

Research Article

Improving Urban Resilience through Green Infrastructure: An Integrated Approach for Connectivity Conservation in the Central City of Shenyang, China

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Green infrastructure (GI) as an operational physical framework is being increasingly recognized as the most cost-effective way to mitigate and adapt to social-ecological challenges through multifunctional ecosystem services. Conserving the connectivity of GI is conducive to maintaining biodiversity and facilitating ecological processes, which contributes to promote urban resilience and implies that urban governance has made a conscious effort to prepare for uncertainties. Though important, there are few studies on operating GI practically to navigate urban resilience. Based on interdisciplinary knowledge and multiple techniques, this study provides an integrated approach, in which relationships between GI connectivity, resilience potential, and conservation strategies are better addressed. The results indicate that significant changes have taken place in terms of the composition, layout, and connectivity of GI in the central city of Shenyang between 1995 and 2015. Through pinch point identification and barrier detection, conservation strategies by protecting key structures, eliminating local barriers, and implementing differentiated measures according to land use types are therefore proposed. The strategies may be helpful for future policy formulation, planning, and management by rehabilitating a GI network to increase urban social and ecological resilience in the study area and other similar megacities. This integrated approach based on a generic process of geometric analysis has general applicability to make interdisciplinary contributions toward urban resilience.

1. Introduction

Contemporary cities have undergone extensive strains on their safety, liveability, and sustainability as they experience rapid urbanization and aggravated global environmental change [1]. As earth systems are urbanized at an unsustainable pace, ecosystems and biodiversity undergo large-scale destruction and human well-being and urban resilience are now experiencing unprecedented challenges [2]. A spectrum of acute shocks and chronic stress events such as extreme heat waves, soil contamination, droughts, floods, and air pollution, which have steadily escalating effects, are increasing in frequency. These challenges create serious vulnerabilities in cities and heighten the risk of losses causing a divergence from a sustainable trajectory of development [3, 4].

Cities need to create positive interactions with their life-support systems to build a broad resilience capacity while undergoing stresses, rather than develop at the expense of them [5, 6]. In the last two decades, there has been a growing consensus on the essential role of reconnecting people in urbanized areas to the biosphere to address current environmental challenges, achieve long-term survivability, and thrive [7]. Nature-based solutions that incorporate natural capital components to address urban environmental issues create multiple economic, social, and ecological benefits, which are now widely acknowledged for cities [8, 9]. Green infrastructure (GI) has therefore emerged and been identified as a concept closely related to and embedded within the framework of nature-based solutions. It provides an integrated and valuable approach for the transition to an inclusive, resilient, and sustainable urban environment [10, 11].

Moving beyond traditional green spaces, which are good for urban aesthetics and public health, GI is discussed more as a cost-effective solution to realign urban areas toward long-term resilience and sustainability [12–14]. As a constantly evolving concept, GI is generally viewed as a strategically planned network of natural and seminatural areas with other environmental features designed and managed to generate and deliver a wide range of ecosystem services under the discourse of sustainability [15, 16]. Although GI provides only a small portion of ecosystem services, in urbanized areas it has strategic significance in the key arena of human-nature interdependence. Human interventions may contribute to urban resilience changes in the current, human-dominated era of the Anthropocene, the era when increasingly negative effects of human activities on natural systems are aggravated [17]. While GI has received increased attention in both academic and practical fields in last decades, there is a lack of clarity around the role that planning and management can play in operationalizing GI to enhance urban resilience and translating that effort into future policy.

Regardless of differentiated project types and local settings, GI is firmly characterized by its multifunctionality and connectivity, which reflects on how it may be used and its capacity for the provisioning of ecosystem services [18]. Multifunctionality is the primary mechanism for GI contributing to urban resilience, making it possible to perform in a flexible way through diversified ecosystem services to respond to uncertainties [19]. Since it is not economically feasible to cover large sections of urban areas with GI, coupled with the growing habitat fragmentation by human activities during the rapid urbanization process, connectivity plays a critical role in maintaining GI function. Good connectivity is conducive in alleviating the isolation effect and maintaining ecological processes, and thus, securing sustainable ecosystem services effectively [20]. Mounting evidence for the provision of ecosystem services to improve resilience suggests the need for better understanding and sustaining GI connectivity [21, 22].

Connectivity represents the degree to which an activity impedes or facilitates ecological processes, e.g., movement of species and gene flow among habitat patches, and determines the proportion of the total habitat area that may be reached and is available in a landscape [23]. Studies suggest that the effects of GI for connectivity may directly influence the magnitude of species movement and indirectly influence biodiversity and ecosystem functions that GI contains [24]. Appropriate connectivity can have a positive influence on biodiversity protection and resilient ecosystem service provision at each location, while decreased connectivity is certain to lead to negative effects on the integrity and stability of ecosystem [25–27]. Two critical aspects of connectivity, structural and functional connectivity, are both of significance in an urban landscape context. Structural connectivity describes the physical relationships between the components of GI networks, while functional connectivity

conversely concerns the behavioural response of biological species to the physical structure [28]. Although they are not necessarily related, it is commonly agreed that functional connectivity will increase when an improvement in the landscape structure allows for the movement or flow of species across the landscape. Furthermore, functional connectivity plays a key role in guaranteeing the provision of ecologically valuable services [29, 30].

Relevant literatures indicate that the significance of urban GI connectivity is largely reflected in its promotion of biodiversity within the site, the movement of organisms, and ecosystem functions [19, 22, 24]. To achieve sustainability in cities, the research and application of GI should focus on the overall improvement of GI connectivity [31]. Notwithstanding, a knowledge gap still exists with respect to connectivity modeling of GI networks and their performance for optimization in real world practice. This deficiency may hinder effective intervention in planning and management of urban GI to improve urban resilience [32]. In terms of connectivity representation, landscape indices and GIS-based methods which can only extract GI network elements, that is, nodes and corridors separately for analysis are common. There is no doubt that these methods make it unlikely for us to intuitively and comprehensively understand the structure and function of a GI network and create obstacles for comprehensive suggestions to improve GI connectivity. Due to the complexity of GI networks, an integrated approach involving multidisciplinary knowledge and multidomain technology is needed to quantitatively simulate the connectivity of GI networks and identify conservation priorities, making reasonable and multiaspect suggestions for strategic GI network and habitat conservation planning [33].

This study focuses on three specific issues. The first is GI network construction and connectivity modeling, the second is the identification of pinch points and barriers of the GI network, and the last is proposing a connectivity conservation strategy considering the first two. The remainder of this study is structured as follows. Section 2 describes the study area, data processing, and the associated methods. The results of the progression, pinch points, and barriers of urban GI corridors, as well as the related analysis, are presented in Section 3. Section 4 proposes some pertinent strategies for connectivity conservation. Section 5 further discusses the advances and limitations of this research. The concluding remarks are summarized in Section 6.

2. Data and Methods

2.1. Study Area. Located in the middle of the Liaohe Plain from 41°11'N to 43°02'N and from 122°25'E to 123°48'E, Shenyang is the capital city of the Liaoning Province. The city has 8.3 million permanent residents (within a total area of 12,860 km²) with 5.3 million residents living in the central city (1353 km²) as of 2015. The elevation of the city's landscape decreases from the northeast to southwest, and

the terrain varies from hilly mountains to alluvial plains. The average elevation is approximately 41.45 m above sea level (see Figure 1). It has a temperate continental climate with an average annual temperature of 6.2–9.7°C. Nearly 27 rivers, including the Liaohe and Hunhe, run through its territory.

2.2. Data Source and Processing. The datasets collected for this study consist of Landsat remote sensing images (at a resolution of 30 m in 1995 and 2015), Google Earth images (at a resolution of 14 m and 3 m in 1995 and in 2015), 1 : 1000 land use maps from the urban master plan (1996–2010), and its revised version (2016). For data processing, we first conducted preprocessing of the two-stage Landsat images. The preprocessed images were then interpreted in the way of human-computer interaction. According to “The Code of Current Land Use Classification” (GB/T 21010-2017), the land use of the study area is classified into five types: agricultural land, forest land, meadow land, built-up land, and water area and wetland with verified accuracy (a precision of over 90%). Second, registration and vectorization were performed on the Google Earth images and land use maps. Then, the green space in the urbanized area was identified and extracted by referring to “The Code for Classification of Urban Land Use and the Planning Standards of Development Land” (GB50137-2011). Finally, the subdivided urban green space (such as urban parks and green belts) was added to the initial classification result, and a total of five categories, along with urban green space, including natural and seminatural elements capable of providing ecosystem services were obtained and recognized as GI, while the rest were designated as background objects. The results of land use classification of the study area are shown in Figure 2.

2.3. Methods

2.3.1. Morphological Spatial Pattern Analysis (MSPA). Morphological Spatial Pattern Analysis (MSPA) originated in mathematical morphology and was later introduced into the science of image analysis and landscape ecology. This method is often used to conduct segmentation on an input binary map and provide a generic pattern analysis framework for detecting and measuring the morphometric aspects through quantitative analysis of the shape, connectivity, and spatial arrangement of digital images [34]. Based on geometric algorithms such as corrosion, expansion, opening, and/or closing operations, it generally divides the foreground objects (objects of interest) of the binary map into seven mutually exclusive morphological feature classes: core, edge, perforation, bridge, loop, branch, and islet [35] (see Figure 3). In this study, all GI elements are defined as a foreground area, whilst urban construction land (excluding urban green land) is recognized as the background. Only the foreground was incorporated into the MSPA segmentation. In contrast to the traditional landscape pattern analysis methods (e.g., landscape indices), the results of the MSPA identify the areas that are important to the flow of material and energy at the pixel level. Moreover, it has additional advantages such as avoiding the shortcomings of

redundancy and high repeatability of landscape features and displaying the segmentation results in a raster format explicitly, which can further be implemented to inform the spatial planning practice.

2.3.2. GI Network Building. The GI network in this study was constructed in four steps (see Figure 4): first, identify adjacent nodes; second, build a network using adjacent nodes and distance data between the nodes; third, calculate cost-weighted distances; and fourth, calculate and mosaic least-cost corridors. The input data and necessary calculations involved in the network construction process are explained below.

- (1) Identify the nodes: based on the MSPA results, the importance of all the cores was evaluated to determine the nodes of the GI network. Since the percentage of integral index of connectivity value loss (dIIC) and the percentage of probability of connectivity index value loss (dPC) can be used to quantify the relative variations of the overall connectivity in the case when a particular patch is missing, the two indicators were thus introduced to examine the contribution of every single core area in terms of its significance for maintaining and enhancing the overall connectivity of the GI network in this study. The larger the values of dIIC and dPC, the more important are the patches that they represent to the GI network [37]. The equations of the indicators and corresponding interpretations are shown as follows [38]:

$$\begin{aligned} \text{dIIC} &= \frac{\text{IIC} - \text{IIC}'}{\text{IIC}} \times 100, \\ \text{IIC} &= \frac{\sum_{i=1}^n \sum_{j=1}^n [a_i a_j / (1 + nl_{ij})]}{A_L^2}, \end{aligned} \quad (1)$$

where dIIC quantifies the importance of a particular green patch to maintain the IIC in the GI network, IIC is the integral index of connectivity, IIC' is the value of IIC after the removal of the patch area from the landscape, n is the total number of green patches, a_i and a_j are attributes of patch i and j , nl_{ij} is the number of links in the shortest path (topological distance) between patch i and j , and A_L is the total area of GI. In general, $0 \ll \text{dIIC} \ll 1$. When all the green patches are not connected, dIIC equals zero. dIIC equals 1 in the case when the total landscape is occupied by GI:

$$\begin{aligned} \text{dPC} &= \frac{\text{PC} - \text{PC}'}{\text{PC}} \times 100\%, \\ \text{PC} &= \frac{\sum_{i=1}^n \sum_{j=1}^n a_i a_j p_{ij}^*}{A_L^2}, \end{aligned} \quad (2)$$

where dPC quantifies the importance of a particular green patch to maintain PC in the GI network, PC is

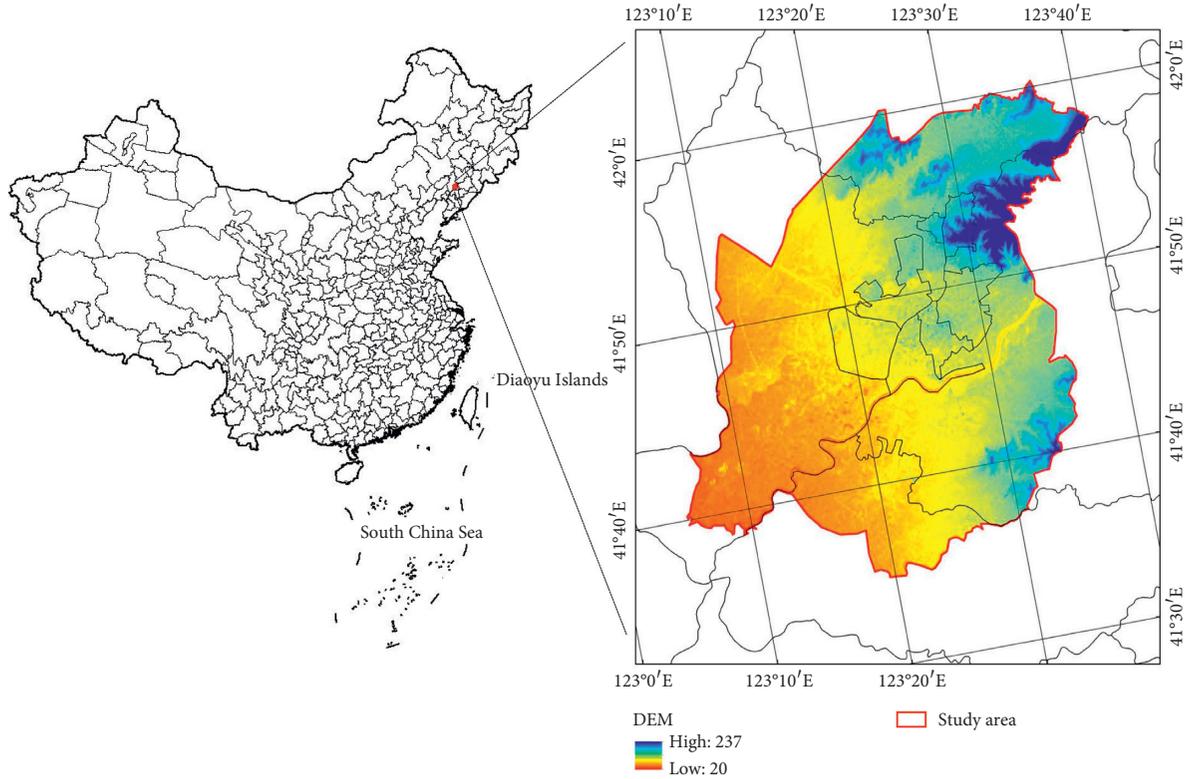


FIGURE 1: Location of the study area.

probability of connectivity, PC' is the value of PC after the removal of the patch area from the landscape, p_{ij}^* is the maximum product probability of all paths between patch i and j , and the meanings of other parameters are the same as above. The value of dPC ranges from 0 to 1 [33].

- (2) Create a resistance raster: a resistance raster is needed to model the impacts of landscape surfaces such as the difficulty, energetic cost, and mortality risk on ecological processes. Ecological processes to provide ecosystem services are generally affected by the accumulated resistance of all the landscape types involved. In the study area, the resistance mainly comes from the artificial and built surfaces, so it is expected to be large in the main urban area and may become quite small in the urban periphery. The resistance values of different landscape types were assigned through referring to the similar study [39] (see Table 1).
- (3) Specify Euclidean distance between the nodes: a text file specifying Euclidean distances between all core pairs can be obtained by using the Conefor Inputs tool, taking the results of the MSPA as input data. The parameters were set to make sure that only the distance between the core areas is less than 1000 m which can be viewed as connected, and not vice versa.

2.3.3. Pinch Point Analysis. Efforts to increase urban resilience through a GI-based approach emphasize the

importance of the functional connectivity within the GI network. Applying circuit theory into the research makes it incorporate functional connectivity analysis in the GI network exploration effectively [40]. Through abstracting the heterogeneous landscape to the conductive surface and the species or genes to electrons, ecological processes such as migration and diffusion of species or genes across complex landscapes according to the characteristics of the random walk of electrons in a circuit were simulated [41]. In specific simulation, some nodes are grounded while the current is inputted to the other nodes, and the current density between the nodes may represent the magnitude of diffusion probability of electrons along a certain path, and the areas with obviously large current densities are defined as pinch points [42, 43].

2.3.4. Barrier Detection and Improvement. Barriers are landscape features that impede ecological processes between ecological areas, and the removal of whom would significantly improve the connectivity potential of the whole network. Detecting and identifying the influential barriers would quantitatively provide an alternative restoration option for practical conservation investments. In addition to focusing on maintaining pinch points from a point of view, removing barriers is a more active but neglected way to promote GI network connectivity. Specifically, based on the modeled least-cost corridors, the barriers and the corresponding improvement scores are obtained. Improvement score quantifies the extent to which conservations can be

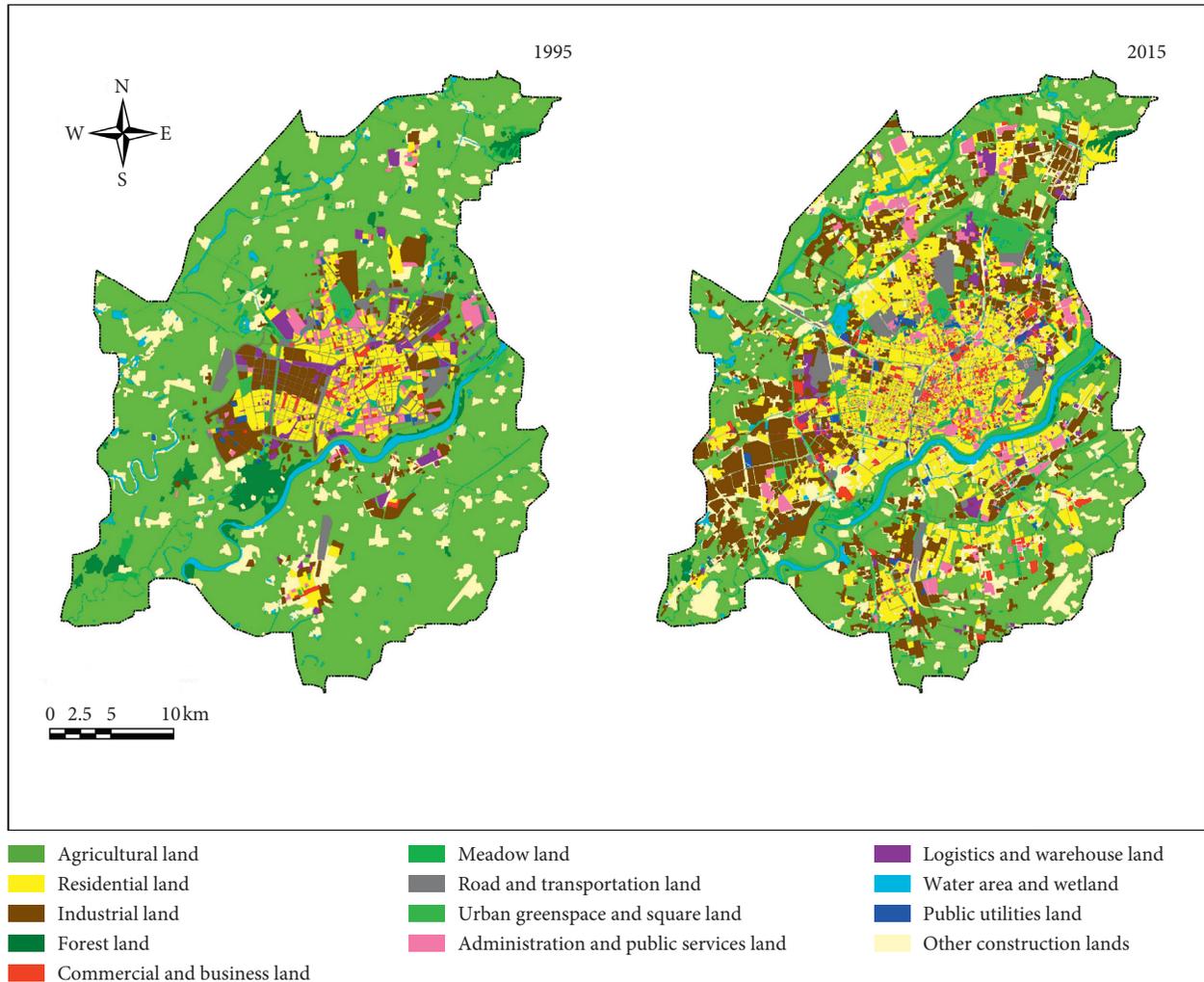


FIGURE 2: Land use patterns of the study area.

expected to improve connectivity. Restoration of the barriers according to improvement scores will greatly lead to the reduction of moving difficulty while increasing the connectivity of the total landscape. A larger value of the improvement score indicates higher connectivity improvement after removing the barriers [44].

3. Results and Analysis

3.1. Pattern and Evolution of Urban GI. Significant changes have taken place in terms of the quantity, components, and layout of GI in the central city of Shenyang between 1995 and 2015 (see Table 2 and Figure 5). The overall area of GI, which accounts for 64.27% of the total study area in 1995 and for 35.08% of the total study area in 2015, decreased by nearly 38.76% over last 20 years. Although not significant in the overall area, cultivated (agricultural) land still represents the dominant type of land for GI. According to the results of the MSPA of the study area, specifically, core takes the largest proportion amongst the associated types for GI. However, due to apparent scale heterogeneity, most of the cores are too small, indicating that there are limited core

patches suitable for acting as nodes of a GI network. Except for cores, the areas of perforation and edge are also in large proportions. Over the past 20 years of development, the area of perforation has decreased, while that of edge has significantly increased. Additionally, the shares of other morphological types, i.e., Bridge, Loop, Branch, and Islet, to varying degrees, have all increased by 2015 despite the fact that they remain in smaller ratios when compared with the core, edge, or perforation.

Regarding spatial distribution, cores which are mainly made up of cultivated land and major urban parks are situated contiguously in the periphery and scattered across the central urban area. In terms of variation, other than the concentrated built-up area, the contiguous GI patches are either destroyed and/or divided, leading to the core patches with reduced area and fragmented form. However, moderate connectivity is still retained because of the growth of loop, bridge, and branch, which may provide effective connections. Meanwhile, the number of edge and perforation obviously increased due to the fragmentation of the cores, which may limit the ecological processes for the fringe effects that these morphological types cause to a certain extent.

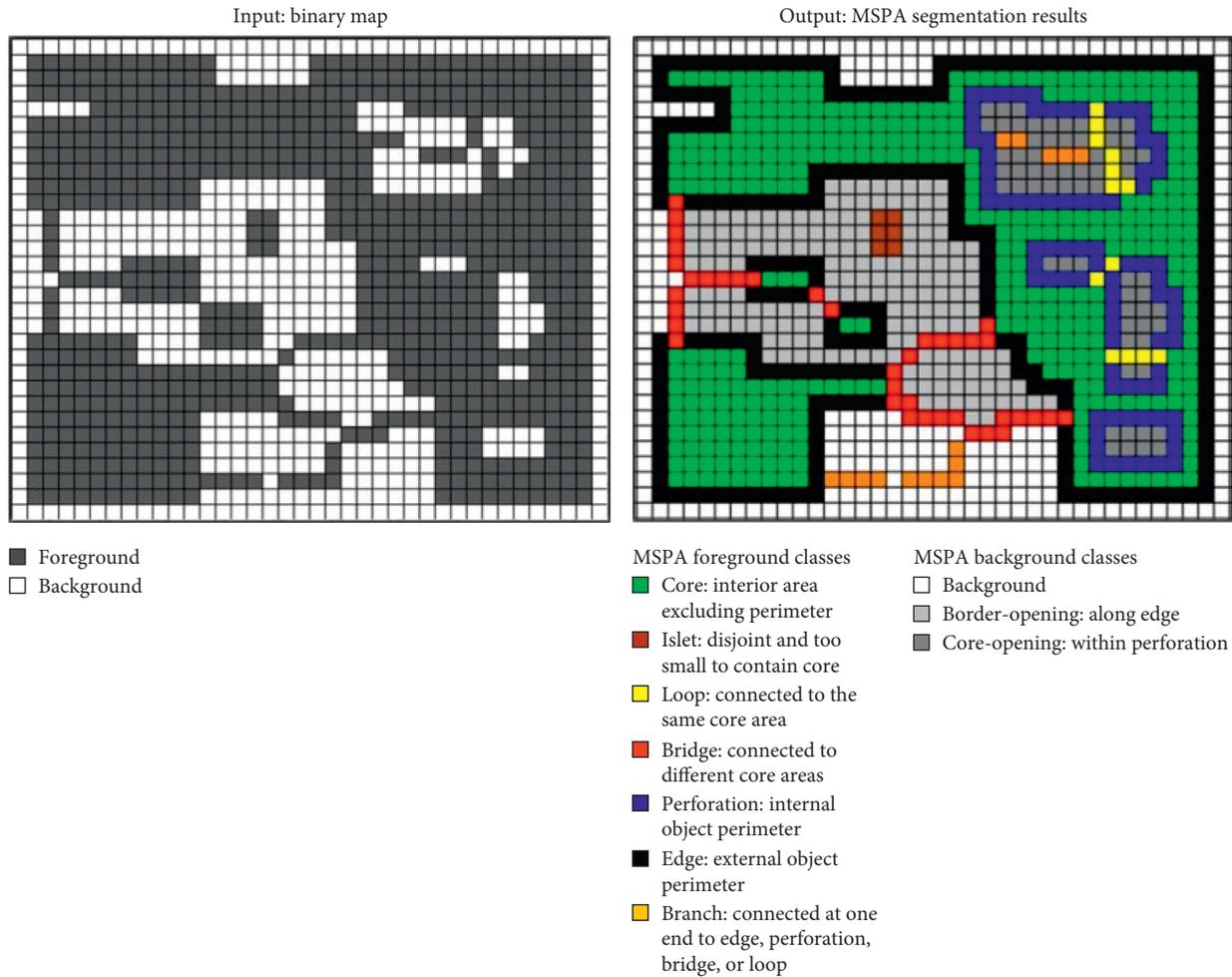


FIGURE 3: The MSPA segmentation (source: [35]).

3.2. Features of GI Network Structure. Both the 1136 cores with unique identification information dataset and a text file of distances between the cores were imported to recognize the nodes of the GI network. The output of dIIC and dPC were sorted by value, and consequently, 31 cores were selected as the nodes of the GI network (see Table 3). All the 31 patches occupy approximately 24.74% of the total study area. Moreover, based on the cost-weighted distance and least-cost path calculation, 43 least-cost paths were generated. The GI network which includes 31 nodes and 43 potential paths is identified and shown in Figure 6.

The pattern of the GI network illustrates that the spatial distribution of nodes and paths is uneven with the nodes primarily located in the northside and southside of the city area and the corridors concentrated on the middle part communicating the nodes on both sides. In the central area, GI elements are insufficient or missing and are also greater distances apart. Considering the characteristics of the nodes, the number and size of nodes in the main urban area are deficient except for uneven distribution, and the fragmentation within the interior of node patches is quite evident. In terms of the paths, the lengths of the paths are comparatively short, ranging from 0.03 km to 11.6 km. The paths that are

longer than 5 km account for approximately 12% of the paths, and those with lengths greater than 1 km approximately account for 40% of the total paths. Furthermore, the longest paths are primarily aligned southwest to northeast in the main urban area where node density is low. These central paths link up a majority of the existing important ecological sources such as the Century Golf Club, Tiexi Forest Park, Labor Park, Zhao Mausoleum Park, Huanggu Hero Park, and several other parks along the Hunhe river. However, the shorter paths connect the smaller nodes in the main urban area as well as those in larger size near the periphery.

3.3. Pinch Point Identification and Protection. The connectivity characteristics are further explored quantitatively based on circuit theory, and the pinch points in the corridors of GI network are presented in Figure 7. In the figure, the locations with darker yellow have a greater contribution to functional connectivity and can be determined as being the pinch points of the GI network. The location where the color transitions from blue to yellow suggests increased current density from small (blue) to large (yellow). The pinch points are mainly located in certain long but narrow corridors in

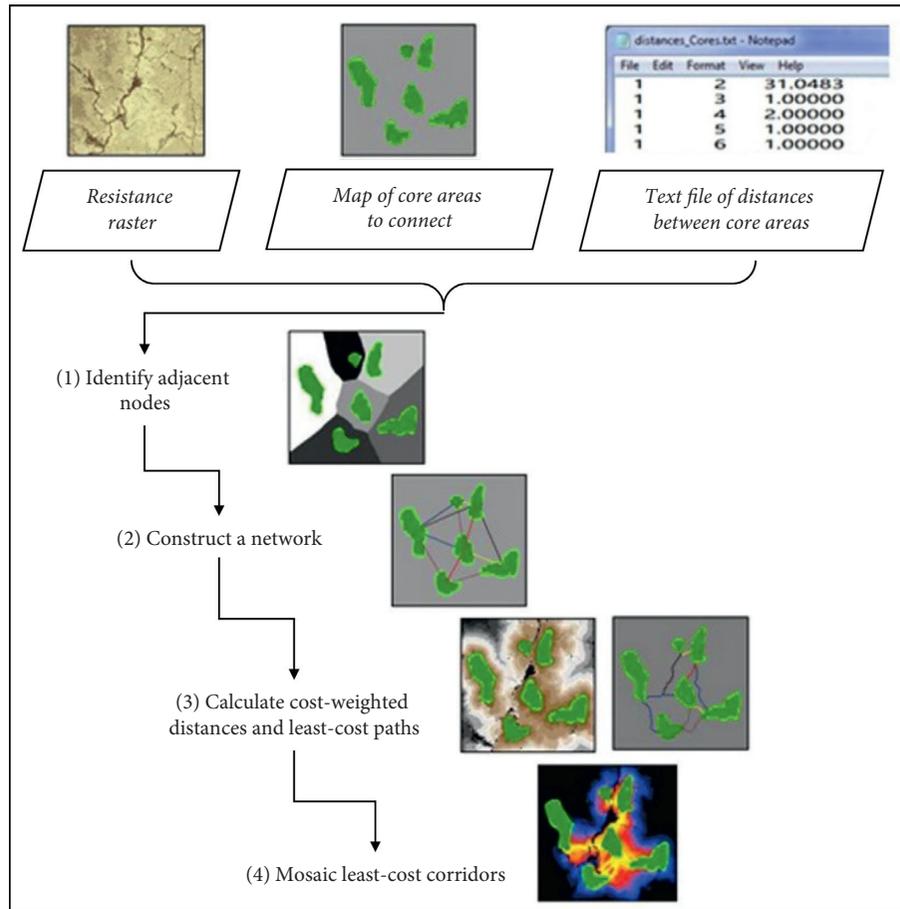


FIGURE 4: Schematic diagram for GI network building (source: reference [36]).

TABLE 1: Resistance values for different landscape types.

Type	Core	Bridge	Islet	Edge	Loop	Branch	Perforation	Background
Resistance	1	10	15	30	30	60	80	100

TABLE 2: Statistical results for classification of GI landscape based on MSPA.

	1995			2015		
	Area (km ²)	Ratio to GI (%)	Ratio to the total area (%)	Area (km ²)	Ratio to GI (%)	Ratio to the total area (%)
Core	746.49	94.73	64.27	407.51	84.45	35.08
Islet	0.63	0.08	0.05	4.75	0.98	0.41
Perforation	24.85	3.15	2.16	6.82	1.41	0.59
Edge	12.76	1.62	1.15	49.29	10.21	4.51
Loop	0.52	0.06	0.03	1.51	0.31	0.07
Bridge	1.01	0.12	0.04	5.19	1.07	0.24
Branch	1.76	0.22	0.15	7.48	1.55	0.64

central locations of the main urban area. They represent green belts with good connectivity along the main roads and rivers. However, in the south-western and north-eastern parts of the study area, current density is low and pinch points can rarely be seen, which indicate poorer functional connectivity.

The identification and analysis of pinch points may offer informative suggestions for connectivity conservation. The

areas with stronger yellow should be given priority for protection to promote necessary ecological processes that provide ecosystem services. Moreover, the analysis also finds that the nature of a node can affect the pinch point qualities. If the size and quality of GI nodes on both sides of the corridors are appropriate, the pinch point in the corridors is obvious. Conversely, if the nodes are in small scale and poor quality, the pinch point is quite inconspicuous.

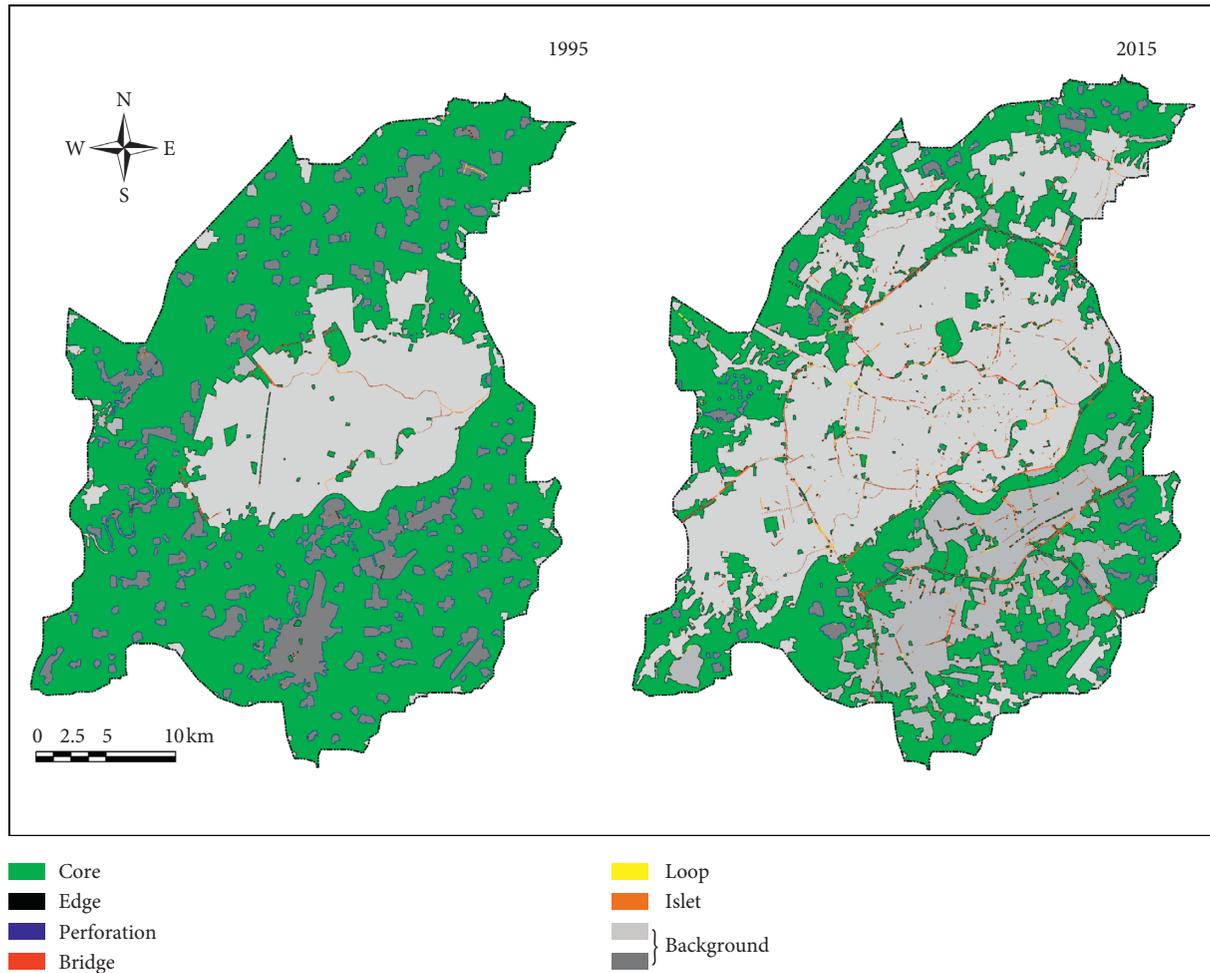


FIGURE 5: Landscape pattern of GI according to MSPA.

3.4. Barrier Diagnosis and Connectivity Improvement. Investigation through identifying pinch point locations highlights the crucial role of areas that need to be protected in order to maintain present connectivity. Moving one step beyond, detecting current barriers will provide an alternative restoration option since the reduction of barriers implies a practical strategy for connectivity optimization. The consequences of barrier analysis, as shown in Figure 8, identify the areas that can be modified for improved connectivity within the GI network. Due to the large-scale destruction by man-made construction, especially by industrial activities during the process of rapid urbanization, most of the GI corridors need to be restored to improve the connectivity of the GI network.

In general, most of the identified barriers are distributed between the geographically isolated nodes. The area of all the barriers is 19.01 km^2 accounting for about 3.94% of the total area of GI. The improvement score which gives expected reduction in least-cost distance per unit distance restored suggests the priority of conservation. Based on the improvement scores, barriers to be optimized can be divided into two levels according to the rule of Natural Breaks. The key improvement areas are those whose improvement scores range from 53.58 to 99.00 and the general improvement area

are those with improvement scores between 0 and 53.58. Spatially, the key improvement areas are mainly distributed in the Shenxi Development Zone and the northeast side of Beiling Park, while the general improvement areas are mostly located around the key improvement areas in a band-shaped manner with the scope depending on the quality and quantity of GI nodes.

4. Strategies for Connectivity Conservation

Since critical locations for GI connectivity in the study area were obtained through pinch point identification and barrier detection, we then proposed the following strategies for connectivity conservation in our study area.

4.1. Protect Key Areas to Maintain the Overall Connectivity. Corridors with currently high densities and the connected node patches deserve attention and should be considered a priority for conservation (see Figure 7). Moreover, to ensure overall connectivity, areas with poor connectivity, especially in the central urban area need to add more dotted green patches (also called steppingstones) to facilitate the regeneration of ecological processes. Meanwhile, attention should

TABLE 3: The importance and ranking of the nodes of GI network.

Patch ID	dIIC	dPC
1	76.16	77.12
783	42.15	49.51
431	14.92	19.28
758	1.35	2.59
66	1.23	1.67
913	1.12	1.53
873	0.75	1.02
778	0.10	0.87
251	0.59	0.80
809	0.05	0.79
164	0.46	0.61
910	0.30	0.40
4	0.28	0.38
226	0.28	0.37
596	0.26	0.35
390	0.19	0.27
115	0.18	0.24
1113	0.17	0.24
1013	0.12	0.17
489	0.11	0.15
829	0.10	0.14
796	0.00	0.14
914	0.10	0.14
866	0.10	0.13
781	0.10	0.13
490	0.09	0.13
777	0.09	0.12
227	0.09	0.12
593	0.09	0.11
699	0.08	0.10
582	0.08	0.10

be paid to improve the quality of the GI structure such as widening the corridors on the western side of the city that connect the southern and northern farmlands and restoring vegetation coverage near large non-GI areas. It also should be noted that the conservation measures advocate scientific and diversified methods to incorporate the complex adaptability of natural ecological spaces rather than suggesting a total ban on construction. For example, in pinch point areas, construction activities and development may be controlled by limiting the volume ratio and specifying the green rate. Conversely, in nonpinch point areas, facilities with different functions can be conditionally constructed to form a composite green infrastructure network pattern.

4.2. Repair Barriers to Enhance Connectivity. The barriers should be removed or reduced one by one, according to their importance and urgency, from the key improvement areas to the general improvement areas. More importantly, green vegetation should be added at the locations where barriers are removed in order to restore their capacity for ecosystem service provision. In addition, other options to improve connectivity can also be considered in the light of local conditions if a barrier is difficult to remove such as by opening new routes between the nodes near the original barriers [45]. The removal of barriers and implementation of

GI could improve the use of public space, activate pedestrian paths, and perform more leisure and health services within the city in addition to being beneficial to the maintenance of ecological functions. These benefits are particularly evident in the main urban area and the Shenxi Industrial Corridor in the southwest part, as well as the Huishan Economic and Technological Development Zone near the north-eastern part.

4.3. Implement Differentiated Measures to Optimize Connectivity. To achieve better connectivity, different measures can be considered for each type of urban land use. For example, residential lands should have green areas added to the barrier areas to expand the coverage of GI and increase the richness of vegetation [46]. As for the barriers around the municipal roads, increasing the number of green patches to broaden greening is suggested in combination with the construction of biological channels combined with other GI corridors. With respect to the barriers in commercial areas, the degree of vegetation can be appropriately increased. Additionally, for the barriers near the rivers, the protective green space on both sides of the rivers should be widened.

5. Discussion

5.1. The Significance of the Integrated Approach to Promote Urban Resilience. Traditional urban risk governance prefers rigid engineering solutions focus on addressing deterministic disasters, which are lagging current experience and are unsustainable, and may even aggravate the sensitivity and vulnerability of urban systems [47]. The efforts to introduce (social-ecological) resilience theory into urban systems provide a new framework for urban disaster governance, which suggests that cities need to improve their awareness of the influence and dependence of social factors on ecological conditions and also increase their attention to the ecological factors [48, 49]. GI provides a feasible tool to improve urban resilience in practice and has attained increased importance for the fields of urban development, planning, and management. The complexity of urban resilience may be exacerbated by the future omission of green solutions and adopting GI as an adaptive response and a cost-effective strategy with both short-term and long-term benefits [15, 50].

To make up for the lack of systematic research on application of GI in practice to increase urban resilience, this study provides a practical and integrated approach for navigating urban resilience through the operation of GI, in which the relationships between GI connectivity, resilience potential, and connectivity conservation are better addressed within the context of climate change and rapid urbanization. Intervention in GI through connectivity conservation represents a consciousness that humans are preparing for uncertainty. The above is especially relevant in the integration of multiple technologies to explore GI connectivity, the involvement of functional connectivity in the quantitative analysis of GI connectivity, and the planning and

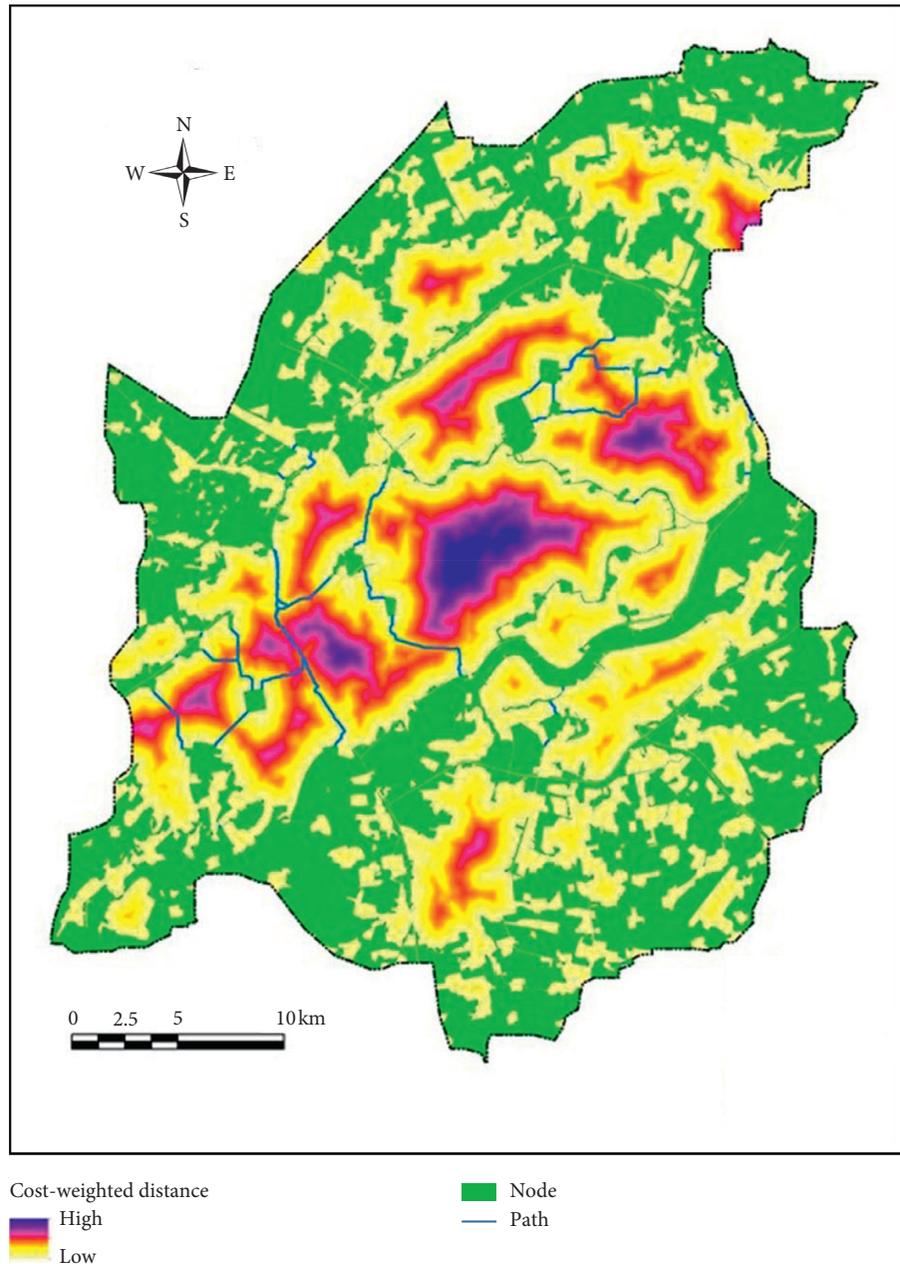


FIGURE 6: GI network based on least-cost paths.

management guidance for Shenyang and other similar megacities in mitigating and adapting to climate change through nature-based solutions, thereby expanding the boundaries of traditional research [51–53].

This study explores an integrated approach that depends on openly and universally available technological methods to foster the interdisciplinary contribution to reshape urban resilience through the extraction and quantification of properties that are contained in raster maps. The conceptual basis of the involved analysis is of a generic nature, for it is based on the process of geometric analysis. Since it is impractical to observe functional corridors for movement, the analysis of functional connectivity through simulations provides an alternative and objective recognition of connectivity for species movement in real landscapes. The

spatially explicit mapping of the results and the conversions between the storage formats of them contribute to this integration research and practical applications of GI network connectivity preservation. Nevertheless, the mathematical models offer the possibility for establishing potential connectivity among patches rather than the preferred pathways used to successfully move between patches [54, 55]. Therefore, this integrated approach can be applied to other empirical studies, with the same input data types but specific parameter settings according to targeted research needs.

5.2. The Implication of Rapid Urbanization on the Changes of GI. As a complex and open system, urban GI is largely affected by urban dynamics and its spatial pattern is

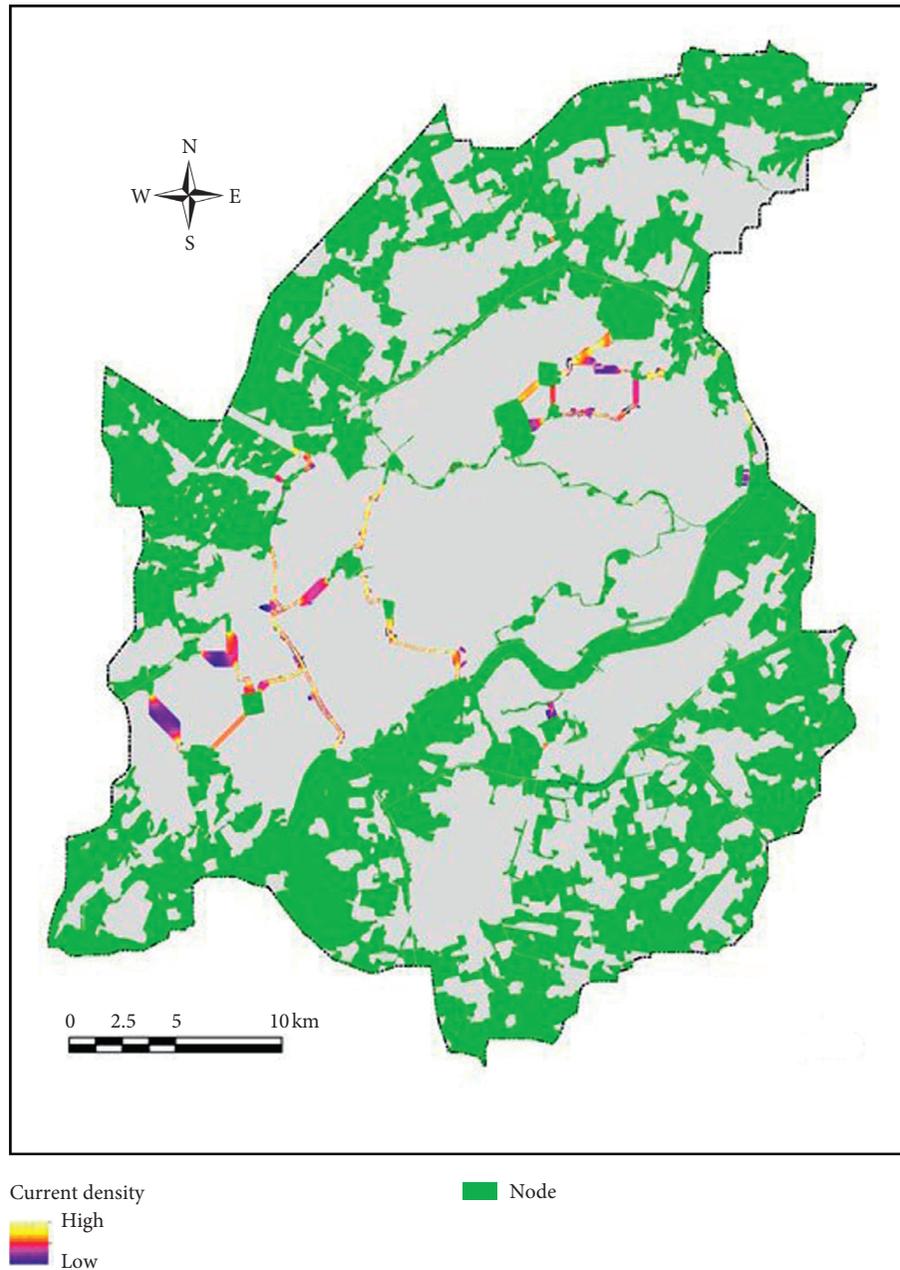


FIGURE 7: Pinch points in the corridors of GI network.

constantly changing [56–58]. The large-scale artificial development and construction during the process of rapid urbanization between 1995 and 2015 have resulted in a large amount of GI components in the central city of Shenyang being swallowed up such that the total area of GI has been significantly reduced and has become more complicated and less connected (see Table 4). The agricultural belt in the suburban areas is seriously damaged, and the GI elements in the main urban area tend to be gradually homogenized, while in the peripheral area they are fragmented. This is particularly evident in the Shenxi Industrial Corridor in the southwest part and in the Huishan Economic and

Technological Development Zone near the north-eastern edge. The process of urbanization has significantly changed the overall pattern and function of GI.

The area and area ratio of the core and perforation are significantly reduced, while those of the bridge and branch are increased suggesting that the large ecological “source area” is divided into small patches and the concentrated urban construction area is connected with the core area through the street green belt. These small-scale GI components to a certain extent help to improving the local environment of the city, provide leisure places for the citizens, and more importantly provide for the possibility of the

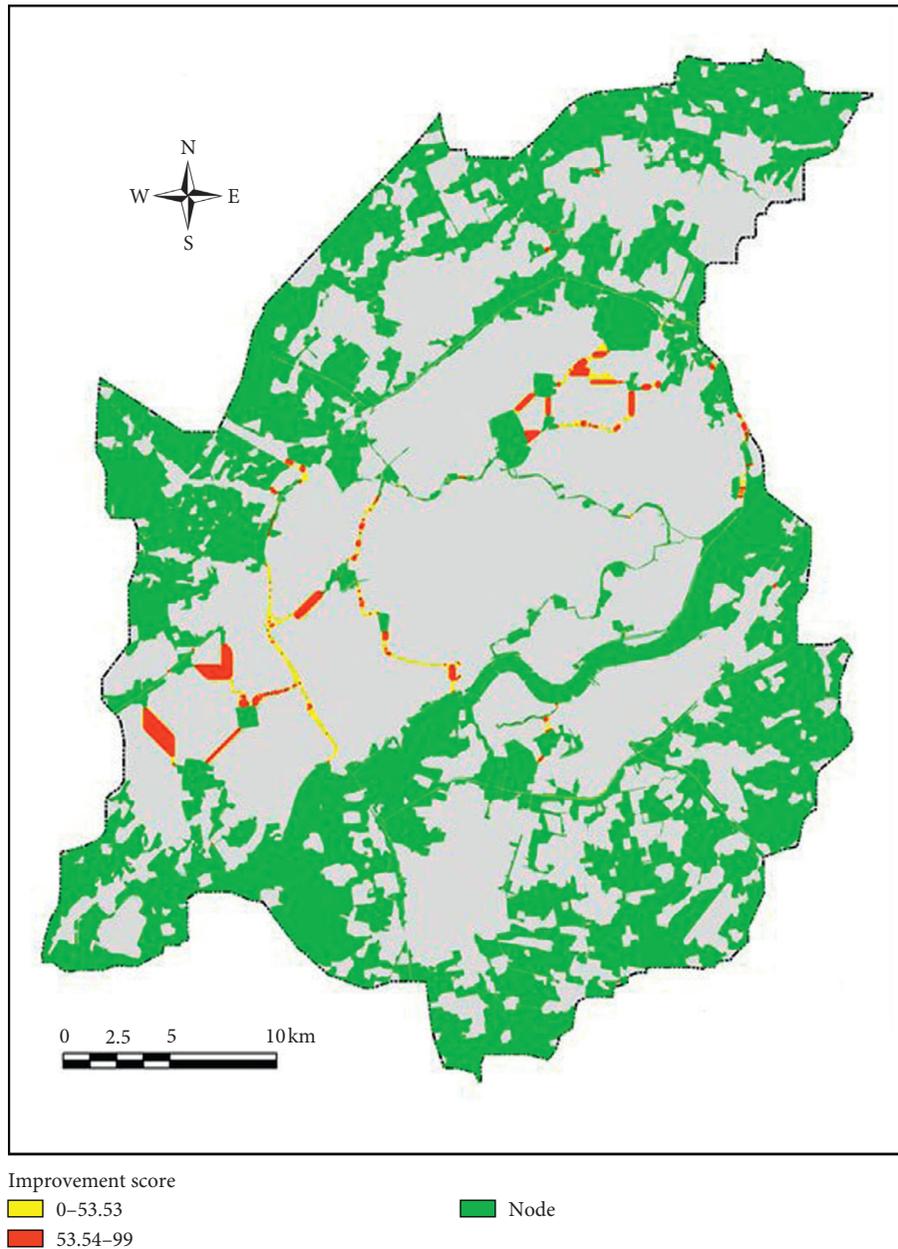


FIGURE 8: Improvement areas based on barrier analysis of GI network.

TABLE 4: The overall connectivity of the landscape.

	1995	2015
IIC	0.28	0.09
PC	0.54	0.29

development of GI network [59, 60]. In this case, the green belt plays a key role in maintaining the total city's social-ecological resilience, and it is also important in conserving and optimizing the whole GI network. Therefore, it can be seen that the fragmentation of GI components caused by the rapid urbanization is also the cause for their evolution from large-scale development and centralization toward the direction of the network. The urban GI can be guided to

a more resilient trajectory and made conducive for the improvement of urban resilience if the opportunity can be seized and scientifically reasonable protection measures are taken [61]. This radically changes our understanding of a larger green space being more suitable for an optimized pattern and function contributing toward the resilient development of the city. Contrarily, we achieve a new realization that suggests that, with the development of an urban GI system, green patches tend to form a network pattern through "self-organization" with diversified spatial structures. The network pattern of GI is the more resilient and desirable structural pattern. Therefore, the intervention of urban planning and governance should focus on the differentiated protection and optimization of the bridge, branch, and edge.

5.3. Limitations. Despite these advances, as a specific work, there are some limitations. First, the MSPA method is extremely sensitive to the scale and granularity of the landscape. With the changes of scale and granularity, the number and size of the seven types of GI components from the MSPA will respond in a nonlinear way. In this case, the way in which the appropriate distance threshold, edge width, and other parameters are set may affect the scientific rationality of the results and the feasibility of practical application. Second, this study only investigates the impact of corridor barriers and improvement measures, that is, local GI structures and their impacts on connectivity. The connectivity optimization measures of the elements' whole network are worthy of further consideration. Finally, some parameters in the selection process of GI components, connectivity distance threshold setting, and pinch point simulation are referenced to the empirical value of the existing research. Therefore, it is recommended that, in further research and practice the relevant parameters should be tailored according to the particularities of specific study areas to improve the overall effectiveness of GI connectivity conservation.

6. Conclusions

To enhance urban resilience and sustainability within the framework of the social-ecological system, this study utilizes interdisciplinary knowledge and multiple analysis techniques by taking the central city of Shenyang as an example to explore an integrated approach through navigating GI. During the past 20 years (1995–2015), the changes in the pattern of GI have shown an increase in fragmentation and overall decrease in GI connectivity in the central city of Shenyang. A GI network based on the least-cost path algorithm is constructed to identify significant structures in connectivity conservation. Based on circuit theory, the pinch points are highlighted as critical to maintain the present connected state of GI components, while barrier diagnosis provide an alternative restoration option for connectivity optimization through governing the improvement areas. For the practical conservation strategy, protecting key areas to maintain the overall connectivity, repairing barriers to enhance connectivity, and implementing differentiated measurements in the light of local condition to optimize connectivity are underscored. It is proposed that, with the development of an urban GI system, large-scale green patches tend to be fragmented and reformed into a network pattern with a diversified spatial structure. In this case scientific planning and governance interventions through protection and optimization of connective structures might guide the development of urban GI toward a more resilient trajectory. The results may provide the basis for future policy formulation, planning, and design practice by installing or rehabilitating a GI network such that it provides a conducive situation for the improvement of urban social and ecological resilience. This integrated approach that is based on a generic process of geometric analysis can be applied universally to foster its interdisciplinary contribution toward improving urban resilience through GI network connectivity conservation.

Data Availability

The land-use data used in this study can be downloaded from the websites <https://www.usgs.gov/> and <https://www.earth.google.com/>.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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