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Forest landscape connectivity change analysis in the Yangtze River basin by multi-temporal satellite data

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This study selected the highly urbanized Wuhan city in the Yangtze River basin as a research area, and used the Landsat 5 TM images from 1990 and the Landsat 7 ETM+ images from 2000 and 2010. These images were combined by using the graph-based integral index of connectivity (IIC), probability of connectivity (PC), and the importance value of the patch to analyze the spatial and temporal dynamic change of the Wuhan urban forest. Results showed the increasing area and the widening Wuhan forest. However, for the past 20 years, their patch structure has been uneven, and composed of several small and super-large patches. The IIC and PC of Wuhan forest tended to increase slightly, whereas the connectivity level of urban forest remained low. The value of the importance of the patch and its range are increasing. Some of its characteristics indicated north is better than south, rural is higher than urban, and the main urban area is lesser than the urban area.

[**Key words***:* urban forest, integral index of connectivity, probability of connectivity, graph theory]

Introduction

The urban forest functions in the maintenance and development of urban biodiversity, water and soil conservation, and improvement of the urban ecological environment[1-3]. In fact, ensuring a good connectivity of forest is crucial in protecting biodiversity, and maintaining the stability and integrity of the ecosystem[4].For these reasons, the study of landscape connectivity of urban forest draws attention from all scholars. The study results are primarily applicable to urban forest planning and pattern transformation, forest resources management, and reserve and urban landscape planning[5-9]. Landscape connectivity refers to the extent landscape promotes or inhibits the motion of source patches of living beings or certain ecological processes, which may reflect the degree of the landscape factor in inhibiting certain horizontal motions. Main methods for measuring landscape connectivity include landscape dynamic, meta-population, experiment tracking, migration and diffusion modeling, and the landscape index, which is based on the minimum cost-distance model and graph theory[10-13]. Index method based on graph theory discusses the spatial continuity of landscape factors, and considers the impact of certain ecological processes, which make up for the shortcomings in subjective evaluation, identification, and parameter setting[14].

Urbanization is the global trend in development. As China undergoes rapid urbanization, forest landscape connectivity also varies tremendously. Taking Wuhan, a typical city in central China undergoing rapid urbanization as an example, the temporal and spatial dynamics of urban forest was analyzed with the landscape connectivity index based on graph theory. This research attempts to identify major habitat patches and variations in urban forest landscape connectivity during fast urbanization, and provides information on protecting the stability of urban internal ecosystems as well as scientific basis for urban biodiversity protection, urban planning, and land-use planning and management.

As a megacity in central China and the largest industrial city and economic center in

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downstream area of Yangtze River, Wuhan is situated at the intersection of the Yangtze and Han Rivers, between 113°41'-115°05'E and 29°58'-31°22'N. The whole city covers an area of 8767 km^2.

Wuhan boasts of rich forest resources, including the Mulan ecotourism area, Jiufeng Mountain, Maan Mountain, Sushan Temple, Songyang Mountain, Qinglong Mountain, Jiuzhen Mountain, Jiangjun Mountain, and other forest patches of various sizes. These areas have a very important study value because of their significant role in maintaining and developing urban biodiversity, preserving water and soil, improving the urban ecological environment, and providing forest products as well as leisure and recreation opportunities.

Materials and Methods

The data used in this study were derived from remote sensed images of Wuhan city taken by the Landsat 7 ETM+ in 2000 and 2010 and the Landsat 5 TM in 1990. These images were downloaded from the International Scientific Data Service Platform. We combined Bands 4, 3, and 2 of the images from the three periods with ENVI 4.7 software, and carried out precise geometrical calibration on them with the use of a topographic map. Atmospheric correction was also conducted based on the geometrically calibrated data. Additionally, we made full use of land-use status maps and field investigation data to establish categorization criteria to conduct HMI-supervised classification. Based on different landscape functions, these data were classified into six land-use types, namely, construction land, arable land, water, forest, unutilized land, and wetland. As this study focuses on urban forest, including forest and grassland, we isolated urban forest with ArcGIS 10.1.

We evaluated the connectivity of the overall landscape by using the integral index of connectivity (IIC) and the probability of connectivity (PC) in the following formula[15]:

$$IIC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{a_i a_j}{1+nl_{ij}}}{{A_L}^2}$$

where n is the number of habitat patches existing in the landscape; A_L is the total landscape area; a_i and a_j correspond to the suitable habitat area inside catchments i and j, respectively; nl_{ij} is the number of connections between patch i and patch j; and 0≤IIC≤1. When IIC equals 0, it means there is no connection between various habitat patches, and when IIC equals 1, it means the whole landscape is a habitat patch.

$$PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i a_j p_{ij}^*}{{A_L}^2}$$

p_{ij}^* is the maximum product of dispersal probabilities along the links of all possible paths between catchments.

Based on IIC, we used the importance value (dPC) to measure the importance of patches[16].

$$dPC = \frac{(PC - PC_{remove})}{PC} \times 100\%$$

where PC is the index value when the landscape element is present in the landscape, and PC_{remove} is the index value after removal of that landscape element. dPC is used to indicate the importance of certain patches in maintaining landscape connectivity by measuring the PC change after removal of the patch.

Both IIC and PC are landscape connectivity indexes based on graph theory. They comprehensively indicate the connectivity of habitat patches at the landscape level. The difference lies in that IIC is based on the binary connectivity model in which landscape patches are either connected or disconnected. PC is based on the probability model in which the probability of connectivity is correlated with the distance between them. Due to the calculation of IIC and PC, it is necessary to set the diffusion threshold distance. For the sake of comparability, the threshold value was set uniformly based on studies by scholars familiar with the actual situation of Wuhan. In the present study, forestland was taken as the habitat patch and the entire landscape in the research area was taken as the background landscape[17]. The calculation of the above indexes was determined by using Conefor Sensinode 2.2 and ArcGIS 10.1.

Results and Discussion

In cities, the size of forest can be deemed as a criterion for classifying forest patches. In this research, the forest patches were sorted into four levels, namely, small patches (smaller than 1 km^2), intermediate patches (1 to 5 km^2), large patches (5 to 10 km^2), and super-large patches (larger than 10 km^2). From 2000 to 2010, the area of forest in the research area increased continuously, and grew by 253.43 km^2. This increase was caused by major projects aimed at building a state-level landscape garden city and a national forest city. These projects include growing a forest along the Ring Expressway, the "Green Wuhan, City in Forest" initiative, the Jiufeng urban forest reserve afforesting plan, and the She Mountain relocation and greening project. These programs all aim at developing urban forests significantly and increasing the area of forest patches to some extent.

However, the number of forest patches increased, and then declined. Yet the total number of patches in 2010 was 3706 more than the figure in 2000. The increased forest patches were mainly dotted and distributed unevenly. For that reason, the fragmentation of forest patches also increased without strong aggregation.

From the perspective of type and structure of patches (Table 1), most types of urban forest patches in Wuhan have been increasing steadily, but with the exception of large patches, which decreased in 2000. Small patches dominated during all three research periods, and accounted for 84%, 86%, and 85% of all patches, respectively. However, the area these patches occupied only accounted for 31.01%, 30.81%, and 37.24%, respectively, and concentrated in the southern and southwestern parts of the research area. Although super-large patches constituted a small portion of the total number of patches in these three years, 1.71%, 1.65%, and 1.59%, respectively, the area they occupied was rather considerable, 48.02%, 55.81%, and 47.81%, respectively. The super-large patches are mainly located in the northern and northeastern parts of the research area. The data show clearly that forest patches in the research areas were distributed extremely unevenly in size and structure during the decade. The research areas were composed of large numbers of small patches and a few super-large patches.

Table 1—Patch Structure of Wuhan Forest

Patch structure	1990		2000		2010	
	Area proportion/%	Patch proportion/%	Area proportion/%	Patch proportion/%	Area proportion/%	Patch proportion/%
Small	32.45	84.00	30.81	86.00	31.92	85.00
Medium	13.55	11.23	12.36	10.87	12.91	11.42
Large	5.95	3.06	2.97	1.48	7.36	1.99
Huge	48.05	1.71	53.86	1.99	47.81	1.59

Table 2 shows the IIC of urban forests in Wuhan has stayed at low levels, but exhibited a tendency for slight increases. This finding indicates the connectivity between forest habitat patches in the study area is poor. Since both the small-sized forest habitat and stepping-stone patches increased, the IIC climbed slightly. In comparison with the IIC, the PC values over the three years were higher, and showed slight increases. The PC value deals with probable connectivity between patches. Probable connectivity diminished with the increase in the dotted urban forest patches and fragmentation of patches in certain degrees. In the process of fragmentation, some important medium-sized patches appeared and served as stepping-stone patches, which in turn maintained and improved the connectivity of the landscape. Both the IIC and PC values of urban forest in Wuhan increased slightly over the recent decade, but the connectivity of the overall landscape remained at a low level. This phenomenon was primarily caused by the disorderly development of urbanization and an intense demand for the expansion of construction land.

Table 2—Overall Connectivity of Wuhan Forest from 1990 to 2010

Year	IIC	PC
1990	0.14	0.17
2000	0.16	0.22
2010	0.17	0.23

For the convenience of comparative analysis on historical data, this research used the range standardization method to carry out the dimensionless treatment on the importance value of patches (dPC). Importance of patches was sorted into five classes according to grade classification on important patches through the natural breaks method. A bigger value indicates the greater importance of a patch as well as better connectivity and biodiversity.

Fig. 1 shows that in the decade from 1990 to 2010, the area percentage of important patches at various levels varies greatly with serious polarization. The area percentage of Class 5 Important Patches rose from 60% in 1990 to 67% in 2000, but declined slightly to 65%. Class 4 Important Patches were fairly constant at around 2% from 1990 to 2000, before increasing to 6% in 2010. The higher area percentage for Class 4 Patches derived mostly from the conversion of Class 5 Patches. As for Class 3 Important Patches, the area percentage was maintained at 3% from 1990 to 2000, and increased to 5% in 2010. The figures for Class 2 Important Patches increased first and then declined with a minor average annual change. Class 1 Important Patches declined sharply from 26% in 1990 to 18% in 2000, but stayed above 18% from 2000 to 2010. The reduced parts were mainly transformed into patches with higher connectivity.

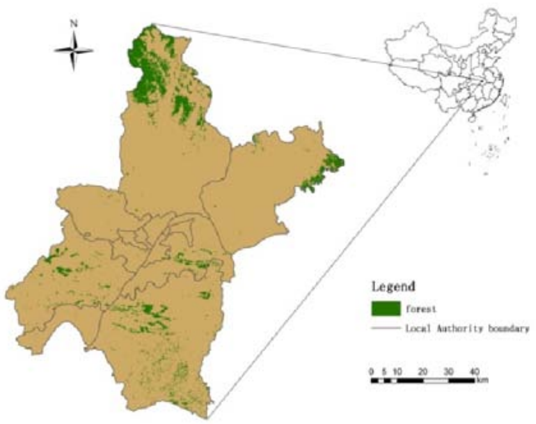

Fig. 1—Location of study area

During the period studied, important forest patches in Wuhan were mainly distributed in the northern part of Huangpi District, the eastern part of Xinzhou District, the mountainous area near Zhifang in Jiangxia District, the eastern part of the East Lake area, and the eastern and western parts of West Lake in the Caidian District. Most of these areas were located in the suburban areas instead of central downtown as Fig. 2 shows.

In 1990, Class 5 Important Patches were mainly distributed in the northern part of Wuhan, including Mulan Mountain in the northern part of Huangpi District, the northeastern mountainous area of Xinzhou, Mafen Mountain in Jiangxia District, Qinglong Mountain, and the forest area south of Liangzi Lake. In 2000, the distribution of patches remained unchanged, but the area involved increased to a certain degree. In 2010, the scope was enlarged to include Songyang Mountain and Jiuzhen Mountain in the northwest part of Caidian District, and Jiufeng Mountain National Forest Park in Hongshan District. Notably, the status elevation of Jiufeng Mountain National Forest Park, which appeared near central downtown as an important high-level forest patch, is mainly attributed to the Jiufeng urban forest reserve afforesting program implemented in 2000. The government restored the urban ecological environment through compulsory urban planning and played a driving role in better protection of the urban ecological environment of Wuhan.

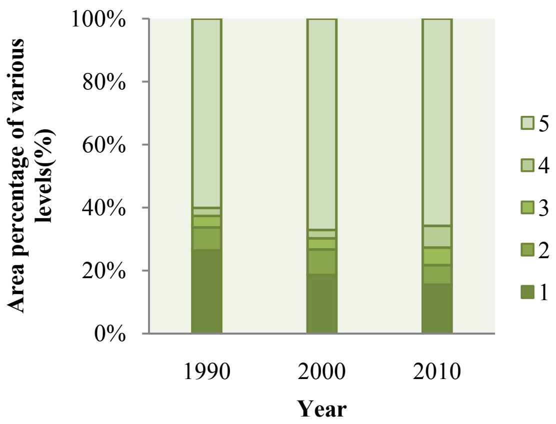

Fig.2—Percentage of Different Patch Classes in Wuhan from 1990 to 2010

Class 4 Major Patches were mainly distributed in Mulan Mountain near Class 5 Patches in the northern part of Huangpi District, the eastern mountainous areas of Xinzhou, and Jiufeng Mountain east of East Lake in 1990. In 2000, the distribution was basically unchanged, but the forest patch in Qinglong Mountain, Jiangxia District was changed into a Class 4 Major Patch and the level of the Jiufeng Mountain forest patch fell. In 2010, both the distribution area and scope of Class 4 Major Patches increased dramatically. Some new patches appeared east of West Lake in Caidian District, in areas near Zhifang of Jiangxia District as well as Mo Mountain, Yujia Mountain, and Maan Mountain near central downtown. The relocation of residents from the Wuchang and Hongshan Districts and planting of green plants further improved the forest landscape connectivity of central downtown.

From 1990 to 2000, Class 3 Major Patches were mainly distributed in a dispersed fashion and in small quantities east of East Lake and near Qinglong Mountain in Jiangxia District. In 2010, its distribution further expanded to Longquan Mountain, lakeside of Liangzi Lake in Jiangxia District, and the eastern part of Caidian District. From 1990 to 2000, Class 2 Major Patches were distributed extensively to the east of East Lake, east and west of West Lake in Caidian District and Qinglong Mountain, and the large area near Bafen Mountain in Jiangxia District. However, the connectivity of forest patches during this period was not so ideal. In 2010, the scope of Class 2 Patches shrunk significantly, and the shrunken parts were substituted with patches of higher class. From 1990 to 2000, Class 1 Major Patches were distributed mainly in the southern part and lakeside of Liangzi Lake in Jiangxia District in an uneven way. Most Class 1 Patches gradually changed into patches of higher class.

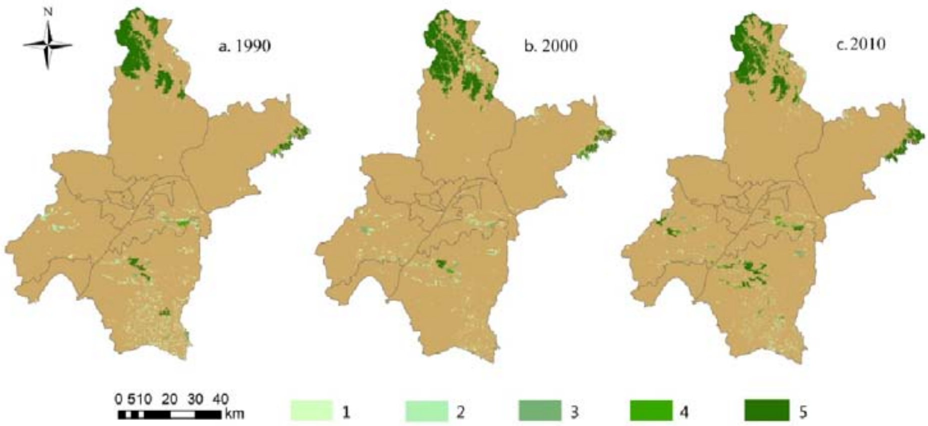

Fig. 3—Distribution of Connectivity of Important Patches in Wuhan from 1990 to 2010

Overall, forest landscape patches changed from low to high class. For example, forest patches composed of some core patches of high class and good connectivity were found in Mulan Mountain, Jiufeng Mountain, Songyang Mountain, Qinglong Mountain, Jiuzhen Mountain, and Bafen Mountain forest parks. These patches played a great ecological role in providing adequate habitats for living beings and in enhancing interaction between flora and fauna in different areas. These areas constituted the north and the central core patch areas. The former includes the Mulan Mountain forest area across the northern part of Huangpi District, which is an embranchment of Dabie Mountain and the eastern forest area of Xinzhou. The latter includes two parallel east-west core forest patches composed of the eastern part of East Lake, both banks of West Lake in Caidian District, and a band of Zhifang in Jiangxia District. These core patches are mostly distributed in areas with high elevation near water sources, and are supposed to be further protected by the government. Unfortunately, these forests have also been distributed extremely unevenly, such that their ecological effect is polarized and cannot be felt fully. Regardless of this development, the northern part, the rural area, and the suburban area enjoy stronger ecological effects than the southern part, the urban area, and central downtown.

Conclusion

From 1990 to 2010, the area of integral forest patches in Wuhan increased continuously. Although the total number of forest patches initially increased and then declined, the figure was still 3,706 more than the number in 1990. Several factors, such as rapid urbanization, affected the new or extended forest patches that appeared in a dotted pattern, with the degree of fragmentation and aggregation effect reduced. Patches were also distributed extremely unevenly in terms of type and structure. They were composed of several small patches and a few super-large patches. Large and intermediate patches comprised a small percentage.

Both the IIC and PC of Wuhan rose slightly during the period studied, but urban forest landscape connectivity still stayed at a low level. Although the government has implemented ecological restoration with respect to urban forest through ecological planning, haphazard urban construction and development rendered these efforts as a drop in the ocean in the course of improving forest ecological environment.

We assessed the patch area, distance, and connectivity between different patches by grading urban forest connectivity. From 1990 to 2010, the importance and distribution scope of patches increased to a certain degree, and some patches of low connectivity gradually changed into ones with high connectivity. However, viewing it from the perspective of the spatial distribution of forest patches in Wuhan, uneven distribution made the northern part, the rural area, and the suburban area superior to the southern part, the urban area, and central downtown. The distribution did not indicate fairness and accessibility of forest patches in improving the urban ecological environment.

In conclusion, although the area of forest patches in Wuhan increases year by year, and the integral and partial landscape connectivity improves gradually, these areas are affected by many factors like urbanization. Several related problems also exist, such as the uneven distribution of urban forest resources, an unbalanced ecological effect, inadequate linear and strip urban forest (planar forest protection and construction are quite good), unreasonable quantitative structure, spatial distribution of urban forest patches, and failure to achieve fairness in forest ecological service function or maximization of the ecological effect.

The following suggestions concerning urban forest construction were addressed in this study. First, enhancing urban forest protection legislation and intensifying urban forest ecological restoration are needed. Second, the quantity of urban forest needs to be increased as well as the optimization of the structure and distribution of urban forest by improving landscape connectivity. Third, persistence should continue in the building of urban forest core patches, protecting major forest patches with good connectivity and stepping-stone effect, and maintaining the high connectivity between forest patches. Fourth, building the idea of harmony between man and nature and promoting sustainable development and utilization of forest resources must be considered.

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