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Review

Non-native species in the Three Gorges Dam Reservoir: status and risks

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Abstract

The Three Gorges Dam Reservoir (TGDR) in China is the world's largest hydropower project, which has significantly impacted ecosystems and environments within the reservoir region. However, the extent and identity of non-native species in the TGDR area is unknown. In this study, we investigated and summarized the literature on non-native species in the TGDR. We found that there are at least 42 non-native aquatic species that have invaded the TGDR. From 2003 to 2015, non-native aquatic species were discovered at a rate of 3.5 species year^{-1}. To our knowledge, this is one of the highest rates of invasion recorded for freshwater ecosystems. Non-native species have mainly been introduced via aquaculture, biocontrol, and the aquarium trade. Some species, such as mosquitofish and water hyacinth, have caused great ecological and economic problems. In the future, additional non-native species are likely to invade the TGDR as a result of human activity. This research can help improve biodiversity conservation and environmental management in the TGDR.

Key words: biological invasions, ecological impacts, invasive species, The Yangtze River, threat

Introduction

Biological invasions are recognized as a serious threat to global biodiversity and ecosystem functions, inflicting great social and economic damage (Mack et al. 2000; Pimentel et al. 2005). It is noteworthy that a higher proportion of non-native species have caused ecological and economic impacts on aquatic environments than terrestrial environments (Vila et al. 2010). Among aquatic habitats, reservoirs are most frequently correlated with invasion by non-native aquatic species (Havel et al. 2005) and thus require particular research effort.

Global rivers have been fragmented by more than 1 million dams (Jackson et al. 2001). In freshwater ecosystems, non-native species introductions are often associated with the construction of dams (Ortega et al. 2015). Moreover, dams may alter hydrological regimes which can facilitate the establishment and spread of non-native species (Bunn and Arthington 2002; Johnson et al. 2008). Many non-native aquatic species have been introduced into Chinese aquatic systems, and as a result China has one of the highest numbers of non-native aquatic species in the world (Xiong et al. 2015; Wang et al. 2016). Although non-native species in China have recently received

increased attention (Xu and Qiang 2011), few studies have focused on non-native species that have become established in reservoirs in China.

The Three Gorges Dam Reservoir (TGDR) is one of the largest hydropower projects in the world (Wu et al. 2004). For a considerable time, the government of China and many ecologists have examined the ecological impacts caused by the Three Gorges Dam in the TGDR, including environment carrying capacity of resettlement, water quality, riverbed erosion, seismic activity and geological hazards, soil erosion, habitat fragmentation, and threats to endemic species (Wu et al. 2003; López-Pujol and Ren 2009; Xu et al. 2013). However, Even in China's authoritative environmental impact statement for the Three Gorges Project, there is no information regarding the non-native species that may have invaded the TGDR (Xu et al. 2013). Recently, some studies have shown that terrestrial non-native species have negative impacts on native biodiversity in the TGDR (Ding et al. 2008), but the potential threats from non-native aquatic species in the TGDR have been neglected. Thus, the aims of this study are (1) to compile a list of non-native species in the TGDR, (2) to summarize their taxonomic status and origin, (3) to characterize the purpose of introduction, and (4) to annotate their impacts to the TGDR ecosystem.

Material and methods

In this study, an inventory of non-native aquatic species in the TGDR was developed from various sources including published literature, institutional reports (grey literature), and field investigations. A total of twenty surveys (including field investigations, fishery market surveys, and questionnaires surveys) were conducted on the TGDR in different seasons from 1990 to 2015. We searched for literature that included the following words: "alien" or "exotic" or "invas*" or "non-native" or "non-indigenous" and "Three Gorges" in the title, abstract, or keywords from the Thomson institute for scientific information (ISI, http://www.isiknowledge.com) and China National Knowledge Infrastructure (http://www.cnki.net). For each non-native species, information on region of origin, purpose of introduction, and information sources were recorded. Most species were introduced into China from other countries and regions. Four Chinese native fish species have been translocated to the TGDR from their original distribution ranges, and we treat these as non-native species.

Shipping and trade may facilitate the introduction of non-native species. We therefore also summarized the number of vessels, lockage, and cargo volume after the ship lock of the Three Gorges Project opened for navigation using data from the State Environmental Protection Administration (1997–2013).

Results

An inventory of non-native aquatic species in the TGDR

A total of 42 non-native species, including one algae, one mollusc, one crayfish, one frog, one freshwater turtle, 14 higher plants, and 23 fishes were found in the TGDR (Supplementary material Table S1). About one third of these species were of North American origin (15 species), followed by Asia (13 species), Central and South America (7 species), Europe (5 species), and Africa (2 species). The geographic origin of non-native species in the TGDR is shown in Figure 1. Approximately 40% of species (17 species) were introduced for aquaculture, followed by ornamental purposes (11 species), unintentional introductions (7 species), forage (2 species), green manure (2 species), biocontrol, food, and ecological restoration (1 species each, respectively).

Ship traffic after the ship lock of the Three Gorges Project opened for navigation

In 2003, the shipping lock of the Three Gorges project opened for navigation enabling large vessels to go through the Three Gorges and reach Chongqing. The number of vessels and cargo has increased quickly (Figure 2). Our field investigations and literature review recorded no non-native aquatic species in the TGDR before 2003, but by 2015, the number of non-native aquatic species had reached 42, giving an average rate of invasion of 3.5 species year^{-1}.

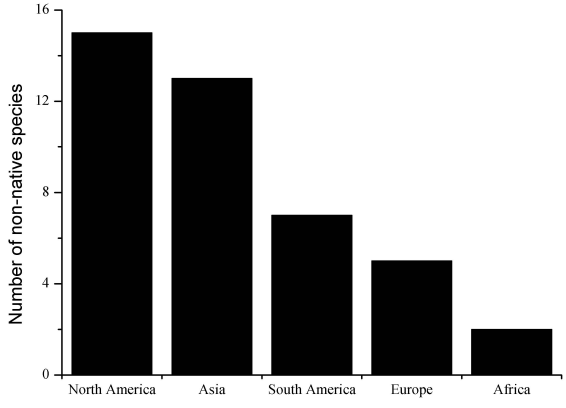

Figure 1. Geographic origin of non-native aquatic species in the TGDR.

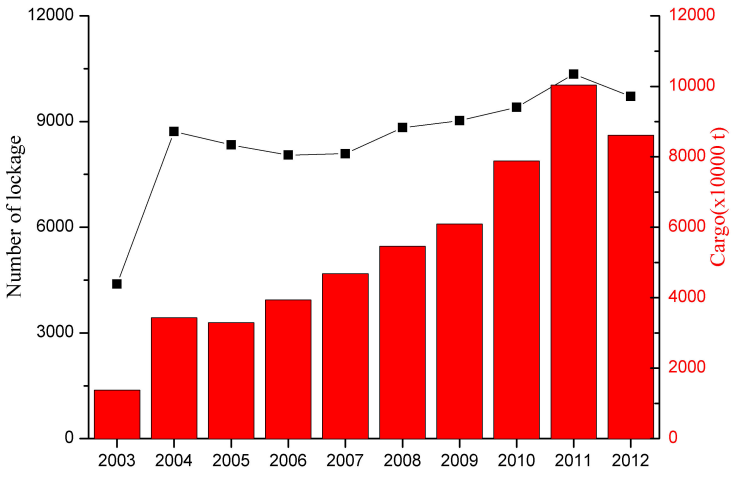

Figure 2. Number of shipping vessels since the ship lock of the Three Gorges Project opened for navigation in 2003.

Discussion

Status of non-native aquatic species in the TGDR

Our study revealed that 42 non-native aquatic species have been introduced into the TGDR. Compared with other waterbodies (for example 182 in the Laurentian Great Lakes basin, 113 in the Hudson River: Ricciardi 2006; Strayer 2006), the TGDR has received relatively fewer aquatic invasions. However, the discovery rate of non-native aquatic species is 3.5 species year^{-1} in the TGDR from 2003 to 2015. To our knowledge, this is one of the highest rates recorded for biological invasion in freshwater ecosystems globally (Ricciardi 2006).

Before the Three Gorges Dam construction, the TGDR was a relatively closed region. No large vessels containing ballast water had access to the TGDR, because of the restricted size of the waterway. Concomitantly, no non-native aquatic species were found in the TGDR before Dam construction (Xiao et al. 2000). However, since the ship lock of the Three Gorges project opened for navigation in 2003, a growing number of vessels and cargo has passed through the Three Gorges (Figure 2) and the number of non-native species detected has likewise increased.

Non-native species in the TGDR originated from all continents except Antarctic and Oceania (Figure 1). North America, Asia, Central and South America, and Europe are the primary origins of non-native species (40 species, 95%), while only a few non-native species were introduced from Africa (2 species, 5%). It is well known that international trade is an important vector for non-native species introduction (Rixon et al. 2005; Xu et al. 2012). Over 94% of the imported goods of Chongqing (the main city in the TGDR) came from these four continents (North America, Asia, Central and South America, and Europe) (ChongQing Statistical Yearbook 2003–2014). Chongqing is one of the fastest developing cities in China, so introduction of non-native aquatic species from these four continents is likely to escalate along with the increasing number of vessels that pass through the TGDR.

Aquaculture is another important mechanism that contributes to the introduction of non-native species (Naylor et al. 2001; De Silva 2012). In the last 20 years, import of aquatic products has increased sharply in China (Xiong et al. 2015). Some non-native fish species (such as *Micropterus salmoides*, *Clarias batrachus*, *Ictalurus punctatus*) were purposely introduced into the TGDR to improve fisheries and the aquarium trade is an ongoing source of non-native species often exceeding other pathways in aquatic ecosystems (Padilla and Williams 2004; Cohen et al. 2007). Moreover, some aquatic plants were introduced into the water level fluctuation zone in the TGDR for vegetation reconstruction and restoration, including one non-native plant (*Chrysopogon zizanioides*) (Bao et al. 2014). Other non-native aquatic plants (such as *Elodea nuttallii*, *Canna indica*, *Cyperus alternifolius*) have also been suggested for use in ecological restoration in the water level fluctuation zone (Zhang and Wang 2007; Luo et al. 2008). Thus, the introduction of non-native aquatic species is likely to increase.

Negative impacts of non-native species

Water quality

Water quality of the TGDR has significantly decreased over time and has become one of the main focuses of many ecologists and the central government of China (Stone 2011; Zhao et al. 2013). The invasions

of some non-native species have exacerbated water quality deterioration in the TGDR (Xiong et al. 2015; Wang et al. 2016; Chamier et al. 2011). For example, water hyacinth (*Eichhornia crassipes*), recognized as the world's worst invasive aquatic weed (Holm et al. 1977), has become broadly distributed in the TGDR watershed and has formed dense mats on the water surface (Ding et al. 2008). Water hyacinth inhibits the diffusion of air into the water, and the decomposition process after death reduces benthic oxygen, ultimately resulting in lower concentrations of dissolved oxygen throughout the water column. The low oxygen conditions in the hypolimnion combined with the increased organic detritus has contributed to water deterioration in the TGDR (Wang et al. 2016).

Geological hazard

The TGDR has increased the risk of geological hazards, including seismic activity, land-slides, and mud-stone flows (Li et al. 2013; Xu et al. 2013). The red swamp crayfish (*Procambarus clarkii*) was introduced into the TGDR and became widely established in the watershed. This crayfish is a tertiary burrower, burrowing to avoid desiccation and to propagate during its reproductive period (Hobbs 1981). Intense digging of red swamp crayfish can cause bank collapse (Correia and Ferreira 1995). It is noteworthy that the reproductive period of crayfish (September–November) and the time of water level rise in the TGDR overlap (New and Xie 2008). The synergistic impact of impoundment and the digging of crayfish could produce greater risk of geological hazard in the TGDR.

Biodiversity

The TGDR is located in one of the world's biodiversity hotspots (Wu et al. 2003; Huang 2001). The World Wildlife Fund includes this area as one of the 200 global priority ecoregions for conservation (Olson and Dinerstein 1998). Many endemic and threatened species occur in the TGDR, including many plants (*Ophioglossum thermal*, *Adiantum reniforme var. sinense*, *Psilotum nudum*, *Metasequoia glyptostroboides*, *Myricaria laxiflora*, *Berchemiella wilsonii*), and fishes (*Acipenser sinensis*, *Psephurus gladius*, *Neophocaena phocaenoides*, *Acipenser dabryanus*, *Myxocyprinus asiaticus*) (Wang and Xie 2004). Some non-native species found in the TGDR have caused negative ecological impacts in other regions. For example, *Gambusia affinis* (Segev et al. 2009) and *Oreochromis niloticus* (Canonico et al. 2005) have been reported to be responsible for the decline and extinction of some endemic species. Thus, we suggest that biodiversity in the TGDR is at great risk of negative impacts.

Management of non-native species in the TGDR

The rapid population increase and dispersal of non-native species could induce great ecological and economic problems in the TGDR. For example, some non-native aquatic plants such as *E. crassipes*, and *A. philoxeroides* form dense mats threatening shipping and hydropower in the TGDR (Wang et al. 2016). The precise cost for controlling non-native species in the TGDR is not certain, but China's government has spent more than 20 million Ren min bi (about US$ 3.3 million) every year solely for the removal of refloating *E. crassipes* and other floating objects in the TGDR (Three Gorges project Corporation 2005). Mechanisms for controlling non-native species include mechanical, physical, chemical and biological methods (Madsen 1997), but unfortunately effects have not been as successful as had been hoped. Mechanical and physical methods were costly and potentially increased the spread of non-native aquatic species through the accidental release of propagules. Chemical methods potentially polluted water, and biological agents also threatened non-target species (Wang et al. 2016).

Conclusion

Freshwater ecosystems are one of the Earth's hotspots of biological diversity (Strayer and Dudgeon 2010). Meanwhile, freshwater ecosystems are recognized as the most vulnerable ecosystems in the world (Dudgeon et al. 2006; Gleick 2003), with an extinction risk significantly higher than that in terrestrial and marine ecosystems (Ricciardi and Rasmussen 1999; Abell 2002). Hydrologic alterations and biological invasions are two of the greatest threats to freshwater biota (Dudgeon et al. 2006; Geist 2011). Large hydraulic projects not only modify water flow and can cause severe consequences for native aquatic biota (López-Pujol and Ren 2009; Dudgeon 2000), but can also promote non-native species invasion (Johnson et al. 2008; Pringle et al. 2000) and many studies have found that invasive species are an important factor in the decline of native biodiversity, especially in freshwater ecosystems (Dudgeon et al. 2006). Thus, we suggest that research on the ecological impacts of non-native aquatic species in the TGDR is vital.

Producing a list of non-native species within a region is the first step needed to manage non-native species (Pysek et al. 2004). This study is the first to

catalogue the non-native aquatic species in the TGDR. It is remarkable that the TGDR is one of the most highly invaded aquatic ecosystems in this planet. Following the construction of a new ship lock, the TGDR could be subject to an extraordinarily high rate of non-native aquatic species invasion. Meanwhile, negative impacts on environmental, ecological and population health caused by non-native species are very likely to emerge in the TGDR. Therefore, environmental researchers, policymakers and managers should pay more attention to non-native species in the TGDR.

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Supplementary material

The following supplementary material is available for this article:

Table S1. A list of all invasive aquatic species in Three Gorges Reservoir.

This material is available as part of online article from:
http://www.reabic.net/journals/bir/2018/Supplements/BIR_2018_Xiong_etal_Table_S1.xlsx