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Spatiotemporal change patterns of urban lakes in China's major cities between 1990 and 2015

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ABSTRACT

China has experienced unprecedented urbanization in the past decades, resulting in dramatic changes in the physical, limnological, and hydrological characteristics of lakes in urban landscapes. However, the spatiotemporal dynamics in distribution and abundance of urban lakes in China remain poorly understood. Here, we characterized the spatiotemporal change patterns of urban lakes in China's major cities between 1990 and 2015 using remote-sensing data and landscape metrics. The results showed that the urban lake landscape patterns have experienced drastic changes over the past 25 years. The total surface area of the urban lakes has decreased by 17,620.02 ha, a decrease of 24.22%, with a significant increase in the landscape fragmentation and a reduction in shape complexity. We defined three lake-shrinkage types and found that vanishment was the most common lake-shrinkage pattern, followed by edge-shrinkage and tunneling in terms of lake area. Moreover, we also found that urban sprawl was the dominant driver of the lake shrinkage, accounting for 67.89% of the total area loss, and the transition from lakes to cropland was also an important factor (19.86%). This study has potential for providing critical baseline information for government decision-making in lake resources management and urban landscape design.

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Urban expansion; lake changes; landscape pattern; human activities

1. Introduction

Inland water bodies, especially lakes, acting as sentinels and regulators of climate change, play an important role in the global environment, by providing habitat for a wide range of species and forming essential components in hydrological, nutrient, and carbon cycles (Tranvik et al. 2009; Feng et al. 2016; Carroll et al. 2009; Carroll and Loboda 2017). However, Earth's surface is suffering from extensive land-use/cover changes under climate change and anthropogenic activities, resulting in dramatic changes in the distribution and abundance of lakes all over the world (Gao et al. 2011; Smith et al. 2005; Ma et al. 2010; Cael and Seekell 2016; Liao, Shen, and Li 2013). In the meantime, urbanization, a major anthropic alteration of the Earth's surface, also poses increasingly significant threats to the global lake resources. More than 50% of the global population lives in urban areas in 2014 (United Nations 2014), leading directly to the increasing demand for water resources. However, the unprecedented urbanization has exerted enormous pressures on water resources, especially the lakes in

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urban areas (Naselli-Flores 2008). Coordinating the conflict between lake conservation and human demand for water resources remains a task for urban development.

Urban lakes, whether natural or man-made, are vitally important components of the water resource in the cities, which tend to be shallow, small, and highly artificial in comparison with other non-urban lakes (Birch and McCaskie 1999). Although occupying a small proportion of the world's lake resources, urban lakes play a significant role in urban ecosystem and human life. Urban lakes are essential elements of urban systems as well as ecological networks, which significantly contribute to environmental, social, and economic functions in urban areas, such as water supply, flood control, species habitat, and microclimate moderation (Birch and McCaskie 1999; Hamer and Parris 2011). Despite the ecological and social importance, the spatial and temporal dynamics of the urban lakes and landscape pattern in response to the rapid urbanization are still not well understood.

Given the high population density in urban areas, urban lakes are under the direct impacts of human activities, and as a result are considered as one of the most vulnerable freshwater ecosystems in the world (Birch and McCaskie 1999; Steele and Heffernan 2014). Due to this high level of human disturbance, especially in a densely populated country such as China, urban lakes vary greatly in terms of spatial distribution, abundance, and ecological function. To meet the needs of growing urban population, China has experienced an accelerated expansion of cities since the 1978 implementation of economic reforms (Chen 2007). Within this broad context, China's urban lakes have been seriously influenced by the intensive land-use changes triggered by rapid urban sprawl and population growth. The lakes in cities have been facing intensive human disturbances via construction, burial, drainage, and reshaping, which have created various negative impacts on the quality and functions of lakes (Du, Ottens, and Sliuzas 2010; Steele and Heffernan 2014). Consequently, the conflict between rapid urbanization and the maintenance of urban lakes in China urgently needs to be addressed (Liu et al. 2007).

There has been a long-standing concentration of research efforts on natural or semi-natural lakes in China (Liu et al. 2013; Sun et al. 2014; Ma et al. 2010; Yang and Lu 2014; Mei et al. 2015; Liao, Shen, and Li 2013; Li et al. 2016), but very little attention has been paid to the urban lakes. Existing studies have primarily focused on (i) changes in the distribution and abundance of urban lakes and the associated impacts of land-use changes (Steele and Heffernan 2014; Du, Ottens, and Sliuzas 2010; Liu et al. 2007), (ii) water quality deterioration due to intensive human activity (Ren et al. 2003; Wang et al. 2016; Novotny, Murphy, and Stefan 2008; Zeng et al. 2009; Birch and McCaskie 1999), and (iii) the effects of water bodies on urban environment, such as mediating local microclimates (Sun and Chen 2012; Sun et al. 2012; Steeneveld et al. 2014; Du et al. 2016). However, most previous studies have been conducted either at the individual lake level or at the single city level. Overall, the spatial distribution, abundance, and landscape change of the lakes in urban areas across China remained unexplored. Given the rapid growth in the urban areas and population in China, understanding the spatiotemporal change pattern of urban lakes as well as the associated driving factors is an essential foundation for urban water management and landscape design (Steele and Heffernan 2014).

In this study, we first performed a dynamic analysis of the landscape spatiotemporal pattern of urban lakes in China's 32 major cities between 1990 and 2015. The objectives of this study were (i) to map the spatial and temporal dynamics of urban lakes in the 32 cities, (ii) to characterize and compare their changes of landscape characteristics, and (iii) to quantify the contributions of the human-induced driving factors.

2. Data and methods

2.1. Study areas and data

Our study focused on 32 major cities in China, which mainly include provincial capitals, municipalities, and autonomous regions. Most of these cities are the cultural, economic, and industrial focal point of China's major provinces. Although the 32 cities differ in history, demographics, and economics, they have experienced dramatic economic growth and landscape changes between 1990 and 2015. Concomitant with rapid urban and economic development, a vast number of natural lands, especially lakes, streams, and wetland in urban or peri-urban areas, have been depleted by the urbanization process. Thus, a quantitative landscape change analysis was conducted to characterize the spatiotemporal dynamics of urban lakes in the 32 cities. To compare and analyze the spatial distribution, abundance, and change patterns of the urban lakes among different regions and cities, a broad regionalization scheme that divides China into eastern, central, and western regions was used (Lin 2002), including 13, 9, and 10 cities in this study, respectively.

We employed the China land use/cover dataset (CLUD), a national land-use/cover change database (http://www.resdc.cn/), to identify and analyze the spatiotemporal patterns of urban lake changes between 1990 and 2015. This dataset is a national high-resolution database (spatial resolution: 30 m × 30 m) developed by the Chinese Academy of Sciences based on the integration of remote sensing and geographical information systems (GIS) technology. Two periods of the CLUD dataset (1990 and 2015) used in this study were generated by visual interpretation and digitalization of more than 500 Landsat TM/ETM/OLI and HJ-1A/1B scenes covering the entire nation (Liu et al. 2005; Zhuang, Liu, and Liu 1999). A hierarchical classification system was established in this dataset, including 6 classes (cropland, forest, grassland, water bodies, built-up land, and unused land) and 25 subclasses. The detailed description of each land-use class can be found in the previous studies (Liu et al. 2005). According to the nationwide field surveys, the average interpretation accuracy was 92.9% for 1990, and more than 94.3% for 2015 (Liu et al. 2014; Liu et al. 2005; Liu et al. 2017). Specifically, urban built-up areas (including residential, commercial, transportation, and industrial land in cities), and the associated urban lakes for the two dates (1990 and 2015) were derived from the CLUD database. In addition, visual inspection with reference to Google Earth images, published literature, and field investigations were conducted to help refine lake boundaries. Figure 1 shows the spatial distribution of urban areas and urban lakes of the 32 cities.

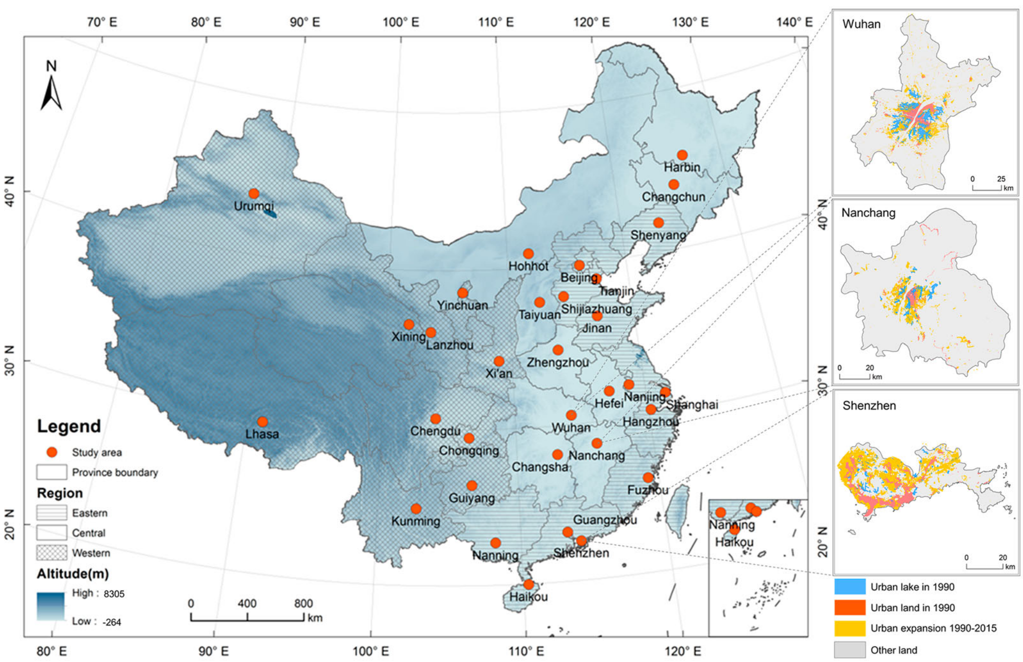

Figure 1. Spatial distribution of 32 major cities in China, with the background map indicating the topography of China. The three geographic divisions in China (eastern, central, and western regions) are illustrated. Urban expansion between 1990 and 2015, and the associated urban lakes in Wuhan, Nanchang, and Shenzhen are highlighted.

2.2. Landscape metrics

To quantify the landscape change patterns of urban lakes, we selected six most commonly used landscape metrics (Seto and Fragkias 2005; Fang, Li, and Wang 2016; Kaza 2013), including total lake area (CA), number of lake patches (NP), mean patch size (MPS), edge density (ED), area-weighted mean shape index (AWMSI), and area-weighted mean patch fractal dimension (AWMPFD). The chosen landscape metrics were used to describe four aspects of the urban lakes: absolute size, relative size, edge metrics, and complexity of urban lakes (Table 1). The total lake area (CA) in city could tend to decrease due to the continuous expansion of urban space, but may increase if new man-made lakes are constructed. An increase in NP may be a symbol of subdivisions of urban lake landscape. Relative size is characterized by MPS, defined as the ratio of the size of urban lakes to the number of lake patches. It is generally recognized that a decrease in MPS mirrors a trend toward fragmentary landscape of urban lakes. ED measures the total edge of urban lakes relative to the total landscape. A high value of ED implies that the level of contiguity for urban lake landscape decreased. In practice, the combination of the MPS and ED is recommended for the analysis of landscape fragmentation (Tyler and Peterson 2004). AWMSI and AWMPFD describe the landscape complexity of urban lakes. An increase in the value of the two metrics indicates that the shape of urban lakes becomes more irregular and complex.

2.3. Three lake shrinkage types

Similar to urban growth type index (Xu et al. 2007; Chen, Gao, and Yuan 2016), three lake-shrinkage types (vanishment, edge-shrinkage, and tunneling) were defined in this study to measure the shrinkage patterns and processes of urban lakes. Vanishment denotes that an existing lake patch has disappeared; edge-shrinkage refers to the fringe of an existing lake being converted to non-lake area; tunneling indicates that an urban lake may be segmented by artificial features, such as road construction. The lake-shrinkage-type index (LSTI) was used to identify the three shrinkage patterns:

$$\mathrm{LSTI} = \frac{L_{\mathrm{common}}}{P_{\mathrm{new}}},$$

where P_{new} denotes the perimeter of a newly shrinking lake patch, L_{common} indicates the length of the common edge of this newly shrinking lake patch and existing lake patch. The value of LSTI ranges

Table 1. Landscape metrics of urban lakes used in this study.

Landscape metrics	Abbreviation	Formula	Description
Total lake area (ha)	CA	$\mathrm{CA} = \sum_{j=1}^{n} a_j (1/10,000)$	a_j = area (m^2) of lake patch j
Number of patches (#)	NP	$\mathrm{NP} = n$	n = number of urban patches
Mean patch size (ha)	MPS	$\mathrm{MPS} = \frac{\sum_{j=1}^{n} a_j}{n}(1/10,000)$	a_j = area (m^2) of lake patch j, n = number of lake patches
Edge density (m/ha)	ED	$\mathrm{ED} = \frac{\sum_{j=1}^{n} e_j}{A}(10,000)$	e_j = total length (m) of edge in landscape involving lake patch j, including landscape boundary and background segments of urban patch, A = total landscape area (m^2)
Area-weighted mean shape index (unitless)	AWMSI	$\mathrm{AWMSI} = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[\left(\frac{0.25P_{ij}}{\sqrt{a_{ij}}}\right)\left(\frac{a_{ij}}{A}\right)\right]$	m = number of patch types, n = number of patch of type i, P_{ij} = perimeter of patch, a_{ij} = area of patch, A = total landscape area
Area-weighted mean patch fractal dimension (unitless)	AWMPFD	$\mathrm{AWMPFD} = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[\left(\frac{2\ln(0.25P_{ij})}{\ln(a_{ij})}\right)\left(\frac{a_{ij}}{A}\right)\right]$	m = number of patch types, n = number of patch of type i, P_{ij} = perimeter of patch, a_{ij} = area of patch, A = total landscape area

from 0 to 1. The lake-shrinkage type is identified as vanishment when LSTI = 1, as edge-shrinkage when $0.5 \leq LSTI < 1$, and as tunneling when $0 < LSTI < 0.5$. The three shrinkage patterns are illustrated in Figure 2.

3. Results

3.1. Landscape change pattern of urban lakes

With the rapid growth of human population, China has been experiencing unprecedented urban land expansion, resulting in drastic changes in spatiotemporal patterns of urban lake landscape between 1990 and 2015 (Table 2). Collectively, the total urban land area of the 32 cities expanded rapidly (approximately 2.31 times), while the total surface area of the associated urban lakes showed a significant decrease of 17,620.02 ha or 24.22% over the 25 years. To further understand the area changes in lakes, the temporal changes of the 20 typical lakes in the 3 cities (i.e. Wuhan, Nanchang, and Changsha) between 1990 and 2015 were investigated by using multiple land cover maps (CLUD). The relative lake area of the typical lakes for 6 periods (i.e. 1990, 1995, 2000, 2005, 2010, and 2015) and the overall trend of the area changes in these lakes are shown in Figure 3. The total area of these typical lakes in Wuhan, Nanchang, and Changsha showed significant decreasing trends ($p < .05$).

Accompanying the decrease in the surface area of lakes, a rapid reduction (30.5%) of the number of lake patches (NP) was also observed in the period of 1990–2015. This suggests that a large number of lake patches have disappeared. From a relative size perspective, the average lake patch size (MPS) increased by 3.60%, which indicates that the degree of fragmentation of lake patches decreased. This also reveals that many small lake patches have vanished, or new lake patches are larger than existing neighborhoods. However, the value of ED of urban lakes increased by 9.04% between 1990 and 2015, which is indicative of the increasing level of fragmentation of urban lakes during urbanization process. AWMSI and AWMPFD for total urban lakes showed a slight downward trend between 1990 and 2015. The values of the two metrics decreased by 4.63% and 0.48%, respectively, suggesting that urban lakes exhibit patterns of decreasing complexity in shape. The shape of urban lakes may provide a useful signature of the type and extent of alteration in cities. The physical reshaping of urban lakes due to intensive human activities may directly lead to a reduction in tortuosity and irregularity of their shorelines (Steele and Heffernan 2014).

3.2. Comparison of lake landscape patterns among various regions

Figure 4 shows the overall spatiotemporal dynamics of landscape metrics of urban lakes in the 32 cities. A comparison analysis of urban lake landscape metrics between 1990 and 2015 is performed in Figure 5. There is relative consistency for different landscape metrics between 1990 and 2015 ($0.61 \leq R^2 \leq 0.87$, $p < .05$). Overall, the cities located in the middle and lower reaches of the Yangtze River (e.g. Wuhan, Nanchang, Nanjing, Hangzhou, and Changsha) had the largest surface area of urban lakes. Wuhan is known as 'the city of a hundred lakes' due to the dozens of lakes in the built-up areas (Figure 1), and Tangxun Lake is the largest urban lake in China, with a surface area of 5259.15 ha. Comparatively, most cities in the semi-arid or arid areas of western China (e.g. Lanzhou, Xining, and Lhasa) had less urban lakes, with an area of less than 100 ha in 2015. Between 1990 and 2015, urban lakes in the western region decreased by 26.43% in area, whereas in central and eastern cities, they experienced an area reduction of 25.55% and 20.16%, respectively. In the case of NP, different changing patterns were found among the three regions compared to the lake surface area. The largest decline in the number of lake patches was observed in the eastern region (41.14%), followed by western region (34.75%) and central region (16.17%). Spatially, Beijing, Nanjing, Guangzhou, and Lanzhou were the primary focus areas with a large reduction of NP. Nevertheless, Shanghai witnessed the rapid growth of 45.45% in the number of lake patches

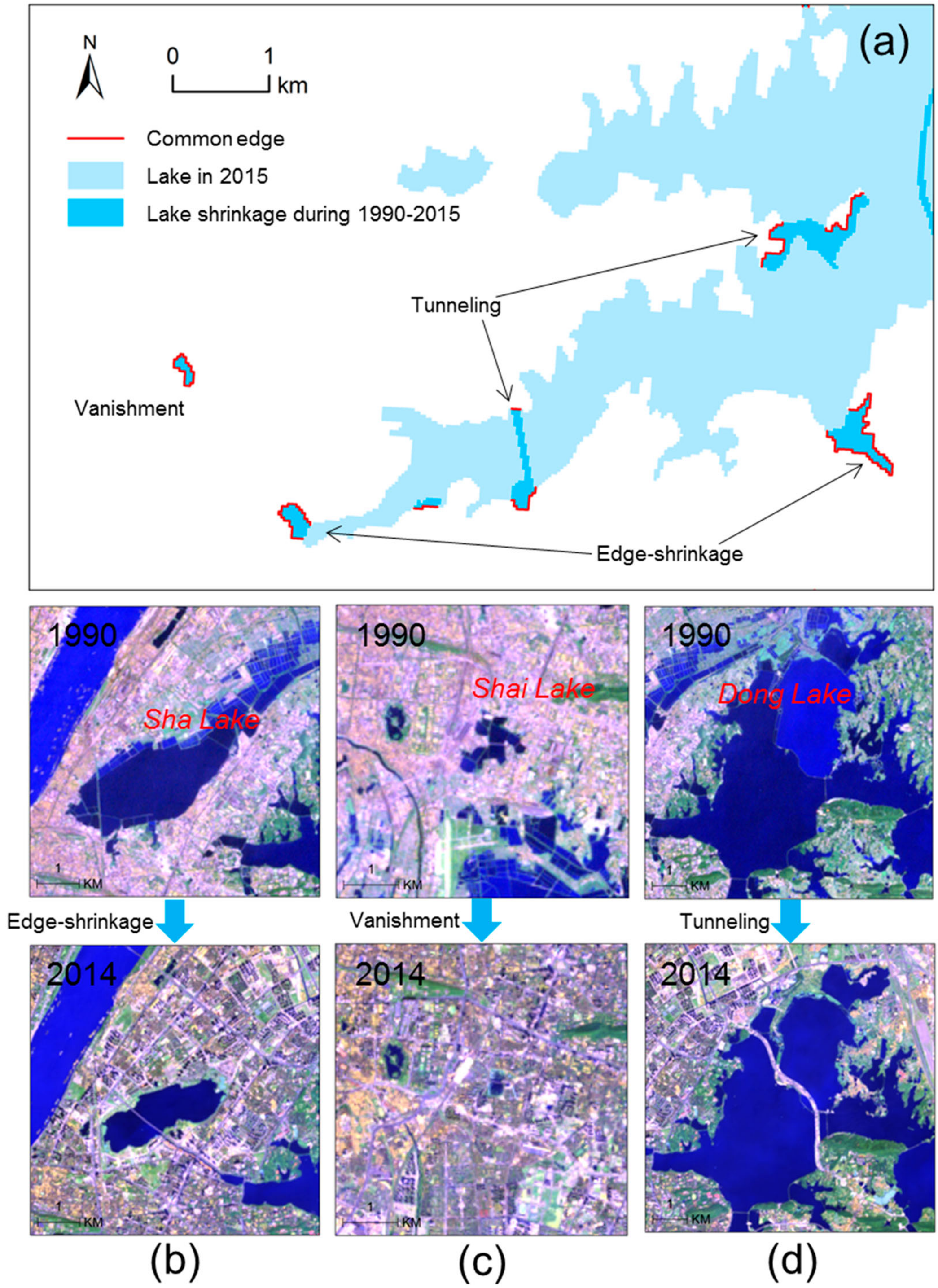

Figure 2. (a) Illustration of the three lake-shrinkage types. (b), (c), and (d) are the Landsat images (2 September 1990 and 6 October 2014) of three typical urban lakes, that is, Sha Lake (edge-shrinkage), Shai Lake (vanishment), and Dong Lake (tunneling), respectively. The Landsat images were obtained from the United States Geological Survey (USGS; http://www.usgs.gov/).

Table 2. Descriptive statistics of landscape metrics of urban lakes.

Landscape metrics		Whole region		Eastern region		Central region		Western region	
		1990	2015	1990	2015	1990	2015	1990	2015
CA	Mean	2273.87	1723.24	1430.61	1142.24	5625.24	4187.90	353.88	260.36
	SD	6398.10	4912.81	1224.41	981.65	11,740.94	9052.07	337.60	271.61
NP	Mean	44.47	30.84	49.92	29.38	59.78	50.11	23.60	15.40
	SD	50.20	39.03	50.76	25.05	69.38	64.09	14.30	10.91
MPS	Mean	33.36	34.56	35.91	44.30	49.78	41.49	15.26	15.65
	SD	34.98	35.36	32.64	40.09	46.82	39.23	14.29	14.57
ED	Mean	134.22	146.35	116.86	122.61	96.01	111.05	191.17	208.97
	SD	63.10	98.49	36.01	62.48	28.83	49.99	75.81	139.89
AWMSI	Mean	1.97	1.88	1.96	2.03	2.35	2.08	1.64	1.50
	SD	0.86	0.71	0.63	0.62	1.38	1.01	0.20	0.28
AWMPFD	Mean	1.09	1.08	1.09	1.10	1.10	1.09	1.08	1.07
	SD	0.03	0.04	0.03	0.03	0.05	0.04	0.02	0.03

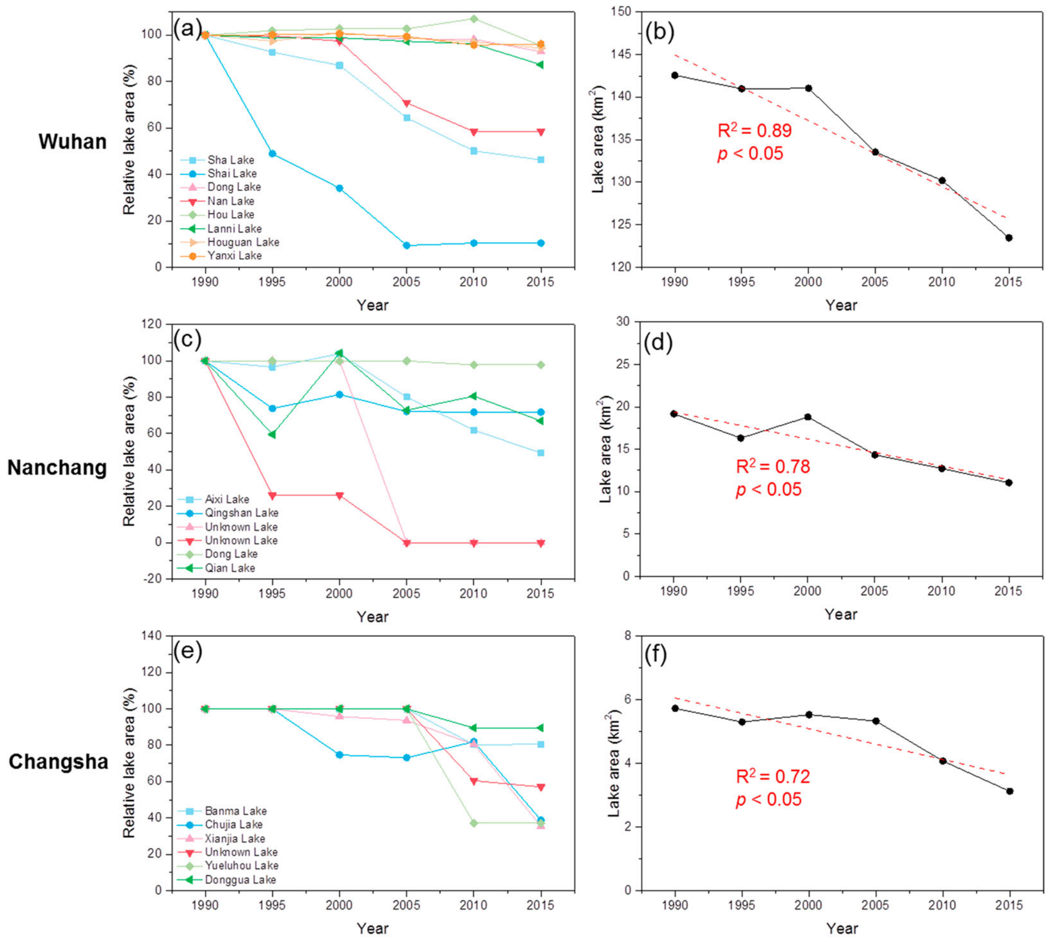

Figure 3. Relative area changes of the 20 typical lakes in Wuhan (a), Nanchang (c), and Changsha (e). The relative lake area is calculated as $A_i/A_i^s \times 100\%$. A_i is the surface area of the ith lake in one of these six periods and A_i^s indicates the surface area of the ith lake in the period of 1990. (b), (d), and (f) show the changing trends of the total area of these typical lakes in the three cities, respectively.

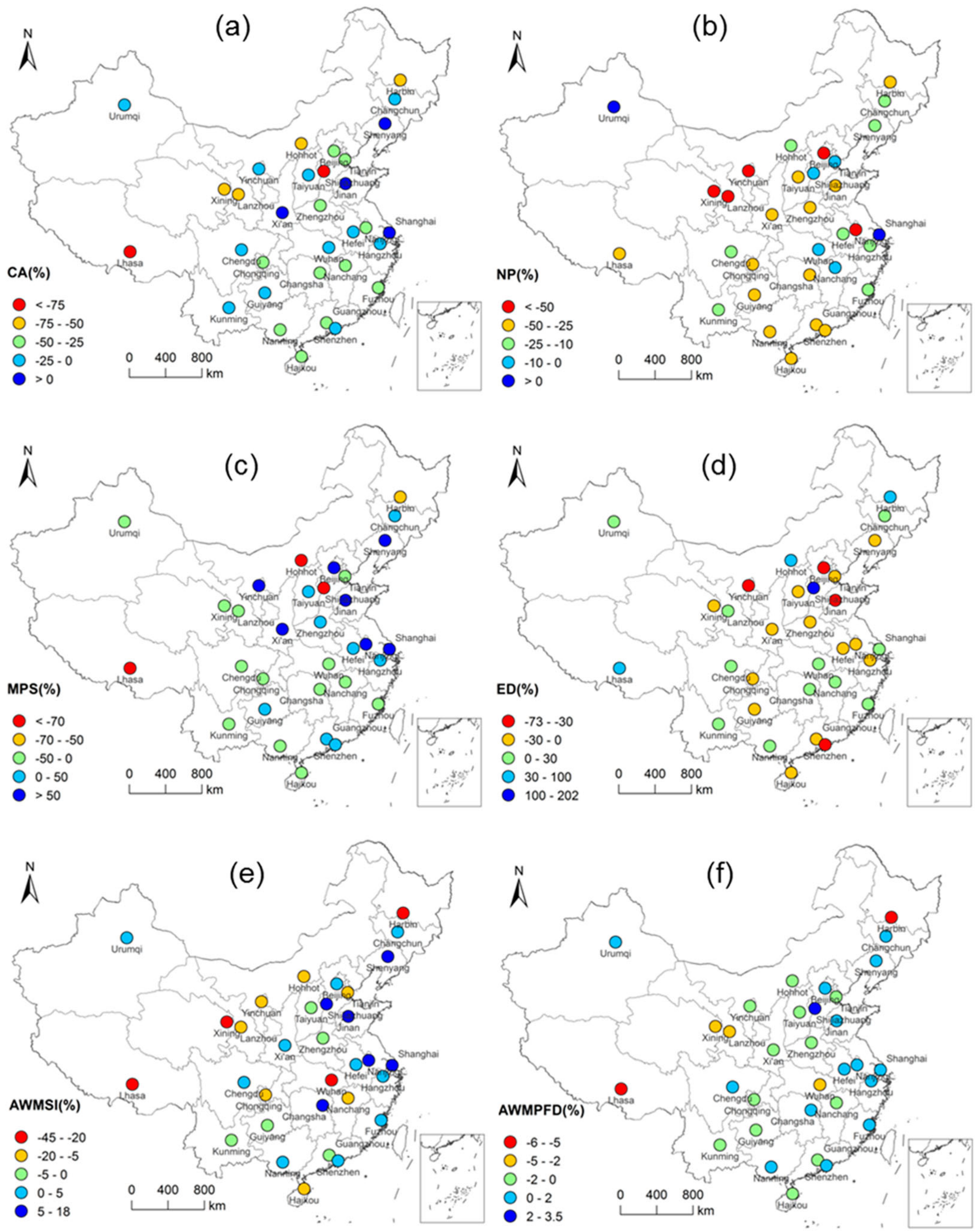

Figure 4. Dynamics of landscape metrics of urban lakes between 1990 and 2015.

owing to the construction of artificial lakes. For example, Dishui Lake, constructed as a landmark project in the main urban area of Shanghai Lingang New City, is the largest man-made freshwater lake existing in China, with a surface area of 423.06 ha.

Although MPS of the whole region increased between 1990 and 2015, regional differences among the three subregions were remarkable. Over the 25 years, MPS of urban lakes in eastern and western regions increased by 23.37% and 2.55%, respectively, whereas the central region experienced a

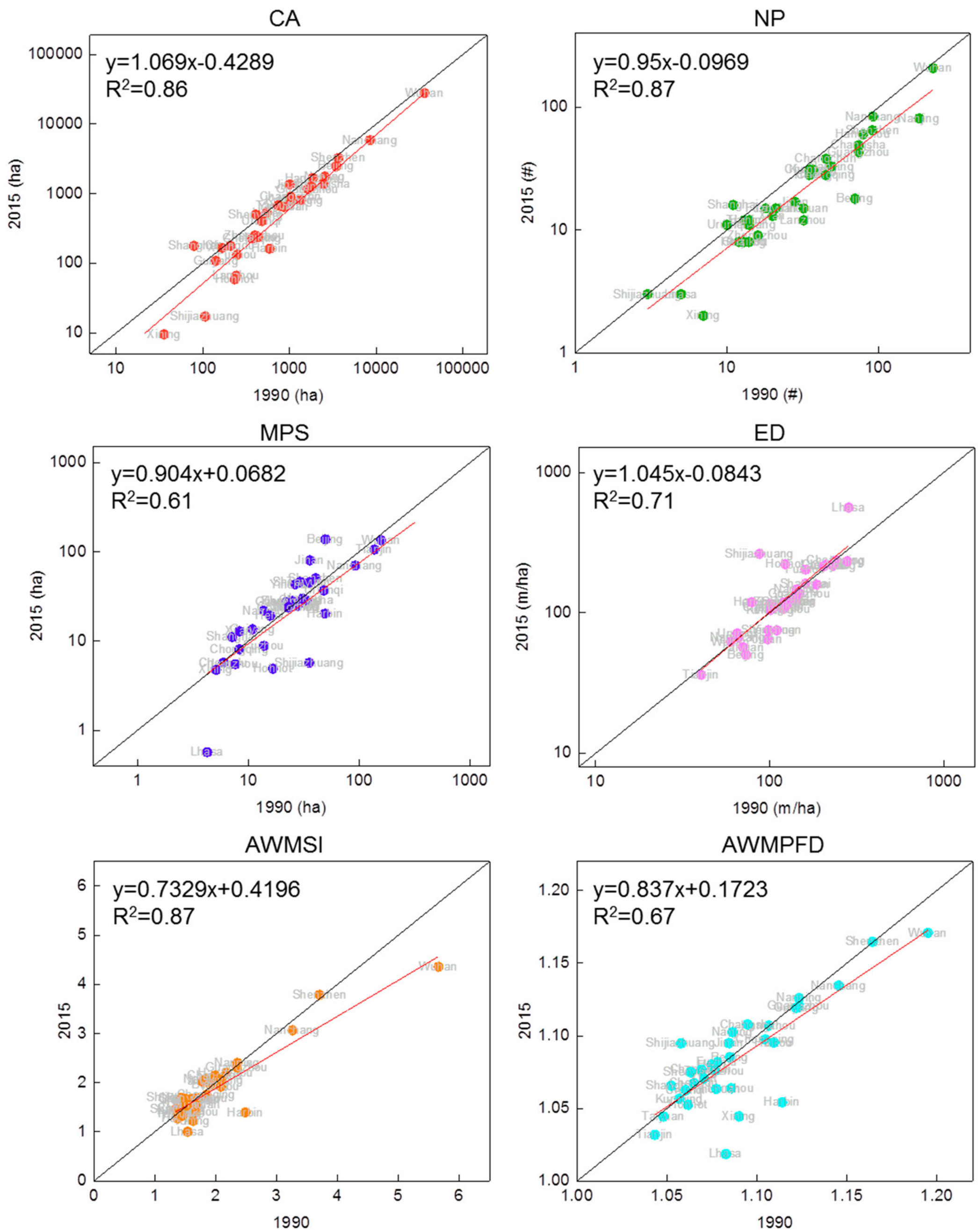

Figure 5. Comparative analysis of urban lake landscape metrics between 1990 and 2015.

decrease of 16.65%. This suggests that urban lakes in the central cities are more fragmented. In terms of spatial distribution, Nanchang, Changsha, and Wuhan are the core areas in central China with a decreasing value of MPS, which implies that more attention should be paid to the strict management for landscape fragmentation of urban lakes.

Although the values of ED of all three regions showed an upward trend, the magnitude of changes was different. The central cities experienced the largest growth in the value of ED (15.66%), followed by the western region (9.31%) and eastern region (4.93%). The observed results revealed that the three regions all had a higher degree of fragmentation of urban lake landscape. Regional variation in the ED indicated that central region had the most significant fragmentation in urban lake landscape.

From the perspective of shape complexity, the whole region witnessed a decline in the value of AWMSI, which is indicative of more regular and simpler shape of urban lakes. Urban lakes in the central cities had a higher mean value of AWMSI than the other regions (Table 2), suggesting that the central areas had the most complex urban lake shapes. In terms of changes, the central region experienced the largest decrease (11.66%) in AWMSI, whereas a slight increase (3.74%) was observed in the eastern region. A different changing pattern was exhibited in the value of AWMPFD, showing a minor reduction in the central and western regions. Along with rapid progress in urbanization, intensive human alterations that reshaped the existing urban lakes may result in a reduction in complexity and irregularity of their shapes. Therefore, effective action is required to prevent further changes to the shorelines of urban lakes, especially in central China.

3.3. Spatial patterns of urban lake shrinkage

To better understand the spatial patterns of urban lake shrinkage, the relative fractions or composition of the three lake-shrinkage types (i.e. vanishment, edge-shrinkage, and tunneling) in terms of patch number or area are illustrated in Figure 6. The fraction of vanishment and edge-shrinkage accounted for 42.99% and 49.65% in terms of patch number, respectively, while the number of tunneling has been the smallest (7.36%) among the three. In the central China, the relative fraction of edge-shrinkage was higher than other regions. For example, urban lakes in Wuhan and Nanchang suffered from the serious encroachment in the fringes, leading to the landscape patterns of lakes to be more regular. The results generally supported the shape of their urban lakes tended to be simpler, indicated by decreased AWMSI and AWMPFD. The urban lakes in eastern regions have disappeared seriously, inducing a large proportion of vanishment in patch number.

In terms of patch area, vanishment was the dominant lake-shrinkage form (63.33%), followed by edge-shrinkage (30.34%) and tunneling (6.33%). Especially in the eastern and western regions, the

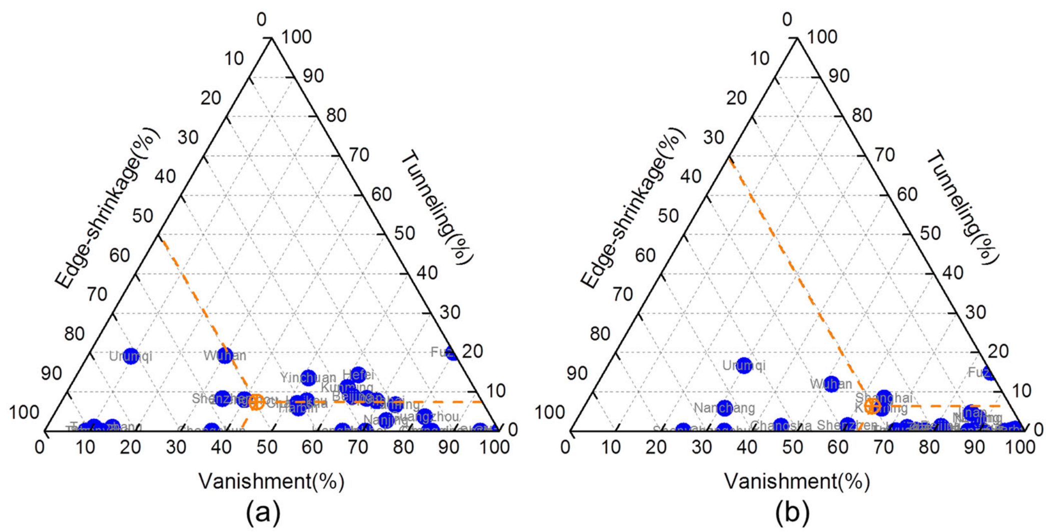

Figure 6. The proportional composition of the three shrinkage types (i.e. vanishment, edge-shrinkage, and tunneling) in terms of patch number (a) and patch area (b). The sum of the proportions equals to 100%; the circle represents the location of the intersection of the three means, shown by the dashed lines.

urban lakes experienced a severe loss in patch area, inducing the weight of vanishment occupied over 80% among the three shrinkage types. For instance, patch vanishment was the most intensive form of lake shrinkage in Guangzhou, Fuzhou, and Chengdu, where a high proportion of small-sized lake patch was completely encroached over the 25 years.

3.4. Driving forces behind landscape change patterns of urban lakes

Under the accelerated process of urbanization, urban lakes have undergone profound land-use changes due to intensive human activities, which converted lake water areas into built-up areas, cultivated land, or aquaculture ponds (Xie et al. 2017). The exploitation of lake resources provided essential ecosystem goods for human development, but at the expense of a rapid loss in lake areas. To explore the driving mechanisms behind landscape change patterns of urban lakes, we investigated the land-use/cover conversions of urban lakes between 1990 and 2015. The land-use changes from lakes to the six general classes and built-up land subclasses (Kuang et al. 2016), that is, grassland, woodland, cropland, water, unused land, and built-up areas (including urban land, industrial land, and rural settlement), are illustrated in Table 3. The results revealed that the significant reduction of lake areas was mainly driven by urban expansion, that is, lakes were directly converted into urban and industrial land, accounting for 47.05% (11,765.58 ha) and 20.84% (5212.26 ha) of the total area loss, respectively. Furthermore, the transition from lakes into agricultural land can also explain a large proportion of decline in surface area (i.e. 4967.18 ha, 19.86%), as a result of extensive lake reclamation for cultivated areas. Spatially, the urban lakes in the central region suffered from the most severe loss in surface area (16,863.07 ha), which was primarily converted into the urban land (44.52%), industrial land (25.51%), and agricultural land (22.29%). The eastern and western regions showed a similar pattern of lake conversions, that is, the lake surface areas were mainly replaced by urban built-up areas, resulting in the area decline of 61.60% and 71.04%, respectively. The percentage distributions of land-use conversions of urban lakes in each subregion (Figure 7) also revealed that the transformation from lakes into developed land accounted for the highest proportion (62.38% on average). Overall, rapid urban sprawl was the leading driving force of severe loss in urban lakes, inducing the land-use transitions from lakes into urban human settlements in the past few decades.

The land-use changes of urban lakes among the 32 cities exhibited different spatial patterns, depending on the regional lake environment and economic conditions (Figure 8). Along with rapid urban expansion over the past several decades, Wuhan, Nanchang, and Changsha, with abundant freshwater lake resources in central China, have experienced the most drastic shrinkage in lake areas (a total loss of 10,436.28 ha, 3223.98 ha, and 1661.77 ha, respectively), which were dominated by the transitions to built-up areas, accounting for 72.58%, 60.09%, and 86.98%, respectively. In the eastern region, Beijing and Nanjing also witnessed a large degradation from lakes to built-up areas, occupying 45.98% (803.97 ha) and 92.75% (1006.34 ha) of the total loss in lake areas, respectively.

Table 3. Land-use changes of urban lakes between 1990 and 2015.

Land-use changes of lakes	Whole region Area (ha)	Whole region Proportion (%)	Eastern region Area (ha)	Eastern region Proportion (%)	Central region Area (ha)	Central region Proportion (%)	Western region Area (ha)	Western region Proportion (%)
Urban land	11,765.58	47.05	3281.14	50.19	7507.40	44.52	977.04	60.75
Industrial land	5212.26	20.84	745.57	11.41	4301.21	25.51	165.48	10.29
Rural settlement	548.09	2.19	467.66	7.15	69.63	0.41	10.79	0.67
Grassland	526.81	2.11	144.15	2.21	318.75	1.89	63.91	3.97
Woodland	239.97	0.96	116.41	1.78	113.71	0.67	9.85	0.61
Cropland	4967.18	19.86	1041.53	15.93	3759.19	22.29	166.46	10.35
Water	1623.84	6.49	740.46	11.33	685.72	4.07	197.67	12.29
Unused land	124.45	0.50	0	0	107.47	0.64	16.98	1.06
Total	25,008.18	100.00	6536.92	100.00	16,863.07	100.00	1608.19	100.00

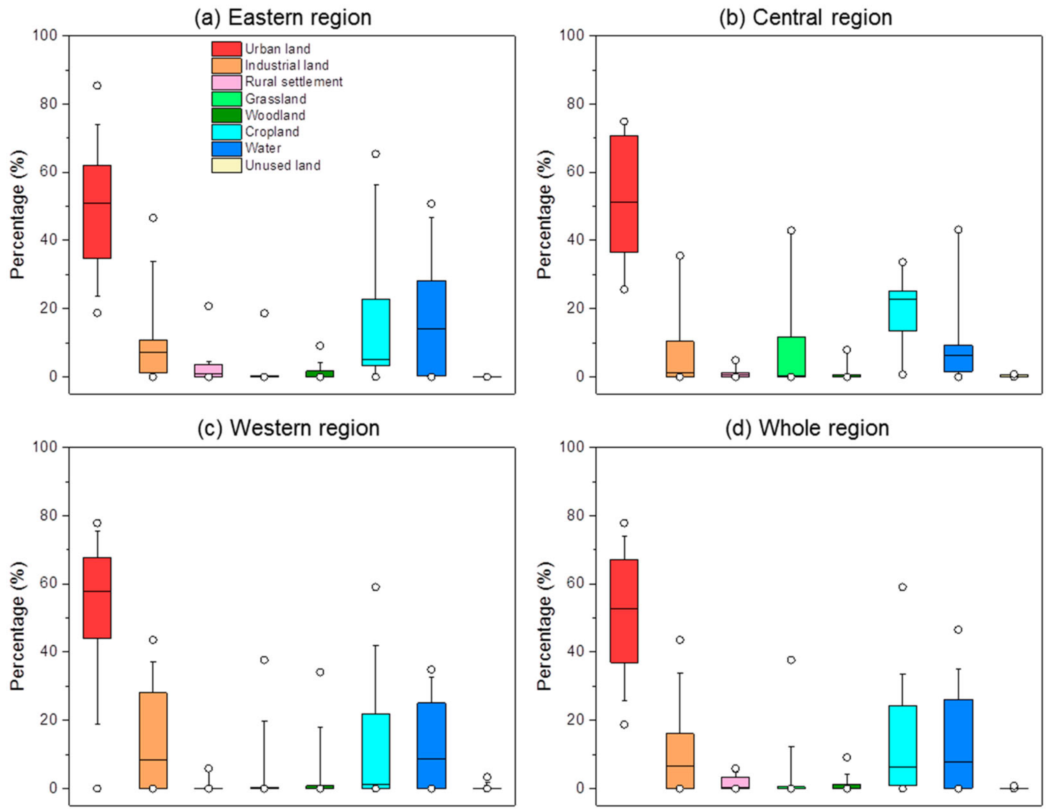

Figure 7. Boxplots show the percentage distributions of land use (including urban land, industrial land, rural settlement, grassland, woodland, cropland, water, and unused land) in area, to which urban lakes were converted between 1990 and 2015 in (a) eastern region, (b) central region, (c) western region, and (d) whole region. The horizontal lines (boxes and whiskers) in each boxplot are the 10th, 25th, 50th, 75th, and 90th percentiles, and the circles indicate the fifth and 95th percentiles.

Yinchuan City is a typical oasis area with the most characteristic and significant wetland resources in the semi-arid/arid region of northwest China, which has experienced a decrease of 303.55 ha (62.39%) in lake surface areas between 1990 and 2015, devoted to urban human settlements.

4. Discussion

Since the economic reform of China in 1978, especially after its land reform in 1987, rapid population growth and urban expansion have given rise to a considerable and sustained demand for urban construction, industrial development and housing (Li et al. 2006). The unprecedented urbanization has posed significant impacts on the landscape patterns of urban lakes due to intensive anthropogenic activities, for example, construction, burial, drainage, and reshaping (Steele and Heffernan 2014). In the cities, small and shallow water bodies are more likely to be drained and replaced by built-up areas, which has a notable effect on the abundance and distribution of urban lakes. For example, the preferential drainage or removal of small-size urban lakes has led to a large decline in the number of patch in the eastern region, for example, Beijing (74.29%), Nanjing (56.22%), and Guangzhou (41.89%). However, the cases in central China (e.g. Wuhan, Nanchang, and Changsha) have showed that nearly all the urban water bodies, either large or small lakes, have been suffering from significant alterations during urbanization (Du, Ottens, and Sliuzas 2010), resulting in the decreases of NP (9.17%, 8.70%, and 33.78%, respectively) and MPS (15.22%, 24.06%, and 14.70%, respectively). The construction of man-made lakes in the urban areas may also affect the landscape

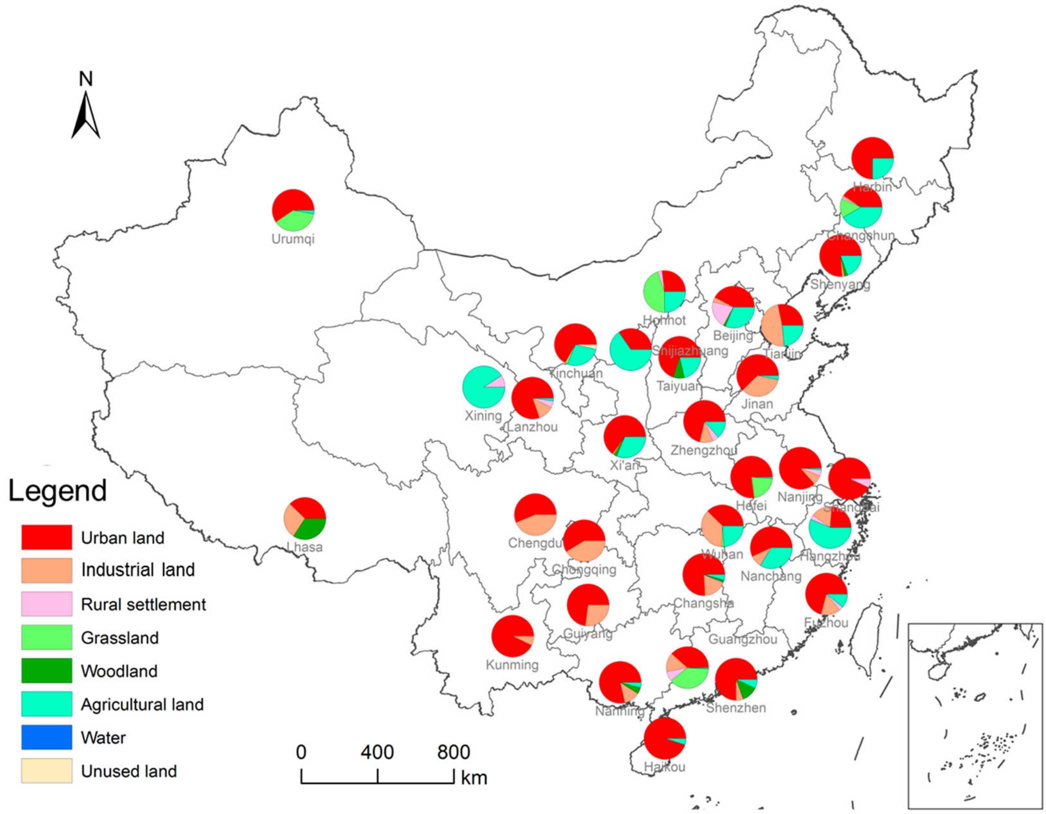

Figure 8. The proportional composition of land-use types, to which urban lakes were converted in China's 32 major cities between 1990 and 2015.

patterns of urban lakes. For instance, the total surface area of urban lakes in Shanghai has increased by 98.91 ha (125.31% in proportion) between 1990 and 2015, with an increase of 45.45% in the number of patches. In addition, the physical reshaping (e.g. construction and impounding) of existing urban lakes contributes to the changes in spatial and geometrical characteristics of urban lakes. For example, the urban lakes in Wuhan witnessed a large reduction in AWMSI (a decrease of 22.99%) between 1990 and 2015, suggesting that the shape complexity tends to be more regular and simpler. Along with rapid urbanization and economic development, the construction of large-scale infrastructure projects (e.g. main roads, outer ring highways, and subways) has resulted in increased fragmentation and reduced connectivity of urban lakes. For instance, the central cities (e.g. Wuhan, Changsha, and Nanchang) experienced a decline in MPS (15.22%, 14.70%, and 24.06%, respectively) and a growth in ED (4.35%, 15.19%, and 1.69%, respectively) between 1990 and 2015, indicating that the three cities all had a higher degree of fragmentation of urban lake landscape. Therefore, more efforts on lake management should be made to restrain the tendency toward a more fragmentary landscape of urban lakes, especially in the central cities.

Rapid urbanization and industrialization have also posed significant threats to the land-use structure in the watershed regions of urban lakes (Liu et al. 2007). For example, accelerated urban sprawl has resulted in intensive land-use alterations in the watershed areas of Nan Lake and Dong Lake in Wuhan (Figure 9), where built-up areas increased by 106.71% and 59.68%, respectively. The excessive urban sprawl resulted in a significant loss in relatively wild habitats, such as lake water areas and urban forests. In comparison, little changes can be found in the water areas of Xuanwu Lake in Nanjing and West Lake in Hangzhou, thanks to the local government's conservation and management in urban scenic spots. However, the two lakes have also witnessed the major land-use transitions from cropland to urban areas, resulting in a significant reduction (86.49% and 30.40%, respectively) of cultivated areas between 1990 and 2015. The process of urbanization is associated with a rapid increase in impervious surface area, which has significant impacts on urban hydrologic cycle (Niemczynowicz 1999). Increased proportion of impervious surface can lead to a reduction in the capacity for the urban landscape to infiltrate precipitation, higher runoff peaks, and total volume of runoff, which increased the risk of water-logging and more frequent flooding in the cities (Shuster et al. 2005). In a developed watershed, the impervious surface may significantly affect the natural groundwater recharge and the connection between lakes and river systems, resulting in decreased water supply to lakes and the shrinkage of lake areas (Du, Ottens, and Sliuzas 2010).

In spite of land-use changes, the human-induced rapid loss in lake areas has exerted significant impacts on the hydrological and ecological services (Fang, Rao, and Zhao 2005; Xie et al. 2017), for example, increasing flood disasters, decreasing biodiversity, and water pollution. The rapid shrinkage of urban lakes and their reduced connection with the river systems has greatly reduced the water storage and drainage capacity, which increased the risk of flooding and water-logging in the cities (Zong and Chen 2000; Wu 2002). Moreover, severe degradation of urban lakes has also resulted in rapid loss of habitats, inducing a decline of biodiversity. For example, the species richness of fishes

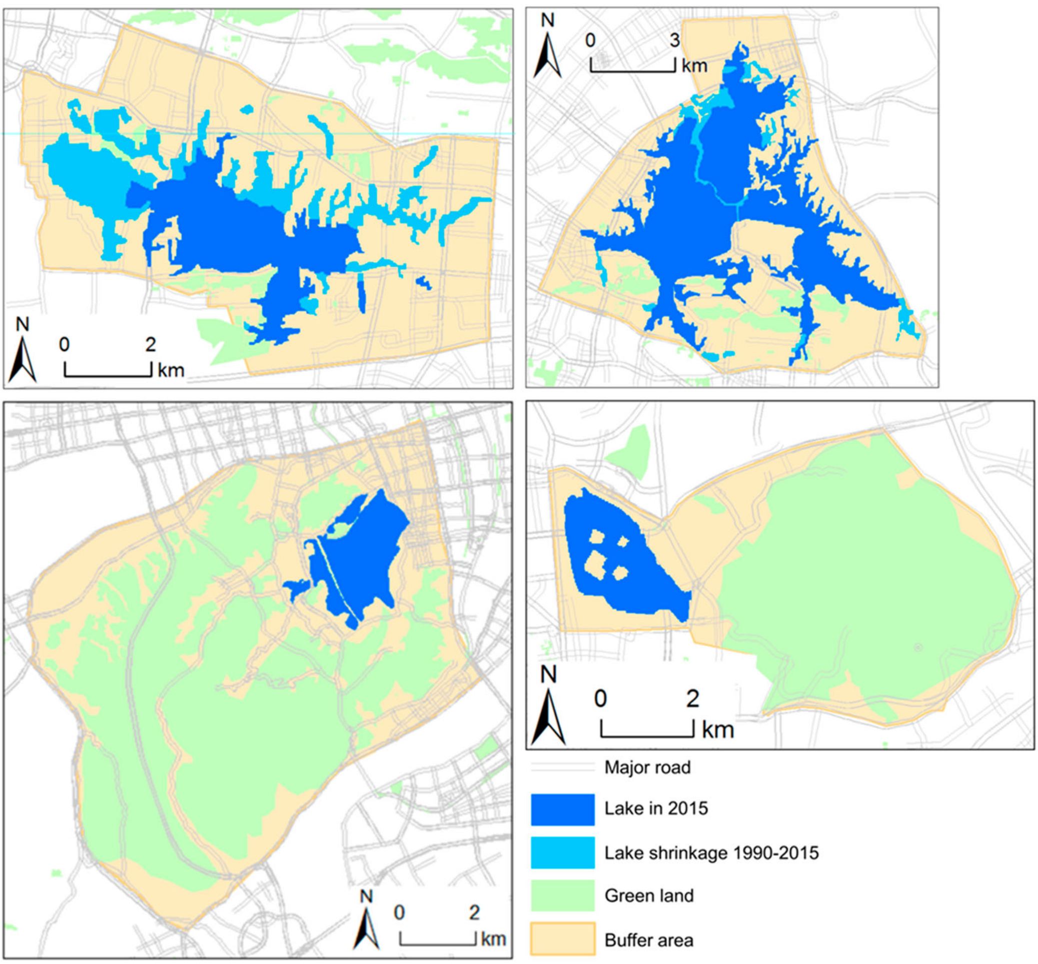

Figure 9. Watershed areas of typical urban lakes: (a) Nan Lake, (b) Dong Lake, (c) West Lake, and (d) Xuanwu Lake.

in Dong Lake (Wuhan) has decreased rapidly during the past few decades, consistent with the loss of lake area. The species richness of aquatic vascular plants in Dong Lake decreased from 50 in the late 1980s to 33 in the early 2000s (Yao, Li, and Xia 1990; Wu et al. 2003).

In addition, rapid urbanization and industrialization have led to intensified land-use changes in the urban lakes and the surrounding watershed areas, which increased the rate of urban contaminant inputs (such as nitrogen and phosphorus) to the lakes, inducing the severe deterioration of water quality (Cheng and Li 2006; Diamond and Hodge 2007; Zhiying et al. 2008; Mei et al. 2010; Chao et al. 2003; Wang et al. 2016; Xiao et al. 2016). For instance, Dong Lake in Wuhan has experienced rapid loss of lake area and severe degradation of water quality. The total nitrogen (TN) and chemical oxygen demand (COD_{Mn}) in Dong Lake increased from 1.92 and 4.7 mg/L in 1986 to 2.46 and 7.6 mg/L in 2000, respectively (Cheng and Li 2006). In the lake watersheds, the human-induced transitions from agricultural land to urban areas may lead to even greater levels of water pollution. For example, with the increase of developed areas in the watershed of Tangxun Lake, the high-value areas of pollutant loads expanded from north to south. The TN and total phosphorus (TP) loads in Tangxun Lake showed an increasing tendency since 1991, and by 2020 the TN and TP loads will increase to 370.06 and 33.89 t/year, respectively (Yanhua et al. 2013). Urban water pollution has significant effects on the function of the lake as a drinking water supply and the landscape value of the surrounding areas in the cities.

To mitigate these negative impacts, local governments have implemented a series of policies, such as lake conservation and restoration projects (Du, Ottens, and Sliuzas 2010; Zhang et al. 2008; Zhiying et al. 2008), which have played an important role in the land-use control and environmental regulation in the watersheds of urban lakes. However, under the accelerated urban expansion and economic development, the lake resources within the urban regions are still suffering from the intensive land-use alterations induced by human activities, leading to serious consequences on the landscape characteristics of urban lakes. Therefore, there is a pressing need to make current ecological knowledge about the landscape change patterns of urban lakes, which can help inform future decision-making for urban landscape design and lake management (Birch and McCaskie 1999).

5. Conclusion

This study aimed to advance the understanding of spatiotemporal change patterns of urban lake landscape and the associated driving forces in China's 32 major cities between 1990 and 2015. The results demonstrated that the total surface area of urban lakes decreased by 17,620.02 ha (24.22% in proportion) over the 25 years, with a significant increase in fragmentation and a reduction in tortuosity and irregularity of the shorelines. The spatial analysis of lake-shrinkage patterns was performed in this study, which revealed that vanishment was the dominant lake-shrinkage form (63.33%), followed by edge-shrinkage (30.34%) and tunneling (6.33%) in terms of patch area. Moreover, we investigated the land-use changes of urban lakes between 1990 and 2015 and found that rapid urban sprawl was the leading driving force of the lake changes, accounting for 67.89% of the total area loss, and the conversion from lakes to agricultural land was also an important factor (19.86%). With its unprecedented urban expansion and population growth, coordinating the conflict between lake protection and land demands for human settlement in the cities will continue to be a primary challenge for China in the future. Our results can provide a scientific foundation for decision-making for urban landscape designs and lake resources conservation.

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