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The 7-Decade Degradation of a Large Freshwater Lake in Central Yangtze River, China

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Freshwater lakes store water for human use and agricultural irrigation and provide habitats for aquatic fauna and flora. However, a number of these lakes have been degraded by human activities at a rapid rate. Here, we used historical land cover information and remotely sensed data to explore a 7-decade (between 1930s and 1998) shrinkage and fragmentation of Dongting Lake, the second largest freshwater lake in China, located in the drainage basin of Central Yangtze River. The water surface area of Dongting Lake decreased by 49.2%, from 4955 km^2 in the 1930s to 2518 km^2 in 1998, with an average decrease rate of 38.1 km^2/yr in the past 7 decades. The lake was also fragmented, as indicated by a decreasing mean patch size from 4.2 km^2 in the 1930s to 1.7 km^2 in 1998. The degradation of the lake is largely attributed to a rapidly growing human population in the lake region that led to extensive impoldering. The degradation of the lake has resulted in negative ecological consequences, such as frequent flooding, a decline of biodiversity, and extinction of some endemic species. Our results also suggest that lake restoration projects implemented in this region since the end of the 1990s will help to decrease the lake degradation.

Introduction

Freshwater shortage has been a serious problem in China and is becoming a global issue, as the usable portion of freshwater is estimated to be less than 1% of all freshwater on earth (*1*, *2*). Freshwater lakes play a vital role in the biosphere, not only because 46% of the global renewable freshwater is stored in these lakes, but also because they provide habitats for aquatic fauna and flora (*3*). However, freshwater lake watersheds have been focal points of human settlement due to their suitable environment for development and food production (*4*, *5*); therefore, the freshwater lakes have been disturbed by human activities to a greater extent as compared to terrestrial ecosystems. The alteration of lake habitats has been found to influence biodiversity for freshwater lake systems (*6*, *7*). How freshwater lakes change under the impacts of human activities and what ecological consequences the lake alterations bring to biodiversity have received increasing attention. Unfortunately, there have been surprisingly few studies conducted at the decadal time scale, especially from a heavily populated developing region.

Dongting Lake was once the largest freshwater lake in China, reaching its maximum surface area of ~6300 km^2 in 1825 (*8*). However, the present lake surface area is approximately 40% (~2500 km^2) of its maximum size. It has become the second largest freshwater lake in the country. The lake was segregated into three sections, East, West, and South Dongting Lake, mainly due to impoldering practices, a special type of land conversion that encroaches lakes and their associated wetlands through the construction of dykes for agricultural purposes (*8*, *9*). Because the lake consists of a number of highly valuable wetlands, it was designated as one of the first seven most important international wetland conservation areas in China and protected by Convention on the Wetlands of International Importance especially as Waterfowl Habitat (*10*). Because of its critical ecological functions, unique biodiversity, and important habitats for an endangered Yangtze River Dolphin or Baiji (*Lipotes vexillifer*), the Dongting Lake watershed was named by the World Wildlife Fund as one of the global 200 conservation priority ecoregions (*11*). Furthermore, Dongting Lake provides other significant ecological services, including water supply, flood mitigation, and fish production. Historically, the Dongting Lake watershed was important for agriculture in China, so that the information on land management of this area is available. This allows us to study its long-term degradation as a result of increased human population and land use. Du et al. (*12*) have recently investigated the impact of the natural siltation on the water surface area of Dongting Lake, but integrated analysis of the shrinkage and fragmentation of the lake and their possible causes have not been reported yet. In this report, we used 7 decades of historical land cover information and remote sensing data to (1) estimate the shrinkage and fragmentation of the Dongting Lake surface area between the 1930s and 1998, and (2) explore the causes of such changes and evaluate the ecological consequences of these changes.

Methods

Site Description. The Dongting Lake area is situated at the southern part of the Central Yangtze River drainage basin, Hunan Province, China (Figure 1). It comprises part of 13 counties, with an area of 15 465 km^2 (111°45′−113°10′ E, 28°35′−29°38′ N). The area has a subtropical climate, with an annual sunlight range of 1757−1832 h, annual precipitation of 1200−1400 mm, and annual mean temperature of 16.4−17.0 °C (*13*). The area harbors approximately 1300 species of plants and a wide variety of threatened fish, birds, and mammals. It is one of the only two remaining retention lakes (Poyang Lake and Dongting Lake) for disastrous floods within Yangtze River Basin. However, this area has supported a number of people. Reclamation of the lake area for agricultural purpose to sustain rapidly growing human

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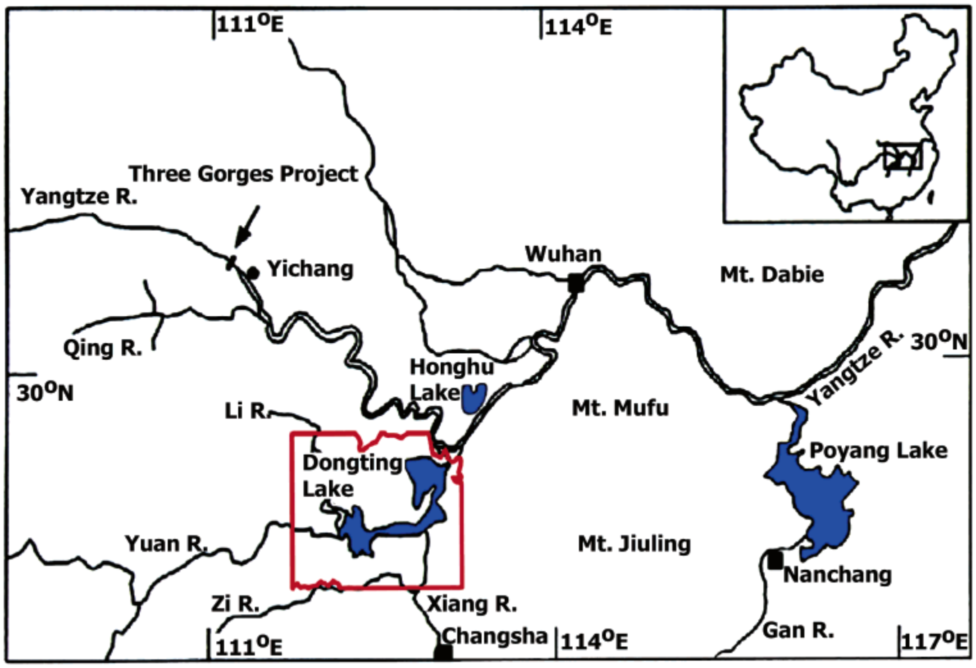

FIGURE 1. Location of the Dongting Lake region.

population is a major and typical way to exploit lake resources (*8*), and there were 15 state farms reclaimed in this area over the past 7 decades; thus, human population is suggested to be the primary driver for the changes in Dongting Lake.

Data and Approaches. The surface areas of Dongting Lake between the 1930s and 1998 were acquired from historical land cover information and remotely sensed data. We collected land cover maps with topography for the 1930s and the 1950s. Land cover information since the 1970s was obtained from Landsat remote sensing images. The data used in this study spanned ~70 years and were divided into five periods: the 1930s, the 1950s, 1978, 1989, and 1998. The land cover data of the 1930s (the earliest ground observation-based land cover information) were obtained from 16 land cover maps with information on topography surveyed by Japanese Land Survey Bureau and General Army Consultation during 1928 and 1939 with a mean surveying year of 1934. These 16 topographies of Xinzhou, Nanxian, Yueyang, Taolin, Dalongshan, Sanxianhu, Lujiao, Xinqiang, Changde, Yuanjiang, Hejiatang, Changlejian, Huangtutang, Yiyangxian, Xiangyinxian, and Pingjiangxian (with a scale of 1:100 000) covered all of the area of Dongting Lake. The land cover data for the 1950s (spanning from 1955 to 1959, with a mean period of 1957) were from six land cover maps surveyed by China Army General Consultation, including topographies of Jinshi, Huarong, Yueyang, Changde, Yuanjiang, and Pingjiang (a scale of 1:200 000). Land cover information since the 1970s was acquired from cloud-free Landsat remote sensing images: Landsat Multispectral Scanner (MSS) data for 1978 and Landsat Thematic Mapper (TM) data for 1989 and 1998. Both Landsat MSS and TM data were obtained from China's Satellite Ground Station and the Center of Remote Sensing, the Institute of Petroleum Survey and Design, China (Landsat MSS: Path 132-40, 16 October 1978; Path 133-39, 17 October 1978; Path 133-40, 17 October 1978; Landsat TM: Path 123-40, 4, December, 1989 and 12, February, 1998; Path 124-39, 10, February, 1989 and 20, December, 1998; Path 124-40, 10, February, 1989 and 20, December, 1998). Because the survey time of remote sensing images (e.g., dry or wet season) can significantly affect the estimation of the lake surface area, we tried to collect images with consistent survey dates for different periods. However, it is unrealistic to obtain the remote sensing data with the same dates over a long-term period because of the changes of the sensors. As described by the above-mentioned dates of imaging, the imageries for 1989 and 1989 used in this study were consistent, focusing on the dry season (February and December), but as for the MSS images in 1978, only the October imageries were available. October is the period switching from the wet to the dry season; this would give some below estimate of lake loss between the 1950s and 1978, but did not alter overall results of this study.

All of the historical maps of the 1930s and 1950s were scanned into digital images at 600 dots per inch, giving a ground resolution of approximately 10 m. The land cover maps with topography for the 1930s and the 1950s contain 40−55 land cover types with explicit boundary. Because we focused on the changes in surface area of the original lake, the final classification consists of only two categories, water and nonwater. We reclassified these 40−55 land cover types into water and nonwater types first through visual interpretation, and then we traced the boundary of each patch of water body using a GIS software (Founder drawing 5.5) and transferred vector maps of the land cover maps into ArcInfo7.1 GIS software to resample to a resolution of 80 m × 80 m to make them comparable with those of remotely sensed data. The image processing software ERDAS 8.4 was used to classify the land cover types of remotely sensed data to acquire the information on land cover of the Dongting Lake region. To provide consistency of band spectrums for different sensors of MSS and TM, the Landsat data were interpreted using similar band combinations with RGB (MSS bands 6, 7, 5 and TM bands 4, 5, 3). All images were geo-referenced according to 1:50 000 topographical maps, and the TM images (30 m × 30 m) were degraded and resampled to a resolution of 80 m × 80 m.

The quality of the classified products was critical to the analyses on the lake changes in the past 7 decades. We then used the method of Jensen (*14*) to assess the accuracy of the classified imagery products, based on field survey, and existing vegetation maps. The resulting classification accuracy of the water body for 1978, 1989, and 1998 was 89%, 92%, and 94%, respectively, which suggested the classified imagery products were of high quality. Land cover information for

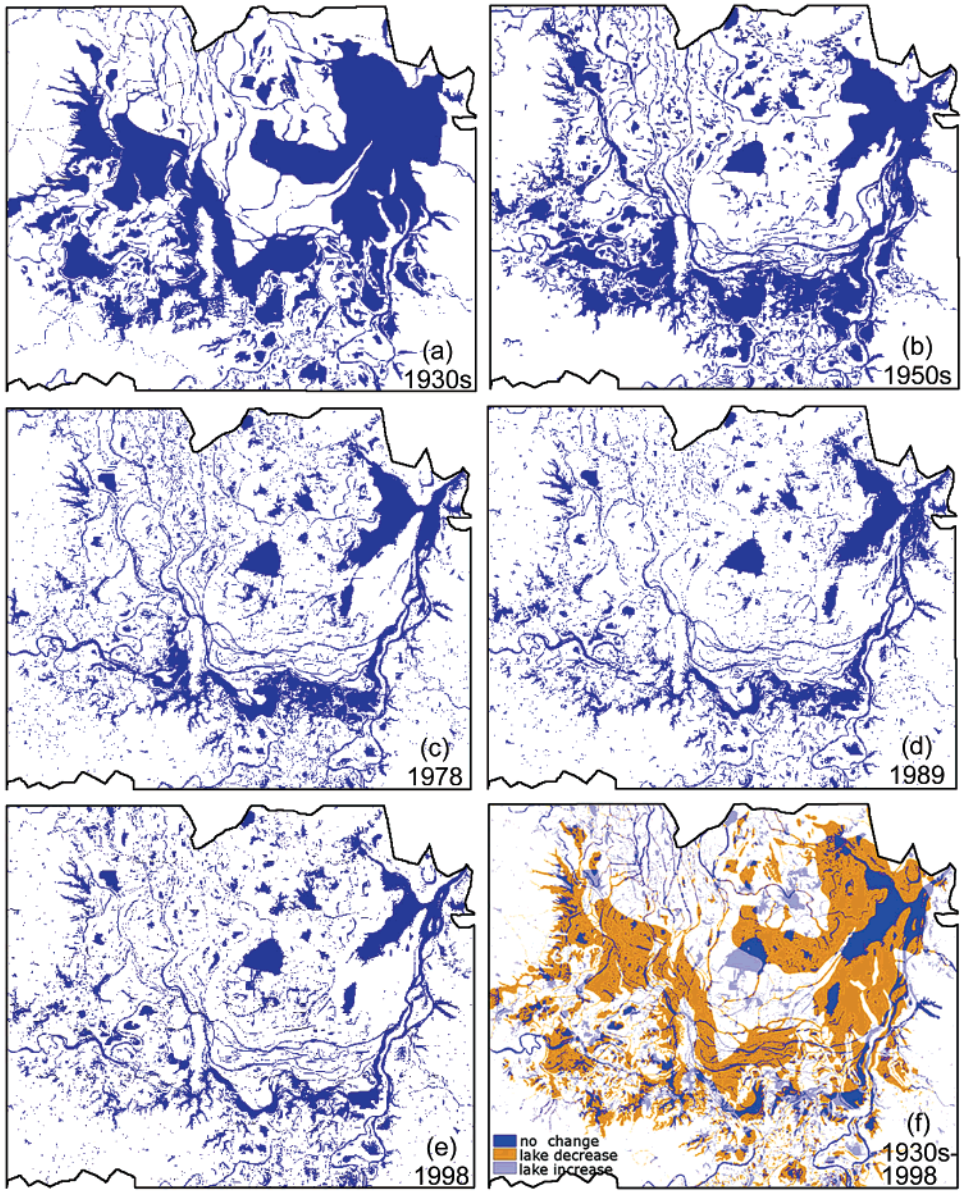

FIGURE 2. Spatial changes in Dongting Lake surface area between the 1930s and 1998. The solid blue areas indicate water body. Figure 2f is an overlap of 1998 and 1930s, indicating a spatio-temporal difference of water surface in the past 7 decades. Not only has the water surface area decreased, but also the location has changed.

the 1930s and 1950s was obtained from the land cover maps that were actually surveyed, and our classification only consisted of water and nonwater categories, and thus classified products for the 1930s and 1950s should be more precise.

A patch is a relatively homogeneous large or small area that differs from its surrounding (*15*), which is the basic spatial unit of land cover. Because the study area we defined was the original basin of Dongting Lake, all of the water body patches in this area consisted of Dongting Lake. The classified water body maps (Figure 2) were exported to the ArcInfo7.1 GIS software, and the patch area and perimeter were derived for each water body patch of the 1930s, the 1950s, 1978, 1989, and 1998; we then calculated the corresponding total water surface area, number of patches, mean patch sizes, and frequency distribution of patch size for these five periods. Annual surface area decrease rates (km^2/yr) were also calculated for four neighboring periods between the 1930s and 1998.

The human population size of the 13 counties along the Dongting lake area for the periods of the 1930s, the 1950s, 1978, 1989, and 1998 were collected by literature review (*16*, *17*). We then calculated the population size of the study area according to the area proportion of each county that the Dongting lake region covered. Population increase rates were also calculated for four neighboring periods between the 1930s and 1998. Finally, we statistically analyzed the correlation between lake size and human population in the study area between the 1930s and 1998 by a simple Pearson correlation module of SPSS 10.0.

Results and Discussion

The water surface of Dongting Lake decreased consistently between the 1930s and 1998 (Figures 2 and 3). In the past 7 decades, not only the area of water surface decreased steeply, but also the location of the water body has changed (Figure 2f). Overall, the lake area decreased by 49.2% from 4955 km^2 in the 1930s to 2518 km^2 in 1998, with an average annual decrease rate of 38.1 km^2/yr. Specifically, the water surface area decreased by 19.1%, 20.7%, 8.0%, and 1.4%, for the periods of 1930s−1950s, 1950s−1978, 1978−1989, and 1989−1998, respectively (Figure 3a). Moreover, the lake also

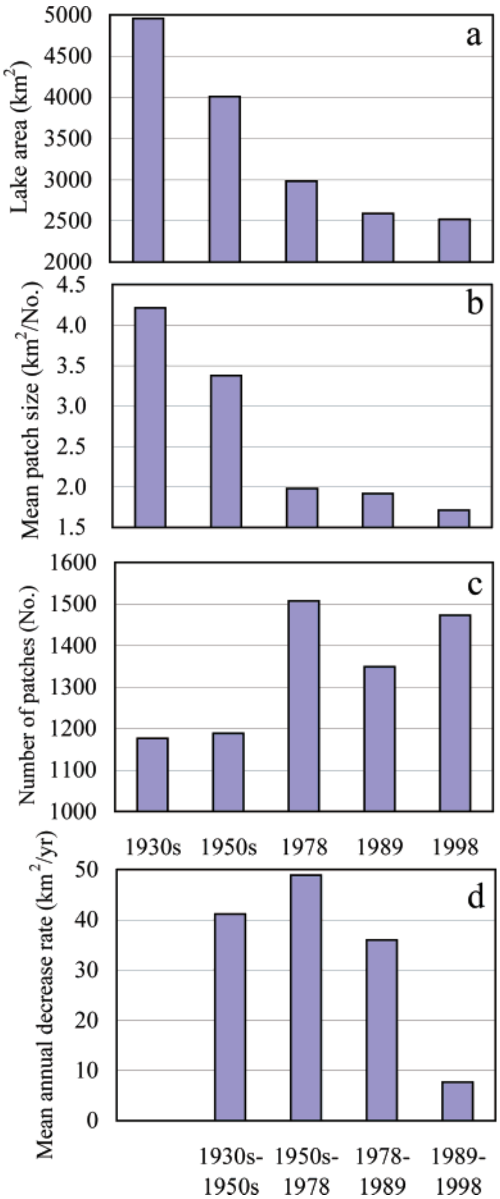

FIGURE 3. Quantitative changes of Dongting Lake in the past 7 decades: (a) water surface area, (b) mean patch size, (c) number of patches, and (d) annual decreased rate of water surface area.

became more segregated, as evidenced by decreases in patch sizes and increases of patch numbers (Figure 3b and c). The mean patch size decreased from 4.2 km^2 in the 1930s to 1.7 km^2 in 1998. In contrast, the patch number increased by 25%, from 1176 in the 1930s to 1473 in 1998.

To further illustrate integrality and fragmentation of lake size, the patch size frequency distribution of Dongting Lake was obtained (Figure 4). The medians of the largest patch size classes (main lake) in the different periods had rapidly decreased from 5033 km^2 (5.7 in log scale) in the 1930s, 2516 km^2 (5.4) in the 1950s, 1258 km^2 (5.1) in 1978 and 1989, to 629 km^2 (4.8) in 1998 (arrows in Figure 4). The figure also demonstrates the smallest number of patches and the smallest kurtosis in the 1930s, the largest median corresponding to the peaked number of patch size classes in the 1950s, and the largest number of patches in 1978, followed by 1998 and 1989.

Figure 3d showed annual decrease rates of water surface during the four neighboring periods. The highest decrease rate of lake size, 48.9 km^2/yr, was between the 1950s and

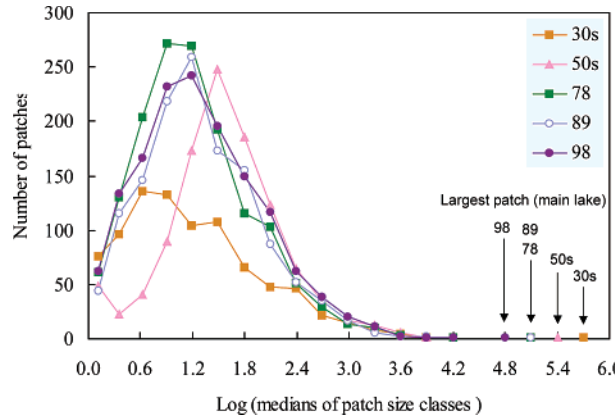

FIGURE 4. Patch size frequency distribution of Dongting Lake in the periods of the 1930s, 1950s, 1978, 1989, and 1998. The frequency distribution was obtained by grouping patches of water body according to the number of pixels, $2^1, 2^2, 2^3, 2^4, ..., 2^{20}$. The medians of these patch size classes were then converted into an area unit according to the resolution of 80 m × 80 m.

1978, whereas the lowest decrease rate, 7.7 km^2/yr, occurred between 1989 and 1998.

The unprecedented annual decrease rates of water surface area resulted largely from a soaring increase of human population in the Dongting Lake watershed. During the past 70 years, human population in the lake region doubled, from 2.8×10^6 in the 1930s to 6.2×10^6 by the end of the 1990s (*16*, *17*) (Figure 5a). The highest increase rate, 7.2×10^4/yr (Figure 5b), was found between the 1950s and 1978, which coincided with the period of rapid lake loss. The size of the lake was negatively related to the size of human population in the region (Figure 5c). Increased human population elevated the needs of the land for living and food production. Impoldering practice was accelerated from the early 1950s to the late 1970s. For example, 15 state farms, occupying 1214 km^2 (of which 659 km^2 were arable land), were established during this period (*18*; Table 1). As a result, the total arable land in the lake region increased by 1,800 km^2 from the early 1950s to the late 1970s (*19*), accounting for approximately 73% of the total lake loss since the 1930s. Although natural siltation of the Yangtze River contributed to the shrinkage of the lake as well, its effect was less important as compared to the reclamation practice. Based on a study of the lake natural siltation by Du et al. (*12*), the contribution of natural siltation to the decrease in water surface of Dongting Lake was estimated as only about 6−7% (about 1% per decade) over the past 7 decades. In addition, the construction of the Three Gorges Dam in the Upper-Central Yangtze may decrease the effects of natural siltation on the Dongting Lake surface area because a large fraction of sediment will be trapped behind the dam.

The degradation of Dongting Lake appears to significantly restrict its hydrological and ecological services in the Central Yangtze River watershed, such as flood retention and supporting biodiversity. For example, the frequencies of flood disasters in the Dongting Lake watershed between the years 1525 and 1998 were increased considerably. For 327 years between 1525 and 1851, an average interval between unusual floods was as long as 20 years, then declined to 4−5 years between 1852 and 1980, to only 1.5 years in the past decade. In particular, between 1990 and 1998, uncommonly disastrous floods occurred almost every year and caused billions of dollars of damage (*20*; Table 2). Moreover, the loss of biodiversity is increasing at an alarming rate. Waterbird species, such as geese and ducks, in the Dongting Lake watershed declined from 31 species in the end of the 1950s to 20 species in 1991−1992, and then to 12 at the end of the

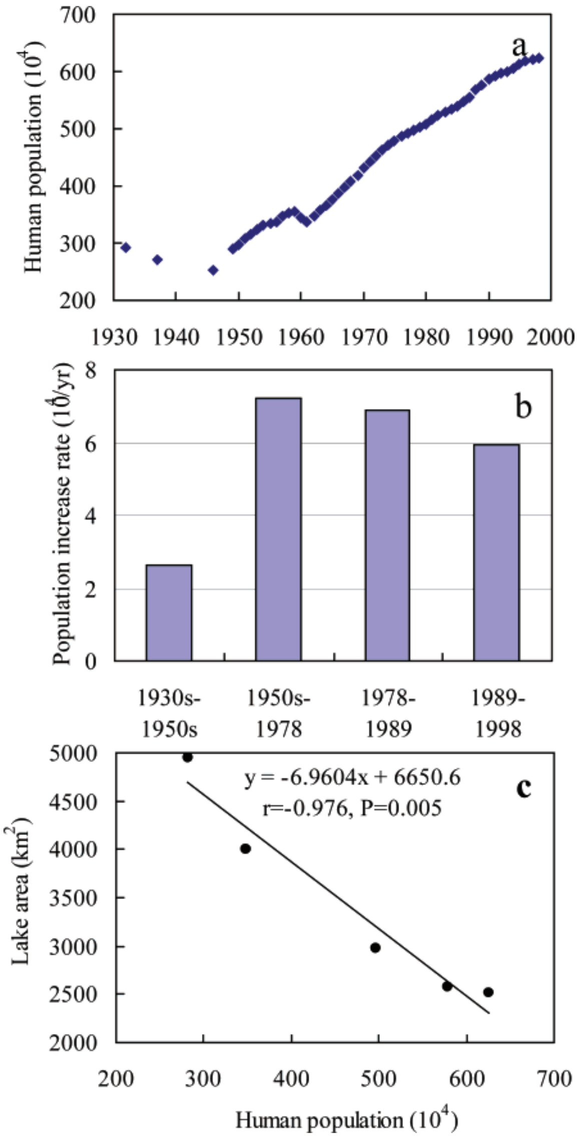

FIGURE 5. Human population (a) and its annual increased rate (b) (original data derived from refs *16, 17*), and the relationship between lake size and human population (c) in the Dongting Lake region between the 1930s and 1998.

TABLE 1. The Established Year and Area of 15 State Farms in the Dongting Lake Region (Based on Ref *18*)

farm name	year establishing	total area (km^2)	arable land area (km^2)
Datonghu	1950	169	58
West Dongting Lake	1954	105	52
West Lake	1954	65	38
Hejiashan	1955	16	10
Cendan	1956	50	22
Jianxin	1956	41	27
Chapanzhou	1958	55	36
Miluojiang	1958	187	100
Huanggaihu	1958	27	19
Qianshanhong	1959	72	42
Junshan	1961	91	63
Jinpeng	1962	43	30
Beizhouzi	1962	37	26
Qianlianghu	1962	215	116
Nanwanhu	1964	40	20
total		1214	659

1990s (*21–25*; Table 3). The population of Baiji Dolphin (*Lipotes vexillifer*), a well-known endemic species of the Yangtze River and "living fossil" whose evolutionary history

TABLE 2. Frequencies of Flood Disasters in the Dongting Lake Region between 1525 and 1998 (Based on Ref *20*)

periods	total years	average interval between floods (yr)
1525–1851	327	20
1852–1949	98	5
1950–1989	40	4
1990–1998	9	1.5

TABLE 3. Decadal Change of Duck and Goose Species in the Dongting Lake Region (Based on Refs *21–25*)[a]

species	1959–1962	1991–1992	1998–1999
Branta ruficollis	+		
Anser cygnoides	+		+
A. fabalis	+	+	+
A. albifrons	+	+	+
A. erythropus	+	+	+
A. anser	+		
A. indicus	+		
Cygnus cygnus	+		
C. columbianus	+	+	+
Dendrocygna javanica	+		
Tadorna ferruginea	+	+	
T. tadorna	+	+	
Anas acuta	+	+	+
A. crecca	+	+	+
A. formosa	+	+	
A. falcata	+	+	+
A. platyrhynchos	+	+	+
A. poecilorhyncha	+	+	+
A. strepera	+	+	
A. penelope	+	+	
A. querquedula	+	+	
A. clypeata	+		
Aythya nyroca	+		
Ay. baeri	+		
Ay. fuligula	+	+	
Aix galericulata	+		
Nettapus coromandeliannus	+	+	+
Clangula hyemalis	+		
Mergus albellus	+	+	
M. squamatus	+		
M. merganser	+	+	+
Bucephala clangula		+	
total species richness	31	20	12

[a] "+" symbols indicate recorded species.

can be traced back more than 20 million years, has rapidly declined (*26*). Its first specimen was collected in Dongting Lake in 1916 (*27, 28*), but it had not been observed in the surveys from 1978 to 1999, which indicated that this species had disappeared from the lake watershed (*29*).

The decrease rate of the lake size has been lessened gradually after the late 1970s, particularly after the late 1980s, largely due to the implementation of the government policy prohibiting impoldering along Central Yangtze watershed and the return of inundated lands to the lake by local people for they are unwilling to repair inundated dyke breaches according to the cost-benefit estimates (*30*). After the unprecedented flood in 1998, the government implemented a 10-yr lake restoration project in the Central Yangtze River watershed. As planned by this project, the surface area of Dongting Lake is expected to increase almost double of its current size by 2010. Whether recreated wetlands will function similarly to the undisturbed condition is currently under debate in restoration ecology and conservation ecology (*31*).

One of the main limitations in answering such a question is the lack of background information before wetland construction. This study elucidates not only the decadal degradation in a large freshwater lake induced by anthropogenic activities and promising future of recent lake restoration efforts, but also provides indispensable baseline information for long-term ecosystem restoration and related studies. The knowledge will undoubtfully benefit our ultimate goals to achieve ecological sustainability of global lake ecosystems and their services such as clean water and biodiversity, one of the great challenges of the 21st century.

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