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Review

Invasive aquatic plants in China

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Abstract

Invasive aquatic plants can cause local losses of species diversity throughout the world and they can also contribute to water quality deterioration. Although widely studied elsewhere, little information exists about invasive aquatic plants and their impacts in China. This study summarizes the taxonomy, origin, vector of introduction, current distribution, and the ecological impacts of invasive aquatic plants in China. This study provides useful information for the management of freshwater habitats and suggests strategies for curtailing the increasing problem of invasive aquatic plants and their impacts. We integrated data based upon original research and a literature review to compile an inventory of invasive aquatic plants in China. In total, we found 152 invasive aquatic plant species belonging to 84 genera and 39 families, representing four major growth forms including emergent (57.24%), submerged (27.63%), rooted floating leaf (9.87%), and free floating (5.26%) categories of aquatic plants. The Poaceae (Gramineae) (23 species) was the most represented and species-rich family, followed by Alismataceae (14 species), Cyperaceae (13 species), Nymphaeaceae and Araceae (both with 10 species). The majority of the invasive aquatic plant species were introduced from South America, and there were also many from North America, Asia, Africa, and Oceania. Most of these species (96.05%) are obligate freshwater species, while a minority (3.95%) is limited to marine or intertidal habitats. The ornamental trade has been the most frequent historic pathway for the introduction of invasive aquatic plants.

Key words: aquatic weeds, biodiversity, China, macrophytes, invasive species, water quality

Introduction

Biological invasions are recognized as a serious threat to global biodiversity and ecosystem function, inflicting great social and economic damage (Mack et al. 2000; Pimentel et al. 2005). The presence and often dominance of invasive species in aquatic habitats has caused comparatively greater ecological and economic consequences than those in terrestrial environments (Vilà et al. 2010). Invasive aquatic plants may alter ecosystem structure, resulting in a significant negative impact on aquatic biodiversity and water quality (Zedler and Kercher 2004; Chamier et al. 2012; Brundu 2015), and thus are of great concern to both ecologists and environmental managers.

China is one of the world's largest countries with a wide diversity of aquatic habitats and environments. It spans 50 degrees of latitude and covers five climatic zones: cold-temperate, temperate, warm-temperate, subtropical, and tropical. There are a number of types of water bodies (marine and coastal habitats, estuaries, rivers, lakes, ponds, reservoirs, and canals), each providing suitable habitats for the many non-native aquatic species that have been intentionally or inadvertently introduced into China. In the last two decades, more and more ecological and environmental problems have been identified as being directly caused by non-native aquatic organisms (Xu et al. 2006). Some endemic aquatic plants, such as *Ottelia acuminata*, became locally extinct because of invasive aquatic plants in the plateau lakes of China (Xiang et al. 2013). In the south of China, invasive aquatic plants such as *Alternanthera philoxeroides*, *Eichhornia crassipes* form dense

floating mats and impede many human uses of water (Ding et al. 1995; Gao and Li 2004; Liu and Yu 2005). The Chinese government spends billions of US dollars for the control of invasive aquatic plants every year (Gao and Li 2004), but the effect remains unsatisfactory in terms of truly managing the problems exacerbated or caused by exotic plants (Gao and Li 2004).

Recently, some studies have focused on the distribution and biological traits of problematic invasive aquatic plant species in China (Jin et al. 2005; Feng et al. 2014). However, comprehensive information on the status and ecological impact of invasive aquatic plants in China is very limited. Therefore, the aims of this study were (1) to compile a list of invasive aquatic plant species introduced into and within China; (2) to annotate their basic taxonomic status and origin; (3) to characterize their growth form and vector of introduction, and (4) to summarize their impacts to the aquatic ecosystem and to the economy.

Materials and methods

Definition of invasive aquatic plants in China

In the literature of invasion ecology, the definitions of "alien", "exotic", "invasive", "naturalized", "non-indigenous", and "non-native" species are often confused (Richardson et al. 2000; Colautti et al. 2004). The ambiguity of these terms often incurs an uncertainty as to the number and influence of invasive species. In this study, invasive species are defined as "due to intentional or unintentional human involvement, all plant species which have arrived at an area in which they are alien, and caused negative ecological or economic impacts" (Pyšek et al. 2004). Pursuant to this definition, invasive aquatic plants in China include those that are native to China but have been translocated outside their natural ranges within China or exotic aquatic plants introduced into China from other countries or regions and that have caused negative impacts.

There is a long history of translocating native aquatic plants among different regions within China. For example, *Nelumbo nucifera* was translocated from Eastern China to northern inland waters during the Han Dynasty (202BC to 220AD) (Hu and Sun 1955). Due to the lack of documentation about many translocation events in history, it is very difficult to provide a comprehensive overview of information about the moving of native aquatic plants within China. Therefore, this study only summarizes documented records of the invasive aquatic plants that were introduced into China from other countries or between regions inside China. In this study, aquatic plants are defined as "all plant species that grow at least a part of their life history submerged or are closely bound to aquatic habitats have been considered" (Cook 1985). While the focus is upon plants in or emergent from aquatic habitats, this survey also includes some species that range from the zone of inundation into the riparian zone - similar to the vascular plant wetland indicator species lists for the United States (Lichvar et al. 2014).

Catalogue of invasive aquatic plant species

Due to the lack of a national monitoring network for invasive species, the information used in this study originated from many diverse sources, including published literature, unpublished grey literature, field investigations, and internet databases in China (references are listed in supplementary Table S1). We searched for papers that contained the following combination of words: "invas*" and "aquatic" or "marin*" or "freshwater" or "macrophyte*" or "plant*" in the title, abstract, or keywords from the Thomson institute for scientific information (ISI, http://www.isiknoledge.com) and CNKI (http://www.cnki.net). We also collected information from some Chinese books, such as Aquatic Plant (Zhao and Liu 2009), Invasive alien species in China (Li and Xie 2002), Chinese aquatic vascular plants Atlas (WBG 1983) et al. This study establishes a preliminary inventory of invasive aquatic plants in China (Table S1), which was verified against the Flora of China (Wu et al. 1989–2013), and no doubt there will be additions in the future as more exotics invade or are established but not yet identified. For each invasive aquatic plant species, information was recorded regarding the region of origin (Cook 1996), vector of introduction, growth forms (emergent, rooted floating leaf, submerged, and free floating), the year of introduction, the aquatic environment they inhabit, and their distribution in China (here we divided China into seven parts. East China: Shanghai, Jiangsu, Zhejiang, Anhui, Shandong, Fujian, and Taiwan; South China: Guangdong, Guangxi, Hainan, Hongkong, and Macau; North China: Beijing, Tianjing, Hebei, Shanxi, and Inner Mongolia; Central China: Hubei, Hunan, Henan, and Jiangxi; Southwest China: Sichuan, Guizhou, Tibet, and Chongqing; Northeast China: Liaoning, Jilin, and Heilongjiang; and Northwest China: Ningxia, Xinjiang, Qinghai, Shaanxi, and Gansu). The Latin names we use

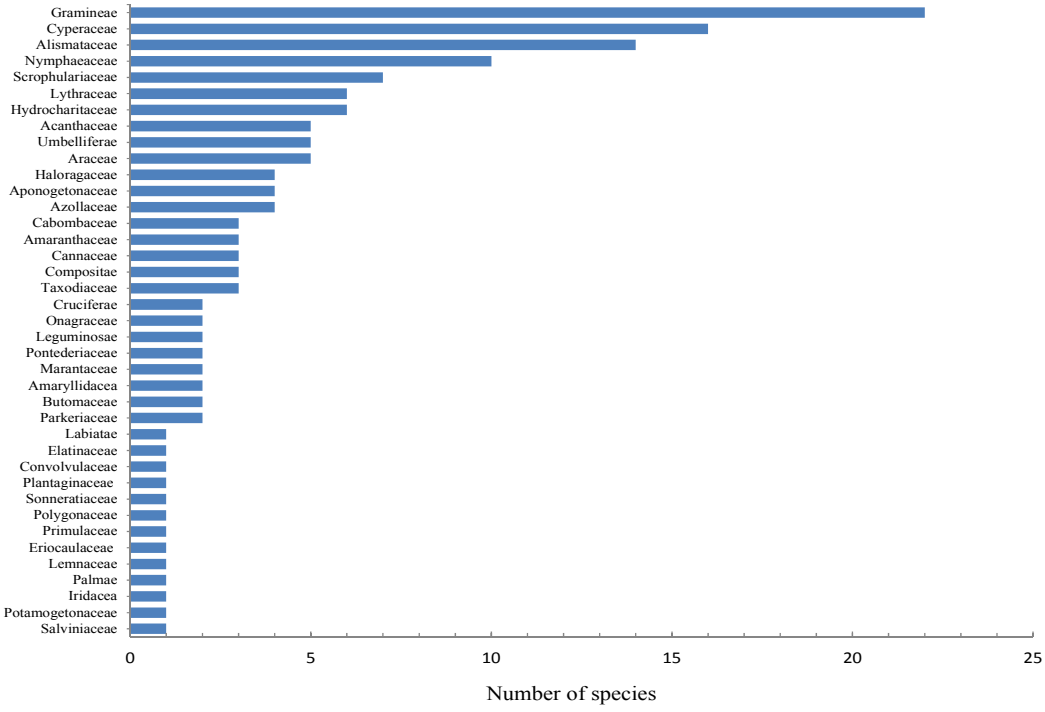

Figure 1. The number of invasive aquatic plants in different families found in China.

are derived from the taxonomy employed in Plantlist (see http://www.theplantlist.org). Some of the aquatic plants listed (e.g. *Lythrum salicaria*, *Ipomoea aquatica*) are native to China and some other countries, and have been introduced from other countries into China.

Results

Taxonomic diversity

We recorded a total of 152 invasive aquatic plant species belonging to 39 families and 84 genera (Supplementary material Table S1). The Poaceae (Graminea) was the family with the highest number of invasive aquatic plant species (22) in China, followed by Cyperaceae with 16 species, Alismataceae with 14 species, Nymphaeaceae with 10 species. Each of the other families possesses less than 10 species of invasive aquatic plants (Figure 1).

Geographic origin

All geographic origin information for invasive aquatic plant species in China is shown in Table S1 and Figure 2. Most aquatic plant species were introduced from South America (25.66% of the species are exclusively native to South America and 9.87% are native to South America with multiple-origins), followed by North America (36 species, 23.68%; 20 species, 13.16%), Asia (23 species, 15.13%; 10 species, 6.58%), Africa (13 species, 8.55%; 6 species, 3.95%), and Australia and New Zealand (1 species, 0.66%; 1 species, 0.66%).

Vectors of introduction

All vectors for the introduction of invasive aquatic plant species in China are listed in Table S1. Most invasive aquatic plant species were introduced into China through the ornamental trade (114 species, 75%). Only a few species were introduced for forage (16 species, 10.53%), ecological restoration (8 species, 5.26%), food (5 species, 3.29%), and green manure (5 species, 3.29%). There were only four species (2.63%) that were unintentionally introduced.

Growth forms and aquatic environments

Classification of aquatic plant species into four fundamental growth forms indicate that the

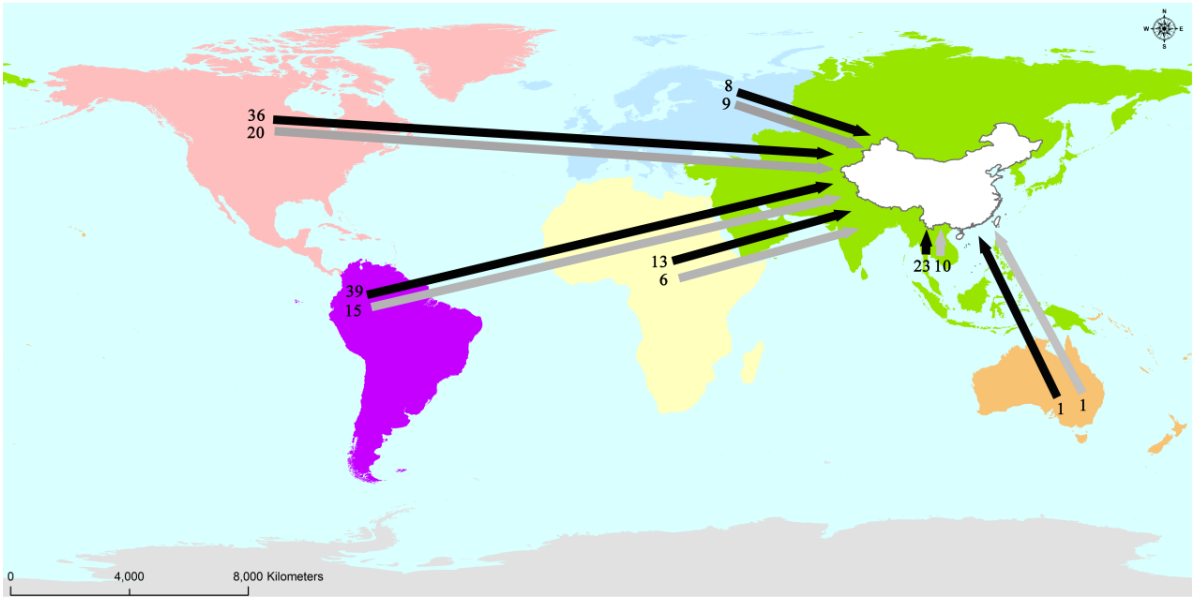

Figure 2. The places of origin of invasive aquatic plants in China. Black arrows mean that aquatic plants are only native to one continent, while grey arrows mean that aquatic plants are native to two or more than two continents.

emergent form is dominant, represented by 87 species (57.24%), followed by the submerged form with 42 species (27.63%), rooted floating leaf form with 15 species (9.87%), and free floating leaf form with 8 species (5.26%). Most of the invasive aquatic plants (146 species, 96.05%) are suited to freshwater environments, while a minority (6 species, 3.95%, *Spartina alterniflora*, *S. anglica*, *S. patens*, *S. cynosuroides*, *Salicornia bigelovii*, and *Sonneratia apetala*) occur in the marine, intertidal or estuarine environments.

Year of introduction and distribution

Because of the lack of a national aquatic non-native monitoring network in China, it is challenging to provide accurate and comprehensive information regarding the exact times of introduction and to fully explain the modern distributions of the current invasive aquatic flora. The year of introduction can only be reliably reported for 21 species (13.81%). The distribution of most of the species (113 species) is presented in Table S1, and indicates that most of the species for which we could find published data upon are distributed in south China.

Discussion

Our study identifies and summarizes data regarding 152 invasive aquatic plant species that have been introduced into China. This level of introduction is greater than that of Kashmir Himalaya (129 species; Shah and Reshi 2014) and Europe (96 species; Hussner 2012). China is one of the countries that has experienced the most introductions of invasive aquatic plant species. The percentage of invasive aquatic plant species (nearly 10%) is much higher than that of invasive terrestrial plant species (about 2-3%) in China (Jiang et al. 2011). Nonetheless, a higher proportion of non-native aquatic species have caused ecological or economic impacts compared to non-native terrestrial species (Vilà et al. 2010). Further studies of invasive aquatic plants in China are clearly needed to better understand and manage the problem.

Most invasive aquatic plants in China were introduced from South America, North America, and from other parts of Asia. The strong bias in their geographical origin is probably due to the fact that the main aquaculture and aquarium trade countries related to China are distributed in South America, North America and Asia. As a

major aquaculture and aquarium trade hosting country, China has imported a vast number of non-native aquatic plants from the US, Peru, ASEAN (Association of Southeast Asian nations), Chile, Brazil, and Canada (Xiong et al. 2015). Many non-native aquatic species were introduced in China intentionally and some unintentionally. From 1992 to 2012, aquaculture imports in China had increased four times in weight (reaching 4.12 million tons) and 13 times in value (reaching US$ 79.98 hundred millions) (Xiong et al. 2015). Since the introduction of exotics is not regulated, it is likely that more and more non-native aquatic plant species will be released into China from Asia, North and South America.

Similar to other regions, the ornamental trade is recognized as one of the most important pathways of introduction of invasive aquatic plants (Padilla and Williams 2004; Cohen et al. 2007; Keller and Lodge 2007; Hussner 2012). Many invasive aquatic plants, such as *Cabomba caroliniana*, *Elodea nuttallii*, *Egeria densa*, *Myriophyllum aquaticum*, were introduced into urban wetland parks in China. The fragments of these plants dispersed to natural water-bodies following water flows, and they became established through vegetative means. At the present time, 298 national wetland parks and thousands of urban wetland parks have been established in China (Pan and Zhang 2014). Within these habitats, invasive aquatic ornamental plants have become widely established (Xie et al. 2010; Xu and Qiang 2011). Ecological restoration is another important pathway for the introduction of aquatic plants in China. Many aquatic plant species, such as *Elodea canadensis*, *E. nuttallii*, *Chrysopogon zizanioides*, were deliberately planted into constructed wetlands for water pollution control (Zhang et al. 2012). Some invasive aquatic plants were brought to China as ornamentals and were widely applied in constructed wetlands in Eastern China because of their high resistance to pollution and because of their ability to remove nutrients such as nitrate and orthophosphate (Wang et al. 2012; Zhang et al. 2012). Before the 1990's, some invasive aquatic plants were introduced into China as food, forage, and for the production of green manure to promote the production of food crops and animal husbandry (Table S1). But in recent decades, no new aquatic plants species were introduced into China for these purposes. In other words, the ornamental plant trade and to a much lesser degree ecological restoration are the main conduits for the introduction of invasive aquatic plants and will likely remain so in the future.

The emergent form is the largest group of invasive aquatic plants. That can be attributed to the abundance of many shallow lakes in China (Wang and Hu 1998). Emergent species prefer shallow water habitats, are good shallow water colonizers, and they flourish under seasonal water-level fluctuations (Shah and Resh 2014). Thus, many invasive emergent species thrive well in most shallow lakes in China (Fang et al. 2006). The submerged form is the second largest group of invasive aquatic plants in China, and that can be directly attributed to their wide use as aquarium plants. Invasive submerged plants thrive well in urban shallow lakes and wetlands, spreading asexually by propagules or clonally (Xie et al. 2010). Especially in the middle and lower reaches of the Yangtze River, many shallow lakes provide a suitable substrate and sufficient light for invasive submerged plants to become established and develop large populations (Jin et al. 2005). All invasive rooted floating leaf plants were introduced to China as ornamentals, and they thrive well in wetland parks, urban lakes and some urban water-bodies. The number of free floating invasive plant species is relatively small, but plants of this form are potentially extremely successful invaders because they restrict light penetration into the water column, thus avoiding some competitors, and they are able to proliferate rapidly (Fleming and Dibble 2015). Because of this, some invasive floating plants have caused great ecological impacts in China. For example, in the Three Gorges reservoir, free floating plants such as *Eichhornia crassipes* and *Azolla filiculoides*, form dense mats on the water surface and have caused a significant deterioration in water quality (Cui 2005; Zhong and Qi 2009).

Although there are some mechanisms that contribute to the invasion of invasive aquatic plants (Fleming and Dibble 2015), eutrophication is recognized as one of the most important factors for the increased invasiveness of non-native aquatic plants in China (You et al. 2014). Indeed, many invasive aquatic plants like *Eichhornia crassipes, Elodea nuttallii*, *Myriophyllum aquaticum* accumulate biomass quickly and produce more asexual propagules at elevated nutrient levels. These species can suppress and out-compete the native taxa (Xie et al. 2010; You et al. 2014). Currently in China, most lakes are eutrophic or are becoming eutrophic (Le et al. 2010; Qin et al. 2013). After introduction, invasive aquatic plants have established large populations in many eutrophic lakes, including Dianchi Lake, Chaohu Lake, Taihu Lake, and others (Gu et al. 2005;

Zhu et al. 2012; Wang et al. 2013). "Enemy release" may be an important factor in promoting the success of invasives (Xiong et al. 2008). For example, a Chinese native species, *Hydrilla verticillata*, has a strong competitive advantage and has displaced *Elodea* species in New Zealand and Europe (Hofstra et al. 1999). However, it was displaced by *Elodea* species in some Chinese lakes (Gu et al. 2005). Xiong et al. (2008) reported that a native snail (*Radix swinhoei*), which has become widely distributed in extensive wetlands in the middle and lower reaches of the Yangtze River, significantly preferred native over non-native aquatic plants. Therefore, non-native aquatic plants may be less palatable than native aquatic plants for native herbivores and could have a potential advantage in invading lakes and wetlands in these regions.

Similar to the pattern seen in many invasive terrestrial plants and other exotic animals (Wu et al. 2010; Xu et al. 2012), most invasive aquatic plants are widely distributed in south China (Table S1). The largest aquarium market in the world, the Huadiwan market, is located in south China (Guangzhou). Through this outlet alone, hundreds of kilograms of aquatic plants are sold weekly and more than half of these are invasive aquatic plants. Regrettably, there is no regulation upon the sale of non-natives, putting both urban and natural areas at risk of invasion. In spite of the lack of detailed information about the species, time of release into the environment, location of the introduction, and quantity material introduced, the unregulated ornamental aquarium trade promotes the introduction and spread of invasive aquatic plants in south China. Most ornamental invasive aquatic plants in China were introduced from South America and Africa (Table S1), from areas having a climate similar to that of south China. The longer growing season and mild climate of south China may facilitate the success of invasive aquatic plants (Liu et al. 2005).

The rapid increase and spread of invasive aquatic plants have caused great ecological and economic problems in China (Xu et al. 2006). Some invasive plants have caused deterioration in water quality in China. Many invasive aquatic plants (including *Eichhornia crassipes*, *Pistia stratiotes*, *Alternanthera philoxeroides*) form dense mats on the surface of some eutrophic lakes (Gao and Li 2004; Wang et al. 2012), which increases siltation, inhibits the diffusion of air into the water, the respiratory process of their decomposition when they die reduces benthic oxygen, and ultimately results in lower concentrations of dissolved oxygen throughout the water column. The low oxygen conditions combined with the increased organic detritus can increase sediment accumulation rates and accelerate eutrophication processes (Yang et al. 2002). Examples of these problems because of *E. crassipes* are Donghu Lake, Chaohu Lake, Dianchi Lake, Taihu Lake (Wang et al. 2002; Wu et al. 2013) and with *P. stratiotes* in Wanfenghu Lake (Wang and Fu 2005).

The invasion and infestation of invasive aquatic plants are important indicators of declining water quality and eutrophication (Gao and Li 2004). Invasive aquatic plants have caused a high local extinction rate among endemic species (Ding et al. 1995). Some invasive aquatic plants can suppress and out-compete the native species, effectively replacing them in natural areas. Xie and Yu (2008) found that four invasive aquatic plants (*Egeria densa*, *Elodea canadensis*, *M. propinquum*, and *M. aquaticum*) produced more biomass and higher lateral expansion than native congeners, especially in high sediment and nutrient rich environments. These results suggest that these invasive species out-compete and exclude most native macrophytes for light. Alleopathy of some invasive aquatic plants (*A. philoxeroides*, *Spartina alterniflora*, *S. anglica*, *E. crassipes*, and others) effectively promotes their successful invasion (Ni et al. 2012), with their chemical products excluding native taxa. For example, some invasive aquatic plants (*A. philoxeroides* and *Chrysopogon zizanioides*) were planted in the water-fluctuation zone of the Three Gorges reservoir to control soil erosion (Ma et al. 2009), but allelopathy of these invasive plants effectively promoted their successful invasion and decreased native biodiversity (Xu and Qiang 2011). By altering habitat and ecosystem functioning, many invasive aquatic species declined, thus reducing native biodiversity. For example, in some plateau lakes of Yunnan, invasive aquatic plants (*E. crassipes*, *A. philoxeroides*, *P. stratioites*, and *Myriophyllum aquaticum*) covered most of the water surface and led to high local extinction or to decrease of native aquatic biodiversity (Ding et al. 1995; Wang et al. 2013).

It is noteworthy that more and more invasive aquatic plants (*E. crassipes*, *A. philoeroides*, *P. stratioites*, and others) have been introduced to high biodiversity hotspots, such as the Three Gorges reservoir and Yunnan Province. Many invasive aquatic plants have negatively impacted human use of aquatic habitats (e.g., swimming, fishing, boating, and hydropower production) (Xu et al. 2003). For example, *E. crassipes* forms dense mats and has greatly impacted navigation

and hydroelectric power generation in Shuikou reservoir, the largest reservoir in East China (Lu et al. 2007). Now, increasingly more water-bodies (Three Gorges reservoir, Wanfeng Reservoir, plateau lakes, etc) have become infested by invasive aquatic plants (Wang and Fu 2005; Wang et al. 2013).

Although more and more non-native aquatic plants have been introduced to China, only a few studies have reviewed detailed information about their distribution and impact (An et al. 2007; Lu et al. 2007; Ren et al. 2009). The status of most invasive aquatic plants is unknown in China. According to investigations by the Ministry of Environmental Protection of China, water hyacinth (*E. crassipes*) is the worst of the invasive aquatic plant species. The number of provinces infested by water hyacinth has increased quickly from three (Taiwan, Guangxi, and Guangdong) in 1940 to 19 in 2004 (Lu et al. 2007). The economic losses caused by water hyacinth were about 14–17% of the total economic diminution due to biological invasions during this period (Yang et al. 2002). The total cost for water hyacinth control is more than 12.35 million US dollars in China every year (Li and Xie 2002). The detailed case study of this issue was documented in Lu et al. (2007).

The damage caused by invasive aquatic plants is becoming more and more significant (Xu and Qiang 2011). Billions of US dollars have been expended annually in controlling and eliminating invasive aquatic plants (Gao and Li 2004). Control choices for invasive aquatic plants include mechanical, physical, chemical, and biological methods (Madsen 1997). Mechanical and physical methods are extremely costly and potentially increase plant fragmentation, promoting the spread of invasive aquatic plants through clonal reproduction. Chemical methods are largely prohibited by law. Biological approaches may be the most promising means for controlling invasive aquatic plants (Madsen 1997). Many non-native biocontrol agents (such as *Agasicles hygrophila*, *Nieochetina bruchi*, *Neochetina eichhorniae*, and *Orthogalumna terebrantis*) have been introduced to contain, limit, and reduce invasive aquatic plants, but the results have often been unsatisfactory (Gao and Li 2004; Lu et al. 2013). Recently, some studies have focused on native biological agents such as *Ctenopharyngodon idellus, Magalobrame tarminalis, Squaliobarbus curriculus*, *Allogyno genticcrucia*, and *Radix swinhoei* to control invasive aquatic plants like *E. crassipes* and *E. nuttallii* (Gao and Li 2004; Li et al. 2009), but native herbivores often prefer native over non-native aquatic plants (Xiong et al. 2008). The question of how to control and eliminate invasive aquatic plants is an extremely important environmental concern in China and does not appear to have an easy answer.

It is well known that prevention is better than control (Leung et al. 2002). We recommend risk assessment tools, such as Weed Risk Assessment (Pheloung et al. 1999), be applied before any additional introductions are allowed. At the same time, a national monitoring network regarding invasive aquatic plants should be established, providing quick information for water resource managers. This list could be presented in a manner similar to the U.S. National Wetland Plant List (http://www.usace.army.mil/Portals/2/docs/civilworks/regulatory/techbio/nwpl_may2012_factsheet.pdf) that has national, regional and many other more local applications. Increased research relationships between China and other countries experiencing these challenges would promote collaborative means to share information and find mutual solutions. Many of these problems have long been discussed in public forums and recommendations, such as the U.S. National Academy of Sciences (1976) publication entitled “Making Aquatic Weeds Useful: Some Perspectives for Developing Countries”. Although there are some taxonomic incongruities, the Jepson Manual (Baldwin et al. 2012) suggests that several dozen of the aquatic non-native vascular plants occur as naturalized populations in California. It would be useful if collections of the Chinese non-natives were made and were preserved in herbaria in China and were represented in key herbaria within other countries such as the British Museum of Natural History, the U.S. National Herbarium and others.

In conclusion, compiling a list of invasive species within a country is an essential method to annotate taxonomic patterns of invasive species, document their mode of entry and distribution, record ecological impacts as best they are known, and is the first step in developing a management strategy for non-native species (Pyšek et al. 2004). Our study is the first to catalogue the invasive aquatic plant species in China.

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The following supplementary material is available for this article:

Table S1. A list of all invasive aquatic plant species currently known in China.

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