



China's wetlands loss to urban expansion

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Abstract

Humans benefit from multiple ecosystem services of wetlands, but massive wetland loss has occurred worldwide due to rapid urbanization. To assess the problem, it is necessary to quantify the spatial extent of urbanization-induced wetland loss. Here, we investigated the amount and pattern of wetland loss in China due to urbanization from 1990 to 2010, based on the China National Land Cover Database (ChinaCover). Our results show that, during these 20 years, China lost 2,883 km² of wetlands to urban expansion, of which about 2,394 km² took place in the eastern regions (Northeast China, North China, Southeast China, and South China). The rate of urbanization-induced wetland loss was 2.8 times higher between 2000 and 2010 (213 km² year⁻¹) than between 1990 and 2000 (75 km² yr⁻¹). Of all wetland categories, reservoirs/ponds and marshes suffered the most severe losses. Most of the wetland loss was due to the expansion of urban built-up areas rather than industrial or transportation lands. Four hotspots of urbanization-induced wetland loss in China were identified: the Beijing–Tianjin metropolitan region, the Yangtze River Delta, the Jiangnan Plain, and the Pearl River Delta. Urbanization and industrialization continue to unfold in China for the next few decades, and the rapid expansion of small- and middle-sized cities and urban traffic networks is expected to encroach on more wetlands. Although great efforts have been made towards wetland conservation in recent years, China must prevent more wetlands from being wiped out by urbanization if the country is to achieve its sustainable development goals.

KEYWORDS

China, remote sensing, urbanization, wetland degradation, wetland loss

1 | INTRODUCTION

Rapid economic development and an obvious increase in population have triggered the evident expansion of urban areas around the world (Seto, Fragkias, Güneralp, & Reilly, 2011; Liu, He, Zhou, & Wu, 2014; Wu, 2014; Wu et al., 2014, a; Kuang, Liu, Dong, Chi, & Zhang, 2016). In China, the fraction of the nation's urban population increased from 17.9% to 52.6% during 1978–2012, especially in the early 21st century, when the urban population significantly increased (Bai, Shi, & Liu, 2014). Meanwhile, China has been among the world's fastest-growing economies and is now the world's

second largest economic entity after the United States. As an economic hotspot, China has been experiencing unprecedented urbanization since economic liberalization began in 1978 (Bai et al., 2014; Kuang, Liu, Zhang, Lu, & Xiang, 2013; Liu, Zhang, & Hu, 2012; Seto, Güneralp, & Hutyra, 2012). Previous studies reported that urban expansion in mainland China was estimated to be 26.5×10^3 km² (the studies did not include the infrastructure areas surrounding cities or between cities) from the late 1980s to 2008 (Liu et al., 2012), and urban areas increased by 43.46% between 2000 and 2008 (Kuang et al., 2013). Extensive urbanization has resulted in the dramatic reduction and degradation of natural landscapes, which

further contributed to the loss of ecosystem services and has increased negative ecological consequences, such as the loss and fragmentation of natural habitat, a decreased food supply, and changes in air and water quality (Grumbine, 2014; He, Liu, Tian, & Ma, 2014; Jantz, Goetz, & Jantz, 2005; Zhang, Yu, Li, Zhou, & Zhang, 2007; Zhao et al., 2005).

Wetlands are found to be important for the biosphere and society in many areas, such as biodiversity conservation, water purification, groundwater replenishment, flood control, shoreline stabilization, storm protection, the provisioning of wetland products, climate change mitigation and adaptation, and cultural values, as well as recreation and tourism (Cao & Fox, 2009; Jafari, 2009). Compared with obvious climate changes, the severe impact of human activities makes these relationships between social or economic development and the protection of wetlands more complicated (Mitsch & Hernandez, 2013; Seto & Fragkias, 2007; Syphard & Garcia, 2001). China has extensive wetlands that account for approximately 6% of the nation's territorial area (Gong et al., 2010). However, 33% of China's wetlands have disappeared during 1978–2008 (Niu, Zhang, & Gong, 2011) and 30% of natural wetlands (50,360 km²) have vanished between 1990 and 2000 (Cyranski, 2009; Gong et al., 2010). This significant loss of wetlands also resulted in ecosystem degradation and further weakened ecosystem services (Duke et al., 2007; Li et al., 2010, b; Wang et al., 2015; Wright & Wimberly, 2013). Protecting wetlands and responding to the degraded quality of wetland ecosystems are challenging given the pressures of social and economic development.

Despite the benefit to the world's population from wetland ecosystem services, massive wetlands are disappearing globally due to urban expansion (Niu et al., 2011; Rebelo, Finlayson, & Nagabhatla, 2009; Schrope, 2001; Smith, 1998; Syvitski et al., 2009). Continued urbanization has severe impacts on wetland ecosystems (Cao & Fox, 2009; Jafari, 2009). The rapid expansion of urban areas has exacerbated the ecological vulnerability of wetlands and caused obvious ecological consequences (He et al., 2014; Seto et al., 2012; Zhao et al., 2005). In economically developed regions, especially coastal areas, the impacts of urbanization on wetlands are more evident (Faulkner, 2004; Giosan, Syvitski, Constantinescu, & Day, 2014; Lee et al., 2006). Some studies focused on urbanization-induced wetland loss have been conducted at the local scale, such as in Portland in the USA (Holland, Honea, Gwin, & Kentula, 1995; Kentula, Gwin, & Pierson, 2004), Balcovas' Delta in Turkey (Bolca et al., 2007), and Lianyungang City in China (Li, Shi, Zhu, Cao, & Yu, 2014). Wetlands in other regions worldwide have apparently shared the same fate (Davis & Froend, 1999; McCauley, Jenkins, & Quintana-Ascencio, 2013; Murray, Clemens, Phinn, Possingham, & Fuller, 2014). Additionally, the construction of roads, ports, and residences and the presence of industrial zones has caused discrepant damage to wetlands based on the level of economic development and differences in population (Ma et al., 2014; Seto et al., 2011). It is therefore necessary to effectively characterize the status of the urbanization-triggered destruction of wetlands at a large scale. How many wetlands have been converted to urban

areas in China, and what are the spatiotemporal patterns of wetland loss due to urban expansion? Related publications are scarce due to the lack of accurate and timely information on the loss of wetlands and its link to urban expansion.

The rapid urbanization process has brought about an enormous loss of wetlands, especially after the establishment of China's socialist market economic system in the early 1990s (He, Bertness, et al., 2014; Jantz et al., 2005), which has been recognized by the Chinese central and local governments (Grumbine, 2014; Yang & Pang, 2006). Many wetland survey projects (e.g., the first and second Chinese National Wetland Inventory, NWI) and protection and restoration programmes (e.g., the China National Wetland Conservation Program) have been implemented (Qiu, 2011; Wang, Wu, Madden, & Mao, 2012). Despite the heightened awareness and promoted policies, little is known about the status and challenges of wetland destruction because of urban expansion, which has rarely been examined. Therefore, for wetland conservation and ecological security, based on updated datasets extracted from satellite images, this paper aims to identify the role of urban expansion in wetland loss and primarily focuses on the wetland loss directly induced by urban expansion in China from 1990 to 2010. For this purpose, we specifically aim (a) to characterize wetland changes and urban expansion during the observed two decades, (b) to examine the spatiotemporal differences in wetland loss due to urbanization, (3) and to discuss the ecological effects of wetland loss induced by the expansion of urban areas and to document the efforts or challenges in conserving wetlands concurrently with urbanization.

2 | MATERIALS AND METHODS

2.1 | Remote sensing datasets and data processing

Distribution datasets for wetlands and urban areas were extracted for 1990, 2000, and 2010 from the China National Land Cover Database (ChinaCover), which was an achievement of the "Strategic Priority Research Program" of the Chinese Academy of Sciences (CAS), Climate Change: Carbon Budget and Relevant Issues. In the process of developing ChinaCover database, satellite images from the Chinese Environmental Satellite (HJ), Landsat Thematic Mapper (TM), and Enhanced Thematic Plus (ETM+) satellites were collected to extract the distribution of China's land cover (Wu et al., 2014, b). The multitemporal images from HJ and TM/ETM+ have a spatial resolution of 30 m and cover the entire nation. Cloud-free images were available from the Satellite Environment Center, Ministry of Environmental Protection and the Internal Scientific Data Service Platform of China. The acquisition of these images from June to October because various categories of land cover can be easily distinguished during this period. Prior to image classification, all images were processed for atmospheric correction using the 6S radioactive transfer model and georectified to 1:100,000 topographic maps using ground control points in the ENVI 5.0 image processing software package. Each scene of the images had at least 30 evenly distributed ground control points, and the root mean squared error of the geometric rectification was less than 1 pixel (or 30 m). After preprocessing, the satellite images

were further used to extract different land cover categories using the eCognition software (Zhang, Li, Yuan, & Liu, 2014).

The object-oriented classification method, which can segment satellite images into homogeneous objects, was used in this classification process because of its accuracy and robustness relative to the traditional pixel-based method (Dronova, Gong, & Wang, 2011). Multiresolution segmentation at different scales, development of different decision rules for various land cover categories, interpretation, and validation were the main steps of image classification. Based on the land cover in 2010, the land cover categories in 2000 and 1990 were updated using Landsat TM/ETM images from 2000 and 1990, respectively, through change detection and the decision-tree method. The image classification for mapping China's land cover was implemented by the CAS, which is the largest scientific organization in the country and has rich experience in image classification and historical databases. Based on the geographic locations, all of the works were divided into eight groups because knowledge of the study area also significantly contributed to the classification process (Wu et al., 2014, b).

In the process of classification, a total of 111,356 field samples and human interpretation were used to support the classification and modification of the land cover dataset in 2010. The samples for land cover in 2010 were primarily obtained from a field investigation in 2011 with global positioning systems (GPS), a camera, and a laptop. Datasets including GPS locations, photos, and landscape categories were recorded. To ensure representative samples were obtained, we designed the sampling routes and density based on the area proportion of each class (statistics in CAS China land use database, CLUD), image operation size of classification, road accessibility, and spectral recognition. Some samples were collected on very high-resolution image and Google Earth interpretation replacing those sampling points that were inaccessible during the field survey. Additionally, historical samples were obtained to support the classification of land cover in 1990 and 2000 (Kuang et al., 2016; Liu et al., 2005), which were also developed by CAS for mapping and validating the CLUD.

In this study, wetlands were categorized as swamp, marsh, lake, river, reservoir/pond, canal/channel, and paddy field (Table 1). Although paddy field is an important type of wetland, it was not considered in our analysis because it is more precisely classified as cropland. To define urban areas, rural lands were excluded using the geographic locations of cities and towns throughout the country. As important support and components of urbanization, industrial and transportation lands were also categorized as urban areas in our analysis, including mining fields and roads connecting cities and towns. Therefore, the urban areas in our study were

categorized as urban built-up land, industrial land, and transportation land (Table 1).

2.2 | Mapping wetlands and urban areas in China

Wetlands can be identified based on standard false colour image composites of the near-infrared band (R), red band (G), and green band (B), which are the optimal settings for wetland delineation (Tiner, Lang, & Klemas, 2015). The normalized difference water index was employed to separate wetlands and other land cover classes, whereas the normalized difference vegetation index (NDVI) was used to separate water bodies and wetlands covered by vegetation. Shape, texture, and phenological features were combined to exclude the paddy fields from natural wetlands. Additionally, object brightness, texture, and NDVI were combined to delimitate swamp and marsh. The shape index calculated from the ratio of the patch area to the patch perimeter and artificial features (e.g., straight boundary features or dam) was used to divide the river, canal/channel, lake, and reservoir/pond.

From the composite satellite images with standard false colour, built-up lands are white in colour and can thus be easily identified. High brightness in the blue band, low NDVI, and a high value of the normalized difference built-up index were used to identify urban areas. The length/width index was used to separate transportation lands from urban built-up and industrial lands, whereas the texture and position of cities and towns were used to divide the urban built-up lands and industrial lands.

In addition, reference data were fully utilized in wetland and urban area identification. Radar images from European Remote Sensing satellites (ERS-2) and Envisat Advanced Synthetic Aperture Radar, and high-resolution images from Google Earth and Satellite Pour l'Observation de la Terre, digital elevation model data, historical wetland datasets, Chinese vegetation maps, geographic information of cities, the statistical yearbook, and ground survey data, as well as published studies (Liu et al., 2005; Gong et al., 2010; Ma et al., 2011; He et al., 2014, b; Kuang et al., 2016), were used to improve the classification accuracy. The preliminary classification results were revised according to visual interpretation following the guidance from wetland and remote sensing experts and abundant field survey data.

The classification accuracy of the ChinaCover datasets was evaluated using independent ground survey samples (29,896 samples for 1990; 30,218 for 2000; and 31,658 for 2010) that were

TABLE 1 Description of the different categories of wetlands and urban areas

Categories	Description	
Wetland	Swamp	A natural wetland with dominant woody vegetation
	Marsh	A natural wetland with dominant herbaceous vegetation
	Lake	A natural polygon water body with standing water
	River	A natural linear water body with flowing water
	Reservoir/pond	An artificial polygon water body with standing water
	Canal/channel	An artificial linear water body with flowing water
Urban area	Urban built-up land	Lands used for residential, commercial, industrial, recreational, and transportation purposes in cities and towns
	Industrial land	Artificial lands used for factories, quarries, and mining outside cities and towns.
	Transportation land	Lands used as roads connecting cities and towns.

independently collected using a random sampling approach (Zhang et al., 2014). The results of the accuracy assessment were confirmed by every provincial environmental department of China, the related experts, managers, and data users have been used to estimate natural capital in China (Ouyang et al., 2016). The average overall accuracies of the ChinaCover datasets were greater than 86% ranging from 81% to 92% over the different climate zones. Specifically, producer accuracy ranged from 86–98% for wetland categories and 79–96% for urban area categories, and user accuracy ranged from 83–96% for wetland categories and 78–94% for urban area categories.

2.3 | Identifying wetland loss caused by urbanization

The study periods 1990–2000 and 2000–2010 were defined as Stages 1 and 2, respectively. The wetland loss caused by urbanization was evaluated using a cross tabulation analysis. First, the reduction in wetland area and urban expansion in the two stages were examined using the ArcGIS 10.0 software package. Second, the loss in area of different wetland categories induced by urbanization and encroachment on wetlands by different urban area categories was investigated. Third, the spatial variation in lost wetlands due to different categories of urban expansion was documented among the nine subregions of China. Typical regions with notable urban expansion and typical wetland categories were chosen to present the obvious wetland loss to urban expansion.

3 | RESULTS

3.1 | Urban expansion in China from 1990 to 2010

Urban area density, the percentage of urban area per 1 km² unit of land area, shows a clear spatial pattern of urban areas in China (Figure 1a). Urban areas are sparsely scattered in western China, while they are clearly clustered in eastern China. Eastern China showed apparent urban expansion during the two decades, especially in the coastal provinces (Figure 1b). Specifically, the Bohai Sea Economic Rim, the middle and lower reaches of the Yangtze River, and the Pearl River

Delta (PRD) were the most prominent regions with rapid economic development and urbanization processes. The urban area in China was estimated to be 68,305 km² in 1990; 86,819 km² in 2000; and 130,376 km² in 2010 (Table 1). A notable increasing trend was documented at a rate of 1,851 km² year⁻¹ in Stage 1 and 4,356 km² yr⁻¹ in Stage 2, with the urban area increasing by 90.9% during the two decades. In addition, the urban area of medium and small cities underwent more distinct expansion in Stage 2 than in Stage 1, especially in the eastern regions, such as Shandong and Jiangsu provinces.

Table 2 displays the areas of each urban area category in different years, indicating that expansion of urban built-up land was the principal component of urbanization. The amount of urban built-up land increased from 46,591 km² in 1990 to 59,755 km² in 2000 and to 88,645 km² in 2010. More than 68% of the increase in the area of urban built-up lands was documented in Stage 2. As an important component of the urban area, industrial land was mainly distributed outside of cities or towns. After 20 years of urbanization and industrialization, the area of industrial lands in China has more than doubled, with an increase rate of 592 km² yr⁻¹. Transportation land provides crucial support for economic and social development, which is closely linked to urban built-up and industrial lands. There was an increase in the area of transportation lands of 2,920 km² in Stage 1 and 5,263 km² in Stage 2 across China.

3.2 | Change in China's wetlands from 1990 to 2010

The spatial pattern and changes of China's wetlands are illustrated in Figure 2. The Tibetan Plateau, Northeast China, and middle-lower

TABLE 2 Area (km²) of different categories of urban area in different years

Urban area categories	1990	2000	2010
Urban built-up land	46,590.9	59,755.0	88,645.4
Industrial land	8,775.5	11,204.7	20,606.6
Transportation land	12,938.8	15,858.8	21,124.4
Total	68,305.2	86,818.5	130,376.4

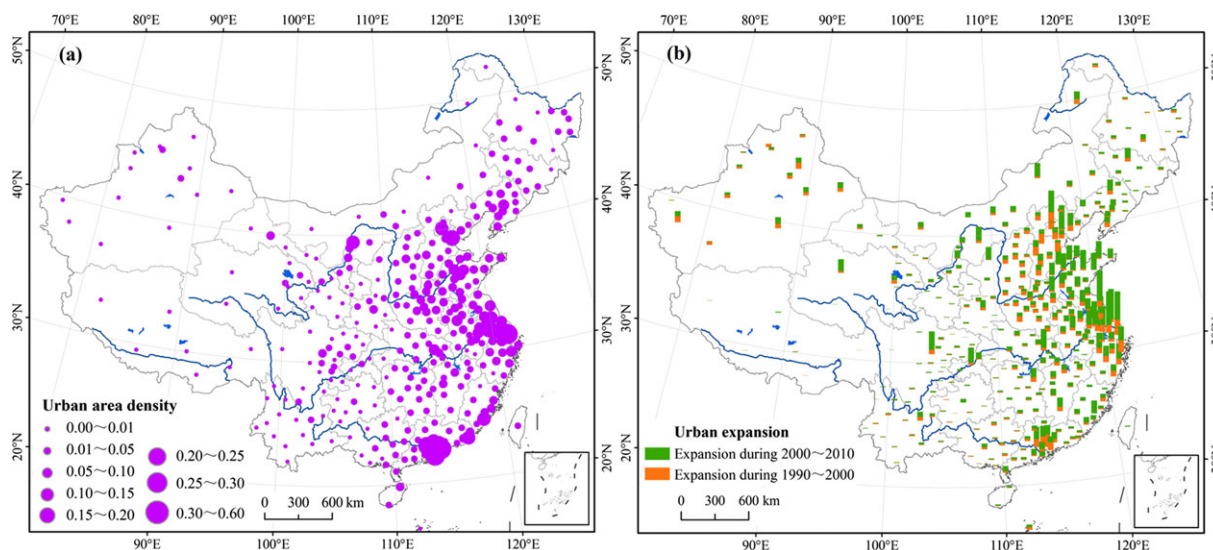


FIGURE 1 Spatial pattern of urban area (a) density and (b) expansion during 1990–2010 [Colour figure can be viewed at wileyonlinelibrary.com]

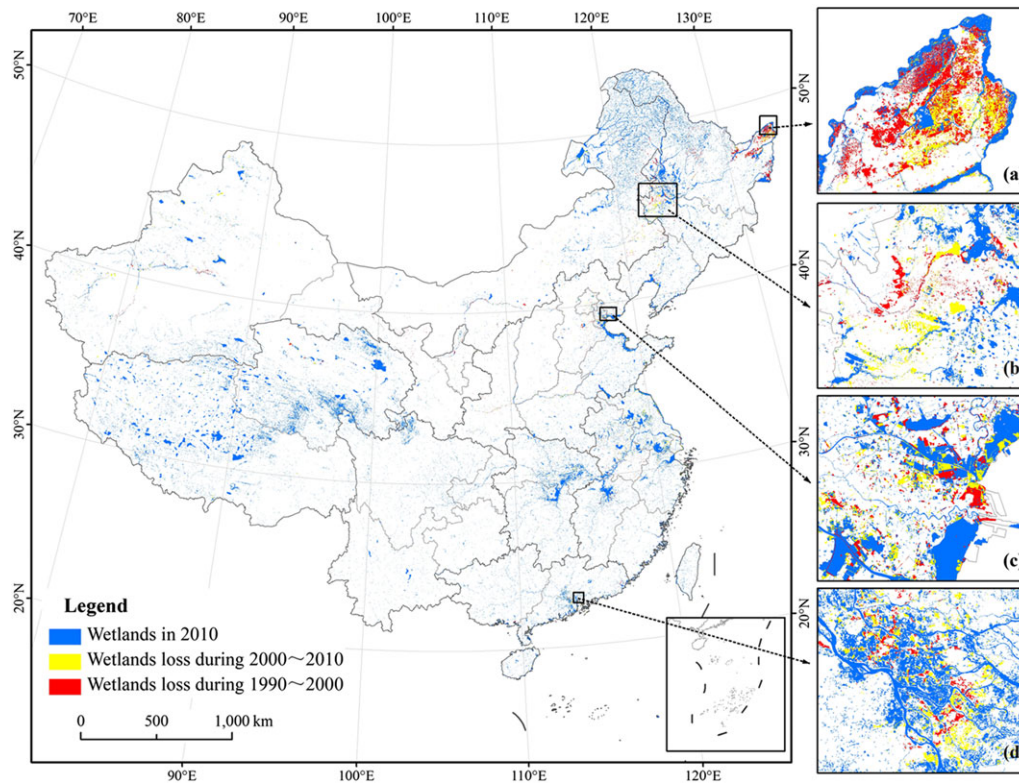


FIGURE 2 Spatial pattern and changes of wetlands in China during 1990–2010 [Colour figure can be viewed at wileyonlinelibrary.com]

Yangtze River Delta (YRD) are the three major regions in which wetlands are distributed. Inconspicuous changes in wetlands on the Tibetan Plateau are revealed, while wetlands were destroyed in Northeast China (Figure 2a and 2b) and coastal regions (Figure 2c and 2d) in particular in the two stages. Our results extracted from satellite images reveal that the total area of China's wetlands was 359,799 km² in 1990; 355,236 km² in 2000; and 357,118 km² in 2010.

Table 3 documents the notable changes that occurred in various wetland categories in China over the investigated two decades. Marsh is the most important and common natural wetland type but was the only category showing a decrease in area. In 2010, the area of marsh was estimated to be 139,552 km², with a loss of 17,752 km² or 11.3%, relative to the area in 1990. Conversely, the area of swamp increased slightly, with increases of 38 km² in Stage 1 and 125 km² in Stage 2. The lake and river categories experienced increases in area of 3.9% and 3.2%, respectively. In addition, human-made wetlands experienced an obvious increase in area. For example, the canal/channel category increased from 2,759 km² in 1990 to 2,856 km² in 2000 and to

2,941 km² in 2010. Although a wide variety of small ponds have been lost, the total area of the reservoir/pond category still showed an obvious increasing trend, especially the reservoirs and aquaculture ponds.

3.3 | Urban expansion encroachment on wetlands

Although some natural wetlands were converted into human-made wetlands, human-induced wetland loss was more significant. From 1990 to 2010, 2,883 km² of wetlands disappeared because of urbanization, which accounts for 6.0% of the total wetland loss. Along with a faster urbanization process, the rate of wetland loss due to urbanization was high in Stage 2 (213 km² yr⁻¹), which was 2.8-times greater than that in Stage 1 (75 km² yr⁻¹). As shown specifically in Table 4 and Figure 3, the area of reservoir/pond that disappeared as a result of urban expansion (1,890 km²) was the highest among the six wetland categories. The urbanization-triggered loss of reservoir/pond had the most significant rate of increase between the two stages. The results also reveal that the losses of reservoir/pond wetlands were mainly distributed in the Bohai Sea Economic Rim and PRD. Second to reservoir/pond, marsh destroyed by urbanization showed a loss of 578 km², which was mostly found in the Northeast China and YRD. Small areas of the swamp and canal/channel categories were consumed by urban expansion.

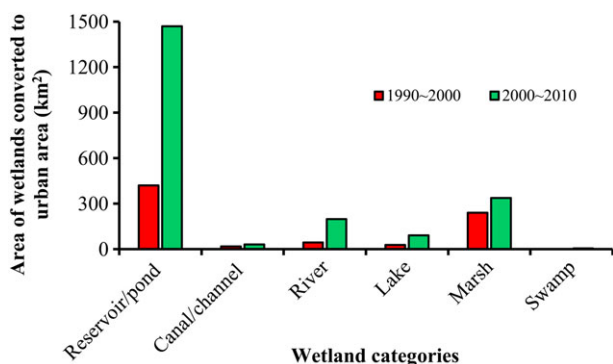
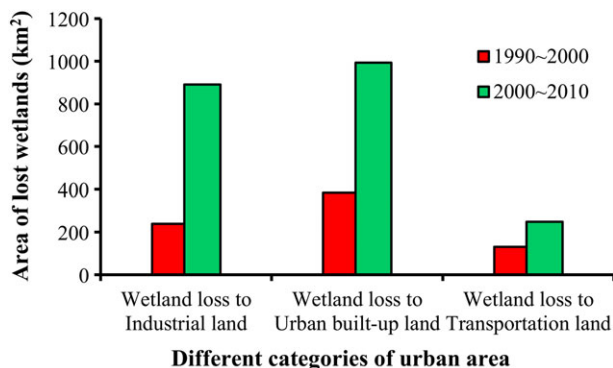
Vanished wetlands attributed to urbanization were mostly converted into urban built-up lands (Figure 4). Accompanied by an influx of rural people into cities, urban built-up land immediately expanded, which propelled the loss of wetlands in China, with a loss in area of 382 km² in Stage 1 and 993 km² in Stage 2. In the pursuit of economic efficiency, a great deal of wetlands were converted into industrial lands, with an area of 239 km² in Stage 1 and 890 km² in

TABLE 3 Area (km²) of different wetland categories in different years

Wetland categories	1990	2000	2010
Swamp	7,760.7	7,798.8	7,923.7
Marsh	157,304.4	144,054.3	139,552.1
Lake	80,578.5	82,775.0	83,723.0
River	61,458.7	61,598.2	63,412.6
Reservoir/pond	49,937.6	56,153.9	59,565.3
Canal/channel	2,759.4	2,855.7	2,941.2
Total	359,799.3	355,235.9	357,117.9

TABLE 4 Area (km²) of conversions from different wetland categories into urban area during 1990–2000 (Stage 1) and 2000–2010 (Stage 2)

Wetland	Urban built-up land		Industrial land		Transportation land		Total	
	Stage 1	Stage 2	Stage 1	Stage 2	Stage 1	Stage 2	Stage 1	Stage 2
Swamp	0.0	0.9	0.3	3.0	0.6	0.5	0.9	4.4
Marsh	54.5	97.0	96.5	160.2	89.7	79.7	240.6	336.9
Lake	6.5	34.9	17.4	32.2	4.2	23.3	28.1	90.4
River	18.0	86.5	16.0	79.9	10.4	32	44.3	198.4
Reservoir/pond	292.4	749.3	108.6	614.3	19.1	106.5	420.1	1470.1
Canal/channel	10.8	24.3	0.3	0.6	6.4	6.3	17.6	31.2
Total	382.2	992.9	239.0	890.2	130.4	248.3	751.6	2131.4

**FIGURE 3** Variation among the losses of different wetland categories due to urbanization [Colour figure can be viewed at wileyonlinelibrary.com]**FIGURE 4** Variations in the area of wetlands converted into different categories of urban area [Colour figure can be viewed at wileyonlinelibrary.com]

Stage 2. In addition, transportation lands, which were constantly expanded to support economic development, led to a 378 km² loss in wetlands. Among the three categories of urban area, expansions of industrial land induced a more evident increasing trend in lost wetlands during the last two decades.

3.4 | Spatial disparity in the decline in wetland area due to urbanization

Figure 5 documents variation in the loss of wetlands caused by the expansion of different categories of urban area. Urbanization-triggered wetland loss was the highest in Southeast China (921 km²,

Figure 5g) and South China (542 km², Figure 5h), which account for 31.9% and 18.8%, respectively, of the total loss of wetlands caused by urban expansion across the country. Approximately 2,394 km² of the wetlands that disappeared due to urbanization were identified in the eastern regions (Northeast China, North China, Southeast China, and South China), which account for 83% of the total urbanization-induced loss of wetlands in China.

Among the different geographic regions, the wetlands converted to industrial lands were greatest in Northeast China, Inner Mongolia, Northwest China, the Tibetan Plateau, and Southeast China, while wetlands converted to urban built-up lands were dominant in North China, Central China, and South China. Southwest China had a relatively smaller population and fewer wetlands, and thus, little wetland area disappeared due to urbanization (Figure 5i). As shown in Figure 5, the more rapid urbanization in Stage 2 (green colour) than in Stage 1 (pink colour) gave rise to a greater loss of wetlands. Meanwhile, a more apparent increase in the area of urbanization-induced wetland loss in Stage 1 than Stage 2 was observed in Southeast China (Figure 5g).

The clear spatial disparity among various levels of urbanization-induced wetland loss at the regional scale (Figure 5) suggests that the pattern of the decrease in wetlands can be closely linked to urban expansion. Figure 6 illustrates the hotspot areas of wetland loss induced by urban expansion with image examples. During the extensive urban expansion in the two decades, considerable losses of wetlands were observed primarily in four identified hotspot areas: the Beijing–Tianjin Metropolitan Region (BTMR), the YRD, the Jiangnan Plain, and the PRD. In addition, the wetlands lost to urbanization in Stage 1 were mostly observed in coastal regions (red colour in Figure 6), especially in the BTMR and the Liao River Delta, while in Stage 2, they mainly occurred in the Jiangnan Plain, YRD, and PRD (green colour in Figure 6). In the hotspot areas, the red colour is surrounded by the green colour, which suggests that the converted wetlands were expanded following urban expansion from Stage 1 to Stage 2.

4 | DISCUSSION

4.1 | Identification of urban areas and wetlands based on satellite images

Integrating the obvious spectral distinction, image texture, and phenology, three categories of urban area and six categories of wetland

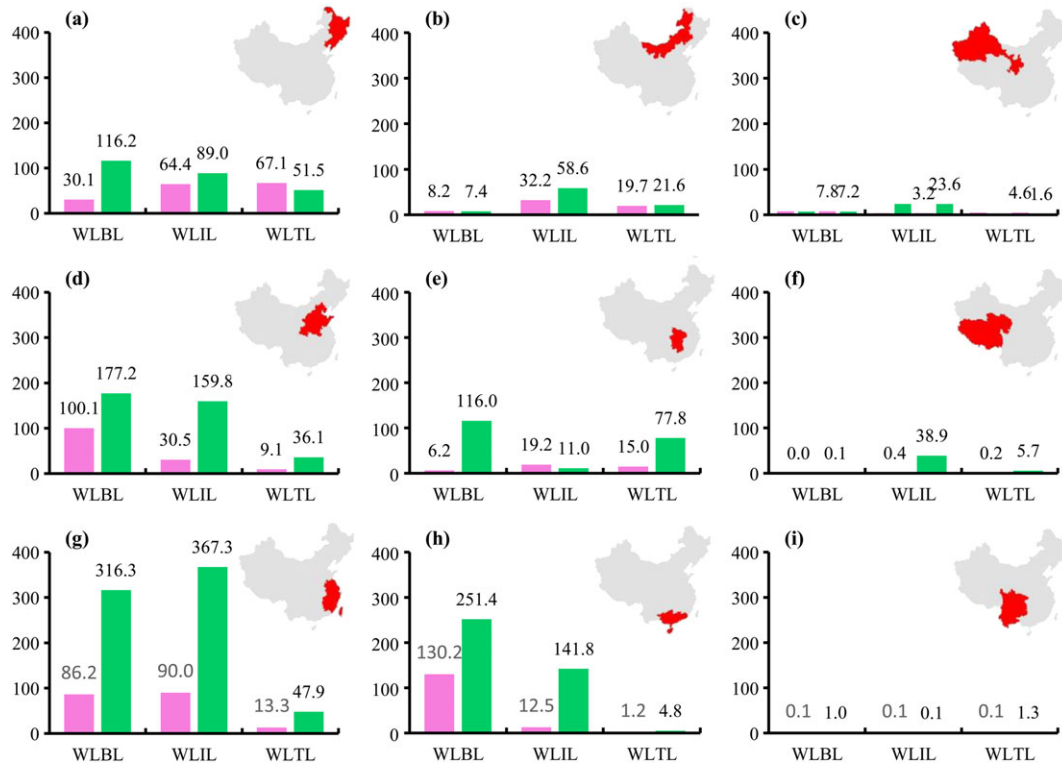


FIGURE 5 Spatial variations in wetland loss induced by the expansion of different urban area categories at the scale of large geographic regions in China [the division of nine subregions is based on Piao et al. (2009)]: (a) Northeast China, (b) Inner Mongolia, (c) Northwest China, (d) North China, (e) Central China, (f) Tibetan Plateau, (g) Southeast China, (h) South China, and (i) Southwest China; WLBL denotes wetland loss due to expansion of urban built-up land; WLIL denotes wetland loss due to expansion of industrial land; WLTL denotes wetland loss due to expansion of transportation land [Colour figure can be viewed at wileyonlinelibrary.com]

were well classified for the whole country (Zhang et al., 2014). Because some industrial and transportation lands located in the cities are difficult to separate from residential lands, we categorized all these lands into urban built-up lands. The role of urban expansion in wetland loss was thus quantified and highlighted in this study. Differing from the classification system of the Ramsar convention, our wetland categories completely and successfully consider image features to obtain the distribution of wetlands across the country. Conducting the classification using the images with a spatial resolution of 30 m inevitably contributed in the classification errors to some degree, especially in the identification of narrow rivers or canal/channel, small lakes or ponds, and isolated marshes. However, we can differentiate canal/channel from river and reserve/pond from lake by means of artificial features, for example, the straight boundary or obvious dams. Additionally, after the rule-based classification, visual interpretation was developed to approve the classification accuracy based on a large number of field survey data. The images from Chinese HJ and Landsat satellites are the optimal data sources for wetland and urban area classification at such large scale (about 9.6 million km²) for a long time series.

Our estimates on the wetland areas differ from the results from other publications (Gong et al., 2010; Ma, You, Liu, & Zhang, 2012; Niu et al., 2012) or Chinese government's reports (Table 5). Results for the years of 1990, 2000, and 2010 in our study are higher than the estimate by workgroup of Niu and Gong mainly based on human interpretation and pixel-based classification of remote sensing technology. We argue that object-oriented method effectively used in this study prevents 'salt and pepper' noise (Dronova et al., 2011). Multiple-

season images, especially incorporating data from wetter seasons, minimize the underestimation of seasonal wetlands. The consistent field investigations for the land use dataset (CLUD) at different times funded by the CAS (Liu et al., 2005; Ma et al., 2011; Zhang et al., 2014) greatly contribute to our classification and accuracy of the datasets. The State Forestry Administration of China have done two NWI during the periods of 1995–2003 and 2009–2013. Large uncertainties exist in the two NWIs because these two surveys were implemented in multiple years and by means of multimethods. In addition to dramatic changes of wetlands would occurred during the observed years, manual survey cannot accurately calculate the area of all wetland patches. Meanwhile, we did not determine the area of shallow sea water with depth lower than 6 m and the intertidal zone because it is difficult to determine by single-date images or mosaicked multirate images. The estimates of the NWI are thus obviously higher than our and Niu's results (Niu et al., 2009). Ma et al. (2012) estimated the area of China's wetlands (excluding Taiwan, Hong Kong, and Macao) based on a synergistic approach integrating previous census and spatially explicit datasets. Although calculated result is close to the wetland area statistics from the first NWI, they did not considered the error sources of the integrated datasets. The produced wetland map also have large uncertainties due to a coarse spatial resolution of 1 km. Various categories of land use were also mapped in the CLUD every 5 years (Kuang et al., 2013; Liu et al., 2005; Liu et al., 2012). However, the CLUD and ChinaCover developed different classification system due to differed application aims and thus produced different results. Marshes are classified as grasslands in CLUD while they

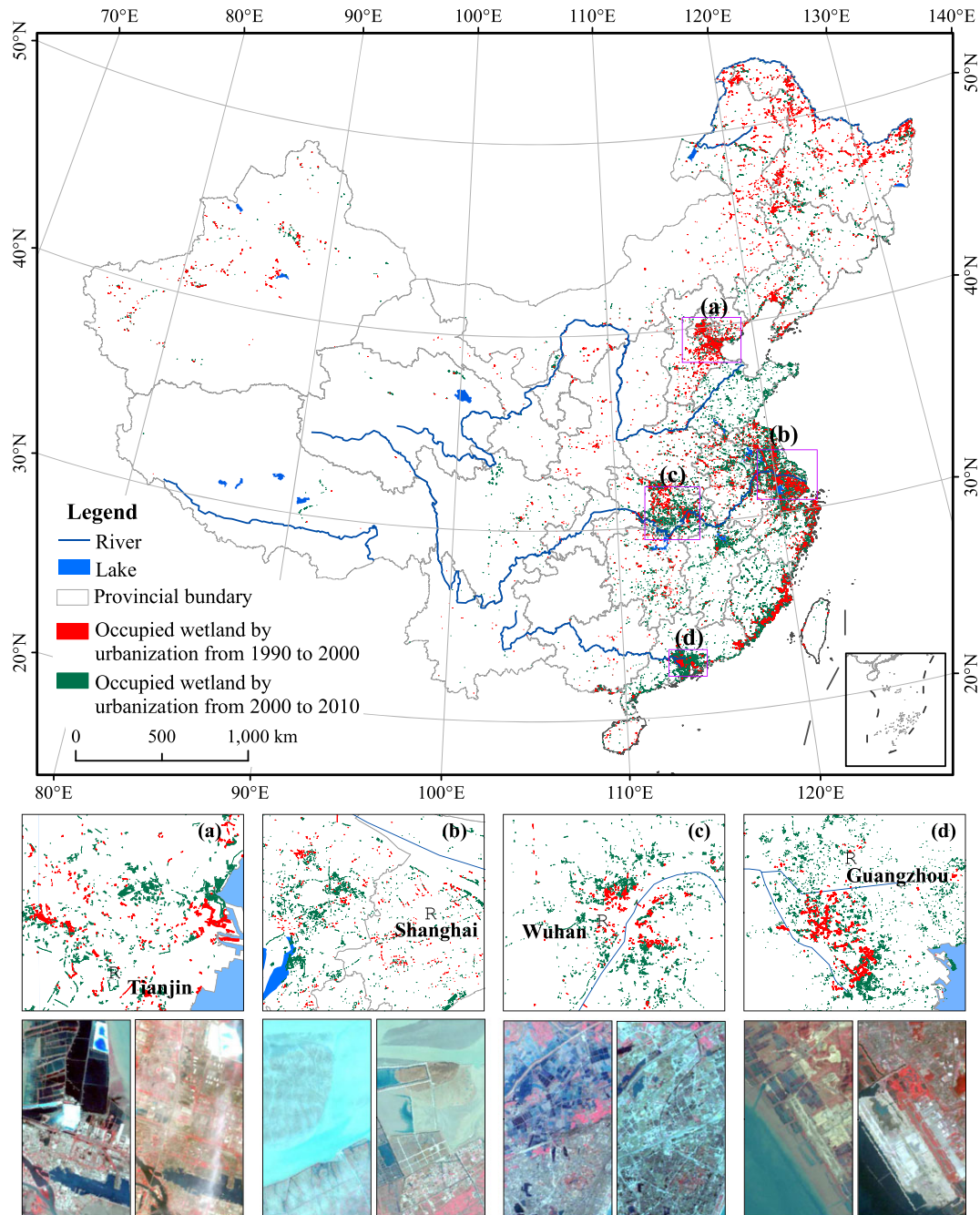


FIGURE 6 Spatial pattern of the wetlands destroyed by urbanization during the periods of 1990–2000 and 2000–2010 for China and hotspot areas with image examples: (a) the Beijing–Tianjin Metropolitan Region, (b) the Yangtze River Delta, (c) the Jiangnan Plain, and (d) the Pearl River Delta [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 5 Comparison between our estimates and other reports

Research	Wetland area in different years (km ²)			Data source and Method
	1990s	2000s	2010s	
This study	359,799	355,236	357,118	China HJ and Landsat TM/ETM+, Object-oriented image classification and visual interpretation.
Niu and Gong Workgroup (Gong et al., 2010; Niu et al., 2012)	355,208	304,849	324,097	Landsat TM and CBERS, Pixel-based classification and manual interpretation
The National Wetland Resource Investigation	—	384,855	536,026	Field investigation and auxiliary remote sensing classification
Ma et al., 2012		384,864		Synergistic approach using census and spatially explicit datasets

are categorized into natural wetlands in our study. Therefore, our estimate on the wetland area in China can provide important database for the wetland researches and managements.

4.2 | Wetland loss and degradation due to urbanization

An apparent expansion of urban areas (Figure 1) linked with a decrease in wetland area (Table 4) was revealed in this study. Compared with previous surveys, our results present more specific information on wetland loss due to urbanization. The second NWI reported that the loss of wetlands in China to constructed lands increased by 9 times relative to the first. However, in this study, we advanced a related result showing that urbanization-induced wetland loss increased by 2 times in the investigated two decades using only remote sensing observations. The reviewed literature indicates that wetlands in metropolitan areas worldwide have been threatened by urban development, such as those in Balçovas' Delta in Turkey, Portland (Holland et al., 1995), and central Florida (McCauley et al., 2013) in the USA, and South Korea (Murray et al., 2014). Because China's urbanization process occurred significantly later than that in developed counties, the conversion from wetlands to urban areas should be minimized as much as possible. Additionally, although the magnitude of wetland loss and the beginning of rapid urbanization processes differ compared with those in other regions worldwide, our results broadly agree with the conclusion that a lack of studies on urbanization-triggered wetland loss at a large or national scale leads to an insufficient assessment of global or regional wetland conservation and ecological security.

Socialist market economy system established in 1992 promoted significant growth of gross domestic product (GDP) and rapid increase of urban population (Figure 7). Additionally, after China joined the World Trade Organization in 2001, a series of national policies promoted rapid economic development (Figure 7). These multiple

factors remarkably drove the expansion of urban area (Kuang et al., 2016). As a hotspot area with significant urbanization in China, wetland loss was particularly evident in the BTMR (Figure 6a), where a large number of small ponds have been transformed into urban residential lands in the past several decades (Yang & Lu, 2014). The increasing urban population and the rising demand for space for residences and infrastructure inevitably encroached on different wetlands categories, especially the lakes and ponds in the city. Similarly, our results demonstrate that the disappearance of vast areas of marshes and lakes can be closely related to the expansion of urban areas in the largest economic zone of China, the YRD (Figure 6b). Economic growth has caused an acceleration of human damage to wetlands (He, Bertness, et al., 2014). As a center of advanced manufacturing and modern service industries and the earliest pilot area of market economy reform, the PRD experienced the most significant population increase and economic development (Figure 7) and urban expansion thus caused the loss of a large area of wetland as observed in Figure 6d (Haas & Ban, 2014; Seto & Fragkias, 2005). Mangroves, an important type of swamp, are threatened by urban expansion, especially in the PRD (Jia et al., 2014; Liu, Li, Shi, & Wang, 2008). Overall, the national policies evidently promote increases in the urban population and GDP and further drive urban expansion in the four hotspot areas. All these changes notably induced the conversion of wetlands to urban areas. Compared with eastern China, the population density and economic development level is clearly lower in central and western China (Bai et al., 2014), which has restricted the expansion of urban areas. Therefore, the area of wetlands converted to urban areas was lower (Figure 6). However, the policies and plans tend to promote regional economic and urban development in the central and western China, and a continuous focus on the effects of urbanization on various wetland categories is therefore needed.

In this study, urban built-up land was not the only type of urbanization that substantially encroached on wetlands. Increasing industrial and transportation lands also destroyed large areas of isolated

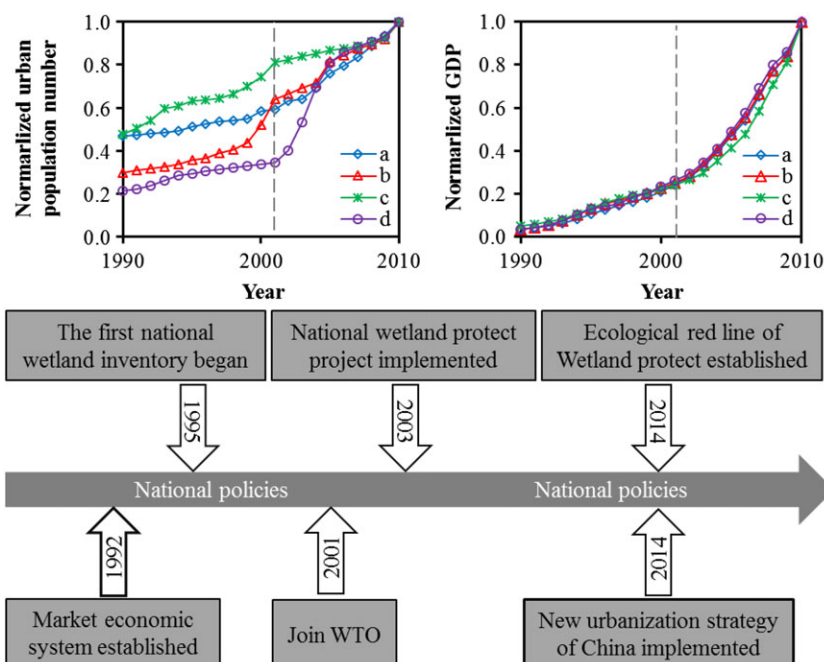


FIGURE 7 Changes in the normalized urban population number and GDP and the related national policies in the hotspot areas of urbanization-induced wetland loss: (a) the Beijing-Tianjin Metropolitan Region, (b) the Yangtze River Delta, (c) the Jiangnan Plain, and (d) the Pearl River Delta (normalized urban population number or GDP denotes the ratio of the value in each year to the maximum value from 1990 to 2010). WTO, World Trade Organization [Colour figure can be viewed at wileyonlinelibrary.com]

wetlands and indirectly led to the loss of wetlands. For example, coal mining is an extremely water-intensive industry and thus plays a critical role in the lake loss in Inner Mongolia (Tao et al., 2015). It is noted that the petroleum industry is flourishing in the Shuangtai estuary (Tian et al., 2017) and Yellow River Delta (Bi, Wang, & Lu, 2011). A growing oil production base caused the development of more roads and ports for transportation and industrial plants for oil refining, all of which caused the massive loss and significant fragmentation of wetlands (Tian et al., 2017). Similar to the result showing that extensive wetlands were converted to industrial and transportation lands along the Yellow Sea (Murray et al., 2014), the increasing construction of roads, ports, and dams directly caused a high degree of wetland loss in coastal areas of China. China's seawalls, which were constructed to protect human habitations and various infrastructure, have increased in 3.4 times in length during the observed two decades (Ma et al., 2014). The changed hydrological conditions due to the construction of seawalls led to notable coastal wetland loss and degradation, which further affected the biodiversity (Ma et al., 2014). It is thus necessary to specifically study the variable responses of wetlands to urbanization due to different urban expansion types at regional scale to contain the conversion trend.

4.3 | Potential ecological effects

Urbanization continually places a heavy burden on local water, soil, and air resources and biological diversity (Zhao et al., 2005). China's wetlands provide the predominant locations for migratory waterfowl and other rare species to feed and rest, but the shrinkage and fragmentation of wetlands caused by urban expansion have led to the loss and degradation of natural habitat (He, Liu, et al., 2014; Wang et al., 2012), which further affects biodiversity (Faulkner, 2004). Meanwhile, because of the changes in the wetland environment and artificial introductions, biological invasions are becoming one of the top threats to wetland ecosystems (Junk et al., 2013), such as the invasive plants, *Eichhornia crassipes* and *Spartina alterniflora*. As a result of urbanization, wetland hydrological processes can be greatly affected by the increasing area of impervious surfaces (Lee et al., 2006). Human activities associated with urbanization reduce the storage of water in wetlands (i.e., lakes and ponds), downgrade the ability of wetlands to adjust to rainfall, and further increase environmental disasters, such as urban flood disasters and extreme droughts (Yang & Pang, 2006). For example, urban flooding is particularly frequent in Wuhan City along the Yangtze River, which can be largely related to the disappearance of lakes and ponds caused by urban expansion (Bai et al., 2014). Not only have the water and soil quality of wetlands been degraded by domestic and industrial sewage (Wang et al., 2012; Zhao et al., 2005), but massive natural wetlands have also been exploited to become urban areas and aquaculture ponds, which has resulted in intensified ocean disasters and weakened self-purification, and has impaired the interception of sediment and contaminants in the regional ecosystem (Kirwan & Megonigal, 2013; Murray et al., 2014; Seto & Fragkias, 2007). Although wetlands play an important role in optimizing the living environment of cities by reducing the urban heat island effect, haze, and sand storms (Lee et al., 2006; Zhao et al., 2005), the loss of wetlands that has resulted from urban expansion

limits their functions. Additionally, although higher productivity in wetlands has been identified, the decrease in wetland area due to urban expansion has lowered the capacity of wetlands to sequester carbon responding to global climate warming (Allred et al., 2015; Rooney, Bayley, & Schindler, 2012). Although they are important tourism resources, urbanization has progressively encroached on various wetland landscapes, such as those inhabited by *Suaeda heteroptera* in the Shuangtai estuary (Jia et al., 2015) and mangroves in southern China (Jia, Wang, Zhang, Ren, & Song, 2015). Based on the value coefficients provided by Costanza et al. (2014), the declined value of wetland ecosystem service due to urbanization in China was estimated to be 0.75 billion dollars per year. The loss of ecosystem services induced by urbanization should thus be especially concerning.

4.4 | Efforts and challenges of wetland protection in response to urbanization

Compared with agricultural reclamation and aquaculture development, the conversion from wetlands to urban areas is absolutely irreversible. Therefore, the decrease in wetlands induced by urbanization and the resultant ecological and environmental effects should receive greater attention (Lee et al., 2006; Mitsch & Hernandez, 2013). Fortunately, wetland shrinkage and degradation have attracted the attention of the Chinese central and local governments. Currently, an estimated 0.23 million of China's wetlands have been protected in 577 natural reserves and 468 wetland parks (result of the second NWI, www.forestry.gov.cn). The Chinese Government implemented the National Wetland Conservation Program in 2003, which divided the country into eight regions to promote wetland conservation and restoration. The national Five-Year Plans (2005–2020) also had wetland protection as a key component. By 2015, China had 46 sites designated wetlands of international importance (Ramsar sites), and 91 sites designated national wetland reserves (Zheng, Zhang, Niu, & Gong, 2012). Meanwhile, to adapt to the processes of urbanization, 50 national urban wetland parks were constructed. This paper found that the lower and middle reaches of the Yellow and Yangtze Rivers were the hotspots of wetland loss due to urbanization (Figure 6), and they are also the main regions in which the national urban wetland parks are distributed (70%). Although great efforts have been made to protect wetlands and respond to urbanization-induced ecological issues, it should be noted that the rate of wetland loss due to urbanization increased after 2000 ($213 \text{ km}^2 \text{ yr}^{-1}$ between 2000 and 2010). Therefore, scientifically designing a conservation system of wetland ecosystems considering the integrity the upstream and downstream is critical to enhance wetland management in different basins.

The differences in the loss and protection of wetland ecosystems were related to the different levels of economic development and urbanization. Our results demonstrated that the urbanization-induced wetland loss was mostly distributed in eastern developed areas (Figure 6). In particular, China's long coastline contains 70% of the large cities in China, over half of the total population and nearly 60% of the overall economy aggregate (Ma et al., 2014). Thus, greater attention is urgently needed in coastal wetlands and eastern regions, where the urbanization-induced loss of wetlands accounted for 70% of the total losses in China between 2000 and 2010. To narrow the

gap in economic development between eastern and western China, the strategy of rebuilding the old industry base in Northeast China, developing the west, and implementing the Silk Road Economic Belt and the 21st Century Maritime Silk Road will promote a remarkable amount of urbanization in Northeast China and West-Central China. The Chinese central government has proposed clear goals to promote the development of urbanization, for example, by increasing the percentage of the population in urban areas to 60% by 2020 (The Xinhua News Agency, 2014). In the national 13th Five-Year Plan (2015–2020), five national primary urban agglomerations and nine national secondary urban agglomerations were planned as development priorities. Our results indicate that the hotspot areas of wetland loss induced by urban expansion correspond to the major planned national urban agglomerations in China. In addition, the significant expansion of China's urban areas has been forecasted (Seto et al., 2012). Therefore, under the new urbanization strategy, China's plan for economic development and population aggregation creates new challenges for wetland protection and management, especially in terms of the prevention and reduction of wetland destruction due to urban expansion.

4.5 | Implications

It is worth noting that the extensive urbanization in China has consumed a large number of wetlands. In addition, China's urbanization-induced wetland loss has generated negative environmental consequences. Therefore, ongoing studies that focus on the urbanization-imposed influences on wetland ecosystems are desired. Due to the massive number of people migrating into cities, more housing and employment opportunities are urgently needed, which significantly drive the expansion of urban built-up lands and industrial land (Kentula et al., 2004). Rapid urbanization thus makes the contradiction between urban development and the sustainable use of wetlands increasingly prominent (Elmore & Kaushal, 2008; Giosan et al., 2014), especially in the eastern provinces of China. Almost all deltas and coastal ecosystems in China have experienced notable impacts of urbanization on their wetland ecosystems (He, Liu, et al., 2014; Zhao et al., 2005). As we determined, 72.2% of the conversion of wetlands into urban built-up lands and 73.3% of the conversion of wetlands into industrial lands occurred in the 10 eastern provinces. Beside the direct encroachment on wetlands, impacts of landscape fragmentation and degradation on the capacity for ecosystem service of wetlands were intensified by urban expansion (Yeh & Huang, 2009; Li et al., 2010, b). The evident patterns of urbanization-induced wetland loss indicate that the eastern region should receive more attention (Figures 5 and 6).

During 1990–2010, the increasing urbanization rate, the expansion of urban built-up lands in medium and small cities, the transfer of manufacturing or polluting industrial enterprises from large cities to medium and small cities, and a denser traffic network all strongly contributed to the decrease in wetlands and further led to significant environmental consequences, which were clearly observed in Shandong, Jiangsu, and Zhejiang provinces (Figure 6). Urbanization and industrialization are expected to continue to occur in China for the next few decades (Kuang et al., 2016). Therefore, in the

development of planned urban agglomerations, wetland ecosystem services should be brought into and linked to economic decision-making for public policy. Although areas of human-made wetlands showed an obvious increase along with urbanization in China, the ecosystem services of natural wetlands cannot simply be replaced by human-made ecosystems (Murray et al., 2014). In view of the continuous economic reform strategies and the urban dream in China, scientific policies and regulations must be implemented and enforced to minimize the disappearance of wetlands and sustain the conservation and management of the remaining wetlands in the context of rapid urbanization (Bai et al., 2014; Pan & Wang, 2009; Yang & Pang, 2006).

5 | CONCLUSIONS

The urbanization-induced loss of wetlands at the national scale was identified in this study based on updated information regarding wetland change and urban expansion extracted from multisource satellite images. Our study reveals an obviously increasing trend and a notable spatial disparity in wetland loss due to urbanization in China. During 1990–2010, China lost 2,883 km² of wetlands due to urban expansion, most of which occurred in the eastern regions. Southeast China and South China were confirmed to be the primary two regions with dramatic wetland loss due to urbanization. Four hotspot areas of urbanization-induced wetland loss in China were identified: the Beijing–Tianjin Metropolitan Region, the YRD, the Jiangnan Plain, and the PRD. Of all wetland categories, reservoirs/ponds and marshes suffered the most severe losses. The rate of wetland loss induced by urbanization continued to increase after 2000. Although great efforts have been made towards wetland conservation in recent years, China must prevent more wetlands from being wiped out by urbanization if the country is to achieve its sustainable development goals. In view of the continuous economic reform strategies, effective policies and regulations must be implemented and enforced to sustain regional wetland conservation. The conservation of wetlands should be brought into and linked to economic decision-making for public policy.

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