Applied Geography 167 (2024) 103272

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

Trade-offs of landscape connectivity between regional and interregional ecological security patterns in a junction area of Beijing-Tianjin-Hebei region

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A R T I C L E I N F O

Handling Editor: Dr. Y.D. Wei

Keywords:
Connectivity robustness
Trade-offs of landscape connectivity
Interregional perspective
Regional perspective
Ecological security pattern

A B S T R A C T

Highly urbanized areas are confronted with insufficient space for regional ecological conservation. Therefore, the implementation of ecological conservation has shifted from region to inter-region in China. However, the effectiveness of interregional ecological conservation remains unknown. Taking Tongzhou District and the Three Northern Counties of Hebei Province (TZ&TNC) for example, the key issue was explored based on ecological security pattern (ESP) construction and an index of landscape connectivity. The results showed that 93 (73) ecological corridors connected 63 (45) ecological sources from the regional (interregional) perspective. The trade-offs in landscape connectivity between the two perspectives were obvious, and the interregional ESP enhanced the landscape connectivity of the whole study area with significantly increasing in Tongzhou and Sanhe, but decreasing in Xianghe. However, after removing 70% and 56% of the ecological sources in Tongzhou and Sanhe respectively, the importance of landscape connectivity reversed from interregional perspective to regional perspective, indicating that the effectiveness of interregional ecological conservation varied with number proportion of protected patches. This study explored the trade-offs of landscape connectivity between regional and interregional ESPs, highlighting the priority of interregional ecological conservation.

1. Introduction

Urbanization has led to a series of ecological problems, such as intensified habitat fragmentation and biodiversity loss, especially in the urban junction areas (Haddad et al., 2015; Luo et al., 2021). Because of the inconsistency of administrative boundaries and ecosystem boundaries, interregional ecological conservation is particularly critical in these areas (Barnett & Belote, 2021; Lenschow et al., 2016). The key measure to achieve interregional ecological conservation is to ensure the connectivity among various habitats (Roberts et al., 2020; Wolstenholme & Pedley, 2021). Landscape connectivity can measure the ability of important habitats to facilitate species movement and thus has become a key indicator characterizing ecological conservation effectiveness (Choe et al., 2021).

To address the key issue of sustainable landscape patterns identification, the mapping of ecological security patterns (ESPs) based on landscape ecology has been widely applied. ESP has become an important approach to enhancing ecosystem services and optimizing landscape configuration through identifying important landscape elements (e.g. patches and corridors), which can guarantee the stability and sustainability of regional ecosystems (Peng et al., 2018; Yu, 1996). At present, ESP construction has formed the basic paradigm of “ecological source - ecological resistance surface - ecological corridor” (Li et al., 2023; Peng et al., 2018; Zhang et al., 2017). Specifically, ecological sources can undertake important ecological functions, which are mainly identified by comprehensively assessing key characteristics of ecosystems, such as ecosystem service importance, ecological sensitivity, ecological degradation risk, and landscape connectivity (Peng et al., 2018; Zhou et al., 2021). The ecological resistance surface reflects the horizontal obstruction of ecological process in the heterogeneous

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https://doi.org/10.1016/j.apgeog.2024.103272
Received 9 January 2023; Received in revised form 9 April 2024; Accepted 13 April 2024
Available online 25 April 2024

landscape, which is usually measured based on land use type and revised by combining with indicators such as nighttime light intensity, representing the intensity of human activities (Jiang et al., 2021). Based on the mapping of ecological resistance surfaces, ecological corridors can be identified, which are the pathways of ecological flow. The most commonly used identification methods include the minimum cumulative resistance (MCR) model, and circuit model (Diniz et al., 2020).

For a long time, ESPs have been constructed from a regional perspective, aiming to ensure ecological security within a certain range. However, constructing interregional ESPs has been emphasized recently, as it can guarantee the continuity and integrity of the ecosystem and strengthen the connection of ecological sources between the target conserved area and the surrounding areas (Dong et al., 2021; Liu et al., 2018). Due to the different ecological backgrounds across various regions, interregional ESPs might over-rely on the ecological services supply of regions with better ecological conditions (represented as the synergy between interregional and regional conservations), while ignoring the ecological conservation demand of regions with lower ecological quality (represented as the trade-off between interregional and regional conservations) (Pouzols et al., 2014; Huber et al., 2010). Therefore, it is necessary to clarify the trade-offs and synergies between different regions in constructing interregional ESP, which is the premise of carrying out interregional sustainable ecosystem management.

Landscape connectivity is an important index to evaluate the overall performance of ESPs and can be quantified through network analysis (Luo et al., 2020; Mu et al., 2022). Network analysis based on graph theory can identify and quantify the contribution of key elements such as patches and corridors to the overall landscape connectivity, which has been widely used in previous studies (Sahraoui et al., 2021; Saura & Pascual-Hortal, 2007). By calculating network parameters and combining node removal scenarios with habitat loss patterns in migration networks, the importance of nodes to the maintenance of landscape connectivity can be quantitatively analyzed (Dhanjal-Adams et al., 2017; Xu et al., 2020).

With the rapid development of urbanization, the integration of regional development strategies has become an important planning issue of urban agglomerations in China. Exploring the strategies of interregional ecological conservation is also one of the key approaches to guaranteeing sub-national ecological security (Peng et al., 2017). Tongzhou District and Three Northern Counties of Hebei Province (TZ&TNC) in China, identified as the core areas of the Beijing-Tianjin-Hebei coordinated development, are facing a critical challenge due to the conflict between urban expansion and ecological conservation. To solve these problems, the Coordinated Development Plan for Tongzhou District of Beijing and Sanhe, Dachang, and Xianghe counties of Hebei Province was proposed in 2020 to jointly construct interregional ESP. However, the key question of the difference in the impacts of interregional ecological conservation on the ecological conservation effectiveness among different regions is still unclear. Taking TZ&TNC as the study area, ESPs from interregional and regional perspectives were constructed in this study respectively, and the difference of landscape connectivity from these two perspectives was explored with network analysis. We further clarified the trade-offs of interregional ecological conservation among various administrative units. More specifically, this study was aimed at the following scientific questions: What were the differences in landscape connectivity between regional and interregional conservations? Which region's landscape connectivity would be sacrificed or enhanced through interregional ecological conservation?

2. Methods

2.1. Study area and data sources

TZ&TNC (39°36′ ~ 40°05′N , 116°32′ ~ 117°15′E) is located in the central part of the Beijing-Tianjin-Hebei region, including Tongzhou District of Beijing City, and Sanhe City, Dachang County and Xianghe County of Hebei Province (Fig. 1). Although there are administrative division boundaries between regions, regional economic development tends to be integrated, forming an increasingly enhanced collaborative development context. TZ&TNC covers an area of 2164 km^2, with a total population of 3.43 million by the end of 2020. The study area is located in the farming area of the North China Plain, with Chaobai River and Beiyun River draining each of the counties. The land use type is mainly cultivated land and construction land. To balance the needs of urban expansion and ecological conservation, the central government issued the policy of regional collaborative development by putting forward the requirements of collaborative construction of ESP, through the conservation of large ecological patches, construction of ecological corridors, and comprehensive promotion of ecological conservation and restoration.

The datasets used in this study include: (1) Land use and land cover (LULC) data in 2018 with spatial resolution of 30 m from the Resource and Environmental Science Data Center (http://www.resdc.cn/); (2) ASTER GDEM data derived from the Geospatial Data Cloud (http://www.gscloud.cn/) with spatial resolution of 30 m; (3) Nighttime light data of September 2018 obtained from LJ1-01 data platform (http://59.175.109.173:8888/app/login.html), characterized by high imaging quality and spatial resolution of about 130 m; (4) Annual precipitation data during 2010–2018 from 24 meteorological stations in Beijing-Tianjin-Hebei region obtained from the China Meteorological Data Service Center (http://data.cma.cn/), which was used to obtain the rainfall map with spatial resolution of 30 m of TZ&TNC in 2018 by applying the co-kriging interpolation technique in ArcGIS10.5, with DEM as the covariate; (5) Road network data in vector format collected from Open Street Map (http://www.openstreetmap.org/); (6) Soil-related data obtained from the Harmonized World Soil Database (http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/), with spatial resolution of 1 km; and (7) MODIS17A Net Primary Productivity (NPP) data with spatial resolution of 500 m from the United States Geological Survey (https://www.usgs.gov/). All datasets were resampled using the nearest neighbor method with spatial resolution of 30 m.

2.2. ESP construction

The ESPs of TZ&TNC were constructed from both regional and interregional perspectives. From the interregional perspective, the ESP was constructed by taking four counties as the research area. From the regional perspective, the ESP of each county was constructed individually. The ESPs from two perspectives were constructed in three steps: (1) to identify the ecological sources through the assessment of ecosystem service importance; (2) to construct an ecological resistance surface based on land use types and nighttime light intensity; and (3) to extract ecological corridors with MCR model.

2.2.1. Identification of ecological sources

As an important element of ESP, ecological sources can provide an amount of maximum ecosystem services within a limited space (Peng et al., 2019). TZ&TNC has suffered from dense population, resulting in a shortage of water resources and limited forest coverage. Based on the natural background characteristics of the study area, in this study we selected and evaluated four important ecosystem services, i.e. habitat maintenance, water conservation, soil retention, and carbon fixation (Xu et al., 2023; Zhang et al., 2017). After the normalization of each kind of ecosystem services, the comprehensive importance of ecosystem services was obtained through superimposing the four ecosystem services with equal weight. Subsequently, the ecological patches with the comprehensive importance of ecosystem services in the top 20% and the area bigger than 1 km^2 were selected as ecological sources.

In detail, habitat maintenance refers to the ability to maintain habitat conditions and biological resources to continuously provide

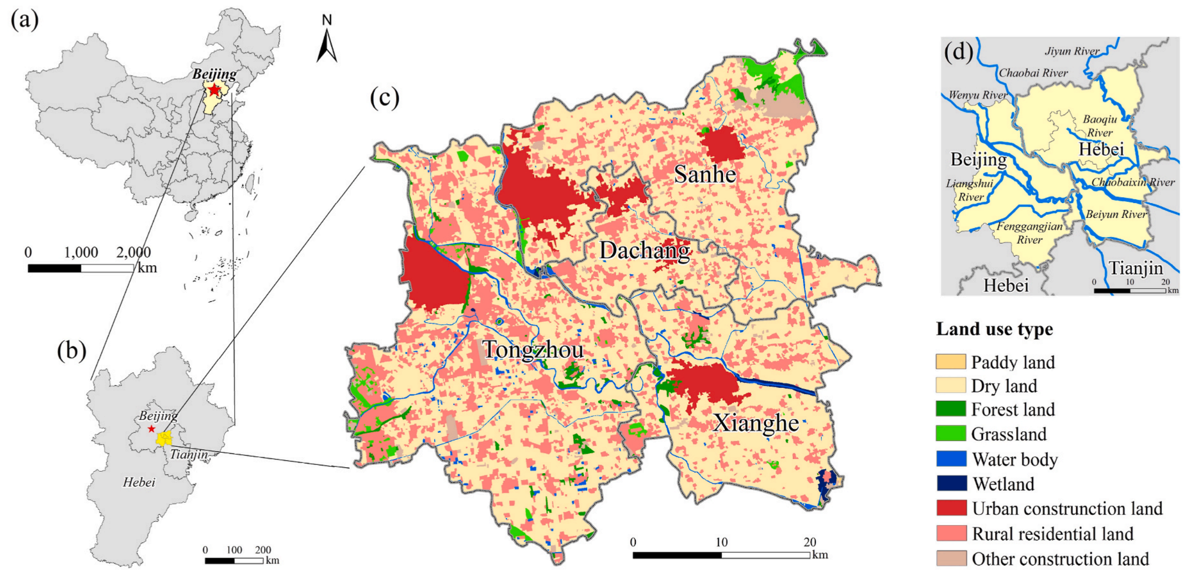

Fig. 1. Geographical location and land use types in TZ&TNC: (a) Beijing-Tianjin-Hebei region in China, (b) TZ&TNC in Beijing-Tianjin-Hebei region, (c) land use types of TZ&TNC in 2018, and (d) main rivers in TZ&TNC.

suitable living conditions for individuals and populations (Dong et al., 2021). The habitat quality module of the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model was used to evaluate habitat maintenance service in TZ&TNC. This model evaluates the degradation degree of different land use types by determining threat sources and suitable habitats, combined with factors such as sensitivity to threat sources and maximum distance to threat sources (Wang et al., 2022a, 2022b). Suitable habitats included forest land, grassland, water body, and wetland, while threat sources were cities, railways, primary roads, secondary roads, and cultivated land. The service of habitat maintenance was calculated as follows:

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(\frac{\omega_r}{\sum_{i=1}^{R} \omega_r} \right) r_y i_{rxy} \beta_x S_{jr} \quad (1)$$

$$Q_{xj} = H_j \left(1 - \frac{D_{xj}^z}{D_{xj}^z + k^z} \right) \quad (2)$$

where D_{xj} and Q_{xj} represent the habitat threat level and habitat maintenance of pixel x in the habitat type j, respectively; R is the number of threat sources; Y_r is the set of grid cells on r's raster map; ω_r is the influence weight of r^{th} threat source; r_y is the actual value of pixel y on the r^{th} threat source layer; i_{rxy} is the influence degree of pixel y on the r threat source; β_x is the conservation degree of the habitat pixel x under current conditions; S_{jr} is the sensitivity of the habitat type j to the r threat source; H_j is the suitability of the habitat type j; and k and z are scaling parameters.

Water conservation refers to the function of a natural ecosystem to intercept and detain precipitation through forest canopy, litter layer, root system, and soil layer, enhance soil infiltration and storage, and thus effectively conserve soil water, regulate surface runoff, and replenish groundwater (Zhang et al., 2017). In this study, the water balance equation was used to calculate the water yield based on the water yield module of the InVEST model. In addition, topography, evapotranspiration, and other factors were considered to adjust the amount of water conservation as follows (Walston et al., 2021):

$$\mathrm{R} = \min(1, 249 / \mathit{Velocity}) \times \min(1, 0.9 \times \mathrm{TI} / 3) \times \min(1, K_{sat} / 300) \times \mathrm{Y}_{xj} \quad (3)$$

$$Y_{xj} = \left(1 - \mathrm{AET}_{xj} / \mathrm{P}_x\right) \times \mathrm{P}_x \quad (4)$$

where R is water conservation (mm); K_{sat} is soil saturated hydraulic conductivity (cm/D); *Velocity* is velocity coefficient; *TI* is the topographic index; Y_{xj} is water yield; AET_{xj} is the annual average evapotranspiration of pixel x of land use type j; and P_x is the annual precipitation of pixel x.

Soil retention refers to the ability of an ecosystem to control soil erosion and maintain sediment storage (Peng et al., 2019). In this study, the Revised Universal Soil Loss Equation (RUSLE) was used to quantify soil retention service in TZ&TNC as follows:

$$A = R \times K \times LS \times (1 - C \times P) \quad (5)$$

where A is the soil retention ($t/hm^2 \cdot a$); R is rainfall erosivity factor ($MJ \cdot mm/hm^2 \cdot h \cdot a$); K is soil erodibility factor ($t \cdot hm^2/hm^2 \cdot MJ \cdot mm$); LS is slope length and steepness factor; C is vegetation cover management factor; and P is soil erosion control measure factor.

Carbon sequestration is an important regulation service of natural ecosystems and contributes to reducing atmospheric CO_2 concentrations (Post & Kwon, 2000). The carbon fixation capacity of an ecosystem is provided by the vegetation and soil (Chen et al., 2019). Existing studies have shown that vegetation fixes 1.63 units of carbon when accumulating 1 unit of net primary productivity (Hua et al., 2021). Soil carbon fixation of cultivated land was 0.38 t/ha (Jiang et al., 2021). In this study, NPP data and LULC data were used to calculate the carbon fixation capacity as follows (Jiang et al., 2020):

$$CS = 1.63 \times NPP_{C,F,G} + CS_c \quad (6)$$

where CS is the carbon sequestration; $NPP_{C,F,G}$ is NPP of cultivated land, forest land and grassland; and CS_c is soil carbon sequestration of cultivated land.

2.2.2. *Extraction of ecological corridors*

As key carriers to maintain a smooth flow of ecological processes between core patches, ecological corridors can provide shelters for the migration of animals, and more generally, the diffusion of species (Li et al., 2017). The MCR model is one of the most widely used methods to identify ecological corridors, which can extract the path with the minimum cumulative resistance when considering the migration of species from one ecological source to another (Mcrae et al., 2008). The calculation is as follows:

$$MCR = f \min \sum_{j=n}^{i=m} D_{ij} \times R_i \tag{7}$$

where MCR is the minimum cumulative resistance; f is the positive correlation between the minimum cumulative resistance and ecological process; D_{ij} is the movement distance of species from ecological source i to ecological source j; and R_i is the resistance of ecological source i.

In this study, the Linkage Mapper Toolbox of ArcGIS 10.5 was used to extract ecological corridors. The determination of ecological resistance coefficient R_i depends on the construction of the particular ecological resistance surface. The ecological resistance surface reflects the horizontal obstruction degree of ecological process in heterogeneous landscapes (Zhou et al., 2021). The basic resistance coefficients of different land use types were assigned as 30, 20, 1, 10, 50, 10, 500, 400, and 300 for paddy field, dry land, forest land, grassland, water body, wetland, urban construction land, rural residential land and other construction land, respectively. However, this homogenization would not represent the difference in the impact of human disturbance on the ecological resistance under the same land use type. As a comprehensive representation of human activity intensity, nighttime light intensity can be used as a proxy for characterizing urbanization, economic development, population density, and energy consumption. Therefore, nighttime light intensity was used to modify the basic ecological resistance surface as follows:

$$R_i = \frac{NL_i}{NL_a} \times R \tag{8}$$

where R_i is the modified ecological resistance of the grid i; R is the basic resistance coefficient corresponding to the land use type of the grid i; NL_i is the nighttime light intensity of the grid i; and NL_a is the average nighttime light intensity corresponding to the land use type of the grid i.

2.3. Comparison of landscape connectivity

Landscape connectivity indicates the degree of convenience of a landscape to facilitate ecological flow (Hamonic et al., 2023). In this study, the index of connectivity robustness was used to evaluate the difference of landscape connectivity corresponding to ESPs constructed from different perspectives (Minor & Urban, 2008). Specifically, connectivity robustness refers to the ability of the network to remain connected even after some nodes are destroyed (Luo et al., 2020). We extracted the patch center of the ecological sources as ecological nodes, and then conducted 100 random node removal experiments using the igraph package in R to simulate the random destruction of one ecological node each time. The connectivity robustness is calculated as following:

$$R = \frac{C}{N - N_r} \tag{9}$$

where R is the connectivity robustness of the ESP; C is the number of nodes in the maximum connected subgraph of the network after removing some ecological nodes; N is the total number of network nodes; and N_r is the number of nodes removed.

Comparing the landscape connectivity of ecological nodes is helpful to provide a specific and effective basis for interregional ecological conservation policies. Therefore, the index of connectivity robustness was used to compare landscape connectivity of individual nodes between the interregional and regional perspectives. Firstly, the intersecting ecological sources of interregional and regional perspectives were extracted. Secondly, each ecological source was taken as the first node in the network, and the connectivity robustness after the node was removed from the two perspectives was calculated respectively, which was named the landscape connectivity importance (LCI) of this node. Subsequently, the LCI of all intersecting ecological sources was calculated one by one. Finally, the difference of LCI (LCID) of the intersecting ecological sources was obtained by subtracting the LCI of the regional perspective from the LCI of the interregional perspective as follows:

$$LCID = LCI_i - LCI_r \tag{10}$$

$$LCI = 1 - R \tag{11}$$

where $LCID$ is the difference of landscape connectivity importance between the two perspectives of certain intersecting ecological sources; LCI is the landscape connectivity importance of the specific ecological source; LCI_i and LCI_r are the landscape connectivity importance from the interregional perspective and regional perspective respectively; and R is the connectivity robustness of remaining ESP after removing the specific ecological source.

3. Results

3.1. Spatial distribution of ecosystem services

The spatial distribution of the four ecosystem services (i.e. habitat maintenance, water conservation, soil retention, and carbon sequestration) had similar characteristics across the TZ&TNZ (Fig. 2). The areas of high ecosystem service importance were distributed in the Pan Mountain in the northeast of Sanhe City, with higher vegetation coverage and less human activities. The low ecosystem service importance was mainly distributed across impervious surface areas such as urban construction land and rural residential areas. These areas lacked vegetation coverage and were characterized by high intensity of human activities.

In details, the distribution of habitat maintenance service and water conservation service had similar spatial distributions. In addition to Pan Mountain, the forest land in the western part of Tongzhou District, the Chaobai River across the four counties, the Wenyu River and Beiyun River in Tongzhou District, the Chaobaixin River in Xianghe County, and the wetlands around these rivers all had good habitat maintenance and water conservation capacity. Areas with high soil retention service were only distributed in the forest land in the northeast of Sanhe City. Because of the high altitude and high degree of topographical complexity, these areas had a large potential of soil erosion. And thus the potential erosion of soil could be maintained by enhanced vegetaton coverage. However, Tongzhou district, Dachang County, and Xianghe County had low soil retention due to flat terrain. Areas with high carbon sequestration were mainly distributed in forest land, grassland, and cultivated land, while the carbon sequestration in urban areas with high population densities was close to zero.

3.2. ESPs from regional and interregional perspectives

The ESP in TZ&TNC from interregional perspective was shown in Fig. 3a. There were 45 ecological sources with a total area of 362.62 km^2, accounting for 16.76% of the total area of the study area. The largest ecological source was located in the central region across the administrative boundary of the four counties, including Chaobai River, Beiyun River and other important rivers, covering an area of 243.43 km^2, accounting for 67.13% of the total ecological sources. The ecological sources were mainly distributed in Tongzhou District, Xianghe County, and Sanhe City, accounting for 41.72%, 30.39%, and 23.62% of the total ecological sources in the study area from interregional perspective, respectively. Dachang County had the least ecological sources, only accounting for 4.27% of the total ecological sources. The ecological sources were effectively connected by 73 ecological corridors, with a total length of 190.52 km. The ecological corridors were mainly distributed in Tongzhou District, accounting for 69.47% of the total length of ecological corridors in the study area.

The ESP from the regional perspective was obtained by integrating

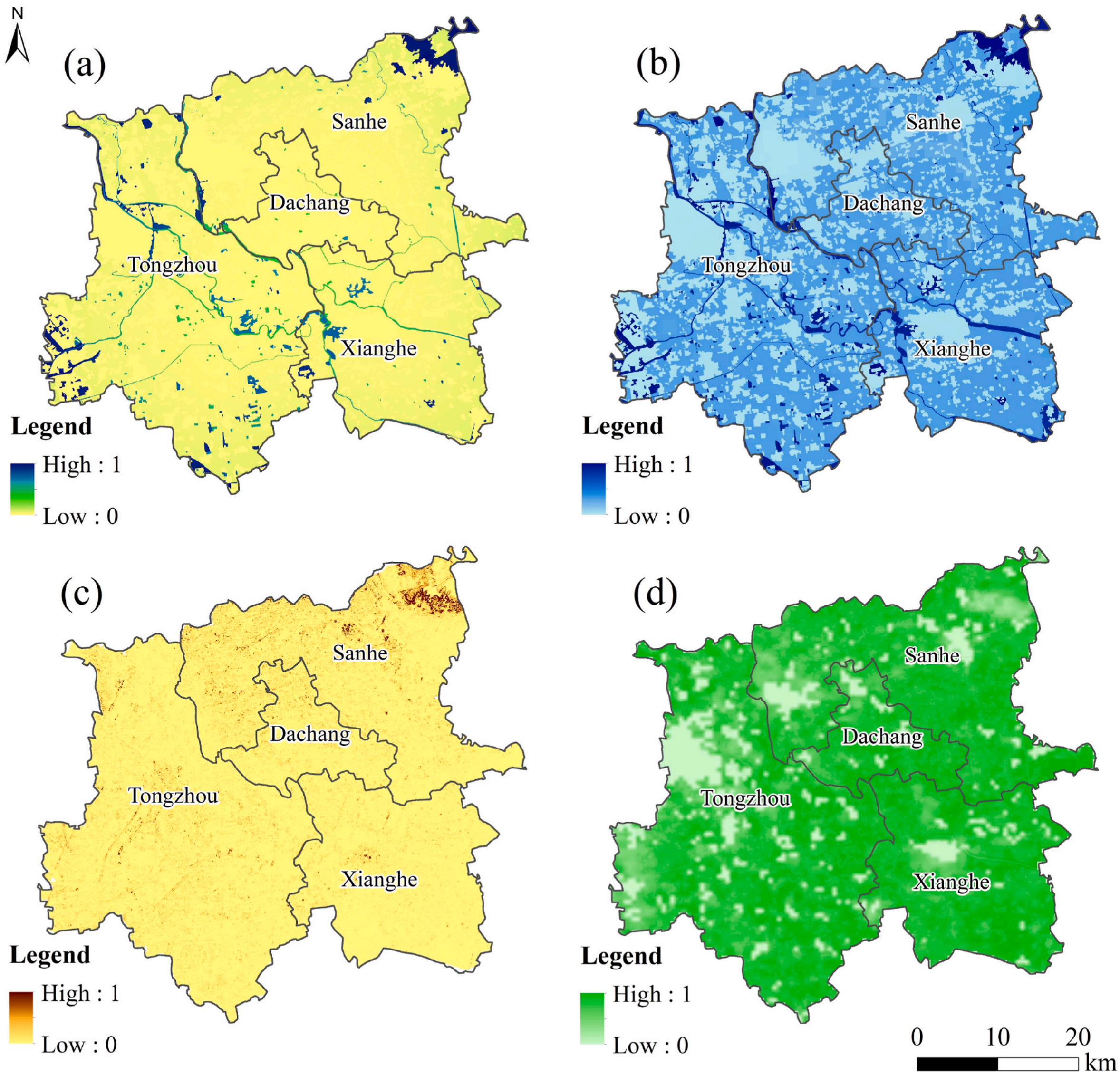

Fig. 2. Spatial patterns of ecosystem service importance in TZ&TNC: (a) habitat maintenance, (b) water conservation, (c) soil retention, and (d) carbon sequestration.

the ecological sources and ecological corridors identified from each county alone (Fig. 3b). The total area of ecological sources from the regional perspective was roughly equivalent to that from the interregional perspective, which was 353.61 km^2. However, they had different spatial distributions. There were 63 ecological sources in the four counties, mainly distributed in Tongzhou District, Sanhe City, and Xianghe County, accounting for 43.41%, 28.05%, and 22.23% of the total ecological sources in the study area from regional perspective, respectively. The ecological sources on the boundary of each county were connected, and the ecological corridors only connected the ecological sources within each county. There were 56, 19, 5, and 13 ecological corridors connecting ecological sources in Tongzhou District, Sanhe City, Dachang County, and Xianghe County respectively, with a total length of 264.40 km.

The overlapping area of the ecological sources of regional and interregional perspectives in TZ&TNC accounted for 80.12% of the total area of all ecological sources (Fig. 3c). Important rives (i.e. Chaobai River - Chaobaixin River, and Wenyu River - Beiyun River) and significant habitats such as Pan Mountain were identified as ecological sources in both perspectives. The overlapping area proportions of ecological sources in Tongzhou District, Sanhe City, Dachang County, and Xianghe County were 85.37%, 85.75%, 61.15%, and 71.35%, respectively. This indicated that Dachang County had the worst ecological background conditions across the study area, whereas Tongzhou District and Sanhe City were relatively better. The wetlands and cultivated land around Chaobaixin River in Xianghe County were identified only from interregional perspective, while the wetlands around Fenggangjian River and Yongle Ecological Park in Tongzhou District, the wetlands around Baoqiu River in Dachang County, and cultivated land in Sanhe City were identified only from regional perspective.

Affected by the distribution of ecological sources, the overlap of ecological corridors was relatively low. The length ratio of ecological corridors overlapped in the study area was 43.72%, and the overlapping rates in Tongzhou District, Sanhe City, Dachang County, and Xianghe County were 51.23%, 40.06%, 43.4%, and 71.67%, respectively. The overlapping rate of Xianghe County was significantly higher than the other three counties. In addition, the overlapping rate of ecological sources was also more than 70%, indicating that Xianghe County had the least difference in ecological conservation goals between the two perspectives.

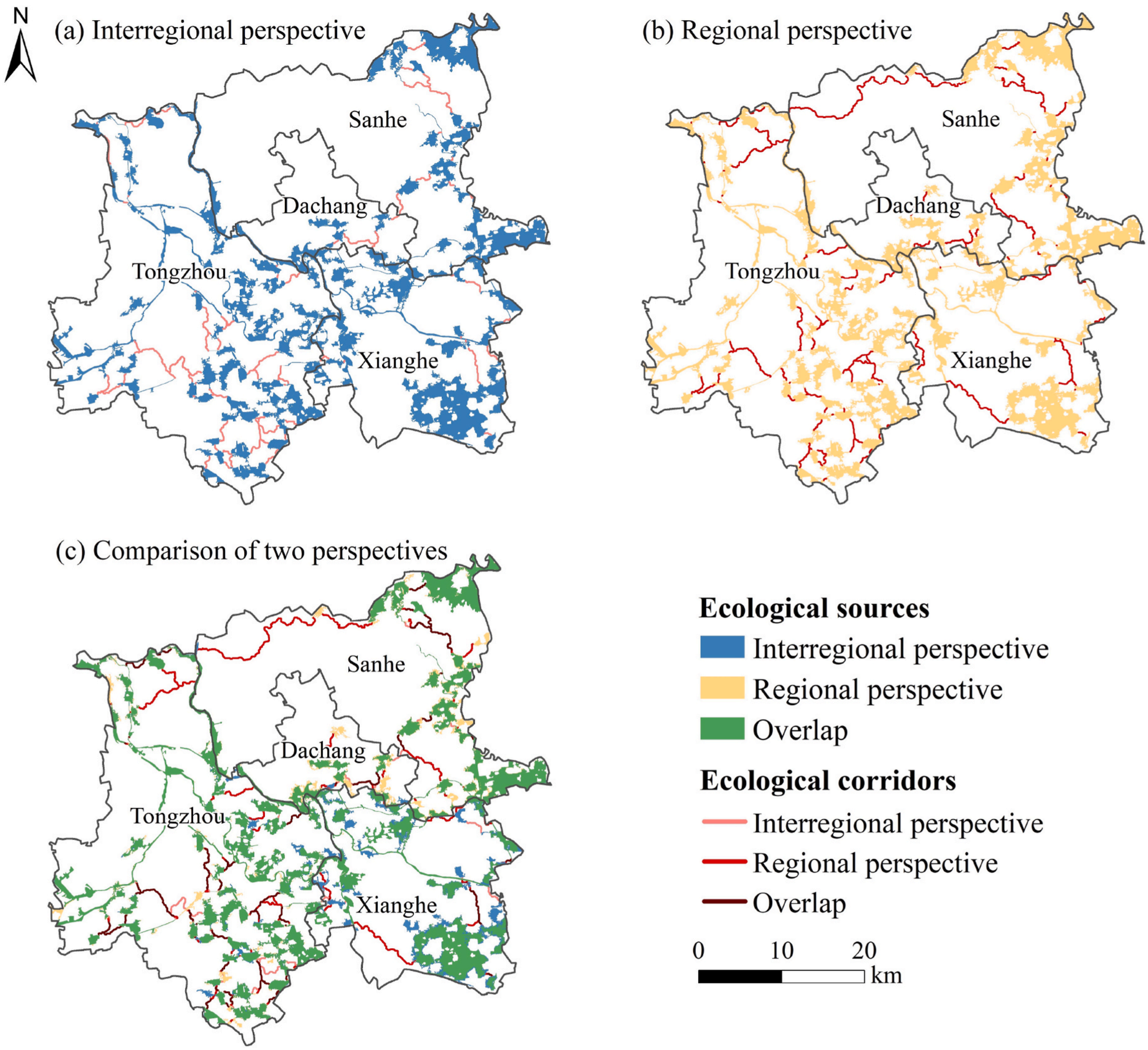

Fig. 3. Ecological security patterns in TZ&TNC: (a) interregional perspective, (b) regional perspective, and (c) their comparison.

3.3. *Landscape connectivity of ESPs from interregional and regional perspectives*

In order to avoid the contingency of experimental results, the median of the results of 100 random node removal experiments was used to measure the landscape connectivity of ESPs (Fig. 4). The initial value of landscape connectivity in TZ&TNC from the interregional perspective was 1 (Fig. 4a). After 8% nodes were removed, the landscape connectivity began to decrease. After removing 78% nodes, the landscape connectivity was below 0.25 and the network nearly collapsed. From the regional perspective, the initial value of landscape connectivity was 0.5 due to the lack of effective connectivity of ecological sources in different counties. As the nodes were removed in turn, landscape connectivity slowly declined until the network collapsed.

The change of landscape connectivity of ESPs in Tongzhou District was shown in Fig. 4b. When the first 20% nodes were removed, the landscape connectivity remained to be 1 in both interregional and regional perspectives, indicating that there were redundant nodes in the networks, and the removal of these nodes did not affect the overall connectivity of the networks. After 28% nodes were removed, the landscape connectivity from the interregional perspective decreased slowly from 0.88, while that from the regional perspective decreased rapidly from 0.89. After 70% nodes were removed, the landscape connectivity from the regional perspective was higher than that from the interregional perspective.

The change in landscape connectivity of ESPs in Sanhe City (Fig. 4c), was similar to that of Tongzhou District. The initial value of landscape connectivity from the interregional perspective was 0.96. When 11% nodes were removed, the landscape connectivity dropped sharply for the first time. From the regional perspective, the initial value of landscape connectivity was 1. When the first node was removed, landscape connectivity began to decline sharply until 56% nodes were removed, and then landscape connectivity was higher than that from the interregional perspective.

The change in landscape connectivity of ESPs in Dachang County was more erratic from both perspectives (Fig. 4d). From the interregional perspective, landscape connectivity remained at 1 during the removal of the first 35% nodes, and then decreased slowly. When 50% nodes were removed, the landscape connectivity declined dramatically and the network almost collapsed. When the first 40% nodes were removed, the landscape connectivity from the regional perspective remained to be 1, and then, it decreased sharply to 0 with the removal of 80% nodes. When the first 35%–45% and 52%–70% nodes were removed, the landscape connectivity from the regional perspective was higher than that from the interregional perspective.

The change in landscape connectivity of ESPs in Xianghe County (Fig. 4e) was the opposite to that of Tongzhou District and Sanhe City. It did not decline until 20% nodes were removed from the interregional

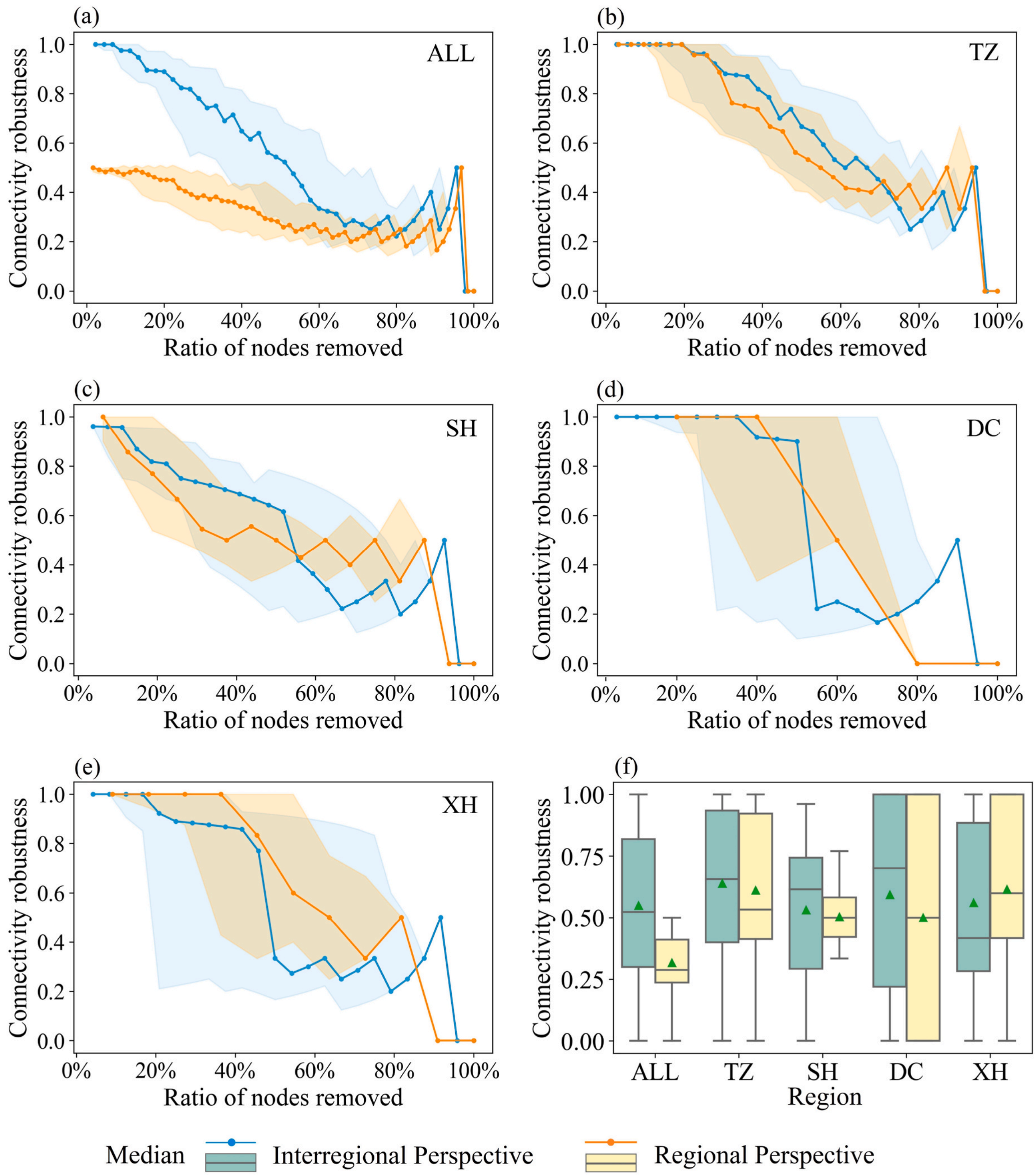

Fig. 4. Line charts and box-plots of landscape connectivity from interregional and regional perspectives in TZ&TNC: (a–e) line charts for the study area (ALL), as well as Tongzhou (TZ), Sanhe (SH), Dachang (DC), and Xianhe (XH) counties respectively, with the upper and lower shaded boundaries representing the upper and lower quartiles of the landscape connectivity, and (f) box-plots.

perspective. When 46% nodes were removed, it decreased sharply until the network collapsed. From the regional perspective, the landscape connectivity was 1 until the removal of the first 46% nodes, and then declined sharply. When 88% nodes were removed, the landscape connectivity from the interregional perspective was higher than that from the regional perspective.

In general, the construction of ESP from interregional perspective enhanced the landscape connectivity of TZ&TNC, Tongzhou District, Sanhe City, and reduced the landscape connectivity of Xianghe County, without significant impact in Dachang County (Fig. 4f). With the continuous removal of nodes, the landscape connectivity in Tongzhou District and Sanhe City changed from "interregionally high & regionally low" to "interregionally low & regionally high", indicating that in both counties the ESP from the interregional perspective was more able to resist slight disturbance, while the ESP from the regional perspective was more able to resist severe damage. In contrast, landscape connectivity in Xianghe County changed from "interregionally low & regionally high" to "interregionally high & regionally low". The change in landscape connectivity of Dachang County was much more complex. The relative level of landscape connectivity of ESP from interregional and regional perspectives changed three times. On the whole, there was little difference in the change of landscape connectivity in Dachang County between the two perspectives.

3.4. Differences of landscape connectivity importance

Reconnecting fragmented habitats is a key objective in the context of interregional ecological conservation (With & Payne, 2021). Network analysis can clarify the impact of removing ecological nodes on the connectivity of important habitats, and thus provide important scientific basis for the enhancement of interregional ecological conservation policies (Pocock et al., 2012). In this study, we further compared the LCID of each ecological source between interregional and regional perspectives (Fig. 5).

Compared with the regional perspective, the total area of the ecological sources with enhanced landscape connectivity importance from the interregional perspective was 104.50 km^2, mainly distributed in the junction of the four counties. For example, the ecological sources of Chaobai River that run through Tongzhou District, Sanhe City and Dachang County, and surrounding wetlands enhanced landscape connectivity importance by 0.52. In addition, the landscape connectivity importance of ecological sources in the Beiyun River, the urban green space and cultivated land around the river in Tongzhou District, the cultivated land in the southeastern part of Sanhe City, and the cultivated land in the eastern part of Xianghe County also increased by 0.52. The landscape connectivity importance of cultivated land in the southeast of Xianghe County and grassland in the southwest of Tongzhou District increased by 0.02. These ecological sources were mainly located at the junction of the four counties, which could not only connect the ecological sources of this county, but also link the ecological sources of other counties from the interregional perspective. However, from the regional perspective, these areas were isolated at the boundaries of each county, with only a few ecological sources that could be connected (Fig. 3b). Therefore, as an important ecological source for maintaining interregional habitat connectivity, these areas should be firstly conserved. Especially for interregional ecological sources, local governments should strengthen cooperation in ecological conservation, maintain consistency of management measures, and avoid the vacuum of "ignoring in both sides" or the conflict of "two rights colliding".

The area of ecological sources with decreased landscape connectivity importance was 80.37 km^2, which were located scattered across the study area. Among them, the landscape connectivity importance of cultivated land in the eastern part of Sanhe City decreased by 0.45, with the decreasing of 0.25 for the landscape connectivity importance of the other two cultivated land patches. The landscape connectivity importance of the Chaobaixin River and Beiyun River in Xianghe County

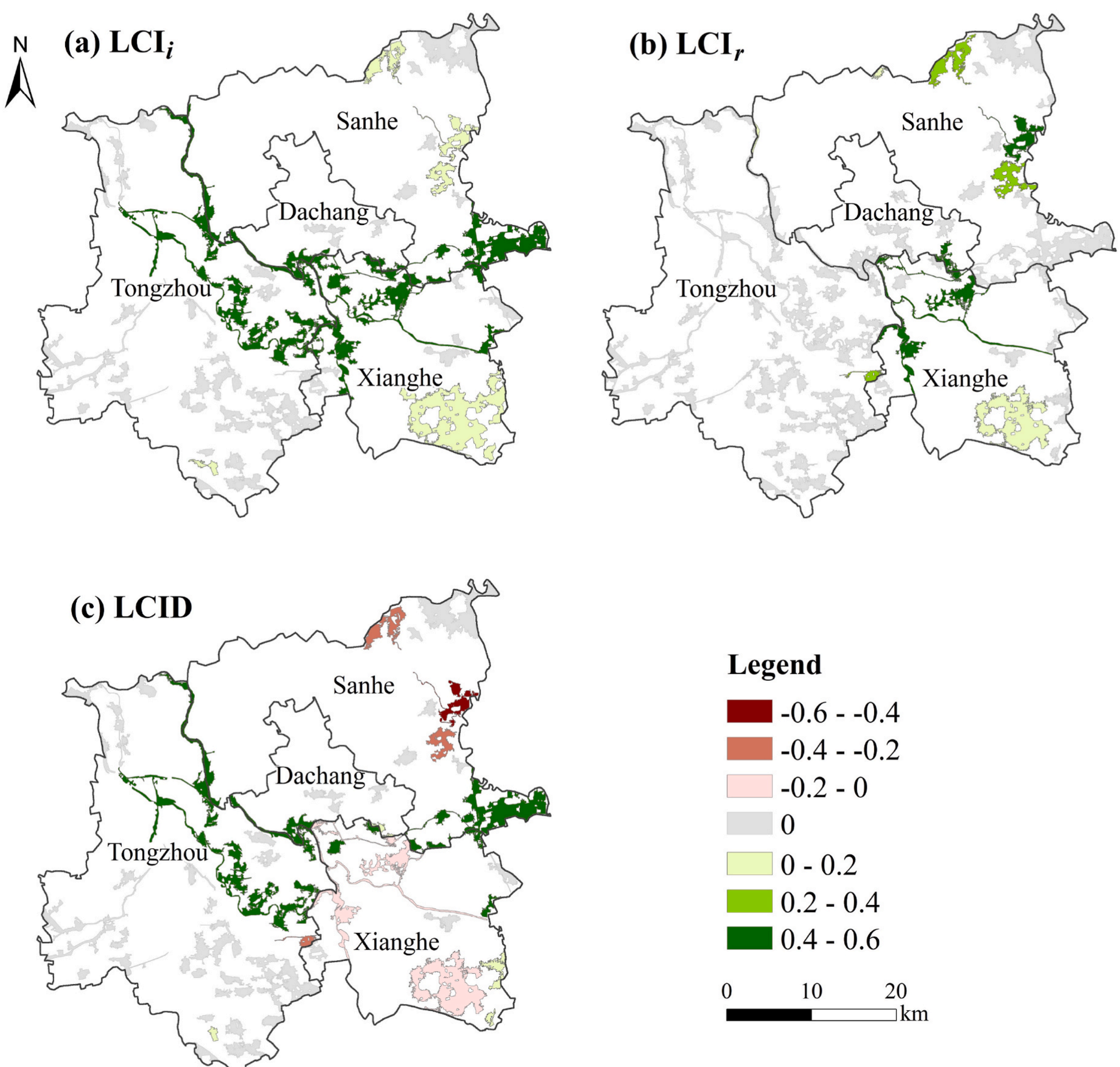

Fig. 5. LCI of ecological sources in TZ&TNC: (a) from interregional perspective, (b) regional perspective, and (c) their difference (LCI: landscape connectivity importance; LCID: the difference of landscape connectivity importance).

decreased by 0.07. Therefore, the government of Sanhe City and Xianghe County should pay attention to the ecological conservation of these areas and avoid the loss of regional habitats while ensuring interregional ecological security.

In addition, 133.82 km^2 of the ecological sources remained unchanged in landscape connectivity importance, mainly distributed in Tongzhou District. Relatively speaking, these ecological sources were located at the boundary of the study area, far away from other ecological sources from the interregional perspective, which was not conducive to landscape connectivity. However, from the regional perspective, these areas could connect with other ecological sources in the county, effectively improving the regional landscape connectivity.

4. Discussion

4.1. Interregional coordination of ecological conservation

Two ESPs identified from interregional and regional perspectives respectively in this study showed different landscape connectivity. Although the whole landscape connectivity in TZ&TNC from the interregional perspective was significantly higher than that from the regional perspective, different counties showed their individual connectivity characteristics considering both perspectives. In particular, Tongzhou District and Sanhe City had higher landscape connectivity from the interregional perspective than from the regional perspective, while in Xianghe County it was higher for the latter. The opposite results clearly indicated that it was necessary to pay more attention to the trade-offs of landscape connectivity when considering the interregional and regional perspectives in constructing ESPs.

Regional planning according to the regional demands can incorporate multiple regional efforts to enhance ecological conservation, but may overlook important benefits from the interregional perspective such as connectivity conservation of important habitats across administrative boundaries (Groves et al., 2002). Restricted by administrative boundaries, ecological corridors identified from the regional perspective can only connect the ecological sources within the county, without linking the ecological sources in the adjacent regions. As a result, the spatial continuity of ecological processes and ecosystem functions is ignored (Wuepper et al., 2020). In this study, important interregional corridors were not identified from the regional perspective, resulting in lower landscape connectivity than that from the interregional perspective.

In addition, the regional ESP would split the important ecological sources located on administrative boundaries and reduce the integration of natural ecosystems (Dong et al., 2021). For example, the Chaobai River, which flowed through the Tongzhou District, Sanhe City, and Dachang County, was divided into several adjacent ecological source patches located on both sides of county boundaries when considering the regional perspective, but could be identified as an integrated source patch from the interregional perspective. Hence, the interregional perspective promoted the landscape connectivity (LCID = 0.52). These results indicated that the traditional ecological conservation policies which considered the administrative region as a management entity might affect the effectiveness of larger-scale (e.g. sub-national) ecological management to a certain extent. Therefore, future policies of regional ecological conservation need to consider and involve the focus of interregional ecological conservation.

However, when addressing interregional ecological conservation, it might omit the areas with relatively higher regional ecological importance. This study showed that the landscape connectivity of several ecological sources from the interregional perspective was lower than that from the regional perspective, which might result in ineffective conservation of several regional ecosystems characterized by weaker ecological conditions. For example, some cultivated land in Sanhe City was not identified from the interregional perspective, which resulted in a decrease in its area proportion of total ecological sources from 28.05% to 23.62% compared with the regional perspective. Furthermore, when considering public participation, the inability of local residents to benefit substantially is limiting the deeper recognition and support for ecological conservation actions (Huber et al., 2010).

It is worth noting that different counties have their individual advantages of landscape connectivity when considering different perspectives. In other words, it is not necessary to sacrifice all regions to meet the needs of interregional ecological conservation. The landscape connectivity of Tongzhou District and Sanhe City was enhanced by interregional ecological conservation, but that of Xianghe County was decreased. This also indicates that ecological conservation should not blindly pursue interregional coordination, but clearly clarify the impact of interregional conservation across different administrative regions, with a particular focus on the trade-offs of landscape connectivity. Therefore, the government needs to determine the beneficiaries and victims of interregional ecological conservation by considering regional equity as well. For the benefited counties, local governments should actively strengthen interregional cooperation, and also give certain compensation to the counties that are negatively affected. The compensation could also be used for enhanced conservation of the ecological sources that meet regional needs, which might further lead to the feedback of promoting the overall ecological conditions at a larger scale in the future.

4.2. Limitations and future research directions

In this study, ESPs were constructed from regional and interregional perspectives respectively to quantify the differences in landscape connectivity. However, there were still some shortcomings. On the one hand, the feedback relationship between landscape patterns and ecological processes varies with the spatial scales considered (Wu, 2004). Hence, the question "how to reasonably select the research scale", needs to be discussed in detail by taking the different regional background and development needs into consideration (Rohr et al., 2014). In combination with administrative division and policy orientation, in this study, we only selected county and multi-counties levels, and thus lacked a comparative analysis and coordinated optimization of ESPs with broader regions, such as the provincial level and urban agglomeration level. In the future, we can combine the current level of territorial spatial planning to further identify and analyze more complete and systematic multi-level ESPs (Dong et al., 2021; Jiang et al., 2021). On the other hand, the landscape connectivity analysis was directly related to the identification of ESPs, which were largely dependent on the selection and quantitative evaluation of ecosystem services. In this study, habitat maintenance, water conservation, soil retention, and carbon sequestration were selected as the representative ecosystem services to carry out the identification of ecological sources. However, it was not guaranteed that these ecosystem services could fully represent the ecological background of TZ&TNC. In addition, the area threshold when identifying the ecological sources is also very important for the final results (Peng et al., 2018). In this study, a single threshold of 20% was set, which made it difficult to effectively identify the conservation priority areas under different conservation inputs in the future.

5. Conclusion

Taking TZ&TNC as the case study area, ESPs were constructed from interregional and regional perspectives, and the trade-offs of landscape connectivity were explored between the two perspectives by characterizing connectivity robustness of complex networks. In this study, 45 ecological sources were identified from the interregional perspective, connected with each other through 73 ecological corridors; whereas 63 ecological sources and 93 ecological corridors were identified from the regional perspective. The overlapping rates of ecological sources and ecological corridors from the interregional and regional perspectives were 80.12% and 43.72%, respectively. The interregional ESPs enhanced the landscape connectivity of TZ&TNC, as well as promoted the landscape connectivity of Tongzhou District and Sanhe City, but led to the decline of the landscape connectivity of Xianghe County. By comparing landscape connectivity from two different perspectives, this study highlighted the trade-offs of enhancing landscape connectivity among different administrative units, providing a scientific basis for the enhancement of interregional ecological conservation policies.

CRediT authorship contribution statement

Menglin Liu: Formal analysis, Methodology, Software, Writing – original draft. **Jian Peng:** Conceptualization, Supervision, Writing – review & editing. **Jianquan Dong:** Methodology, Writing – original draft, Formal analysis. **Hong Jiang:** Methodology, Writing – review & editing. **Dongmei Xu:** Methodology, Writing – review & editing. **Jeroen Meersmans:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare no competing interests.

Acknowledgements

This research is financially supported by the National Natural Science Foundation of China (42130505).

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