Ecosystem service of green infrastructure for adaptation to urban growth: function and configuration

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ABSTRACT

Objectives: (1) to explore what kind of green infrastructure (GI) meets the demand for urban ecological security of rapid urbanization areas; (2) to figure out how to determine the specific function and configuration of GI from ecosystem service requirements of urban ecological security.

Methods: (1) Through the literature review, this article summarizes the function and structure evolution of GI in order to adapt to urban growth. (2) Standing on the imperfect ecological functions and unreasonable spatial configurations, this article builds up a conceptual model for the optimization of green infrastructure ecosystem services to meet the demand for the green infrastructure pattern needed by urban growth.

Results: The optimization framework consists of four central function modules and its regulating and controlling mechanisms, including: (1) Balancing supply and demand of GI’s ecosystem service; (2) Measuring and evaluating GI’s ecosystem services; (3) Elevating and optimizing GI’s ecosystem service; (4) Building urban ecological security pattern with high efficiency of GI’s ecosystem services. Moreover, this framework provides guidance for the planning and design of GI and the urban ecological security pattern building in rapid urbanization areas based on balancing supply and demand of GI’s ecosystem services.

Conclusion: The conceptual model of GI’s ecosystem service optimization based on balancing supply and demand shows a new path to meet the needs of urban growth and build a city’s ecological security pattern through upgrading and optimizing GI.

The unbalancing supply and demand of green infrastructure resulted from urban growth

The supply of green infrastructure in the context of urban growth

The research and practice of green infrastructure (GI) began in the United States in the mid-1990s, as we all know the concept of GI did not exist at that time, but the landscape played the same roles of today’s GI. With the growth of cities in scale, population, construction, and others, the ecological problems related to human health, well-being, and development in cities are also increasing. Therefore, over the last 10-15 years, in line with international developments, GI provides “life support services” for urban ecological security needs and it has become an important research topic (Lafortezza et al. 2013; Hegetchweiler et al. 2016). Benedict and McMahon (2002) defined GI as the “natural life support system,” indicated that it comprises waterways, wetlands, woodlands, wildlife habitats, greenways, parks, working farms, ranches and forests, wilderness and other greenery, and open spaces in and around the city at all spatial scales (Benedict and McMahon 2002; Abunnasr, 2013). However, in the process of urbanization, the urban construction space externally spreads to the surrounding rural areas and other natural spaces, which also internally erodes the nonconstructive land within the city. Reducing in both size and type as well as destroyed in the spatial configuration and connectivity, green spaces which are regarded as GI decline in the ecosystem service capacity provided by them, for the provision of urban ecosystem service of GI depends on their quantity, quality, and diversity (Andersson et al. 2013; Mcphearson et al. 2015; Calderón-Contreras and Quiroz-Rosas 2017). In short, the space occupation brought about by urban growth affects the function and configuration of the existing GI. The consequent decline in the ecosystem service capacity results in many ecological problems, such as the loss of biodiversity and the spatial fragmentation in cities, which further affect the ecosystem services provided by the green spaces in cities (Lafortezza et al. 2010) including cleaning the air, filtering water, cycling nutrients, generating soils, regulating climate, sequestering carbon, etc. (Costanza et al. 1998; Weber, Sloan, and Wolf 2006). There is no doubt that the current GI which...
provides ecosystem services as the supply system in the cities cannot meet the growing and changing needs of urban ecological security in the process of urban growth.

**The demand of green infrastructure adapting to urban growth**

However, urban growth is inevitable, and meeting the demands of urban growth is one of the ways to ensure sustainable urban development. The sustainable development of cities is devoted to building urban resilience and improving human health and well-being (Mansor and Said 2008b; Kuppuswamy 2009; Meerow and Newell 2017). Calderón-Contreras and Quiroz-Rosas (2017) point out that many approaches to achieve urban resilience are standing on the hypothesis that it can be fostered through securing the local provision of urban ecosystem services (Schewenius, Mcphearson, and Elmqvist 2014; Calderón-Contreras and Quiroz-Rosas 2017). Kuppuswamy (2009) proposes that the psychological, physical, and social benefits related to human health come from the contact with nature as well as the provision of ecosystem services, which will decline and vanish in urban community due to the disengagement of residents from the natural environment (Kuppuswamy 2009). At the same time, as the inevitable result of urban growth, the expansion of urban scale also raises the demand for the type and total amount of GI’s ecosystem service. The demand growth is embodied in temporal–spatial structures, the former mainly manifests in the increasing seasonal demands of large and super-large cities, such as the flood control of southern cities in the rainy seasons and the haze prevention of northern cities in the heating seasons, and the latter is mainly manifested as the demand for more open spaces and green spaces in line with the expansion of urban areas. In addition, the expansion of urban scale and the formation of urban agglomerations make the urban demands for GI transform from monomer facilities or specific projects on site gradually to the integrated GI on the regional level, so as to realize the close spatial organization and functional contact between cities (Fang and Yu 2017) as well as providing more complicated and comprehensive ecosystem services. Certainly, urban growth needs more new services to meet the demands of urban ecological security in the process of sustainable development; therefore, more and more GI as the carrier of ecosystem services is needed to respond appropriately to meet the needs of urban growth. It is to say that urban ecological security demand for ecosystem services is also the demand for GI as a supplement.

**The unbalanced supply and demand of green infrastructure adaptive to urban growth**

Urban growth has brought about the unbalanced supply and demand of GI’s ecosystem service. On the one hand, ecological or green space transformation and fragmentation caused by urbanization lead to the capacity decline of existing GI’s ecosystem service; on the other hand, the sustainable development of city requires more supports of ecosystem services of urban GI. In cities, the unbalanced supply and demand manifests the decrease and fragmentation of ecological spaces, the reduction in biodiversity, the transformation from ecological spaces to artificial ones, etc., bringing about series severe impacts on cities such as floods and city heat islands. These urban diseases give threats to the security of both people and city on a large degree, hinders the sustainable development of the city, and brings great challenges to the construction of city resilience and the promotion of human well-being. Facing the unbalanced supply and demand, however, little theoretical research of existing GI is based on the supply and demand equilibrium of ecosystem services needed by the urban ecological security; and the present status of supply and demand for ecosystem services is also lack of scientific measurements and evaluation standards. What is more, little practical research of GI starts with the targeted ecosystem services to analyze, measure, and determine the specific function and configuration of GI needed for urban ecological security, thus leads to the lack of guidance and implementation of GI in spatial–temporal optimization practices. Therefore, the article raises and discusses the following questions: What kind of GI can meet the urban ecological security needs in the rapidly urbanized areas? How to determine the spatial and temporal configurations and specific functions of GI from the perspective of ecosystem services of urban ecological security? (Figure 1).

**The challenges, responses, and contradictions in the development of green infrastructure**

**The function evolution of green infrastructure adapting to urban growth**

In the process of urban growth, GI has always been a response passively to the needs of urban growth and also is the main source of ecosystem services for urban ecological security. At different stages of city, the demand for ecosystem services and for GI as the response is also different; it can be said that the demand changes in the process of urban growth have shaped the evolution of GI in terms of types, scales, function, spatial layout, and construction concepts (Table 1).
To meet the needs of human livability: park and open spaces

From the middle of nineteenth century to the middle of twentieth century, under the wave of industrial revolution, a large number of people from the countryside flooded into the city. Consequently, urban space has been unprecedentedly expanded and spread. The sustained urban growth led to the invasion of rural landscape and the destruction of natural landscape (Du et al. 2008). In this period, the ecological and environmental security and livability were in urgent need. The emergence of urban parks in 1850s marked the beginning of the early embryonic stage of GI (Luan, Chai, and Wang 2017). This stage of GI consisted of parks, forests, wetlands, farmlands, urban public green spaces, and other series of open spaces, distributed around the peri-urban areas in forms of green wedges, green blocks, green hearts, and annular spaces (Ouyang et al. 2004), forming a “green control belt” which controlled the urban sprawl and urban integration. This belt played a role in preventing the erosion of arable land and rural areas as well as improving the public environment in urban areas. The provision of ecosystem services from GI were mainly supporting services and regulating services such as providing life information, improving environmental quality, and providing leisure and entertainment resources (Du et al. 2008). Green belts in UK (Amati and Yokohari 2006), green heart in Randstadt of the Netherlands (Kühn 2003), and greenbelts in Moscow (Fan 1995; Blinnikov et al. 2006) were all representative cases in this period that constructed GI based on the idea of “controlling.”

To meet the needs of biological conservation: greenways and ecological networks

From mid-twentieth century to the end of the period, the speeding up of urbanization has brought about urban sprawl and the great damage to natural landscape in peri-urban area as well; the phenomenon of natural landscape degradation and fragmentation had become increasingly serious (Du et al. 2008). The loss of agricultural and natural landscape, as well as the decline of the ecosystem service capacity as a result, placed greater pressure on urban green spaces (Lovell and Taylor 2013). In order to compensate the important ecological, production, and cultural functions that were available from rural and natural areas in the past, beginning with the development of the ecological protection movement in 1960s, GI had entered a preliminary stage of development (Luan, Chai, and Wang 2017). In order to reduce the ecological impacts of space fragmentation, greenways, ecological corridors, and ecological networks were planned and constructed under the concept of “connectivity.” Through the connections of linear landscape, the scattered green spaces dispersed in the city and surrounding areas were organically combined together to reduce the fragmentation of the landscape (Ahern 1995; Fábos 2004), prevent the fragmentation of natural areas and the extinction of species, enhance the connection between urban and rural areas, and strengthen the ecological, productive, and cultural functions of urban and rural green spaces (Fábos and Ryan 2004; Jongman, Külvik, and Kristiansen 2004). In this period, the ecosystem services provided by GI were more comprehensive in terms of service types, including improving environmental quality, supporting urban and rural natural and human processes, providing recreational resources, and so on. The rural landscapes in Parsons’ Mills of New England (Walmsley 2006), the
| Period          | Challenge                             | Demand                                                                 | GI functions in need                                                                                                         | GI types              | GI layout                          | ES of GI                                      | Concept                          | Representative cases                                                                 |
|----------------|---------------------------------------|------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|-----------------------|------------------------------------|----------------------------------------------|-----------------------------------|-----------------------------------------------------------------------------------|
| 1850–1960      | Urban sprawl swallowed rural land and obliterated natural landscapes           | Safe and livable living environment                                     | Limiting urban sprawl and urban integration, protecting arable land and rural areas, improving public environment           | Open spaces: parks, forests, wetlands, farmlands, urban public green spaces | Green wedges, corridors, hearts... distributed around urban surroundings | Providing means of livelihoods, improving environmental quality, providing recreational resources | control                          | Green belts in UK, green heart in Randstadt of the Netherlands, greenbelts in Moscow |
|                |                                       |                                                                        |                                                                                                                             |                       |                                    |                                                              |                                   |                                                                                   |
| 1960–1990      | The acceleration of urbanization increases the natural landscape fragmentation | Biological and ecosystem conservation                                   | Preventing the fragmentation of natural areas and the extinction of species, enhancing the connection between urban and rural areas, improving ecological, productive and cultural functions of urban and rural green spaces | Greenways, ecological corridors, ecological networks                      | Linear land elements as greenways; greenway interwoven to form ecological networks | Improving the quality of the environment, supporting natural and human processes, providing recreational resources | Connectivity                      | The rural landscape in Parsons’ Mills of New England, the greenways in Meewasin of Saskatoon, the ecological network in South Florida |
|                |                                       |                                                                        |                                                                                                                             |                       |                                    |                                                              |                                   |                                                                                   |
| 1990–today     | Global urbanization makes urban and rural areas lack of co-ordination and integration; urban ecosystem has systematic disorder | Greening of municipal engineering facilities, low-impact development and smart growth | Spatially (on regional and urban scale), the localization and integration of urban and rural spaces, technically (on local scale), the transformation of engineering infrastructure from gray to green | Networks: green/blu gray networks; links: green corridors, rivers; hub: green spaces, wetlands, forests, farmlands... | Mutual coupling of network systems | Providing means of livelihoods, improving environmental quality, regulating urban climate, promoting economic development, playing educational values, protecting historical context, providing recreational resources... | Transformation & Integration          | The theory of “Controlled mixture of urban and rural landscapes” proposed by Japanese scholar Makoto Yokohara; & Sustainable rain-flood management technology and other ecological technologies |
greenways in Meewasin of Saskatoon (Taylor, Paine, and Fitzgibbon 1995), and the ecological network in South Florida (Bueno, Tsihrintzis, and Alvarez 1995) were representative cases in this period that built GI under the concept of "connectivity."

To meet the needs of smart growth: networks and green technologies

In the twenty-first century, the phenomenon of global urbanization makes the production, ecology, and living spaces in urban and rural areas lack of co-ordination and integrated development. In megacities, a large number of traditional engineering facilities and a small amount of GI can only solve the local problems of single target providing low efficiency of urban ecological services. As a result, the systemic disorders in urban ecosystem hinder the sustainable development of the city (Luan, Chai, and Wang 2017). During this period, the demands for land conservation, smart growth, low-impact development), and recovery of watercourses in the process of urban growth have become the promotion for GI entering into a rapid development phase in many fields (Wu and Fu 2009). In this stage, on urban and regional scales, under the concept of “integration,” constructing spatial structures constituted of “hubs-links-networks,” integrating urban and rural spaces through local landscape, and merging urban spaces into green natural spaces created by GI (Saroinsong et al. 2007; Du et al. 2008), and on a local scale, under the concept of "transformation,” transforming urban engineering infrastructures from gray to green occurs, thereby improving and restoring urban ecosystem services (Wu and Fu 2009; Luan, Chai, and Wang 2017). Ecosystem services provided by GI are more abundant on the specific services, including providing means of livelihood, improving environmental quality, regulating urban climate, promoting economic growth, playing educational values, protecting historical context, and providing recreational resources. The theory of “Controlled mixture of urban and rural landscapes” proposed by Japanese scholar Makoto Yokohari is an example of building GI under the concept of "integration" (Saroinsong et al. 2007; Du et al. 2008); Sustainable rain-flood management technology, ecological water conservancy and river ecological restoration, road ecological engineering, ecological restoration of polluted wasteland, and other ecological technologies (Kondolf 1998; De 2000; Adalberth, Almgren, and Petersen 2001; Dietz 2007; Ahiablame, Engel, and Chaubey 2012) are mature researches on technology of GI under the concept of “transformation.”

The structure evolution of green infrastructure adapting to urban growth

In the process of analyzing, evaluating, and building the function and configuration of GI, lots of questions need to be answered, such as “what elements should be contained?” and “What patterns should each factor present?” All these are the big questions related to GI planning. The methods to build the GI in landscape scale mainly include the following (Table 2):

1. The "layer-cake model" based on overlaying process and suitability mapping approach (Mcharg 1981). Based on the theoretical foundation of traditional ecology, overlay the elements of existing landscape units in environment, such as geology, soil, hydrology, vegetation, and animal, and according to the comprehensive results of suitability evaluation of existing waters, forests, wetlands, and other ecological factors, select the best fit as a "hub" or "center" and all kinds of most suitable units nested together, and finally form the "point-line-surface" superimposed structure of GI (Walmsley 2006; Jia and Dai 2015).

2. The "source-sink-corridor" based on horizontal ecological processes and “patch-corridor-matrix” mapping approach (Yu 1996; Cao and Lv 2011). Based on the theory of landscape ecology, first of all, calculate the “resistance” of horizontal flows according to the existing environment factors and by using “the minimum cost model” for suitability analysis of corridor based on GIS, determine the distribution and pattern of corridors (Pei 2012; Jia and Dai 2015); Second, by simulating the process of horizontal movements, the landscape security pattern with “source-sink-corridor” structure is formed, which plays important network of GI for biodiversity (Adriaensen et al. 2003; Weber, Sloan, and Wolf 2006). (3) "Corridor connectivity evaluation" method based on graph theory and "node-link" graphic mapping approach (Zhang, Xia, and Wei 2009; Wang 2014). Using graph theory and network analysis as an effective tool for establishing and analyzing landscape connectivity (Pei 2012), first of all, find out the existing habitats and species diffusions in the ecological environment, and simplify them as “nodes” and “links” in graph theory; thus, the network topology of different complexity and connectivity is derived (P 1989; Zhang and Wang 2006); Second, evaluate the corridor connectivity of the network structure and chose the optimal scheme with high connectivity and low cost to form the GI network formed by nodes and their connections (Jia and Dai 2015). (4) “Morphological spatial pattern analysis” (MSPA) (Qiu, Chang, and Wang 2013) based on the theory of geometrical morphology extracts GI components as “foreground” and other elements for the “background.” After binary image rasterizing treatment,
| Construction method | Theoretical basis | Environmental factors | Existing landscape | Network mechanism | Configuration | Connection mode |
|---------------------|------------------|-----------------------|--------------------|-------------------|--------------|----------------|
| The “layer-cake model” based on overlaying processes | The theory of traditional ecology | The element of existing landscape units in environment such as geology, soil, hydrology, vegetation, and animal | The existing ecological factors such as woodlands, water wetlands, forests, and ecological corridors | Overlay the element information of existing landscape units in environment; According to the comprehensive results of suitability evaluation, select the best fit as “hub” or “link” of GI | The “point-line-surface” superimposed structure | Structural linkage |
| The “source-sink-corridor” based on horizontal ecological processes | The theory of landscape ecology | Environmental factors such as land cover, water system, width of waterfront area, aquatic population condition, road condition, and slope and land management | Horizontal ecological processes and existing landscape patterns in the environment | Calculate the “resistance” of horizontal motion; use “the minimum cost model” to determine the position and pattern of corridors; by simulating the process of horizontal movements, form the potential “point-line-surface” network of GI | The “source-sink-corridor” network | Structural and functional linkage |
| “Corridor connectivity evaluation” method based on graph theory | The theory of graph | Environmental factors and ecological habitat patches, corridors, and species diffusion | Ecological processes such as ecological habitat and species diffusions | Use node to represent habitat patches, and use links to represent species diffusions; Evaluate the corridor connectivity of the network structure, and chose the optimal scheme with high connectivity and low cost to form GI network | The network topology: “nodes-link” connections | Structural linkage |
| “Morphological spatial pattern analysis” (MSPA) based on morphology | The theory of geometrical morphology | Information and data of the land cover changes | The existing woodland, water, wetlands, farmland, and other nonconstruction land | After binary image rasterizing treatment, divide the “foreground” into seven morphological structure elements for analysis; Based on the “center” and “bridge” derived from MSPA, build the “hub” and “corridor” in the green infrastructure network | Bridge, loop, branch, edge, perforation, islet, and core | Structural linkage |

Source: By Authors.
the “foreground” can be divided into seven morphological structure elements for analysis, including bridge, loop, branch, edge, perforation, islet, and core. The GI network can be built based on the “center” and “bridge” derived from MSPA (Soille and Vogt 2009; Wickham et al. 2010).

The above four methods of determining the elements and patterns of GI are in common as the following: First, the purpose is to find the potential elements in urban spaces that can be used as “hubs” and “links,” and through further planning to form the interconnected network pattern of GI (Pei 2012); Second, in order to find the optimal solution and select the most suitable “hubs” and “links” from potential factors to form the network of GI through the suitability mapping; Third, in the process of ultimately connecting each spatial element to shape network of GI, the structural linkage is the main connection mode among the four methods.

Challenges faced by green infrastructure: function weakening and structure unbalancing

It is important but difficult to determine elements and patterns in planning of GI integrating urban and regional areas in the process of demand and supply equilibrium. However, the study found that GI gradually cannot meet the needs of urban growth with the development of towns and urban agglomeration, in the context of unceasingly changing and growing of the demands for urban ecological function and urban ecological security. The development of GI is facing function weakening, structure unbalancing, and many other challenges.

Overemphasizing on the supply while less attention to city’s real demand for ecosystem services

The elements and components of GI such as “hubs” and “linkage” are mainly based on the existing green space, green resources, and ecological processes in the environment. It is dominant existing planning approach for supply system of GI through different methods of suitability analysis to map the specific type and its layout. However, facing of urban growth eroding green spaces and green resources, urban GI providing urban ecosystem services has reduced greatly in terms of size, number, and type, especially green or ecological space; subsequently, the quality of GI as well as its efficiency and ability to provide ecosystem services has declined so fast. Too much emphasis on the supply role of the ecosystem, while seldom paying attention to city’s real demands on ecosystem services in terms of type, size, structure, and the temporal–spatial relationships in the process of urban growth (Hegetschweiler et al. 2016), city’s real need for services is greatly weakened. Under this kind of challenge, the existing green space and green resources (including forests, wetlands, rivers, lakes, fields, parks, open space, etc.) which are regarded as the supply of GI are not able to meet the demands for urban ecological security in rapid urbanization areas.

Increasing the quantity while setting aside the quality of urban ecosystem services

In the current planning methods, the ecological network of GI with the structure of “point-line-surface” is based on suitability mapping approach which is mainly to find the space suitable for, that is to say the network is determined just by ecological suitability. The integration of variable blocks of land through the connection of linear spaces forms a network system in geometric form. However, the invasion of new residential area, roads, in the process of urban growth caused fragmentation and isolation of urban green spaces, and the spatial unbalance has upgraded the difficulty in GI planning with a view of “connection” and “integration.” At the same time, the current research and practice focus to increase the number of GI in the city and create shallow form on vision, always divorced from any concept or understanding of natural process (Lyle 1991), setting aside the importance of the GI to increase the provision of urban ecosystem services (Calderón-Contreras and Quiroz-Rosas 2017), as well as if the shallow characters play a role in urban functionality and internal processes which are described as deep forms of city (Lyle 1991). This is reflected in the researches lacking measurement and evaluation of the supply and demand of GI’s ecosystem service, which are not able to build the spatial structure needed for urban ecological security in rapidly urbanized areas.

Concentrating on sites while lacking the research on overall temporal–spatial relationship

It can be seen that the past and current researches are concentrated on the problems of GI at site scale in city, which solves a particular problem of GI providing specific ecosystem services; on the other hand, it appears as the microstructure of scale and structure, namely, the building of GI is mostly limited to small fields or microstructure. Obviously, this idea of building GI is not enough to meet the macrodemand of urban development in the process, and it is not able to take the temporal–spatial relationship on a large scale into account as part of the whole urban ecosystem. The current research methods adapting to urban growth through GI itself are not enough to deal with the problems and challenges in the process of rapid urbanization. Therefore, it is necessary to upgrade the point of view to the regional scale and study its overall temporal–spatial relationship and the integrated ecosystem services.
The optimization framework of green infrastructure’s ecosystem service based on balancing supply and demand

**Conceptual model of green infrastructure’s ecosystem service based on balancing supply and demand**

Aiming at the problems of ecological degradation and functional damage in the rapid urbanization areas, combined with the current challenges in GI described as functional weakening and structural imbalance, under the interaction mechanism between urban growth and functional changing of GI’s ecosystem service, it is a big question that the ES supplied by existing GI is the real needs of GI changing with urban growth. How to build the GI through matching the ecosystem service supply and demand in spatial-temporal process and how to build strong ecological security pattern through elevating GI’s level of ecosystem service? In order to answer these questions, this article initiates a conceptual model for the optimization of GI ecosystem service to meet the demand for the GI pattern needed by urban growth. The framework is committed to achieving the following goals: (1) balancing the supply and demand of GI under the interaction between urban growth and changing of GI’s ecosystem service; (2) building the measurement and evaluation model of ecosystem service level of GI; (3) carrying out effective supply and demand regulations of GI through function upgrading and structure adjustment; (4) building urban ecological security pattern through elevating GI’s ecosystem service level (Figure 2).

**Balancing supply and demand of green infrastructure’s ecosystem service**

On the one hand, being targeted to the existing GI providing ecosystem services (supply), including rivers and wetlands, green space, and ecological corridors, and gray infrastructure such as roads, the type, size, and structure of GI and its spatial pattern influence ecosystem services. The supply of GI’s ecosystem service is determined by land use and ecological conditions, so the quantity and structure are important, but in reality the area shrinkage and structure mismatching of GI decreases the capability of supply; on the other hand, aimed at the government, enterprises, residents, and other stakeholders and urban participants in cities or communities, the quantity, structure, and layout of GI are changing with urban growth

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**Figure 2.** The conceptual model of GI’s ecosystem service based on balancing supply and demand.
and population increase, and more and more GI’s ecosystem services are needed with the rapid urbanization. In order to balance the supply and demand, the rate of urbanization is the key factor to consider the relation between GI’s supply and demand. Third, at the beginning and with lower rate of urbanization, the supply is much bigger than the demand of GI’s ecosystem service, but with the rapid urban growth and higher rate of urbanization, the supply decreases and demand increases, and balancing GI’s ecosystem service is to build an equilibrium state which can decrease disaster and damage and sustain the ecological security at specific stage of urban growth. The difficult question here is what kind of supply–demand balance is an equilibrium state. The equilibrium state does not mean the supply can cater the demand absolutely but relatively, which needs to regulate with resilience.

**Measuring and evaluating green infrastructure’s ecosystem service**

The quantitative research on the supply and demand of GI’s ecosystem service is one of the essential researches. First, for the supply, the index should be based on the scale, type, structure characteristics, and management methods of existing GI in the city. For the demand, the type of urban functions, industrial structure, geographical environment, the social form, and local cultural characteristics as well as the spatial distribution of the demand subjects are the factors to consider in measuring and evaluation index (Wang, Shen, and Xiang 2017). Second, evaluating the threshold effect of the supply and demand balances model of GI’s ecosystem service. The spatial and temporal distribution of rivers and wetlands, green spaces and ecological corridors, and gray infrastructures such as roads can create different effect of the ecosystem services. Based on the demand, the threshold value of the ecosystem service is evaluated under the premise of maintaining the basic demand of GI. For the supply of GI’s ecosystem service, the resilience efficiency can be evaluated through the supply redundancy index. For the demand level of GI’s ecosystem service, the demand validity index is used to evaluate the demand validity. Based on the evaluation results of supply redundancy and demand validity, apply the Data Envelopment Analysis Model and Matrix Model, and use the equilibrium validity index to achieve the validity evaluation of the supply and demand balance of GI’s ecosystem service (Wang and Zheng 2015).

**Elevating and optimizing green infrastructure’s ecosystem service**

Standing on two key points of function and configuration, it is urgent to improve the service of existing GI in urban area and optimize its spatial and temporal patterns. According to the coupling mechanism as well as the characteristics of GI’s ecosystem service of multi-scale and multi-type, the regional GI system is much more efficient rather than a specific one or some sort of GI individuals for elevating and optimizing GI’s ecosystem service. Therefore, aimed at the rivers and wetlands, green spaces and ecological corridors, roads, and other infrastructure gray ecological networks, on the one hand, the GI’s ecosystem service can be analyzed and regulates the index and key links in terms of the characteristics of GI (type, nature), the size and structure (sequence, number, level), the structure and function of supply (space configuration, connectivity, network), as well as the structure of demand (sensitivity, adaptability, ecological risk) on regional scale. On the other hand, the GI’s ecosystem service can be discussed through the spatial–temporal structural characteristics and matching rules of regional GI, such as the water surface ratio, density and configuration of river networks, the green space ratio and connectivity, as well as the water and land space composite structure. Therefore, based on the matching of the efficient GI’s ecosystem service with type, time, structure, and configuration, as well as the typical spatial and organizational mode of efficiency, through the control elements such as size, type, structure, and management, the GI’s ecosystem service can be optimized with redundancy.

**Building urban ecological security pattern with high efficiency of green infrastructure’s ecosystem service**

Building urban ecological security pattern with high efficiency of GI’s ecosystem service is the finial purpose of the conceptual model. First of all, it is the starting point to build the urban ecological security pattern by determining the type, size, and structure of GI meeting the regional and urban ecological security. Second, based on the coupling relationship between ecological process and pattern on regional–urban–local scale, as well as the spatiality of GI and ecosystem service, the high-efficient GI’s ecosystem service should develop the temporal and spatial allocation methods and standards for constructing GI for urban ecological security. This is the spatial basis and support to form the general urban ecological security pattern. In this process, the GI’s ecosystem service technology chains are the support of the network building. Third, the GI will be built as resilient GI and corridors with multi-scale, multi-level, and multi-type starting from the mosaics which are network coupling, node compound,
and function comprehensive. With the final goal of land-use optimization, putting forward the fusion method and pattern regulation and control mechanism for GI and traditional planning contents include natural environment and humanistic resources protection, municipal infrastructure, urban disaster prevention, and reduction. In this way, the construction of GI is integrated with traditional planning technology system.

Discussion

This article tries to point out how to implement the building of GI that provide the ecosystem services needed by the city in three scales, through the researches on the mechanism of balancing supply and demand as well as the measurement and evaluation for the level of ecosystem services. However, as a theoretical guidance, this conceptual framework needs further studies to translate and implement the concept into specific ecological practices (Xiang 2017), including researches on (1) the process model and realization mechanism of the supply and demand equilibrium of GI’s ecosystem service, (2) the determination of the measurement and evaluation index and model for the supply and demand level of GI’s ecosystem service, and (3) the promotion of the specific technics for the GI’s ecosystem service, which are the keys of GI planning based on balancing supply and demand of high-efficient ecosystem service. For example, the measurement and estimation of the demand of the ecosystem services of GI is one of the prerequisites for the study of balancing supply and demand of GI’s ecosystem service. According to the optimization framework: first, it is necessary to clarify the demands of a certain type of ecosystem services, including the government, enterprises, residents, and other stakeholders in the city. Second, determining the specific demands in the region of a certain scale and selecting the social indicators that can measure the degree of the demands, such as population density, green/open space density, facility density, household income, and real estate value. Third, by importing the statistics and data into ArcGIS, rating and ranking the demand level of the ecosystem services of GI, and mapping the demands of the ecosystem service to show spatially explicit information, such as geological distribution, spatial pattern, and the proportion. By simulating the demand process, the gap can be established through comparing the demand with the supply capacity of the ecosystem services of GI in the region. The determination of demands and its estimation indicators for the degree of demands, rating standards, and analysis models needs to be guided by the optimization framework and gradually implemented into practice. In the future, according to specific targets and strategies on each scale, it is necessary to explore the regulating process of efficient ecosystem service through adjusting function and configuration. As well, it is important for healthy development of the cities and ecological coupling of the urban and regional areas to enhance the technology of GI’s ecosystem service for typical urbanization areas, so as to reveal the basic rules and basis for building regional ecological security patterns through GI planning and design.

Conclusion

Building urban-region integrated green infrastructure through balancing supply and demand of high-efficient ecosystem services

In the context of global urbanization, the existing research, theory, and practice of GI rarely based on the balance between supply and demand of ecosystem services. What kind of GI meets the demand for urban ecological security of rapid urbanization areas? How to determine the specific function and configuration of GI from ecosystem service requirements of urban ecological security? For the above questions, this study draws the following conclusions: (1) In the challenge of the green spaces and resources being invaded, the current GI based on the existing supply system, the specific function and configuration of which are constructed through suitability evaluation, cannot meet the growing and changing needs of urban ecological security in the process of urban growth. (2) The GI networks most of which the connection mode is structural linkage, namely, the geometric form shaped by several blocks connected by linear spaces, cannot construct the spatial configuration needed by the urban ecological security in rapid urbanization areas in consideration of the fragmentation and isolation of green spaces. (3) The research method of GI itself for adaptation to urban growth on the microscale cannot meet the macrodemand of ecosystem services in the region and city during the rapid urbanization process.

Building urban ecological security pattern through elevating green infrastructure’s ecosystem service based on balancing supply and demand

The conceptual model of GI’s ecosystem service optimization based on balancing supply and demand shows a new path to meet the needs of urban growth and build a city’s ecological security pattern through upgrading and optimizing GI. First, the supply and demand balance of GI on regional–urban-site scales is explored; Second, the measurement and evaluation methods of GI’s ecosystem services are established; Third, through the
adjustment of water system, the appropriate layout of green space and adjustment of drought and flood, and other temporal–spatial optimization measures, the resilience regulation process of efficient ecosystem services is explored, and the technology of functional promotion of GI ecosystem service for typical urbanization areas is developed; Finally, based on the above technology, measures, and strategies, the building of regional ecological security pattern based on GI is achieved.

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Highlights
1. The supply and demand of GI’s ecosystem service for the city is unbalanced.
2. The function and structure evolution of GI in order to adapt to urban growth is reviewed.
3. An optimization framework of GI’s ecosystem service level adapted to urban growth is proposed.
4. Build urban-region integrated GI through balancing supply and demand of high-efficient ecosystem services.
5. Build urban ecological security pattern through elevating GI’s ecosystem service based on balancing supply and demand.

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