Urban green space network development for biodiversity conservation: Identification based on graph theory and gravity modeling

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ARTICLE INFO

ABSTRACT

Urban areas can contain rich flora that contribute significantly to biodiversity, but loss and isolation of habitats due to urban sprawl threaten biodiversity and warrant limits on development. The connectivity provided by urban green spaces offers habitats and corridors that help conserve biodiversity. Researchers and planners have begun using landscape ecology principles to develop green space networks and increase connectivity to preserve and restore biodiversity. In this paper, potential corridors were identified in Jinan City, China, using the least-cost path method, and green space networks were developed and improved based on graph theory and the gravity model. Spatial analysis revealed that the proposed plan decreased fragmentation and increased connectivity. Plaza and roadside green spaces were the main types of green space that increased, but they only weakly improved networks and biodiversity. Identifying potential corridors using least-cost path analysis made the results better approximate the real landscape by including impedance along links. The potential networks revealed problems in the current greening plan. The green space network developed based on graph theory and the gravity model simplified and systematized the complex landscape, helping to identify the significance of each green space and guiding urban planning for biodiversity conservation.

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1. Introduction

Since the 1992 United Nations Convention on Biodiversity (UNCED, 1992), biodiversity has become a fundamental conservation value. Because urban areas may contain a rich flora that contributes significantly to biodiversity, urban biodiversity conservation should receive more attention (Miller, 1988; Duhme and Pauleit, 1998). Urban green spaces can be defined as outdoor places with significant amounts of vegetation, and exist mainly as semi-natural areas (Jim and Chen, 2003). Urban green spaces offer important harbors for remnant biodiversity. However rapid urbanization has eliminated ever more green space, particularly dispersal corridors (Harris and Scheck, 1991). The proportion of the world's population living in cities is expected to surpass 65% by 2025 (Schell and Ulijaszek, 1999), and dramatic population increases have been accompanied by intensified urban development. China's urban population in 2001 equaled 37.7% of the nation's total population; this proportion is projected to reach 75% by 2050 (Chinese Mayor's Association, 2002). As a result, the remaining urban green space is increasingly encroached upon and

fragmented as cities become denser to accommodate population growth (Jongman, 2008a). Habitat fragmentation, loss, and isolation seriously threaten biodiversity and are a primary cause of the present extinction crisis (Collinge, 1996; Adriaensen et al., 2003). For example, more than 180 plant species became locally extinct in the past 100 years in Munich, Germany, alone (Duhme and Pauleit, 1998). This specially made nature conservation change from site protection towards conservation of green space networks including the wider landscape (Opdam, 1991). Green space networks can provide a solution to the problems of intensified land use and fragmentation, enabling natural populations of species and threatened habitats to survive (Jongman, 2008a).

Connectivity is the opposite of fragmentation. To reduce the isolation of habitat fragments, ecologists and conservation biologists recommend maintaining habitat connectivity by preserving corridors that permit movement of species between remaining habitats and by developing urban green space networks (e.g., Jordán et al., 2003; Parker et al., 2008; Esbah et al., 2009). Development of these networks is increasingly considered a suitable approach to improve the ecological value of urban green space (Cook and van Lier, 1994; Hepcan et al., 2009). Landscape-level habitat connectivity plays an important role in population viability by maintaining gene flow and facilitating migration, dispersal, and recolonization (Hargrove et al., 2004; Saura and Pascual-Hortal, 2007). Thus, establishing or

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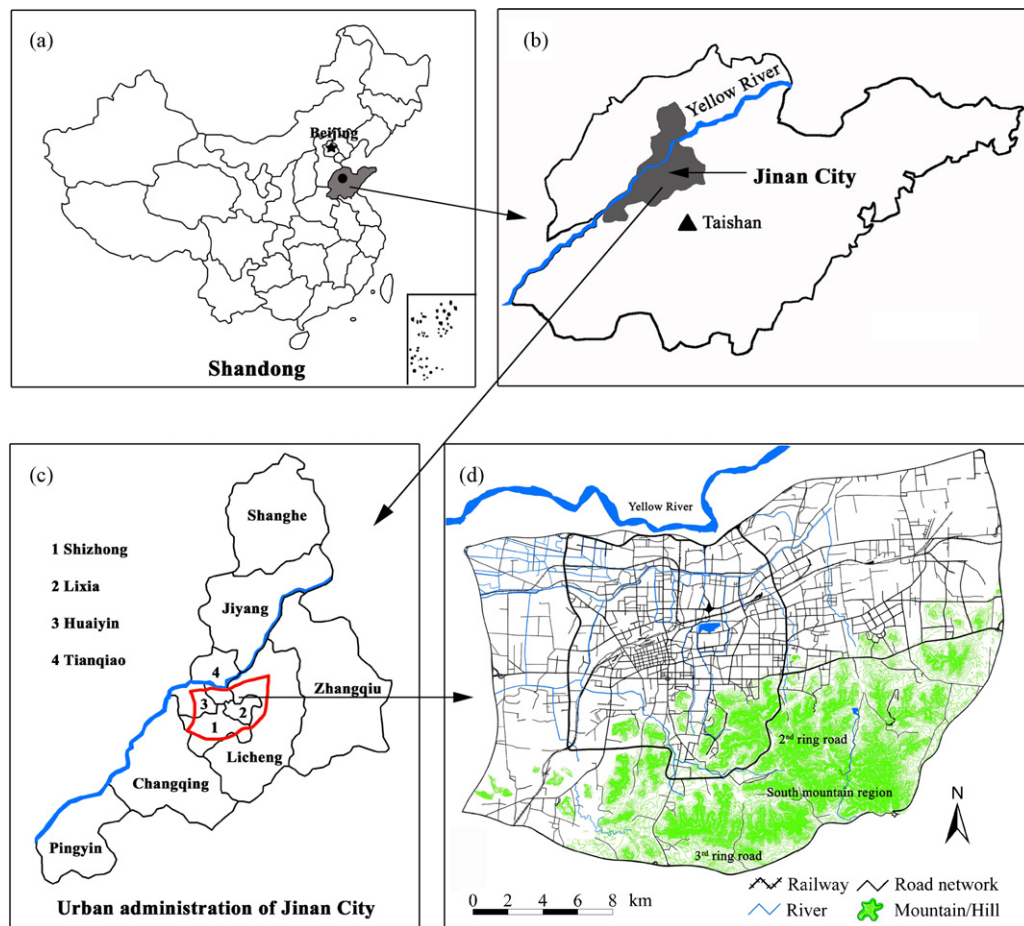E-mail address: fanhuakong@163.com (F. Kong).

Fig. 1. Location of the study area.

maintaining connectivity among patches is essential to facilitate biodiversity conservation.

The landscape-scale spatial configuration and distribution of habitats determine species distribution and migration (Swingland and Greenwood, 1983; Debinski et al., 2001). The spatial pattern and functional analysis of the "patch–corridor–matrix" are basic components of landscape ecology. Landscape ecologists use connectivity (corridors) to describe a landscape's structural and functional continuity in space and time (e.g., Forman and Godron, 1986). In sustainable urban development, urban greening is a key element, but biodiversity must be an integral component of this greening. Consequently, preserving habitat and dispersal routes and developing a comprehensive green space network that can maintain landscape-scale connectivity have become crucial factors in urban biodiversity conservation (Bennett, 2003; Parker et al., 2008).

The development of urban green space networks includes protection of existing green spaces, creation of new spatial forms, and restoration and maintenance of connectivity among diverse green spaces. To maintain or restore connectivity, planners must identify the best habitat and potential corridors by considering distances and the barriers between habitats (impedance) posed by the landscape and land use (Opdam, 1991). However, no current analytical tools comprehensively identify potential dispersal corridors in real-world landscapes while considering impedance to movement along corridors in terms of island biogeography theory (Noss, 1987; Hargrove et al., 2004). Planners generally consider only distances between habitat patches, not the spatially heterogeneous impedance of the landscape matrix (Hargrove et al., 2004). In the present paper, we propose the identification of potential corridors

using least-cost path tools provided by geographical information systems software. We also used the gravity model and graph theory to develop green space networks from potential corridors so planners can identify the relative high-quality habitats and choose the best opportunities to maintain and restore connectivity.

The goals of our study were: (a) to conserve critical urban green space; (2) to model potential corridors and develop green space network based on the least-cost path method; (3) to develop planning scenarios for green space networks and accordingly identify the relative significance of each habitat or corridor based on the gravity model and graph theory; (4) to assess whether or not planned green spaces would improve the green space network, and subsequently identify opportunities for allocation and planning of new green space to optimize the network.

2. Study area

Jinan City (36°42′N, 117°02′E) lies in the middle of Shandong Province of China (Fig. 1a), in the eastern coastal region, north of Taishan and straddling the Yellow River (Fig. 1b). Jinan City is the capital of Shandong Province, and has existed for more than 2600 years. It has experienced dramatic population and spatial growth in the last 50 years: the population increased from 3.19 million in 1952 to 5.90 million in 2005 (Jinan Statistics Bureau, 2005) and the built-up area increased from 24.6 km² in 1949 to more than 190 km² in 2003 (Jinan Statistics Bureau, 2003). Jinan consists of six districts, three counties, and one county-level city (Fig. 1c). The Jinan Planning Bureau's 2004–2020 Master Plan proposed to expand the city eastward, with the urban area expanding to the third ring road (Fig. 1d). The area examined in this study includes
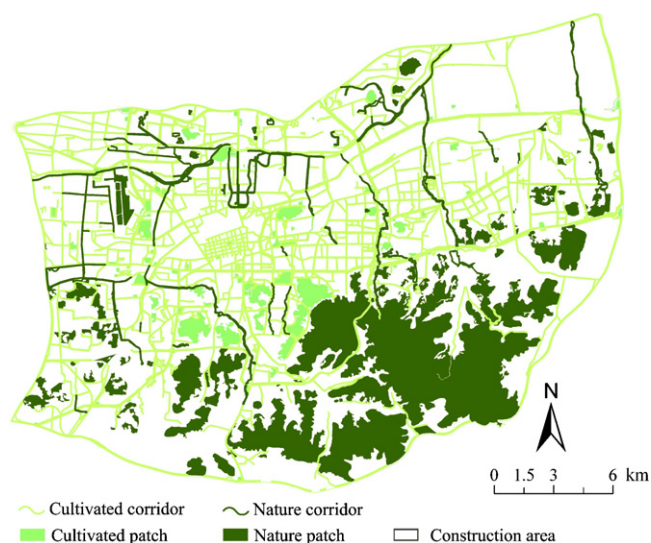
Fig. 2. The Jinan Landscape Bureau's green space plan (1996–2010) for the study area.

the entire part of the city inside the third ring road, and covers about 538 km^2 (Fig. 1d). The Jinan Planning Bureau's 2004–2020 Master Plan proposes the construction of new towns, mainly east of the city, to expand the built-up area to a total of 400 km^2. If this plan is executed, the built-up area would then cover 74.33% of the study area, creating significant direct impacts in an area almost twice as large as the present city's extent.

High-density development and rapid urban sprawl have affected the urban vegetation's composition and biodiversity. For example, the original natural vegetation included *Salix babylonica* L., which is now partially or completely absent. As a result, a landscape once described as having "springs and willows in every courtyard" (Liu, 1903) is all but gone. In addition, increasing numbers of exotic species have been imported to take advantage of their amenity characteristics. Today, the dominant species are *Platanus orientalis* L., *Sophora japonica*, *Populus tomentosa* Carr., *Platycladus orientalis* Franco., *Forsythis suspense* Vahl., and *Euonymus japonicus* Thunb. (Jinan Landscape Bureau, 2001).

Rapid urban growth has increasingly encroached on green spaces. Scenery forests within the study area decreased by about 1550 ha (more than 13%) from 1989 to 2004 (Kong and Nakagoshi, 2006). Facing this serious situation, the local municipality promoted several greening policies. In 1996, a new green space planning system was proposed for implementation by 2010 (Fig. 2).

In this urban green space plan, the Jinan People's Government proposed a "One Ring, Three Greenbelts and Nine Wedges" green network system and sought to build a "National Garden City" (Jinan Landscape Bureau, 2001). Especially, the government hopes through this plan to improve the green spaces' ecological value and enhance ecological sustainability by reducing fragmentation, maintaining natural vegetation, and increasing the ecological compatibility of the urban landscape matrix. The plan will lead to considerable improvement if implemented, but still has many shortcomings that will decrease the plan's ability to promote sustainable urban development. Jinan continues to experience rapid population growth and habitat destruction, and the threat of habitat loss and fragmentation remains severe. Thus, developing green space networks that identifies and protects connected green spaces is essential to conserve biodiversity and permit sustainable urban development.

3. Methods

Our study used 2004 SPOT images (resolution 10 m) to produce digital land use and green space maps. The images were rectified and georeferenced using a topographic map (1:10,000) and aerial photographs (1:10,000) produced in 2000. Categorical land use and green space maps were created by manual interpretation using ESRI's ArcInfo software combined with field surveys and ground-truthing. Apart from this, the urban green space planning map (1:50,000) from 1996 to 2010, made by the Jinan Landscape Bureau was also digitized (Fig. 2).

Developing green space networks requires improvement of the spatial pattern of urban green space. To identify potential improvements, we compared the predicted development of planned cultivated and natural green spaces (2010) (Fig. 2) with the existing situation (2004) using six spatial indices (Table 1), which are commonly cited indices of landscape pattern interpretation and have their specific ecological significance, as well as their ability to predict habitat connectivity (Schumaker, 1996; Tischendorf, 2001; Zhang and Wang, 2006; Pham and Nakagoshi, 2007). We hope that the spatial landscape metrics, which were characterized by differing dominance, connectivity, or aggregation, would have enough explanatory power to characterize the composition and configuration of the landscape, and consequently to express its ecological significance. The indices were calculated by FRAGSTATS (Version 3.3) (McGarigal et al., 2002a,b) in raster format at a resolution of one pixel = 5 m × 5 m. Simple descriptions of these indices were given in Table 1. Developing green space networks begins with identifying potential corridors, followed by prioritizing the resulting networks (in this paper, based on the gravity model and graph the-

Table 1
Descriptions of landscape metrics (based on McGarigal et al., 2002a,b).

Landscape metrics (abbreviation)	Description
Class area (CA)	CA equals the sum of the areas (m^2) of all patches of the corresponding patch type divided by 10,000 (to convert to hectares). It is a measure of landscape composition.
Patch density (PD)	The number of patches per 100 ha. It is a simple measure of the fragmentation of the patch type.
Mean patch size (MPS)	The area occupied by a particular patch type divided by the number of patches of that type. It is a simple measure of the fragmentation of the patch type.
Largest patch index (LPI)	LPI equals the area (m^2) of the largest patch of the corresponding patch type divided by total landscape area (m^2), multiplied by 100 (to convert to a percentage). It is a simple measure of dominance.
Euclidian mean nearest-neighbor distance (MNN)	MNN equals the distance (m) mean value over all urban green space patches to the nearest neighboring patch, based on shortest edge-to-edge distance from cell center to cell center. It is a simple measure of patch context and has been used extensively to quantify patch isolation.
Patch cohesion index (COHESION)	COHESION equals 1 minus the sum of patch perimeter (in terms of number of cell surfaces) divided by the sum of patch perimeter times the square root of patch area (in terms of number of cells) for patches of the corresponding patch type, divided by 1 minus 1 over the square root of the total number of cells in the landscape, multiplied by 100 to convert to a percentage. It measures the physical connectedness of the corresponding patch type.
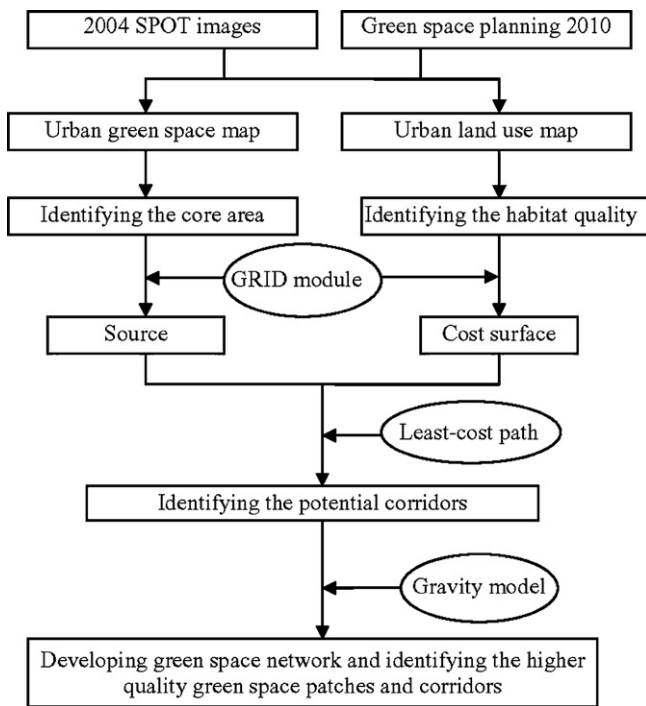
Fig. 3. The process used to identify potential corridors and develop an urban green space network.

ory). The relatively high-quality green spaces in structure and area, and important corridors were then identified. The overall process is shown in Fig. 3, and the methods are described in more detail in Sections 3.1 and 3.2. Most of the work was done in raster format using ArcInfo's GRID module. The analysis used 5 m × 5 m pixels to minimize the risk of missing narrow potential corridors.

3.1. Modeling potential corridors based on least-cost path analysis

The least-cost path function is a raster-based optimization algorithm in the GRID module that was originally designed to find the least-expensive path for a road between two points using a theoretical cumulative-cost surface constructed outward in all directions from the destination (Walker and Craighead, 1997). This analysis can also be applied to identify habitat linkages to maintain or restore connectivity (Adriaensen et al., 2003). Walker and Craighead (1997) used least-cost paths to simulate movement corridors by calculating a cumulative-cost surface based on habitat preferences for several species. They assumed that wildlife follows an optimum route between habitats to minimize its exposure to intervening low-quality habitat, and that movement would be facilitated by such routes. Because good data for key species are often lacking in urban areas, vegetation communities could be used as a surrogate for the habitat value (Cook, 2000). In this paper, we determined the least cost by calculating the cumulative cost from source to destination patches based on the quality of each vegetation community throughout the landscape.

The first step in least-cost path analysis is to identify core areas that serve as sources or destinations. We selected 12 existing and planned green spaces for this purpose (Fig. 4a) based on the following two principles: (1) patch area is not smaller than 12 ha. Choosing a specific species is a problem in this study area, especially in a landscape level, so 12 ha was chosen as a hypothetical minimum area requirement. Large patches are more valuable because they support large, persistent populations, and patch area is related to wildlife abundance, persistence, and diversity (Rudd et al., 2002;

Noss, 2004; Belisle, 2005); and (2) their location such that it permits connectivity with areas outside the city, as in node 2. Most were located at the boundary of the study area, in eight main directions. Although this is somewhat arbitrary, it will be helpful to connect green space patches or pass through green space corridors inside of the study area when developing a network. These patches included plaza green space (0.70%), public parks (2.99%), and scenery forest (96.3%), for a total area of 7840.6 ha (53.12% of the total urban green space and 14.57% of the study area).

The dispersal efficiency of corridors depends on the source habitats and the impedance created by the mosaic of land uses between sources and destinations (Forman, 1983). However, the impedance for wildlife dispersal between habitats with heterogeneous land use depends on the development history, environmental conditions, and human impacts on the land mosaic (Jim and Liu, 2001; Adriaensen et al., 2003). It is also important to note that the impedance values for a given corridor will have different values for different species; for example, bodies of water represent a significant barrier for terrestrial organisms, but not for aquatic organisms or birds. This makes corridors difficult to visualize before the actual landscape and species are analyzed. Thus, the second step in corridor identification is to evaluate habitat suitability and corridor impedance. As plant communities are the major determinant of wildlife dispersal and habitat suitability (Miller et al., 1998; Jongman, 2008b), and since impedance values were not available for the specific animal species in our study area, we chose impedance values weighted mainly according to vegetation coverage (%) and type, and also weighted according to the age of the green space and degree of anthropogenic disturbance (Table 2) (Matthews et al., 1988; Linehan et al., 1995; Cook, 2002). The contribution of vegetation coverage and type to ecological health can be used to define wildlife habitat quality (Matthews et al., 1988; Oliver et al., 2002; Carter et al., 2006; Sandström et al., 2006; Esbah et al., 2009), whereas the age and degree of anthropogenic disturbance strongly influence wildlife presence and survival (Gilbert, 1989; Sandström et al., 2006). The vegetation coverage, type and degree of anthropogenic disturbance of green spaces were calculated from aerial photographs, SPOT images, and field surveys. Age data were obtained from local government records and from individuals such as forest managers who we interviewed during our field survey.

Based on available literatures (e.g., Guan et al., 2007; Xiong et al., 2008) and expert judgments of the staff who conducted the field surveys, the impedance values were appointed to each land-use type (Table 2). The weights (impedance values) that we assigned to each land-use type were assumed to represent the disturbance level or degree of difficulty wildlife would encounter moving between patches. These impedance values are theoretical variables that represent estimates of the resistance to movement in each landscape type (Knaapen et al., 1992). In our analysis, it is the relative impedance of each category that is important, not the exact values. The weighted land-use map created in this manner was transformed into a habitat suitability map for use as a cost surface in the least-cost path analysis. In this cost surface, the costs for roads and other transportation land ranged from 1000 to 5000 according to their width and traffic density, whereas bodies of water were assigned a cost of 10,000 (i.e., we focused on their impedance for terrestrial species, not aquatic species or birds). Some construction areas included green space (e.g., residential green space) that could function as habitat or corridors, but these areas suffered from strong human disturbance and strong separation from other patches; thus, they were assigned a large cost (50,000) that almost excluded them from the path analysis. Based on the cost surface, 12 impedance surfaces were created to represent each cell's relative suitability as a destination for each source using a cost–distance algorithm. The least-cost path function was then used to find the optimal path for

selected source–destination pairs. Paths selected by this analysis were widened by increasing the impedance threshold to include all contiguous cells with appropriate habitats or land uses. Altogether, 66 potential paths were identified (Fig. 4a).

3.2. Identification of green space networks based on graph theory and gravity modeling

The least-cost path analysis can identify potential corridor which has the least impedance value from one source to each of the others. However, it provides less information on the relative significance of each source and corridor when the connections are developed from one source to many others (Sklar and Constanza, 1991; Linehan et al., 1995). The graph theory and the gravity model solved the problem of choosing which corridor to develop first as there will be several corridors when establishing connections from one source to another.

The graph theory analyzes networks to optimize a given flow-related objective (Linehan et al., 1995). Landscape ecologists have used the theory to reduce complex landscapes into understandable spatial configurations and uncover flow patterns (Cantwell and Forman, 1993; Bunn et al., 2000). The graph theory redefines complex systems as a finite set of nodes and linkages, and uses rules to define which edges join which pairs of nodes (Wilson, 1979). The networks in the present study were described in this manner using green spaces as nodes and corridors as links.

Interactions between nodes are usually assessed using the gravity model (Forman and Godron, 1986; Sklar and Constanza, 1991).

The level of interaction represents the efficiency of corridors and the significance of linked nodes: pairs of nodes with higher habitat quality and lower impedance have greater interaction. Interactions between nodes are calculated as follows (Linehan et al., 1995; Rudd et al., 2002):

$$G_{ab} = \frac{N_a N_b}{D_{ab}^2} \tag{1}$$

where G_{ab} is the interaction between nodes a and b, N_a and N_b are the corresponding weights, and D_{ab} is the normalized cumulative impedance of the corridor between these nodes. The node weights are defined using the weighted impedance of different types of green space (Table 2) and their normalized patch size:

$$N_i = \frac{1}{P_i} \times \ln(S_i) \tag{2}$$

where N_i is the weight, P_i is the node weight, and S_i is the normalized patch size of node i, respectively. D_{ab} is defined as:

$$D_{ab} = \frac{L_{ab}}{L_{max}} \tag{3}$$

where L_{ab} is the cumulative impedance of corridor L between nodes a and b which can be captured through the query function of ArcMap 8.3, and L_{max} is the maximum value of the impedance calculated in the study area.

Eq. (1) can be re-expressed as follows:

$$G_{ab} = \frac{N_a N_b}{D_{ab}^2} = \frac{L_{max}^2 \ln(S_a S_b)}{L_{ab}^2 P_a P_b} \tag{4}$$

Table 2
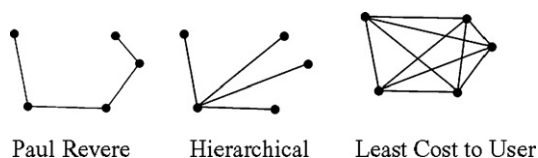Land-use type classification and impedance weights for the urban green space network.

Category		Description	Range of impedance values
Urban green space in the ecological network	Scenery forest	Protects and preserves flora and fauna, and provides scenic beauty, within a mosaic of remnant or naturalized habitat types. Vegetation is predominantly natural, though some exotic species may have invaded.	0.1–0.5
	Public park	Provides education, pleasure and recreation, with both natural and planted vegetation present with high biodiversity.	1–3
	Riparian green space	Linear corridors along bodies of water, mostly with a natural habitat type, and often with high plant diversity.	5–6
	Green buffer	Linear corridors, such as those that protect high-voltage transmission lines, screen against the wind and trap pollutants. Mostly covered with planted vegetation, but some remnant natural species may be present.	8–9
	Nursery	Areas used for propagating and cultivating vegetation, as well as for breeding and supplying saplings of species used for urban greening.	10
	Plaza green space	Provides open space and recreational opportunities, but much of the land will be paved or otherwise unsuitable for vegetation; primarily has planted vegetation (seldom trees, mostly shorter shrubs and grassland), and low diversity.	12–15
	Roadside green space	Linear corridors between sidewalks and curbs or island patches at crossroads, used to buffer people from traffic, and to screen against noise and solar radiation. Primarily planted vegetation, with limited plant diversity	20
Other land-use types	Agriculture	Sites used to grow crops for export and for local consumption.	30
	Transportation land	Land such as railway lines and roads used primarily for transportation. Little vegetation of any kind, except for weeds and invasive species.	1000–5000
	Open water	Lakes, rivers, streams, and canals. Aquatic vegetation was not included in the present study.	10,000
	Construction area	Land used for the construction of residences, public facilities, municipal utilities, warehouses, and industrial purposes. Little or no vegetation is present, though some areas have some planted vegetation (primarily shrubs and grasses).	50,000
	All other cells	Primarily artificial land types with negligible vegetation and strong barriers to dispersal of organisms.	80,000

Notes: Low impedance values represent high suitability for dispersal of organisms.
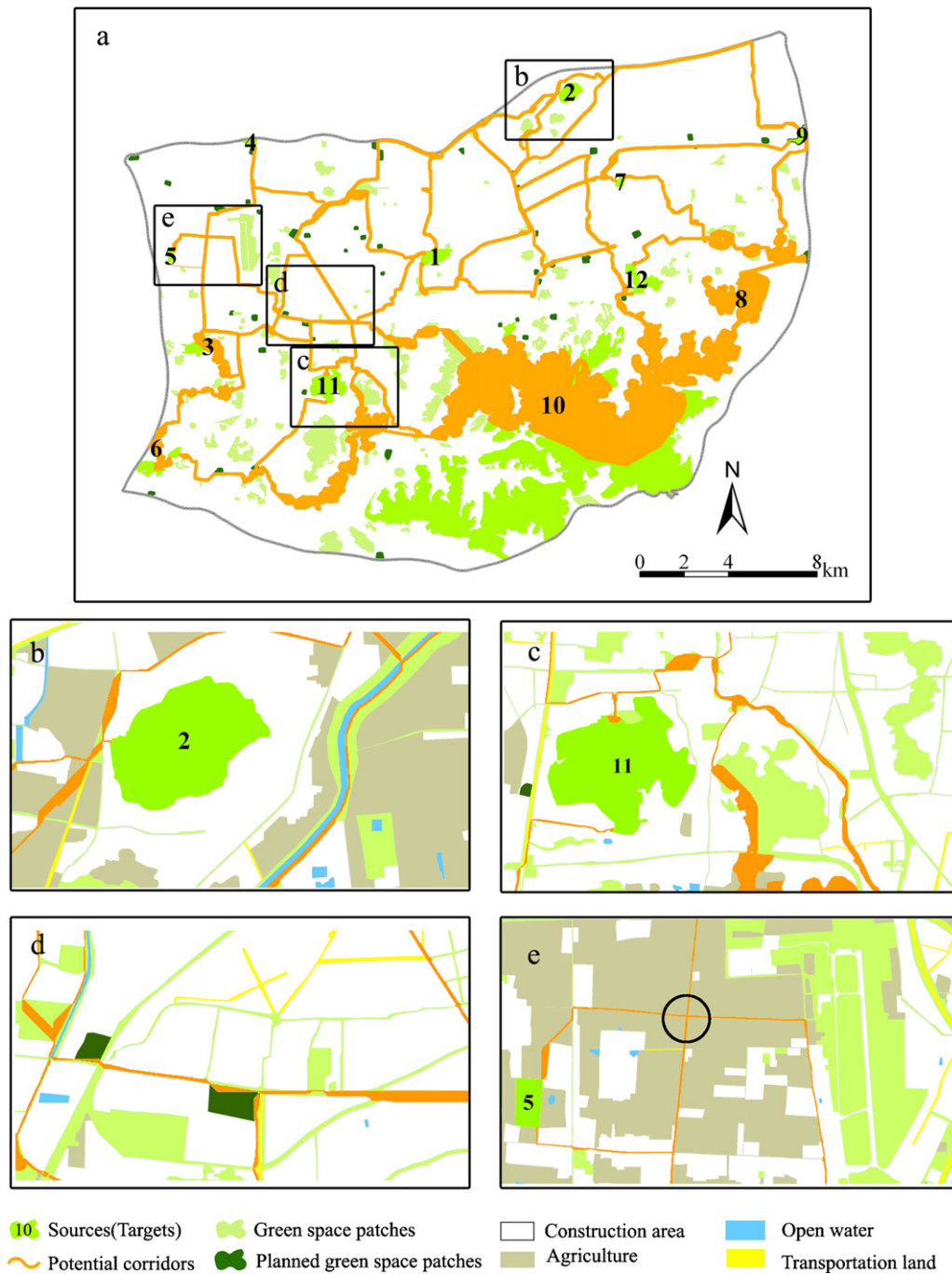
Fig. 4. (a) Potential corridors connecting core areas based on least-cost path analysis. (b) Potential corridor through a construction area. (c) A construction area that represents a barrier to connectivity. (d) Planned green spaces that are usable as stepping stones along the potential corridor. (e) The intersection (black circle) of the potential corridors.

where S_a and S_b represent the normalized sizes of patches a and b, and P_a and P_b represent the corresponding node weights. The gravity model generates a series of simplified networks. Hellmund (1989) summarized common network typologies ("cost to user" versus "cost to builder") based on the simulation's objectives (Fig. 5). To minimize the builder's cost, the network will be a min-

imum spanning tree, as in the Paul Revere example, in which all nodes are visited only once, with no extraneous segments. Models with the least cost to the user minimize the travel cost between two points, and represent an ideal situation in which all points connect directly; in a real landscape, this is rare because large impedances arise along certain linkages. Hierarchical networks are a least-cost-to-user network in which flow passes through a central point. More complex networks form closed loops. However, no matter what types of networks would be developed, the ideal solution depends on the relative importance of builder and user costs in a real landscape, and commonly, the intermediate solutions are typically adopted (Linehan et al., 1995). To identify this ideal solution, we examined the network typologies in Fig. 5 and prioritized each network under different scenarios in Fig. 6.

Fig. 5. Common network typologies (Hellmund, 1989).
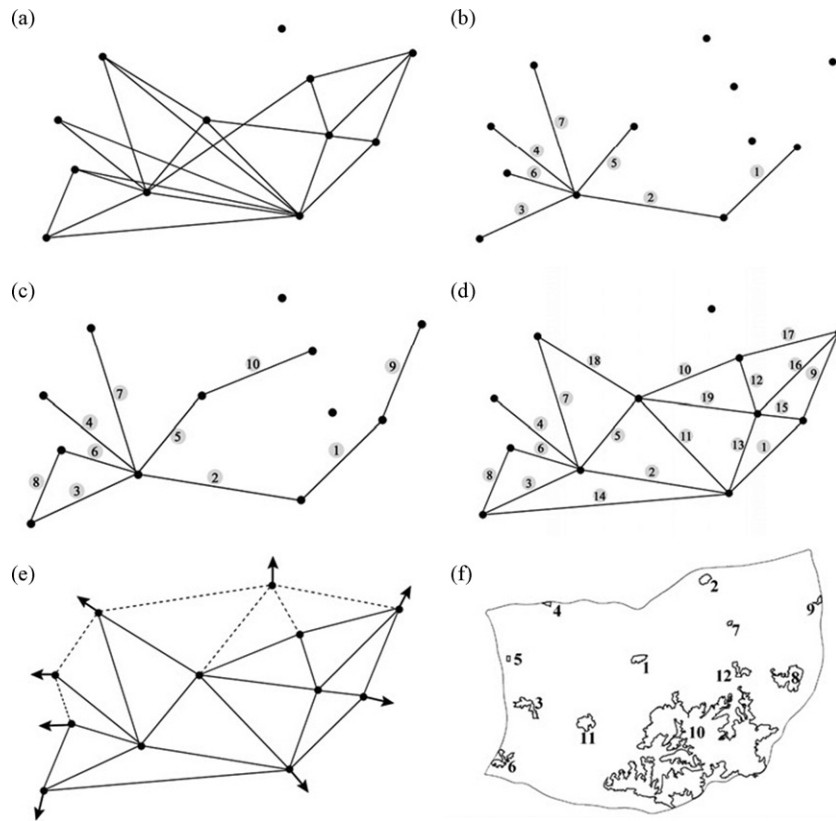
Fig. 6. Scenarios for urban green space networks based on the gravity model and graph theory. (a) Least-cost-to-user, (b) Scenario 1, (c) Scenario 2, (d) Scenario 3, (e) project (designed links), and (f) the present green space (1–12) distribution. Numbers ①–⑲ along the links indicate the connection order; the dashed lines in (e) represent designed links.

3.3. Evaluation of green space networks

The evaluation of green space networks includes analyses of patch and corridor characteristics, and the circuitry and connectivity (Cook, 2002; Zhang and Wang, 2006). The first analysis used patch or corridor density, patch or corridor area, and corridor length. This analysis compared features existing in 2004 with the planned result in 2010. The linkage of network elements can be analyzed in terms of circuitry and connectivity using alternative network scenarios generated by the gravity model. The degrees of circuitry and connectivity become indices in this analysis. Several indices have been developed for this purpose (Taylor et al., 1993; Goodwin and Fahrig, 2002), and we selected four: alpha (α), beta (β), gamma (γ), and a cost ratio, which are considered to be ecologically meaningful (Forman, 1999). They are defined as follows:

$$\alpha = \frac{\text{actual number of circuits}}{\text{maximum number of circuits}} = \frac{l - v + 1}{2v - 5} \tag{5}$$

where l is the number of links and v is the number of nodes. This index represents the proportion of the network formed by loops. Loops provide important alternative dispersal routes for organisms that must avoid disturbances or predators (Cook, 2002).

The β index represents the number of links divided by the number of nodes:

$$\beta = \frac{l}{v} \tag{6}$$

If $\beta < 1$, a dendrogram occurs; if $\beta = 1$, there is a single circuit; and if $\beta > 1$, more complex levels of connectivity exist (Haggett and Chorley, 1972; Linehan et al., 1995):

The γ index equals the number of links in the network divided by the maximum number of possible links (i.e., the degree of connectivity):

$$\gamma = \frac{l}{l_{\max}} = \frac{l}{3(v - 2)} \tag{7}$$

where $l_{\max}$ is the maximum possible number of links. The γ index ranges from 0, indicating that none of the nodes is linked to 1, where every node is linked to every other possible node (Forman and Godron, 1986; Bueno et al., 1995).

All three indices only consider the spatial attributes of nodes and corridors, without accounting for their cost-effectiveness. The cost ratio index also accounts for costs:

$$\text{cost ratio} = 1 - \left(\frac{n}{d}\right) \tag{8}$$

where n is the number of links and d is the total impedance of the links calculated according to the least cost of the potential corridors (Linehan et al., 1995):

$$d = \sum_{i=1}^{n} L_i \tag{9}$$

where L_i is the cumulative impedance of corridor i. Thus, the cost ratio equals the number of links in the network divided by their total impedance, resulting in a value per unit of impedance that accounts for cost differences between alternative networks and links.

4. Results

4.1. Spatial patterns of urban green space

The improvement of the spatial pattern of urban green spaces is the basic content for developing green space networks. To com-

Table 3
Metrics chosen to compare the spatial pattern of green space between 2004 and the planned 2010 pattern.

Landscape metrics	Cultivated green space		Natural green space
	2004	2010	2004 and 2010
Total area (ha)	4772	5341	10,487
PD (patch density; number km^{-2})	0.40	0.31	0.38
LPI (largest patch index; %)	4.77	5.15	11.03
MPS (mean patch size; ha)	22.20	32.2	51.4
ENN (Euclidean nearest-neighbor distance; m)	77.89	68.66	103.8
COHESION (patch cohesion index)	99.87	99.89	99.83

Note: Natural green spaces include scenery forests and part of riparian green spaces; cultivated green spaces include parks, plazas, roadside green spaces, attached green spaces, and part of riparian green spaces in Table 2. Because the city's plan protects all natural green space that existed in 2004, the metrics for this category do not change during the study period.

prehensively identify potential improvements, we firstly compared the predicted development of planned cultivated and natural green spaces (2010) (Fig. 2) with the existing situation in 2004 using six spatial indices (Table 3).

Because the city's plan is to protect all natural green spaces that existed in 2004, the metrics for this category did not change during the study period. Cultivated green spaces increased by 569 ha, the largest patch index (LPI) increased from 4.77 to 5.15%, the mean patch size (MPS) increased from 22.2 ha to 32.2 ha, whereas patch density (PD) decreased from 0.40 km^{-2} to 0.31 km^{-2}. All of these results indicated that the degree of fragmentation declined in the planned urban green space system. While, the patch cohesion index (COHESION) increased only slightly, from 99.87 to 99.89, and the Euclidean nearest-neighbor distance (ENN) decreased from 77.89 m to 68.66 m, indicating a decreasing isolation of the green space patches in the urban matrix.

4.2. Potential linkages based on least-cost path analysis

Fig. 4 shows the potential corridors based on least-cost path analysis. The green space network covers about 9676.04 ha (65.56% of total green space and 17.98% of the study area). The core sources and destinations account for 81.03% of the total network. Scenery forest constitutes the core area and functions as a key corridor (85.44% of the corridor space; Table 4) to nearby green space.

The 5664.27 ha of green space in the network that functions as corridors covers 58.54% of the total ecological network (9676.04 ha), and amounts to 10.53% of the total study area. The main linear corridors are roadside green space, followed by riparian green space and parks (4.74, 3.78, and 3.45%, respectively; Table 4). The corridors correspond to roadside and riparian green spaces that connect other green spaces and form the backbone of the network. These corridors are largely forested, though gaps formed by

agricultural land (1.60%) or other land uses such as construction areas (0.01%) may occur along linkages. Consequently, for roadside and riparian corridors to play key roles in the network, management must close these gaps to increase continuity and improve connectivity.

Water is not a preferred corridor, but strong corridors still exist through open water (0.21%). Because of the proximity of these patches, seeking the lowest cumulative cost created potential corridors despite the high impedance value of the water. It is not surprising that the network was sometimes interrupted by high-density buildings in residential areas and by roads within or surrounding habitat islands (Fig. 4b). Buildings and roads are serious barriers to connectivity and serve to isolate green space. Another example occurs in the southwestern part of the study area, where scenery forest is surrounded by a residential area, and potential corridors cannot link from these patches to others, instead requiring a circuitous route to other patches (Fig. 4c). Here, designing a functionally integrated network will require mitigation (e.g., creating new green space corridors or patches).

The green space network should be built upon the existing urban green space pattern. This means that the present urban green spaces would be strengthened and the green space unit might be developed in line with the existing structures, to improve the network and spatial cohesion. Strategically planned urban green space could become "stepping stones" between existing reserves (Fig. 4d). Planned stepping stones will improve the resilience of fragmented patches and reinforce weak corridors. However, our modeling showed that some planned patches did not succeed. For example, only 16.35% of the total planned green space (composed of plaza and roadside green space) creates corridors in the network (Table 4); thus, their spatial distribution must be improved. Some interactions between potential corridors in agricultural areas or corridors composed of agricultural areas (Table 4 and Fig. 4e) had a strong propensity to revert to construction areas due to urban

Table 4
Structural analysis of the potential green space network.

Land use	Total area	Area of network as corridors (ha)	% of each land-use type as corridors	% of the network as corridors	% of the total planning green space
Scenery forest	9963.17	4839.53	48.57	85.44	–
Public park	1153.98	195.41	16.93	3.45	–
Riparian green space	560.62	214.05	38.18	3.78	–
Green buffer	252.47	8.17	3.24	0.14	–
Nursery	105.83	3.74	3.53	0.07	–
Plaza green space	317.13	31.65	9.98	0.56	1.02
Roadside green space	2588.35	268.63	10.38	4.74	15.33
Agriculture	14,663.86	90.39	0.62	1.60	–
Transportation	1483.12	0.30	0.02	0.01	–
Open water	230.64	11.90	5.16	0.21	–
Construction area	18,845.67	0.48	0.00	0.01	–
Other	3645.74	0.03	0.00	0.00	–
Total	53,810.57	5664.27	10.53	100.00	16.35

Table 5
Node interaction (*G*) based on the gravity model.

Node	1	2	3	4	5	6	7	8	9	10	11	12
1	0	0.0001	0.0357	0.3648	0.0033	0.2412	0.2205	0.7650	0.1097	1.0193	12.2797	0.3078
2		0	0.0003	0.0006	0.0000	0.0025	0.0031	0.0029	0.0028	0.0031	0.0433	0.0042
3			0	0.0872	0.0022	3.9853	0.0803	0.3580	0.0727	0.4402	10.3208	0.1600
4				0	0.0086	0.2311	0.1599	0.4686	0.0901	0.5902	10.1668	0.1858
5					0	0.3142	0.1297	0.4235	0.0786	0.5285	12.8045	0.1758
6						0	0.0641	0.5490	0.0883	0.7041	13.1219	0.2020
7							0	0.1667	0.4511	0.1579	1.6850	0.8167
8								0	0.2709	65.6297	37.3941	0.6041
9									0	0.2826	2.4629	0.5217
10										0	60.3547	0.7207
11											0	0.3901
12												0

sprawl, suggesting that new stepping stones or corridors should be developed to reinforce their function in the network.

4.3. Identified green space networks

We also prioritized potential green space based on the gravity model to identify corridors and patches with the best opportunities to create a network that will conserve biodiversity in the long term and permit sustainable urban development. Table 5 presents the interaction matrix for the 12 nodes in Fig. 4a. And then, based on the graph theory, scenarios for green space networks were developed to simplify and systematize the complex landscape (Fig. 6).

We assumed that links are unfeasible and will be eliminated if *G* < 0.3 and if the link is redundant owing to convergence upon another similar node when the potential corridor is developed. The links that passed this test were mapped (Fig. 6). The connectivity for each alternative network was then evaluated using the four connectivity indices (Table 6).

Fig. 6a represents the least-cost-to-user solution (Hellmund, 1989), in which all links have *G* > 0.3. The networks in Fig. 6b–d represent a continuum of increasing complexity and connectivity based on the *G* values (Table 5), with each a subset of the next: Scenario 1 (Fig. 6b) links the major nodes in a spanning tree (a hybrid of the Paul Revere and Hierarchical forms), Scenario 2 (Fig. 6c) links 10 nodes and forms the first small circuit (connecting nodes 3, 6 and 11 which are three scenery forests) and corresponds to the southwestern land-use pattern with less construction area, and Scenario 3 (Fig. 6d) joins the links in Fig. 6c via several circuits. Fig. 6a–d reveal no link with node 2, which is surrounded by construction area (Fig. 4b); though potential corridors exist, their high impedance blocks interaction between node 2 and other nodes.

The *G* values and prioritization process develop the first southern link between nodes 10 and 8, connecting two large scenery forests. The potential corridor mainly runs through an area with no construction in the southeast (Fig. 4a). The largest scenery forest (node 10) has the highest habitat quality, but its "radiating routes" (Yu, 1997) are blocked. Table 5 and Fig. 6b–d reveal western links from nodes 10 to 11, but especially in the north, links to nodes 1 and 12 are delayed. Thus, the most significant bottleneck appears along the northern and western sides of node 10, where spreading development seriously constrains the network. As node 10 is the most important remnant of natural green space in Jinan, protection and restoration of linkages between it and other habitats are critical.

Green spaces in the north (nodes 2 and 4) and northeast (nodes 7, 9 and 12) are poorly connected, especially in the northeast. Though some riparian green space exists along the Yellow River and other green space exists along the roadsides, few large patches have high habitat quality; nodes 4, 5 and 9 are plaza green spaces, node 1 is a public park, and construction threatens them with isolation (e.g., node 2 in Fig. 4b), increasing the impedance along potential corridors. Consequently, it is hard to develop connections within the network. The third ring road around the city (Fig. 1d) is also a barrier between important natural habitats near the Yellow River and outside the study area. With this analysis in mind, we designed an alternative scenario (dashed lines in Fig. 6e) to increase connectivity that is more realistic than the least-cost-to-user alternative (Fig. 6a). However, although the connectivity indices all increase in this scenario, the cost ratio increases greatly (Table 6). Thus, increasing connectivity and decreasing impedance along the corridors are the most important tasks to improve the potential corridors. Fig. 6e also includes links to areas outside the study area that are very important; the network is an open system, which means that wildlife dispersal and migration can be strengthened and maintained by connectivity with areas outside the city. Unfortunately, linkage through these areas is becoming difficult due to fragmentation resulting from rapid urban sprawl.

4.4. General evaluation of green space networks

To evaluate the potential improvement, we compared the situation in 2004 with the planned situation for 2010 by classifying green space into corridors and patches. The density and area of the corridors and patches and the corridor lengths are shown in Table 7. The proposed plan will increase patch and corridor sizes by 2010 (Table 7). The increased patch and corridor densities indicate the planned green space system will help maintain or establish linkages among patches and corridors. The increased corridor length by 2010 will potentially increase network connectivity, since longer corridors may increase the possibilities for connectivity within the network. However, our analysis assumes that the city's plan will be implemented as planned.

Table 6
Connectivity indices for evaluation of the green space network scenarios.

Network	Nodes	Links	Alpha (α)	Beta (β)	Gamma (γ)	Cost ratio
Theoretical maximum	12	30	1.00	2.50	1.00	–
Least-cost-to-user (Fig. 6a)	12	22	0.58	1.83	0.73	0.51
Scenario 1 (Fig. 6b)	12	7	–	0.58	0.23	0.30
Scenario 2 (Fig. 6c)	12	10	–	0.83	0.33	0.41
Scenario 3 (Fig. 6d)	12	19	0.42	1.58	0.63	0.48
Project (Fig. 6e)	12	25	0.74	2.08	0.83	0.84

Table 7
Comparison of current and planned green space network indices.

Network index	Corridors		Patches	
	2004	2010	2004	2010
Density (no. km^{-2})	0.61	0.81	0.37	0.47
Area (km^2)	28.50	32.56	113.44	115.07
Length (km)	1028.10	1185.60	–	–

Note: Corridors include roadside green spaces, riparian green spaces, and green buffers; patches include parks, scenery forests, plazas, nurseries, and attached green spaces.

Further evaluation can thoroughly analyze the linkages of network elements in terms of circuitry and connectivity. The increases in α, β, and γ (Table 6) as connectivity increases (Fig. 6) reveal improvements in the network. However, the cost ratio favors simpler and more efficient networks, which may be less desirable for wildlife because simple networks are more sensitive to disturbance than complex networks with higher connectivities. Thus, it is useful to compare the two most complex networks (the least-cost-to-user network and our proposed network; Fig. 6a and e, respectively). The three indices α, β, and γ values are a little greater in Fig. 6e than in Fig. 6a (Table 6). However, the cost ratio increased greatly in our network (from 0.51 to 0.84), suggesting that the least-cost-to-user network (which approaches the theoretical maximum) is most desirable. However, this network includes only 11 of the 12 nodes and 22 links (Fig. 6 and Table 6), whereas our proposed method (Fig. 6e) contains all 12 nodes and 25 links, and has higher values of all three connectivity indices. In particular, it includes node 2, a key contributor to northern green space networks that provides linkages with habitats outside the study area. The decreased cost-effectiveness (increased cost ratio), however, has significant implications for corridor construction because the cost ratio was calculated based on the planned green spaces. High cost ratios indicate high impedance along potential corridors. If the proposed network in Fig. 6e was desired, planners could argue that the advantages offered by its greater connectivity will bring corresponding social and ecological benefits.

5. Discussion and conclusions

The combined and integrated application of remote sensing, landscape metrics, least cost analysis, gravity model and graph theory analysis represented an innovative approach for the development of urban green space networks for biodiversity conservation. This study put forward four goals, and sought to realize these by green space network development.

In this study, similar with other research studies such as by Linehan et al. (1995), Bunn et al. (2000), Rudd et al. (2002) and Zhang and Wang (2006), the identification of potential corridors using the least-cost-path analysis made a better approximate of the real landscape by including impedances along links. The creation of links using the gravity model analysis is much more effective than randomly selecting links as done by Bunn et al. (2000) and Zhang and Wang (2006). The green space network developed based on graph theory, especially by combining with the gravity model, simplified and systematized the complex real landscape and helped identify the relative significance of each green space, and guide urban green spaces planning. Forman (1999) stated that in the future, the gravity model would be useful to understand species that move along connected corridors, while the node-network analysis would be useful to understand species that move across corridors to patches. In real landscapes, the complexity of the green space system makes it difficult to assess the value of a planned network, especially from a connectivity perspective. Therefore, a method to quantify connectivity in proposed networks is required. The approach described here comprehensively identifies potential corridors and patches that can serve as network nodes while

accounting for the characteristics of potential corridors. Abstraction of the network based on graph theory and connectivity indices offers a good means of evaluating connectivity.

Modeling and development of networks can identify core areas and potential corridors to conserve biodiversity and restore ecological conditions. In addition, the networks are also important to maintain the ecological components of a sustainable urban landscape (Sandström et al., 2006). The green space network development through the method presented in this paper could serve as a skeletal framework to guide the green space planning. Planners and managers must propose configurations in which management can dramatically improve connectivity among patches; least-cost path analysis can reveal such configurations. Maps of potential corridors reveal locations where corridors passing through low-quality habitats weaken the network or where planned green spaces would lose their function as stepping stones. As the results shown, in the proposed plan by 2010, plaza and roadside green spaces were the main types of green space that increased, but they only weakly improved networks and biodiversity. It is general in the process of building "garden city" in most of Chinese cities. They often fail to consider the sizes, locations and the green space community composition. The green spaces were built more arbitrarily than based upon scientific analyses (Yu et al., 2006). The gravity model helps prioritize components of the networks and reveals key locations for large patches or corridors. Using site-specific management would improve the network by providing a more diverse urban landscape. The increase in corridors and patches measured by connectivity indices quantifies the improvements resulting from management. However, the government's proposed plan requires some improvements. Thus, combining least-cost path analysis with the gravity model and connectivity indices provides a "what if?" tool for evaluating prospective changes in the green space pattern before implementing a plan. The developed green space networks cannot solve all biodiversity conservation problems, but are a cost-effective complement to existing reserve systems (Linehan et al., 1995). We hope this case study will provide some lessons for other cities and the approach presented here can help them to solve the problems they might meet in the green space planning.

The development of green space networks is a significant step forward in the biodiversity conservation of Jinan City. However, there are still many issues and questions that need to be addressed. There is little consensus on whether networks designed for biodiversity conservation would work as designed, because the approach has not yet been tested and the analysis includes many subjective factors (Linehan et al., 1995; Walker and Craighead, 1997). For example, the inverse cost weighting of habitat suitability in the least-cost path analysis has an obvious effect on the identification of potential corridors. Although networks function mainly as a guiding framework for urban planning, detailed work should account for actual site conditions. In this paper, we tried to analyze potential network configurations by overlaying the land-use patterns and demonstrated that networks developed in this way could reflect the real landscape and reveal problems that may be encountered if the network is constructed as well as opportunities to maintain or restore connections between important green spaces. Certainly, such broad landscape analyses of connectedness are use-

ful, but species-specific analyses are also essential for determining the potential for connectivity of particular populations (Beier and Noss, 1998; Hoctor, 2003). The same landscape may have different degrees of connectivity for different species (Kindlmann and Burel, 2008). Creating connected green space networks is inherently complex. As it was said by Jongman (2008b) that the development of networks could not be based entirely upon species distribution data but have to be based on a more general long-term strategy. The green space network as an open system should be developed at a multi-scale not only in the urban area as in this study, limited to the third ring road, but also in the administrative region of the city as shown and explained in Fig. 6-6 (G). The development of the green space network in a multi-scale with consideration on structural and functional connectivity will be one of the aims for future research.

The urban green space network is essential for biodiversity conservation, but because green spaces are developed by people, they become important parts of the cultural landscape by integrating economic, historical, cultural, esthetic and recreational goals (Jongman, 2008a). The government of Jinan City proposed a development project in 2002 to integrate hills, springs, lakes, and rivers with the city. One goal was to connect Huashan Mountain (node 2), Queshan Mountain (indicated by the arrow from node 2 in Fig. 6e), and the southern mountains (node 10) to form a triangular pattern (Fig. 6e) that protects nine famous scenic spots. The network proposed in this paper could accommodate this project, or could identify where new corridors should be developed and key locations must be protected. Accordingly, development of the network would be compatible with the construction of a cultural landscape. The development of the green space network for the ecology as well as for the people will be one of the other aims of future research.

Acknowledgements

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