Secondary impacts of eutrophication control activities in shallow lakes: Lessons from aquatic macrophyte dynamics in Lake Taihu from 2000 to 2015

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Abstract: Aquatic macrophytes in lakes and rivers are highly sensitive to changes in water quality and ecological conditions. Satellite remote sensing of aquatic macrophyte distributions can map changes in freshwater ecosystem dynamics. However, macrophyte mapping by remote sensing is challenging in lakes dominated by algal blooms or with high turbidity. In this study, we mapped the composition and distribution of emergent/floating and submerged macrophytes in the large turbid and eutrophic Lake Taihu, China. We used a novel classification method and 16 y of MODIS images to map these data. The inter-annual trends in macrophyte distribution and cover show complex dynamics in this heavily-managed lake. The area occupied by emergent/floating macrophytes increased from 39.3 km^2 in 2000 to 90.3 km^2 in 2015 (a 230% increase), whereas the area dominated by submerged macrophytes decreased from 404.6 km^2 in 2001 to 167.5 km^2 in 2015 (a 59% decrease). We also used the annual date of initial macrophyte occurrence and growth period to examine temporal variation in species composition and biodiversity of macrophytes. Aquatic macrophytes in different parts of the lake responded differently to temporal trends in water quality (Secchi disk and nutrient concentrations), hydrology (water level), and meteorological data (daily temperature, precipitation, and h of sunlight). Changes in lake transparency occurred over the study period, reducing the availability of underwater solar irradiance. Light availability was the most influential local environmental factor for macrophyte dynamics. We also found that eutrophication control projects indirectly reduced lake ecosystem quality in some bays. These control projects included water transfers from the Yangtze River (dilution), aquaculture management actions, macrophyte removal, and dredging. Our findings suggest the species composition and area covered by aquatic macrophytes in this shallow lake are driven by multiple mechanisms. These results highlight that efforts to manage the increase in algal-dominated lake areas require a more complete understanding of the direct and indirect impacts of management activities. We also show that satellite-based remote sensing measurements of macrophyte spatial and temporal dynamics provide a useful indicator to evaluate the impacts of these activities.

Key words: Aquatic macrophytes, spatial-temporal dynamics, remote sensing, eutrophication management, MODIS

Accelerated eutrophication of lakes and reservoirs is a world-wide challenge, with the continued degradation of water quality usually attributed to human activities such as agricultural, industrial, and urban growth (Qin 2009). Many eutrophication control programs that have successfully improved water quality and reduced algal blooms (Jeppesen et al. 1997, Qin 2009, Qin et al. 2010) have also created potentially detrimental effects on lake macrophytes, especially submerged macrophytes. A better understanding of multiple impacts of eutrophication control activities is fundamental to support national and local governments to make more robust decisions about the indirect impacts of past and present management actions in lakes. Remote sensing can provide an important tool to understanding the impact

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of management actions on overall water quality and algal bloom frequency as well as on macrophytes distribution.

Lake Taihu (30°55′40″–31°32′58″N, 119°52′32″–120°36′10″E) is located in the Yangtze River Delta. The lake has a water surface area of 2338 km^2 and mean depth of 1.95 m (Fig. 1; TBA and MWR 2015). The Lake Taihu Basin is one of the most industrialized areas in China and has high population density, urbanization, and economic development (Qin et al. 2007). The lake provides ecosystem services including flood management (storage), irrigation and drinking water supply, aquaculture, and a tourism industry to the local population of 36 million (Wang et al. 2006). However, dramatic economic development in the Lake Taihu catchment since the 1980s has caused water quality to deteriorate, resulting in elevated eutrophication and persistent algal blooms (*Microcystis* spp; Qin et al. 2007).

Lake Taihu can be divided into 2 spatially-distinct areas: the eastern lake sections that are dominated by aquatic macrophytes, and the north, south, and western lake areas that are dominated by high turbidity caused mostly by high algal biomass. Algal blooms were first observed in the northern bays. After the year 2000, these blooms spread to the center and southern parts of the lake (Duan et al. 2009). Aquatic macrophytes have dominated the eastern lake sections since the 1960s. Their area increased into eastern bays Xukou and Gonghu in the 1980s (Qin et al. 2007), which contain key areas from which municipalities of Wuxi, Suzhou, and (indirectly) Shanghai withdraw potable water (Wang et al. 2006, Qin et al. 2007, TBA and MWR 2015).

Pen-fish aquaculture has been a major economic activity in East Taihu Bay since 1993 and covers almost all of the shoreline (Wu et al. 2000). Nutrient loading from these activities has been reported (Rennie et al. 2019). In fact, the high density of pen-fish aquaculture was associated with a change from submerged to emergent and floating macrophytes in Lake Taihu, often with respect to the reduced water movement (Qin et al. 2007). This change resulted in an increase in the overall macrophyte areas in the East Taihu Bay.

In an effort to control the increasing eutrophication in Lake Taihu, the Chinese government started a series of programs for pollution control in 1996 (Qin et al. 2007). These programs included industrial emissions directives, domestic wastewater treatment, and hydrological changes. The hydrological changes included water transfer from the Yangtze River to Lake Taihu (Wang et al. 2006). In-lake management actions included macrophyte removal, restriction of aquaculture facilities, and lake dredging.

Water quality monitoring was also increased in 1996, and high frequency nutrient monitoring programs were started in several lake areas. To extend these site-specific measurements and create long-term records, this monitoring also included the remote sensing of both algal bloom dynamics (Duan et al. 2009, 2014a, 2014b, Hu et al. 2010a,

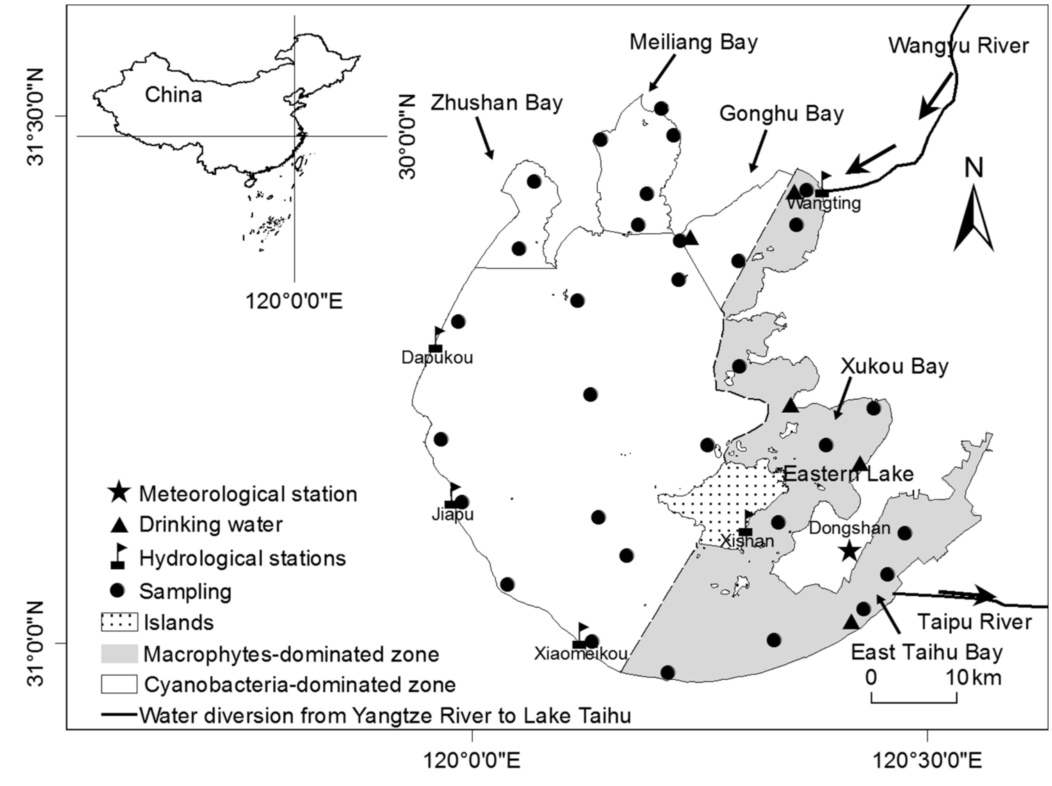

Fig. 1. The location of Lake Taihu in China (red arrows indicate the flow direction of Water Diversion Project).

Huang et al. 2014, Zhang et al. 2016b) and aquatic macrophyte spatial distributions (Ma et al. 2008, Zhao et al. 2012a, 2012b, 2013). However, remote sensing studies in shallow eutrophic lakes have difficulty distinguishing between areas covered with macrophytes and areas with high density cyanobacterial scum. This problem occurs because emergent and floating macrophytes and cyanobacterial scum have similar spectral characteristics in the red and near infrared wavebands (Liang et al. 2017). The inability to distinguish cyanobacterial scum from aquatic macrophytes makes it difficult to use remote sensing data to evaluate management actions and long-term trends.

To evaluate the impacts of eutrophication control measures on the aquatic macrophyte dynamic in lakes, new tools are needed that take advantage of the high temporal frequency of remotely-sensed data, with respect to the lower spatial resolution that characterize these data. In this study, we use long-term medium resolution satellite data from the Moderate Resolution Imaging Spectroradiometer (MODIS) system to identify the spatial and temporal dynamics of macrophytes with respect to management actions and environmental control factors. We use this information to make inferences about the indirect impacts of past and present management actions in Lake Taihu.

METHODS

We processed satellite reflectance data from MODIS to identify aquatic macrophyte typology and macrophyte spatial and temporal dynamics in Lake Taihu from 2000 to 2015. Water quality and hydrological and meteorological data were compared to macrophyte dynamics to identify key environmental drivers with respect to efforts related to large-scale provincial eutrophication control projects.

MODIS data

We obtained MODIS Level-0 data, collected by Terra (2000–2002) and Aqua (2003–2015), which are 2 MODIS instruments, from the NASA Goddard Space Flight Center through its Ocean Biology Processing Group (https://ladsweb.modaps.eosdis.nasa.gov). These data spanned our entire study region in Lake Taihu. We used reflectances in 5 wavebands (469 nm, 555 nm, 645 nm, 859 nm, and 1240 nm) to monitor both algal blooms and macrophytes. These wavebands are less sensitive to similar wavebands on ocean satellite sensors but have a larger dynamic range that makes them less susceptible to saturation in highly turbid waters. The ground resolution of the 645 nm and 859 nm bands is 250 m, and the resolution of the other bands is 500 m. Comparison of Terra and Aqua MODIS is important to assess calibration quality and consistency to ensure continuity of these 2 observational datasets. Terra and Aqua MODIS reflectances were 2% different based on Advanced Very High Resolution Radiometer (Wu et al. 2008) and <1% different based on lunar observations (Xiong et al. 2008). Thus, we were able to use both in our study. We used a maximum of 4 MODIS images/mo based on availability and cloud conditions (Table S1) to ensure that the spatial and temporal distributions in this study were comparable between mo.

Water quality and hydrological and meteorological data

We obtained monthly water quality and water level data, based on 31 measurement sites across the lake, from the Taihu Basin Authority (Table 1, Fig. 1). Water transparency was measured with a Secchi disk. Total phosphorus (TP) and total nitrogen (TN) concentrations were determined with combined persulfate digestion (Ebina et al. 1983), followed by spectrophotometric analysis for soluble reactive phosphorus and nitrate. The TN and TP recovery efficiencies were 98.4 and 99.7%, respectively. Water level was determined from the mo average of 5 hydrological stations in Lake Taihu (Wangting, Dapukou, Xishan, Jiapu and Xiaomeikou; Fig. 1). Synchronous meteorological data including temperature, hours of sunlight, wind speed, and precipitation were obtained from the Dongshan Meteorology Station of the China Meteorological Administration.

MODIS data preprocessing

All MODIS data were processed with SeaDAS (v7.0, NASA, USA) software. First, we converted the data from Level-0 to calibrated radiance (Level-1B). We then applied a partial atmospheric correction to correct for gaseous absorption (mainly by ozone). Finally, we applied Rayleigh (molecular) scattering to Level-1B data, resulting in Rayleigh corrected reflectance (R_{rc}, dimensionless):

$$R_{rc}(\lambda) = \rho_t(\lambda) - \rho_r(\lambda) = \rho_a(\lambda) + \pi \times t(\lambda) \times t_0(\lambda) \times R_{rs}(\lambda) \qquad \text{(Eq. 1)}$$

Where R_{rs} is the water leaving reflectance, ρ_{t} is the top of atmosphere reflectance after adjusting for atmospheric (gas) absorption, ρ_{r} is the reflectance from Rayleigh scattering, ρ_{a} is the reflectance from aerosol scattering and aerosol-Rayleigh interactions, t is diffuse transmittance from the image pixel to the satellite, and t_0 is diffuse transmittance

Table 1. Descriptive statistics for water level (WL), Sechi disk depth (SDD), chemical oxygen demand (COD), total nitrogen (TN) concentration, and total phosphorus (TP) concentration in Lake Taihu from 2000 to 2015. SD = standard deviation.

	WL (m)	SDD (cm)	COD (mg/L)*	TN (mg/L)	TP (mg/L)
Min	2.77	8	7	0.08	0.01
Max	4.06	166	401.83	19.30	0.72
Mean	3.23	38	15.95	2.56	0.08
SD	0.21	16	13.16	1.93	0.06

* COD data was measured from 2003 to 2015.

from the sun to the image pixel. Note that ρ_a, t, and t_0 are functions of aerosol type, aerosol optical thickness, and solar geometry. The above formulation assumes contributions from whitecaps and sun glint are negligible.

We mapped the R_{rc} data to a cylindrical equidistant projection for further analysis. First, we used the R_{rc} data at 645 nm, 555 nm, and 469 nm to compose the Red-Green-Blue true color images to screen for clouds and sun glint. After visual inspection, we selected a total of 565 MODIS images between 2000 and 2015 for long-term analysis. These images had no detectable cloud cover or sun glint.

Aquatic macrophyte identification

The spectral reflectance of aquatic macrophytes and cyanobacterial scum are very similar in the red and near infrared wavelengths, so it is difficult to distinguish them in waterbodies where they can both occur (Oyama et al. 2015). This difficulty is further complicated by the limited wavebands available in these spectral regions on the multispectral sensors with the longest historic datasets. Recently, Liang et al. (2017) developed a novel classification tree method to simultaneously monitor algal blooms, aquatic macrophytes, and turbidity with MODIS imagery (see Fig. 4 in Liang et al. 2017). This new approach allows for the synchronous determination of the distributions of Cyanobacteria blooms and aquatic macrophytes in eutrophic shallow lakes. The classification tree uses 3 indices: a Cyanobacteria and macrophyte index (Liang et al. 2017), a turbid water index (Feng et al. 2012), and a floating algae index (Hu 2009). The spatial resolution of MODIS images is coarse, so we combined emergent and floating macrophytes into a single group. In situ reflectance spectra, field investigations, and high spatial resolution data were used to validate the results (Liang et al. 2017). Field validations between 2013 and 2016 showed an overall classification accuracy of 87, 81, 77, 88 and 73%, respectively. Estimated aquatic macrophyte distribution from MODIS imagery were consistent with existing estimates based on Landsat TM/ETM+ (Zhao et al. 2013) and HJ-CDD data (Luo et al. 2014).

Estimating macrophyte frequency of occurrence

The value of a pixel j in a MODIS image $i(C_{j,i})$ was set to 1 when identified as submerged macrophytes or floating/emergent macrophytes or to 0 when no macrophytes were present based on the output of the aquatic macrophyte identification model. We then evaluated macrophyte frequency over the 16-y MODIS dataset:

$$F(j) = \frac{\sum_{i=1}^{n} C(j,i)}{n} \quad \text{(Eq. 2)}$$

where F is the frequency of macrophyte presence in each pixel j of the total images (n; Liu et al. 2015, Zhang et al. 2016b). We then combined all of the MODIS images in the maturity period (July–September) to determine the composition of different macrophytes.

Determining the macrophyte growth period

For each pixel, we defined the initial mo as the 1st mo within a particular y in which we identified macrophytes with MODIS images. We defined the macrophyte growth period as the number of mo from the initial mo to the final mo that macrophytes were detected with MODIS images. We quantified the length of the growth period for each y in our study set and considered a cycle to be from February to the next January.

Statistical analyses

Linear model fitting We used linear regression to identify the long-term trends in the distribution, initial appearance, and growth period of macrophytes as well as the relationship between temporal changes in water-quality attributes and annual total water transfer volume. The linear models were assessed quantitatively with regression coefficients (R^2) and significance levels (p).

Pearson correlation analyses We used Pearson correlation analyses to explore the effects of various environmental factors on macrophyte distribution in the lake. Environmental factors considered in the present study included water quality (Secchi disk and nutrient concentrations) and hydrological (water level) and meteorological (daily temperature, precipitation, and hours of sunlight) data on inter-annual and monthly scales. Prior to the analyses, we tested normality and homoscedasticity of the data. To facilitate the comparisons of different data, we analyzed difference from the mean (Δ).

Redundancy analysis To quantify the effects of environmental conditions on inter-annual variation in aquatic macrophyte occurrence, i.e., frequency of pixels with macrophytes and initial mo macrophytes were detected, we conducted a Redundancy Analysis (RDA) with CANOCO software (Ter Braak and Smilauer 2002). RDA allowed us to independently determine the contribution of each explanatory variable on the dependent variable (i.e., macrophyte cover area) by converting some of the variables into virtual complex variables (Dong et al. 2014, Zhao et al. 2015). When data were not normally distributed, we $\log(x+1)$ transformed and Z-standardized the data (mean = 0, standard deviation = 1; Dong et al. 2014). We used manual forward selection to determine which environmental variables were correlated with inter-annual variation in aquatic macrophyte characteristics (Monte Carlo test with 999 permutations, $p < 0.05$). We tested the statistical significance of macrophyte–environment correlations for the ordination axes generated in RDA with Monte Carlo tests based on 999 permutations (Dong et al. 2014). To quantify the effects of environmental conditions on inter-annual variation in aquatic macrophyte characteristics (frequency and initial mo of occurrence), we conducted an RDA with a manual variable selection process (499 nonrestrictive screening cycles) based on the Monte Carlo permutation method to identify significant variables (Table 4). The full model and reduced model analysis modes were run simultaneously but separately. We obtained eigenvalues for the ordination axis, the correlation coefficient between aquatic macrophyte characteristics and environmental conditions and the ordination axis, and the total variance.

RESULTS

Aquatic macrophyte dynamics

Aquatic macrophytes were most abundant in the southern portion of Gonghu Bay and the eastern sections of Lake Taihu ($F = 7.8\% \pm 4.8\%$ and $26.6\% \pm 5.3\%$, respectively) including East Taihu Bay, Xukou Bay, and smaller bays (Fig. 2). All large lake segments had a maximum frequency of macrophyte cover in 2002, with a decreasing trend of macrophyte cover in the following decade. For the eastern lake sections, macrophyte cover declined linearly from 36% in 2002 to 17% in 2015, a reduction of 1.5% per y. Before 2004, macrophytes occupied up to almost $^1/_2$ of Gonghu Bay ($F = 13.5\% \pm 4.1\%$ for the whole y), but had nearly disappeared by 2008. After 2009, macrophytes returned to the southern part of Gonghu Bay but were only present in 5% of the bay. Between 2000 and 2003, small patches of macrophytes occurred near the north shorelines of Meiliang Bay and Zhushan Bay, but these disappeared in 2004. A pollution-resistant submerged macrophyte (*Potamogeton crispus*) appeared in these bays in 2013 and 2014.

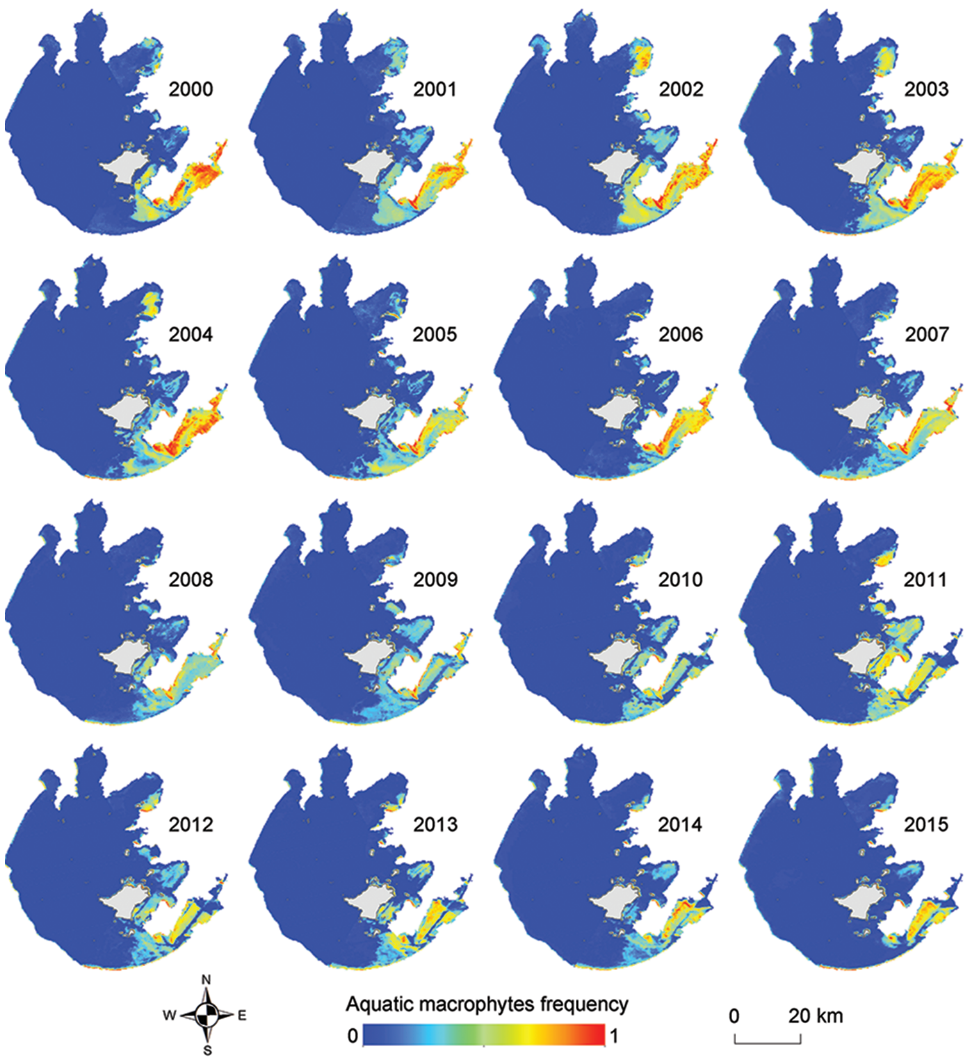

Fig. 2. Annual MODIS-derived aquatic macrophyte frequency of occurrence from 2000 to 2015. Frequency for a pixel is defined as the % of the total number of MODIS images that aquatic plants were detected in a y.

The seasonal distribution of macrophyte cover (Fig. 3) shows the dormant (January–February), growth (March–June), maturity (July–September), and senescence (October–December) periods, which follow the expected life cycle of aquatic macrophytes at this latitude. This result shows that aquatic macrophytes exist in East Taihu Bay for the entire y. In Xukou Bay and the southern portion of Gonghu Bay, submerged vegetation occurred in extremely low abundance from January to February each y. The eastern section of the lake was covered primarily by floating macrophytes, which were most common from May to December.

Compositional change in macrophyte cover

The area occupied by emergent/floating and submerged macrophytes and the temporal dynamics of different macrophyte types have both changed markedly over the past 16 y. We found that the area covered by submerged macrophytes decreased significantly throughout the study period (R^2= 0.51, p = 0.002; Fig. 4A–B). The area occupied by emergent/floating macrophytes changed from 39.3 km^2 in 2000 to 90.3 km^2 in 2015 (a 230% increase). Emergent macrophytes covered the most area (174.2 km^2) in 2013. In contrast, submerged macrophyte cover decreased from 404.6 km^2 in 2001 to 167.5 km^2 in 2015 (a 59% decrease). Thus, floating/emergent macrophytes comprised a greater percentage of total aquatic macrophytes in the latter part of the study period, with a 21.3% increase (from 125.4 km^2 in 2010 to 174.2 km^2 in 2013), although the percentage then decreased to 35.0% in 2015. Conversely, the % of total macrophyte area covered by submerged macrophytes decreased from 88.5% in 2000 to 45.8% in 2013 and then increased to 65.0% in 2015.

Initiation mo and growth period

The initial mo and growth period of aquatic macrophytes varies across species (Li 1997, Wang et al. 1999). March is typically the initial mo macrophytes are detected in Lake Taihu (Luo et al. 2016). Analysis of macrophyte growth period, in turn, can reveal general trends such as species change and abundance. Within a given y, aquatic macrophytes were generally first observed in the aquaculture area of East Taihu Bay (Fig. 5). Before 2003, macrophytes appeared earlier in the y on the north shorelines of Zhushan Bay and Meiliang Bay. Macrophytes disappeared in these bays until 2013. For the whole lake, macrophyte cover reached its maximum from May to July. In 2015, aquatic macrophytes occupied much less area during the fast-growing period, especially in East Taihu Bay. Senescence occurred after 3 to 6 mo, with the last observations occurring in aquaculture areas of East Taihu Bay (Fig. 6). These observations were probably of the

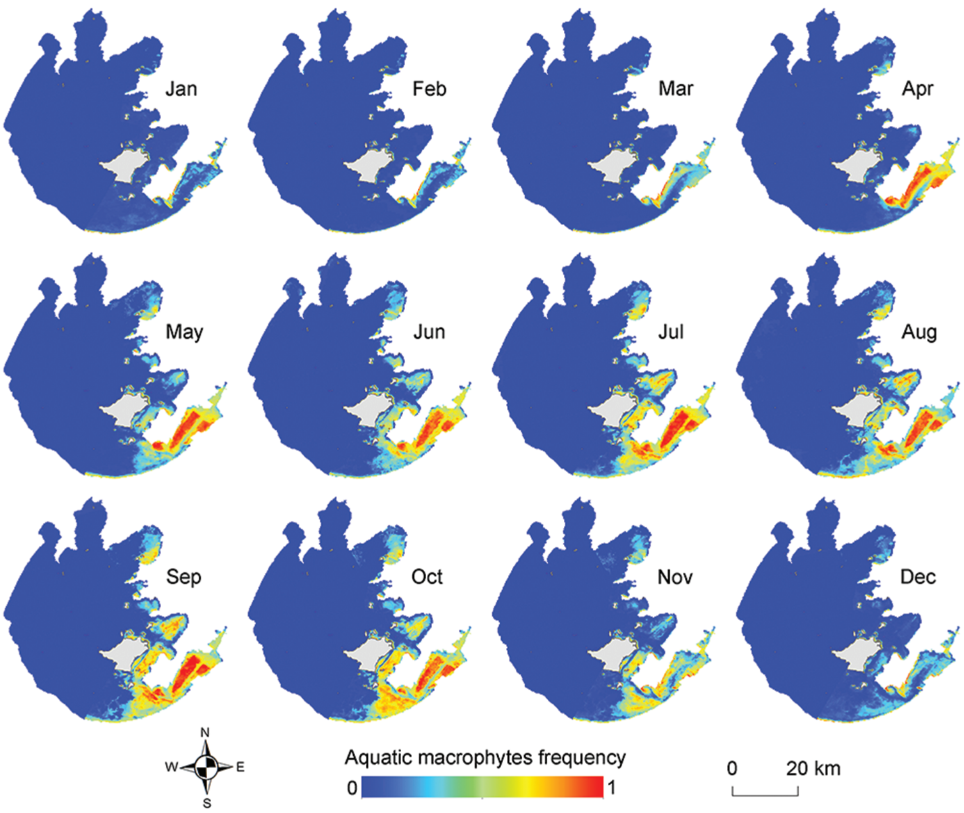

Fig. 3. Monthly MODIS-derived aquatic macrophyte frequency of occurrence from 2000 to 2015. Frequency for a pixel is defined as the % of the total number of MODIS images that aquatic plants were detected in a mo.

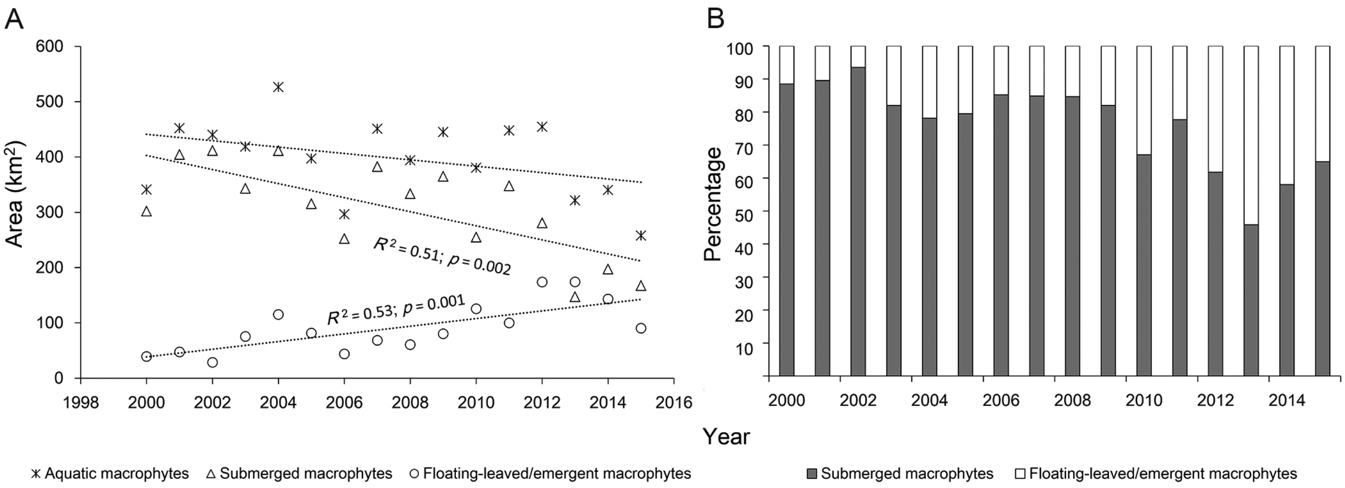

Fig. 4. Average area (km^2) of aquatic macrophytes (A) and the % of submerged and floating/emergent species (B) in Lake Taihu from July to September (2000–2015).

Fig. 5. Initial month that aquatic macrophytes appear in Lake Taihu from 2000 to 2015.

Fig. 6. Duration of the macrophyte growth period in Lake Taihu from 2000 to 2015.

dominant macrophyte *Elodea nuttallii* (Table 2). Growth periods >6 mo decreased significantly over the study period ($p < 0.01$; Fig. 7A–B). In 2008, no macrophytes were present for >6 mo.

Potential environmental drivers

The relationship between the monthly dynamics of potential environmental drivers and the amount of macrophyte cover depended on the lake segment studied (Table 3). We found no significant correlations between the environmental factors and macrophyte cover area in neither Zhushan Bay nor Meiliang Bay. In Gonghu Bay, the difference of Secchi disk depth (ΔSDD) was weakly and positively correlated with variation in macrophyte cover. In the eastern lake sections, ΔSDD was also positively correlated with the inter-annual variation in macrophyte cover. The difference of nutrient concentrations, ΔTN and ΔTP, were negatively correlated with the amount of macrophyte cover in Eastern Lake. We also found very weak correlations of seasonal variation in macrophyte cover with temperature (ΔT; $r = 0.15$, $p = 0.044$) and lake water level (ΔWL; $r = -0.17$, $p = 0.018$).

Based on the RDA, the relationship between the inter-annual dynamics of environmental drivers and the amount of macrophyte cover in different segments (Table 4) showed that TP and SDD were significantly correlated with the inter-annual characteristics of macrophytes in Gonghu Bay and in Zhushan Bay, respectively. None of the measured environmental factors explained the inter-annual aquatic macrophytes characteristics of Meiliang Bay. In the Eastern Lake sections, 3 environmental factors (SDD, TN, and S) affected inter-annual macrophyte characteristics: the first 2 RDA axes explained 33.6% of the variance in aquatic macrophyte cover and 87.6% of the variance in the macrophyte–environment relationship. The 2nd RDA axis was highly

Table 2. Main dominant aquatic macrophytes and the characteristics of their life cycle and habit in Lake Taihu as inferred from the field investigation.

		Life cycle					Life habit	
Aquatic macrophyte type	Dominant macrophyte	Germination time	Fast-growing period	Time of canopy arrival at 0.5 m underwater	Max biomass period	Max height (m)	Environment	Sediment
Emergent	*Phragmites australis*	Mar	Apr–May	–	Jun–Nov	2–5	Wind resistant	Soft/firm
	Zizania latifolia	Mar	Apr–Aug	–	Aug–Nov	1.6–2	Wind resistant	Soft/firm
Floating	*Nymphoides peltata*	Mar	May	Jun	Jul–Nov	Surface	Wind resistant	Soft/firm
	N. indica						Wind resistant	Soft/firm
	Trapa maximowiczii	Late Apr	Jun	Jul	Aug–Oct	Surface	Wind resistant	Soft/firm
Submerged	*Potamogeton maackianus*	Early Apr	May	Jun	Jul–Nov	Surface	Static	Soft
	P. malaianus						Wind resistant	Soft
	Vallisneria natans	Early May	Jun–Jul	–	Aug–Nov	–1.2	Static	Firm
	Ceratophyllum demersum	Late Mar	Apr	May	Jun–Nov	Surface	Static	Soft
	Hydrilla verticillata	Late Mar	Apr	May	Jun–Nov	Surface	Static	Soft
	Chara	Apr	Jun–Jul	Aug	Sep–Nov	–0.5	Static	Firm
	Myriophyllum spicatum	Late Mar	Apr	May	Jun–Nov	Surface	Wind resistant	Soft
	Elodea nuttallii	Feb	Mar	Apr	May–Dec	Surface	Static	Soft
	P. crispus	Feb	Apr	May	Jun–Jul	Surface	Wind resistant	Soft

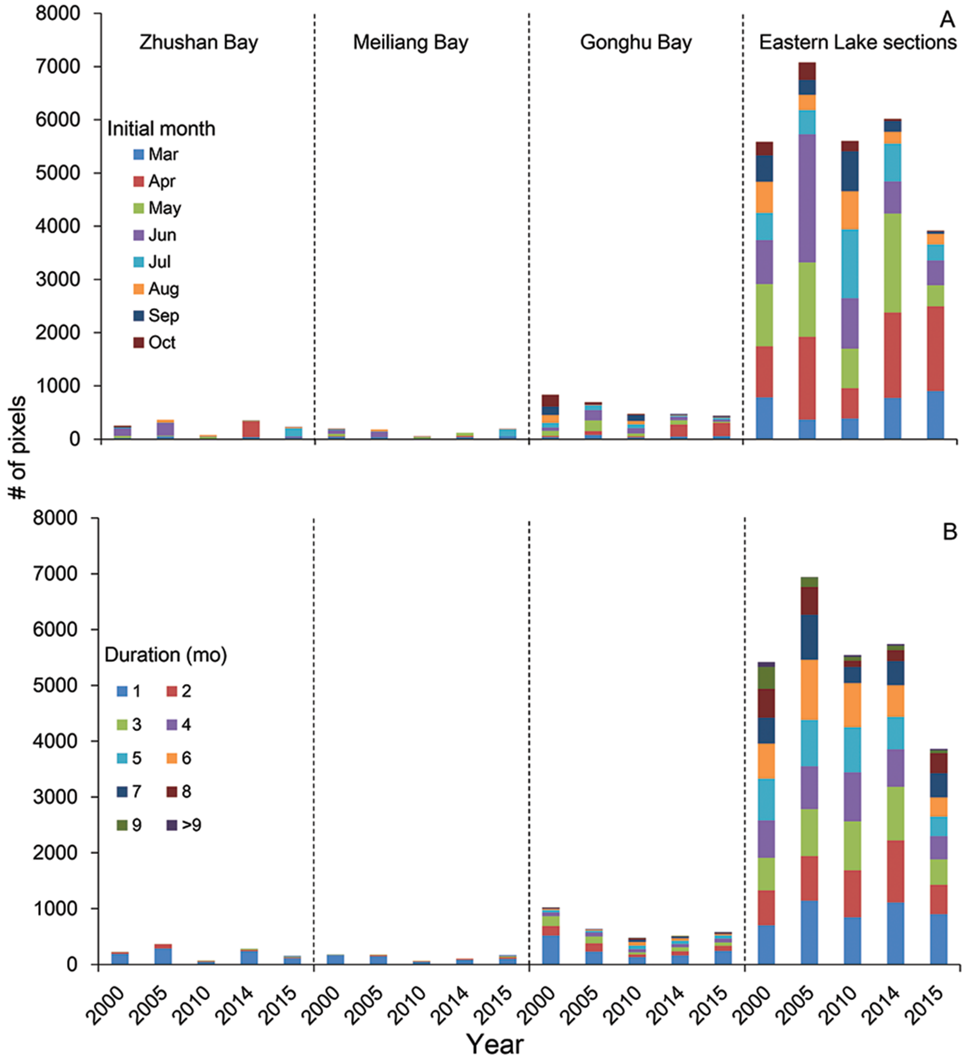

Fig. 7. Initial month of occurrence of aquatic macrophytes (A) and duration of their growth period (B) in different segments of Lake Taihu in 2000, 2005, 2010, 2014, and 2015.

correlated with both SDD (0.53) and hours of sunlight (−0.69), which reflected the availability of underwater irradiance. In Lake Taihu, water depth (3.2 ± 0.2 m) was not correlated with area of macrophyte cover (r = 0.002).

DISCUSSION

Species and biodiversity variation of aquatic macrophytes

In shallow lakes, anthropogenic-related eutrophication can influence both the macrophyte species diversity and the amount of the lake they cover (Feldmann and Nõges 2007, Kolada 2010, Thomaz and da Cunha 2010). This study focused on the dynamics of broad aquatic macrophyte groups rather than on species because of the relatively coarse spatial resolution of the MODIS dataset (250 and 500 m). However, we could compare these data with in situ observations. Fourteen dominant species of aquatic macrophytes were identified in historic surveys in Lake Taihu (Table 2; Lei 2006). These species included 2 emergent species, 3 floating species, and 9 submerged species. In Zhushan Bay and Meiliang Bay, submerged macrophytes, dominated by *Potamogeton malaianus*, occurred along the north shoreline in 2001 (TBA and MWR 2000) but had disappeared completely between 2005 and 2010. *P. crispus* had also disappeared in these 2 bays in 2005 but recurred in 2013 and could be observed only from April to July. In Gonghu Bay, a longer growing season resulted in a rich diversity of aquatic macrophytes in 2000, which shifted to *P. malaianus* and *Nymphoides peltata* in 2014 and 2015, accompanied by *Myriophyllum spicatum*. In the eastern lake sections, in 2000, *Elodea nuttallii* appeared 1st in the pen aquaculture area, followed by *Ceratophyllum demersum* (Gu et al. 2005), and then *P. malaianus* and *N. peltata* in East Taihu Bay, Xukou Bay, and the

Table 3. Pearson correlation coefficients between temporal variation in aquatic macrophyte cover and environmental factors in different segments (n = 192).

Correlation		Hydrology	Water quality			Meteorology		
		ΔWL (m)	ΔSDD (m)	ΔTN (mg/L)	ΔTP (mg/L)	ΔT (°C)	ΔP (mm)	ΔS (h)
Zhushan Bay	Pearson	0.02	0.01	0.10	0.08	0.06	–0.12	–0.10
	P	0.757	0.910	0.150	0.247	0.385	0.093	0.191
Meiliang Bay	Pearson	0.06	0.11	0.13	0.11	0.04	–0.11	–0.11
	P	0.385	0.118	0.082	0.124	0.542	0.149	0.137
Gonghu Bay	Pearson	–0.12	0.22	0.11	–0.11	0.05	–0.13	–0.14
	P	0.097	0.002	0.141	0.116	0.541	0.077	0.053
Eastern Lake sections	Pearson	–0.17	0.41	–0.28	–0.25	0.15	–0.13	–0.06
	P	0.018	0.000	0.000	0.001	0.044	0.066	0.448

Δ = deviation from the mean; WL = water level; SDD = Secchi disk; TN = total nitrate; TP = total phosphate; T = air temperature; P = precipitation; S = hours of sunlight.

waterway between Xishan and Dongshan. *Vallisneria natans* was found in Xukou Bay in August 2000 (TBA and MWR 2000). In 2005, *Elodea nuttallii* association, *P. malaianus*, and *N. peltata* dominated the whole eastern lake sections (Lei 2006). In 2010, in parallel with the reduction in pen aquaculture, the area of *E. nuttallii* decreased. In following y, *E. nuttallii* cover increased and became the dominant macrophyte in the eastern lake sections in 2015. At the same time, *P. malaianus* and *N. peltata* almost disappeared.

Impacts of management activities since 2000

Water quality is a basic environmental factor that can affect macrophyte growth and permanence. Some of the observed changes in water quality were very likely the result of catchment management activities to reduce eutrophication. We consider these, in addition to in-lake management changes, as having potentially direct as well as indirect impacts on macrophyte dynamics (Zhao et al. 2012a).

Hydrological changes to the lake and catchment To improve water quality and control algal blooms in Lake Taihu, the national government created a Water Transfer Project in 2002, bringing water from the Yangtze River into Gonghu Bay through the Wangyu River and discharging water from the lake into the Taipu River from the East Taihu Bay (Fig. 1; Hu et al. 2008). During water transfer periods, water flow in the Wangyu River goes from the Yangtze River to the lake, while in the remainder of the y, water discharges from the lake to the Yangtze, with a reverse of the Wangyu River flow direction (Hu et al. 2010b, Wang 2015). However, the inflow of the Yangtze River water did not produce significant reductions in nutrient concentrations in Gonghu Bay, despite

Table 4. RDA ordination axis correlations between annual macrophyte characteristics (frequency and initial month distributions) and environmental factors in different segments (n = 16).

Segment	Significant variables[a]	Correlations[b]				Explanatory ability		
		AX1[c]	AX2	AX3	AX4	Explained variance[d]	% of total variance	*P*
Zhushan Bay	TP	0.790	0	0	0	0.128 (0.492)	26.0	0.048
Meiliang Bay	–	–	–	–	–	−(0.510)	–	–
Gonghu Bay	SDD	−0.719	0	0	0	0.145 (0.478)	30.3	0.040
Eastern Lake	SDD	−0.221	0.526	−0.572	0	0.135 (0.609)	22.2	0.046
	TN	−0.260	−0.235	0.736	0	0.115 (0.609)	18.9	0.022
	S	−0.346	−0.685	0.200	0	0.134 (0.609)	22.0	0.038

[a] SDD = secchi disk; TN = total nitrate; TP = total phosphate; S = hours of sunlight.
[b] Correlations report the relationship between the axis and environmental factors.
[c] AX1 represents the 1st axis, AX2 represents the 2nd axis of RDA ordination, and so on.
[d] Explanatory power of all variables on water quality spatial variation in the analysis of RDA (full model).

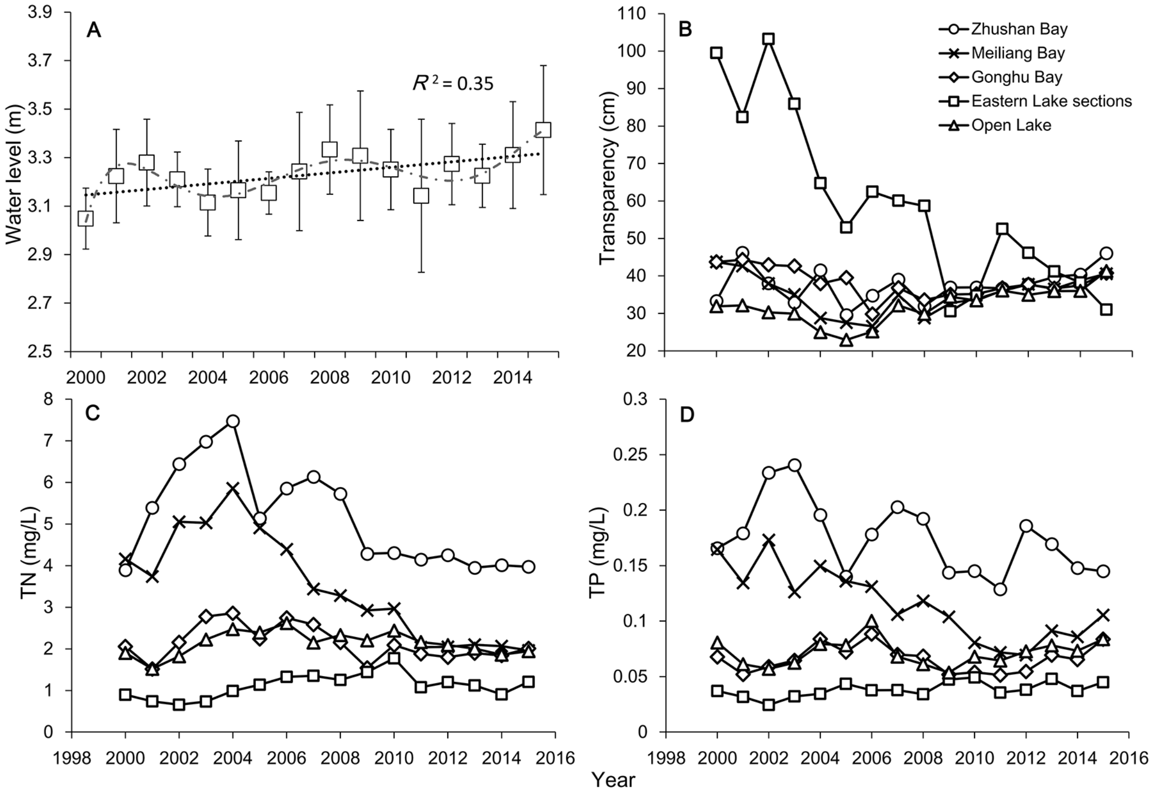

Fig. 8. Variation in water level (A), transparency (B), total nitrate (TN; C), and total phosphate (TP; D) in Lake Taihu between 2000 and 2015.

a reduction in Chl *a* concentrations in Lake Taihu (Fig. 8A–D). This was likely the result of both the high nutrient concentrations in the river inputs (Hu et al. 2008, Zhai et al. 2010) as well as the modified hydrodynamic processes (Hu et al. 2010b). In fact, this change in flow direction increased mixing in the lake water column, which appears to have increased nutrient concentrations and reduced transparency in the Gonghu Bay. Both of these changes were important environmental drivers to aquatic macrophyte dynamics by decreasing transparency (Table 3).

Changes in the hydrodynamics of the Taipu River, the eastern outflow of the lake and a major water source for Shanghai City, were linked with a general degradation of conditions in East Taihu Bay (Li et al. 2011; Zhang et al. 2016a). An increase in water flow from the lake to the Taipu River led to a decrease in SDD in East Taihu Bay (Fig. 9). The decrease in SDD was associated with an increase in the flow of high nutrient concentrations from other lake segments to the eastern lake sections and East Taihu Bay. A linear model showed a strong negative relationship ($R^2 = 0.764$; $p < 0.001$) between the cumulative annual flow in the Taipu River and annual average transparency in East Taihu Bay during the period in which water transfers occurred (Fig. 9).

A sediment dredging project in East Taihu Bay was performed between 2003 and 2004 from Dongjiaozui to the sluice gate of Taipu River. This project resulted in the removal of 4.38×10^6 m^3 of sludge (Chen et al. 2006), which included the removal of aquatic macrophytes. This project increased suspended matter and nutrients. As a result, there was an increase in turbidity, lower residence time (increased flowrate), and reduced macrophyte cover. These changes were compounded by the low water level in 2005 (2.92 m) that occurred because precipitation during the 2005 rainy

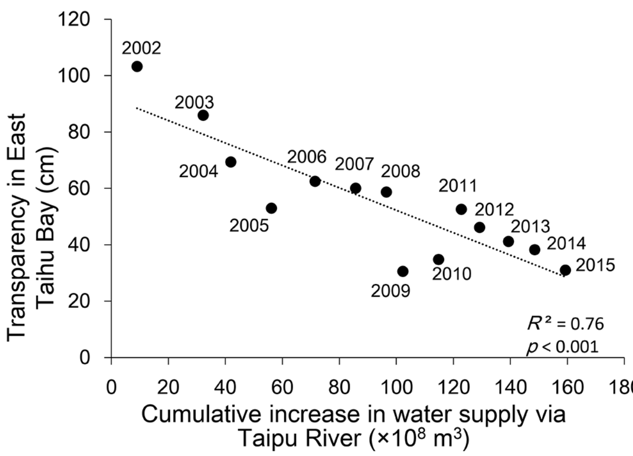

Fig. 9. The relationship between the annual total flow from Lake Taihu to the Taipu River and the annual average transparency in East Taihu Bay since 2002.

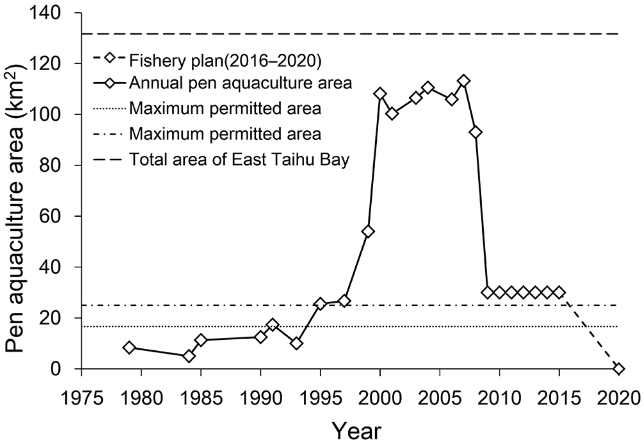

Fig. 10. Temporal variation of pen aquacture area compared with local fishery area management requirements in East Taihu Bay.

season was 13.6% lower than average (2000–2015) for the same period.

Pen-fish aquaculture activities in East Taihu Bay Pen-fish aquaculture in East Taihu Bay began in the late 1970s (Fan et al. 2012) and covered an area of 26.7 km^2 by 1997 (Yang et al. 2005; Fig. 10). Aquaculture then developed rapidly to reach 108.1 km^2 in 2000 (Zhao et al. 2013), covering >80% of the bay (Fig. 10). According to the Pollution Control Plan of Lake Taihu of 1996, the sustainable area for pen-fish aquaculture was set at 16.67 km^2(Yang et al. 2005) with a maximum threshold of 25 km^2 (Wu et al. 2000). The high-density pen aquaculture was associated with a deterioration in water quality in this part of the lake (Zhai et al. 2010). To reverse this trend and ensure vessel traffic remained possible in the East Taihu Bay, new restrictions on pen-fish aquaculture control were imposed in 2008 (Wei 2010, Fan et al. 2012), fragmenting into 3 separate regions (Fig. 2). Aquatic macrophytes disappeared completely in areas no longer used for fisheries, resulting in the sharp reduction of macrophyte area in 2009 and 2010. In 2011, a new pen-fish aquaculture area was created and dominant macrophytes returned, resulting in an increase in macrophyte area.

Aquatic macrophyte planting and harvesting In addition to indirect factors such as water transfer and pen-fish aquaculture, direct human management of macrophytes, including planting and harvesting, influenced the distribution of aquatic macrophytes. As a food source for aquaculture, *Elodea nuttallii* was first introduced to East Taihu Bay in 1986 (Yang 1998). From 0.13 km^2 in 1993, *E. nuttallii* became 1 of the dominant submerged macrophytes in East Taihu Bay in 2000 (Lei 2006). Moreover, *Eichhornia crassipes* and *Phragmites communis* were used for eutrophication control in the littoral zone of Zhushan Bay (TBA and MWR 2015) and covered an area of 5 km^2.

The small amount of macrophyte harvesting for aquaculture food source has always been a traditional activity. However, since 2012 large-scale macrophyte removal has been done to reduce the drinking water security risk from the death and decay of aquatic macrophytes and to solve the obstruction of shipping in the eastern lake sections. The

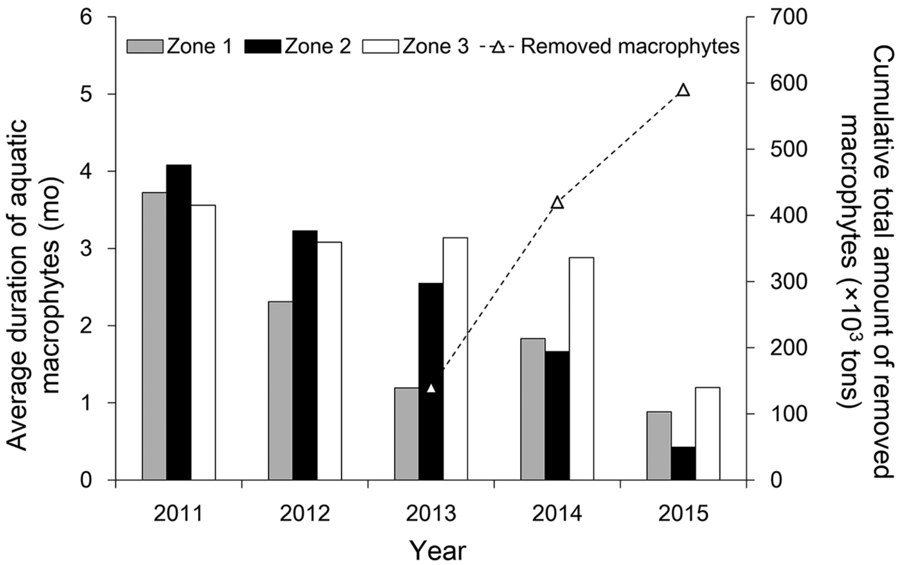

Fig. 11. Variation in average duration of the macrophyte growth period of aquatic macrophytes in the Xukou Bay (Zone 1), the narrow area between Dongshan and Xishan Island (Zone 2), and the mouth of East Taihu Bay (Zone 3) compared with the cumulative total amount of removed macrophytes in these 3 areas from 2013 to 2015.

total annual quantity of macrophyte removal was 0.14, 0.28, and 0.17 million tons (Fig. 11; TBA and MWR 2015). Considering a wet biomass density of 0.8 to 8 kg/m^2, this removal of macrophytes would reduce the total macrophyte cover by between 17 and 178 km^2. Thus, harvesting may have contributed substantially to the reduction in total macrophyte area from 454.6 to 257.8 km^2 over the same period. This was also seen from spatial distribution of macrophytes in 2015, where there were almost no surviving macrophytes in the mouth of East Taihu Bay and the waterway between Dongshan and Xishan, largely because of over-removal from 2013 to 2015 (Fig. 3).

Conclusions

Lake Taihu is a shallow lake that is threatened by anthropogenic eutrophication. It has extensive areas of aquatic macrophytes that provide important ecosystem services. Our results indicate that the total area of aquatic macrophytes in Lake Taihu decreased significantly over the past 16 y. The area occupied by emergent/floating macrophytes increased from 39.3 km^2 in 2000 to 90.3 km^2 in 2015 (a 230% increase), whereas the area of submerged macrophytes decreased from 404.6 km^2 in 2001 to 167.5 km^2 in 2015 (a 59% decrease). In the formerly macrophyte-dominated eastern lake sections, macrophyte coverage declined almost linearly from 36% in 2002 to 17% in 2015. This was largely due to the loss of submerged macrophytes, which decreased significantly from 88.5% in 2000 to 45.8% in 2013.

The present study also indicated that macrophyte temporal dynamics have changed over the last 16 y. These changes were correlated with changing underwater irradiance and nutrient concentrations in several lake sections. Underwater solar irradiance decreased due to both reductions in transparency and cloud cover, as identified by both correlation and redundancy analyses.

Importantly, eutrophication control projects were found to be counterproductive and to have negative impacts on water transparency, which is a key factor in macrophyte areas. The Yangtze River transfer to Lake Taihu, the management of pen-fish aquaculture activities, macrophyte over-removal, and lake and river dredging all have negative impacts on light conditions. These impacts result in a reduction in the colonization of lake areas with aquatic macrophytes. Our findings suggest that effective management strategies for eutrophication control should consider both direct and indirect impacts, in particular on light and nutrient conditions in aquatic macrophyte-dominated areas. Lake management in Lake Taihu is challenging because the lake has multiple uses, complex hydrology, and high-intensity land use. For this reason, indirect impacts of some eutrophication control management actions need to be considered. The use of remote sensing to identify changes in aquatic macrophyte cover and dynamics is a useful tool to monitor these impacts. Over the past 16 y in Lake Taihu, the lake has experienced a significant decrease of macrophyte cover, especially the submerged macrophytes, which has caused significant negative impacts on the lake and its surrounding communities.

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