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RESEARCH ARTICLE

Losses of Ecosystem Service Values in the Taihu Lake Basin from 1979 to 2010

Hui ZHANG[1,2,3], Qiao WANG (✉)[1,4], Guangyu LI (✉)[2], Hanpei ZHANG[3], Jue ZHANG[3]

1 College of Geographical Sciences, Nanjing Normal University, Nanjing 210023, China
2 Nanjing Institute of Environmental Science, Ministry of Environmental Protection, Nanjing 210042, China
3 Jiangsu Collaborative Innovation Center of Atmospheric Environment and Equipment Technology (CICAEET), Nanjing University of Information Science & Technology, Nanjing 210044, China
4 Environmental Satellite Application Center, Ministry of Environmental Protection, Beijing 100029, China

Abstract The Taihu Lake Basin, an east-coastal developed area, is one of the fastest-growing metropolitan areas in China. Ecosystem services in the Taihu Lake Basin have been overexploited and jeopardized. Based on land-use and land-cover change (LUCC) data from 1979, 1984, 2000, and 2010, in conjunction with the adjusted ecosystem service values (ESV), changes in ESV were analyzed in detail. Results revealed that LUCC resulted in a substantial decrease in total ESV from $3.92 billion in 1979 to $2.98 billion in 2010. The ESV of cropland decreased from $1.64 billion in 1979 to $1.34 billion in 2010, which represented a 20.28% reduction. The ESV of water areas decreased from $1.08 billion in 1979 to $0.36 billion in 2010, which represented a 65.62% reduction mainly because of a decline in water quality. In terms of annual change rate, cropland and water areas showed a sustained downward trend. Spatially, ESV declines were mainly observed in Suzhou, Wuxi, Changzhou, and Shanghai, probably due to a combination of economic progress, population growth, and rapid urbanization. The research results can be a useful reference for policymakers in mitigating ESV decline.

Keywords ecosystem service values, land use/land cover, water quality, Taihu Lake Basin

1 Introduction

Since the concept of ecosystem services (ES) was proposed in the mid-1960s, the international community has given increased importance to ES research. Numerous comprehensive studies were conducted from the perspectives of ecosystem processes, ecosystem service functions, and eco-economic value (Brander et al., 2012; Costanza et al., 2014). Since Costanza et al. (1997) published “The Value of the World’s Ecosystem Services and Natural Capital” in *Nature*, ecosystem service valuation has been a major topic in ecological economic research. Moreover, the volume of ES literature has grown (Carpenter et al., 2006; Shi et al., 2009; Bagstad et al., 2013; Kuenzer and Tuan, 2013; de Araujo Barbosa et al., 2015). Most notably, the Millennium Ecosystem Assessment, a monumental work involving over 1300 scientists and the first attempt to fully interpret, understand, and assess the interrelation between ecosystems and human well-being at a global scale, defines ES as the benefits that people obtain from ecosystems. These include provisioning services, such as food and water; regulating services, such as the regulation of floods, drought, land degradation, and disease; supporting services, such as soil formation and nutrient cycling; and cultural services, such as recreation, spiritual, religious, and other non-material benefits (Carpenter et al., 2006, 2009).

Land-use change may be largely attributed to dramatic negative transformations in ES, which has attracted considerable academic attention (Seppelt et al., 2011; Burkhard et al., 2012; de Araujo Barbosa et al., 2015). Previous research can be divided into two cases. Land use/land cover is always used as a proxy for ecosystem service quantification and mapping in either case. In the first case, ecosystem service values (ESV) are calculated by combining different areas of land use types and market prices per unit area, assuming that a linear relationship exists between land cover and market price per unit area (Zhao et al., 2004; Brown, 2013; Estoque and Murayama, 2013). In the second case, by combining remotely sensed biophysical variables, such as vegetation indices (VI) or

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E-mails: wangqiao@sepa.gov.cn (Qiao WANG), lgy@nies.org (Guangyu LI)

net primary productivity (NPP), ecosystem services are quantified and mapped (Ayanu et al., 2012; Wang et al., 2014; de Araujo Barbosa et al., 2015). Even though the second case provides a spatially explicit method for quantifying ES, estimation of ES is affected by resolution of VI and accuracy of ecosystem parameters, like NPP. Compared with land-use and land-cover interpreted by Landsat TM images, the spatial resolution of NDVI images (250 m, 1 km, or 8 km) was crude and data was discontinuous in long time series (Yu et al., 2009; Fensholt and Proud, 2012). Multi-source data could create even more uncertainty and would have to be considered (Ayanu et al., 2012)

Numerous case studies have been conducted on ecosystem services, but limited research has been performed on long-term response of ecosystem services to land-use change and other factors (Wang et al., 2014; Ai et al., 2015). Comparison and analysis of ESV caused by long-term land-use and land-cover change (LUCC) help explain trends in the biological environment. Population growth and urban sprawl in the Taihu Lake Basin have exerted great pressure on local resources. Moreover, water pollution in this area has been exacerbated by algal blooms. Changing water quality may affect multiple ecosystem goods and services (Keeler et al., 2012). Water quality is considered as an important factor that affects ecosystem services. The ESV in Taihu Lake Basin from 1979 to 2010 were calculated based on changes in the area of each land-use and land-cover category and water quality, and changes in ESV by land use type were analyzed. This study aims to evaluate ESV changes in different periods and analyze drivers of ESV change from 1979 to 2010. Overall results could be useful for establishing ecosystem service improvement strategies for the Taihu Lake Basin.

2 Study area and methodology

2.1 Study area

Taihu Lake is the third largest freshwater lake in China. It is located in the south of the Yangtze Delta of East China in the region of 30°28′–32°15′N and 119°11′–121°53′ E, including southern Jiangsu, northern Zhejiang, most of the Shanghai area, and a small part of Anhui Province (Fig. 1).

The Taihu Lake Basin is dominated by a monsoon climate, with a May–September rainy season (750–850 mm) alternating with a dry season (250–350 mm). Annual mean temperature varies from 14.9°C to 16.2°C. Annual mean precipitation is 1000–1400 mm. Water depth ranges from 1 m to 2.5 m (average 1.89 m) with a total water surface area of approximately 2338.11 km^2, and a mean water volume of approximately 44.297×10^8 m^3. This region has a long history of high-yield rice farming and its paddy soils are well-developed and relatively uniform.

The Taihu Lake Region is among the most developed and urbanized areas. In 2010, although it is only 0.4% of the total area of China, it contributed more than 10% to the local GDP and 16% to the financial income in China. Its urbanization level was 73.0% in 2010, which was almost twice that of the entire country. Social and economic statistics have been drawn from the Jiangsu Statistical Yearbook, the Zhejiang Statistical Yearbook, and the Shanghai Statistical Yearbook of 2011. With economic development, population growth, industrialization, and urbanization, an increasing demand for construction land has occurred. Massive cropland and water areas have been transformed for construction; at the same time, water pollution has been worsening dramatically (Wang et al., 2009).

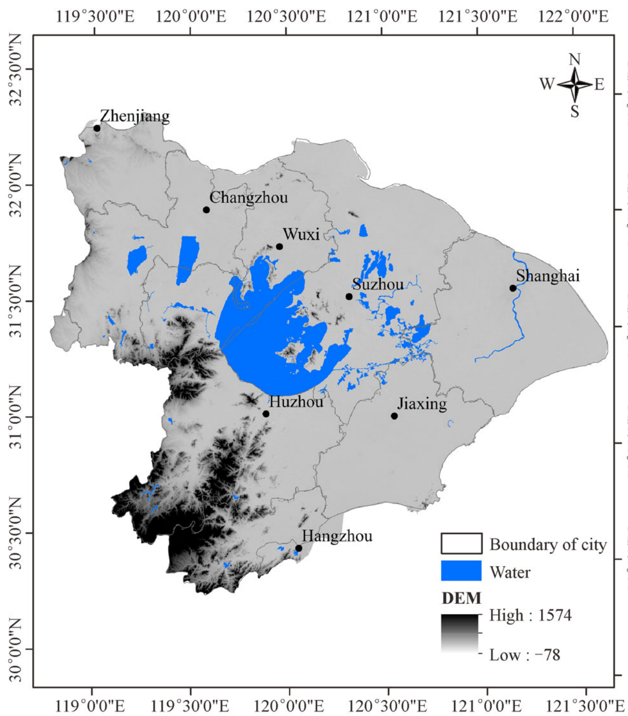

Fig. 1 Location of the Taihu Lake Basin.

2.2 Materials and methods

2.2.1 Data collection

Remote sensing data acquired for this study included Landsat MSS data for 1979, Landsat TM data for 1984, Landsat ETM data for 2000, and Chinese HJ-1 Satellite data for 2010. The Chinese Environment satellite (HJ-1), the first satellite used for environment and disaster monitoring in China, was launched in September 2008; it had a CCD camera, an infrared camera (IRS), and a hyper-spectral imager, and its resolution and first four bands of CCD camera were the same as that of the TM. Landsat MSS data, Landsat TM data, and Landsat ETM data were obtained from the Global Land Cover Facility (http://glcf.umiacs.umd.edu/data/) and the International Scientific Data Service Platform (http://datamirror.csdb.cn/). The Chinese HJ-1 Satellite data were downloaded from the Download Network Address of Environmental Satellite in the Environmental Protection Department (http://60.247.54.34/secPortal/portal/ index.faces). Specifications of the satellite data acquired for change analysis are shown in Table 1.

2.2.2 Image pre-processing and classification

Data were pre-processed in ENVI 5.0 for geo-referencing, mosaicking, and image subsetting on the basis of area of interest. Geometric registration was conducted using the quadratic method. Specification for image-to-image registration was 0.5 pixels in both directions, and this precision requirement was used for both years. The maximum likelihood classifier (MLC) was used for spectral classification of images. The study area was classified into six major land cover/use classes: cropland, woodland, grassland, water areas, construction land, and unused land. Six major land cover/use classes were further divided into 23 subtypes: cropland was classified into 2 subtypes (drylands, paddy fields); woodland was classified into 5 subtypes (forest, shrub, sparse woods, orchard, and tea garden); grassland was classified into 3 subtypes (high coverage, moderate coverage, and low coverage grassland); water areas were classified into 6 subtypes (rivers, lakes, reservoir, fish pond, tidal marsh, and beach); construction areas were classified into 4 subtypes (urban construction, rural construction, transportation, and mining); and bare land was classified into 3 subtypes (saline land, bare soil, and bare rock). Confusion matrixes were created to assess the accuracy of image classification. Accuracy assessments showed that overall accuracy was 85% for 1979, 84% for 1984, 86% for 2000, and 88% for 2010 (Ji et al., 2013). Changes in land use/cover from 1979 to 2010 were detected and calculated by comparing classified land use/cover maps.

2.2.3 Assignment of ecosystem service value according to land-cover data

Costanza et al. (1997) presented a model for placing economic value on different biomes and their services. They classified the global biosphere into 16 types of ecosystems and 17 types of service functions and then estimated their ecosystem service value upon their model. Some researchers stated that the ecosystem service coefficients proposed by Costanza et al. (1997) were higher than the actual value (Alexander et al., 1998; Seidl and Moraes, 2000). Xie et al. (2008) pointed out that in China, certain deviations exist in Costanza et al.'s estimate. For instance, cropland ecosystem services had been insufficiently valuated or ignored, whereas some ecosystem services, such as swamp, river, and lake ecosystem services, had been overestimated. The equivalent weight factor of ecosystem service per hectare of terrestrial ecosystem in China had been modified based on surveys conducted among 38 Chinese ecologists in 2002 and 213 Chinese ecologists in 2007, as shown in Table 2 (Xie et al., 2008). Based on parameters by Costanza et al. (1997) and Xie et al. (2008), numerous Chinese scientists have been using the methods to evaluate ecosystem service values in different regions throughout China (Li et al., 2011; Liu et al., 2011; Wang et al., 2012; Fu and Zhang, 2014).

Location and ecological zones are important factors that influence ecosystem service value. The practical application was limited in local regions because of coarse classification of land use and land cover. For example, the farmland was not divided into paddy fields and dry land; differences in these subcategories of ecological services are relatively large. Therefore, supported by "Remote sensing monitoring and assessments of landscape and ecological pattern changes in the Taihu Lake Basin

Table 1 Overview of satellite data. The third column indicates the path-row for the related sensor

Year	Sensor	Scene	Date of acquisition
1979	Landsat MSS	128-038	25 May 1979
		127-038;127-039	04 Aug 1979
		129-038	06 Aug 1979
1984	Landsat TM	118-038;118-039	08 May 1984
		119-038;119-039	04 Aug 1984
		120-038	3 Aug 1984
2000	Landsat ETM	119-038	17 Mar 2000
		119-039	04 May 2000
		118-038;118-039;120-038	14 Jun 2000
2010	HJ-1A CCD1	450-76	31 Jul 2010
	HJ-1B CCD2	448-80	05 Aug 2010

based on HJ-1 Program" of the National 11th "Five-Year" Technology Support Programs, this study established an expert questionnaire and consulted with 30 experts on land use and land cover change or ecosystem service value assessment from universities and institutes located in the Taihu Basin.

In the Taihu region, water pollution is a very serious problem. The ESV of the river and lake depend basically on water quality, and differences exist in the ESV supplied by different levels of water. Poorer water quality leads to a lower ESV (Pinto et al., 2010; Simonit and Perrings, 2011). As a result of water pollution in China, the equivalent value per unit area was lowered for rivers and lakes; these values decreased by 12.66% and 65.1%, respectively (Xie et al., 2008). Therefore, adjusting the equivalent weight factor of water areas is necessary on account of the water quality in the Taihu Lake Basin. Referring to the water quality report of the Taihu Lake Basin and other literature and sources (Wang et al., 2009), we obtained the percentages of water quality levels in 1979, 1984, 2000, and 2010. The data for 1979 were replaced by those for 1980 (Jin et al., 1999). Most of the water quality in the Taihu Lake basin has fallen from grade II to V from the early 1980s to 2010s, whereas water nutrition had been converted from mid-nutrition to eutrophication (Table 3).

According to Costanza et al. (1997) and Xie et al. (2008), the economic value of the ecosystem service equivalent factor was \$54 ha^{-1} per year throughout China. In the Taihu Lake Basin, the actual average food production of cropland was approximately 6000 kg/ha in recent years, which was approximately 1.5 times that of the Chinese average; therefore, the ESV of one equivalent weight factor for the Taihu Lake basin region was adjusted to \$81 ha^{-1} per year. Based on expert questionnaire results, the equivalent value per unit area of ecosystem services for each land use and land cover subcategory was determined (Table 4). Values of transportation, mining, and bare land were set to 0, which are not shown in Table 4.

2.2.4 Calculation of Ecosystem Service Value

Once the ESV of one unit area for each land-cover category is extracted, the service value for each land-cover category and service function can be presented in Eq. (1) as follows:

$$\begin{aligned} ESV_k &= \sum_f A_k \times VC_{kf} \\ ESV_f &= \sum_k A_k \times VC_{kf} \\ ESV &= \sum_k \sum_f A_k \times VC_{kf}, \end{aligned} \tag{1}$$

Table 2 Equivalent value per unit area of ecosystem services in China in 2002 and 2007

Category	Subcategory	Forest		Grassland		Cropland		Wetland		River/lake		Desert	
		2002	2007	2002	2007	2002	2007	2002	2007	2002	2007	2002	2007
Provisioning services	Food production	0.93	0.33	1.23	0.43	1.00	1.00	0.3	0.36	0.77	0.53	0.00	0.02
	Raw material production	2.73	2.98	0.19	0.36	0.10	0.39	0.07	0.24	0.11	0.35	0.01	0.04
Regulating services	Gas regulation	0.65	4.32	0.29	1.50	0.13	0.72	1.8	2.41	0.06	0.51	0.17	0.06
	Climate regulation	3.10	4.07	1.14	1.56	1.00	0.97	17.10	13.55	0.68	2.06	0.12	0.13
	Hydrological regulation	2.36	4.09	0.19	1.52	0.13	0.77	15.50	13.44	122.98	8.77	0.00	0.07
	Waste treatment	1.78	1.72	1.60	1.32	0.17	1.39	18.18	14.40	0.10	4.85	0.01	0.26
Supporting services	Soil formation and conservation	8.86	4.02	2.41	2.24	1.70	1.47	1.71	1.99	0.22	0.41	0.00	0.17
	Biodiversity conservation	3.80	4.51	3.60	1.87	1.00	1.02	2.50	3.69	0.87	3.43	0.07	0.40
Cultural services	Aesthetic values	1.80	2.08	0.36	0.87	0.06	0.17	5.55	4.69	3.97	4.44	0.02	0.24
Total		26.01	28.12	11.01	11.67	5.29	7.9	62.71	54.77	129.76	45.35	0.40	1.39

Table 3 Percentage of different water quality class of Taihu Lake Basin

Water quality	1980	1984	2000	2010
Grade II	69	59.4	2.6	1.9
Grade III	30	36.6	12.4	10.6
Grade IV	1	3.2	48	21.2
Grade V	—	0.8	14	22.7
Worse than Grade V	—	—	23	43.6

where ESV_k is the ESV of land-cover category k; ESV_f is the value of ecosystem services function type f; ESV is the total ecosystem service value; A_k is the area (ha) for land-cover category k; and VC_{kf} is the value coefficient ($\$ha^{-1}$per year) for land-cover category k and ecosystem service function type f.

Changes in ESV were estimated by calculating the differences between estimated values for each land cover category in 1979, 1984, 2000, and 2010.

2.2.5 Changes of ecosystem services value for each land use category

Data from different land use types were normalized and used to estimate profits and losses of ecological service values, namely value flow, which is conductive to find the causes of ecosystem function decline in the Taihu Lake Basin. Using the following formula, the value transfer of ecosystem services between six land use types were calculated:

$$VCL_{ij} = (VC_j - VC_i) \times A_{ij}, \tag{2}$$

where VCL_{ij} is the change in ESV in a particular land-cover category; i is conversion to land-cover category in 1979; j is conversion to land-cover category in 2010; VC_i is the ESV coefficient of land-cover category i; VC_j is the ESV coefficient of the land-cover category j; and A_{ij} is the area of land-cover category i in 1979 converted to land-cover category j in 2010.

An increase in ESV is regarded as a positive flow because of transformation of land use types, whereas loss is regarded as a negative flow.

3 Results

3.1 Land use/cover change

Table 5 and Fig. 2 show the land-use changes in the Taihu Lake Basin during 1979–2010. Cropland was a dominant land-use type, which accounted for approximately 67.3%, 65.8%, 61.9%, and 53.6% in 1979, 1984, 2000, and 2010, respectively. The amount of cropland declined more sharply than the other land use types, decreasing by 0.66% per year during 1979–2010. The annual rate of

Table 4 Per unit area of ecosystem services value in Taihu Lake basin region ($\$ ha^{-1}$)

Category	Sub-category	Food production	Raw material production	Gas regulation	Climate regulation	Hydrological regulation	Waste treatment	Soil formation and conservation	Biodiversity maintenance	Aesthetic values	Total
Cropland	Drylands	81	31.59	58.32	78.57	62.37	112.59	119.07	82.62	13.77	639.9
	Paddy fields	98.01	34.02	59.94	81	81	133.65	51.03	103.68	49.41	691.74
Woodland	Forest	26.73	263.25	529.74	528.12	134.46	140.13	430.11	367.74	211.41	2631.69
	Shrub	25.11	244.62	353.16	391.23	124.74	106.92	314.28	297.27	187.92	2045.25
	Sparse woods	55.08	166.05	180.63	212.22	107.73	89.1	210.6	226.8	170.1	1418.31
	Orchard, tea garden	98.82	168.48	136.08	141.75	69.66	78.57	144.18	126.36	144.99	1108.89
Grassland	High-cover grass	54.27	166.86	166.86	180.63	99.63	549.18	216.27	213.03	213.03	1859.76
	Middle-cover grass	37.26	115.02	150.66	131.22	82.62	261.63	179.01	159.57	80.19	1197.18
	Low-cover grass	30.78	66.42	110.16	103.68	74.52	95.58	132.84	117.45	66.42	797.85
Water areas	River/lake (Grade II)	42.93	28.35	249.48	959.85	1099.17	29.16	35.64	328.05	359.64	3132.27
	River/lake (Grade III)	28.35	21.06	192.78	589.68	627.75	30.78	26.73	230.85	277.83	2025.81
	River/lake (Grade IV)	9.72	12.96	78.57	345.06	271.35	34.02	17.82	93.15	127.98	990.63
	River/lake (Grade V)	0.81	0.81	55.08	231.66	182.25	40.5	8.91	4.05	25.92	549.99
	River/lake (Worse than Grade V)	0	0	0	98.82	0	48.6	0	0	0	147.42
	Reservoir and fish pond	183.06	34.83	123.93	254.34	215.46	0	0	86.67	78.57	976.86
	Tidal marsh	29.16	19.44	195.21	1097.55	1088.64	1166.4	161.19	298.89	379.89	4436.37
	Bench	9.72	10.53	2.43	8.91	26.73	17.01	8.1	0.81	46.98	131.22
Construction land	Urban construction land	0	0	0	0	0	0	0	19.44	22.68	42.12
	Rural construction land	0	0	0	0	0	0	0	29.97	31.59	61.56

decrease in cropland increased from approximately 0.28% per year during 1979–1984 to 1.33% per year during 2000–2010. By contrast, the percentage of construction land increased from 7.42% in 1979 to 19.02% in 2010, with an annual growth rate of 5.05% per year. Woodland increased from 474,778.4 ha in 1979, to 474,868.2 ha in 1984, to 484,853.7 ha in 2000, and to 498,848.18 ha in 2010. Water areas increased from 428,869.4 ha in 1979 to 470,720.3 ha in 2010, with an estimated annual growth rate of 0.31% per year. Grassland and unused land occupied less than 1% of the total area, and slightly increased during 2000–2010. We can conclude from Table 5 and Fig. 2 that most of the lost cropland was converted into construction land, woodland, and water areas. This finding was a combined result of urban sprawl, the policy of returning farmland to woodland and grassland, and adjustment of planting structure.

3.2 Changes of ESVs

In the Taihu Lake Basin, LUCC resulted in a significant decreasing tendency in ESV from 1979 to 2010 (Fig. 3). Total ESV decreased from \$3.92 billion in 1979 to \$3.85 billion in 1984, to \$3.21 billion in 2000, and to \$2.98 billion in 2010. A 23.96% net decline was observed in estimated ESV in the Taihu Lake Basin, and a decline in ESV per year was estimated to reach upwards of \$940.02 million during 1979–2010. Based on the assumption of a linear decline in ecosystem services from 1979 to 2010, this decline represented a cumulative loss of \$14,570 million in ecosystem services over the 31-year period. The ESV of water areas and cropland decreased rapidly. The ESV of cropland decreased from \$1.68 billion in 1979 to \$1.34 billion, and those of water areas decreased from \$1.04 billion in 1979 to \$0.36 billion in 2010. The ESV of

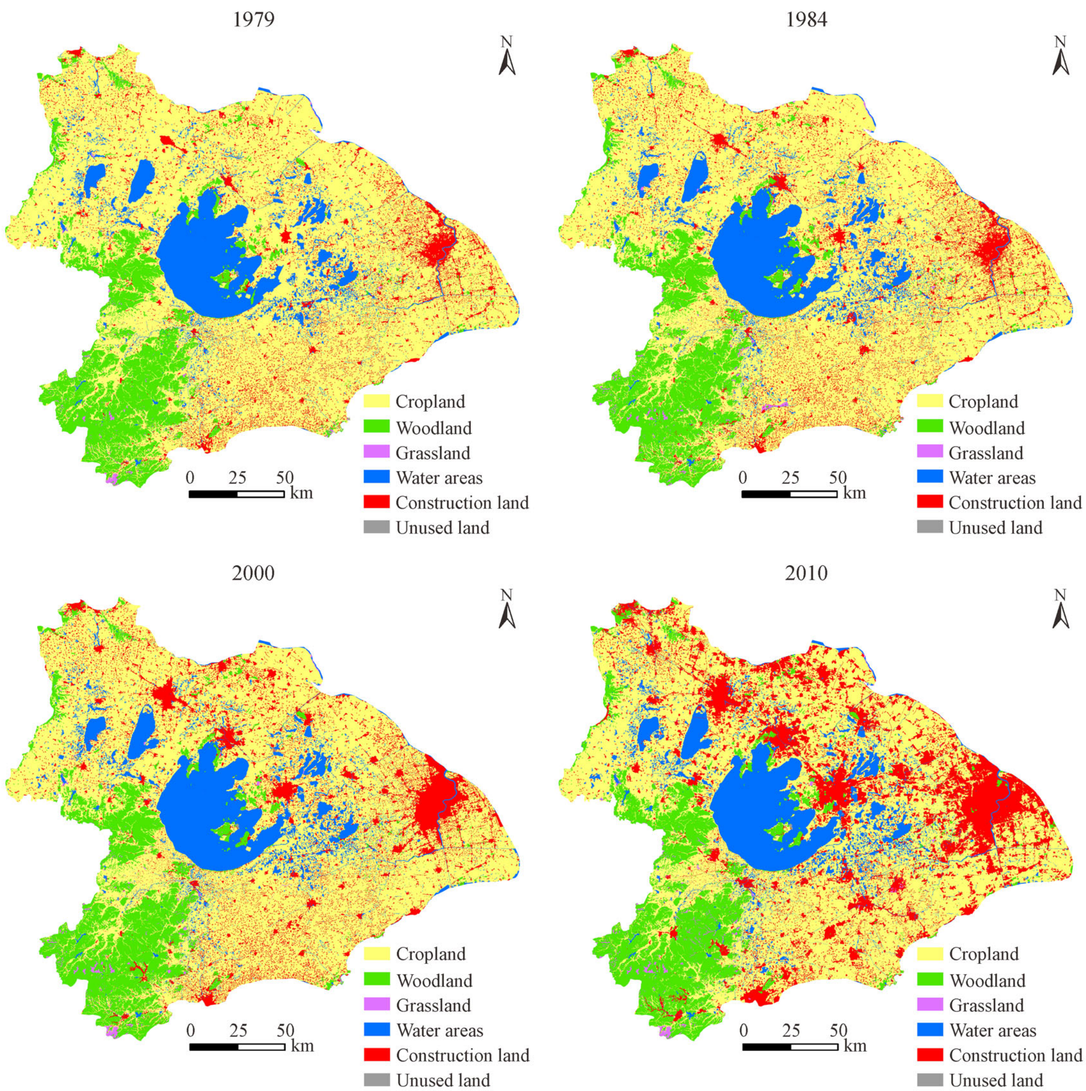

Fig. 2 Land use map of the Taihu Lake Basin during 1979–2010.

cropland and water areas declined to \$341.35 million and \$680.92 million annually from 1979 to 2010, respectively. Results indicated a small increase in the ESV of woodland and grassland, which grew by 4.43% and 61.99% from 1979 to 2010. Although the ESV of woodland and grassland exhibited an increasing tendency, the amount of woodland and grassland is limited. Consequently, the total value of ecosystem services still diminished by \$4.74 ha^{-1} per year.

During 1979–2010, negative changes in ESV in cropland and water areas amounted to \$11.01 million and \$21.67 million per year, respectively. Positive changes occurred in woodland, grassland, and construction land, and the changes were \$1.67, \$0.43, and \$0.56 million per year, respectively. The decline within the periods 1979–1984, 1984–2000, and 2000–2010 fluctuated. The ESV decreased by 1.27% per year from 1984 to 2000, which was higher than 1.02% per year from 1979 to 1984, and higher than 0.56% per year from 2000 to 2010. The ESV of water areas decreased by 4.42% per year from 1984 to 2000, higher than 0.55% per year from 1979 to 1984, and higher than 1.55% per year between 2000 to 2010 (Fig. 3).

At the city level, spatial change in ESV presented an overall downward trend. The largest reduction appeared in Suzhou, Wuxi during the entire study period. ESV of Shanghai also declined sharply during 1984–2000 and 2000–2010 (Fig. 4). This result is highly correlated with the water area and built-up area of a specific city. Change in ESV at the city level exhibits an apparent spatial heterogeneity. Ratios of negative changes in total ESV appeared in Suzhou, Wuxi, and Changzhou during 1979–1984 and 1984–2000. Changes in relative losses of ESV were higher in Suzhou, Wuxi, and Shanghai during 2000–2010. This result is highly correlated with water quality change and LUCC.

3.3 Changes of ESV by land use type

The ESV of cropland mainly flowed to the woodland, grassland, and water areas. Woodland occupied the largest proportion, valued at \$200.02 million; the second was the water areas, valued at \$52.10 million; compared with the former two, the value flowing to the grassland was the least at only \$21.09 million. Conversion from cropland to construction land and unused land caused a sharp decline in ESV, decreasing by \$1214.8 million. Value flowing from woodland to the cropland suffered most, which decreased by \$44.28 million. For water areas, value flowing to construction land suffered sharp declines with \$32.20 million. Change in ESV of grassland accounted for a small percentage of the total because grassland is a small area. As construction and unused lands were converted to other land-use types, ESV increased by \$161.7 and \$0.8 million, respectively (Table 6).

The primary reason for ESV losses was conversion from cropland, woodland, and water areas in 2000 to other land-

Table 5 Total area of each land-use category in the Taihu Lake Basin region

Land use category	1979		1984		2000		2010	
	Area/ha	Ratio/%	Area/ha	Ratio/%	Area/ha	Ratio/%	Area/ha	Ratio/%
Cropland	2,446,165.5	67.3	2,391,488.2	65.8	2,247,889.8	61.9	1,948,000.0	53.6
Woodland	474,778.4	13.1	474,868.2	13.1	484,853.7	13.3	498,848.2	13.7
Grassland	13,016.5	0.4	15,294.1	0.4	18,473.3	0.5	22,316.6	0.6
Water areas	428,869.4	11.8	438,352.9	12.1	454,797.5	12.5	470,720.3	13.0
Construction land	269,481.0	7.4	312,083.3	8.6	425,438.7	11.7	690,942.6	19.0
Unused land	1098.7	0.0	1322.8	0.0	1956.4	0.1	2581.7	0.1
Total	3,633,409.4	100.0	3,633,409.4	100.0	3,633,409.4	100.0	3,633,409.4	100.0

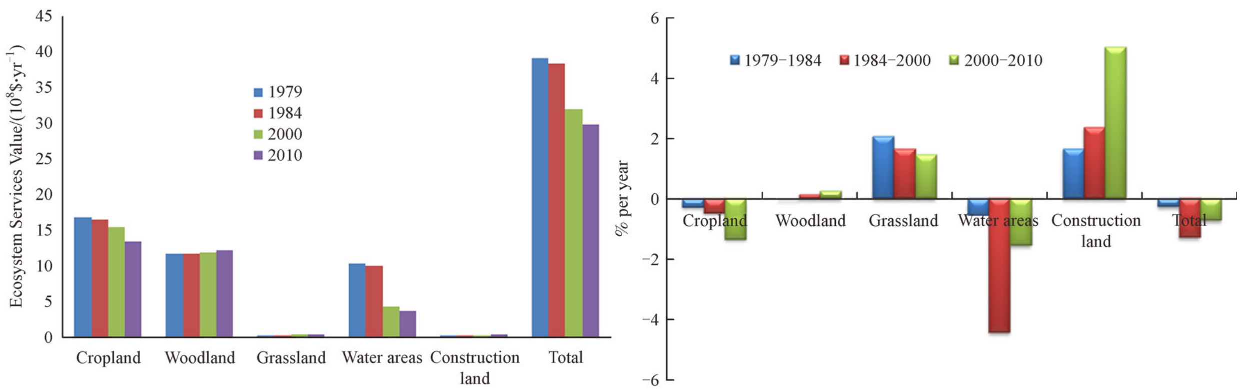

Fig. 3 ESV (a) and annual change ratio in ESV (b) of each land-use category during 1979–2010.

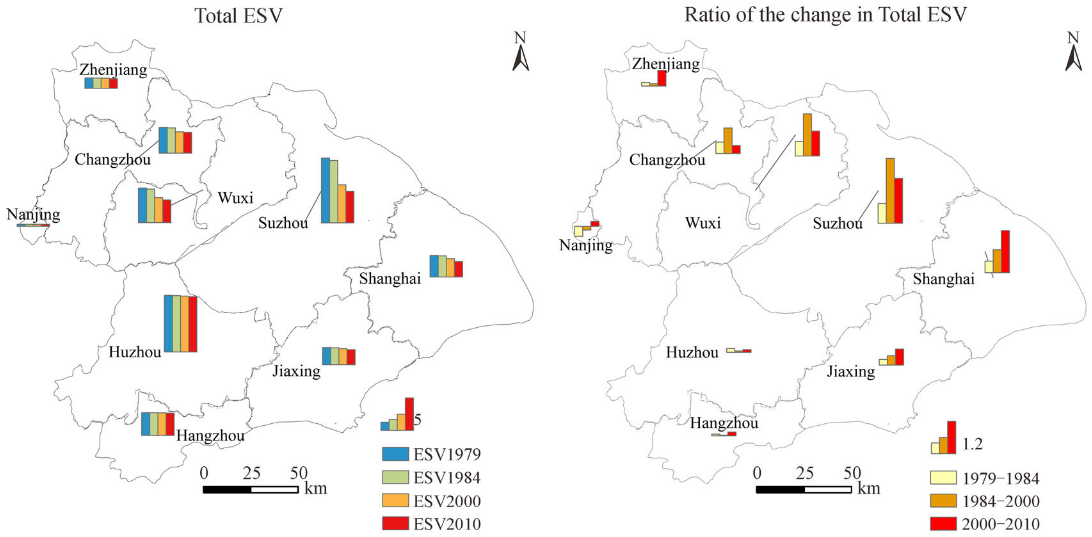

Fig. 4 ESVs (10^8 \$/yr) (a) and ratio of negative changes in total ESVs (%) (b) for 9 cities during 1979–2010.

Table 6 ESVs flow of each land use category (10^6 \$/yr)

		2010						Total
		Cropland	Woodland	Grassland	Water areas	Construction land	Unused land	
1979	Cropland	—	+200.0	+21.1	+52.1	−1214.8	−2.0	−943.6
	Woodland	−44.3	—	−5.8	−8.9	−40.5	−3.1	−102.3
	Grassland	−0.4	+8.9	—	−2.1	−0.8	0.0	+5.6
	Water areas	−27.5	−1.5	−0.2	—	−32.2	−0.8	−62.2
	Construction land	+146.4	+12.9	+1.5	+0.9	—	0.0	+161.7
	Unused land	+0.1	+0.3	+0.1	+0.2	—	—	+0.8

use types in 2010. Although conversion from construction and unused lands to other land-use types partly offset the loss of ecosystem services, the total ESV of the Taihu Lake Basin declined by \$940.02 million from 1979 to 2010. Thus, conversion between various land-use types during 1979–2010 directly caused ESV reduction.

4 Discussion

Rapid economic and dramatic population growths led to a decline in ESV in the Taihu Lake Basin. From 1979 to 2010, this area exhibited great progress in economic development; GDP increased from 41.02 billion CNY in 1979, to 920.34 billion CNY in 2000, and to 3555.53 billion CNY in 2010 (Fig. 5). As the conflict between economic development and ecological protection intensifies, a compromise must be addressed. Internal migration has also intensified net loss of ESV in the region. Urban sprawl is another important factor that contributes to the decrease in ESV. Industrial pollutant discharge and pesticide and fertilizer abuse directly cause or exacerbate water pollution, and both have directly led to a sharp decline in ESV during the past three decades. To improve water quality, the industrial structure needs to be optimized and upgraded urgently, and municipal wastewater treatment and agricultural nonpoint source pollution should be controlled. In response to the decline in cropland ESV, the protection of basic farmland needs to be strengthened, and reasonable urban planning should be proposed.

Along with global climate change and rapid economic development and progress in urbanization, China suffers increasing pressure on resource environment and ecology. Urbanization has strongly influenced land-use conversion in the regional development of the Taihu Lake Basin, and construction land has increased 1.56 times in the last three decades. Since the late 1970s, the lakes and rivers in this region have experienced dramatic water quality degradation associated with rapid land and economic developments. A main contribution of this study are the results that reflect the temporal changes and spatial variations of ESV in the long term, formed by comprehensive effects of land-use changes, water pollution, and other indirect acting factors. This ESV evaluation approach is applicable to

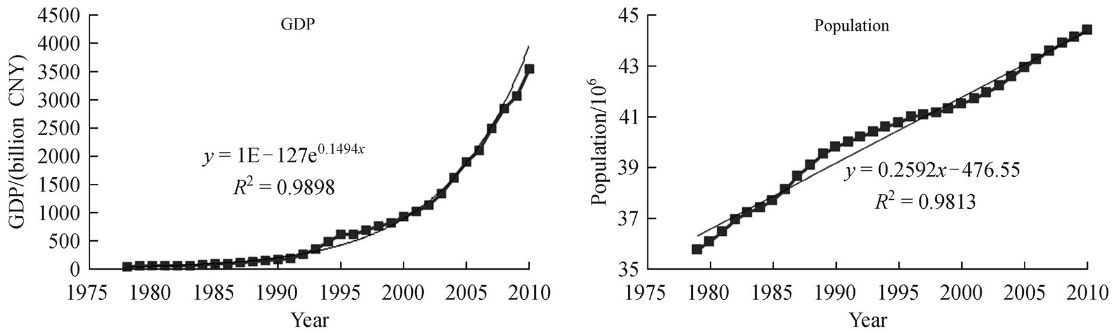

Fig. 5 Change in GDP and population in the Taihu Lake Basin, 1979–2010. Note: The data are obtained from the Jiangsu Statistics Yearbook (2011), the Zhejiang Statistics Yearbook (2011), and the Shanghai Statistics Yearbook (2011).

areas that lack adequate longitudinal data collected through field observations for diverse ecosystems.

The method we used to estimate ESV was modified based on the work of Xie et al. (2008) and a questionnaire was conducted in the Taihu Lake Basin. Land use can be used as a proxy measure of ecosystem services by matching the land-use categories with equivalent biomass, and valuation of ESV can then be conducted. ESV were derived by multiplying the area of a given land-use type by the corresponding ecosystem value coefficient. However, the method has been criticized on various grounds, mainly because the results are coarse with deviations and uncertainty caused by the complex, dynamic, and non-linear properties of ecosystems (Limburg et al., 2002; Turner et al., 2003); limitations of economic valuation of land use types (Kreuter et al., 2001); and double counting and scales (Hein et al., 2006). In addition, accuracy and reliability of the estimated results are affected by accuracy of value coefficients. The accuracy of the modified value coefficients (Table 3) may also cause errors because they largely depend on expert knowledge of study area conditions. Importance of field data to improve the accuracy of ESV was proposed and should be accounted for in future studies (Li, 2010; Xie et al., 2010; Zhang et al., 2010; Lautenbach et al., 2011).

5 Conclusions

Functions of ecosystem services in the Taihu Lake Basin have been heavily overexploited and jeopardized because of anthropogenic changes. The objective of this study is to evaluate the dynamics of ecosystem service values in the Taihu Lake Basin from 1979 to 2010. Considering the negative effects of water pollution, we adjusted the equivalent weight factor of water areas in the Taihu Lake Basin region. Based on the LUCC data produced from integrating Landsat TM images of the Taihu Lake Basin in 1979, 1984, 2000, and 2010, the results showed that the total value of ecosystem services supplied by the Taihu Lake Basin decreased from \$3.92 billion in 1979 to \$2.98 billion in 2010, as the changes of land use and ecosystem services value were trending down, which was associated with the decline in the area of cropland, which decreased by 498,165.48 ha from 1979 to 2010; and the area of construction land, which increased by 421,461.63 ha from 1979 to 2010. Furthermore, detailed analysis showed that another primary threat to the Taihu Lake Basin is the decline in water quality caused by water pollution, which is why the value of ecosystem service supplied by water areas dropped sharply from \$1.04 billion in 1979 to \$0.36 billion in 2010 over 31 years, although water areas appeared to be increasing.

Beyond these findings, our study estimated the flow of ecosystem service values from 1979 to 2010 and investigated the potential driving forces. It also showed that changes in the value of ecosystem services over time depend on the interaction of changes in various land cover types. Compared with the contribution of other landscape types to ESV, that of cropland was the largest; however, the value flow of cropland decreased the most for construction land by \$341.35 million from 1979 to 2010. Thus, the urban sprawl has profoundly affected the Taihu Lake Basin and has caused heavy damage to the value of ecosystem services. Trade-offs between increased development density and decreased ESV should be seriously considered in the policymaking process. Practical countermeasures must be taken in response to declining ESV, such as transforming the economic development pattern, drawing city boundaries, and improving the water environment. In addition, payment for ecosystem service initiatives can be advocated as “win-win” opportunities for ecological protection in the high-value region of ecosystem services.

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References

Ai J, Sun X, Feng L, Li Y, Zhu X (2015). Analyzing the spatial patterns and drivers of ecosystem services in rapidly urbanizing Taihu Lake Basin of China. Front Earth Sci, 9(3): 531–545

Alexander A M, List J A, Margolis M, D'arge R C (1998). A method for valuing global ecosystem services. Ecol Econ, 27(2): 161–170

Ayanu Y Z, Conrad C, Nauss T, Wegmann M, Koellner T (2012). Quantifying and mapping ecosystem services supplies and demands: a review of remote sensing applications. Environ Sci Technol, 46 (16): 8529–8541

Bagstad K J, Johnson G W, Voigt B, Villa F (2013). Spatial dynamics of ecosystem service flows: a comprehensive approach to quantifying actual services. Ecosystem Services, 4: 117–125

Brander L M, Wagtendonk A J, Hussain S S, McVittie A, Verburg P H, de Groot R S, van der Ploeg S (2012). Ecosystem service values for mangroves in Southeast Asia: a meta-analysis and value transfer application. Ecosystem Services, 1(1): 62–69

Brown G (2013). The relationship between social values for ecosystem services and global land cover: an empirical analysis. Ecosystem Services, 5: 58–68

Burkhard B, Kroll F, Nedkov S, Müller F (2012). Mapping ecosystem service supply, demand and budgets. Ecol Indic, 21: 17–29

Carpenter S R, Bennett E M, Peterson G D (2006). Scenarios for ecosystem services: an overview. Ecol Soc, 11(1): 29, URL:http://www.ecologyandsociety.org/vol11/iss1/art29

Carpenter S R, Mooney H A, Agard J, Capistrano D, Defries R S, Díaz S, Dietz T, Duraiappah A K, Oteng-Yeboah A, Pereira H M, Perrings C, Reid W V, Sarukhan J, Scholes R J, Whyte A (2009). Science for managing ecosystem services: beyond the millennium ecosystem assessment. Proc Natl Acad Sci USA, 106(5): 1305–1312

Costanza R, D'arge R, De Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'neill R V, Paruelo J, Raskin R G, Sutton P, Van Den Belt M (1997). The value of the world's ecosystem services and natural capital. Nature, 387(6630): 253–260

Costanza R, De Groot R, Sutton P, Van Der Ploeg S, Anderson S J, Kubiszewski I, Farber S, Turner R K (2014). Changes in the global value of ecosystem services. Glob Environ Change, 26: 152–158

de Araujo Barbosa C C, Atkinson P M, Dearing J A (2015). Remote sensing of ecosystem services: a systematic review. Ecol Indic, 52: 430–443

Estoque R C, Murayama Y (2013). Landscape pattern and ecosystem service value changes: Implications for environmental sustainability planning for the rapidly urbanizing summer capital of the Philippines. Landsc Urban Plan, 116: 60–72

Fensholt R, Proud S R (2012). Evaluation of earth observation based global long term vegetation trends—Comparing GIMMS and MODIS global NDVI time series. Remote sensing of environment, 119: 131–147

Fu B, Zhang L (2014). Land-use change and ecosystem services: concepts, methods and progress. Progress in Geography, 33(4): 441–446 (in Chinese)

Hein L, Van Koppen K, De Groot R S, Van Ierland E C (2006). Spatial scales, stakeholders and the valuation of ecosystem services. Ecol Econ, 57(2): 209–228

Ji D, Zhang H, Shen W, Wang Q, Li H, Lin N (2013). The response relationship between underlying surface changing and climate change in the Taihu Basin. Journal of Natural Resources, 28(1): 51–62 (in Chinese)

Jiangsu Bureau of Statistics (2011). Jiangsu Statistic Yearbook 2011. Beijing: China Statistics Press (in Chinese)

Jin X, Ye C, Yan C, Ren B, Zhang Y, Wang X, Wang Y (1999). Comprehensive treatment plan for key-polluted regions of Lake Taihu. Research of Environmental Sciences, 12(5): 1–5 (in Chinese)

Keeler B L, Polasky S, Brauman K A, Johnson K A, Finlay J C, O'neill A, Kovacs K, Dalzell B (2012). Linking water quality and well-being for improved assessment and valuation of ecosystem services. Proc Natl Acad Sci USA, 109(45): 18619–18624

Kreuter U P, Harris H G, Matlock M D, Lacey R E (2001). Change in ecosystem service values in the San Antonio area, Texas. Ecol Econ, 39(3): 333–346

Kuenzer C, Tuan V Q (2013). Assessing the ecosystem services value of Can Gio Mangrove Biosphere Reserve: combining earth-observation-and household-survey-based analyses. Appl Geogr, 45: 167–184

Lautenbach S, Kugel C, Lausch A, Seppelt R (2011). Analysis of historic changes in regional ecosystem service provisioning using land use data. Ecol Indic, 11(2): 676–687

Li W (2010). Progresses and perspectives of ecological research in China. Journal of Resources and Ecology, 1(1): 3–14

Li Y, Deng O, Zhang D, Han D, Feng Z (2011). Land use and ecosystem service value scenarios simulation in Danjiangkou reservoir area. Transactions of the Chinese Society of Agricultural Engineering, 27 (5): 329–335 (in Chinese)

Limburg K E, O'neill R V, Costanza R, Farber S (2002). Complex systems and valuation. Ecol Econ, 41(3): 409–420

Liu H, Chen X, Huang R, Lu J, Cai X, Li H, Wu J, Song Z, Yu Z (2011). Evaluation method of regional sustainable development based on land use information. Transactions of the Chinese Society of Agricultural Engineering, 27(11): 306–312 (in Chinese)

Pinto R, Patrício J, Neto J M, Salas F, Marques J C (2010). Assessing estuarine quality under the ecosystem services scope: ecological and socioeconomic aspects. Ecol Complex, 7(3): 389–402

Seidl A F, Moraes A S (2000). Global valuation of ecosystem services: application to the Pantanal da Nhecolandia, Brazil. Ecol Econ, 33(1): 1–6

Seppelt R, Dormann C F, Eppink F V, Lautenbach S, Schmidt S (2011). A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead. J Appl Ecol, 48(3): 630–636

Shanghai Bureau of Statistics (2011). Shanghai Statistic Yearbook 2011. Beijing: China Statistics Press (in Chinese)

Shi N, Zhan J, Wu F, Du J (2009). Identification of the core ecosystem services and their spatial heterogeneity in Poyang Lake area. Front Earth Sci China, 3(2): 214–220

Simonit S, Perrings C (2011). Sustainability and the value of the 'regulating' services: wetlands and water quality in Lake Victoria. Ecol Econ, 70(6): 1189–1199

Turner R K, Paavola J, Cooper P, Farber S, Jessamy V, Georgiou S (2003). Valuing nature: lessons learned and future research directions. Ecol Econ, 46(3): 493–510

Wang L, Cai Y, Fang L (2009). Pollution in Taihu Lake China: causal chain and policy options analyses. Front Earth Sci China, 3(4): 437–444

Wang Y, Gao J, Wang J, Qiu J (2014). Value assessment of ecosystem services in nature reserves in Ningxia, China: a response to ecological restoration. PLoS ONE, 9(2): e89174

Wang Y, Yu X, He K, Song S, Jia G, Huang Z (2012). Ecosystem services value based on land use change in Huairou reservoir watershed. Transactions of the Chinese Society of Agricultural Engineering, 28(5): 246–251 (in Chinese)

Xie G, Zhen L, Lu C, Xiao Y, Chen C (2008). Expert knowledge based valuation method of ecosystem services in China. Journal of Natural Resources, 23(5): 911–919 (in Chinese)

Xie G, Zhen L, Lu C, Xiao Y, Li W (2010). Applying value transfer method for eco-service valuation in China. Journal of Resources and Ecology, 1(1): 51–59 (in Chinese)

Yu D, Shao H B, Shi P J, Zhu W Q, Pan Y Z (2009). How does the conversion of land cover to urban use affect net primary productivity? A case study in Shenzhen city, China. Agric Meteorol, 149(11): 2054–2060

Zhang B, Li W, Xie G (2010). Ecosystem services research in China: progress and perspective. Ecol Econ, 69(7): 1389–1395

Zhao B, Kreuter U, Li B, Ma Z, Chen J, Nakagoshi N (2004). An ecosystem service value assessment of land-use change on Chongming Island, China. Land Use Policy, 21(2): 139–148

Zhejiang Bureau of Statistics (2011). Zhejiang Statistic Yearbook 2011. Beijing: China Statistics Press (in Chinese)