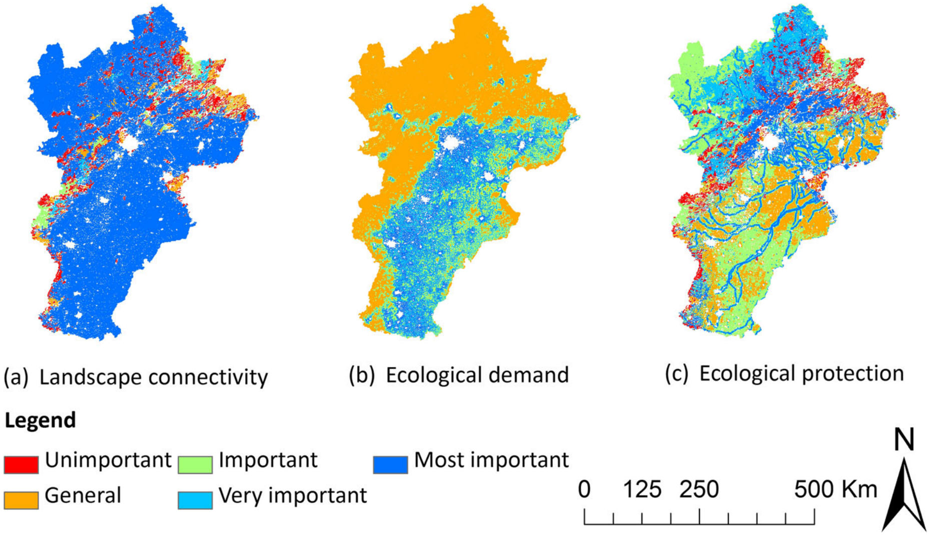
Regarding the protection importance of different land use types (see Fig. 5), water bodies have the best overall protection importance: 93.15% of water bodies are among the most important patches, while 70.89% of wetland patches and 52.65% of forest land are among the most important patches. Regarding protection importance for each city (see Fig. 6), Beijing has the highest proportion of most important patches (over 65%). Tianjin and Chengde rank second and third (38.73% and 32.37% respectively).

According to our source recognition method, the most important patches regarding protection importance are the LESP ecological source area. This area covers 36,245.50 km^2, or 21.26% of the total ecological land in Beijing–Tianjin–Hebei region. The ecological sources consist of large blocky patches and linear patches. The linear patches are rivers and their buffer zones. Regarding the land use composition of sources, farmland accounts for most of the sources, with the amount of 40.48%. The second, third and fourth largest source areas are forest land, grassland, and water bodies respectively (32.18%, 25.14%, and 1.88%). Only 0.19% of the source area consists of unused land, and 0.13% of that is wetland. Regarding the source distribution across cities, source areas are mainly distributed in Chengde and Beijing (27.14% and 19.97% respectively), followed by 11.06%, 9.16%, 6.06%, 5.61%, 3.71%, 3.68%, 3.59%, 3.25%, 3.06%, 2.02%, and 1.69% of the sources in Zhangjiakou, Tianjin, Baoding, Tangshan, Handan, Cangzhou, Xingtai, Shijiazhuang, Langfang, Qinhuangdao, and Hengshui respectively.

Ecological corridors

The result regarding the basic resistance surface is shown in Fig. 7a, and the spatial distribution of nighttime light intensity is shown in Fig. 7b. The areas with high TLI values are mainly distributed in Beijing and Tianjin; the mean TLI value for the

Fig. 4 Evaluation results of landscape connectivity importance, ecological demand importance, and ecological protection importance


(a) Landscape connectivity (b) Ecological demand (c) Ecological protection

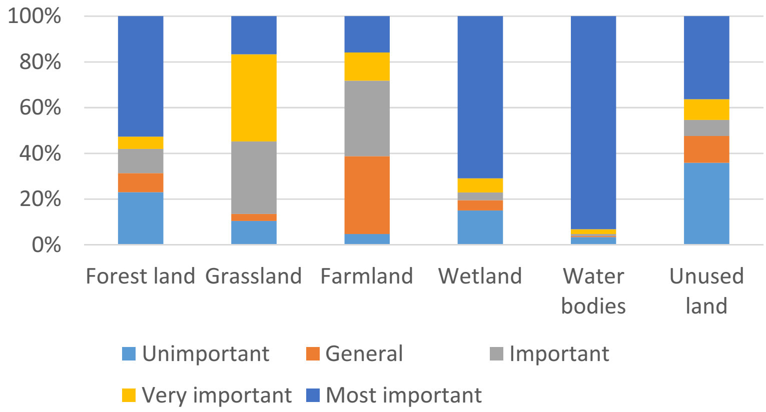


Fig. 5 Ecological protection importance composition in each land use type

whole Beijing–Tianjin–Hebei region is 11.02. The average TLI values for construction land, unused land, farmland, wetland, water bodies, grassland, and forest land are 42.47, 16.55, 14.99, 14.15, 12.18, 3.94, and 3.00 respectively. When looking at the mean TLI value for each city, Chengde and Zhangjiakou have the smallest value of 2.05 and 2.93 respectively because of the small proportion of construction land area in these two cities. Tianjin, Beijing, Langfang, and Tangshan have high TLI values and the corresponding values are 29.07, 22.62, 23.20, and 19.34 respectively.

Based on basic resistance surface and nighttime light intensity distribution, the modified resistance surface was obtained as shown in Fig. 7c. The average value and maximum value of the modified resistance coefficient in the whole region is 57.89 and 10,848.70. Compared with the initial basic resistance value ranged from 1 to 500, this modified outcome gets a considerable higher precise disparity. By calculating the mean of modified resistance coefficient for each city, Tianjin, Beijing, Tangshan, and Langfang was found to have the highest mean value of 172.27, 169.95, 100.43, and 90.00, while Chengde and Zhangjiakou have the lowest mean value of 8.10 and 19.13 respectively. As for different type of land use, the mean value for construction land, unused land, water bodies, wetland, farmland, grassland, and forest land are 398.82, 194.19, 62.00, 60.05, 51.25, 40.98, and 17.83 respectively.

Based on the result of source recognition and resistance surface construction, corridors are identified using GIS. As shown in Fig. 7c, the ecological corridors cross the whole region from northeast to southwest, similar to the direction of the Yanshan–Taihang Mountain Chain. The corridors are mainly located in mountainous areas with good ecological environments, away from places with intense human disturbances such as construction land and farmland. The corridors can thus facilitate species migration and energy flow among ecological sources. The length of the potential corridors is 12,654.38 km and that of the key corridors is 1545.52 km. More than 74% of the potential corridors is comprised of forest land; the remainder is mainly grassland and farmland. The composition of the key corridors is similar to that of the potential corridors: 66.97% of the key corridors is comprised of forest land. The modified resistance coefficients of the corridors are calculated to measure the pressure exerted on them by humans. The mean value for potential corridors is 0.48, and that for key corridors is 1.15, indicating that key corridors are under greater pressure. Therefore, more attention should be paid to the protection of key corridors.

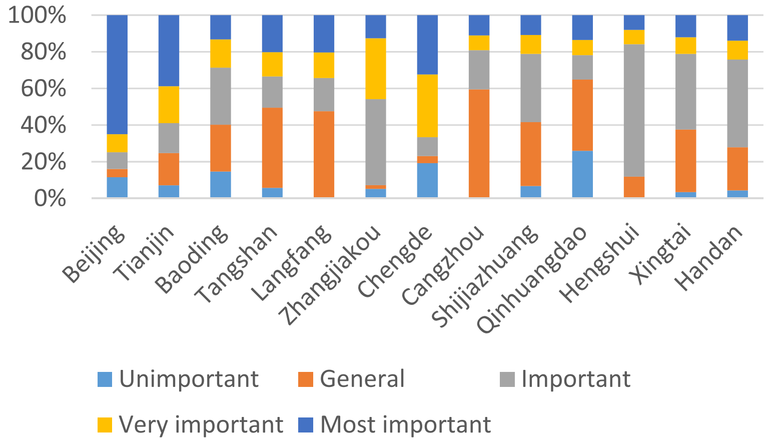
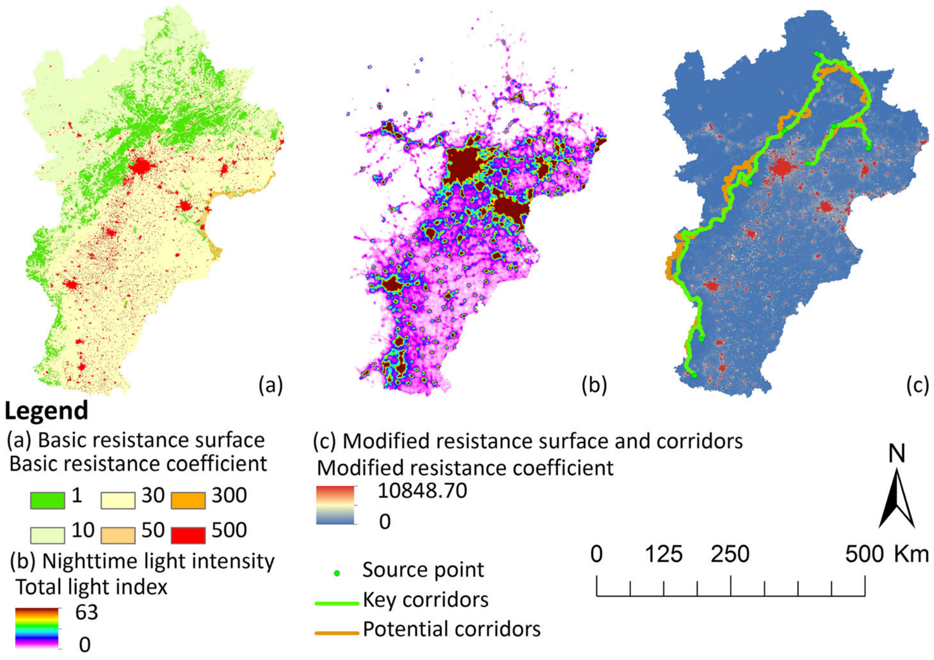


Fig. 6 Ecological protection importance composition in each city

Fig. 7 Ecological corridors identified based on basic resistance surface and nighttime light intensity



Landscape ecological security pattern

Ecological sources and ecological corridors are the core of the LESP. Recognizing these two components, we constructed the LESP as shown in Fig. 8. To verify the validity of the recognition outcome, we obtained the spatial distributions of 18 national nature reserves and 35 provincial nature reserves from the World Database on Protected Areas (WDPA) for comparison. Overlaying the nature reserves map on the LESP map shows that all the national nature reserves are distributed within the scope of the security pattern and that only three provincial nature reserves fall outside of the scope. These three nature reserves are Haixing Volcanic Geological Remains, Haixing Wetland Nature Reserve, and Huanghua Ancient Shell Dike Nature reserve in the east of Cangzhou. They are all near the security pattern area and are located within a radius of 10 km of the nearest ecological source or corridor. Thus, the recognition result is largely reliable.

The ecological sources are mainly located in the districts of Fangshan, Mengtougou, Changping, Yanqing, Huairou, and Miyun in Beijing, the counties of Xinglong, Chengde, Luanping, Fengning, and Longhua in Chengde, and Chicheng in Zhangjiakou. The ecological corridors comprise three parts: existing corridors, potential corridors, and key corridors. Existing corridors consist of rivers and water bodies, which are spread out over the whole region. There are intensive distributions of existing corridors in Beijing and Tianjin. Key corridors cross the region from north to south, linking Chengde, Beijing, Tangshan, Langfang, Baoding, Shijiazhuang, Xingtai, and Handan. The distribution of potential corridors is similar to that of key corridors, with some differences (see Fig. 8). The migration paths among each two sources are greater than that of the key corridors, and some potential corridors pass through Zhangjiakou. Overall, the LESP in Beijing–Tianjin–Hebei region are mainly located in the northern and western mountainous areas. In plain area there locates the existing corridors.

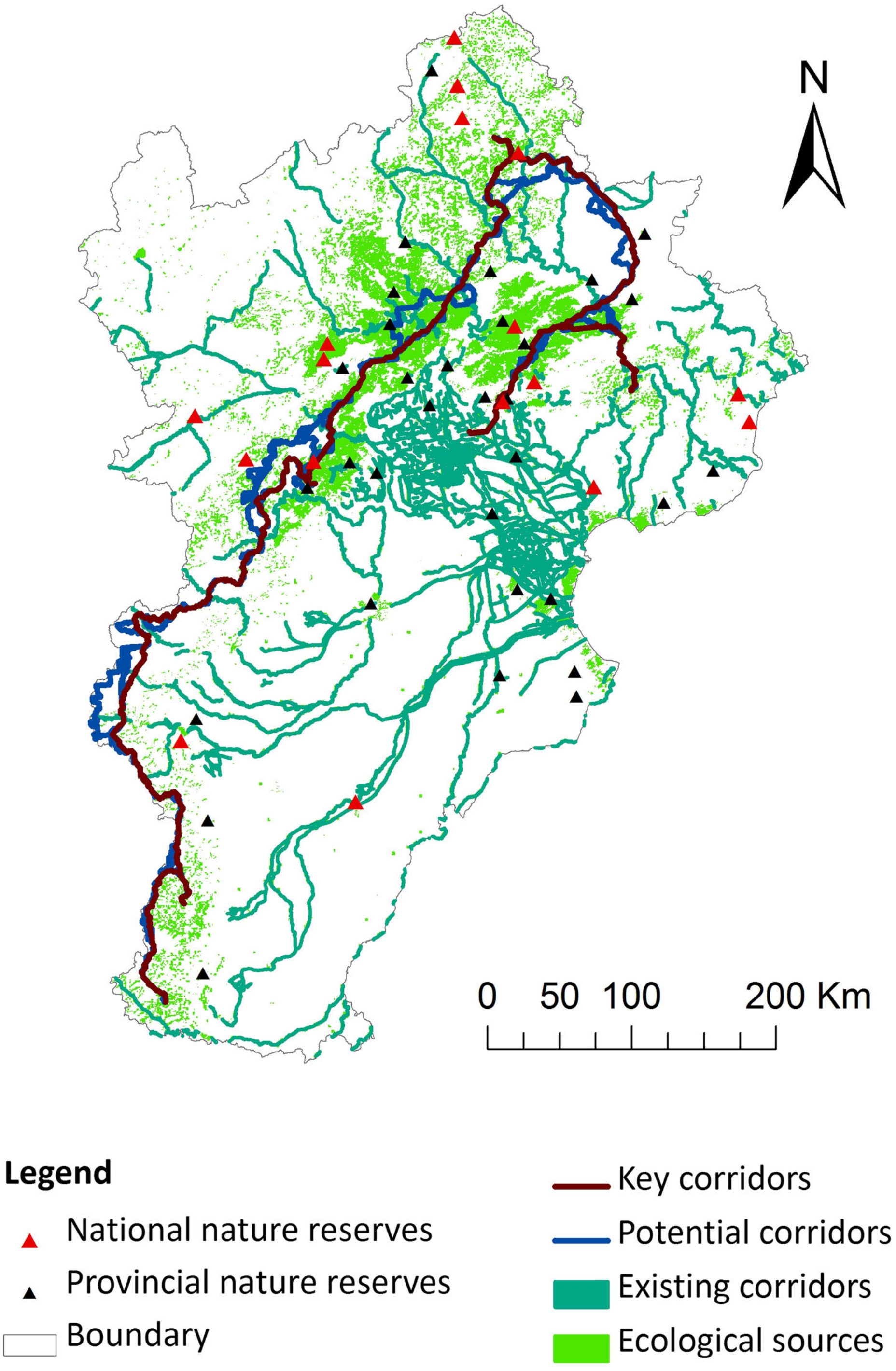
The Beijing–Tianjin–Hebei Coordinated Development Guideline, which was approved by the Chinese government on April 30, 2015, indicates that more economic development activities will occur across the whole region. This will mean more complex flows of materials and energies, which may exert new pressure on the ecosystem. To ensure sustainable development, ecological construction is urgently required to maintain ecological security. The LESP of this region is essential for the ecological protection of the whole urban agglomeration. Therefore, great efforts should be made to integrate the resources needed for ecological conservation from every city so as to protect every part of the identified LESP. The natural resources in Chengde, Beijing, and Zhangjiakou and the water resources of the whole region should be given high priority for conservation. During new construction, the source areas and corridors should be protected from exploitation.

Discussion

Methodological advantages

The LESP is a form of spatial distribution outcome obtained from a recognition process aiming to conserve critical ecological land. There are diverse LESP identification approaches for different conservation objectives and

Fig. 8 Landscape ecological security pattern and nature reserves of Beijing-Tianjin-Hebei region



emphases, but previous studies offer a common idea regarding the identification approaches for LESP source areas, all of which focused on the ability of landscape patterns to provide ecosystem services by developing different evolution systems (Kong et al. 2010; Lin et al. 2016). In this study, three main indicators—ecosystem services importance, connectivity importance, and human ecological demand importance—were integrated into the evaluation framework for recognizing ecological sources. This research expanded the traditional purely ecological understanding of LESP. We took a step forward by including the social dimension of urban ecosystems in the identification of LESP source areas.

The first main advantage of this new approach is seen in the study's comparison of ecological sources and patches with the highest degree of habitat importance. The patches with the greatest habitat importance cover 65,505.75 km^2, while the ecological sources cover 36,245.50 km^2; the latter is nearly half of the former. Thus, the new approach proposed in this study produces a more precise outcome. Moreover, the results of previous approaches can only ensure that high level of ecosystem services are provided by the LESP, leaving the question of whether people can receive the benefits of these ecosystem services unanswered. The LESP identified in this study not only provides a good supply of critical ecosystem services but can also fulfill people's usage demand, thus ensuring that more people can easily obtain benefits from approaching these places.

The second advantage of this new approach is the rationality and feasibility of the human ecological demand importance assessment method. We measured human ecological demand importance based on the accessibility of ecological land, recreation behavior characteristics, and the beneficiary population. Specifically, an integrated indicator combining accessibility and population density is used to measure the ability of ecological patches to fulfill people's demand on weekdays, weekends, and holidays. This assessment at different timescales offers a new perspective.

Another advantage of the comprehensive methodology concerns resistance surface creation, and is related to the use of nighttime light data to modify the basic resistance surface. A much greater heterogeneity of resistance coefficients is obtained by considering human activity intensity than the basic resistance surface constructed based on the spatial distribution of land use types. Ecological land featuring high levels of human disturbance was excluded from the least-cost paths. Consequently, the identification result for ecological corridors is more rational and precise.

Significance and application of this new approach

The approach proposed in this study performed a linkage of supply and demand to identify important ecological patches based on the evaluation principle whereby important ecological land should be appropriately distributed with high human demand. Ours appears to be the first study to integrate both the supply and demand of the ecosystems into source area identification. The correspondence between the identified LESP and the nature reserves shows the feasibility of this new methodology. Overall, this approach adds new insights into the methodology of source identification and importance assessment of ecological land.

This study also has practical significance. The results can advance the understanding of local contexts. For example, the results of the importance evaluation for the three key ecosystem services in this region can be used for additional ecosystem services analysis. This study also enriches related studies of urban agglomeration. In China, most relevant studies have focused on the city level (Cen et al. 2015; Wu et al. 2013; Xie et al. 2015; Zhou et al. 2014). Very little work has been done on the level of urban agglomeration (Gao et al. 2012). Beijing–Tianjin–Hebei region, one of the three largest urban agglomerations in China, is under severe environmental pressure. It was recently announced that a world-class city agglomeration ecosystem would be built in the near future. The LESP identification in this study can offer immediate inspiration for decision makers and planners and help them balance environmental conservation and economic development.

This study's approach of coupling ecosystem services supply and human ecological demand to identify LESP can be used in other areas. To facilitate the application of this new approach, two main issues are noteworthy. First of all, specific conservation objectives should be identified before the development of an evaluation system. Field survey and expert consultation should be carefully conducted to evaluate local ecological conditions and identify the problematic and critical ecological issues. In a coastal region, for example, wetland conservation and water resource protection should be given high priority.

For the second part, this case study is only an initial template for constructing LESP in other areas. It is not necessary to apply the methodology proposed in this study in its entirety. Approaches should be adjusted to local contexts and their specific ecological and social characteristics. When evaluating both the supply and demand, the assessment indicators can be modified according to various emphases. In evaluating ecosystem services supply, many other factors, such as the resilience and health of the ecosystem, can influence the supply of ecosystem services (Farley and Voinov 2016; Peng et al. 2017). Therefore, the corresponding indicators can be included in the assessment framework to produce a more accurate result. Regarding human ecological demand, a more in-depth investigation of how local residents interact with ecological land and their preference for ecological land can be performed to better evaluate the demand importance. Other methods, such as participatory methods, expert-based methods, and the process modeling methods described by Wolff et al. (2015), can also be used to enrich the understanding of demand.

Limitations and future research direction

Despite this study's important contributions, it also has limitations. First, identifying LESP by coupling the supply–demand of ecosystem services is only the first stage in protecting the ecological environment. Maintaining LESP is also critical for guaranteeing their ecological conservation effectiveness. Thus, further study on conservation prioritization of patterns based on the consideration of maintenance costs is required. Second, only three types of ecological process were considered in evaluating the quality of ecological land to provide ecosystem services. Future studies could involve more ecological processes in the evaluation system. The results of relevant studies done in the same region could be incorporated into the identification of ecological sources. Third, concerning ecological corridors, this study deals only with the identification stage, without discussing construction issues. The width of the corridors can directly affect their ecological functions (Gilbert-Norton et al. 2010). Further efforts should be made to determine the width of each corridor in the security pattern.

Conclusion

Following landscape ecology principles, this study identifies LESP of Beijing–Tianjin–Hebei region based on the theory of LESP combined with the application of GIS analysis. Previous studies fail to adequately consider the demand for ecosystem services when identifying ecological sources. We introduced a more integrated approach that includes human ecological demand importance evaluation in the identification framework, combined with habitat importance and connectivity assessments. In the construction of the resistance surface, disparities within the same land use type were detected using nighttime light data, which provided more accuracy. Then, through the MCR model, we identified a reliable ecological security pattern consisting of source areas and ecological corridors, validated by the location of national and provincial nature reserves. The pattern is mainly located in the northern and western mountainous areas. The main findings on the security pattern can not only promote the understanding of local ecological characteristics but also serve as a useful reference to guide decision makers in conducting rational exploitation.

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