

Research Article

Optimizing Spatial Distribution of Urban Green Spaces by Balancing Supply and Demand for Ecosystem Services

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Received 29 October 2019; Accepted 5 December 2019; Published 26 March 2020

Guest Editor: Jia-Bao Liu

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The capacity and ecological flows of ecosystem services as well as the demand for them are key areas of urban and rural ecological planning that have been studied using the spatial-explicit model as a decision support tool. This study develops a framework for mapping the relationships among the capacity of and demand for ecosystem services, ecological flows, and planning management. This is done by estimating the ecosystem services based on the space for recreation and environmental conditions and assessing planning for green spaces using the spatial-explicit model. The results show that the carrying capacity of green recreational space was high in the northwest, southwest, and southeast parts of the city of Hefei in China, where this space was highly sustainable in the northwest and southwest. The data also show that the carrying capacity for air purification was higher in the northwest, southwest, and southeast suburbs of Hefei, while areas with high demand for air purification were mainly located in the northeast. The spatial variation in the flows of supply and demand for ecosystem services remained high and unbalanced in the northeast and southwest of Hefei. The excessive use of ecosystem services was concentrated in the urban center while their use in suburban areas was sustainable. The results show that the gap between the supply and demand of space for recreation increased with distance while that between the supply and demand of air purification decreased with increasing distance. The results of assessment based on spatial visualization show that green space was abundant in areas with low demand for it, while those with high demand for it tended to have limited green space in Hefei. This analysis shows that indices for the demand for green spaces in the context of ecosystem services can be improved via public participation, interactions between different scales of ecosystem services for green space, and use of decision support in urban and rural planning systems. These areas will form important directions for future research.

1. Introduction

With rapid urbanization and the attendant increase in urban population, the ecosystem of urban green space has been significantly influenced by the activities of humans and undergone major changes [1]. A growing number of problems with the urban ecological environment, such as soil erosion, loss of biodiversity, erosion of green land, and air pollution, have significantly reduced the benefits of the ecosystem services provided by urban green spaces [2]. Green spaces are an important part of the urban ecosystem, which contribute to the human health, recreation, and

survival. Important challenges in this context include finding ways to assess the balance of urban green spaces, considering the relationship between supply and demand for such spaces and better coupling the recreational activities of urban residents and the function of urban green spaces.

The term “ecosystem services” refers to the provision, regulation, and support provided by nature for humans [2, 3]. The provision of ecosystem services depends on the ecological and socioeconomic conditions (of urban areas) [4–6]. Against the backdrop of rapid urbanization, ecosystem services provided by urban green spaces have generated a great deal of interest in academia. Work on the

evaluation of ecosystem services provided by urban green spaces has emphasized the value of carrying capacity and supply-demand relationships [5–7].

The assessment of ecosystem services from a static perspective, in the absence of considerations of dynamic delivery, is absent from previous work [8]. Ecological flow is a functional dynamic that is indicative of the relationships among material metabolism, energy conversion, information exchange, increases and decreases in value, and biological migration within ecological systems, all of which are concrete manifestations of ecological processes [9]. It is the movement of ecosystem services from source to sink in time and space driven by nature and human beings. Assessing the flow of ecosystem services is an important issue in the relevant research, which is in its incipient stage. The concept of ecosystem service flow is vague, and research has yielded two main interpretations: (1) the process of service transfer from the ecosystem to humans; (2) a of ecosystem services used to advance the well-being of humans [10, 11]. Both interpretations emphasize the flow of materials and energy of the ecosystem to service people, rather than the operation and dissipation of other aspects of the ecosystem. Based on the concept of ecosystem service flow, Baró et al. conducted a quantitative study on outdoor leisure and air purification in Barcelona, Spain, in 2016. They identified areas where the supply and demand of ecosystem services did not match [12]. Ecological carrying capacity refers to the ability of an ecosystem to develop in a healthy and orderly fashion to provide goods and services [13]. Ecological demand refers to socioeconomic system requirements with respect to the dynamic delivery of ecosystem services and ecological environmental resources within natural ecosystems in light of economic activities [14]. These are inseparable within the ecological system of urban green space with respect to ecological flows and carrying capacity and demand [15]. This is indicative of the sustainable development of ecosystem dynamics, flows, and demand as well as the supply and demand of goods and services within dynamic ecological systems [16]. These variables also provide a breakthrough in the dynamic evaluation of ecosystem services. Scholars divide the ecosystem services of urban green spaces into three levels: carrying capacity, flows, and demand [17–20]. This has enabled a dynamic evaluation of the sustainability of the ecosystem services of urban green spaces as well as the supply and demand for them [21]. The area chosen for this study is the city of Hefei, China. A framework is proposed to map the relationships among carrying capacity, ecosystem service flows, and demand for green spaces [22, 23]. Planning for green spaces in urban areas is evaluated using the results of the spatial-explicit model [24–26].

2. Research Area and Methods

2.1. Concepts and Frameworks. A conceptual framework for the assessment of ecosystem services based on capacity, flows, and demand is indicative of the relationship between

ecosystem characteristics, functions, services, benefits, and human preferences [27]. Ecosystem service capacity is therefore defined as the ability of an ecosystem to provide services on the basis of biophysical characteristics, social conditions, and ecological functions even though service flows are services that are actually produced that people use or experience. At the same time, ecosystem service demand refers to the amount of services required or expected by society [28]. This approach can be further developed into an operational framework (Figure 1) that represents the degree of mismatch between ecosystem services, and how this influences decision making based on the relationships among capacity, flow, and demand [29–31]. In cases where the carrying capacity of ecosystem services is smaller than the flow, overuse or unsustainability is implied [20]. When the flow does not meet social demands, the ecosystem services remain incompletely utilized [29].

2.2. Summary of Research Area. The area used for this study is located in Hefei city in Anhui Province, China (Figure 2). Hefei is the political, economic, and cultural center of Anhui Province as well as an important national scientific, and educational center, modern manufacturing base, and regional transportation junction. It is between the Yangtze and Huaihe Rivers on the shore of Chaohu Lake (31°31'N–32°37'N, 116°40'E–117°52'E). Hefei has a number of important regional advantages, including linking east and west and connecting north to south. It covers an area of 7,047 km² consisting mainly of low hills and plains. The region has a subtropical humid monsoonal climate, with an annual average temperature of 15.7°C and annual average precipitation of 1000 mm. Its population is 7.86 million, including a central urban zone with a population of 3.6 million. The population continues to grow because of the rapid economic development of Hefei. The area of urban construction land in this region has expanded significantly in recent years and has had a significant impact on the urban green space system. This study chose the central urban area of Hefei. The central urban area is divided into four administrative regions: Shushan, Baohe, Luyang, and Yaohai districts (Figure 2).

2.3. Methods

2.3.1. Models

(1) Ecosystem Services. In the context of ecosystem services, recreational functions are helpful for improving the physical and mental health of citizens [32–34]. Recreational space (i.e., urban green space) is used in this analysis to evaluate the functions of ecosystems of green spaces in Hefei.

In the context of functions regulating ecosystem services, air purification is among the most important ones [35]. Vegetation in the urban green space can absorb pollutants and improve air quality. Sulfur dioxide (SO₂) was used as exemplar to calculate the annual volume of standard pollutants absorbed by vegetation.

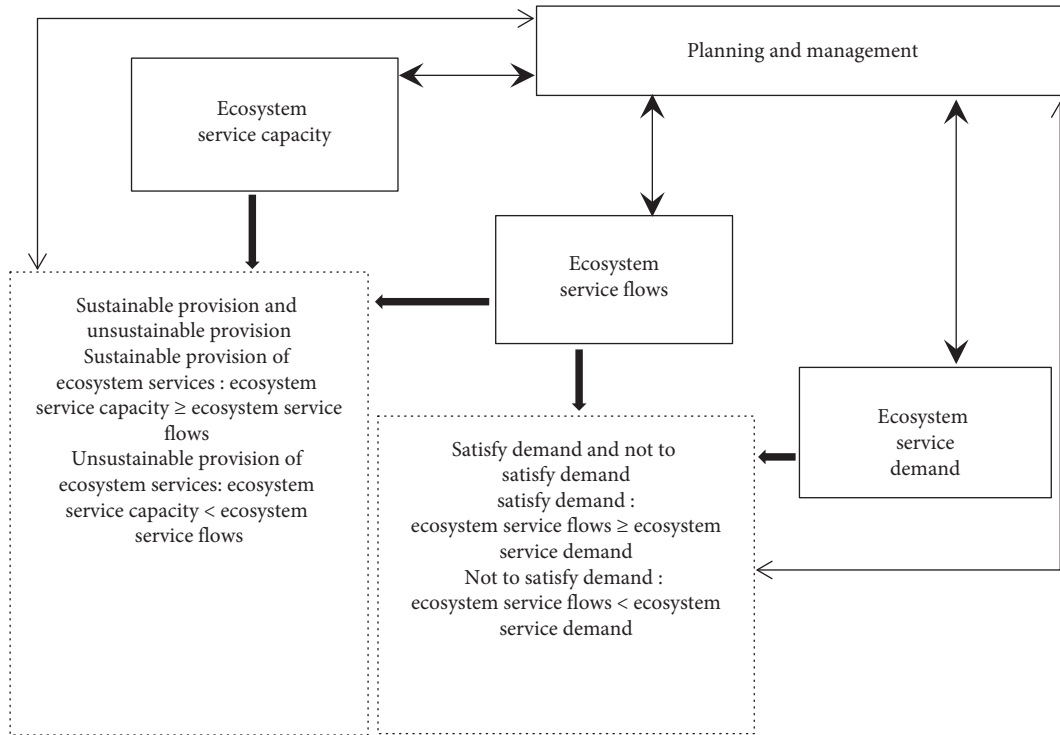


FIGURE 1: Flow chart of relationships among ecosystem service capacity, traffic, demand, and planning management.

(2) *Indicators Used for Assessment of Ecosystem Services.* An evaluation index along with the relevant data were used to assess the ecosystem services provided by urban green spaces, as summarized in Table 1.

(3) *Standardized Treatment.* To compare data in different dimensions, the results of the calculated recreational space, capacity for air purification, flow, demand, sustainable supply, and unmet demand were standardized. The formula used is as follows:

$$x' = \frac{x - x_{\min}}{x_{\max} - x_{\min}}, \quad (1)$$

where x' denotes the standardized value, x_{\max} denotes the maximum value of the sampled data, x_{\min} denotes its minimum value, and x denotes the original data.

2.3.2. Recreational Space. The model used to evaluate recreational space emphasizes natural recreation in daily life. The carrying capacity of green spaces was evaluated using the attraction model [38], where the area occupied by green spaces and the distance to these areas were key factors. The area of green spaces was calculated using the software package ArcGIS [36], as was the distance between the green space and the center of each block within Hefei. The attraction was calculated as follows:

$$F_{kl} = \frac{a_k}{d_{kl}^2}, \quad (2)$$

where F_{kl} denotes the attraction of green space K at point l , a_k denotes the area of green space K (m^2), and d_{kl} is the linear distance between green space K and point l (m).

The flow of recreational space was derived using a 1 km distance threshold for green space, which denotes daily outdoor activities in close proximity. ArcGIS was used to build a 1 km buffer zone with green space as source. These data were then superimposed onto a population density grid to calculate the number of residents arriving at green spaces as a measure of the flow of recreational space [33]. The results of the calculation of carrying capacity and flow of recreational space were divided into grades 1–5 using the natural fracture method of ArcGIS.

The demand for recreational space was evaluated based on an intersection matrix of the distance between the center of each block and the green space and the population density of the block. Thus, given the assumption that all residents have similar aspirations for their daily recreational spaces, spatial intersection was performed using the Euclidean distance between each reclassified block and the recreational space and the population density grid.

The sustainable supply and unmet demand of recreational space were evaluated using the conceptual framework outlined in Table 1. The results were divided into grades 1–5 using the natural fracture method. The sustainability of recreational spaces was calculated as follows:

$$V_{\text{sr}} = V_{\text{cr}} - V_{\text{fr}}, \quad (3)$$

where V_{sr} denotes the sustainable supply of recreational space, V_{cr} is the carrying capacity of such space, and V_{fr} denotes the flow of recreational space. This means that, if $V_{\text{sr}} \geq 0$, the recreational space was considered to have been used sustainably, but if $V_{\text{sr}} < 0$, it was being used excessively.

The area of the recreational space that did not meet the above demand was calculated as follows:

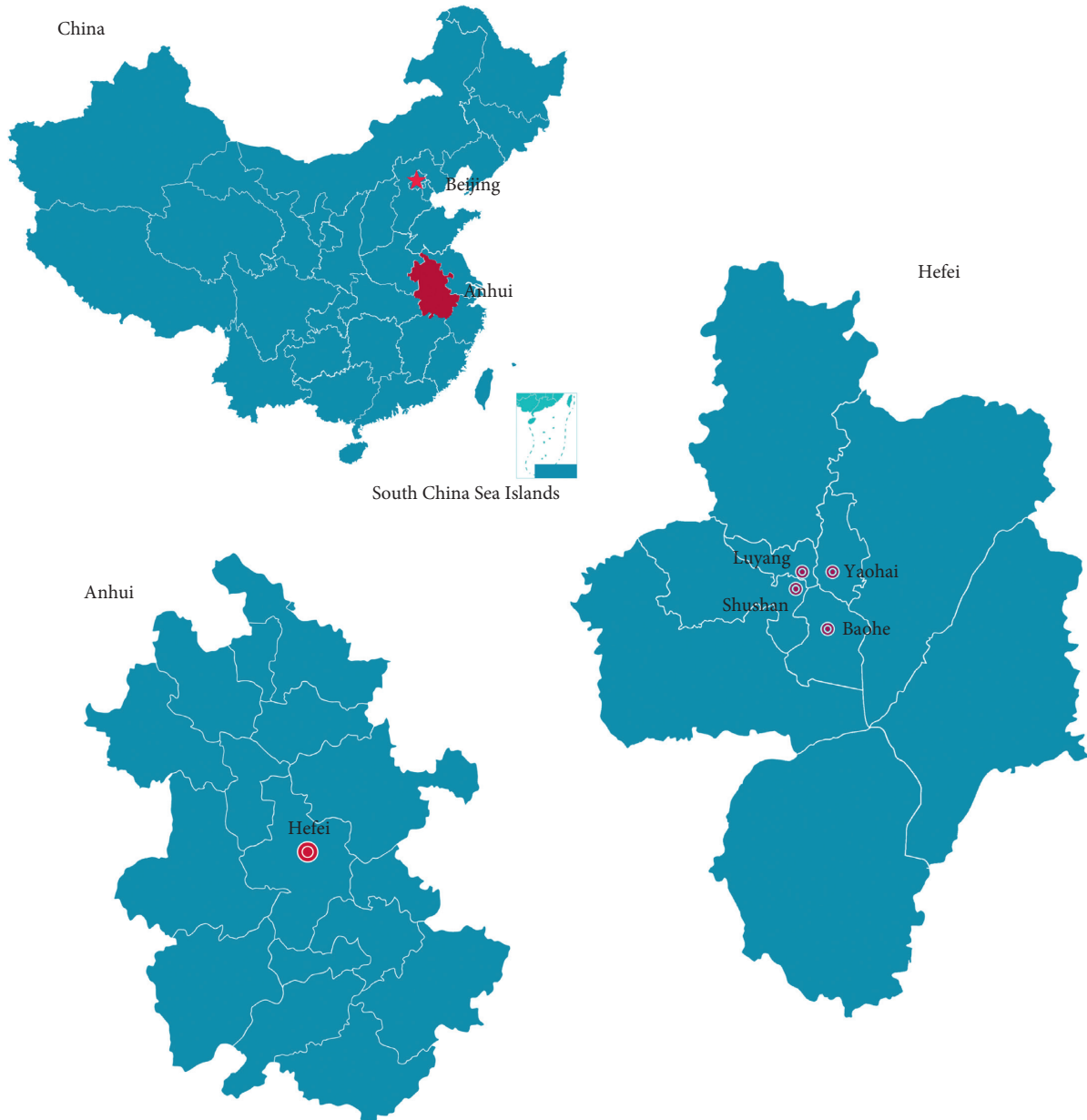


FIGURE 2: The study area: Hefei in Anhui Province, China.

$$V_{ur} = V_{fr} - V_{dr}, \quad (4)$$

where V_{ur} denotes the extent to which the given recreational space failed to meet demand, V_{fr} is the flow of recreational space, and V_{dr} is demand for it. If $V_{ur} \geq 0$, the recreational space was considered to have met demand, whereas if $V_{ur} < 0$, the demand was not met.

2.3.3. Air Purification (SO_2). This research focuses on SO_2 as air pollutant. In terms of evaluating the carrying capacity of air purification, the literature suggests that the maximum threshold of the absorption of SO_2 per unit area of green space is $88.65 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ [37] as follows:

$$V_{ca} = 88.65 \times \frac{S_{sub}}{S}, \quad (5)$$

where V_{ca} denotes the carrying capacity of air purification, S_{sub} is the area of green space, and S is the area of green space.

A review of the literature on the flow evaluation of air purification shows that the annual volume of SO_2 absorbed through woodlands and grasslands is 123.5 t/hm^2 and 7.92 t/hm^2 , respectively [37]:

$$V_{fa} = A_g \times 7.92 + A_f \times 123.5, \quad (6)$$

where V_{fa} denotes flow rate of air purification, A_g is the area of grassland within a green space system, and A_f denotes forested area.

TABLE 1: Standards and data used to evaluate ecosystem service models.

Function	Composition	Indicators	Data sources	
Recreational function (daily life)	Capacity of recreational space	Recreational area and distance from street center	Landsat8 remote sensing (RS) image	
	Recreational space flows	Number of residents visiting recreational space	Demographic data from the Hefei Civil Affairs Bureau	
	The demand for recreational space	Distance of recreational area from street center and population density	Demographic data from the Hefei Civil Affairs Bureau	
	Sustainable supply of recreational space	Carrying capacity minus flow is greater than or equal to zero: sustainable supply of recreational space		Landsat8 RS image
		Carrying capacity minus flows is less than zero: unsustainable provision of recreational space		Demographic data from the Hefei Civil Affairs Bureau
Supply and demand of recreational space	Flow minus demand is greater than or equal to zero: satisfy demand of recreational space	Flows minus demand is less than zero: not to satisfy demand for recreational space	Landsat8 RS image Demographic data from the Hefei Civil Affairs Bureau	
Air purification (SO ₂)	Air purification capacity	Maximum annual absorption of SO ₂ by vegetation	Reference [36]	
	Air purification flows	Actual annual SO ₂ uptake by vegetation	Reference [37]	
	Air purification demand	SO ₂ average concentration and population density of blocks	Monitoring data from the Hefei Environmental Protection Bureau	
	Sustainable supply of air purification	Carrying capacity minus flows is greater than or equal to zero: sustainable supply of air purification		Reference [36, 37]
		Carrying capacity minus flow is less than zero: unsustainable provision of air purification		
Supply-demand relationship of air purification	Flows minus demand is greater than or equal to zero: satisfy demand of air purification	Flows minus demand is less than zero: does not satisfy the demand for air purification	Reference [37], monitoring data from the Hefei Environmental Protection Bureau	

The demand for air purification was evaluated based on the concentration levels of SO₂ in each block as well as population density. The spatial intersection between variables was evaluated using the same method as that used to calculate demand for recreational space. Thus, the obtained indices represent the demand for air purification in the range from 1 (low demand) to 5 (very high demand).

The sustainable supply of air purification and unmet demand were calculated using the conceptual framework outlined in Table 1. Sustainable air purification was calculated as follows:

$$V_{sa} = V_{ca} - V_{fa}, \quad (7)$$

where V_{sa} denotes a sustainable supply for air purification, V_{ca} is carrying capacity, and V_{fa} is the flow rate of air purification. $V_{sa} \geq 0$ implies the sustainable use of air purification, whereas $V_{sa} < 0$ implies excessive use.

The formula used to calculate the level of air purification that does not meet demand is as follows:

$$V_{ua} = V_{fa} - V_{da}, \quad (8)$$

where V_{ua} denotes the degree to which air purification cannot meet demand, V_{fa} refers to the flow of air purification, and V_{da} denotes demand for air purification. If $V_{ua} \geq 0$, air purification meets demand, whereas if $V_{ua} < 0$, it does not.

3. Results and Analysis

3.1. Capacity, Flow, and Supply and Demand for Ecosystem Services

3.1.1. Recreation. The ecosystem services evaluation model was used to obtain the carrying capacity, flow, and supply and demand for Hefei. These data show that the carrying capacities of recreational green space in the northwest, southwest, and southeast of the city were relatively high, including the Dongpu and Dafangying reservoirs as well as urban forests and the Binhu Wetland Park. Scores of the carrying capacity for green spaces in this area were 2.34, 2.11, 1.79, and 1.17; the data suggest that the carrying capacity of green spaces in parks in the central urban area of Hefei was moderate and included Swan Lake, Around the City Park, and Hefei Nanyanhu, with scores of 0.73, 0.64, and 0.45, respectively. Recreational spaces featuring significant activity included Around the City Park, Swan Lake, and Binhu Wetland Park. The data showed a highly sustainable supply of recreational space in the northwest and southwest of the city, while the supply of green space along Changjiang Road and Huizhou Avenue had low sustainability. The main reason for this result is that the parkland area around these roads was small, while the surrounding residential areas were large and housed a large population. At the same time,

the space for recreational activity was large, and areas with high demand for recreational space were mainly located in the east and southwest of Hefei. On the whole, the demand was greater than the supply. The relationship between supply and demand in this region was moderate and thus unsatisfactory.

3.1.2. Air Purification. The capacity of green spaces for air purification in the northwest, southwest, and southeast suburbs of Hefei was high. The scores of green space for the Dongpu reservoir, Dafangying reservoir, Urban Forest Park, and Binhu Wetland Park were 3.02, 1.68, 1.34, and 4.38, respectively. The capacity for air purification of green space in the city center was moderate, while scores for Tangxihe Park, Feicui Lake, and Hefei Nanyanhu were 0.79, 0.84, and 0.88, respectively. The air purification capacities of suburban green spaces were higher than those of their central urban counterparts. Areas with the highest flow of air purification were in the northwest, southwest, and southeast of Hefei and included the Dongpu and Dafangying reservoirs, Urban Forest Park, and Binhu Wetland Park. These green spaces absorbed more SO₂ because of the high vegetation coverage in their suburban areas, whereas the flow of air purification in park green spaces and protected green spaces was low. Areas with the highest demand for air purification in Hefei were mainly located in the northeast. It is an old city containing an industrial zone with high population density and a high concentration of SO₂. The capacity for air purification was inadequate in the northeast and southwest of Hefei.

In general, spatial differences in the flow of supply and demand for in green spaces were significant in Hefei. However, the northeast and southwest remained unbalanced with respect to supply and demand. The most significant factors controlling these differences were small green areas, high population density, and concentration of pollutants.

4. Discussion

4.1. Detecting Unsustainable Use of Green Spaces. A visual analysis of the flow of supply and demand for urban green spaces as ecosystem services shows that they were not fully coincident with the planning for urban green systems, and the local green space system with high demand is not perfect. To make planning more effective, the function of ecosystem services should be applied, especially because it is important for the use of resources and fairness. Such a plan can support urban green spaces for ecosystem services in a comprehensive way. A strategic and comprehensive process can help ensure the provision of ecosystem services owing to urban green space. The model to evaluate these ecosystem services provides a flexible tool to optimize the spatial layout of green space by assessing the supply and demand for them. This can help implement comprehensive land use governance to enhance the potential of multifunctional ecosystem services by balancing the supply and demand for green ecosystem services. Although the model can be used for spatial planning based

on spatial restoration, it should not be considered an analysis of the suitability of land because it does not consider specific plots, land use, cost, and other effects on the green space. Public participation can also be used to improve the index of the demand for green space, interaction of ecosystem services at different scales, and decision support for urban and rural planning systems [39].

At present, the suburban green space is divided into the urban green space system in the urban and rural planning, and the suburban green space has the risk of destruction in the future urbanization process. Therefore, planning for Hefei should seek to protect the carrying capacity and discharge of ecosystem services in these sensitive areas. The demand for recreational spaces was mainly located in the eastern part of the city, close to the center. To address unsatisfactory demand, green infrastructure planning should be implemented to protect green spaces and develop ways to restore them or to create new green space. The assessments of air purification show that reducing or limiting private traffic in certain areas, encouraging the use of public transport and nonmotorized or low-emission vehicles, strengthening transport planning to achieve shorter commuting needs through tree planting or the selection of strategies such as trees with high air pollution removal capacity, and policy interventions can help solve the mismatch between the flow of air purification and demand for it [40].

5. Conclusions

The results of this study validate the relationships among the capacity, flow, and demand for ecosystem services as well as their applicability to a system of planning for urban green spaces. They also show a significant spatial difference in the flow of supply and demand for ecosystem services owing to green space within Hefei. The data show that the northeast and southwest of the city were significantly unbalanced with respect to supply and demand, where the excessive use of such services was concentrated in the urban center but was sustainable in suburban areas. The gap between the supply and demand for recreational space increased in concert with distance, whereas the gap between variables influencing air purification decreased with distance [41, 42].

The limitations of the proposed method are its suitable indicators of the unsustainable use of green spaces. Policies implemented in the future should seek to harmonize different components of this framework based on the characteristics of the city or area of interest. Urban policies for air purification should focus on reducing the concentration of pollutants, while the optimization of recreational spaces relies on planning tools to maintain and promote the carrying capacity and flow of ecosystem services. A combination of regulatory policies (e.g., enforcement caps and stricter green infrastructure ratios) as well as economic incentives (e.g., environmental taxes, subsidies, and payments) are feasible options.

Future work in this area should emphasize improvements in the service demand index of green space ecosystems by means of public participation, interactions among green space ecosystem services at different scales, and decision support for urban and rural planning systems.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

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

Acknowledgments

This work was supported by the National Key R&D Program of China (2017YFC0505706).

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