Research Article

Invasions of two estuarine gobiid species interactively induced from water diversion and saltwater intrusion

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Abstract

The East Route of South-to-North Water Transfer Project of China (ESNT) uses the Grand Canal as the main pathway for water conveyance from the Yangtze River upstream to northern China and links five major lakes that serve as water storages along the route. The ESNT was completed in 2013. It was expanded from the existing Northern Jiangsu Water Transfer Project (NJWT), which had been in place since the 1960s. We observed invasions of two estuarine gobiids, *Taenioides cirratus* (Blyth, 1860) and *Tridentiger bifasciatus* (Steindachner, 1881), into the linked lakes. *Taenioides cirratus* was first reported in Luoma Lake in 2005 and Nansi Lake in 2011. *Tridentiger bifasciatus* was first observed in Luoma and Nansi lakes in 2015 and in Dongping Lake in 2016. Invasion of *T. cirratus* was probably associated with the operation of the NJWT, and then enhanced by operation of the ESNT. Invasion of *T. bifasciatus* was associated with operation of the ESNT. The ESNT/ NJWT is mainly operated during winter and spring when the Yangtze River is at the annual minimum discharge. Impoundment of reservoirs at the upper Yangtze River and its tributaries has dramatically reduced river discharge, which induces saltwater intrusion upstream to the donor area of the ESNT. Thus, estuarine gobiids can reach the donor region, and be dispersed upstream through water diversion. There are several other fish species in the Yangtze Estuary that have life history traits similar to these two gobiids and can also live in a wide range of salinities. It is important to evaluate their invasive risks in the future.

Key words: fish invasions, *Taenioides cirratus*, *Tridentiger bifasciatus*, water transfer, saltwater intrusion

Introduction

Inter-basin water transfer projects (IBWTs) have been applied worldwide to resolve the uneven distribution of water resources for multiple purposes such as irrigation, municipal and industrial water supply, and navigation (Oelkers et al. 2011; Zhuang 2016). An IBWT artificially withdraws water from one drainage basin (the donor, e.g., reservoir or stream channel) and adds it to another (the recipient, e.g., reservoir or lake) by conveyance facilities (e.g., canals, channels, aqueducts, conduits, tunnels and/or pipelines) over long distances (Yevjevich 2001). The negative impacts of IBWTs on ecosystems, particularly on the recipient systems, have been a cause of major concern, such as introduction of non-native species, changes in water physicochemical properties, alteration of hydrological regimes, and modification of habitats (Meador 1992; Bunn and Arthington 2002; Zhuang 2016). The introduction of non-native species is one of the most prevalent impacts caused by IBWTs (Meador 1992). An IBWT breaks down natural biogeographic barriers among aquatic organisms, thus facilitates dispersal of aquatic organisms from a donor to a recipient region (Rahel 2007; Zhan et al. 2015). At the same time, environmental changes induced by water diversion may decrease stability of the recipient ecosystem and make it more vulnerable to invasions (Bunn and Arthington 2002; Kadye and Booth 2012).

Gobiids are a group of fishes with a high invasion risk. A variety of gobiids have been reported to invade various environments worldwide, for example, estuary species to estuaries (e.g., *Acentrogobius pflaumii*; Francis et al. 2003; Maddern and Morrison 2008), estuary species to freshwater systems (e.g., *Neogobius fluviatilis*; Pinchuk et al. 2003; Kessel et al. 2009; and *Proterorhinus marmoratus*; Grabowska et al. 2008), and freshwater species to freshwater systems (e.g., *Rhinogobius giurinus* and *Rhinogobius cliffordpopei*; Yuan et al. 2010). These invasive gobiids usually possess biological attributes that promote invasion, for example, a wide tolerance for environmental conditions (euryhaline and eurythermal species, e.g., *Neogobius melanostomus*; Lee and Johnson 2005; Cross and Rawding 2009), concealment behavior associated with passive dispersal by ships (e.g., *N. fluviatilis*; Ahnelt et al. 1998), natural dispersal during the planktonic larval stage (e.g., *A. pflaumii*; Francis et al. 1999), sedentary behavior or occupation of burrows to decrease predation risk (e.g., *N. melanostomus*; Kornis et al. 2012). Invasive gobiids have caused many adverse ecological impacts via competition, predation, transmission of pathogens and/or parasites and modification of biochemical cycles (Kanou et al. 2004; Kornis et al. 2012; Hempel et al. 2016; Herlevi et al. 2017).

The South-to-North Water Transfer Projects of China have been developed to resolve water resource shortage in northern China (Liu et al. 1984). Three routes have been proposed (i.e., the eastern, middle and western routes), corresponding to the water sources at the lower, middle and upper sections of the Yangtze River basin, respectively (Zhang 2009). The East Route of South-to-North Water Transfer Project (ESNT) was expanded from the northern Jiangsu Water Transfer Project (NJWT), which had been in place since the 1960s (Jiang 2012). Although water diversion has occurred more than 50 years due to the operation of NJWT, less attention has been given to the risk of biological invasion associated with the water transfer.

The donor region of the ESNT/NJWT is adjacent to the Yangtze Estuary. Euryhaline fishes, such as many gobiids, may reach the donor region following saltwater intrusion. We observed invasions of two estuarine gobiids, *Taenioides cirratus* (Blyth, 1860) and *Tridentiger bifasciatus* (Steindachner, 1881), in lakes along the ESNT. *Taenioides cirratus* inhabits coastal waters along the Indo-west Pacific, primarily in shallow, muddy estuaries (e.g., the Yangtze Estuary; Zhuang et al. 2006). It lives in burrows (Nayar 1951; Itani and Uchino 2003) and is carnivorous, feeding mainly on small-sized fishes and shrimps (Nayar 1951; Geevarghese 1983; Wu and Zhong 2008). *Tridentiger bifasciatus* is native to estuaries along the coasts of the west Pacific from Hokkaido to Hong Kong, including the Yangtze Estuary (Wu and Zhong 2008). It is a cavity nester. Females spawn repeatedly in nests during March through August, while males simultaneously guard the nest of eggs that are usually from one or more females (Moyle and Cech 1996; Matern 1999). Lifespan of *T. bifasciatus* is 1–2 years. The maximum length recorded was approximately 105 mm (Matern 1999). This species is carnivorous, feeding primarily on benthic invertebrates (Matern and Brown 2005). In the present study, we analyzed invasion processes of these two species in the lakes along the ESNT in relation to patterns of water transfer.

Methods

Study area

The ESNT pumps water up from the lower reaches of the Yangtze River at Yangzhou, Jiangsu Province. Water is then diverted using the Grand Canal as the main channel and five lakes along the route as storages (i.e., Gaoyou, Hongze, Luoma, Nansi and Dongping lakes; Figure 1). Thirteen pumping stations were built to elevate water from the Yangtze River to Dongping Lake, the highest point across the ESNT. Water then flows by gravity from Dongping Lake, and is diverted into two canals, one leading to the Tianjin Municipality and another to the Jiaodong Peninsula of Shandong Province. The section from Yangzhou to Dongping Lake is 617 km (Liu et al. 1984), which stretches across three drainage systems. The water source is from the Yangtze River; the section from Yangzhou to the Gaoyou, Hongze, Luoma, and Nansi lakes, is part of the Huai River basin; Dongping Lake is a part of the Yellow River basin (Jiang 2012). Construction of the ESNT started in 2003. The first phase of construction was completed in 2013 with an annual capacity of 8.9 billion m^3. The ESNT was designed to have second and third construction phases that would increase the annual capacities to 10.6 and 14.8 billion m^3, respectively (Jiang 2012).

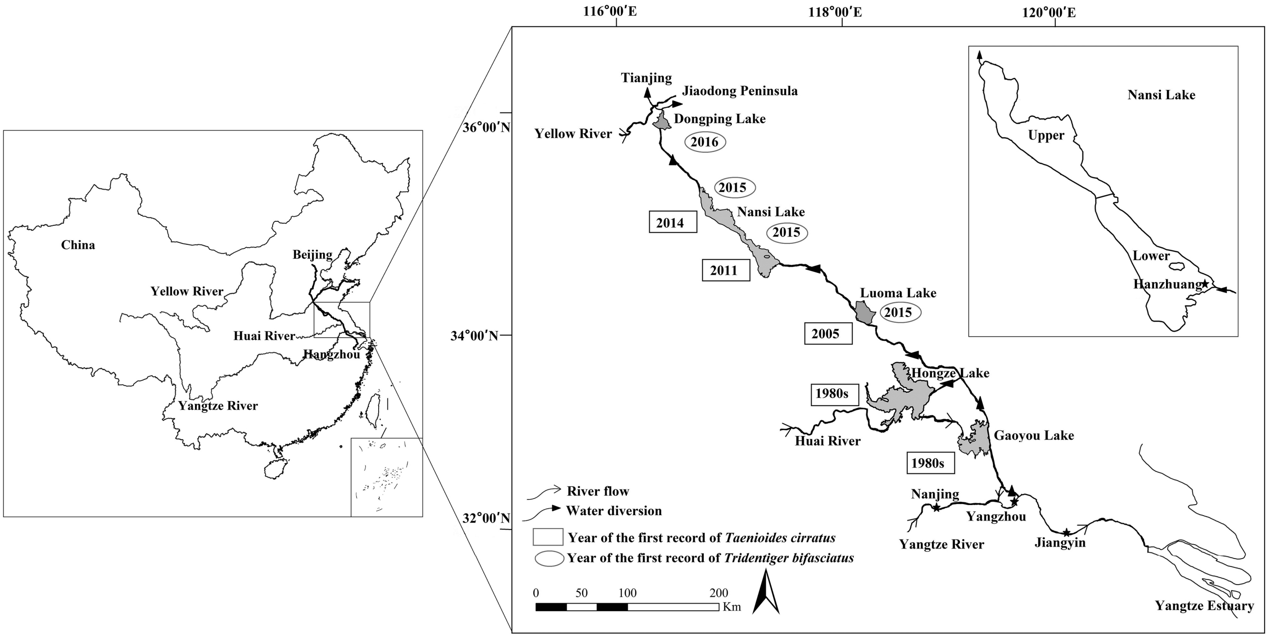

Figure 1. The East Route of South-to-North Water Transfer Project, showing the five major lakes along the route (shadow areas) as storages, the Grand Canal as conveyance, and geographic relationships of the major rivers (i.e., the Yangtze River, the Huai River, and the Yellow River) with the route. The Nansi Lake is separated into the Lower Nansi Lake and Upper Nansi Lake by the Erji Dam. The year of the first record of the two invasive species, *Taenioides cirratus* and *Tridentiger bifasciatus*, in each of these lakes was indicated to show their invasion patterns.

The Grand Canal was constructed in ancient China approximately 2400 years ago for navigational purposes linking Beijing and Hangzhou (Zhejiang Province), with a total length of approximately 1800 km (Piao et al. 2017) (Figure 1). The section used for water transfer in the ESNT is between Yangzhou and Dongping Lake. Elevation of the canal bed and water level is higher in the north than in the south with a difference of 65 m (Liu et al. 1984). This part of the canal was not a free-flowing stream. Instead, it was composed of several separated sections by navigation lock gates. Even within a section, the canal was usually separated into several subsections (Jiang 2012).

The Huai River flows into Hongze Lake on its west side and flows out on its east bank, mainly (70%) through the Sanhe Dam into Gaoyou Lake, and then into the Yangtze River at Yangzhou (Li et al. 2017) (Figure 1). Thus, the Hongze and Gaoyou lakes are a part of the lower reach of the Huai River.

Water diversion events of the NJWT and ESNT

Water diversion events of the ESNT and NJWT were collected from local government agencies managing the ESNT and NJWT (i.e., the Northern Jiangsu Water Transfer Commission, Huai River Water Resources Commission and Shandong Water Transfer Commission), and published reports (Jiang 2012) (Table 1). The NJWT was constructed and extended in different phases. The first phase was between 1965 and 1975 when water could be diverted up to Hongze Lake. The second phase was between 1978 and 1989 when water could be diverted up to Luoma Lake. The third phase

Table 1. Historic water diversion events of the Northern Jiangsu Water Transfer Project (NJWT) and the East Route of South-to-North Water Transfer Project (ESNT).

Water transfer events	Recipient areas	Volume of water transferred		Data sources
		Abstracted from the Yangtze River	Diverted to the Lower Nansi Lake	
NJWT				
1965–1975	up to Hongze Lake	Average 20×10^8 m^3 (annual)	NA	Jiang (2012)
1978–2001	up to Luoma Lake with one exception to lower Nansi Lake	Average 33×10^8 m^3 (annual)	NA	Jiang (2012)
January to October, 1989	Lower Nansi Lake	148×10^8 m^3	NA	Huai River Water Resources Commission
2001–2012	up to Luoma Lake with two exceptions to lower Nansi Lake	Average 46×10^8 m^3 (annual)	NA	Jiang (2012)
December 8, 2002 to January 26, 2003	Lower Nansi Lake	NA	1.1×10^8 m^3	Huai River Water Resources Commission
October, 2010 to July, 2011	Lower Nansi Lake	48×10^8 m^3	NA	Huai River Water Resources Commission
ESNT				
May 17 to June 14, 2013	Dongping Lake and Jiaodong Peninsula	NA	NA	Northern Jiangsu Water Transfer Commission
October 19 to 25, 2013		1.3×10^8 m^3	0.85×10^8 m^3	Northern Jiangsu Water Transfer Commission
November 15 to December 10, 2013		0.34×10^8 m^3	NA	Northern Jiangsu Water Transfer Commission
May 7 to June 11, 2014		0.61×10^8 m^3	0.45×10^8 m^3	Northern Jiangsu Water Transfer Commission
August 5 to 24, 2014		NA	0.8×10^8 m^3	Northern Jiangsu Water Transfer Commission
April 20 to May 20, 2015		NA	3.1×10^8 m^3	Northern Jiangsu Water Transfer Commission
November 10 to December 7, 2015		NA	NA	Northern Jiangsu Water Transfer Commission
January 8 to 29 and March 1 to June 13, 2016		7.58×10^8 m^3	3.27×10^8 m^3	Shandong Water Transfer Commission
December 16, 2016 to January 13, 2017 and March 20 to May 18, 2017		NA	8.89×10^8 m^3	Northern Jiangsu Water Transfer Commission

NA indicates that data is not available.

was between 1989 and 2013 (until operation of the ESNT) when water could be diverted up to Nansi Lake. However, only three water diversion events to Nansi Lake were reported, including one in 1989, one during December 2002 through January 2003, and one during October 2010 through July 2011 (Table 1).

Water has been diverted to Nansi and Dongping lakes every year since operation of the ESNT in 2013. At present, water is mainly further diverted to the Jiaodong Peninsula of Shandong Province.

Ichthyological survey and determination of non-native species

Ichthyological surveys in the lakes along the ESNT were usually carried out annually in two periods in a year (i.e., during May through July and during September through November), when fishing intensity was generally high. When surveying, we checked catches of the major fishing gears (shrimp trap, fyke net, and gill net) from local fishermen in 3–4 major fishing areas across each lake and visited the major local fishery markets. The ichthyological surveys were carried out in Nansi Lake since 2007, in Hongze Lake since 2015, in both Luoma and Gaoyou lakes in 2015, and in Dongping Lake since 2016. Non-native species were determined by referring to historical records of fish fauna of these lakes (Jining Science and Technology Committee 1987; Sun et al. 1990; Zhu and Dou 1993; Cheng and Zhou 1997; Ni and Wu 2006). The earliest record of a non-native fish in a lake was further determined by visiting local fishermen and referring to published literature if available (Ni and Wu 2006; Ding 2010; Lin et al. 2013).

Results

Invasion of T. cirratus

Our first observation of *T. cirratus* in Nansi Lake was during the fish spawning season survey in May 2012. It occasionally occurred in the catches of commercial shrimp traps in lower Nansi Lake, but not in upper Nansi Lake above the Erji Dam (Figure 1). Fishermen reported that this fish was initially caught by shrimp traps in lower Nansi Lake in 2011, only in the lake area near Hanzhuang where the Grand Canal flows into the lake (Figure 1). By 2013, this species had become a common species in the harvest of shrimp traps throughout lower Nansi Lake. It was first found in upper Nansi Lake in 2014. We observed adults with mature gonads in the spawning season and recruitment of young-of-the-year juveniles since 2014, suggesting successful establishment of the population.

Taenioides cirratus was first reported in Luoma Lake in 2005 (Ding 2010), and it has become common in the catches of local fishermen since then (local fishermen, personal observation). This species was occasionally recorded in Gaoyou and Hongze lakes in the 1980s (Ni and Wu 2006; Lin et al. 2013). However, there were no reports of population establishment at either lake at that time. *Taenioides cirratus* likely increased abundance in Gaoyou Lake in the early 2000s (local fishermen, personal observation), but the abundance fluctuation data is not available. It is currently a common species in Gaoyou Lake. However, this pattern did not occur in Hongze Lake, where this species is still rare.

Occurrence of this species in Hongze and Gaoyou lakes in the 1980s may be due to either its upstream migration against the water flow of the Huai River or dispersal by water transfer of the NJWT from the Yangtze Estuary. The appearance of *T. cirratus* in Luoma Lake was likely induced by water transfer of the NJWT from sources either in Gaoyou Lake or the Yangtze Estuary. Invasion of this species into Nansi Lake was likely via the NJWT water diversion events in 2011 from Luoma Lake and may have been enhanced by operation of the ESNT since 2013 (Table 1).

Currently, this species is still not documented as occurring in Dongping Lake.

Invasion of T. bifasciatus

We observed *T. bifasciatus* in catches of commercial shrimp traps in both lower and upper Nansi Lake in May 2015. The catches were dominated by juveniles varying from 35 to 45 mm standard length in August 2015. This species was not observed in Nansi Lake in our previous surveys and was not reported by fishermen before. We then specifically surveyed the other lakes along the ESNT for this species and found that it was distributed throughout Luoma Lake in July 2015. We also first observed this fish in Dongping Lake in November 2016. However, it has not yet been observed in Hongze and Gaoyou lakes. We observed adults with well-developed gonads and new recruitment of young-of-the-year juveniles of this species in Nansi Lake since 2016, suggesting successful establishment of the population.

The ESNT operated from April 21 to July 1, 2015, transferring water up to Dongping Lake. Dispersal of drifting larvae has been reported as the primary way that this species expands its distribution (Matern and Fleming 1995). Water transfer events in 2015 covered the spawning season of this species (Matern 1999). The dispersal of drifting larvae, probably from the Yangtze Estuary, through water flow by the water transfer events, may explain occurrence of this fish in the lakes.

Discussion

We observed invasions of *T. cirratus* and *T. bifasciatus* in the lakes along the ESNT. Invasion of *T. cirratus* was probably due to operation of the NJWT and enhanced by operation of the ESNT; invasion of *T. bifasciatus* was due to the operation of the ESNT. Operation of the ESNT is usually carried out during October through the following May when discharge of the Yangtze River is at an annual minimum (Jiang 2012; Hou and Zhu 2013). The donor region of the ESNT/NJWT is approximately 330 km from the mouth of the Yangtze Estuary. Previously, up-eddy of saltwater in the Yangtze Estuary was usually below Jiangyin, 110 km downstream of the donor region of the ESNT/NJWT under normal river discharge (Xu et al. 2012), and could rarely reach to the donor region of the ESNT at Yangzhou (Yang et al. 2012). With the construction of many dams in the upstream reaches of the Yangtze River and its tributaries, particularly the Three Gorges Dam, river discharge in winter and spring has declined dramatically since 2000s (Chen et al. 2015; Zhang et al. 2015). Meanwhile, operation of the Middle Route of the South-to-North Water Transfer Project has further reduced river discharge (Xu et al. 2014). Furthermore, sea level rise due to global warming in the last decades may have also been increasing upstream saltwater intrusion in the Yangtze Estuary (Kuang et al. 2017). As a consequence, intensity and duration of saltwater intrusion have been strongly enhanced (Wu et al. 2016). Currently, saltwater could frequently reach Nanjing, 140 km upstream of the donor region of the ESNT (Lu et al. 2016), which induced increasing of salinity in the donor region (Zhang et al. 2014). Dispersal of drifting larvae is a common way for many fishes to expand their distribution range (Zens et al. 2018). Both *T. cirratus and T. bifasciatus* are gobiids native to the Yangtze Estuary. Water diversion of the ESNT is carried out in a period overlapping with the spawning seasons of most fish species in the Yangtze Estuary, including many euryhaline fishes, such as many gobiids (Gao 2014; Ren 2015). Thus, larvae that are transferred by the saltwater intrusion current may occur in the donor region and then be pumped up and dispersed into the lakes. We hypothesize that increased saltwater intrusion, together with water diversion of NJWT and ESNT, induced invasion of the two estuarine gobiids, *T. cirratus* and *T. bifasciatus*, into the lakes along the ESNT.

Propagule pressure is one of the factors that determines invasive success of non-native species (Williamson 1996; Lockwood et al. 2009; Simberloff 2009), especially during the initial stages of colonization (Marchetti et al. 2004a). Invasion success increases with the number of propagules and frequency of introductions (Williamson and Fitter 1996). The Grand Canal itself had been divided into several isolated sections at different elevations and was not a free-flowing canal. Thus, water exchange of the Grand Canal with the Yangtze River, and among different sections within the Grand Canal, was rare before operation of water transfer, and risk of biological invasion during that time was low, and there had been no record of estuarine fishes invading these lakes historically. In this view, we may be able to learn more from operation of the ancient Grand Canal. Although *T. cirratus* had previously been observed in Hongze and Gaoyou lakes, it did not establish a population in Gaoyou Lake until the 2000s and did not establish a population in Hongze Lake up to now. Compared to the NJWT, the ESNT is operated over a much longer period each year, with a larger magnitude and higher frequency of water transferred (Jiang 2012). Thus, the risk of invasion from the ESNT is much higher than from the NJWT. Furthermore, water diversion has been dramatically changing environments of the linked lakes. Water level increases by 0.5 m or more, and flow direction is reversed across these lakes during the water diversion system in winter and spring each year (Jiang 2012; unpublished data). We also observed increased salinity (up to 0.7‰) in Nansi Lake in winter and spring associated with water diversion (unpublished data). Such environmental changes may have made these lakes more vulnerable to invasions (Moyle and Light 1996; Kadye and Booth 2012). Ecological consequences of such environmental changes need to be further investigated.

Biological invasion is one of the major threats to biodiversity and health of ecosystems (Dudgeon et al. 2006; Cucherousset and Olden 2011). The lakes along the ESNT have important ecological service functions (e.g., fishery resources, wetlands and scenery). Both *T. cirratus* and *T. bifasciatus* are typical carnivores that feed on small-sized fish, shrimp and benthic invertebrates (Matern and Brown 2005; Wu and Zhong 2008). We hypothesize that invasion of *T. cirratus* and *T. bifasciatus* will negatively impact native fish populations and ecosystems, specifically through trophic interactions. Additional research should be carried out to monitor their population status and to evaluate their influences on native fish populations and ecosystems of these lakes. There are several other fish species in the Yangtze Estuary that can live in a wide range of salinities (e.g., *Johnius belengeri* and *Apogonichthys lineatus*; Yu 2008), including some other gobiids (e.g., *Acanthogobius ommaturus*; Zhuang et al. 2006). There is little information about the biology and ecology of these fishes. It is important to investigate their distribution, movement and life history traits to evaluate invasive risks of these species pose to the lakes and to develop potential strategies to prevent their possible invasions.

Biological invasion from water diversion has been a major ecological concern of IBWT. Most of the previous studies focused on the influences of water diversion itself by dispersing organisms from the donor system to the receipt one (Meador 1992; Zhan et al. 2015). The present study demonstrated invasions of two estuarine species induced by combined effects of water diversion and saltwater intrusion. This interactive consequence had not been expected in the previous environmental assessments of the ESNT and has not been reported in other water diversion projects. Donor regions of many water diversion projects are located at the lower reaches of river systems with some of them near estuaries (Meador 1996). Additionally, most of the river systems around the world have been or are planned to be dammed, and therefore it is very important to evaluate potential biological invasion risks from the estuaries under such circumstances. Several factors, for example, water conveyance patterns, seasonality of water diversion operation and saltwater intrusion, and life history traits of potential invasive species, may critically influence invasion success (Marchetti et al. 2004b; Wang et al. 2006; Gallardo and Aldridge 2018). Further research should be conducted to generate models to predict invasion success of potential invasive species by considering influences of such factors.

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