



Applying a socio-ecological green network framework to Xi'an City, China

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Abstract

Green–blue space loss and fragmentation are particularly acute in Chinese cities due to rapid urbanization, large ring-road system and the following city compartments. Therefore, connecting urban green–blue spaces has been recently advocated by central government. This paper revised and applied the recently developed urban green network approach to the case of Xi'an city, China, a city which has been rarely studied before from this perspective. The focus was on connecting fragments of urban green–blue spaces to compact green–blue networks, integrating both social and ecological functions into a fully functioning entity. Landscape metric analysis was added to identify that the main city outside the city core should be a planning priority zone. The Eurasian tree sparrow (*Passer montanus*), Asiatic toad (*Bufo gargarizans*) and humans at leisure were selected as three focal species to meet the emerged socio-ecological benefits. Sociotope and biotope maps were drawn up to identify patches with high human recreation and wildlife shelter values and providing crucial network structures. Least-cost-path model was used for identifying potential linkages between patches. This model was based on network structures and cost surface, which measures the theoretical energy cost of travelling between landscape elements. By integrating the potential paths for the selected organisms with density analysis, the updated framework generated three improvement maps for species indicators, and 10 network corridors for establishing green–blue networks at city scale. At neighbourhood scale, one site with habitat and linkage examples illustrated specific measures that could be taken in local practice.

Keywords Habitat fragmentation · Landscape metrics · Sociotope · Biotope · Cost surface · Connectivity

Introduction

Habitat fragmentation is a major issue in cities worldwide as a result of dissection of built-up areas by roads and railroads in the pace with rapid urbanisation (Chen et al. 2013; Forman 1995; Haddad et al. 2015; Miao et al. 2014; Saunders et al. 1991; Wu et al. 2013). Biodiversity loss, declining resource availability and dysfunctional provision of ecosystem services are direct consequences of this process. This

issue is likely to continue as the transport networks throughout China and many other fast urbanizing countries become increasingly dense and urban areas expand (UNDP 2012).

In studies on landscape and habitat fragmentation, various methods and principles of landscape ecology have been applied in recent years. For example, landscape pattern metrics use a variety of quantifiable indices to test pattern and structure relationships of landscape patches and predict fragmentation issues at a broader spatial level (Hargis et al. 1998; Uuemaa et al. 2013). The landscape connectivity approach combined with graph theory has been proposed as a promising approach for analysing and investigating potential linkages between isolated elements (Adriaensen et al. 2003; Kong et al. 2010; Teng et al. 2011; Zetterberg et al. 2010). Landscape connectivity measures the degree to which organisms can move among resource patches (Taylor et al. 1993), showing their species- and landscape-dependent character (Tischendorf and Fahrig 2000). This connectivity is a key contributor to many ecosystem services in cities such as biodiversity, genetic resources and providing a setting

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for recreation, although it also aids the spread of invasive species and diseases (Teng et al. 2011). Graph theory, in the sense of graph application through mathematical algorithms, was introduced into landscape ecology by Bunn et al. (2000). Drawing nodes (N) and links (S) in a graph/network can analogue landscape elements and organism dispersal among patches, respectively. This method could thus easily be adopted in landscape representation for further systematic analysis.

In addition, various techniques such as remote sensing (RS) and geographical information system (GIS) facilitate connectivity studies involving modelling physical environments, wildlife activities and human disturbance (Teng et al. 2011). For example, cost-distance modelling uses accumulated resistance values to determine and predict the optimal dispersal routes of species (Adriaensen et al. 2003; Kong and Nakagoshi 2006; Kong et al. 2010; Teng et al. 2011; Zetterberg et al. 2010). Suitability modelling uses species range to search for suitable habitats on potential routes of dispersal (Wang et al. 2008). Among these modelling techniques, least-cost-path (LCP) analysis is regarded as a powerful and efficient approach for optimising selection of networks. An important advantage of LCP analysis is its ability to incorporate wildlife behaviours, species persistence and explicit landscape configuration into one entity (Minor and Urban 2008; Teng et al. 2011).

Since 2000, many Chinese cities have become aware of the landscape isolation issue and have attempted to conserve urban green–blue spaces. Some Western concepts were introduced such as those of greenbelt, green corridor and green infrastructure. At present, another guidance concept, that of connecting urban green–blue space networks, is being advocated by Chinese central government through its document ‘Strengthening Urban Planning’, published on February 6th, 2016 (The State Council 2016). This concept aims at improving quality of life for urbanites and highlights the importance of urban ecology principles by means of connecting green–blue spaces to unified networks from regional to city and neighbourhood scales.

This study examined the issue of landscape and habitat fragmentation from a socio-ecological perspective to meet the central guidance policy and exemplify one way to merge ecological and social benefits based on empirical data. For this purpose, an urban green network framework, that was previously developed and tested in Stockholm, Sweden, was applied to Xi’an city, China. This framework integrates green and blue spaces planning into landscape connectivity analysis linking species movement and human recreational access. It develops networking plans at city and neighbourhood scales, dealing with loss of green spaces in a time of city densification (Xiu et al. 2017). However, the Stockholm testing indicated a need for further investigations and tests of the framework in more locations, for instance not only in

European cities but also in cities such as in Chinese cities that face rapid development and major challenges to sustainable planning. This analysis could be important to understand the research area and identify the planning priorities’ zones (Zhang and Wang 2006), but has rarely been used in green networks planning. A further aim of the present study is to determine how the framework can be applied in fast-growing Chinese cities such as Xi’an and identify adjustments that might be needed in a local context. Specific objectives of the study were to: (1) identify and evaluate the fragmentation situation in the city of Xi’an; (2) locate important structures of ecological and social functions within the city environment; (3) explore potential linkages among isolated patches; and (4) provide comprehensive suggestions for compact green networks in multiple scales.

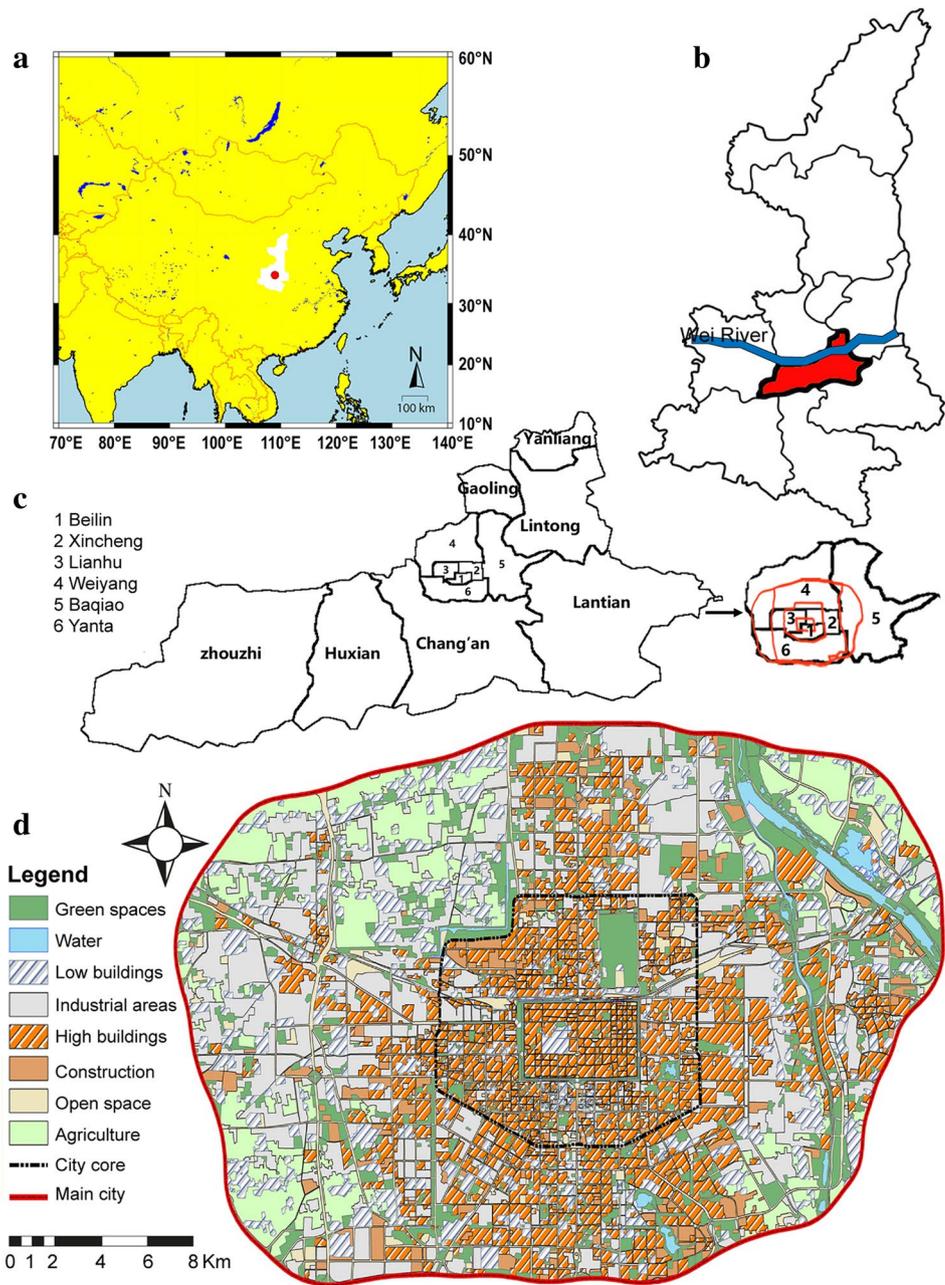
Case study

Xi’an (34° 16′ N, 108° 56′ E) is the capital city of Shaanxi province, located in the north-west of China (Fig. 1a). It is in the middle of the Guanzhong Plain, which is an alluvial plain created by the Wei River (Fig. 1b). As one of the oldest cities in China, Xi’an city has existed for more than 3000 years and was known as Chang’an city until the fourteenth century. The average elevation of Xi’an is 400 m above sea level (elevation of the Yellow Sea system). It consists of 10 districts and three counties (Fig. 1c). Four ring roads divide the city into two parts: the city core (including the first and second rings) and the main city (including the third ring and the ring expressway) (Fig. 1c). This study examined the entire area of Xi’an city inside the express ring road, covering about 458 km² (Fig. 1d).

Xi’an has experienced dramatic city expansion and population increase in the past 6 decades. According to the Xi’an Statistics Yearbook (2014), the population increased from 2.53 million in 1952 to 8.07 million in 2013. The built-up area expanded from 133 km² (mainly inside the city core) in 1985 to 504.68 km² (whole city region) in 2013. These numbers are still growing because of urbanisation and migration. For instance, the population is expected to grow to more than 10 million by 2020 (Xi’an City Planning Bureau 2016).

The latest master plans (2008–2020) produced by the Xi’an City Planning Bureau (2010 and updated in 2016) clearly show that the city is expected to expand outside the ring expressway and cover the whole region. More transport roads are planned to speed up urbanization and link the city with neighbouring cities. Rapid urban sprawl has encroached on green–blue space and impacted on all ecosystem services. The general land use map of Xi’an (Fig. 1d) shows that over 65% of the land is occupied by built-up area (including residential and industrial areas), hard surface (roads and other open spaces) and artificial areas. Green–blue spaces in the city are scarce

Fig. 1 Maps of Xi'an city and the surrounding area showing the location of the study area in **a** Shaanxi Province, China and **b** the region; **c** urban administration and four ring roads of Xi'an city; and **d** land use in the study area



and fragmented. To comply with the new guidance policy on networking of urban green–blue spaces, an augmented plan for Xi'an with the aim of conserving and restoring green–blue

space networks for wildlife, as well as fulfilling social functions for citizens, is required.

Table 1 List of materials

Database	Description
Vector digital line graphic map	1:50,000 updated in 2014
Raster ASTER digital elevation model map	Updated in 2011, 20 m elevation and 30 m spatial resolution
Topographic maps	Satellite images in 2016-02-06, level 17 (1:4,514) of Tiandi map
Human disturbance map	Population data (10,000 persons per unit) from Xi'an Statistics Yearbook 2014

Methods

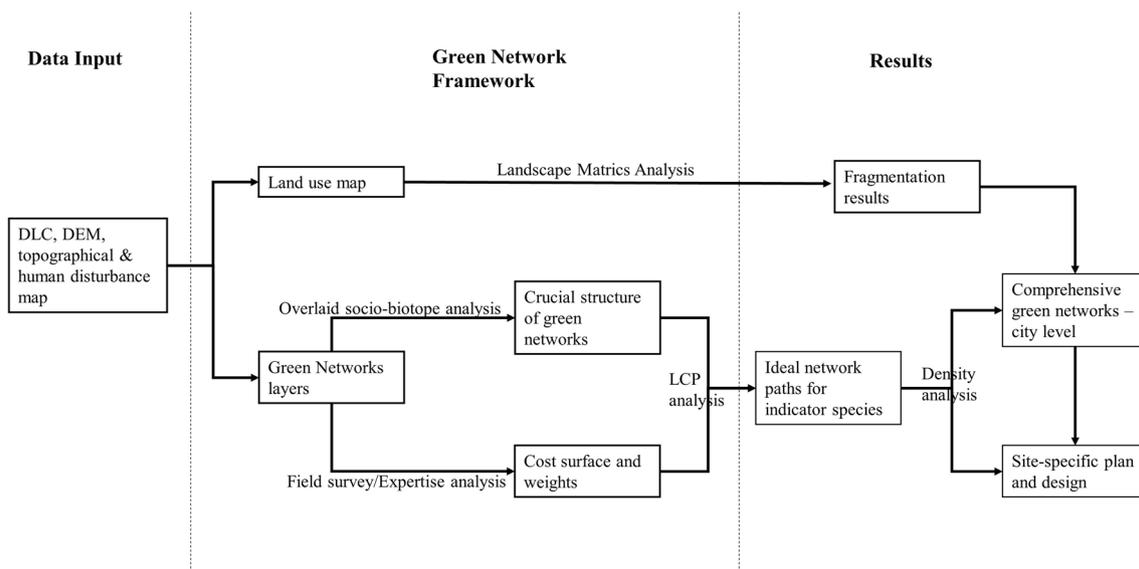
Materials and workflow

Three main digital geographical databases with complete coverage of the area (Table 1), obtained from the National Geomatics Center of China, were used. These were a vector Digital Line Graphic map (1:50,000) updated in 2014, a raster ASTER Digital Elevation Model map of 2011 with 20 m elevation resolution and 30 m spatial resolution, and topographical maps georeferenced using satellite images (captured in 2016-02-06) in level 17 (1: 4514) of Tianditu map from the State Bureau of Surveying and Mapping. Population data (10,000 persons per unit) for the human disturbance map were obtained from the Xi'an Statistics Yearbook published by Xi'an Municipal Statistics Bureau (2014).

To reduce errors caused by different geographical coordinate systems and resolutions, all the maps were converted to a common projected coordinate system (Xian 1980, 3DegreeGKCM108E). Categorical land use/cover

maps were then created in ESRI's ArcMap (2015.3.1) and manually combined with the results of field surveys. The general land use/cover was categorised into eight groups: green spaces, agricultural land, industrial areas, open spaces, high buildings, low buildings, construction areas and water (Fig. 1d). Green spaces mainly include parks and gardens in the urban environment; agricultural land refers to farmland with vegetation; industrial areas are in use for commercial purposes, industry, factories, stores etc.; open spaces (hard surfaces) include roads, railways, plazas and squares, which usually have limited greening; high buildings are built-up areas with more than six floors (normally built after 2000); low buildings are those housing areas built generally before 2000 and private villas completed in recent years in Yanta District; construction areas are land under constant construction; and water is the main rivers (the Chan and the Ba), as well as large-scale man-made lakes.

To achieve the research objectives, a series of methods were used in this study (Fig. 2). The first set was for fragmentation situation analysis which was added in this study compared with previous test. Landscape metrics

**Fig. 2** Work process and sets of methods used to test the framework of green networks in Xi'an city

were applied at the level of city core and the whole city (city core plus main city) so as to identify areas of planning priority in the city. The second set was designed for examining the framework of green networks in Xi'an city. It involved a process of visualizing representations of networks and their crucial habitats, which used the developed process but adjusted to local conditions. The third set comprised least-cost-path (LCP) analysis to identify potentially effective linkages between habitats for dedicated species. The last set was used to produce comprehensive plans for compact green networks at the city scale and detailed designs at neighbourhood scale based on density analysis and the results generated in previous steps.

Landscape metric analysis

To measure and evaluate the fragmentation situation in Xi'an city and search for areas of urgent needs, spatial landscape indices were divided into three categories: composition (basic characteristics) (McGarigal 2014), shape (patch complexity) (Rutledge 2003) and configuration (degree of isolation or connectedness) (Moilanen and Hanski 2001). To identify different characteristics and potential improvements in different zones, the spatial indices for city regions between 2006 and 2016 were compared using 7 metric indices (Table 2). To reduce the scale dependence of landscape metric analysis, indices from both class and landscape levels, were used to interpret landscape patterns and predict habitat connectivity in the urban environment (Hargis et al. 1998; Rutledge 2003; Zhang and Wang 2006). All indices were calculated by FRAGSTATS (version 4.2) in raster format at a pixel resolution of 5 m × 5 m to maintain data consistency. Detailed algorithms and calculation methods are listed in the FRAGSTATS document (McGarigal et al. 2012).

Network visualisation and its crucial structure using sociotope and biotope maps

In terms of graphic visualisation of green networks, the first and most important issue is defining nodes (N) and links (L) in the context of the city environment. One commonly used approach is to take the important habitats of green–blue spaces as node sources and the movement and dispersal among habitat patches as links (Adriaensen et al. 2003; Kong et al. 2010; Teng et al. 2011; Zetterberg et al. 2010). For the purpose of studying both social and ecological functions, in the present study, we used two newly developed reference maps based on precise land surveys data in setting criteria for source selection, namely sociotope and biotope maps.

Sociotope mapping was first proposed by Ståhle (2006) with inspiration from the biotope mapping method, which uses maps to indicate and identify important plant assemblages for ecological protection (Sukopp and Weiler 1988). The sociotope map investigates and visually presents socially significant areas. These socially significant areas can be widely used public places for recreation, favourite places, aesthetic locations, etc. To generate two reference data maps for Xi'an city, we conducted two parallel surveys in seven city districts within the scope of a case study in the period April–June 2015.

The sociotope mapping methodology aimed to indicate the most widely used green–blue spaces for human recreation. On the basis of the original method of producing sociotope maps [see detailed explanation in Ståhle (2006)], below process was used: (1) two groups of respondents were identified, namely general public and experts. Fifty residents (age range 15–65+ years) from each district were randomly selected as representatives of the general public since random selection avoids systematic bias in sampling and achieves a representative sample that allows for generalisation to the entire population (Flyvbjerg 2006).

Table 2 The 7 landscape metrics used this study

Landscape metric (abbreviation)	Description	Index category	Analytical parameter
Class area (CA)	The total area of corresponding patch type (ha). This study selected type of green spaces	Composition	Class
Patch density (PD)	The number of patches per 100 ha		
Mean patch size (MPS)	The average area of the given patch type		
Edge density (ED)	The total length of all edge segments per hectare		
Mean fractal dimension index (MN-FRAC)	The average value of perimeter-area ratio in the form: $2\ln p/\ln A$, where A is the total area of the landscape and P is the total length of patch edges	Shape	Landscape
Euclidian mean nearest-neighbour distance (MNN)	Distance from one patch to the nearest patch	Configuration	Landscape
Patch cohesion (COHESION)	Area ratio divided by area-weighted mean shape index, multiplied by 100 to convert to a percentage		

Two city planners from each district were also selected for expert interviews. The total number of participants was thus $50 \times 7 = 350$ (general public) and $2 \times 7 = 14$ (planning professionals). (2) Residents were asked to point out their most frequently used (more than three times per week) green–blue spaces (up to three places) using district paper maps. (3) Planners from each district were asked to evaluate these places and transfer them into GIS vector maps. Based on these, 598 socially active patches were compiled from each district and identified to create the sociotope map of the city.

In addition, the 14 selected city planners from district landscape bureaus plus three landscape ecologists, from Chang’an University, Northwest A&F University and Xi’an Municipal Landscape Bureau, were involved as expert references to generate the biotope maps. They were interviewed to help to determine focal biotope species and the relation to the landscape such as plant communities for breeding, gene migration, winter–summer hibernation, etc. Based on the information obtained, the Eurasian tree sparrow (*Passer montanus*) and Asiatic toad (*Bufo gargarizans*) were selected as representatives of birds and amphibians which are crucial network users, and a total of 1041 patches were identified as biotope sources. Both of these species are listed as species worthy of protection in China (Wang 2000). Tree sparrow prefers trees, shrubs and other green spaces and the Asiatic

toad is adapted to both moist and dry surroundings. Both are resident species of Xi’an and provide fundamental functions in ecological systems (Wu 2011; Xu et al. 2013). They not only have cultural and educational meanings, but are also popular among citizens, according to our surveys.

To clearly show the sociotope and biotope patches obtained above in a merged vector map, the ‘Feature to point’ tool in ArcMap was deployed using the central point to represent the location of every habitat polygon. The geographical location of certain points overlaid each other, which would suggest that they are functional in both a sociotope and biotope sense. These doubly important habitats can fulfil both human recreational and ecological values for wildlife in green networks. We extracted points with such values and set them as crucial network nodes. A distance of 100 m was used to avoid edge effects when transferring from an irregular polygon shape of habitat patches to central points. In all, a total of 468 nodes were recognised as crucial structures of green networks in Xi’an city for further network analysis (Fig. 3).

Cost surface and least-cost-path analysis

To build an LCP model of green networks, the next step was to measure the cost surface when targeted species

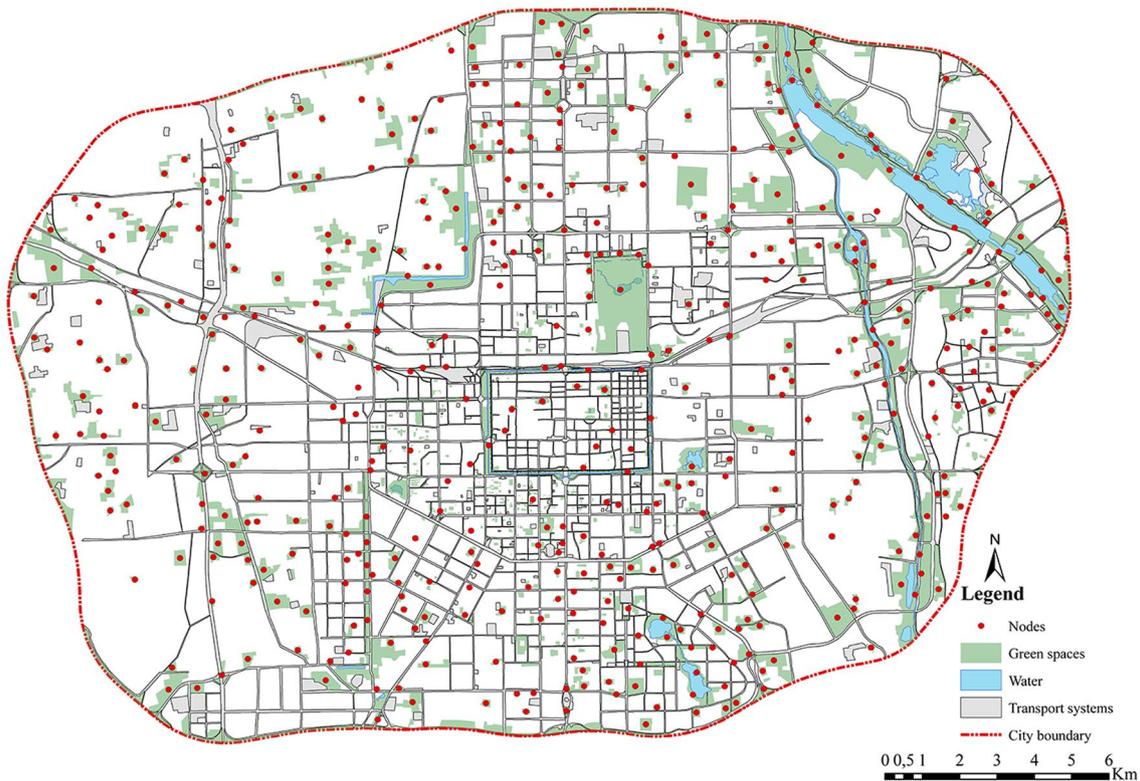


Fig. 3 The 486 nodes of green networks in Xi’an city identified as providing both social and ecological values

travel from one node to another. In this analysis, every landscape unit (grid cell) was assigned a cost and this cost accumulated when crossing cells from one point to another (Adriaensen et al. 2003). The relative quantification method was applied in this study to determine the energy cost of movement. It is also based on expert assessments (landscape architects/ecologists mentioned above) and scientific publications such as Adriaensen et al. (2003), Kong et al. (2010), Rayfield et al. (2010), Teng et al. (2011), Parks et al. (2013), Braaker et al. (2017), etc.

High values represent a high cost of travelling and low suitability for dispersal of species. Compared with previous test in European city, four factors were considered in this analysis: land use/cover (C_l), elevation (C_e), human disturbance (C_h) and green space distance (C_d). Although in real life, there are many more factors which can influence the cost surface, the selected factors are the common impedance indicators and can show the degree of accumulated travelling impedance (Rabinowitz and Zeller 2010). For example, land use/cover has been proven in many studies to be a key determinant of impedance level (Adriaensen et al. 2003; Teng et al. 2011; Braaker et al. 2017). Crossing different land use/cover, such as green spaces, roads, buildings, etc., requires varied resistance values (Sitzia et al. 2014; Braaker et al. 2017). Similar characters are landscape elevation (DEM, Digital Elevation Model), human disturbance (assuming that human density leads directly to anthropogenic impedance, it was employed here as a human disturbance indicator) (Adriaensen et al. 2003; Teng et al. 2011; Xiu et al. 2017) and green space distance (Euclidean distance from the green space under analysis to other green spaces, with a shorter distance giving a higher possibility of connecting and lower cost of travelling) (not included in initial test in Stockholm) (Teng et al. 2011).

Among the factors, the elevation of the city received a smaller weight because of Xi'an's plain condition (while Stockholm got a higher weight due to its more varied topography). Green space distance was added as influencing determining factor of cost distance, as Xi'an as compared with the affluent green spaces in Stockholm (one third of the city is occupied by green space) has a scarcer situation of green space which may imply the distance between each green–blue space play a more important role in connecting the compact green networks.

Yet, the success of precisely quantitative assessment of the cost value is far-fetched, using relative numbers to represent cost surface is still an important and reliable component in LCP analysis (Kong et al. 2010; Teng et al. 2011; Parks et al. 2013). The overall cost value can be calculated as combined value of individual cost components (C_l , C_e , C_h and C_d) multiplied by the corresponding weight (W_l , W_e , W_h and W_d):

$$\text{Cost} = C_l \times W_l + C_e \times W_e + C_h \times W_h + C_d \times W_d, \quad (1)$$

where the total sum of $W_l + W_e + W_h + W_d$ is equal to 1.

Table 3 illustrates the extent of the four factors in accordance with the indicator species. A 1–10 range was applied for human recreation, 1–1000 for bird movement and 1–10,000 for the theoretical cost of toad movement to highlight and distinguish the degree of impedance to different species. Amphibians normally need greater efforts to cross different landscapes than the other two groups, while birds' migration may be more easily hindered by human activities (Teng et al. 2011; Xiu et al. 2017). Therefore, the impedance degree was determined as toad > bird > human. However, bird and toad shared a similar trend of costs, which was different to that of humans to indicate the difference between wildlife and humans in terms of species movement.

Different land use/cover types also play differing roles in determining cost surface. For example, a river or other water body together with construction areas can serve as great barriers to all three species; green space is simple to go through for birds/toads but an obstacle for humans (Kong et al. 2010), whereas railways and roads with little vegetation impose more barriers and higher cost due to high mortality of wildlife but represent convenience for human movements. C_e , C_h and C_d each included 6–7 attributes based on level of natural elevation, human population density and habitat distance to other green–blue spaces, using natural breaks to divide types (Jenks and Caspall 1971).

Since Xi'an city is situated on a great plain where elevation does not change very much, the influence of the DEM factor occupied a smaller percentage than the other three factors. However, a high percentage weight was given to the land-cover variable to highlight the driving effects of land use/cover changes. The Weighted-Overlay tool in ArcMap (ESRI 2015) was used to calculate and integrate the four types of costs and weights. A final cost-distance map was then generated for the LCP analysis. Based on the reference nodes and cost surfaces, the Cost-Distance tool was used to compute the accumulated cost distance and corresponding backlink surfaces.

Exploring improvement potential at city and neighbourhood level

To generate the most cost-saving network paths for the target species and explore the improvement potential of habitat connections, we ran the LCP model differently for city and neighbourhood scales. The city level analysis focused on illustrating prospective large-scale corridors for comprehensive networking maps and suggestions, while the neighbourhood scale concentrated on finding particular geographical sites that could be modified for improvement and enhancement of connections. These two levels are interrelated,

Table 3 Cost surface and weights used for the four landscape factors according to the three indicator species

Variable	Attribute	Eurasian tree sparrow		Asiatic toad		Human	
		Costs	Weight	Costs	Weight	Costs	Weight
Land cover (C_l)	Water	1,000	0.4	10,000	0.45	10	0.6
	Construction	800		8500		9	
	Agriculture	100		100		7	
	Other open space	500		5000		2	
	Industry/Commercial area	900		9000		5	
	Green spaces	1		1		6	
	High buildings	700		7000		4	
	Transport areas	750		8000		1	
	Low buildings	300		2000		3	
Human disturbance (C_h)	< 5000 people/km ²	1	0.25	1	0.3	1	0.2
	5000–9000	10		150		2	
	9000–10,000	20		300		4	
	10,000–18,000	45		500		6	
	18,000–20,000	70		700		8	
	20,000–27,000	85		900		9	
	> 27,000	100		1000		10	
Digital elevation model (DEM) (C_d)	< 380	1	0.1	1	0.05	1	0.1
	380–394	30		300		3	
	394–408	50		500		5	
	408–428	70		700		7	
	428–460	90		900		9	
	> 460	100		1000		10	
	Green distance (C_d)	< 200 m	1	0.25	1	0.2	1
200–400		30		300		2	
400–600		50		500		4	
600–800		70		700		6	
800–1000		90		900		8	
> 1000		100		1000		10	

because connectivity on a larger scale is composed of systematic minor links (or nodes) (Zetterberg et al. 2010). Adding or removing links (or nodes) at city level can influence the detailed network connectivity at neighbourhood sites, and vice versa.

At the city level, the 468 reference patches (Fig. 4) were all too large to compute and some of them were located quite close to each other. Therefore, these nodes needed to be aggregated to a smaller number for easier calculation and visualisation. The aggregate point tool in ArcMap was applied to cluster points within 1 km (corresponding to the maximum annual migrating distance for Asiatic toad and the shortest annual movement distance of the three target species) so as to correlate polygons and select each polygon as one patch point. Another patch selection criterion was for large plant communities, since larger habitats play a more important role in urban connectivity and demand planning priority (Hoffmeister et al. 2005; Teng et al. 2011). Therefore, patch area of more than 1 ha was filtered in the study

area. Finally, 78 patch nodes were selected for running the LCP model at the city scale. Based on three categories of cost surface, three independent maps of efficient network paths were created.

By transferring these three maps into one vector database, certain routes with high repetition rates on the three maps were assumed to play a more important role in linking habitats. Because of their higher repetition, higher values and potential, these paths can be used in reality (Teng et al. 2011). Therefore, they should be indicated as prioritised corridors and receive more attention in subsequent comprehensive plans. The line density tool in ArcMap was then used to categorise different classes of iteration in the overall paths. Three classes of iteration level were identified, using the natural break method (Jenks and Caspall 1971). Setting land use/land cover map as background, maps of potential green network linkage were compared with the density map, which clearly revealed where the suggested connections should be. Nodes and links located in areas of higher density level

Fig. 4 Maps of Xi'an city showing potential network paths for indicator species. **a** Effective corridors for Eurasian tree sparrow; **b** effective corridors for Asiatic toad; and **c** effective corridors for human recreation

represent the stepping stones and suitable locations of connectivity zones. Therefore, they need to be considered in the prioritised plan and detailed analysis.

At the neighbourhood level, the aim of the analysis was to make small changes that could nevertheless have large consequences for the system. From the overall reference patch nodes (468 patches), one specific site was selected to re-run the LCP model. Three criteria were applied for location selection: (1) the site should have high line iteration level based on density analysis, since a higher level represents higher needs by indicator organisms and more possibility of use in reality; (2) it should be located in more fragmented areas in urgent need of improvement; and (3) it should preferably be situated between the city core and main city, so as to link different splinter areas. Optimal small-scale corridors for different species were suggested using the LCP model. The effective corridors were aggregated into one vector map, potential paths were determined and detailed sketches on how these links can be designed were prepared.

Results

Fragmentation analysis of Xi'an city

The results of the landscape metric analysis of the city core and the whole city (city core plus main city) between 2006 and 2016 are shown in Table 4. These indices revealed the present fragmentation situation of green spaces at two scales. Both the city core and the whole city increased total area of green spaces in the studied period (803–1108 ha in the city core and 5479–6026 ha in the whole city). From 2006 to 2016, patch density (PD) decreased from 3.05 to 2.15 per km² and mean patch size (MPS) increased from 67.60 to 88.88 ha, indicating that green spaces had become more aggregated into larger patches in the city core. Edge density (ED) value decreased from 31.55 to 30.76 m/ha, suggesting that the patchwork of green spaces is currently not as complex as it was a decade ago. These four indices all illustrate that fragmentation level is decreasing in the city core. However, for the whole city, PD increased from 2.14 to 4.56 per km² and MPS decreased from 28.39 to 23.56 ha, showing that green spaces are more splintered into smaller patches, therefore, raising the degree of fragmentation. The ED increased from 26.59 to 27.83 m/ha, revealing that the patch shape has become more complex.

In terms of landscape-level analysis, the spatial indices showed similar features. Small and large increases in

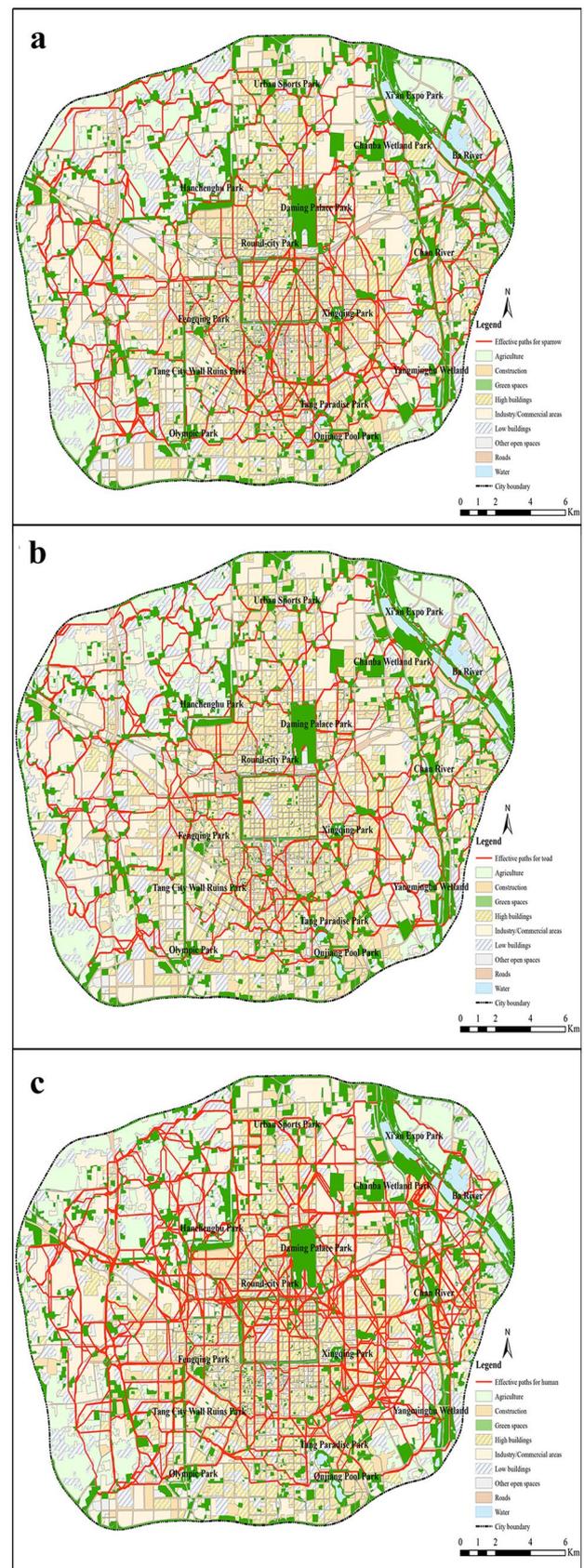


Table 4 Comparison of the 7 landscape metrics applied in this study at city core and entire city scale

Level	Landscape metric	City core		Whole city	
		2006	2016	2006	2016
Class	Class area (CA; ha)	803	1108	5479	6026
	Patch density (PD; number/km ²)	3.05	2.15	2.14	4.56
	Mean patch size (MPS; ha)	67.60	88.88	28.39	23.56
	Edge density (ED; m/ha)	31.55	30.76	26.59	27.83
Landscape	Mean fractal dimension index (MN-FRAC)	1.0634	1.0636	1.0638	1.0649
	Euclidian mean nearest-neighbour distance (MNN; m)	94.99	94.03	119.74	124.35
	Patch cohesion (COHESION)	99.66	99.77	99.77	99.73

mean fractal dimension index (MN-FRAC) in the city core (1.0634–1.0636) and in the whole city (1.0638–1.0649) indicated that patch shape and structure of green spaces are simpler inside the city. The Euclidian mean nearest neighbour distance (MNN) decreased from 94.99 to 94.03 m and Patch cohesion (COHESION) increased from 99.66 to 99.77, both revealing that the fragmentation issue is decreasing in the city core. With respect to the whole city, MNN increased from 119.74 to 124.35 m, whereas COHESION decreased from 99.77 to 99.73. Thus, all the landscape metrics applied in this study showed that the fragmentation issue of green spaces is more serious in the newly developed areas outside the city core.

Potential network paths for indicator species

Three maps of the effective linkages for the selected species in the study area were developed (Fig. 4). In the map of convenient connections for Eurasian tree sparrow (Fig. 4a), there are 2844 corridors with length ranging from 0.83 to 46.98 km and a total length of 31,402 km. The routes are more intensively distributed in the east, centre and south of the city, where most of the crucial habitats are located, including Chanba Wetland Park and Expo Park, Daming Palace Park, Xingqing Park, Tang Paradise Park and Qujiang Pool Park. This network provides more opportunities for tree sparrow and other bird species to use the habitats and facilitates their movement among different patches.

The effective path map for Asiatic toad (Fig. 4b) contains 2844 corridors with length ranging from 0.93 to 57.59 km, comprising 34,733 km in total. Most of the paths are concentrated along river and lake areas. Ba River and Chan River are two significant network hubs located in the eastern part of Xi'an city. Qujiang Pool Park in the southern part of the city also intersects many potential corridors. Another possible network system centre is in the north-west of the city, where Hanchenghu Park is situated. In the centre of the city, Daming Palace Park plays a crucial role and connects the most convenient routes from all directions, although it is not a natural water site. Within these efficient paths, species

migration for toad and other amphibians between water and green spaces can be promoted.

The map shown in Fig. 4c supplies city residents with effective opportunities to make contact and move easily among green–blue spaces. There are 2844 potential paths and every route is in the range of 0.75–37.46 km long, making up 30,048 km in total. These corridors mostly run along streets and other transport strips that connect highly populated areas and recreational green–blue destinations. Therefore, more paths are distributed in the north-west, east-centre and south-east of the city. Citizens in different districts can be provided with more chances to use green–blue spaces and contact with nature. The network of human recreation ties social, recreational and aesthetic values of green–blue spaces and promotes people's physical activities between residential areas and significant natural spots.

From the three maps, two possible conclusions can be drawn. First, the suggested path length is human > bird > toad, which indicates that more efforts are required to establish compact green networks for toad and bird than human beings, which may also imply that the current condition of green–blue spaces still emphasises human needs instead of those of other species, particularly amphibians. Second, some common habitats (parks in the east, center and south of the city) play a crucial role in linking the green networks for all three species indicators (Fig. 4a–c). This indicates that these parks are significant from both social and ecological perspectives. Therefore, their functions should be recognized and promoted in the future planning and design process.

Line density and comprehensive green networks at city level

Based on density analysis of merged essential paths for the three indicator species, we first incorporated an iteration level map (Fig. 5a). Using simple visualisation, this shows how the thousands of potential corridors are distributed over the city. Three scales are used in the diagram to represent the line repetition density from low to high. Middle and high levels of density are shown in light and heavy red colour. As

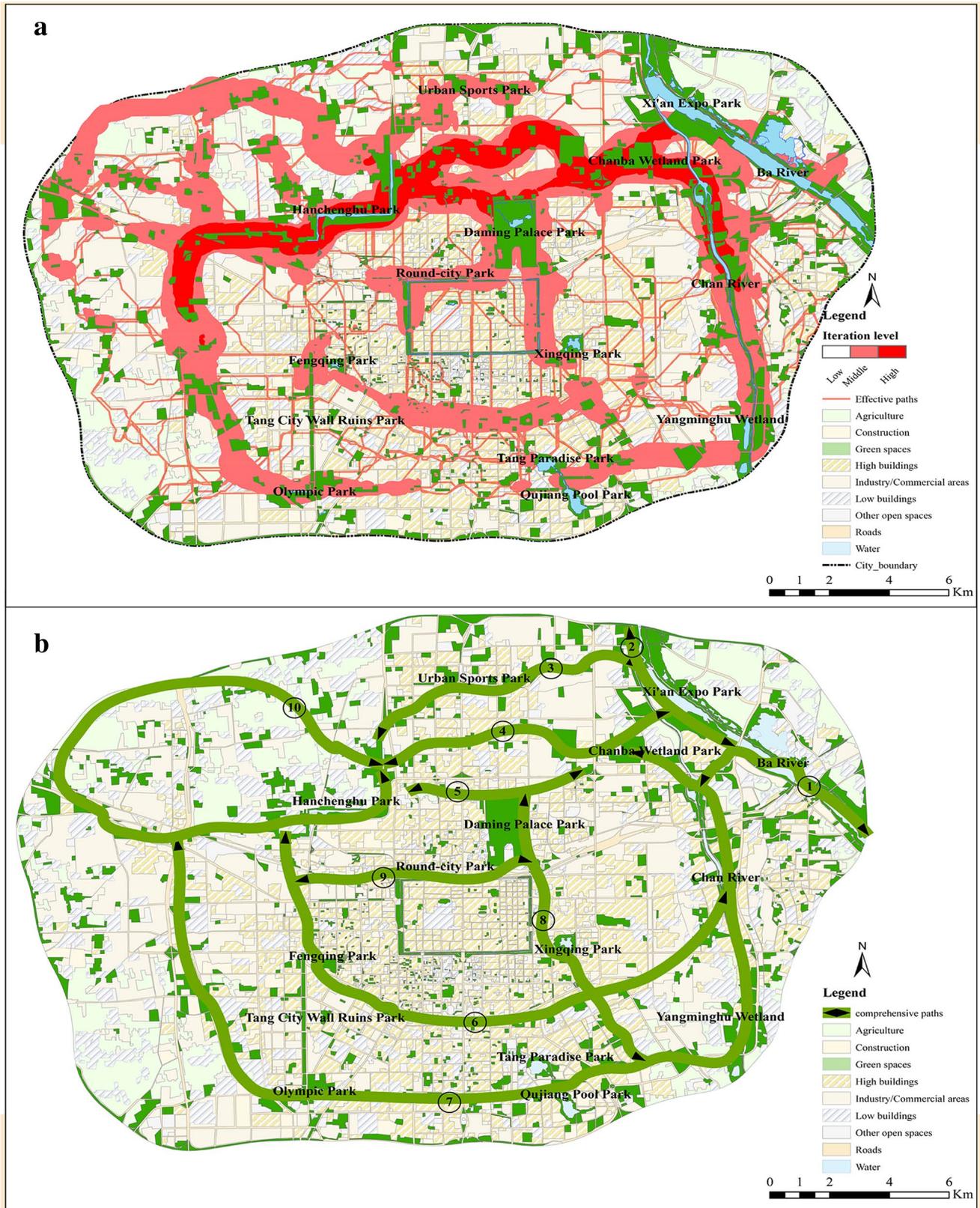


Fig.5 Path density map and improvement plan for Xi'an city. **a** Iteration level of merged effective paths for the three indicator species. A higher level indicates higher values of path repetition and connectiv-

ity in the city; **b** 10 comprehensive network linkages for constructing the city's connectivity system

can be seen, high density is concentrated in the middle and north of the city, where in general the most highly prioritised linkage should be located. Thus, the linkage should go from Xi'an Expo Park together with Chanba Wetland Park in the east, passing through Daming Palace Park in the middle and connecting Hanchenghu Park in the north-west. The middle level of iteration is dispersed in the whole city, linking the crucial habitats in the eastern and southern part of Xi'an, for instance from Daming Palace Park to the Round City Park, Xingqing Park and Fengqing Park in the city core, and from Chan River and Ba River to Yanminghu Wetland, Tang Paradise/Qujiang Pool Park, Olympic Park and Hanchenghu Park in the main city.

By integrating the maps of current land use/cover, the optimal network paths and density analysis into one dataset, a comprehensive green network map was developed (Fig. 5b). This map highlights the important habitats and existing linkages, such as the parks mentioned above and the linear Tang City Wall Ruins Park. It connects Fengqing Park and Olympic Park directly between the city core and the main city. Thus, these crucial patches and paths should be conserved and prioritised in the master plan. The second suggestion concerns 10 large potential corridors, with the aim of constructing a green–blue space connectivity system for the city (Fig. 5b). The first two corridors (marked ① and ②) in Fig. 5) link up the two main rivers and can potentially be used to connect habitats outside the city. The following five corridors (③ to ⑦ in Fig. 5) also start from the water body and run to the rest of the city. Another two routes, (⑧ and ⑨), focus on the city core and join Daming Palace Park with the Round City Park and Xingqing Park, respectively, to the previous seven corridors. The last path (marked ⑩) is located within the Hanchenghu Park area, which is part of a network circuit in the north-west of the city.

Figure 5 also illustrates that Xi'an has highly scarce and isolated green–blue spaces. To connect these sparse areas, three main aspects need to be considered. First, existing crucial habitats, particularly all the mentioned parks that have proven social-ecological functions in the city. Second, existing linkages between green–blue spaces, such as the linear Tang City Wall Ruins Park. Third, developing potential networks with effective paths between habitats. All these three aspects need to be recognized and addressed in the neighbourhood design.

Site-specific plan

In the analysis centred on the neighbourhood level, the focus was directed towards the potential connection between Chanba Wetland Park, Daming Palace Park and Hanchenghu Park, since this area has the highest level of optimal path density and possibility of frequent use in reality. The zone mainly contains the northern part of the second ring

road and neighbouring areas. Based on the cost surface and 67 nodes selected from the overall 468 patches, the LCP model was recalculated and the most probable corridors were identified (Fig. 6a). The optimal network comprises four paths, connecting the three crucial nodes and some other habitats. Compared with other land use/cover in this region, the main road poses more barriers, particularly to birds and amphibians. Therefore, the fine-scale design work concentrated on this road. It contains three flyover bridges, namely Xinjiamiao, Weiyang and Wenjing. The Xinjiamiao and Weiyang flyovers are also two of the 468 crucial habitats for the entire city. Thus, the fine design was applied for the Weiyang flyover and one part of the road as representative suggestions (Fig. 6a).

The detailed plan for the two sites are shown in Fig. 6b, c for both habitat and linkage examples. The Weiyang flyover is currently a bare motorway, which raises a variety of issues relating to air pollution, noise, carbon emissions, etc. (Bocci et al. 2010). Revitalising the elevated roads to create green arteries is an emerging necessity for all of the city's polluting motorways. Adding greener amenities along the roads, particularly in spaces below flyovers, would enhance biodiversity, improve air quality, reduce noise pollution and so forth. The vertical green columns of the overpasses can connect green spaces below flyovers and the road planting as an entity (Fig. 6b). As for the present part of the second ring road, green spaces along the streets are quite limited. There is thus an urgent need to reinvigorate the green spaces as a result of their value for connectivity for the neighbourhood and the city's system. Our suggestions range from enlarging the greening in the middle of the road to integrating linear planting on both sides of the street. Joining the drain inlets along the road with trees is likely to lead to more effective use of natural drainage water (Fig. 6c). Setting the drain inlets into greening also allows water to work as irrigation and afterwards the extra water can flow out naturally (inserted in Fig. 6c).

Discussion

Fragmentation analysis

Considering the context-based issue of landscape fragmentation, quantitative measurements were used to obtain a direct picture of how the issue differs in a single city, Xi'an. Although landscape metrics have been widely used in studies of landscape ecology, their application in green–blue networks planning is still limited. Most previous fragmentation studies, such as those by Kong et al. (2010), Zhang and Wang (2006) and Lausch et al. (2015), have selected a temporal perspective to analyse the trend of spatial changes and have challenged the scale-dependent characteristic of

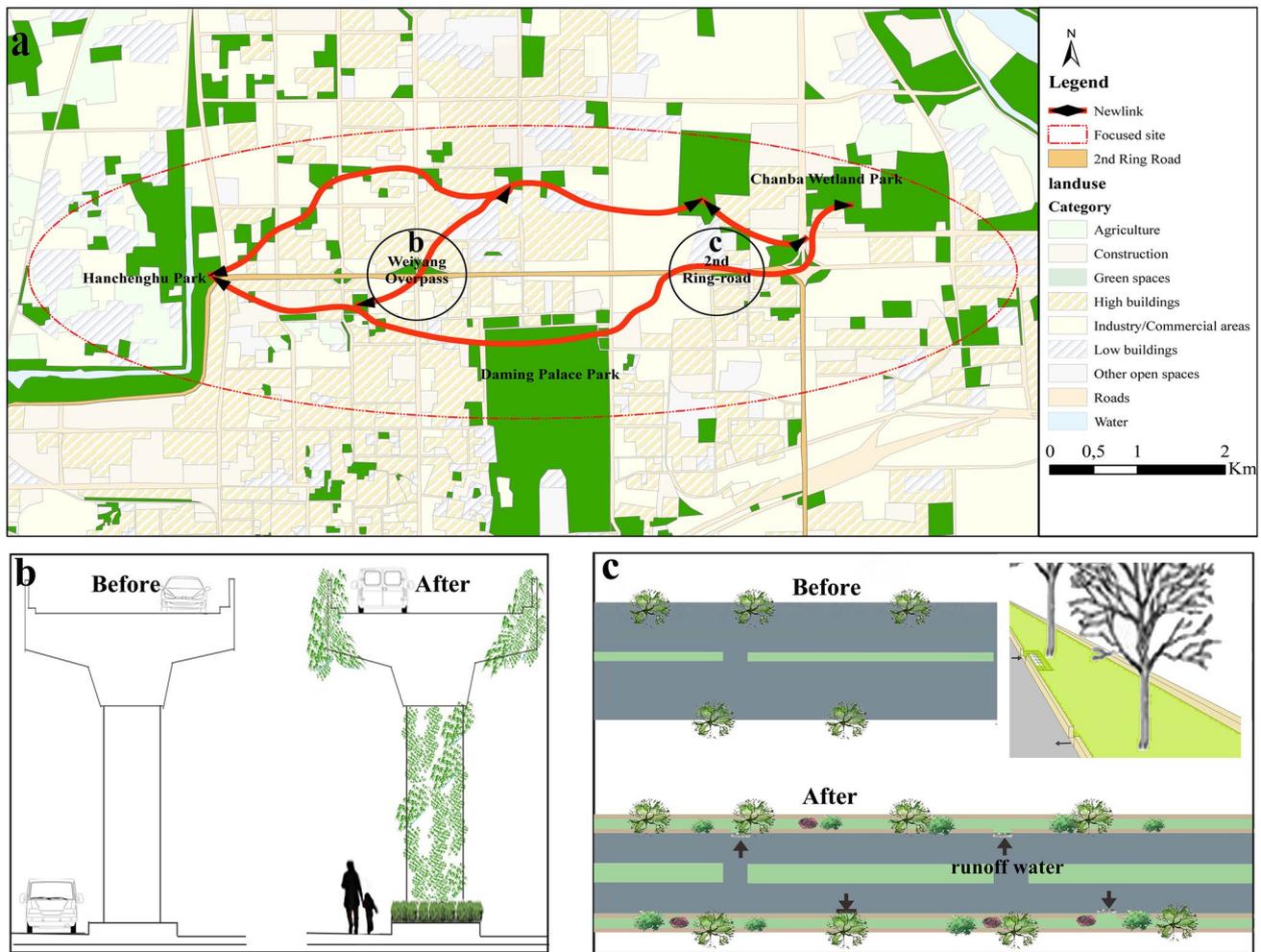


Fig.6 Green networks at the neighbourhood scale and suggestions for physical improvements. **a** Optimal linkages between Chanba Wetland Park, Daming Palace Park and Hanchenghu Park; **b** present situation and suggested greening design for the Weiyang flyover; **c** pre-

sent condition and potential street greening design for the second ring road; and inset shows street greening design integrating underground drains with trees for the second ring road

indices. To reduce these influences, consistent pixel resolution and land use/cover types were used in this study. The seven used indices are also commonly applied in studies of habitat fragmentation, e.g., those by Hargis et al. (1998) and Wu et al. (2002). This study indicated that the fragmentation of green space is more severe in the newly developed areas of Xi'an. One possible reason is that the existing greening policies and practice accompanying the latest master plan focused more on the city's core. According to the Xi'an Statistics Year Book (2016), sparse green spaces have been compensated by larger parks, gardens and street greening in the city core. Thus, more attention should be given to the newly developed areas.

This study only focused on the spatial changes in green spaces. However, from the city core to the whole city scale, more complex impact factors of fragmentation may exist. For example, in a fast-growing urbanized area, one of the

leading factors of fragmentation in land use/cover is the increasing number of built areas. Therefore, more related spatial indices and land use/cover types can potentially be used to obtain a complete overview of landscape isolation processes.

Framework adjustment and augmented strategies

Although landscape/habitat fragmentation has been recognized as a serious issue in cities worldwide, empirical research on current isolated situation and rebuilding landscape connectivity has not been sufficient. Xi'an, which has experienced rapid urban sprawl and a representative urban landscape form with its ring-road transport and city division (Xiong 2006), has been a rare city case in Chinese studies. In accordance with the advocated central guidance policy and requirement from the local municipality,

this paper updated and applied a previous formulated framework which was successfully tested in a European city. This aligns with the need to learn from Western approaches but revise research and planning frameworks in line with local conditions. Using the updated framework and local data/references, different potential maps for species indicators and multiscale green networks were generated. Therefore, the framework has proven to be functional in two very distinct urban contexts. Verification of the framework in two very different city cases has been very valuable for its further development and application.

In terms of the updated framework, the foremost is selecting species indicators. Compared with other similar research, such as that by Zhang and Wang (2006), Kong et al. (2010), Zetterberg et al. (2010) and Teng et al. (2011) whose focus was on biotic flow, sociotope and biotope mapping in this study offers an integrated socio-ecological approach in determining important structures in urban green networks. That is not only focal wildlife but also human recreation were regarded as target indicators. Although human activity and ecological conservation are often in conflict, identifying places that can provide both values is necessary. Moreover, these maps can represent valuable references for other studies. For example, sociotope maps could be used for human activity network, while biotope maps could be utilised for conservation planning of target species.

Furthermore, modelling and development of optimal landscape networks always raises the issue of cost distance, which is widely discussed in “[Network visualisation and its crucial structure using sociotope and biotope maps](#)” in this paper and in previous studies by Adriaensen et al. (2003), Rayfield et al. (2010), and Rabinowitz and Zeller (2010), among others. Running LCP model requires data on the cost distance, but measurement of real time or energy costs is extremely difficult. Therefore, using theoretical and relative numbers to represent the real costs has become widely accepted. Rayfield et al. (2010) summarised studies on cost surface and suggested that relative quantification is a reliable approach. In reality, numberless factors would influence the ultimate cost value. However, selecting factors and judging the weight of cost surface is context-based. For instance, due to the geographical location and scarcer condition of green space in Xi’an, elevation was not given a large percentage weight and green distance was added as an influencing factor in this study compared with the initial test in Stockholm other factors were also assigned with different weight. Transport-related areas were separated from open spaces, since they were considered to be convenient for people but to pose great barriers to wildlife because of high mortality and friction. Human disturbance was assigned the second largest weight to recognise its significant driving force in the city environment.

Based on network nodes and cost distance, LCP model can create effective network linkages that enable species movement with the lowest resistance. However, these potential routes in theory may be in conflict with practice and, therefore, it is necessary to propose suggestions for improvements in accordance with the actual situation (Pinto and Keitt 2009). This study showed one possible solution in improvement strategies that can be transferred between city and neighbourhood scale, because the two levels are correlated and interdependent. The line density tool was used for differentiating the possibility of frequently connecting paths on a large scale. Recurrent habitats which were transited and connected by the efficient links were thus highlighted. However, habitats not covered in this improvement plan are also important for the whole city’s system. The green networks at the city level put structuring the city’s connectivity system first, while more green–blue spaces are likely to be covered in the next step. By moving the focus from large to small scale, site improvements were targeted to illustrate how habitat and linkage can be improved. Selection of modified sites requires instrumental approaches such as density analysis, but depends on local contexts, too operational advice should consider the specific components of location and network users. In terms of suggesting an improvement plan, street greening may be an important component of the compact green city. However, when the green network framework is implemented in other locations, different solutions are highly possible. This opens the door for further studies on framework testing, adjustment and improvement. The three examples shown in Fig. 6 offer similar ideas for street greening research and the like. This highlights another strength of this study, as it integrates existing research results to tackle the fragmentation issue. Combining current research with the green networks model can result in an easier process in both implementation and operation.

From green–blue fragments to compact green networks

Green–blue spaces are becoming victims of urban sprawl and corresponding landscape fragmentation. To transfer these fragmented green–blue spaces to compact green networks, several factors need to be considered. First, green and blue spaces need to be integrated together, since green spaces cannot be separated from blue spaces spatially, socially or ecologically. For instance, “[Potential network paths for indicator species](#)” has shown that green–blue spaces in Xi’an city (different parks) are commonly crucial. Both of them play an equally significant role in offering wildlife habitats as well as social, recreational, educational and historical places for human beings. Second, a holistic socio-ecological perspective is fundamental. Although more studies are leading urban planning in this direction,

green–blue spaces still emphasise human needs instead of ecological functions (Barbosa et al. 2007; Wang et al. 2016). Both humans and wildlife use the urban environment, and thus planning and design measures working for both groups are necessary. This paper only shows one example to identify the commonly important habitats in the city. More in-depth knowledge about the interrelated social and ecological systems is thus required. Last but not least, compact green networks are based on the network and landscape connectivity method, which is normally utilised for conservation planning (Kong et al. 2010; Zetterberg et al. 2010). This paper extends the approach to multifunctional networks, detailed planning and design implementation. Based on the results in “Line density and comprehensive green networks at city level” and “Site-specific plan”, three aspects affect the effective paths in the city, namely habitats and existing and potential linkages. All of these aspects need to be included in the city and neighbourhood strategies to achieve compact green networks.

Conclusion

Fragmentation has been recognised as a serious threat to ecosystems and ecosystem services in cities. This issue is also visible in Xi’an city where it has become severe given the pace of urban expansion in recent years. To support planning policy, combining landscape connectivity with graph theory was shown here to be an appropriate methodology for analysing and addressing this issue. Testing of the green network framework in a fast-growing city in China produced a series of results and suggestions for improvement and indicated good operability and applicability of the method in, for example, identifying important structures of ecological and social functions within the city environment, exploring network linkages among isolated patches, and providing comprehensive suggestions for compact green networks in multiple scales. Separate maps of effective paths for target indicator species can be used for conservation and social activity planning. The habitat structure and city-scale green linkages suggested here are likely to help in improving the present master plan for a greener and more well-connected Xi’an city. A detailed sketch and a design integrating existing studies makes application of the framework convenient. However, the process of testing the framework also illustrated its contextualised character. Moreover, all elements depend on selection of appropriate organism species and accurate calculation of cost surface. This calls for more studies on contextualisation and including relevant theoretical and empirical perspectives are required. Fragmentation is a process that changes according to time and space. Network influx is not solely confined to the city but also dependent on even larger and smaller scales. These call for more

studies that cover varied scales of areas and more detailed spatial–temporal fragmentation analysis to achieve more holistic green networks.

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