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Urban ecological corridors construction: A review

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ABSTRACT

An ecological corridor, with both ecological and cultural functions, is a symbol of urban ecological or green civilization, and has therefore become one of the major topics in the fields of landscape ecology, urban ecology, and ecological planning. On the one hand, along with the prominent contradiction between regional ecological protection and economic development, as well as between the growing ecological demands of urban residents and the destruction of natural ecosystems, the construction of urban ecological corridors is very challenging. On the other hand, with contemporary urbanization and ecological civilization development, the standards and requirements for the construction of urban ecological corridors are set higher and higher. Constructing an urban ecological corridor is therefore particularly important, and must adopt a spatial approach that balances the relationship between ecological protection and economic development. In this study, the classification of urban ecological corridors was firstly conducted according to the structural or functional differences. Secondly, research progress on the construction of urban ecological corridors was systematically summarized and the main inadequacies were indicated. Following the analysis of the main methods employed in the construction of urban ecological corridors, existing methods were classified into three kinds, i.e. qualitative analysis, quantitative analysis, and spatial analysis. In addition, the advantages and disadvantages of the methods of subjective judgment, suitability and sensitivity analysis, network analysis, and minimum cost path analysis were compared. To provide theoretical support for the construction and management of urban ecological corridors, four key research directions were also pointed out, i.e. the identification of key nodes of urban ecological corridor, the determination of the width of urban ecological corridor, the measurement of integrated effect of urban ecological corridor, and the multi-scale integration of urban ecological corridor. The present study will aid in accelerating and improving the process of ecological corridors construction in China's new-type urbanization.

1. Introduction

As an inherent part of urban ecological security patterns, urban ecological corridor plays an important role in promoting the variety natural flows and resisting negative effects of human activity, especially in guarding against the unidirectional diffusion of human influences. At the same times, urban ecological corridor meets the needs of urban residents towards the recreation and ecological green living open space. Ecological corridor has the heterogeneity characteristic when compared to the surrounding landscape. Urban ecological corridor refers to a linear or ribbon ecological landscape, which has the functions of natural habitat, green open space or human habitat isolation in the artificial eco-environment of the city or urban area [1–2]. In recent years, in the context of China's rapid urbanization and regional integration, urban ecological corridor plays a vital role, especially for transportation green corridors, and green belts in city or intercity, which can not only accelerate regional natural species flow, but also effectively isolate or filter environmental pollutions. As a result, ecological corridor has become an essential part of ecological construction in urban agglomeration.

Urban ecological corridor has the basic characteristics of the ecological corridor, and it is also a symbol of urban ecological or green civilization. Thus, it has been a hot topic in the field of landscape ecology, urban ecology, and ecological planning in a long time. However, on the one hand, there is a sharp increase in the demand for urban construction land in the background of China's rapid urbanization. On the other hand, urban ecological corridor has the unique advantages compared to other non-construction land, such as lower re-development cost, relatively complete transportation facilities, while at the same time, there is a lack of strict control measures in the planning and management of urban ecological corridor. Hence, in the driving of maximum economic benefits, urban ecological corridor can be easily transformed into construction land [3]. Faced with the contradiction between the economic development and ecological protection, and the outbreak of urban

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environmental problems and the increasing human ecological demands, the effective construction and management of urban ecological corridor becomes a possible way to resolve this contradiction. Therefore, in this study, a comparison of ecological corridor and related concepts was conducted, with the classification of urban ecological corridor from the structural and functional perspectives, respectively. Then, a brief history of urban ecological corridor construction in China and the world was summarized. It was also focused on comparing the advantages and disadvantages of the main construction methods. Finally, based on the inadequacies of the current research, key research directions for the future were discussed, in order to effectively promote the scientific construction and effective management of urban ecological corridor in the process of rapid urbanization.

2. Concept of urban ecological corridor

Currently, the concepts related to ecological corridor include greenway, green belt, green corridor, ecological network, habitat network and ecological infrastructure. The comparative analysis of the connotation, origin, focus and main application areas of those concepts, can make great contribution to a better understanding of the conceptual connotation and denotation of ecological corridor (Table 1): (1) Greenway. Its first thought can date back to the Boston Park System in the 1860s, which refers to the channel for local residents to be close to the nature originally. It sets off a worldwide craze of greenways movement since the 1990s when the term of greenway was officially recognized by President's Commission on Americans Outdoor [4]. The most representative definition of the greenway in all the understandings is Ahern's, who pointed out that the greenway is the land network system which is consisted of linear elements, designed to achieve a variety of utilizations with ecological, cultural, recreational, aesthetic and other functions [5]; (2) Greenbelt. This concept was first proposed in the 1600s by the William Petty, but it attracted wide attention in 1898 when Howard proposed the concept of garden city [6]. Greenbelt is a green open space outside the city established for dividing urban and rural areas, focusing on the function of playing its suppression on urban sprawl and providing recreational areas for residents [7]; (3) Ecological network and habitat network. Sourced from biological protection field, both concepts are defined as a network-like landscape which is consisted of eco-nodes or eco-core areas, ecological corridors, buffer zones and other nature reserve areas [8]. Constructing the regional ecological networks to enhance the connectivity of natural habitats, is considered to be an effective way to protect wildlife habitats and biodiversity, and a basic skeleton to maintain the regional ecological security system [9]; (4) Ecological infrastructure. This concept was firstly released in urban ecological planning report of Man and Biosphere Programme (MAB) in 1984 [10]. It refers to the resource allocation network system which includes supporting points, lines, surface and networks supporting for human system operation and durable survival. The concept of ecological infrastructure stresses the priority to protection and aims to maintain the important ecological resources and critical ecosystem structure [11], so as to keep sustainable provision of regional ecosystem services with guaranteed ecological security; (5) Ecological corridor. It is a kind of ecological landscape with the line or strip configuration with the integrated ecological, social, cultural and other functions. Ecological corridor was originally proposed to connect isolated habitats of wild animals by establishing migration corridors, so as to achieve the purpose of wildlife protection. International Union for the Conservation of Nature (IUCN) in 1980 applied the concept of ecological corridor to global conservation strategy [12]. From then on, the ecological corridor began to change from the sole function of natural habitat to multi-function direction. Furthermore, green corridor and ecological corridor, particularly close to each other, are not clearly distinguished in the current academic research and practical applications in China.

In summary, it is not difficult to find that the development of related concepts of ecological corridors essentially reflects the change of different human needs. For example, the construction of urban green space system in China initially only focused on the construction of individual parks and green belts. However, along with the rapid development of urban expansion, biodiversity loss and landscape fragmentation, the constructions of small-scale neighborhood greenways and greenbelt have not met the real needs. It is necessary to focus on urban ecological corridor at a larger-scale of urban and rural space level, and its ecological, social, cultural and other features began to be widespread concerned [13]. The habitat/ecological networks, are proposed when ecological function of a single point-like or linear natural habitat highly degraded due to the habitat fragmentation, and it is urgent to realize the integration of ecological function by means of the connection in space. In the framework of this network, important point and line elements are defined as ecological nodes and ecological corridors respectively, and especially the latter has become an important component to deal with fragmentation, and to significantly enhance the connectivity of the network. The connotation of ecological infrastructure is consistent with ecological network, but it emphasizes more on the initiative and antecedence of ecological construction. In the construction of ecological infrastructure, the ecological corridor is also an important indispensable component.

3. Classification of urban ecological corridors

There are diverse classifications of urban ecological corridor because of its complexity in the structure and function. At the same time, accurately identifying and classifying the type of urban ecological corridor can be a great help for its scientific management. At present, with the continuous connotation extending of urban ecological corridor, a variety of urban ecological corridor classification systems have been proposed, but in essence all are classified according to the structure or function of urban ecological corridor.

Table 1
The contrast of ecological corridor and related concepts.

Concept	Connotation	Source	Focus	Application
Greenway	The linear landscape owning multiple functions such as ecological, cultural, recreational and aesthetic functions	1860s Boston Park System	Landscape recreational, aesthetic function and spatial pattern optimization	Landscape planning
Green belt	Green open space set up in urban peripheral, used for urban and rural segmentation	1890s Garden City	Urban boundary and sprawl, and recreation function	Urban planning
Ecological corridor	Linear or strip landscape with the ecological, social, cultural and other functions	1980 IUCN	Ecological, recreational and aesthetic function, and urban growth boundary control	Natural protection and ecological planning
Habitat/ecological network	Reticular landscape consisting of ecological node, corridor, buffer and nature reserve area	1980s Europe	Biodiversity and conservation	Ecological planning
Ecological infrastructure	Reticular landscape or open space with basic ecosystem services consisting of point, line, and surface	1984 MAB	Conservation and ecosystem services provision	Ecological planning

3.1. Structural classification

Urban ecological corridor can be divided into river corridor, green transportation corridor, biodiversity conservation corridor, heritage corridor and recreation corridor. The last two kinds have attracted the attention gradually in China in recent years. Among them, the river corridor takes a river, wetland or lake as the mainstay, supplemented by a range of buffering in surrounding area. It has water purification, soil conservation, water conservation features and so on [14]. Green traffic corridor means green belt situated on both sides of roads and railways, which plays an important role in easing the barrier effects on natural ecosystems caused by different transportations, as well as air purifying, local micro-climate adjusting and other ecological functions [15]. Biodiversity conservation corridor is mainly composed of the living and migration channel of wildlife, having an important significance to connecting the fragmented habitats and thus conserving the biological diversity [16–17].

Heritage corridor is a kind of landscape that regards the historical and cultural heritage as the center, such as the Silk Road, the Beijing-Hangzhou Grand Canal, Tea-Horse Ancient Road, which are all a special collection of cultural resources [18]. Through the connection of natural landscape and historical or cultural heritages, the heritage corridor is to achieve the overall protection of urban heritage and the natural environment, and at the same time it has recreational, educational, aesthetic and enlightening functions. In the guide of resident-oriented ecological city planning, urban residents put forward higher requirements to improve the level of infrastructure and green open space or recreational space. As a result, recreation corridor came into being. Recreation corridor has an aesthetic characteristic, and adapt to local customs, religion and social culture, and has a certain tourism value [19]. It usually takes green space and country park as a main body, providing green open space for residents to walk and cycle, so it is an important part of urban ecological corridor currently [20].

3.2. Functional classification

According to the role of corridors to a specific flow, urban ecological corridors can be divided into two types: barrier corridor and communication corridor. Among them, barrier corridor generally has an impeding effect to the material, energy, information flows. On the one hand, it can protect the special species from external interference or predators attack, and the establishment of nature reserves is to achieve the purpose of the conservation of biodiversity by isolating from the outside world; it can inhibit the proliferation of toxic and hazardous substances, just like the road green corridors which can effectively prevent dust drifting on both sides of the road; it can also act with ecological constraints of urban expansion and prevent urban sprawl, such as the greenbelt construction in London, Seoul, Beijing and other cities. On the other hand, barrier corridor may also cause fragmentation of natural habitats, reduce landscape connectivity, and even lead to the increasing of local species extinction risk because the introduction of alien species. As a result, it may be a handicap to the biodiversity conservation and population diffusion [21].

Communication corridor provides important channels for the water, nutrients, energy, plants, animals and other elements to flow into the substrate, and thus increases the connectivity possibility between important patches, such as the construction of the Qinghai-Tibet Railway setting aside the biological corridor specifically for wildlife migration. Communication corridor helps to connect the fragmented patches, corridors and ecological protection zones, plays an important function of connecting the landscape patches, eliminating the effect of isolated island effect, and promoting the species diffusion, gene flow and so on. Communication corridor is usually measured by connection degree of both ends of the corridor [22]. In essence, there is not a very clear boundary between the barrier corridor and communication corridor, but sometimes a corridor can undertake two functions simultaneously, namely a barrier feature in the direction which is perpendicular to the corridor, while a communicating feature in parallel with the corridor.

4. Development of urban ecological corridors construction

4.1. Urban ecological corridors construction in the world

As we know, the term of ecological corridor firstly appeared in the field of biology. Along with the breadth and intensity strengthening of human activities, it becomes more and more prominent for natural habitat fragmentation in the world, which is difficult to be eliminated even if a mass of ecological parks and natural reserve areas have been built. Under this background, Wilson and Willis suggested to mitigate the negative effects of habitat fragmentation by means of corridors connecting in 1975. In 1980, International Union for the Conservation of Nature (IUCN) applied the viewpoint of ecological corridor for the first time to global conservation strategy [12], and in 2000 Ferenc Jordán formally proposed the concept of ecological corridors [23]. In recent years, the connotation and denotation of ecological corridor have been greatly extended, its construction direction has changed from the ecological function to the integrated functions of landscape aesthetics, recreation, and historical and cultural protection. The planning of urban ecological corridor has a leading level in the United States for a long time, since it began the planning practice of green parks system in the 1960s and established the Emerald Necklace style park corridor system in the Boston area. The concept of outdoor space construction has been widely approved in the 1980s. Hence, large-scale projects of ecological corridor construction appeared in the support of a series of relevant regulations, and as a result, a set of urban ecological corridor system owning social, cultural, recreation and biodiversity conservation features has been developed. In the 20th century, it began to transform to the network construction of multilevel ecological corridors [24], and the ecological corridor system covering various scales such as national, state, regional, and local, has formed.

Influenced by the greenway thoughts in the United States, the European's large-scale ecological corridor construction began in the 1990s, and the Pan-European Biological and Landscape Diversity Strategy provided a programmatic guidance to ecological corridor construction in Europe. In the early 21st century, the conceptual framework of European Ecological Network (EECONET) was set up, which was committed to the green conservation with more emphasis on network construction based on landscape ecological connectivity [25–26]. Overall, due to the differences in cultural background, social structure, development stage and urban characteristics, there is distinct difference between the constructions of urban ecological corridor in Europe and the United States. Specifically, the construction of urban ecological corridor in the United States aims to protect the natural landscape and provide open space for urban residents, while the construction of urban ecological corridor in Europe is focused on the urgent need for biodiversity conservation in the context of great human stress due to high population density. However, both are committed to maintaining sustainable development of the coupled human and natural system of the city, which also provide an instructive example for the urban ecological corridor construction in China.

4.2. Urban ecological corridors construction in China

Urban ecological corridor construction in China started later than western countries, but developed rapidly in recent years. In the 1970s, China established a large-scale ecological corridor system of Three-North Shelterbelt in the arid region as the first project to explore the construction of ecological corridor. After 1990, China government began to attach great importance to urban ecological corridor construction, with the announcement of State Council notification on further promoting national green construction and other documents, which set off a wave of urban ecological corridor construction. The Pearl

River Delta region firstly began to explore the construction and management of urban ecological corridor in China. Beijing, Shanghai and other cities also took ecological corridor construction as an important content in their urban planning and management, resulting in various transportation green corridors for roads and railways, and riparian ecological corridors at multi-scales. For example, the ecological city master planning in Guangzhou City for the period of 2010–2020 was emphasized on the construction of seven ecological corridors. It was also proposed to build special ecological corridors at multi-scales of city, functional zone, and community in Nanjing City, according to the spatial patterns of mountain, water, road, forest, and farmland [27].

Generally speaking, ecological corridor construction in China is mostly confined to a small scale inside the city, and simply focuses on a specific function, especially the function of biological protection or landscape greening. With the increasing demand of urban residents for the livable inhabiting environment, only one specific function of ecological corridor cannot meet the diverse needs of urban development. Hence, it is a great challenge to integrate the limited urban ecological corridors to form a comprehensive ecological network, in order to achieve the target change from the point, line, and surface protection to a protection system with greater ecological protection achievements. At present, although some scholars have carry out related studies in Jinan City [28], Hunan Province [8], Jiangsu Province [29] and other places to explore the urban ecological network construction, case study of urban ecological network system is still few, with the study area mainly concentrated on the small-scale areas. In addition, compared with the passive protection of ecological corridor to natural ecosystems, ecological infrastructure construction emphasizes more on an active ecological restoration and construction of green spaces. Since it was introduced in China in 2002, it has attracted a great deal of attentions [30], and provided a new idea for the construction of urban ecological corridor.

5. Methods for urban ecological corridors construction

Along with the development of urban ecological corridor over the past few decades, its construction methods also experienced the transformation from qualitative analysis to quantitative analysis, and to spatial analysis. Among them, the qualitative analysis mainly refers to the method of empirical judgment, the quantitative analysis mainly includes suitability or sensitivity analysis, and the spatial analysis includes the methods of network analysis and minimum cumulative resistance analysis. Generally speaking, from qualitative analysis to quantitative characterization, the methodological validity of urban ecological corridor construction has been greatly improved. The introduction of spatial analysis, is also essential to achieve the integration of demanding quantity accounting and spatial allocation of urban ecological corridors.

5.1. Empirical judgment

Empirical judgment is usually used to qualitatively identify regional or urban ecological corridor. Widely used currently in the field of urban planning, the validity of empirical judgment highly depends on the experiences and expertise of researchers. This method mainly relies on the qualitative analysis of natural eco-environmental background of the study area, with a special focusing on the spatial distribution of landscape elements, such as mountains, rivers, green spaces and other linear landscapes. For example, Li et al. took considerations on the ecological vulnerability and such socio-economic factors as population distribution, transportation, and proposed to construct several ecological corridors through ecological planning in Ji Triangle Region [31]. Guan et al. developed an ecological corridor plan with three rings, five wedges, and multiple green paths and nodes based on the spatial patterns of mountains, water, roads, forests, farmlands, and other natural elements in Nanjing city [32]. Li et al. [33], and Yan et al. [34] also carried out the ecological corridor planning for areas along the Yangtze River in Anhui Province, and Panyu District of Guangzhou City, respectively, which both applied the qualitative method of subjective experience judgment based on the distribution of regional ecological and environmental elements.

Overall, empirical judgment is simple to conduct without the requirements for massive quantitative or spatial data. However, it excessively relies on researchers' subjective experiences, and what's the most important is that, it cannot specify the number, width and position of ecological corridors. In addition, as remote sensing technology has been widely used in the disciplines of urban ecology and urban planning, it has become an important auxiliary way of experience assisted determination of ecological corridors to identify current ecological corridors through remotely sensed images interpretation [35–36].

5.2. Suitability/sensitivity analysis

Suitability/sensitivity analysis is the main quantitative method for urban ecological corridor construction, which is mainly based on the natural ecological characteristics of the study area to select a few representative factors to quantitatively evaluate the suitability or sensitivity of ecological corridors, so as to quantitatively identify the location of urban ecological corridors. For example, Liu et al. selected flood zone, soil suitability and habitat patch size, and other factors related to greenways' ecological function, to develop greenways network using Analytic Hierarchy Process (AHP) method to determine factors' weight [37]. Through the suitability evaluation using such factors as landscape type, topography, distance from roads, and altitude, Li et al. carried out ecological corridor planning in Daixi Town of Huzhou City, Zhejiang Province [38]. Based on the grading evaluation of ecological sensitivity using such factors as rivers, roads, residents, habitat and migration channels, Zhong et al. identified the ecologically sensitive areas, made a suitability evaluation according to the traffic location, soil properties, topography, and thus made clear urban ecological corridors through suitability and sensitivity analysis [3].

In general, the method of suitability/sensitivity analysis is of high systematicness and comprehensiveness, with low data requirements, and the methodological principle is simple and easy to understand. The most shortcoming is that there is often a high correlation among evaluation factors selected, and is also not yet formed a system which is highly recognized. Meanwhile, due to the lack of comparison and different cognition of different scholars, it is difficult to make clear the limiting threshold of suitability or unsuitability, and sensitivity or insensitivity. It just can compare the degree level or degree change of suitability or sensitivity, which results in an ineffective guideline to the number and size of corridors.

5.3. Network analysis

Network analysis, also known as the method of landscape metrics [39], is essentially based on graph theory. In this method, the landscape is abstracted as network structure composed of point, line, and surface. The effectiveness and connectivity of network are quantified using the patch number, patch size, patch density, landscape connectivity, and other landscape metrics, and then the optimal solution is chosen to determine ecological corridors. In the application of graph theory, it is generally considered that the high connectivity areas can play better function in the network of ecological corridors. For example, Cai et al. extracted green corridors according to the patch perimeter and area index in Wuhan City, and assessed network structure of green corridors based on point-line rate, connectivity indicators [40]. Han constructed the skeleton of ecological corridors in Wanyuan City, Sichuan Province using landscape metrics related to landscape fragmentation, agglomeration and connectivity, based on the combination of the elevation, slope and land use [41]. Wang and Zhang used 10 landscape metrics such as patch size, edge density, landscape evenness, etc., and some network

based indexes such as connectivity, closure, and point-line rate, to conduct the ecological network optimization in Xiamen Island [42].

The advantages of network analysis are the avoidance of subjective assumptions, and the validity of urban ecological corridor construction has been improved. In addition, by means of GIS technologies, quantitative analysis and spatial location of ecological corridors can be implemented. However, there are also some methodological disadvantages. Firstly, only spatial connectivity and adjacent relationships of different patches can be quantified, and functional differences between various patches are neglected, especially the provision of ecosystem services. Secondly, the vulnerability and adaptability of patches to the target flow in the proposed corridors are also not considered.

5.4. Minimum cumulative resistance analysis

Minimum cumulative resistance analysis is also called the minimum cost model [43] or the minimum path method [44]. In this method, the resistance faced by wildlife moving through different landscape components, is used to characterize the difficulty of spatial migration between two points in the landscape. Based on the minimum cumulative resistance between the source and sink in the landscape, the most effective movement path can be identified, which is also regarded as the ecological corridor with great possibility. For example, based on RS and GIS technologies, Yin et al. used minimum cumulative resistance analysis to quantitatively simulate the change of potential ecological corridors in urban agglomeration of Hunan Province in different scenarios [8]. Cai et al. used the improved minimum path method to simulate potential biological corridors in Great West River Pilot Area in Changsha City, taking into account the uncertainty and redundancy in animal migration path selection [45]. Because the method of minimum cumulative resistance can calculate the minimum cost path according to the resistance coefficient of spatial unit, which takes into account the geographical features and biological behavior fully, it is of high operability and feasibility, and thus has become the most common way to identify urban ecological corridors.

Nevertheless, the resistance factors selection and resistance coefficients determination, have still not reached an agreement. Previous studies have mostly chosen terrain, slope, vegetation coverage and land use types to quantify the resistance, while the factors closely related to human activities such as population density, road density are little considered. Only Wen et al. selected the ecosystem services and topographical factors to characterize ecological resistance in identifying ecological corridors in Guanzhong-Tianshui Economic Zone, which is a useful exploration for resistance factors selection [46]. On the other hand, resistance coefficient is often set by experience judgment or according to the results of previous studies. That is to say, it is difficult to avoid subjectivity. To resolve this shortcoming, Wu et al. suggested determining the resistance coefficient through field investigation [47], but it was regarded to be impracticable at large scale due to large consumption of manpower and materials.

5.5. Methodological contrast

Comparing the four commonly used methods discussed above (Table 2), it can be found that, along with the transformation from qualitative to quantitative, and to the integration of spatial pattern analysis, there is a continuous improvement of methodological effectiveness of urban ecological corridor construction. Generally speaking, in recent studies on urban ecological corridors construction, some of the key parameters are still assigned by experiences judgment, it is necessary in regional background analysis for ecological corridors construction to make a sensitivity or suitability analysis, and the identification of critical nodes and corridors often results from minimum cumulative resistance analysis. Thus, it can be seen that, it is in great need for the integration of qualitative analysis, quantitative analysis and spatial analysis. The three kinds of methods are not completely separated in the actual study, and both the qualitative and quantitative analyses provide an important basis for spatial analysis.

Specifically, various methods have different advantages and disadvantages. Firstly, empirical judgment method can avoid complex quantification of ecological processes and functions, making decisions based on experts' experiences. As a result, it is straightforward and easy to operate, saving manpower and related resources. However, this method is criticized to lack objectivity and it cannot respond effectively to the amount, width and position of ecological corridors, which are fundamental issues in the practical construction. That is to say, only the method of empirical judgment cannot meet all the needs of the reality. Secondly, the method of suitability or sensitivity analysis can overcome the subjectivity and arbitrariness of empirical judgment method through selecting representative indexes to comprehensively evaluate the suitability or sensitivity for the construction of ecological corridors. However, the shortcoming is also obvious, which include the lack of unified evaluation indexes and their weights, and the difficulty in determining the suitability or sensitivity threshold. Thirdly, network analysis is to measure the network connectivity and identify the ecological corridors using landscape metrics on the basis of full consideration of landscape matrix characteristics. It can avoid the negative influence of subjective decision, but fails to consider the differences of patch functions, especially the ecosystem services. Lastly, the significant advantage of minimum cumulative resistance analysis is the combination of natural environment and biological behaviors in the study area, which establishes an association between landscape patterns and ecological functions or processes. As a result, it is widely used at present because of its operability and practicality, although it is still facing with the subjectivity problems in resistance factors selection and weights assignment, which is similar to the method of suitability or sensitivity analysis.

Furthermore, it is worthy to noting that the construction of ecological corridors is a long-term project. When the minimum cumulative resistance method is used, some potential influencing factors, such as the change of natural environment and migratory behavior of species caused by climate change, should also be incorporated into the evaluation index system. In the terms of weights setting, there are two types in

Table 2
The contrast of methods used to construct urban ecological corridors.

Methods	Basic contents	Advantages	Disadvantages
Empirical judgment	Based on experts' experiences to make decision subjectively	Simple and clear, and easy to operate	The number, width and location of corridors are difficult to be determined
Suitability/sensitivity analysis	To select representative indicators to evaluate suitability or sensitivity of ecological corridors	Making up the arbitrariness of subjectivity judgment	The lack of generally accepted evaluation index system with the uncertain threshold, and the weight is set subjectively
Network analysis	Taking the landscape as points, lines, and surfaces, to select landscape metrics to quantify network connectivity	Simple and quantitative measurement according to the characteristics of ecological corridors, avoiding the subjectivity	Only landscape spatial attributes are considered, lack of ecological functions, particular the ecosystem services
Minimum cumulative resistance analysis	To identify minimum cumulative resistance path between the source and target as potential ecological corridor	Giving full consideration to geographical features and biological behaviors, with high operationality	Uncertainties in factor selection and the setting of resistance coefficient

general, i.e. subjective and objective weight setting methods. The former has a high subjectivity, while the latter may exist the shortage that may be not conform or even contrary to the reality [48]. Therefore, a scientific and rational set of index weights is still a key issue to improve the methodological effectiveness of minimum cumulative resistance analysis. In further studies, it needs to introduce the theory and methods of urban planning, social survey methods of sociology, and ecosystem monitoring methods of ecology, to the construction of urban ecological corridors. It should also fully take the advantages of spatial monitoring and analysis of RS and GIS technologies, to explore the urban ecological corridors construction through the integration of multiple disciplines and technologies.

6. Research prospects of urban ecological corridors construction

It is acknowledged that under the pressure of intensive human activity, urban expansion has greatly changed the structure and function of landscapes in the earth surface rapidly and intensively, resulting in a sharp decline of landscape connectivity and numerous corresponding environmental problems. As the construction of urban ecological corridor can effectively promote the contaminant filtration, soil and water conservation, flood control, and biodiversity conservation, it has become an important spatial approach to dealing with urban eco-environmental issues. With the advance of China's new urbanization and ecological civilization construction, urban ecological corridor will take more important role in urban eco-environmental issues. There is an urgent need to carry out urban ecological corridor construction under substantial scientific foundation.

On the other hand, land resources in rapid urbanization areas are often scare. Under the premise of limited financial resources of local government investment, ecological corridor construction is required with minimal investment for maximum benefit. At present, although ecological corridor construction has been largely carried out in China, there are a few deficiencies. For example, a great majority was conducted focusing on one specific function without multi-functional corridors, and the constructed corridors are not yet connected with each other at the regional scale. It is still in great need of effective functional integration mechanism across multi-spatial scales. It has not yet reached an agreement of the width for different ecological corridor, and few studies are focused on the key nodes identification or the comprehensive effects assessment on urban ecological corridors. Therefore, focusing on the complexity of ecological corridors' structure and function and the interactions of nature, society, and ecosystem in urban areas, comprehensive researches are highlighted deeply in the construction of urban ecological corridors in the view of multidisciplinary approach.

Based on the foregoing discussion, the current research of urban ecological corridor construction should emphasize on four directions, namely the key nodes identification, width determination, comprehensive effect assessment, and multi-scale integration of urban ecological corridors (Fig.1). Firstly, the key nodes of ecological corridors have a great influence on the flows of material, energy and information in the landscape. As a result, its recognition is one of the basic points of urban ecological corridor construction. Secondly, the width determination has been a key step in the process of ecological corridor construction. Due to the complexity of the interaction between human and the nature, it has not formed a recognized solution yet. Thirdly, based on the multi-angle, multi-discipline, and multi-agent, the comprehensive effects assessment on the eco-environmental and social dimensions, is the essential core content of the urban ecological corridor construction. Finally, the multi-scale integration of multi-functional ecological corridors under the framework of compound ecological network, which helps to fulfil the functional connection of corridors at various levels, will become an important practical application of urban ecological corridor research.

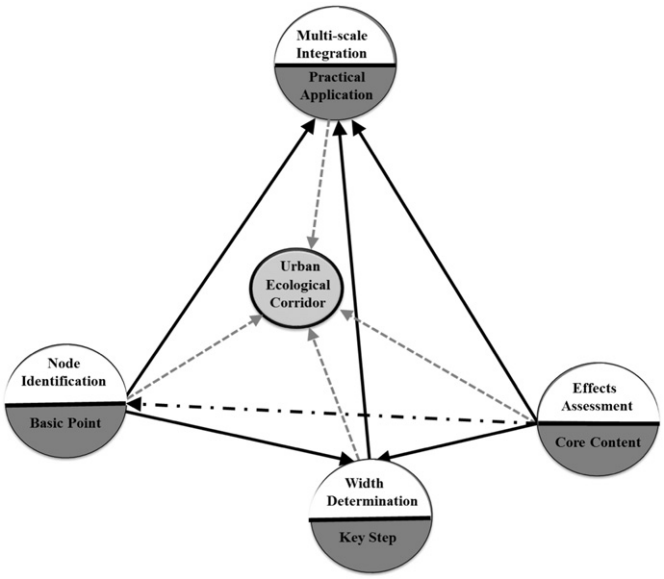

Fig. 1. Key issues in urban ecological corridor research.

6.1. Key nodes identification of urban ecological corridors

Ecological nodes are the basic elements of ecological corridors, according to the patch-corridor-matrix paradigm of landscape ecology. It is acknowledged that a critical node can guarantee the basic human ecological demanding or provide ecosystem services at a high level, with a large area [19]. The key nodes of the ecological corridor mainly include two types, i.e. intersection node and breaking node. Among them, the former is an important strategic point for the flow of matter, energy or information in an ecological network, and plays an irreplaceable role in guiding in the structure and function of the entire ecological network. The cross points of minimum cost path and maximum cost path are potential ecological nodes [49]. However, the latter is a dramatic turning point of urban ecological corridor formed in the matrix of the landscape where it is vulnerable to natural or human disturbances [50]. Breaking nodes often refer to spatial discontinuity of ecological corridors. The fewer the breaking points have, the higher connectivity the corridors are, with the better continuity for spatial structure and ecological functions of ecological network. Once the breaking point appears, it is difficult to recover naturally, or a long time with large resources investment will be occupied. Therefore, more attentions should be paid to special protection of breaking nodes in the practical management.

Generally speaking, the key node is a prerequisite and foundation for maintaining higher structural and functional connectivity of ecological corridors. Its quantitative identification is the basic point for the overall promotion of urban ecological corridors. The critical question for ecological node identification is to determine the suitability threshold [51]. Due to the difficulty in the threshold determination, the location, size, structure and other characteristics of ecological nodes are not easy to identify.

6.2. Width determination of urban ecological corridors

Ecological corridors are a kind of landscape components with a certain width. In general, the wider an ecological corridor is, the better it is for habitat quality. However, the land resources are scarce in urbanized areas. The construction of urban ecological corridors not only needs to consider the ecological benefits, but also take into account the spatial demanding from economic development. Therefore, it is particularly important to set a reasonable width of urban ecological corridor. At present, some scholars had adopted the width of 100 m, 150 m, and 260 m to create river corridor, shelterbelt corridor, and coastal corridor

in Shenzhen City respectively [52], or considered 9–12 m as the corridor width to protect invertebrates [53]. Based on the previous studies, Zhu et al. proposed that 3–12 m, 12–30 m, 60/80–100 m and 100–200 m could be the suitable width of different types of biodiversity conservation corridors. However, all the studies were failed to clarify its scientific basis. Because of the difference of urban ecosystems and environmental problems, it is difficult to form a uniform width standard for ecological corridor, and it has become a critical step for urban ecological corridor construction.

The core issue for determining the ecological corridor width is to make certain the influencing factors highly correlated with corridor width. Zhu et al. suggested determining the corridor width according to the ecological processes [54]. Hobbs indicated to apply such indicators as microclimate, nutrients, water, and invasive species inside the corridor to determine the biological corridor width [55]. Teng et al. regarded that width determination of biological corridor should consider the biological resource selection, land use, and corridor's length and structure, and the width determination of ecological corridor associated with soil and water conservation, sand fixing and urban greening should pay attention to such elements as surface runoff, slope length, slope, surface properties, and vegetation characteristics [56]. Due to the diversity and interaction complexity of factors which affect corridor width, it can be grouped into two categories. One is internal environmental factor which mainly considers the biophysical characteristics inside the corridors, ecosystem services, and corridors' structural or functional characteristics. The other is external environmental factor, which is associated with human activities, land use, and topography. In future, combining with social survey, traditional ecological observations, and new techniques in GIS and RS, it is necessary to study deeply the effect of each influencing factor on the ecological corridor width, and the interaction among various influencing factors, so as to set the corridor width scientifically.

6.3. Comprehensive effects assessment of urban ecological corridors

The construction of ecological corridors is related with various benefit groups, including local residents, governments, land users, as well as planners and designers, whose benefits demanding differ in thousands ways. Meanwhile, it is generally considered ecological corridors in such a complex coupled human and nature system as city, play an irreplaceable ecological function [57], although some scholars believe that the significance of ecological corridor construction should be treated differently [58]. For example, the diffusion routes of butterflies do not strictly follow the certain corridor [59]. It is even believed that the construction of ecological corridors will bring some negative effects, such as providing rapid spreading channel for harmful substances, intruders, predators, and disease [60], and increasing commuter amount, infrastructure, and land prices due to green belt construction [7]. Obviously, the possibility of establishing an effective mechanism to assess the effects on the ecological, environmental, economic and social benefits of urban ecological corridor construction, is a core content, which is greatly affecting the benefit of urban ecological corridor, and thus can remedy a leak or vacancy in the construction timely.

At present, scholars have started to pay attention to assess the effects of ecological corridors. For example, Xu et al. discussed the relationship between nature reserves and local community [61], and Li et al. investigated the awareness and attitudes of 196 villagers in 5 villages towards the corridor construction for conserving Asian elephants in Xishuangbanna using contingent valuation method [62]. However, the research on comprehensive effects assessment of urban ecological corridors has not been largely carried out, and relatively few study cases cannot provide effective feedback to the construction of urban ecological corridors. Therefore, it is important to carry out more comprehensive participatory assessment of economic and social effects from multi-angle, multi-discipline, multi-agent. The scientific assessment can provide a reference to coordinate the benefits demanding of all the groups, to make trade-offs between ecological and economic benefits, and to effectively solve the contradiction between economic development and ecological protection.

6.4. Multi-scale integration of urban ecological corridors

It has been proved that large-scale ecological corridors are more advantageous for biodiversity conservation [63], which has been launched in North America [64], Australia [65] and India [66]. However, in China, ecological corridors are mostly constructed in the scale of neighborhoods and communities. Except the Three-North Shelterbelt, few ecological corridors are constructed in urban agglomerations, or national scale. Meanwhile, it is acknowledged that the ecological corridor should have multiple functions [67], while in China, the majority of urban ecological corridors is planned and constructed emphasizing on one core function. For example, biological conservation corridor focuses on the function of biological protection, and urban green corridor pays more attention to its aesthetic function, having insufficient consideration of ecological benefits [68]. All have ignored the coordination of social, economic, ecological, aesthetic and other functions of ecological corridors. Thus, multi-scale integration of urban ecological corridors is in great need, which should be conducted through such two ways as regional integration and functional integration. Among them, the regional integration is to better achieve the functional integration, while functional integration depends on regional integration at multi-scales. That is to say, the former is a carrier to the latter, while the latter is a nature or target to the former.

In further, it is essential for regional integration to focus on the effective combination and scale expansion of ecological corridors at different level, so as to implement the functional connectivity between urban ecological corridors in the cities and regional ecological corridors across the cities. As a result, there is a transformation from ecological corridor construction at city or community scale to the ecological barrier construction at such large scale as urban agglomeration, which has become an important trend to entirely improve the construction of urban ecological corridors in China. Meanwhile, on the basis of regional integration with multi-scale, the functional integration of ecological corridors should be more advanced, to set up the multifunctional corridors with multiple ecological, economic, social, and aesthetic functions, which develops from pure green system to ecological network emphasizing on the optimization of shape, structure and function.

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