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Changes of urban wetlands in Wuhan, China, from 1987 to 2005

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Abstract

Urban wetlands play a significant role in the sustainable development of the urban eco-environment. However, accelerated urbanization has caused rapid changes in urban wetland landscape patterns, which may seriously affect their functions. Based on land-use maps, TM images, and field data from the Wuhan wetlands, the spatio-temporal evolution and wetland landscape pattern were quantitatively analyzed, with reference to landscape ecology indices of diversity, fragmentation, dominance, shape, and dimension. The results showed that: (1) the natural wetland area decreased: lake wetlands and marsh wetlands decreased by 18.71% and 50.3% from 1987 to 2005, respectively; (2) artificial wetland area increased by 47.75% in Wuhan over the same period; (3) the lake wetland area of Wuhan declined due to the conversion of large lakes to smaller ones; (4) the value of the diversity index (*H*), evenness index (*E*), and fragmentation index (*F*) decreased, while the value of the dominance index (*D*) increased from 1987 to 2005; (5) the landscape shape index (*LSI*) and fractal dimension (*FD*) of the river wetlands, lake wetlands, bottomland wetlands, and marsh wetlands decreased, while the *LSI* and *FD* of the reservoir and pond wetlands increased from 1987 to 2005; and (6) natural, societal, and economic, as well as human, activities are major factors for the structural changes in the Wuhan wetland landscape, as revealed by canonical correlation analysis. Results suggest that the ecological environment of urban wetlands should be protected to maximize the services of urban wetland ecosystems in Wuhan, China.

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Keywords
driving force, ecological method, Geographic Information System (GIS), landscape pattern, TM imageries, Wuhan

I Introduction

Urban wetlands mainly refer to those wetlands lying within the boundaries of cities, towns, and non-agricultural areas adjacent to the urban region, including those wetlands located within the region of satellite towns around centre cities. Wetlands form an important ecological infrastructure of urban areas and provide varied ecological and social services in urban eco-environments. It is now widely recognized that the sustainability of urban development depends on the provision and maintenance of forward-looking municipal and ecological infrastructures. Therefore, it is important to investigate the dynamic evolution of the urban wetland landscape pattern and their driving mechanisms (Weber and Puissant, 2003; Xu *et al*., 2009) in rapidly urbanizing environments.

Landscape ecology deals with the patterning of ecosystems in space and time. It emphasizes the interaction between spatial patterns and ecological processes, and the causes and consequences of spatial heterogeneity across a range of scales (Turner *et al*., 2001). One approach to achieving better understanding and characterization of the changes in urban wetland landscapes lies, therefore, in analysis of wetland structure, spatial-temporal pattern, ecological process, and driving mechanism using landscape ecological methodologies and theories.

To date, most research has focused on analyses of spatial-temporal dynamic change in landscape structures (Frohn, 1998; Turner *et al*., 2001; Tang *et al*., 2007). Others have studied the ecological planning, design, and management of landscapes by using landscape ecological concepts and metrics (Berger, 1987; Pauleit and Duhme, 2000; Jim and Chen, 2003; Corry and Nassauer, 2005). Some research has focused on biodiversity conservation and ecological environment assessment (White *et al*., 1997; Joyal *et al*., 2001). In recent years, the dynamics of wetland landscape patterns in China have been investigated using different methods in different locations, including land-use changes in the Dongting Lake wetland using landscape indices (Zhao *et al*., 2002), wetland patterns in Sanjiang Plain (Wang *et al*., 2003), and the characteristics and driving forces of wetland changes in the middle-lower reaches of the Taoer River (Guo *et al*., 2004) using landscape ecological methods. All these studies contribute to the development of wetland science and landscape ecology. However, research on the dynamic changes in the urban wetland landscape pattern and the driving mechanisms is still limited, particularly in a specific region with some unique wetland characteristics, such as Wuhan, China.

Wuhan, a metropolitan area in Hubei province, is in the centre of China. The city lies at the junction of the Yangtze River and the Hanjiang River, where rapid urbanization has occurred. It is known as the 'hundreds-of-lakes-urban' because it has many lakes (Figure 1). Until 2003, there were a total of 138 lakes whose areas were larger than 0.1 km^2 in the city, mainly connected to Caidian, Huangpi, Jiangxia, and Dongxi Lakes. They accounted for 20% of the total lakes in the main city areas (Zhang and Deng, 2005) and consisted of typical natural wetland landscapes (river wetlands, lake wetlands, bottomland wetlands, and marsh wetlands) and artificial wetland landscapes (reservoir and pond wetlands) in the urban areas of Wuhan. They played an important part in balancing the ecosystem, maintaining the water cycle, connecting rivers and lakes, and preventing or controlling flooding in Wuhan. Thus, there is, historically, a close relationship between the evolution of the wetlands and the urban development

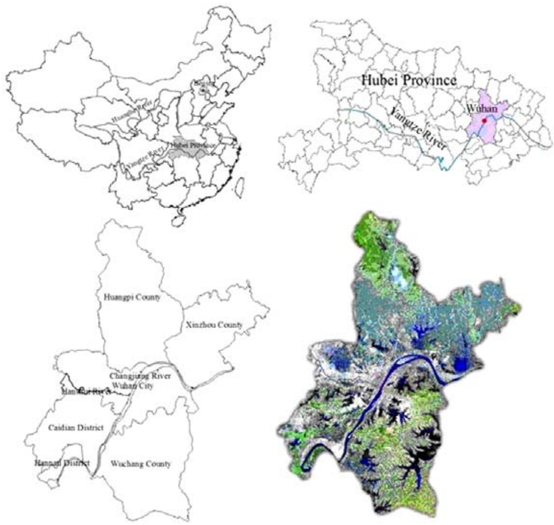

Figure 1. Maps and imagery of Wuhan, Hubei Province of China

in Wuhan. However, with the rapid development of the economy, the continuous growth of the population, and the accelerated urbanization in Wuhan in recent years, overexploitation of the urban areas has taken place in the areas adjacent to wetlands. As a result, urban wetland areas have strikingly decreased in extent, water quality has deteriorated, ecological function has been disturbed, and the flood-prevention or flood-mitigation ability of the rivers and lakes has been lowered. In total, the social and economic sustainable development of the wetland regions has been seriously affected, while flooding is increasing (Deng, 2005).

The objective of this paper is, therefore, to analyze changes in the urban wetland landscape pattern and the driving mechanisms for this from 1987 to 2005 in Wuhan, China, and to gain a better understanding of the historical evolution of the process, causes, and recent changes, using landscape ecological methodologies and theories. This understanding will provide important information to assist in the planning and maintenance of sustainable urban wetlands, and to enhance the services of the urban wetland landscape.

II Field area, data sources, research methods and research design

1 Field area

Wuhan belongs to the transition zones from the southeastern highlands to the foothills in the south piedmont of Dabie Mountain, and covers from E113°41′ to 115°05′ in longitude and from N29°58′ to 31°22′ in latitude. The middle part is low and flat, while the south part and north part are hills. The landform types of Wuhan belong to the alluvial plain of the rivers. The climate of Wuhan is semitropical monsoon ranging from hot, humid, and rainy summers to cold winters. The multiyear average of sunshine hours is 2057. The average temperature and annual rainfall is 16.3°C and 1220 mm, respectively. The altitude in the region is less than 50 m. The soil types vary, with the largest area having paddy field soil, covering about 45.5% of the total area (Wang *et al*., 2008).

2 Data sources

The data sources of this study include the terrain map of Wuchang county for 1993, with a scale of 1:50,000; the land-use map of Wuhan for 1995, with a scale of 1:100,000; the Landsat-TM imageries of Wuhan urban areas for September 1987, September 1994, April 2000, and April 2005, with a resolution of 30 m; and the statistical data from the Hubei Statistical Yearbook on Wuhan urban wetlands from 1953 to 2005.

3 Wuhan urban wetland landscape types, coding, and definitions

According to the state land-use classification system, the urban wetland landscape of Wuhan is divided into five wetland types: river wetlands, lake wetlands, reservoir and pond wetlands, bottomland wetlands, and marsh wetlands. These wetland types are based on the classification system used in landscape ecology and the characteristics of the urban wetlands of Wuhan derived from TM satellite imagery's spectral characteristics. The types, coding, and

Table 1. Landscape coding, types, and definitions of Wuhan urban wetlands

Coding	Types	Definitions
41	River wetlands	The land below natural or artificial formation of rivers and perennial water main channel
42	Lake wetlands	The land below naturally formed areas of perennial water level
43	Reservoir and pond wetlands	The land below construction of artificial recharge of perennial water level
46	Bottomland wetlands	The land between water-flow period and floodwater level of rivers
64	Marsh wetlands	The land of surface-growth wet plants and flat, low-lying topography, the chronically damp, the seasonal perennial water or stagnant water

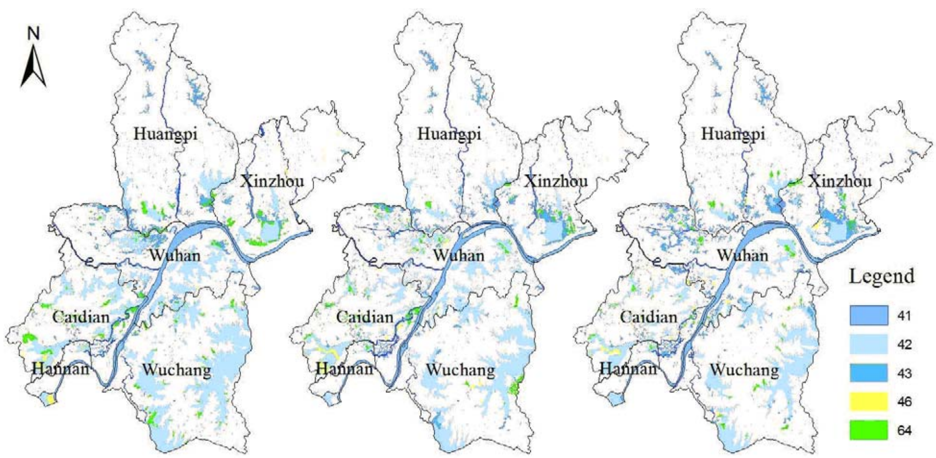

Figure 2. Wuhan urban wetlands in 1987, 1994, and 2005

definitions of the urban wetland landscape of Wuhan are shown in Table 1.

4 Research methods and research design

The wetland system is self-organizing and complex in nature, which exhibits a discontinuous character in time-space as well as a conspicuous non-linearity. Change in wetlands results from a combination of natural, social, human, and other factors. The spatial pattern of wetland landscapes contains different types of wetland patches and the spatial and temporal characteristics of the landscape can reveal the evolution of the wetlands through a quantitative analysis of the landscape pattern. Therefore, the spatiotemporal evolution of the Wuhan wetland landscape was analyzed with respect to their statistical, spatial, heterogeneous, and complex characteristics from 1987 to 2005. These analyses not only build a foundation for further analyzing the changes in the Wuhan wetlands, but also provide the rationale for exploring and planning the sustainable development of urban wetland resources.

Six steps were taken in analyzing the changes of Wuhan urban wetlands. First, the Landsat-TM images were processed using the ERDAS IMAGE software system. Second, the Wuhan urban wetlands spatial database and attribute database of 1987, 1994, and 2005 were established by using ArcGIS in combination with Landsat-TM imageries, 1993 terrain map, and 1995 land-use map. The results can be seen in Figure 2. Third, using the databases mentioned

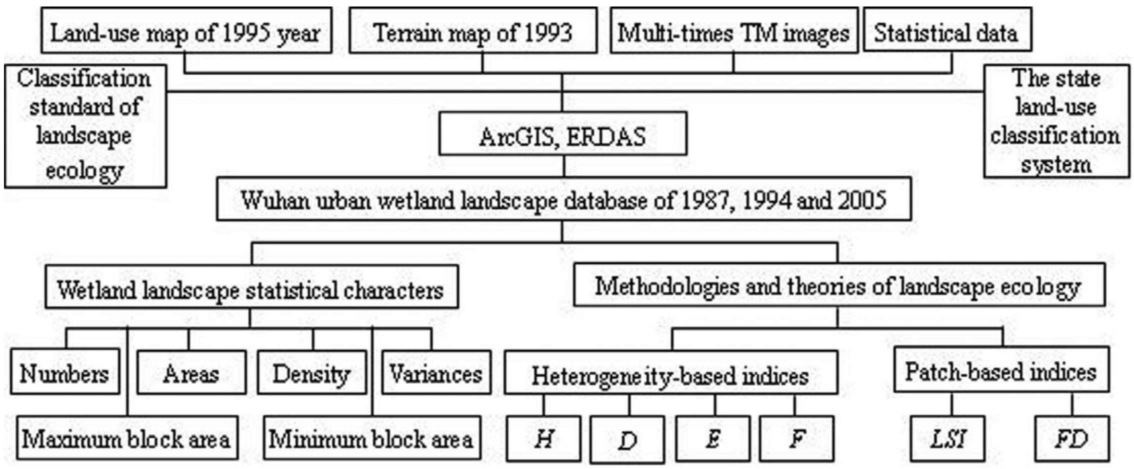

Figure 3. Calculation flowchart of landscape ecological indices of urban wetlands

above, the statistical and spatial change characteristics of the Wuhan urban wetland landscape were analyzed using the patch number, patch area, average patch area, patch area variance, and other characteristics. Fourth, the landscape ecological indices of the Wuhan wetlands were calculated using common landscape ecology indices. Fifth, the Wuhan urban wetlands' spatiotemporal change characteristics, evolution processes, and driving forces for the past 19 years were quantitatively analyzed using canonical correlation analysis. The research design is shown in Figure 3. Finally, some recommendations were formulated to better develop, recover and reconstruct a positive eco-environment and to promote sustainable development in Wuhan urban areas.

5 Selection and calculation of the landscape ecological indices of the Wuhan wetlands

Landscape ecological theory provides a set of quantitative tools (namely landscape indices or metrics) to characterize landscapes and to measure a region's landscape changes through time (Reed *et al.*, 1996). It is widely accepted that a general association exists between landscape patterns and ecological processes (O'Neill *et al.*, 1988; Turner *et al.*, 2001). However, many of these indices have substantial overlap in their use and interpretation (Giles and Trani, 1999; Tischendorf, 2001). In order to reduce the redundancy in the use of these indices, we selected the patch-based and heterogeneity-based indices that have the least mutual correlations but which possess complementary ecological meanings. These included: diversity index (*H*), dominance index (*D*), evenness index (*E*), fragmentation index (*F*), landscape shape index *(LSI*), and fractal dimension (*FD*). Among these indices, the *LSI* and *FD* are the patch-based indices that characterize the configuration of the individual landscape class at the whole landscape scale (Forman and Godron, 1986; Schumaker, 1996; Chuvieco, 1999; Imbernon and Branthomme, 2001). Regarding the spatial heterogeneity-based indices, we chose *H* to describe the landscape diversity, *D* to measure to what extent several principal landscape types control the whole landscape, *E* to measure the even degree of different landscape types, and *F* to measure the landscape fragmentation. These indices have been widely used to provide useful information on biophysically changed phenomena associated with patch fragmentation at large spatial scales (Viedma and Meliâ, 1999; Fuller, 2001). The calculation methods used to derive the landscape ecological indices are shown in Table 2.

Table 2. Calculation methods and definition of landscape ecological indices

Type	Landscape ecological indices	Formulae	Meanings
Heterogeneity-based indices	Diversity index (H)	$H = -\sum_{i=1}^{m}(P_i) \times \lg(P_i)$	Reflects the type of urban wetland landscape of Wuhan and the portion of uniformity. The greater the H value, the larger the diversity of Wuhan wetland types.
	Dominance index (D)	$D = H_{\max} - H = H_{\max} + \sum_{i=1}^{m}(P_i) \times \lg(P_i)$	Measures one or a few types of wetland landscape dominant players for different wetland landscape pattern. The greater the D value, the larger the differences in landscape types.
	Equality index (E)	$E = \frac{H}{H_{\max}} = \frac{-\sum_{i=1}^{m}(P_i)\times\lg(P_i)}{\lg(m)}$	Reflects the uniform distribution in the different types of wetland landscapes. The greater the E value, the more uniformity in the composition of the wetland landscape.
	Fragmentation index (F)	$F = \sum_{i=1}^{m}(N_i/A)$	Refers to the degree of wetland landscape being divided into parts, and reveals the degree of impact of human activities on the pattern changes of a wetland landscape.
Patch-based indices	Landscape shape index (LSI)	$LSI = L_i/2\sqrt{\pi A_i}$	Represents the complexity of the geometric shape of the wetlands. It could indirectly reflect the degree of human activities in the wetlands.
	Fractal dimension (FD)	$FD = 2\frac{\ln(0.25L_i)}{\ln(A_i)}$	Reflects the self-organization and complexity of the wetland landscape patch. It could indirectly reflect the degree of interference.

m is the type of numbers of wetland landscape; i is patch type; A is the total area of wetland landscape; N is the total number of patches; L is the total perimeter of wetland landscape; A_i is the area of the ith wetland landscape area; P_i is the proportion of the ith wetland landscape area to the total area; N_i is the total patch number of the ith landscape types; L_i is the total perimeter of the ith landscape; H is the diversity index; H_{max} is the largest in uniform under the conditions of the diversity index.

III Results

1 Changes in the characteristics of the Wuhan urban wetland landscape pattern

Regional characterizations of the patterns and changes in the urban wetland landscape from 1987 to 2005 are summarized in Figure 4. The total number of patches, total areas, patch area variance, maximum patch area, and the minimum patch area of the Wuhan wetland landscape gradually decreased by 9.82%, 8.11%, 10.11%, 15.61%, and 31.17%, respectively, from 1987 to 2005 (Figure 4, A–B and D–F). The only exception is that the average patch area increased by 2.71% from 1987 to 1994, and then decreased 1.71% from 1994 to 2005, but the general trend showed a 1% increase from 1987 to 2005 (Figure 4C). Overall, the area of the Wuhan urban wetlands decreased by 8.11% during the 19-year period.

Similarly, the total areas of the river wetlands, lake wetlands, bottomland wetlands, and marsh wetlands also decreased by 13.36%, 18.71%, 6.16%, and 50.33%, respectively. In contrast,

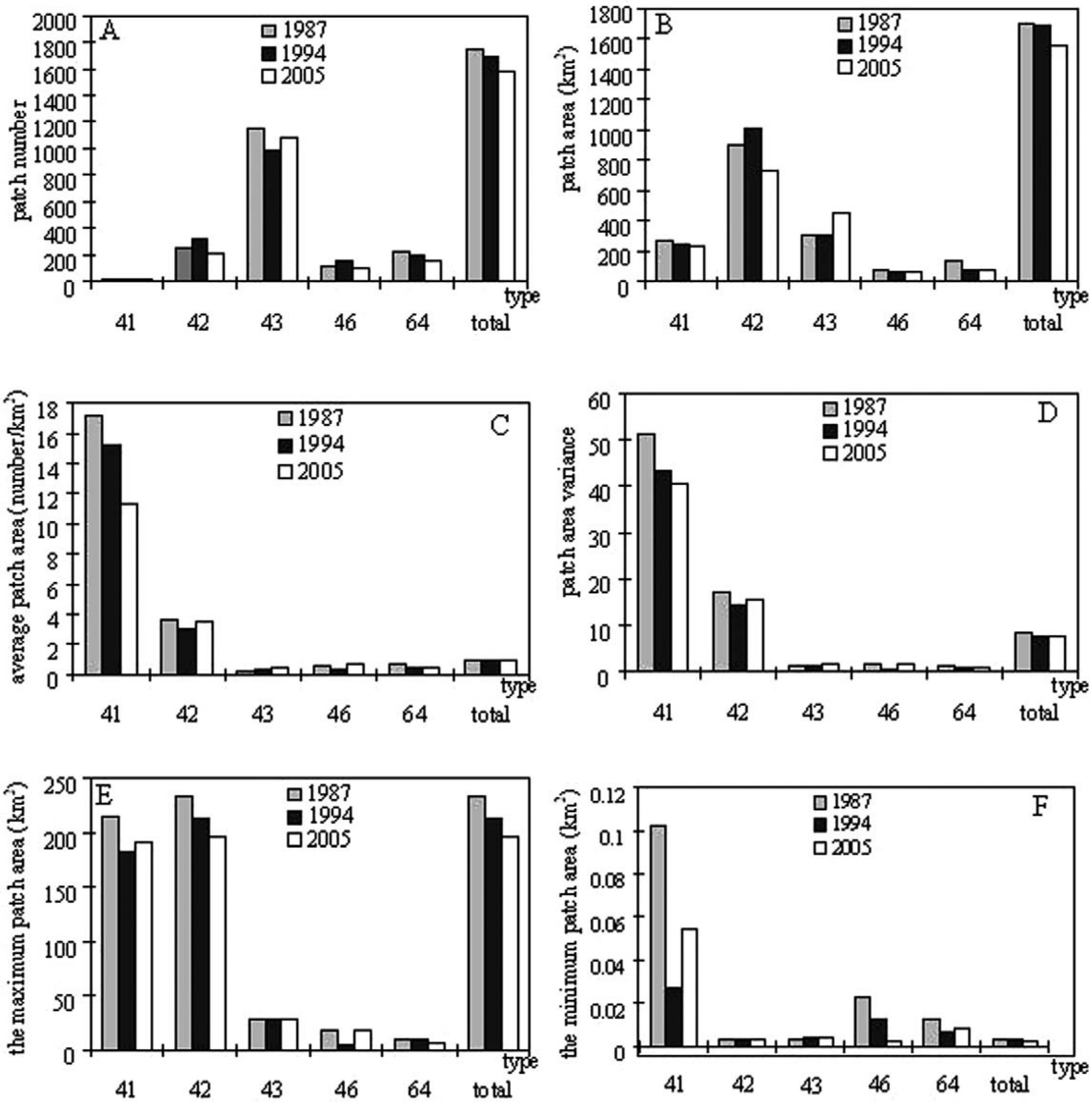

Figure 4. Histograms showing the statistical characteristics of changes in the Wuhan urban wetland landscape from 1987 to 2005: (A) patch number; (B) total area; (C) average patch area; (D) patch area variance; (E) maximum patch area; (F) minimum patch area

the total area of the reservoir and pond wetlands increased by 47.75% from 1987 to 2005 (Figure 4B). Overall, the natural wetland area decreased. In particular, the lake wetlands and marsh wetlands decreased sharply, while the artificial wetland areas increased in Wuhan.

The patch numbers, the total areas, the average patch areas, and the maximum patch of lake wetlands and marsh wetlands decreased by 17.79%, 18.71%, 1.12%, 15.61%, 26.94%, 50.33%, 32.02%, and 45.31% from 1987 to 2005, respectively (Figure 4, A–C and E). These changes are due to the fact that the larger lake wetlands and marsh wetlands were divided into smaller ones. These fragmentations resulted in the decline of the Wuhan lake wetlands and marsh wetlands, since the ecosystem of small lakes and marsh wetlands is fragile and tends to decline either naturally or artificially (Deng, 2005). Our analysis further indicated that the human disturbance in the lake wetlands and marsh wetlands increased due to the increase of population and economic development over the region during the past 19 years in Wuhan.

2 Heterogeneity analysis of Wuhan urban wetland landscape pattern

The analysis of heterogeneity is mainly designed to reveal landscape diversity, dominance, evenness, and fragmentation in size and distribution of patches in the landscape. It is preferable to adopt these indices when speculating on a spatial pattern because landscape patterns possess both homogeneous and heterogeneous attributes. The *H, D, E*, and *F* are calculated based on heterogeneity indices that reflect spatial heterogeneity by quantifying the spatial structures within the landscape.

Using the spatial and attributes databases of 1987, 1994, and 2005 of the Wuhan urban wetland landscape mentioned above, and the formulae in Table 2, the *H, D, E*, and *F* values can be calculated (Figure 5). The *H, E*, and *F* were the largest and *D* was the smallest in 1987 (Figure 5). The results show that the diversity of the Wuhan wetland resource was largest in 1987, comprising lake wetlands, river wetlands, and reservoir and pond wetlands. In addition, the results also showed that the patches in the Wuhan wetland landscape were distributed evenly, and the impact from human activities was the lowest in 1987.

The values of *H, E*, and *F* decreased, while the value of *D* increased from 1987 to 1994. These changes indicate that the later Wuhan wetland landscape tended to be more homogeneous, and the diversity decreased while the impact from human activities increased. The values of *H, E*, and *D* slightly increased while *F* decreased from 1994 to 2005. These changes show that the most recent Wuhan wetland landscape became gradually more diverse, while the impact from human activities increased from 1994 to 2005. Nevertheless, the general trend of *H, E*, and *F* decreased from 1987 to 2005, and the general trend of *D* increased for the same period.

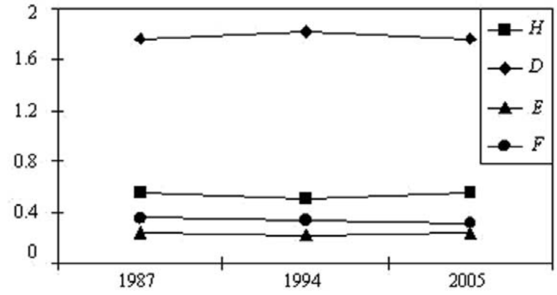

Figure 5. Heterogeneity analysis of Wuhan wetland landscape pattern from 1987 to 2005

3 Complexity analysis of Wuhan urban wetland landscape pattern

The analysis of complexity is designed to reveal the degree of complexity of the spatial patch properties in a wetland landscape and assess the impact of anthropogenic activities. The analysis can suggest the degree of impact of human activities on the pattern change of the wetland landscape. The *LSI* and *FD* values are the most important indices of the analysis. For examples, Rex and Malanson (1990) reported that there was a significant relationship between *FD* and the impact of human activity on the riparian forests in Iowa. Wickham *et al*. (1994) found that the *FD* of the wetlands increased as the number of agricultural and residential land-cover components of the landscape pattern types increased. Liu and Cameron (2001) found that there was a significant difference in the fractal dimension of the wetlands when classified according to land use, vegetation type, size, and level of human disturbance. Zhang *et al*. (2004) found that *FD* can be used to show the relationship between the spatial structure and the pattern of the wetland resources. In contrast, others have demonstrated that the *FD* of the wetlands decreases as the surrounding agricultural and human land use increases (Forman and Godron, 1986).

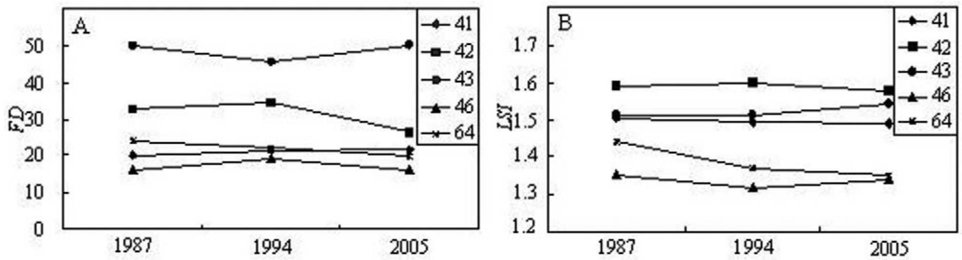

Figure 6. (A) LSI and (B) FD analysis of Wuhan wetland landscape pattern from 1987 to 2005

The present analysis reveals that the *LSI* and *FD* of the bottomland wetlands were the smallest, while the *LSI* and *FD* of the reservoir and pond wetlands were the largest (Figure 6). The results indicated that the shape of the bottomland wetlands was the simplest and the impact of human activities there was the smallest, while the shape of the reservoir and pond wetlands was the most complex and the impact of human activities was the largest over the past 19 years. These analyses suggest that the impact of human activities on the natural landscape was smaller than that on the artificial landscape (eg, reservoirs and ponds).

The *LSI* and *FD* of the river wetlands and marsh wetlands reduced from 1987 to 2005 (Figure 6). For the same period, the *LSI* and *FD* of the lake wetlands and bottomland wetlands increased, and then decreased from 1994 to 2005. However, the overall trend of *LSI* and *FD* decreased from 1987 to 2005 (Figure 6). The results suggest that the shapes of the river wetlands, marsh wetlands, lake wetlands, and bottomland wetlands became simpler and their self-similarity decreased. However, the impact of human activities increased from 1987 to 2005, while the *LSI* and *FD* of the reservoir and pond wetlands increased from 1987 to 1994, and then decreased from 1994 to 2005. The overall trend showed an increase from 1987 to 2005 (Figure 6). These results indicate that the shape of the reservoir and pond wetlands tended to become more complex and that the self-similarity increased over the past 19 years. The dry climate has resulted in a reduced amount of water in the rivers and lakes. Along with a rapidly increasing population, the degree of development and utilization of marsh wetlands and bottomland wetlands were increased. As a result, many marsh wetlands and bottomland wetlands have been replaced by agricultural land, while the reservoir and pond wetlands have been replaced by refined fishponds (Deng, 2005).

IV Discussion

The Wuhan urban wetlands are mainly distributed along the Jianghan Plain (an alluvial plain along the Yangtze River and the Hanjiang River; Figure 2). The formation and evolution process of the Wuhan wetlands have a close relationship with the Yangtze River since they were originally and directly connected. Before the 1980s, all the lakes and reservoirs overflowed in the flood season and separated from each other in the dry season. However, the natural connections among the Yangtze River, river wetlands, lake wetlands, and reservoir wetlands have reduced since the 1980s due to economic development, population growth, and accelerated urbanization (eg, the construction of a flood-control dykes, sluice gates, and pumping stations). These changes have affected the flood course of the Yangtze River and the storage function of the lake wetlands and reservoir wetlands, and have also cut off the biological connections and reduced the biodiversity and biomes.

Table 3. Canonical loading of landscape indices by canonical correlation analysis

		Canonical loading			
Variable	Meaning	Canonical variable 1	Canonical variable 2	Canonical variable 3	Canonical variable 4
variable Y	Landscape ecological indices				
Y_1	*D*	–.489	.418	.765	.630
Y_2	*E*	.734	–.240	–.623	–.125
Y_3	*F*	–.436	.296	.850	.016
Y_4	*H*	.265	.865	–.310	.294
variable X	Social factors				
X_1	GDP	–.131	–.779	–.612	–.031
X_2	Cultivated land area	.059	.915	–.380	.118
X_3	Total population	–.103	–.921	.376	.013
X_4	Gross output value of agriculture, forestry, animal husbandry and fishery	–.421	.477	.016	.771
X_5	Area of aquatic farming	.055	–.957	.186	–.215

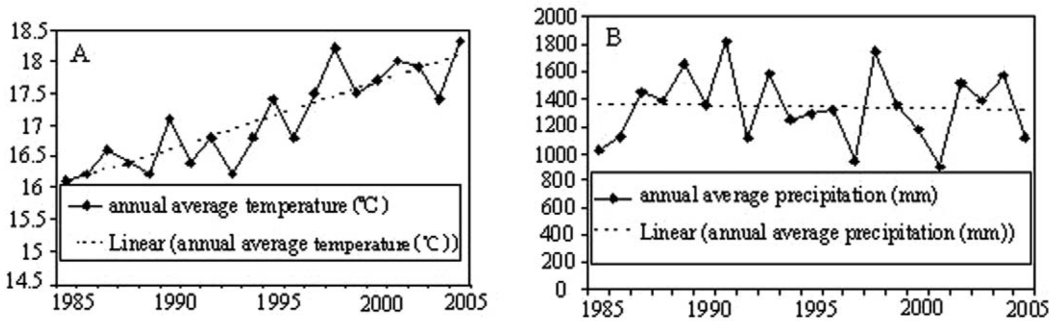

Figure 7. The annual average (A) temperature and (B) precipitation at Wuhan from 1985 to 2005 from the China Statistical Yearbook of 1985 to 2005

Using canonical correlation analysis methods (see discussion below and Table 3), we found a significant relationship between urban wetland landscape ecological indices and socio-economic factors. In addition, the large-scale reclamation of the lakes and rivers has caused the wetland ecosystem to deteriorate; as a result, the wetland biodiversity has decreased, but flood disasters continue to increase. The natural, social, and human activities thus combine to cause these changes.

1 Role of regional temperature and precipitation

There is a close relationship between the region's temperature and the precipitation and the wetland area. The annual average temperature of Wuhan increased each year, but the annual precipitation remained unchanged from 1985 to 2005 (Figure 7). Evaporation also gradually increased during the past 21 years, and the climate of Wuhan became warmer and dryer. This was key to changing the shape and

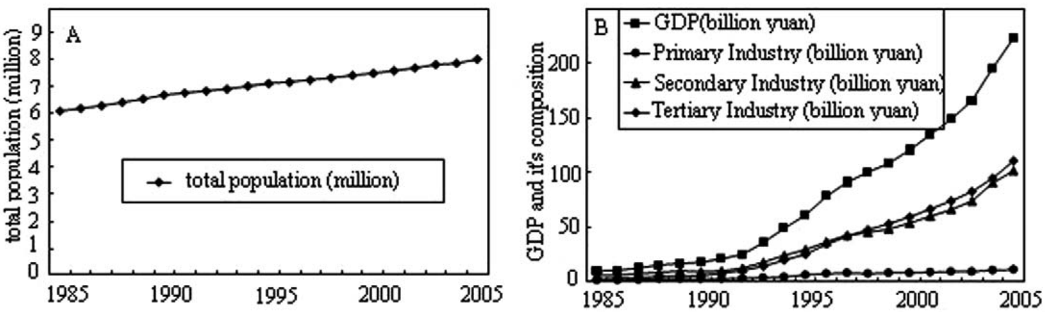

Figure 8. Change chart of (A) total population and (B) GDP and its composition of Wuhan from 1985 to 2005 from the China Statistical Yearbook of 1985 to 2005

structure of the Wuhan wetland landscape pattern, especially the transformation from marsh wetlands to grassland and farmland.

2 Role of population increase and economic development

The Wuhan population increased and the economy was developed rapidly between 1987 and 2005. These were the major factors causing the changes in the Wuhan wetland landscape pattern (Figure 8). Particularly, the country's grain production in Jianghan Plain increased dramatically, while the population increased and the economy developed rapidly. The population of Wuhan increased from 6.084 million people by the end of 1985 to 8.014 million people by the end of 2005 (Figure 8A). The Gross Domestic Product (GDP) of Wuhan also increased from 9.732 billion yuan in 1985 to 223.8 billion yuan in 2005 (Figure 8B). At the same time, primary, secondary, and tertiary industry showed a strong growth trend (Figure 8B). Such rapid population growth and economic development certainly have had a profound effect on the scale, structure, distribution, and intensity of land use in Wuhan. This will inevitably affect the structure, scale, and distribution of the Wuhan urban wetland landscape.

Table 3 provides the results of a quantitative analysis of the relationship between urban wetland landscape ecological indices and socio-economic factors, using canonical correlation analysis methods. *X* is the independent variables related to socio-economic factors from the Hubei Statistical Yearbook of 1985 to 2005, and *Y* is the standard variables related to urban wetland ecological indices. We identified five independent variables as common factors using factor analysis before the correlation analysis, in order to reduce mutual interference between the independent variables.

The first variable is *E* and its typical load is 0.734, with negative correlation to gross output values of agriculture, forestry, animal husbandry, and fishery, and GDP (canonical loading is –0.421 and –0.131, respectively). This indicates that *E* decreased with the growth of GDP and gross output value of agriculture, forestry, animal husbandry, and fishery. Correspondingly, marsh near urban areas was turned into arable land or building sites, or converted into ponds for fishery, and *E* declined with the decrease of area of marsh wetlands from 1987 to 2005 in Wuhan.

The second variable is *H* and its typical load is 0.865, with negative correlation to the area of aquatic farming and total population (canonical loading is –0.957 and –0.921, respectively), indicating that *H* decreased with the growth of the area of aquatic farming and total population. Artificial enclosure to support aquatic culture in the lakes was the factor that determined the reduction in area of the lake wetlands, which led to *H* decreasing with the simplification of wetland types from 1987 to 2005 in Wuhan.

The third variable is *F* and its typical load is 0.85, again with negative correlation to GDP and cultivated land area (canonical loading is –0.612 and –0.38, respectively), indicating that *F* decreased with the growth of GDP and cultivated land area. With population increase and the development of the economy, more wetland area is required for housing, transportation, public facilities, and recreational facilities, and *F* decreased, also reflecting the division of larger wetlands into smaller ones from 1987 to 2005 in Wuhan.

The fourth variable, *D*, is distinct in behaviour from the other variables. Its typical load is –0.30, with a positive correlation to gross output value of agriculture, forestry, animal husbandry, and fishery (canonical loading is 0.771), indicating that *D* increased with growth in these. This is explained by the fact that, with the decrease in area of lake wetlands and marsh wetlands, there was a simplification in wetland types, between 1987 and 2005 in Wuhan.

3 Role of artificial enclosure

Artificial enclosure for aquatic culture in the lakes was the factor that determined the rapid reduction in the area of natural wetlands and rise in the artificial wetlands in the middle of the 1980s. The areas of the Wuhan reservoir and pond wetlands increased rapidly from 302.34 km^2 in 1987 to 446.71 km^2 in 2005. The artificial enclosure for aquatic culture in the lakes resulted in overharvesting of water grass, accelerating the loss of biodiversity of the aquatic plants and weakening the self-purification ability of the lake wetlands. The results made the *LSI* and *FD* of the reservoir and pond wetlands increase from 1987 to 2005 (Figure 6). The shape of the reservoir and pond wetlands tended to become more complex and the self-similarity increased over the period. In addition, excessive breeding and massive mixed feed pouring accelerated the pollution of the urban lake wetlands, reduced the lakewater transparency, lowered the biodiversity of the whole lake region, and degraded the ecosystem of the urban lake wetlands. Simultaneously, the areas of lake wetlands sharply decreased from 904.99 km^2 in 1987 to 735.67 km^2 in 2005, and affected the lake storage function, which led to the frequent occurrence of flood disasters.

4 Role of accelerated urbanization and the rapid expansion in Wuhan

The accelerated urbanization and the rapid expansion of urban and real estate development resulted in lake and pond wetlands of Wuhan urban and peri-urban being filled and occupied with residential housing or industrial land. Statistical analyses show that the Wuhan urban lake surface, especially in the Hankou region, reduced by 154.6 km^2 and then decreased by nearly 60% due to subsequent reclamation and occupation. As a result, Neisha Lake reduced in area from 0.39 km^2 to 0.03 km^2; Waisha Lake from 4.73 km^2 to 4.23 km^2; and Houxian Lake from 0.17 km^2 to 0.04 km^2. Eight lake wetlands no longer exist. In addition, the building of Hankou Zhongshan Road, Jiefang Road, and Hankou Railway Station took away a large number of lake wetlands. Furthermore, Nan Lake, Shai Lake, Simeitang Lake, and Tangxun Lake inundated residential property from time to time (Zhang and Deng, 2005). *LSI* and *FD* of the river wetlands, marsh wetlands, lake wetlands, and bottomland wetlands decreased, while the *LSI* and *FD* of the reservoir and pond wetlands increased from 1987 to 2005. The results indicate that the shape of the river wetlands, marsh wetlands, lake wetlands, and bottomland wetlands become simpler and their self-similarities decreased. However, the shape of the reservoir and pond wetlands tended to become more complex and the self-similarity increased over the past 19 years.

V Conclusions

Using landscape ecological indices, we examined spatiotemporal evolution characteristics and dynamic changes in the pattern of urban wetland landscape in Wuhan from 1987 to 2005. TM images, land-use maps, surveyed field data, and statistical data on Wuhan wetlands were used to support the analysis. We found that:

(1) Urban wetland area decreased by 137.5 km^2; natural wetland area decreased by 281.87 km^2; and artificial wetland area increased by 144.37 km^2.
(2) The types of urban wetlands became less homogeneous, because the value of *H, E*, and *F* decreased, while the value of *D* increased from 1987 to 2005. In addition, we also found that *LSI* and *FD* of the river wetlands, lake wetlands, bottomland wetlands, and marsh wetlands decreased, while the *LSI* and *FD* of the reservoir and pond wetlands increased.
(3) There is a close interaction between the landscape ecological indices and socioeconomic factors (GDP, cultivated land area, total population, gross output value of agriculture, forestry, animal husbandry, fishery, and area of aquatic farming), as revealed by canonical correlation analysis, indicating that the changes of types, numbers and total areas of urban wetlands in Wuhan were at least partly caused by urbanization and development of the economy from 1987 to 2005.

Our research also suggests that ecological landscape methodologies can be used as a basis for decision-making in the appraisal of wetland environments and for utilizing wetland resources in a sustainable way. In order to maximize the services of the Wuhan urban wetlands, we suggest that appropriate adjustment of the adjacent land use is a critical component in Wuhan urban wetland conservation. At the same time, biological and engineering technology and comprehensive measures can be utilized to save and restore the positive services and functioning of Wuhan urban wetland ecosystems, such as returning farmland to lakes, opening the flood storage to the lakes, dredging the expansion lakes, and controlling pollution. Moreover, slowing down wetland degradation caused by human activities is important to recovering and rebuilding the damaged wetland ecosystem and to maintaining the balance between the supply of the renewable natural resources and the needs of humans. To have sustainable urban development, the services and advantages of wetland ecosystems should be preserved wherever possible in Wuhan.

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References

Berger, J. 1987: Guidelines for landscape synthesis: some directions-old and new. *Landscape and Urban Planning* 14, 295–311.

Chuvieco, E. 1999: Measuring changes in landscape pattern from satellite imageries: short-term effects of fire on spatial diversity. *International Journal of Remote Sensing* 20, 2331–46.

Corry, R.C. and Nassauer, J.I. 2005: Limitations of using landscape pattern indices to evaluate the ecological consequences of alternative plans and designs. *Landscape and Urban Planning* 72, 265–80.

Deng, H.B. 2005: *Research on Jianghan lake groups and evolution and lake area regional sustainable development*. Beijing: Economic Science Press (in Chinese).

Forman, R.T.T. and Godron, M. 1986: *Landscape ecology*. New York: Wiley.

Frohn, R.C. 1998: *Remote sensing for landscape ecology: new metric indicators for monitoring, modeling, and assessment of ecosystems*. Boca Raton, Florida: Lewis Publishers.

Fuller, D.O. 2001: Forest fragmentation in Loudoun County, Virginia, USA evaluated with multi-temporal Landsat imagery. *Landscape Ecology* 16, 627–42.

Giles, R.H. and Trani, M.K. 1999: Key elements of landscape pattern measures. *Environmental Management* 23, 477–81.

Guo, Y.D., He, Y., Zhang, M.X. and Yan, D.H. 2004: Characteristics and driving forces of wetlands changes in middle-low reaches of Taoer River. *Journal of Soil and Water Conservation* 18(22), 118–21.

Imbernon, J. and Branthomme, A. 2001: Characterization of landscape patterns of deforestation in tropical rain forest. *International Journal of Remote Sensing* 22, 1753–65.

Jim, C.Y. and Chen, S.S. 2003: Comprehensive green space planning based on landscape ecology principles in compact Nanjing city, China. *Landscape and Urban Planning* 65, 95–116.

Joyal, L.A., McCollough, M. and Hunter, M.L. 2001: Landscape ecology approaches to wetlands species conservation: a case study of two turtle species in southern Maine. *Conservation Biology* 15, 1755–62.

Liu, A.J. and Cameron, G.N. 2001: Analysis of landscape patterns in coastal wetlands of Galveston Bay, Texas (USA). *Landscape Ecology* 16, 581–95.

O'Neill, R.V., Krummel, J.R., Gardner, R.H., Sugihara, G., Jackson, B., Deangelis, D.L., Milne, B.T., Turner, M.G., Zygmunt, B., Christensen, S.W., Dale, V.H. and Graham, R.L. 1988: Indices of landscape pattern. *Landscape Ecology* 1, 153–62.

Pauleit, S. and Duhme, F. 2000: Assessing the environmental performance of land cover types for urban planning. *Landscape and Urban Planning* 52, 1–20.

Reed, R.A., Johnson, J. and Baker, W.L. 1996: Fragmentation of a forested Rocky Mountain landscape 1950–1993. *Conservation Biology* 75, 267–77.

Rex, K.D. and Malanson, G.P. 1990: The fractal shape of riparian forests. *Landscape Ecology* 4, 249–58.

Schumaker, N.H. 1996: Using landscape indices to predict habitat connectivity. *Ecology* 17, 1210–25.

Tang, J., Wang, L. and Yao, Z. 2007: Spatial-temporal urban landscape change analysis using the Markov chain model and a modified genetic algorithm, *International Journal of Remote Sensing* 28, 3255–71.

Tischendorf, L. 2001: Can landscape indices predict ecological processes consistently? *Landscape Ecology* 16, 235–54.

Turner, M.G., Gardner, R.H. and O'Neill, R.V. 2001: *Landscape ecology in theory and practice: pattern and process*. New York: Springer.

Viedma, O. and Meliâ, J. 1999: Monitoring temporal changes in the spatial patterns of a Mediterranean shrubland using Landsat-TM images. *Diversity and Distributions* 5, 275–93.

Wang, A., Zhang, S. and Zhang, B. 2003: A study on the change of spatial pattern of wetlands in the Sanjiang Plain. *Acta Ecological Sinica* 23, 237–43 (in Chinese with English abstract).

Wang, X.L., Ning, L.M., Yu, J., Xiao, R. and Li, T. 2008: Changes of urban wetland landscape pattern and impacts of urbanization on wetland in Wuhan city. *Chinese Geographical Science* 18, 47–53.

Weber, C. and Puissant, A. 2003: Urbanization pressure and modeling of urban growth: example of the Tunis metropolitan area. *Remote Sensing of Environment* 86, 341–52.

White, D., Minotti, P.G., Barczak, M.J., Sifneos, J.C., Freemark, K.E., Santelmann, M.V., Steinitz, C.F., Kester, A.R. and Preston, E.M. 1997: Assessing risks to biodiversity from future landscape change. *Conservation Biology* 11, 349–60.

Wickham, T.J., Filardo, E.J., Cheresh, D.A. and Nemerow, G.R. 1994: Integrin $\alpha_V\beta_5$ selectively promotes adenovirus mediated cell membrane permeabilization. *Journal of Cell Biology* 127, 257–64.

Xu, K., Kong, C.F., Wu, C.L., Liu, G., Deng, H.B. and Zhang, Y. 2009: Dynamic changes in Tangxunhu wetland over a period of rapid development (1953–2005) in Wuhan, China. *Wetlands* 29, 1255–61.

Zhang, Y. and Deng, H.B. 2005: Discussion of the evolution and use of the lakes in Wuhan. *Journal of Central China Normal University (Natural Sciences)* 39, 559–63.

Zhang, Z.F., Gong, H.L., Zhao, W.J. and Fu, R.H. 2004: Fractal research on dynamic change of the Beijing Wild Duck Lake wetland resources based on GIS and RS. *Remote Sensing for Land and Resources* 3, 42–45 (in Chinese with English abstract).

Zhao, S., Fang, J., Chen, A. and Cui, H. 2002: Land use/cover changes in Dongting Lake area between 1955–1998. *Resources and Environment in the Yangtze Basin* 11, 536–42 (in Chinese with English abstract).