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Global loss of aquatic vegetation in lakes

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A R T I C L E I N F O

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A B S T R A C T

Quantitative global assessments of aquatic vegetation dynamics in lakes are lacking despite reports of the losses of submerged aquatic vegetation. We conducted a comprehensive global assessment of aquatic vegetation at 155 study sites. We also included ≥ 2 yr of information on the absolute or relative area of aquatic vegetation from the literature. We calculated the difference between initial and final observed aquatic vegetation area (or cover) to represent the overall trends over time. We classified the study sites of aquatic vegetation into the categories "increasing", "decreasing" or "no change" using a threshold of 10%. Aquatic vegetation area (or cover) decreased in 101 study sites, particularly in China (35 study sites), increased in 43 study sites, and showed no marked changes in 11 study sites. Our results revealed an accelerating decrease rate (vegetation loss in terms of area or cover) over time: 13.5 ± 16.9%/yr (1900–1980), 21.8 ± 28.9%/yr (1980–2000) and 33.6 ± 59.8%/yr (after 2000). Moreover, the area (or cover) increase rate in lakes where aquatic vegetation showed recovery decreased from 23.5 ± 29.9%/yr (1980–2000) to 16.8 ± 13.2%/yr (after 2000). We conclude that aquatic vegetation loss is accelerating, especially that of submerged aquatic vegetation and particularly in lakes with an area larger than 50 km^2. The predominance of decreasing vegetation found in our study is likely caused by multiple stressors such as eutrophication, algal blooms, land reclamation, aquaculture cultivation and global climate changes.

1. Introduction

Lakes provide a variety of important ecological services and are affected by multiple human activities as well as global climate change. Due to the important ecological and socioeconomic services provided by aquatic vegetation, including increasing water clarity, stabilizing sediments and further decreasing the rate of nutrient cycling, improving water quality, and providing food and habitats for many aquatic animals (Jeppesen et al., 1998; Horppila and Nurminen, 2003; Orth et al., 2006; Carr et al., 2010), numerous studies conducted over the past five decades have focused on monitoring the changes in the aquatic vegetation of lake ecosystems and identifying the mechanisms driving its distribution, abundance and dynamics (Sand-Jensen et al., 2000; Körner, 2002; Liira et al., 2010; Kolada, 2014; Liu et al., 2015; Phillips et al., 2016). These studies collectively suggest that the loss of aquatic vegetation is a global phenomenon caused by intensified human activities such as land reclamation, aquaculture, and eutrophication as well as global climate change and its resultant increase in temperature and CO_2 and greater UV-B exposure (Sand-Jensen et al., 2000; Körner, 2002; Phillips et al., 2016; Short et al., 2016). Similarly, a global loss of seagrass has been observed in the marine ecosystems (Orth and Moore, 1983; Lotze and Jackson, 2006; Waycott et al., 2009).

The loss of submerged aquatic vegetation, especially in shallow lakes, may trigger a shift from a clear macrophyte-dominated state to a turbid phytoplankton-dominated state (Scheffer et al., 1993). A reduction in the biomass and biodiversity of aquatic vegetation also results in habitat degradation, which negatively affects a variety of aquatic animals and leads to a reduction in ecosystem service functions (Jeppesen et al., 1998). However, some human impacts (*e.g.*, eutrophication) may enhance the cover and biomass of aquatic vegetation that harvests light at or above the water surface (*e.g.*, free-floating species), which may also negatively affect ecosystem services and biodiversity when cover is too high (Villamagna and Murphy, 2010). Moreover, moderate to high nutrient concentrations may lead to

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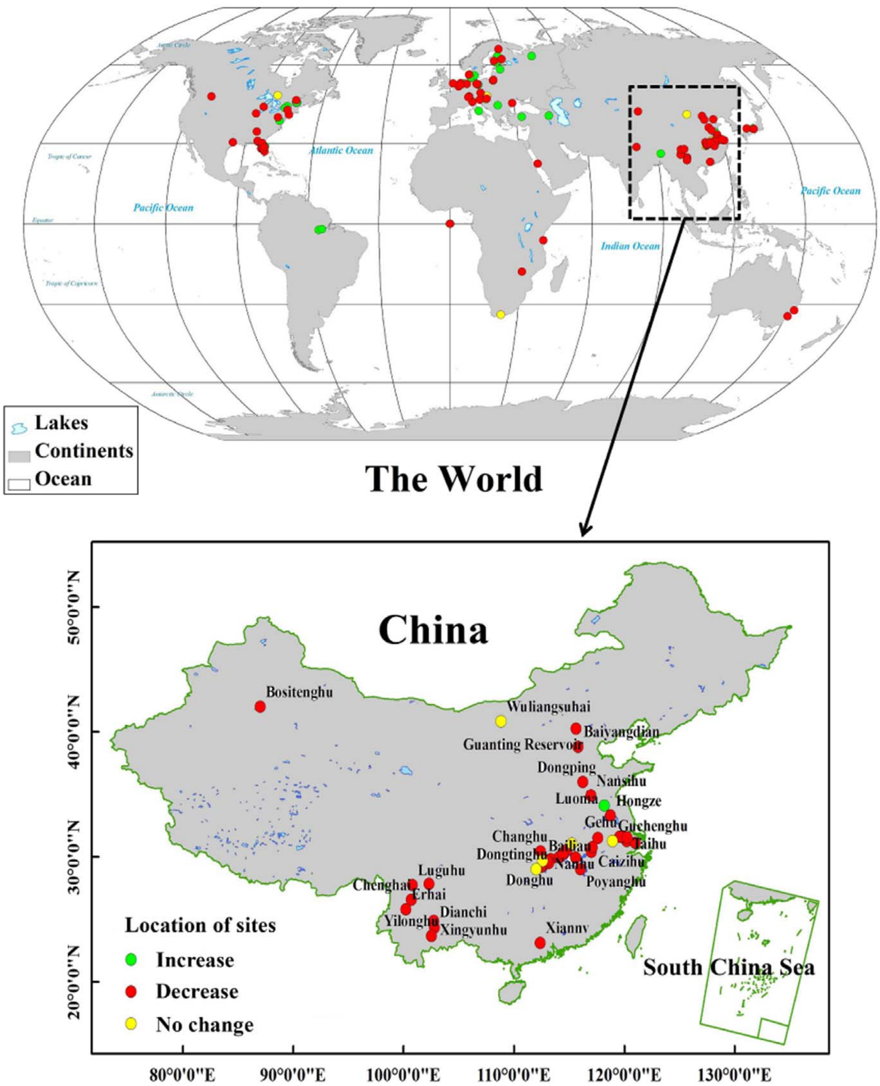

Fig. 1. Spatial distribution of study sites around the world and in China. Green indicates a decrease, red an increase, and yellow no change in aquatic vegetation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

excessive macrophyte growth, which may hinder boating, commercial fishing and angling.

Previous efforts to assess general trends in the distribution of aquatic vegetation in lakes and its abundance, composition, richness, and diversity have focused on one or a few lakes within a small geographical area (Sand-Jensen et al., 2000; Körner, 2002). Most studies have also been based on limited quantitative data (Schelske et al., 2010; Cheruiyot et al., 2014; Dong et al., 2014; Baastrup-Spohr et al., 2016), yielding ambiguous results. Some studies demonstrate a widespread and abrupt decline (Sand-Jensen et al., 2000; Körner, 2002), while others show a less dramatic decline (Havens et al., 2005; Oťaheľová et al., 2011) or, occasionally, a local increase (Liira et al., 2010; Depew et al., 2011; Baastrup-Spohr et al., 2016). However, no global dataset of the temporal changes in aquatic vegetation cover in freshwater ecosystems exists, which prevents a comprehensive and systematic assessment of the global trends of aquatic vegetation in lakes.

Historical data offer valuable information on the temporal changes in the aquatic vegetation of lakes, although they may be somewhat biased towards lakes with major changes and the time series may be irregular or affected by differences in sampling techniques. Accordingly, we conducted a global literature review following standardized criteria and generated a quantitative dataset from 155 study sites around the world covering the 1900–2015 time period and a range in lake area from < 0.1 km^2 to > 1000 km^2 (Table S1). The objectives of our study were to provide a global assessment of changes in aquatic vegetation area or cover in lakes in recent decades and to assess if the temporal trends are related to regional and lake size differences. Furthermore, we discuss the potential driving mechanisms and highlight approaches that can be used in the recovery of lake aquatic vegetation. Our global analysis fills a gap in current knowledge and serves as a basis for further systematic ecological investigations, monitoring, assessments, management and restoration of aquatic vegetation in lakes around the world.

2. Methods

2.1. Literature review

We searched the Science Citation Index (SCI) Expanded database and generated almost 4000 references about aquatic vegetation. Specifically, we searched the data in the SCI Expanded database, Web of Science (1900–2015) using the topic words (“aquatic vegetation*” or “aquatic plant*” or “macrophyte*” or “submerged plant*” or “submersed plant*” or “floating plant*” or “emergent plant*”) and (“lake*”) and (“loss*” or “change*” or “dynamic*” or “decline*” or “increase*” or “decrease*” or “recovery”). To cover the Spanish and Portuguese speaking world, we also used the words in Portuguese: (*vegetação aquática** or *vegetacao aquatic* or *planta* aquática* or *planta* aquatic** or *macrófita** or *macrofita**) and (*lago** or *lagoa**) and (*perda** or *mudança** or *mudanca** or *dinâmica** or *dinamica** or *declínio** or *declinio** or *aumento** or *decréscimo** or *decrescimo**) and in Spanish (*vegetación acuática** or *vegetacion** *acuatica** or *planta** *acuática** or *planta** *acuatica** or *macrófita** or *macrofita**) and (*lago** or *laguna**) and (*perdida**or *cambio** or *dinámica** or *dinamica** or *decaimiento** or *declinio** or *incremento**). Therefore, aquatic vegetation in this review includes submerged, floating, and emergent plants in lake.

We basically followed the protocol proposed by Waycott et al. (Waycott et al., 2009) to obtain our corresponding variables. We only included results providing ≥ 2 years of information on aquatic vegetation absolute or relative area, or aquatic vegetation absolute or relative cover so as to calculate the rate of change. If the initial and/or final observations of aquatic vegetation at a given site covered more than one year, we used the midyear point (*e.g.*, 1955 for the period 1947–1963) to calculate the change rate. In total, we obtained 116 lake study sites (site meaning a lake or a part of a lake in the case where a lake was only partially samples) from around the world (see Supplementary information for a detailed list of studies included).

In addition, we searched for data from the China Academic Journals Full-text Database using the same search terms. A total of 41 Chinese lake studies were included in the analysis, covering the period 1981–2015 (see Fig. 1). The final database included quantitative data on the area or cover of aquatic vegetation from 155 study sites (see SI data sources), including submerged, floating, floating-leaved, and emergent aquatic vegetation (see details in Table S1).

We calculated the difference between initial and final observations of aquatic vegetation area (or cover) at each site to represent the overall trends relative to time period. The percent rate of change (η, %/yr) at each site was calculated over time interval (yr) from the initial to the finally reported areas (or covers) (A_o and A_t, respectively) as follows: $\eta = [\ln(A_t/A_o)/\text{yr}] \times 100$, which was successfully used to assess the loss of seagrasses (Waycott et al., 2009).

We compared the numbers of lakes with "aquatic vegetation increase", "aquatic vegetation decrease" and "no change" using three different thresholds for significant change (5%, 10% and 15%) in aquatic vegetation expressed as the area (or cover) at the end of the study compared with that of the initial year (Table 1). The number of lakes belonging to each of these categories proved to vary only slightly with the selected threshold (Table 1). Consequently, we classified the aquatic vegetation into the categories of "increasing" or "decreasing" if the area (or cover) changed by > 10% over time and as "no change" if the area (or cover) changed by ≤ 10%. This threshold of 10% is typically within the error of assessment (Kendrick et al., 1999) and it was also used to assess global seagrass dynamics (Waycott et al., 2009).

In addition, we divided the data into three periods: before 1980, 1980–2000, and after 2000 and calculated the overall percent rate of change for each particular period (as described previously). In order to further describe the global trend in aquatic vegetation, and to assess whether the rates of change in aquatic vegetation area or cover varied with lake area, we divided the 155 study sites into three categories: ≤ 10 km^2 ($n = 68$), 10–50 km^2 ($n = 33$), and ≥ 50 km^2 ($n = 54$).

Table 1
Number of study sites belonging to each category (decreasing, increasing, or no change in aquatic vegetation) in different periods using three different thresholds of changes.

		< 1980	1980–2000	> 2000	Whole observation
Threshold = 5%	Increase	0	35	8	44
Threshold = 10%		0	35	8	43
Threshold = 15%		0	34	7	42
Threshold = 5%	Decrease	15	60	19	104
Threshold = 10%		14	55	18	101
Threshold = 15%		13	54	14	95
Threshold = 5%	No change	0	2	2	7
Threshold = 10%		0	7	3	11
Threshold = 15%		1	9	8	18

2.2. Statistical analyses

Statistical analyses, including calculations of average, maximum, and minimum values of the percent rate of change for lakes around the world were performed using Statistical Program for Social Sciences (SPSS) 17.0 software. We performed *t*-test analysis of the percent rate of change among the three different periods using SPSS software, and the results were reported as significant ($p < 0.05$) or non-significant ($p > 0.05$).

3. Results

The results of the global literature review demonstrated that aquatic vegetation has declined worldwide since the earliest records in 1900, both in the northern and southern hemispheres and at high and low latitudes. A comparison of all 155 sites revealed a decrease in 101 (65.2%) sites, an increase in 43 (27.7%) sites and no change in 11 (7.1%) sites (Fig. 2a). Accordingly, the number of sites with aquatic vegetation decline was more than twice as high as the sites with aquatic vegetation increase. If only sites with submerged aquatic vegetation were considered, a decrease occurred in 66 of 101 sites (65.3%). In the 15 sites without submerged aquatic vegetation a decrease occurred in 4 sites (26.7%) while an increase was found in 8 sites (53.3%). These results showed, as expected, a more marked decreasing trend for submerged aquatic vegetation than for all aquatic vegetation combined, reflecting an increasing trend in floating, floating-leaved, and emergent aquatic vegetation together (Table S1).

When dividing the data into the three periods, we found the number of sites with declining aquatic vegetation to be greater than those with an increase for all periods (14 *vs* 0, 55 *vs* 35, and 18 *vs* 8 before 1980, in 1980–2000, and after 2000, respectively) (Fig. 2a). Before 1980, the sites exhibiting a decline in aquatic vegetation were mainly located in Europe and North America (Table S1). Since the implementation of nutrient loading reduction in the 1980s with the aim of lake restoration, aquatic vegetation has partially recovered in some European and North American lakes (Table S1). In contrast, aquatic vegetation loss has been recorded at almost all study sites in Chinese lakes, coinciding with the rapid social and economic development in the country since the 1980s (Fig. 2b, Fig. S1). Only one (Lake Luomahu) out of the 41 lakes studied in China exhibited a slight increase in aquatic vegetation, while another five showed little variation during the entire study period (Table S1). The aquatic vegetation loss in the investigated lakes has, therefore, been greater in China (and likely in other rapidly developing countries as well, but little data is available) than in the rest of the world during the past three decades. Even if the Chinese lakes were excluded, the number of lakes exhibiting vegetation loss was much higher than those showing recovery (13 *vs* 0, 43 *vs* 35, 10 *vs* 8, and 66 *vs* 42 before 1980, in 1980–2000, after 2000, and throughout the entire observation period, respectively) (Fig. 2c).

Particularly, substantial aquatic vegetation loss was found in large lakes (area ≥ 50 km^2) (loss *vs* recovery: 40 *vs* 11) and especially in China (23 *vs* 1); however, even if the Chinese lakes were excluded, the number of large lakes exhibiting vegetation loss relative to those showing recovery was proportionally higher for the large lakes than for the other two size categories (17 *vs* 10) (Fig. 3). In addition, eight of the 11 large lakes (area ≥ 50 km^2) with an increase in aquatic vegetation, were colonized by emergent aquatic vegetation, while only three were colonized by submerged aquatic vegetation (Table S1). Consequently, the increase in aquatic vegetation in these large lakes was largely attributed to emergent aquatic vegetation and not submerged aquatic vegetation. In contrast, aquatic vegetation recovery was mostly recorded in small and medium-sized lakes (area < 50 km^2). For 43 lakes with aquatic vegetation recovery, the percentage of large lakes was 25.6%, while for 101 lakes with aquatic vegetation loss, the percentage of large lakes was 39.6%. Whether this is because the risk of losing aquatic plants is higher in large lakes or it simply reflects higher focus

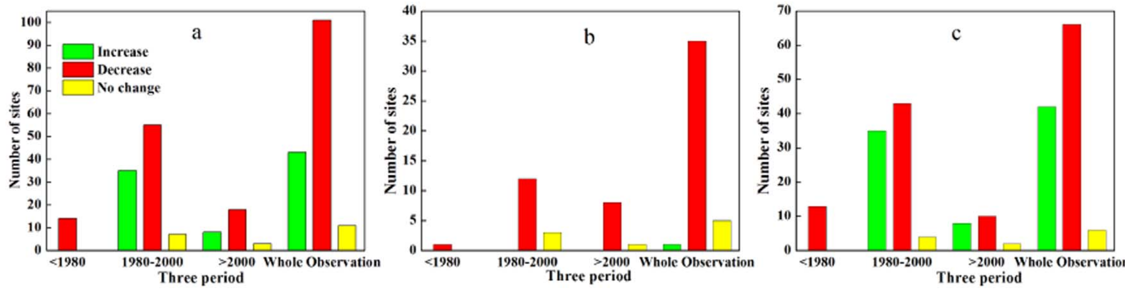

Fig. 2. Number of study sites in each category (decreasing, increasing, no change) in different periods. World (a), China (b), world without China (c).

on restoring medium-sized or small lakes requires further investigation.

The rate of area (or cover) loss has significantly increased over time, as evidenced by dividing the data into the three periods: 13.5 ± 16.9%/yr (mean ± SD; before 1980s), 21.8 ± 28.9%/yr (1980–2000) and 33.6 ± 59.8%/yr (after 2000s) (*t*-test, $p < 0.05$) (Fig. 4a). In contrast, for the lakes exhibiting an increase in vegetation area (or cover), the increase rate decreased from 23.5 ± 29.9%/yr in 1980–2000 to 16.8 ± 13.2%/yr post-2000s. For the whole observation period, the decrease rate of 19.1 ± 28.7%/yr in lakes with loss of vegetation was higher than the increase rate of 14.0 ± 19.5%/yr in the fewer lakes gaining vegetation. Thus, our compiled global dataset on aquatic vegetation in lakes showed an accelerating declining trend of aquatic vegetation around the world despite vegetation recovery in some European and North American lakes.

For the Chinese dataset, the decrease rates of the three periods before 1980, during 1980–2000, and after 2000 were 8.3%/yr, 5.5 ± 5.5%/yr, and 55.7 ± 87.0%/yr, respectively, with a particularly sharp decline in aquatic vegetation area since 2000 (Fig. 4b). For the entire observation period, the decrease rate of aquatic vegetation was 14.7 ± 30.3%/yr. An increase of aquatic vegetation in lakes in China was almost absent, resulting in an area loss of aquatic vegetation of 3370 km^2. For instance, in Lake Poyang, which is the largest freshwater lake in China, vegetation cover has decreased by 834 km^2 (= 46%) since 1983 (Table S1). Other lakes with large losses of aquatic vegetation area (> 200 km^2) in China included Lake Dianchi (257 km^2, a 97% decrease), Lake Hongzehu (375 km^2, 72%), Lake Honghu (288 km^2, 84%), and Lake Nashanhu (279 km^2, 33%) (Table S1). All these lakes are nationally or even internationally important wetlands. Even when excluding the Chinese lakes, the decrease rate of 21.5 ± 27.7%/yr in lakes showing a loss of vegetation was higher than the increase rate of 14.6 ± 19.7%/yr in lakes gaining vegetation for the whole observation period (Fig. 4c).

4. Discussion

4.1. Trends identified and factors affecting lake aquatic vegetation changes

Our main finding is that there has been an overall decrease in aquatic vegetation area (or cover) in lakes over the last four decades (Figs. 2, 3 and 4). Moreover the decrease has accelerated during the last decades. Some lakes in Europe and North America have shown recovery of the vegetation in the last two decades due to extensive efforts devoted to reduce nitrogen and phosphorus loads and restore aquatic vegetation (Körner, 2002; Lauridsen et al., 2003; Depew et al., 2011). In Chinese lakes, however, signs of vegetation recovery were almost absent. In agreement with our findings, previous studies have demonstrated that a considerable number of coastal wetlands in the North American Great Lakes have been degraded, particularly Lakes Michigan, Erie, and Ontario (Cvetkovic and Chow-Fraser, 2011), although no detailed quantitative data on loss rates are available.

Human activities that lead to nutrient enrichment from point and non-point sources, land reclamation, damming, aquaculture, overfishing, boat propellers, and lake engineering both directly and indirectly result in vegetation loss (Scheffer et al., 1993; Sand-Jensen et al., 2000; Körner, 2002; Qin et al., 2007; Phillips et al., 2016). One of the most serious consequences of eutrophication in shallow freshwaters is the disappearance of submerged aquatic vegetation, whereas floating, floating-leaved and emergent aquatic plants are less affected or even stimulated following eutrophication. For example, since 1961 phosphorus concentrations have increased by 28 times in Lake Dianchi, a typical large eutrophic shallow lake in China, and submerged aquatic vegetation that used to grow at depths of 5.0–6.5 m is now confined to water < 3 m deep (Lu et al., 2012). Furthermore, the 17 species and 88% cover recorded in 1961 had decreased to 9 species and only 2% cover by 2010, including three turbidity-tolerant communities (Lu et al., 2012). Additionally, benthivorous fish can influence the survival of submerged aquatic vegetation through physical uprooting and disturbance of the sediment. In a survey of 28 lakes, those with high benthivorous fish biomass were characterized by few species of submerged aquatic vegetation (Zambrano et al., 2006); so, introduction of benthivores may precipitate submerged aquatic vegetation loss (Hanlon et al., 2000). Extensive and high intensity aquaculture has caused a catastrophic loss of aquatic vegetation in many Chinese lakes (Qin et al., 2007; Xiao et al., 2010; Pan et al., 2011), and this is likely also the case in many other countries in South East Asia. In contrast, submerged aquatic macrophytes recovered and increased in abundance as a response to nutrient loading reduction and in some cases biomanipulation in several European lakes, especially small and shallow lakes (Lauridsen

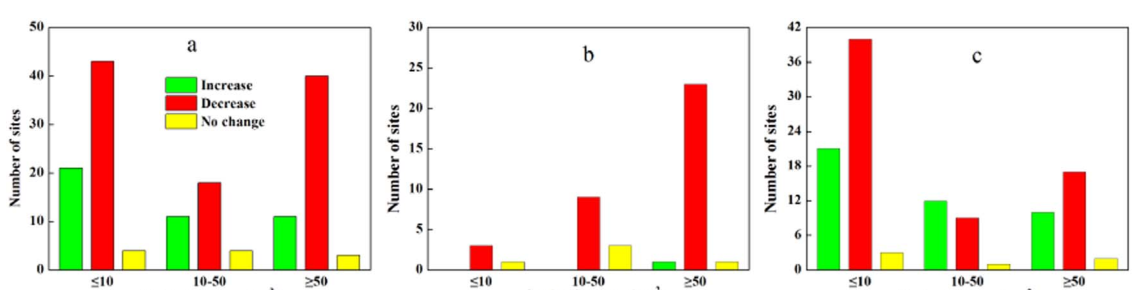

Fig. 3. Number of study sites in each category (decreasing, increasing, no change) for different study sites. World (a), China (b), world without China (c).

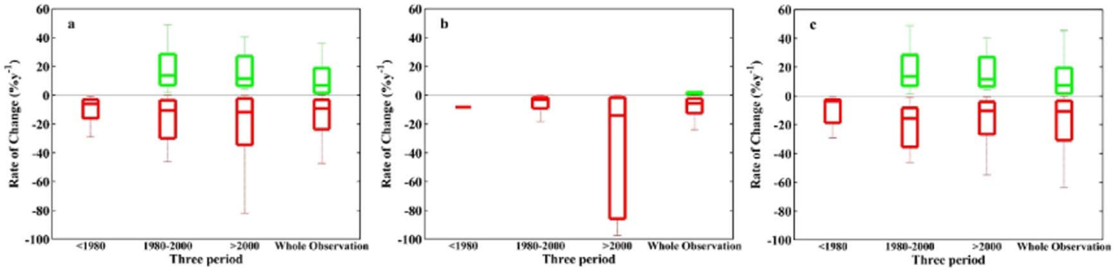

Fig. 4. Rate of change in different periods across sites. The box is based on maxima and minima of all data, 25th and 75th percentiles, and median values (horizontal lines). World (a), China (b), world without China (c).

et al., 2003; Bakker et al., 2013), which likely explains some of the examples of increases in submerged aquatic vegetation found in our survey.

Global climate change (*e.g.*, increases in water temperature and the frequency and intensity of storm events and associated prolonged floodings) has had significant impacts on the health of macrophyte-dominated lake ecosystems around the world. Although the decreases in aquatic vegetation found in our survey are probably primarily associated with eutrophication and other human impacts, we cannot discount the effects of global climate change. For example, extreme climatic events such as hurricanes and prolonged deep flooding can result in the loss of both emergent and submerged aquatic vegetation due to light limitation (Van der Valk, 1994; Havens et al., 2005) triggered by pulsed turbidity events following strong rainfall and flooding. In addition, the more eutrophic conditions resulting from increased precipitation-induced nutrient loading or higher internal phosphorus loading may favor phytoplankton growth of at the expense of submerged aquatic vegetation (Jeppesen et al., 2009; Short et al., 2016).

Global, regional, and local stressors can all independently create large-scale or small-scale changes in the aquatic vegetation of lakes. However, the aquatic vegetation is often simultaneously influenced by multiple stressors at different temporal and spatial scales. Therefore, the deterioration of lake aquatic vegetation is expected to continue in the coming decades, not only because of the changing climate but also the intensification of human activities due to global development and an increasing population.

4.2. Consequences of the accelerating global loss of lake aquatic vegetation

Because of the important ecological roles played by aquatic vegetation in lake ecosystems and their provision of high-value ecosystem services compared with other lake communities, the accelerating global loss of aquatic vegetation reported here is an issue of concern. Loss of aquatic vegetation will potentially deteriorate lake water quality and threaten the safety of drinking water (Williamson et al., 2008), especially if linked to loss of submerged aquatic vegetation which maintains a clear water state. For example, minimum aquatic vegetation cover of 10%, or in some cases even 50%, is required to maintain a clear water state (Bakker et al., 2013). In addition, aquatic vegetation yields a net uptake of atmospheric CO_2 and also provides carbon to the detrital pool (Tokoro et al., 2014), some of which acts as food for invertebrates (Suren and Lake, 1989) and fish (Lopes et al., 2007). Thus, we predict that the loss of aquatic vegetation may have had and more so in the future will have negative consequences for fisheries and waterfowl populations, and that it may lead to decreased primary production and alteration of the nutrient cycling in the lakes. An important portion of the excess organic carbon that is produced is buried within lake sediments and acts as hotspots for carbon sequestration in the biosphere (Dong et al., 2012). Therefore, the loss of aquatic vegetation will probably negatively affect the carbon sequestration in lakes. Another consequence of the extirpation of aquatic vegetation is the decrease in biotic resistance to invasions, since native aquatic vegetations compete with exotic ones, thereby reducing their invasion success (Xu et al., 2004; Michelan et al., 2013). In fact, lakes in China, where the reduction in aquatic vegetation cover was more pronounced than in Europe and North America, have been massively invaded by aquatic vegetation of different life forms (152 species, according to Wang et al. (2016)). In addition, biodiversity is typically higher within aquatic vegetation than in adjacent vegetation-less/less vegetation-rich areas, and faunal densities are often several orders of magnitude higher inside aquatic vegetation (Bolduc et al., 2016). Loss of aquatic vegetation will therefore decrease species richness and lake biodiversity and threatens the future of endangered species (Carpenter and Lodge, 1986; Bakker et al., 2013). If the current rate of aquatic vegetation loss is sustained or continues to accelerate, ecological losses will also increase, causing even greater economic losses that cannot be afforded.

The severe impacts of the loss of aquatic vegetation in lakes have, so far, received only limited and decreased scientific and public attention compared with other lake environmental problems. For example, we compiled a bibliography from the Science Citation Index (SCI) database using TS = "aquatic vegetation*" and TS = "algal bloom*" as search terms to capture the current degree of attention directed at aquatic vegetation and algal blooms. In 1996, the total number of publications related to aquatic vegetation was almost similar to that related to algal blooms (55 *vs* 52) (Fig. S2). However, since 2000 the number of publications on algal blooms has been much larger than that on aquatic vegetation. More importantly, since 1996 the exponential increase rate of total publications on algal blooms per year has been 0.126, which is 1.5 times greater than that on aquatic vegetation (0.080) (Fig. S2). These data indicate that despite the importance of aquatic vegetation to the maintenance of water quality and biodiversity, studies of this community have been neglected in comparison with those related to other aquatic producers, such as phytoplankton.

4.3. Aquatic vegetation monitoring, management, and restoration

Effective and accurate monitoring of lake aquatic vegetation is an important task for local and state government management agencies in their efforts to manage, protect, and restore the aquatic vegetation that is so vital to lake water quality and the local economy. However, the lack of comparable surveys of lake aquatic vegetation precludes a global assessment of aquatic vegetation dynamics. In addition, the use of a limited number of measurements derived from traditional shipboard cruises to cover the distribution of aquatic plants throughout the lake has proven to be problematic in large lakes with high spatial and temporal variations given the time, cost, and difficulty involved. Multitemporal and spatial remote sensing images have also been successfully applied to characterize aquatic vegetation cover and temporal processes (Gullström et al., 2006; Liira et al., 2010; Silva et al., 2010; Liu et al., 2015; Villa et al., 2015). Therefore, the development of a remote sensing method or model resembling the land Normalized Difference Vegetation Index (NDVI) is recommended to monitor temporal and spatial dynamics as well as to analyze the long-term trend in the variations in the aquatic vegetation in medium- and large-sized lakes (> 10 km^2) at a global scale using high or moderate spatial resolution satellite data (Landsat or MODIS) as well as drones for smaller lakes.

Other important tasks aiming at maintaining (or even enhancing) aquatic vegetation are related to the management, conservation, and restoration actions that are urgently needed to address the marked habitat degradation and reduction of aquatic vegetation area (or cover) observed around the world. The management of lake aquatic vegetation, for example, requires an integrated approach, including efforts to avoid excessive nutrient and organic inputs from agricultural areas, aquaculture, and urban sources (Ju et al., 2009) and to prevent sediment loading that deteriorates water quality and the underwater light climate, which is critical for the growth of submerged aquatic vegetation (Zhang et al., 2016). Interestingly, although these practices have been widely employed in the context of the phytoplankton community (*e.g.*, control of eutrophication), they are less frequently used to preserve aquatic vegetation. Improving the habitat conditions for aquatic vegetation, including reducing wind and wave disturbance (*e.g.*, by adding artificial structures that reduce fetch) and, when possible, lowering the water level to improve the underwater light climate, might be implemented to create a window of opportunity for the (re)establishment of aquatic vegetation. In some cases, transplantation of aquatic vegetation after the successful reduction of external loadings and other restoration measures have led to a major increase in aquatic vegetation cover (Jeppesen et al., 2012; Liu et al., 2014).

Despite our survey's revelation of decreasing aquatic vegetation, improved management practices have resulted in a marked recovery of aquatic vegetation in some European and North American lakes. For example, since 1990, the introduction of phosphorus-free detergents, the installation of phosphorus elimination steps in large wastewater treatment plants, and the reduced application of fertilizers in agriculture have diminished the nutrient loading in many lakes and rivers; in Germany, for instance, nitrogen and phosphorus loads in river systems have decreased by 60% and 25%, respectively, and the recolonization or expansion of aquatic vegetation have been observed in six lakes (Körner, 2002). Therefore, further reduction of nutrient loadings, regulation of water levels, removal of large grass carp, and control of sediment resuspension may be needed to increase the abundance of submerged aquatic vegetation. A minimum aquatic vegetation cover of 10%, or in some cases even 50%, is required to maintain a clear water state (Bakker et al., 2013).

4.4. Data uncertainty and unevenness

Our analysis endeavored to include all data on aquatic vegetation area (or cover) in lakes available in the literature over minimum a ≥ 2-year period. The compiled dataset includes aquatic vegetation data collected using different methods (*in situ* observation and remote sensing interpretation) and different spatial scales (*e.g.*, field transect surveys or different techniques using remote sensing). In total, *in situ* observations were used for 115 sites, remote sensing interpretations were used for 25 sites, and both *in situ* observation and remote sensing interpretation were used for the remainder 15 sites. Thus, the differences in study methods may have created some errors or uncertainties in the absolute area and cover of aquatic vegetation. However, we used "percent rates of change" what makes the results of different methods to be reasonably comparable because they express the relative (not absolute) temporal trends of aquatic vegetation. In addition, with a threshold of change of 10% we assume that the direction of change is sufficiently well determined based on our sensitivity analysis, which encompassed three different thresholds (5%, 10% and 15%).

Another potential weakness is that the study sites we found were not evenly distributed globally. Europe, North America, and East Asia were well represented as monitoring efforts are generally greater in these regions than elsewhere. In contrast, there were major gaps in the information on the aquatic vegetation of lakes in Central Africa, South America, and the north-west Pacific area of the United States (Fig. 1), where there are numerous small lakes with surface areas between 1 and 10 km^2 (Downing et al., 2006). In these regions, existing studies only provide aquatic vegetation monitoring data for a single year (Cheruiyot et al., 2014), whereas almost no long-term studies are available (Shekede et al., 2008), even though the aquatic vegetation in these regions provides vital ecosystem services to the local human population, supports local economic development, and maintains biological diversity (Denny, 1985; Pérez et al., 2010). Considering the rapid population growth and development pressures in these sites, there is an urgent need for acquiring more data on changes in aquatic vegetation dynamics. In addition, detailed data on the long-term dynamics of aquatic vegetation area (or cover) are not available for many large or old lakes such as Lake Superior, Lake Victoria, Lake Tanganyika, Lake Baikal, and Lake Malawi (Cvetkovic and Chow-Fraser, 2011; Cheruiyot et al., 2014). Even more important is the lack of data in the Southern Hemisphere, especially Africa and South America where aquatic vegetation richness is higher than in the northern-temperate regions (Chambers et al., 2008).

5. Conclusions

Our study is the first to present a systematic global assessment of the trend in the variations of aquatic vegetation in lakes based on the available literature. We conclude that the loss of aquatic vegetation is accelerating, especially that of submerged aquatic vegetation and particularly in lakes with an area larger than 50 km^2. The area (or cover) decrease rate showing aquatic vegetation loss markedly increased, while the increase rate showing aquatic vegetation recovery markedly decreased during the three periods (before 1980, 1980–2000, and after 2000). Additionally, the decrease rate was substantially larger than the increase rate and may rise even further in the future in response to enhanced nutrient inputs and a higher frequency of extreme events caused by global climate change. The present study helps to fill in knowledge gaps concerning global variation trends in lake aquatic vegetation; yet, more research is required to develop, for example, a consistent remote sensing method or a model similar to NDVI for land to monitor the temporal and spatial dynamics and analyze the long-term trend in the variation in the aquatic vegetation of medium- and large-sized lakes (> 10 km^2) at the global level using high- or moderate-spatial-resolution satellite data (Landsat or MODIS).

Data accessibility

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.earscirev.2017.08.013.

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