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LAND-COVER CHANGES IN AN URBAN LAKE WATERSHED IN A MEGA-CITY, CENTRAL CHINA

YAN LI[1], SHUQING ZHAO[1], KUN ZHAO[1], PING XIE[2] and JINGYUN FANG[1,*]
[1]*Department of Ecology, College of Environmental Sciences, and Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing, China;*
[2]*Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan, China*
*(*author for correspondence, e-mail: jyfang@urban.pku.edu.cn)*

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Abstract. Urbanization can exert a profound influence on land covers and landscape characteristics. In this study, we characterize the impact of urbanization on land cover and lacustrine landscape and their consequences in a large urban lake watershed, Donghu Lake watershed (the largest urban lake in China), Central China, by using Landsat TM satellite images of three periods of 1987, 1993 and 1999 and ground-based information. We grouped the land covers into six categories: water body, vegetable land, forested land, shrub-grass land, open area and urban land, and calculated patch-related landscape indices to analyze the effects of urbanization on landscape features. We overlaid the land cover maps of the three periods to track the land cover change processes. The results indicated that urban land continuously expanded from 9.1% of the total watershed area in 1987, to 19.4% in 1993, and to 29.6% in 1999. The vegetable land increased from 7.0% in 1987, 11.9% in 1993, to 13.9% in 1999 to sustain the demands of vegetable for increased urban population. Concurrently, continuous reduction of other land cover types occurred between 1987 and 1999: water body decreased from 30.4% to 23.8%, and forested land from 33.6% to 24.3%. We found that the expansion of urban land has at least in part caused a decrease in relatively wild habitats, such as urban forest and lake water area. These alterations had resulted in significant negative environmental consequences, including decline of lakes, deterioration of water and air quality, and loss of biodiversity.

Keywords: Central China, Donghu Lake, land cover change, landscape characteristics, remote sensing, urbanization, urban lake watershed

1. Introduction

Human activities have greatly altered the earth's land surface (Turner *et al*., 1990; Vitousek *et al*., 1997). Urbanization is one of the most pervasive anthropogenic land conversions, which can significantly affect the land cover and landscape characteristics in considerably short period of time. Urban expansion generally occupies arable land (Lopez *et al*., 2001; Chen *et al*., 2003). However, with the accelerating of urban growth, relatively wild habitats, such as urban forest and lake area, also became the target of urban expansion. Despite limited size of forest and water body in urban ecosystems, they provide important services, such as habitats for wildlife, water supply, and air filtering (Bolund and Hunhammar, 1999). How urban expansion influences relatively wild components of urban ecosystems and what consequences these impacts will bring to urban ecosystems are becoming interesting topics (Pickett *et al.*, 1997).

Since the economic reform in the late 1970s, especially after the land reform launched in 1987, rapid urbanization has taken place across China (Cheng and Masser, 2003). As the largest mega-city in Central China, Wuhan City along Central Yangtze River has experienced an extensive urban growth. Donghu Lake, located in Wuhan City, is the largest urban lake in China. In the Donghu Lake watershed, lake water, urban forests, city, arable land, and other land cover types co-exist, and therefore the watershed has provided an ideal area to explore the effects of urbanization on relatively wild habitats (lake and urban forest) and their consequences.

In this study, we integrate satellite remote sensing data and geographic information system (GIS) to define the boundary of Donghu Lake watershed and then to quantify land cover changes for 1987, 1993 and 1999 in the watershed. Our objectives are to (1) estimate the changes in land cover and lacustrine landscape under the impacts of the urbanization, and (2) assess impacts of these changes on urban forest and lake water dynamics and their environmental consequences.

2. Data and Methods

2.1. Study area

Donghu Lake (114°21′–114°28′E, 30°31′–30°36′N) is situated at the eastern part of Wuhan City, the capital of Hubei Province, Central China, with a surface area of 33 km^2 at the maximum water level of 21 m. The lake area has a subtropical climate, with an annual precipitation of 1160.3 mm, and annual mean temperature 16.7 °C (Liu, 1995). The lake and its watershed provide habitats for a wide variety of wildlife, such as hydroplants and fishes. As a typical urban lake, Donghu Lake also provides other important ecological services, including urban water supply, aquaculture, and aesthetic value.

2.2. Boundary of lake watershed

Donghu Lake watershed was estimated as an area of ~190 km^2 (e.g. Gong *et al.*, 1965), but its boundary has never been explicitly examined. In order to define the explicit boundary, we digitalized topographical maps covering this area with a scale of 1:10,000 by using a GIS software (Founder drawing 5.5), and then obtained the digital elevation model (DEM) for the watershed. The DEM and existed boundary of water body were used to examine the boundary of the watershed using ArcInfo GIS software. As a result, we defined the watershed between 114°20′ and 114°30′ E in longitude and 30°29′ and 30°37′N in latitude with an area of 177.3 km^2. Its western part includes Shahu Lake, another main water body linked to Donghu Lake (Figure 1). As part of Jianghan plain in Central Yangtze, the watershed is fairly flat, with an altitudinal range of 20–157 m, and 85% of total area is below 35 m.

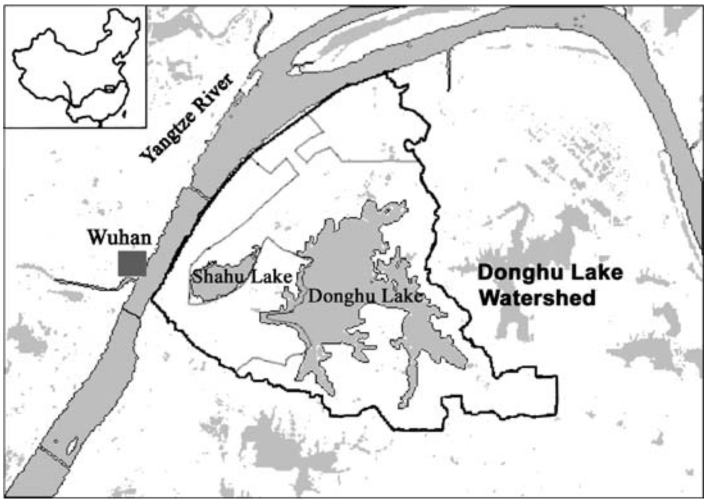

Figure 1. Sketch map of Donghu Lake watershed.

2.3. Land cover information

We used the image processing software IDRISI (Clark University, USA) to classify the land cover types for the three periods of 1987, 1993, and 1999, using a data set of a 3-band RGB combination (Bands 4, 5, and 3) of Landsat Thematic Mapper (TM) imagery. In order to minimize the impact of possible interpretation errors due to survey date of images, we acquired the images of the three periods with similar survey dates (September 26 for 1987, October 12 for 1993, and September 27 for 1999). We geo-referenced all these images according to 1:50,000 topographical maps and then, using the maximum likelihood method, classified the land covers into six categories: water body, vegetable land, forested land, shrub-grass land, open land, and urban land (Table I and Figure 2a–c). In order to determine the accuracy of the image classification, we used the stratified random sampling method (Jensen, 1996) to generate reference points, and obtained a total of 230 reference points for

TABLE I
Descriptions for land cover types in the study area

Land cover category	General description
Water body	Areas that lake and ponds used to aquaculture.
Vegetable land	Mainly vegetable land, plus some farmland.
Forest	Area covered conifers, broadleaved trees in hilly land and orchard in the plain.
Shrub-grass land	Areas with shrub or grass vegetation, including urban lawn.
Open land	Open lands in urban fringe with little vegetation cover.
Urban land	Built-up land.

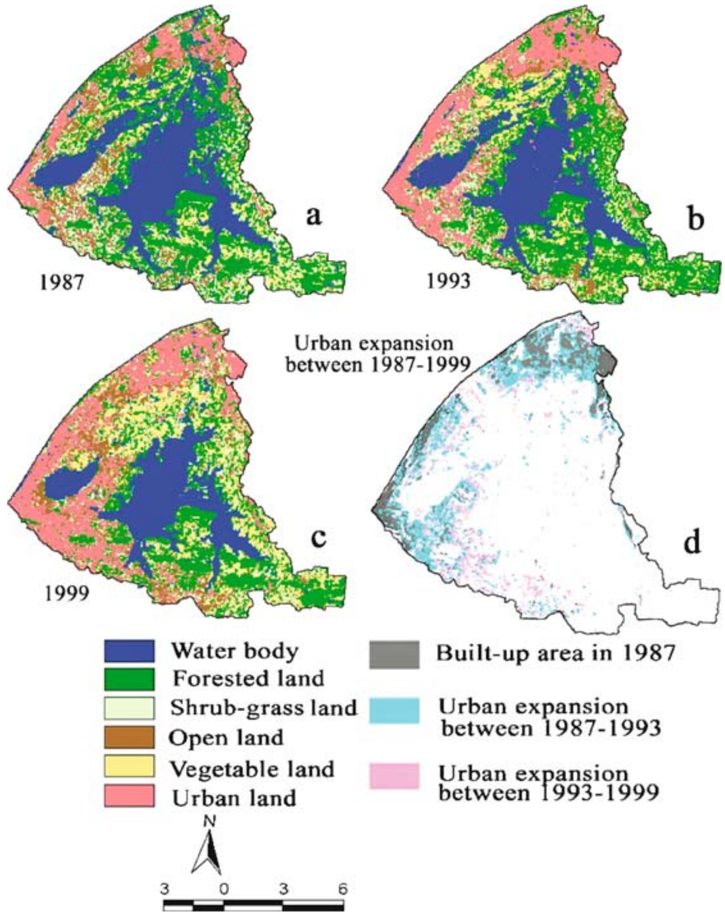

Figure 2. Land cover types of Donghu Lake watershed in 1987 (a), 1993 (b), 1999 (c), and spatial distribution of urban expansion between 1987–1999 (d).

each of classified images. The accuracy of three classified products was assessed by verifying general land cover delineations on topography maps, municipal maps and field survey. The resulting overall classification accuracy was 89, 85, and 89% for the three images, respectively. Through overlaying the classified land cover maps for 1987, 1993 and 1999, we achieved transition matrix and spatial pattern of urban expansion to understand the land cover change processes between 1987–1993 and 1993–1999.

2.4. Parameters of patches

Patch characteristics can be used to describe landscape features (Forman, 1995). We exported the classification maps for 1987, 1993 and 1999 to the PatchGrid Module of ArcView GIS software to obtain each patch area and its perimeter for all the land cover category of the three periods. We used the area and number of patches and mean patch size of all the land covers for all three periods to characterize the changes of landscape characteristics. Mean patch size (MPS) can serve as a fragmentation index of habitat at the landscape level, because a patch type with a smaller MPS might be considered more fragmented.

$$\mathrm{MPS} = \sum_{j=1}^{n} a_{ij}/n_i$$

where i is the ith land cover type, j is the jth patch of the ith land cover type, a_{ij} is the jth patch area (ha) of the ith land cover type, and n_i is the patch numbers of the ith land cover type.

3. Results and Discussion

3.1. Land cover changes

The results indicated that urbanization since 1987 in the Donghu Lake watershed has led to a significant increase in coverage of urban land and vegetable land while to a decrease in that of other land cover types. The area of urban land rapidly increased by 223% from 16.2 km^2 in 1987 to 52.4 km^2 in 1999 (Figure 3a). Concurrently, vegetable land increased from 12.5 km^2 in 1987 to 24.7 km^2 in 1999.

Since the economic reformation of China in 1978, especially after the land reform in 1987, rapid urban growth has taken place in China and urban population has remarkably expanded. As one of the most developed cities in China, Wuhan has experienced rapid urban expansion and its population increased from 6.29 million in 1987, to 6.92 million in 1993, and 7.40 million in 1999 (Wuhan Statistical Year Book, 1990, 1994, 2000), which led to the rapid increase of urban land in the Donghu Lake watershed. Meanwhile, suburban vegetable land was expanded to meet the demands of vegetables for enhanced urban population. The area of vegetable land in Wuhan City increased from 556.7 km^2 in 1987 to 1191.7 km^2 to 1999 (Figure 4), which evidenced our findings. On the other land, forest cover decreased from 59.5 km^2 in 1987 to 43.1 km^2 in 1999, and water body from 53.8 km^2 to 42.2 km^2 in 1999. Shrub-grass land and open land changes also tended to a decline.

A transition matrix (Table II) can help understand the land cover change processes and the change rate among land cover categories between two neighboring periods under the impacts of urbanization. The increase of urban land between 1987–1993 was primarily contributed by conversion from open land, shrub-grass land, and forest to urban land, and the contribution rate of these three land conversions to the coverage of urban land in 1993 were 25.3, 14.0 and 13.7%, respectively. The land conversion from water body to urban land also contributed to the increase

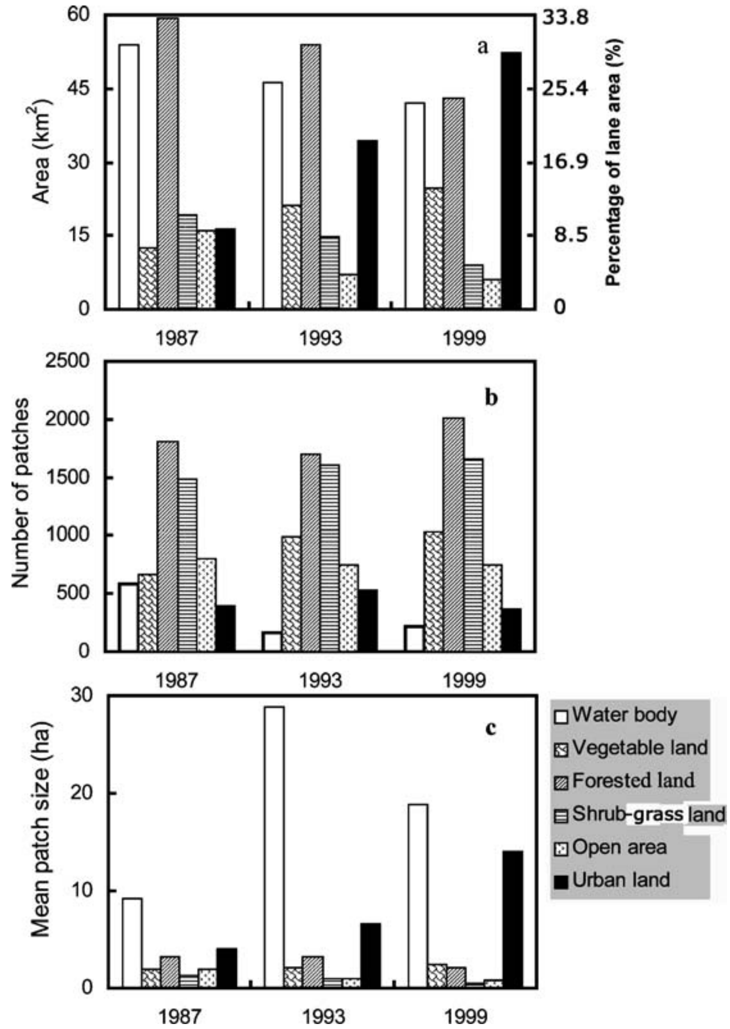

Figure 3. Area and percentage of (a) land area, (b) number of patches, and (c) mean patch size for the land cover types during the period of 1987–1999.

of urban land in 1993 (5.3%). Urban land area further increased between 1993 and 1999 primarily by land transformations from forest, shrub-grass land and open area to urban land at respective rate of 15.1%, 11.3% and 8.3%. These suggest that forested land, shrub-grass land, and open land are the major sources of newly increased urban land during 1987–1999. In the period of 1987–1993, urban sprawl occupied mainly remaining suburban bare areas, while in the latter period of 1993–1999, urban forest became the target for further urban expansion due to no more open area available. As indicated by the classified satellite images and spatial distribution maps of urban expansion (Figure 2a–d), between 1987 and 1993, urban land

TABLE II
Land cover transition and contribution rate (%) between 1987–1993 and 1993–1999

Land cover	Water body a	(b) %	Vegetable land a	(b) %	Forest a	(b) %	Shrub-grass land a	(b) %	Open area a	(b) %	Urban land a	(b) %
1987–1993												
Water body	79.4	(92.6)	2.1	(5.5)	12.8	(12.8)	1.3	(4.8)	1.0	(7.8)	3.4	(5.3)
Vegetable land	2.5	(0.7)	49.4	(29.4)	31.6	(7.3)	8.0	(6.8)	5.3	(9.3)	3.1	(1.1)
Forested land	4.4	(5.6)	17.5	(49.4)	58.1	(64.0)	8.4	(33.9)	3.8	(31.2)	7.9	(13.7)
Shrub-grass land	1.1	(0.4)	12.1	(11.1)	29.6	(10.5)	24.6	(32.3)	7.6	(20.3)	25.1	(14.0)
Open area	0.6	(0.2)	4.8	(3.6)	11.9	(3.5)	16.1	(17.6)	12.3	(27.3)	54.4	(25.3)
Urban land	1.3	(0.4)	1.1	(0.9)	6.0	(1.8)	3.9	(4.3)	1.8	(4.0)	85.9	(40.5)
1993–1999												
Water body	84.2	(92.1)	3.9	(7.2)	6.1	(6.5)	0.5	(2.6)	2.3	(18.0)	3.1	(2.7)
Vegetable land	1.0	(0.5)	47.7	(40.5)	25.6	(12.4)	7.8	(18.0)	5.3	(18.8)	12.7	(5.1)
Forest	4.1	(5.2)	16.2	(35.3)	55.8	(69.8)	6.5	(38.5)	2.8	(25.6)	14.7	(15.1)
Shrub-grass land	1.2	(0.4)	15.1	(9.0)	20.4	(6.9)	16.6	(26.9)	6.2	(15.2)	40.4	(11.3)
Open area	0.5	(0.1)	12.2	(3.5)	5.6	(0.9)	7.7	(6.1)	13.4	(16.2)	60.5	(8.3)
Urban land	2.0	(1.6)	3.1	(4.3)	4.2	(3.3)	2.0	(7.7)	1.0	(5.9)	87.7	(57.4)

a: Transition rate is the percentage of the area of transition type from one land cover to another to the area of certain land cover in the beginning period
b: Contribution rate is the percentage of the area of transition type from one land cover to another to the area of different another land cover in the end period.

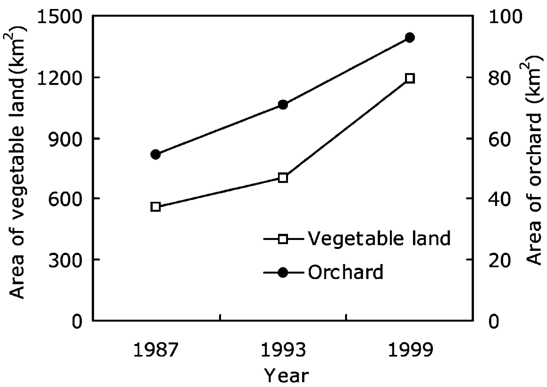

Figure 4. Changes in the size of orchard and area of vegetable land in Wuhan City between 1987 and 1999 (based on Wuhan Statistical Year Book, 1990, 1994, 2000).

growth mainly occurred in open land along the western boundary of the watershed (the bank of the Yangtze River) and around Shahu Lake. In the period of 1993–1999, urban land further expanded resulted mainly from a connection of scattered urban lands. Additionally, during the latter period the spread of urbanization encroached into southern hilly part of the watershed around the Donghu Lake scenic area, where forested land mainly distributed.

The increased vegetable land in 1993 was primarily caused by land transformation from forested land to vegetable land between 1987–1993, at a contribution rate of 49.4%. Simultaneously, the land transformations of shrub-grass land and water body to vegetable land between 1987–1993 contributed to 11.1% and 5.5% to the coverage of vegetable land in 1993. The same land conversions between 1993–1999 as in the period of 1987–1993 have resulted in a continuous increase of vegetable land in 1999, with a contribution rate of 35.3, 9.0 and 7.2%, respectively.

The continuous decrease of water body between 1987–1993 and 1993–1999 was mainly resulted from the land transformation from water body to forested land, at the transition rate of 12.8% in the former period and 6.1% in the latter period, which probably resulted from the reclamation of small water body to orchard (a component of forested land) to provide more fruits for enhanced urban population. This was mirrored by a census of Wuhan socioeconomic development (Wuhan Statistical Yearbooks, 1990, 1994, 2000), which indicated that the area of orchard in Wuhan City increased from 54.3 km^2 in 1987 to 92.8 km^2 to 1999 (Figure 4).

The retention rate (the percentage of the area that keep the same land cover types between two periods) of forested land between 1987 and 1993 was 64% (Table II). The reduction of forested land in this period was mainly caused by the land conversions of the forest to vegetable land, shrub-grass land and urban land, and the transition rate was 17.5, 8.4 and 7.9% respectively. During the period of 1993–1999, the retention rate of forested land amounted to 69.8%, but land conversions of forested land to vegetable land and urban land led to the continuous reduction of forest cover. These results implied that the drop of forest cover in the Donghu Lake watershed was principally resulted from the urban growth and vegetable land expansion in this area.

3.2. Landscape feature alterations

As indicated in Figure 3, urban expansion had significantly altered landscape characteristics in Donghu Lake watershed, but its impacts varied with land cover categories.

Urban land continuously expanded from 9.1% of total watershed area in 1987, to 19.4% in 1993, and to 29.6% in 1999, and became the most dominant land cover type in the watershed area by 1999. Compared to this change, forest and water body were the most dominant land cover types in 1987, which occupied 33.6% and 30.4% of total watershed area, but reduced to 24.3 and 23.8% by 1999, respectively (Figure 3a).

As showed in Figure 3b and c, the patch numbers of urban land increased from 398 in 1987 to 525 in 1993, then decreased to 373 by 1999. The mean patch size of urban land continuously increased from 4.1 ha in 1987 to 14.1 ha in 1999, indicating urban land became more congregated. The results also suggested that urban sprawl between 1987–1993 was accomplish by building up more newly urban land, while redeveloping and connecting built-up scattered urban lands was the way of urban growth in 1993–1999. This was coincided with the planning policy of Chinese Cities. The early policy of city planning was to build more newly urban land before the 1990s; while after the 1990s, urban growth was the mixture of urban expansion and redevelopment (Cheng and Masser, 2003). Although more vegetable land patches developed between 1987 and 1999, the vegetable land became less fragmented following the urbanization process for the increase of total vegetable land. The patch numbers of water body rapidly decreased between 1987 and 1993 then slightly increased from 1993 to 1999. The mean patch size of water body increased from 9.2 ha in 1987 to 28.8 ha in 1993, then dropped to 18.9 ha in 1999. As illustrated by classified satellite images (Figure 2a–c), many small water bodies near the city center disappeared between 1987 and 1993, which led to the increase of the mean patch size of water body despite the decrease of water body coverage in this period. On the other hand, the patch numbers of forested land decreased from 1808 in 1987 to 1705 in 1993, then increased to 2016 in 1999. Forested land became more fragmented, as indicated by the decline of mean patch size, especially between 1993–1999. Shrub-grass land also became more fragmented; the mean patch size declined from 1.3 ha in 1987 to 0.6 ha in 1999.

3.3. Consequences of urban spreading into relatively wild habitats

Rapid urban growth and concurrent expansion of vegetable land were accomplished at the cost of reduction and fragmentation of forested and shrub-grass land and the loss of small water patch and decrease of large water patch. These alterations appear to significantly restrict the functions of relatively wild components in the lake watershed, such as preserving water quality, providing wildlife habitats, and air filtering.

The number of lakes in Wuhan City in 1988 was 35, and declined to 27 in 1998 due to the draining and reclaiming the lakes to urban and vegetable land (Liu *et al.*, 2004). Chemical oxygen demand (COD), an index of water quality in Donghu Lake, was 4.5 mg/L in 1987 (Jin, 1995), and increased to 5.4 mg/L in 1993 (Zhu and Chen, 2001), then to 8.0 mg/L in 1999 (Zhou *et al.*, 2002), indicating a significant deterioration in water quality of Donghu Lake over the past 12 years.

The loss of biodiversity is increasing at an alarming rate. For example, the number of aquatic vascular plants in Donghu Lake decreased from 50 in 1987–1988 (Yao *et al.*, 1990), to 47 in 1994 (Yu *et al.*, 1998), then to 33 in 2001 (Wu *et al.*, 2003). Of which the number of submerged plants, which play a critical role in preserving water quality of aquatic ecosystems (Melzer, 1999), also declined from 18 to 10, then to 9 in the corresponding periods (Wu *et al.*, 2003). Additionally, *Hydrilla verticillata*, an indicative species of water quality was recorded in Donghu

Lake in 1987–1988, but it has disappeared based on a long-term survey of 1994 to 2001 (Yao *et al*., 1990; Yu *et al*., 1998; Wu *et al*., 2003).

The invasion of urban into forested land may have reduced the capacity of forest's air filtering. The nitrogen oxides (NO_x) emissions in Wuhan City increased during the past 12 years; NO_x concentration was 0.054mg/m^3 in 1987 (Yang *et al*., 1991), and increased to 0.068 mg/m^3 in 1993, then to 0.1 mg/m^3 in 1999 (Hu *et al*., 2002). A study on land-use and land-cover change and its impacts in Atlanta Metropolitan Area in Georgia indicated that forest coverage correlates strongly and negatively with nitrogen oxides (NO_x) emissions (Lo and Quattrochi, 2003), which support our results.

4. Conclusions

This study documented that urbanization could greatly alter the land cover patterns and modify lacustrine landscapes of urban lake watershed in a considerably short period, characterizing by the spread of urbanization into relatively wild land cover types, such as urban forest and lake. These alterations have resulted in significant negative consequences, including decline of lakes, loss of biodiversity, and deterioration of water and air quality.

Urban planners and environmental policy makers are more concerned about how to balance the protection of natural ecosystems with the inevitable urban growth. The findings documented in this study not only elucidate the impact of urbanization on land cover changes and landscape characteristics in urban lake watershed and their consequences, but also provide some guide for future urban planning in the similar areas.

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