BioInvasions Records (2022) Volume 11, Issue 4: 1001–1010

Research Article

Fanwort, *Cabomba caroliniana* A. Gray (Cabombaceae) in China: introduction, current status, ecological impacts and management

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Citation: Xiong W, Li C, Cheng F, Ke Y, Qiu C, Xiao K, Wang F, Wang Q, Li Y, Tang W, Bowler PA, Li S, Wang H, Shen H (2022) Fanwort, *Cabomba caroliniana* A. Gray (Cabombaceae) in China: introduction, current status, ecological impacts and management. *BioInvasions Records* 11(4): 1001–1010, https://doi.org/10.3391/bir.2022.11.4.18

Received: 25 April 2022

Accepted: 7 September 2022

Published: 8 November 2022

Handling editor: Carla Lambertini

Thematic editor: Giuseppe Brundu

Abstract

Non-native aquatic plants, as ecological engineers, change physical and chemical characteristics of invaded environments, and re-arrange the biological relationships within the colonized aquatic communities. Fanwort (*Cabomba caroliniana*) is a submerged aquatic plant native to the South America and southeastern United States. This species was introduced to China over 20 years ago and because of its quickly growth, large distribution and negative ecological impacts, it is included in the List of Invasive Alien Species in Chinese Natural Ecosystems by the Ministry of Ecology and Environment of China. Lack of detailed information about this species has limited its effective management and control. We summarize the introduction pathway of fanwort, its current distribution throughout China (including longitude and latitude), and the ecological impact on native species, waterways, agriculture and invasions by other non-native species. based on our investigations and a review of the literature. This study provides useful information for researchers and environmental managers to better control fanwort and other non-native aquatic plants in China.

Key words: aquarium trade, distribution, invasive species, wetland, control

Introduction

Biological invasions are a serious threat to global biodiversity and natural ecosystem functions (Mack et al. 2000). Freshwater ecosystems are more vulnerable to invasive species than their terrestrial and marine counterparts and have suffered extensive ecological transformations, causing significant economic and social impacts in adjacent urban and rural landscapes (Vilà et al. 2010). Non-native aquatic plants change the habitat structure,

predator-prey relationships, physical and chemical traits, and the biological background of waterbodies in which they have established populations (Schultz and Dibble 2012). Because of the direct and indirect changes they cause in aquatic ecosystems, non-native aquatic plants are receiving increasing attention by conservation biologists (Wang et al. 2016).

Chinese freshwater ecosystems support a unique and rich biodiversity (Xiong et al. 2018a, 2019a; He et al. 2020). They have recently been recognized as prominent among China's most seriously threatened habitat types because of the high number of invasive species that have colonized and are expanding within them (Xiong et al. 2015, 2017, 2018b; Wang et al. 2016, 2021). Many non-native plants such as Delta arrowhead (*Sagittaria platyphylla*) and parrotfeather (*Myriophyllum aquaticum*) sustain large wild populations and have caused significant negative ecological impacts in areas where they have become established (Wang et al. 2020; Xiong et al. 2021). Unfortunately, field-based information regarding most non-native aquatic plant species is very limited (Wang et al. 2016).

Fanwort, *Cabomba caroliniana* A.Gray, (Cabombaceae) is a submerged aquatic plant native to South America and the southeastern United States (Wilson et al. 2007). Due to the attractive shape of its leaves and its small white flowers, this species has had long-term popularity in the global aquarium trade (Brundu 2015). Now, this species has been introduced in many countries and/or regions and became an important invasive aquatic plant in North America, the Oceania, Europe, and Asia (ISSG 2005; Hussner 2012; Wang et al. 2016). Fragments of fanwort have high survival rates and it spreads well clonally, easily establishing large monoclonal populations (Bickel 2015, 2017). It has been listed as a significant invasive weed in Africa, North America, Europe, and Oceania and more recently in Asia (Wilson et al. 2007; Coetzee et al. 2011; EU 2014; Hofstra et al. 2021).

China has experienced rapid economic growth over the past forty years, which has led to an improvement in the quality of life for the people. The use of aquaria in domestic setting has become one of the most popular forms of recreation and domestic aesthetic enhancement (Wang et al. 2020; Xiong et al. 2021). As a consequence, a great number of non-native aquatic species have been introduced in China through the aquarium trade (Xiong et al. 2015, 2017; Wang et al. 2016). In the 1990s, fanwort was introduced into China as an ornamental aquarium species. It has subsequently escaped from aquarium and established wild populations in east China (Zhang et al. 2003). Because of its quick spread and the ecological problems that it has caused, fanwort was added to the List of Invasive Alien Species in Chinese Natural Ecosystems (Fourth Batch) (MEE 2016). Nonetheless, detailed information about this species in China has been very limited (Wang et al. 2016).

The objective of this study is provide a comprehensive overview and summary of the introduction pathway, current distribution, ecological and

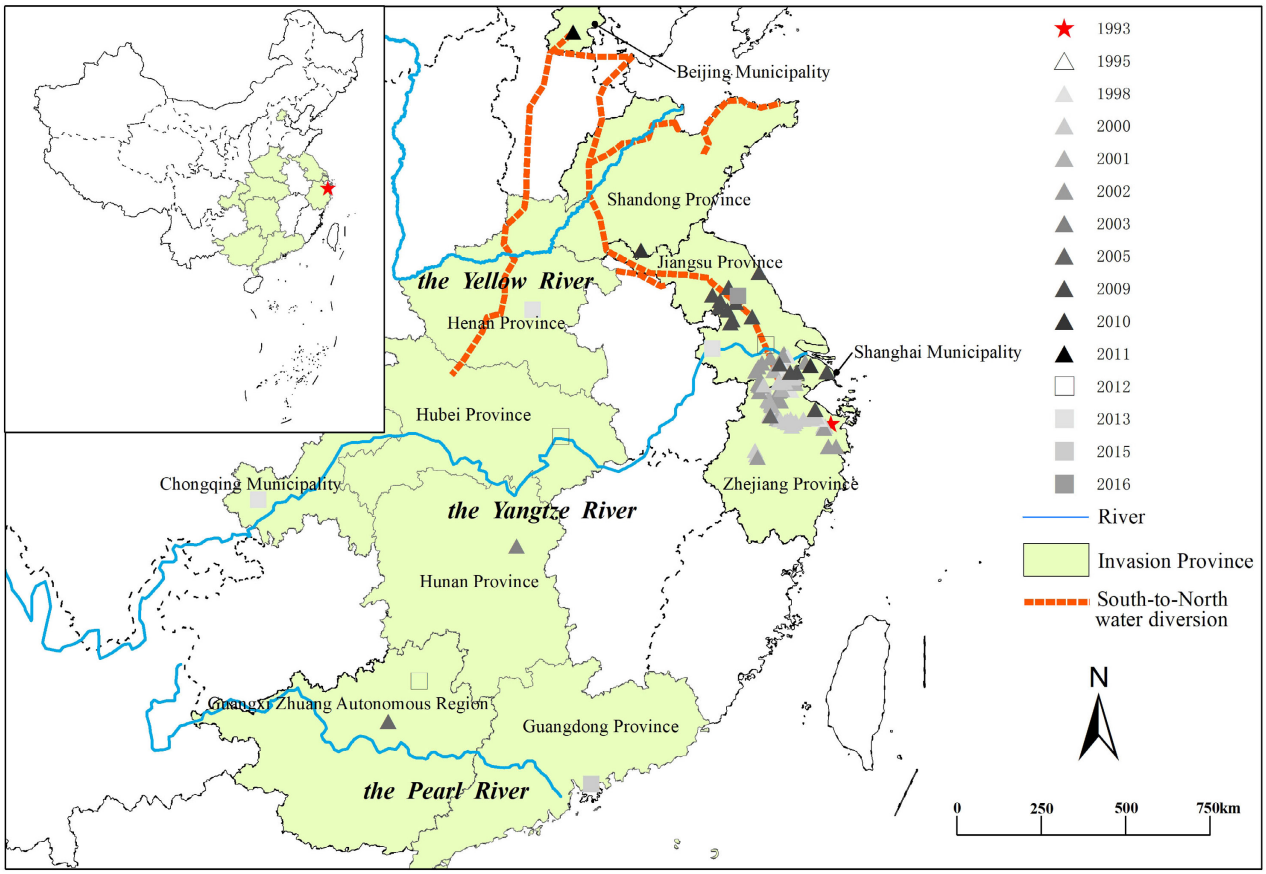

Figure 1. Location of fanwort (*Cabomba caroliniana*) in China.

economic impacts of fanwort in China. Recommendations for a better management and control of this species are presented.

Materials and methods

Both field surveys and a review of relevant literature were used to collect information about fanwort in China. Over 50 botanical surveys were conducted during the main propagation period (May–September) of most aquatic plants over the past twenty years. Over 10 groups of investigators (from three to seven investigators in each group) have sampled more than 1000 sites in China and recorded basic information for each of them. These include their longitude, latitude, elevation, water depth, and the inventory of native and non-native species present (Wang et al. 2020; Xiong et al. 2021). We investigated all known and reported sites of fanwort occurrence (Supplementary material Table S1). Our literature review searched for papers that contained the following combinations of words: "fanwort OR *Cabomba caroliniana*" and "China" in the title, abstract, or keywords from WOS (ISI, http://www.isiknowledge.com) and CNKI (http://www.cnki.net). We also used information from seminal Chinese books such as *Illustrations of Alien Invasive plants in China* (Yan et al. 2016). Based on our surveys and literature review, we created a distribution map of fanwort in China (Figure 1). As aquarium trade is one of the main introduction pathways of

non-native species (Dehnen-Schmutz et al. 2007; Wang et al. 2016), we searched "fanwort" form Taobao website (www.taobao.com), which is the largest online trade platform (March, 2022).

Results and discussion

Introduction pathway

Transporting fanwort fragments on boat trailers has been one of the most prevalent means of dispersal and spread in North America and Europe (Bickel 2015). Nonetheless, aquarium trade and aquaria remain the main sources of introduction for non-native aquatic species in China (Wang et al. 2016). In the past forty years, the global aquarium trade has developed and expanded quickly (Padilla and Williams 2004). With the rapid economic growth and the improvement of the quality of life in China, aquaria have gradually become very popular means for increasing domestic aesthetics and a leisure entertainment (Xiong et al. 2015, 2017; Wang et al. 2016). Many novel and attractive aquatic plants have been used for this purpose, and because of its beautifully shaped leaves and attractive small white flowers, fanwort has become one of the most popular aquarium plants in China (Wang et al. 2020; Xiong et al. 2021). The disposal of surplus aquarium material and escapes from culture for the aquarium trade are common ways that fanwort and other non-native aquatic plants enter natural aquatic environments (Mackey and Swarbrick 1997). For example, the first record of fanwort in the Zhejiang and Shanghai were near ports (Figure 1), which are destinations for the transport of aquarium products and supplies (Zhang et al. 2003). According to the Taobao website, there are nearly 5000 stores that sell water weed through this large online trading platform, and over 80% of them have sold fanwort. This species has most likely been introduced to China multiple times through the aquarium trade (Figure 1).

China's waterways are seriously impaired by eutrophication. To improve water quality, a great number of constructed wetlands have been established to absorb nutrients and decrease algae blooms (Zhang et al. 2012; Qin et al. 2013). Fanwort is very effective in nutrient removal and is widely used in constructed wetlands or as artificial floating islands in constructed wetlands. It can remove over 72% of the total nitrogen and 65% of the total phosphorus at some sites (Jiang and Liu 2017). Constructed treatment wetlands are a source of fanwort inoculum and have exacerbated its colonization and spreading in waterways where treatment wetlands occur (Figure 2).

The central and local government in China have recently established many urban wetland parks for aesthetic and recreational enhancement, and numerous aquatic plants were planted in them to improve ornamental value (Wang et al. 2020; Xiong et al. 2021). In our field surveys, we observed that fanwort occurred in many urban wetland parks in Shanghai, Wuhan, Nanjing, and Suzhou. These urban wetland parks are permanently

Figure 2. Invaded population of fanwort (*Cabomba caroliniana*) in constructed wetland of Donghu Lake (Wuhan, June 2018).

or periodically connected with the Yangtze River. It is well known that fragments of fanwort can survive for a long time and are common means for founding new populations clonally (Bickel 2015), dispersed by flooding (Bickel 2017; Yang 2017).

The native aquatic flora of Chinese lakes has experienced serious reduction in the past forty years (Fang et al. 2006; Zhang et al. 2017). For the protection and enhancement of lacustrine environments, many restoration projects have been implemented in China. A representative example of these efforts are ten natural reserves or wetland parks that were constructed in 2021 (Hubei Forestry Bureau 2021). China planned the restoration of 239,100 km^2 of lake surfaces from 2015 to 2020 (China Government website 2017). In these efforts, fanwort fragments might have been intermingled with other aquatic plants that were introduced in many wetlands. Because of its propensity and the ease with which it establishes invasive clonal populations, fanwort has naturalized in a large range of wetland habitats in China, including severely polluted sites like Taihu Lake (Yao et al. 2018), where it became the dominant aquatic plant (Xie et al. 2020).

Large water diversion projects often facilitate the invasion and dispersal of non-native aquatic species (Daga et al. 2020). The East Route of South-to-North Water Transfer project of China (ESNT), directs water from the Yangtze River to northern China and provides a corridor for the spread of non-native species to north China (Qin et al. 2020). We observed that fanwort has reached Nansi Lake (a storage lake half way of ESNT) and Beijing (the final destination of ESNT) in the last twenty years (Table S1, Figure 1). The optimum temperature range for fanwort is 13–27 °C, and it

can withstand hard cold winters with temperature below 0 °C (Hogsden et al. 2007). These results imply that fanwort can successfully invade most regions of China because it can withstand harsh cold winters. It is therefore likely that the species will disperse to northern China through large water diversion projects, like this.

Spread and distribution

Based on our field investigations and records in the literature, fanwort has a wide distribution in 11 Provinces, Autonomous Regions or Municipalities of China (Jiangsu, Zhejiang, Shanghai, Beijing, Shandong, Henan, Hubei, Hunan, Guangdong, Guangxi, and Chongqin; Figure 1). Fanwort generally prefers shallow (0.2–1.5 m), still or slow-moving waterbodies, including lakes, rivers, marshes, ponds, canals and ditches (Table S1). Our investigation found that rivers are the most frequent habitats (65/95) occupied by fanwort, followed by lakes, ditches, and ponds (Table S1). This species has reached the northernmost point in the Beijing Yuanmingyuan parks in 2013 (40.016257°N; 116.31279°E). We observed that fanwort is sold in almost all commercial aquarium outlets in cities, even in remote regions (such as Tibet and Xinjiang). This suggests that fanwort has potential to be introduced in all regions of China and could survive in most of them (Figure 1). Thus, we predict that fanwort will occur in most regions of China in a foreseeable future.

Potential impacts

Due to its high spreading potential through stem fragments and its rapid growth and colonization ability, fanwort can form dense monoclonal populations quickly, which alter native biodiversity and aquatic ecosystem functions (Hogsden et al. 2007). In our investigated field sites, fanworts developed dense monoclonal populations of over 250 plants m^{-2} in Taizhou, Wuhan and many other sites (Figure 2). The dense aggregates of fanwort stems reduce available light and the biodiversity of native aquatic plants (Noël 2004). The main distribution area of fanwort lies in the Yangtze River, an area that supports very high native aquatic biodiversity and endemic species and is listed as one of the 200 global priority ecoregions for conservation (Olson and Dinerstein 1998). Some native endangered aquatic plants, such as *Najas ancistrocarpa* and *Vallisneria denseserrulata*, have been displaced by fanwort (Ding et al. 2007).

The Yangtze River Basin is a very important area for both agriculture and aquaculture (Wang et al. 2020; Xiong et al. 2021). Fanwort forms dense monoclonal populations in canals and ditches critical for agriculture and aquaculture facilities, and stands can become so thick that they block water flow and reduce production of grain and aquatic products as shown for some other non-native aquatic plants that stop water flow in irrigation ditches and threaten Chinese food security (Wang et al. 2020; Xiong et al. 2021).

Large stands of non-native aquatic plants provide habitat favorable for other non-native species that otherwise might not be problematic (Xiong et al. 2019b). We observed that some non-native species such as mosquitofish (*Gambusia affinis*) and red swamp crayfish (*Procambarus clarkii*) use fanwort monoclonal populations as a refuge to escape large predators like birds and fishes. Non-native herbivorous or omnivorous species preferably consume native aquatic plants, thus facilitating non-native plants invasion and causing an "invasional meltdown" (mutualism between non-native plants and non-native animals that facilitate dispersal of both taxa and eventually cause native species loss and ecosystem changed) (Parker et al. 2006).

Control and management

The four primary approaches to control non-native aquatic plants are mechanical, physical, chemical and using biological measures (Madsen 1997). Mechanical and physical measures are very costly and can easily produce massive stem fragmentation, which can facilitate the spread and clonal invasion of fanwort (Bickel 2015). Chemical measures are expensive and are best suited for small waterbodies, and they are strictly limited by water environmental protection laws (Wang et al. 2016). Thus, biological control approaches are considered as the most effective control measure for curtailing non-native species like fanwort (Madsen 1997). It is difficult, however, to find suitable biological agents to control fanwort in China. Invertebrates, such as snails, are suitable biocontrols for aquatic plants (Lodge 1991), but we found that native snails prefer native over exotic aquatic plants (Xiong et al. 2008). Some fishes, such as grass carp (*Ctenopharyngodon idella* Valenciennes 1844), were used as biological control agents for fanwort in the United States (Wilson et al. 2007). Grass carps consume aquatic plants several times their own weight each day and can act as effective biological agents to eliminate aquatic plants (Mackey and Swarbrick 1997). However, the grass carp is a generalist herbivore and has caused a significant decline of native aquatic plants in China (Zhang et al. 2017). Furthermore, fanwort is not a preferred food source for grass carp, which selects native over non-native aquatic plants and could potentially facilitate invasion by fanwort by reducing native plants' populations (Gibbons et al. 1994). In our field surveys, we observed that some waterbirds, such as the wild duck (*Anas platyrhynchos*), eat fanwort. However, the detailed consumption rate of fanwort by waterbirds is unclear.

Early detection and rapid response is the most effective approach to controlling and managing non-native aquatic plants because they are very difficult to eradicate once they successfully establish (Wang et al. 2016). A comprehensive monitoring network should be established in China (Xiong et al. 2015; Wang et al. 2016), and based on the existing distribution of fanwort, more attention should pay on the eastern China and ESNT regions (Figure 1). The monitoring network must include field investigations,

aquarium stores and internet trade, and citizen involvement in reporting. Cooperation among researchers, environmental protection organizations and the local governments is needed. There is also an immediate need for increased education about the threats posed by non-native aquatic species such as fanwort so that they are not spread further in China's aquatic habitats and for legislation on introduction, trade, and management of these non-native aquatic species.

Acknowledgements

This study was supported by the National Key Research and Development Program of China (2017YFA0605201) and the National Natural Science Foundation of China (No. 31600189). We are grateful to anonymous referees for their helpful comments on earlier versions for this paper.

Authors' contribution

Conceptualization, WX, CL, WT, and SL; methodology, WX, CL, FC, YK, CQ, KX, FW, QW, YL, WT, SL, HW, HS; field work, WX, CL, FC, YK, CQ, KX, FW, QW, YL, WT, SL, HW, HS; writing original draft preparation, WX, Cl, WT, SL; writing review and editing, WX, PAB; supervision, WX, PAB. All authors have read and agreed to the published version of the manuscript.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Records of *Cabomba caroliniana* in China.

This material is available as part of online article from:
http://www.reabic.net/journals/bir/2022/Supplements/BIR_2022_Xiong_etal_SupplementaryMaterial.xlsx