Introduction and use of non-native species for aquaculture in China: status, risks and management solutions

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Abstract

Aquaculture is one of the fast-growing industries in the past decades. The fast expansion of aquaculture largely relies on the introduction and use of non-native species. This forms a paradox: some species significantly contribute to the fast expansion of aquaculture, while negative effects associated with unregulated introduction and irresponsible use of non-native species are increasing in number and area affected. However, lessons from reported disasters are slowly learned, and risks raised have been highly overlooked. Here, we discuss the known and potential risks derived from the introduction and use of non-native species in China to urge the necessity of incorporating sound management into sustainable aquaculture. Sound management needs to be performed based on the characteristics of each aquaculture activity or related event. We discuss risks based on aquaculture activities or related events popularly employed in the past decades in China, including (i) transfers of non-native species; (ii) fellow travellers, accidental introductions; (iii) artificial hybridization; and (iv) mass release of non-native species for ranching. For each aquaculture activity or related event, we provide general background, status of this activity, risks raised and recommendations for management. Finally, we call for the collaboration of researchers from academia, government and aquaculture industry for proper risk assessment and sound management for sustainable development of aquaculture.

Key words: aquaculture, invasive species, non-native species, risk assessment, sustainable development.

Introduction

Aquaculture is the fast-growing section of world primary industry in the past decades (Food & Agriculture Organization of the United Nations (FAO) 2012). In 2010, global aquaculture production reached more than 83 million tons and a value of US\$ 136 million, which are six and ten times more than those 25 years ago (Fig. 1). Now, aquaculture supplies almost half of aquatic food consumed worldwide (FAO 2012). As demands for aquatic food are quickly increasing in global markets, aquaculture is expected to further expand in many countries, including both developing and developed countries (FAO 2012).

Among many factors responsible for fast expansion of aquaculture, the introduction and use of non-native species plays one of the most crucial roles (e.g. Shelton & Rothbard

2006; De Silva *et al.* 2009). However, accelerating introduction and/or use of non-native species have formed a paradox. There is little doubt that, like introduced crops and live-stock for agriculture, the introduction of aquatic species is a valid means to improve aquaculture production (Bartley *et al.* 2005; Gozlan 2008). For example, non-native finfish species contribute to approximately 17% of the world's production (FAO 2012). Some countries rely on farming of non-native aquatic species, for example, 60% of the freshwater harvest in the Philippines and 50% of the production in Brazil is derived from non-native species (Shelton & Rothbard 2006). However, unregulated introduction and irresponsible use of non-native species lead to severe risks and threats to local environments, economies and human activities (e.g. De Silva 2012). Owing to a huge contribution to economic growth, food supply and

Figure 1 Global and China aquaculture production in both quantity (ton) and value (US\$) in each year. Data from FAO at <http://www.fao.org/fishery/statistics/global-aquaculture-production/en>.

employment opportunities, risks have been highly overlooked and underestimated, although they have been pointed out three decades ago (Ryman 1981) and stressed repeatedly in subsequent scientific literature (e.g. Naylor *et al.* 2001; Bartley *et al.* 2005; De Silva *et al.* 2006, 2009; Laikre *et al.* 2010; De Silva 2012). Risks may appear more severe in many developing countries (e.g. De Silva *et al.* 2006, 2009), where economic growth and employment opportunities are considered as the most important national priorities.

Here, we discuss known and potential risks associated with the introduction and use of non-native species in China to urge the necessity of incorporating proper management into sustainable aquaculture. China serves as a good representative case study. Aquaculture in China expands fast in both production and farming area – the total production in 2011 is more than 50 million tons in quantity and US\$ 64 million in value, nine and 15 times more than those 25 years ago (Fig. 1), and the farming area doubled during the past 25 years, reaching 7.8 million hm^2 in 2011, of which the marine aquaculture area is six times more than 25 years ago (China Fisheries Yearbook 2012). Now, China dominates the reported aquaculture production, accounting for more than 60% of the global production (Fig. 1). In addition, the introduction and/or use of non-native species are accelerating in China, and more than 25% of the production is derived from farming of non-native species (Shelton & Rothbard 2006). However, China is vulnerable to establishment of non-native species (Yan *et al.* 2001). China spans five climatic zones (50° latitude), has more than 32 000 km of coastline and 17.5 million hm^2 of inland water bodies, covers approximately 5200 km from east to west, and supports extremely divergent habitats. Non-native species may find suitable habitats to establish and subsequently spread to a wide geographical range (i.e. become invasive), although initial entry points may not provide preferred environmental conditions.

The aim of this review is to clarify the known and potential risks and to recommend solutions for proper management of sustainable aquaculture, rather than to ban the

introduction and/or use of highly valued non-native species. Negative effects may appear suddenly or gradually as the time since establishment of non-native species is extended (Jeschke & Strayer 2005). However, lessons from known disasters are slowly learned (see known disasters in each section). Moreover, some risks and negative effects have been realized, but many remain unknown or overlooked. It is therefore necessary to perform comprehensive risk assessment on species that are proposed for introduction. In addition, research progress on management of harmful species has accumulated in the past two decades (e.g. Lodge *et al.* 2006; Messing & Wright 2006).

Based on such progress, we propose recommendations for the sound management of introduced non-native species for sustainable aquaculture. Sound management needs to be performed based on the characteristics of each aquaculture activity, such as scale, potential adverse effects and risks associated with each activity. Here, we discuss risks based on aquaculture activities popularly employed in the past several decades. We focus on high-risk activities and related events in this review. For each activity, we provide basic background, status of this activity in China, risks associated with this activity, and recommendations for management.

Transfers of non-native species

Background

Aquaculture has become one key driver for the deliberate introduction of non-native species (Naylor *et al.* 2001; Peeler *et al.* 2011). So far, a total of 5612 records of species introduction have been collected by FAO (Database on Introductions of Aquatic Species, <http://www.fao.org/fishery/dias/en>). Given the fact of unavailability of data in some countries, especially developing countries in Asia where aquaculture expands fast, the number of introduction events is likely larger. The underestimated number can also be seen from the statistics performed by FAO: 76% of introduced species are made by unknown groups (Fig. 2).

Figure 2 Organizations responsible for the total of 5612 records for the introduction of aquatic species for aquaculture. Data from Database on Introductions of Aquatic Species (DIAS) at FAO website (<http://www.fao.org/fishery/introsp/search/en>).

Much attention has been paid to the international introduction of non-native species. The domestic transfer of species to locations where they do not naturally occur has been highly overlooked. Despite efforts made to minimize adverse effects, a well-recognized view of degree of risks and approaches to risk assessment have not been achieved in many countries, even those categorized as vulnerable ones to establishment of non-native species (Doupé & Lymbery 2000). Indeed, the domestic transfer is widely employed in geographically large countries such as China, where valued aquaculture species are usually restricted to limited geographical regions. The scale of domestic transfer, including the number of individuals, geographical sale involved and frequency of transfer, is much larger than that of international transfer, especially for commercial aquaculture purposes (e.g. Liu 2005; Shelton & Rothbard 2006). Despite the fact that the transfer of non-native species has gained attention from scientific communities (e.g. Naylor *et al.* 2001; De Silva *et al.* 2006, 2009; Laikre *et al.* 2010; De Silva 2012), many local and/or national governments have not regulated or not strictly regulated aquaculture-related introductions, especially for domestic transfers.

Species introductions in China

The introduction and use of non-native species for aquaculture in China started as early as 1920s (Fig. 3). A total of 179 species (virus and bacteria excluded) were internationally introduced into China for aquaculture or due to aquaculture-related activities (Table 1; Fig. 4a). These species include desired aquaculture species, accidental species transferred along with desired species (i.e. fellow travellers), and those introduced *via* other vectors but used as

aquaculture species after introductions (Table 1). Due to difficulties to track origins and poor historical records of micro-organisms such as virus, bacteria and other pathogens, we excluded this group in this review. Among these 179 species, the top four taxonomic groups are fish (111 species), molluscs (27 species), algae (16 species), and crustaceans (14), accounting for 93.9% of all introductions (Fig. 4a). Among these four groups, fish and molluscs are the most diverse, covering ten orders and eight infraorders/families/superfamilies respectively (Fig. 4a). For introduced fish, the major group is Perciformes (39 species), accounting for 35.1%, while the most abundant groups of introduced molluscs are Haliotidae (7 species) and Pectinoida (7 species), accounting for 51.9% of the total (Fig. 4a).

The number of species introduced before 1970 was small, totally 13 in this half century (1920–1969). Frequent introductions began from 1970s as the total aquaculture production started to sharply increase. More than 150 species were introduced in the past forty years, with an average 3.8 species per year (Fig. 3). The largest number was detected in 1990s, with a total of 56 species introduced. These introduced species contribute to the fast expansion of aquaculture in China. A large proportion of these introduced species (52.5%) has been successfully cultured (Table 1), and these non-native species have contributed to aquaculture production in China (>25% of total production; Shelton & Rothbard 2006). Two well-known examples are the introductions of the Pacific white shrimp *Penaeus vannamei* and red swamp crayfish *Procambarus clarkii*. The total production of the Pacific white shrimp doubled in both marine and freshwater aquaculture in the past 10 years, from 308 947 ton in 2003 to 665 588 ton in 2011 (marine) and from 296 312 ton in 2003 to 659 961 ton (freshwater), accounting for 74.3% (marine) and 43.6% (freshwater) of the total production of category ‘shrimp, prawn, crayfish and lobster’ (Fig. 5). Although negative effects of the red swamp crayfish were well recognized and emphasized in both scientific literature and public media in the beginning of 2000s (e.g. Wang 2003), aquaculture still expands and production keeps increasing, reaching 563 281 ton in 2010, more than ten times than that in 2003 (Fig. 5). Now, the production of this crayfish accounts for more than 30% of the total production of the category ‘shrimp, prawn, crayfish and lobster’ (Fig. 5).

For domestic transfers, almost all provinces in China, including inland and coastal ones, have introduced species for aquaculture. A total of 73 species (virus and bacteria excluded) have clear records of transfer beyond their native ranges (Table 2; Fig. 4b). Among these 73 species, the most abundant group is fish (61 species), accounting for 83.6% of all introduced species (Fig. 4b). The introduced fish cover 12 orders, of which Cypriniformes is the largest (25 species, Fig. 4b). Although 12

Figure 3 Number of non-native species introduced into China due to aquaculture or related activities (bar chart and left x-axis), and total aquaculture production in China in the past 90 years (dotted line and right x-axis).

Figure 4 Taxonomic composition of non-native species internationally introduced into China (a) and domestically transferred within China (b) due to aquaculture or related activities. The number of species in each taxon is shown in brackets after taxon name.

species are detected to have negative effects/history of biological invasions, they have been transferred and employed for aquaculture (Table 2).

For domestic transfers, both the number of individuals and total value of transferred species are extremely large. For example, only in Hongdao, a coastal town in Qingdao city, Shandong Province, the total value of introduced seed

of *Ruditapes philippinarum* and *Sinonovacula constricta* is more than 100 million Chinese Yuan (more than US\$ 16 million) per annum (Liu 2005; Liu *et al.* 2007a). For the fresh water system, lakes in Yunnan Province represent well-known examples. Starting in 1958, the four major Chinese carps (black carp *Mylopharyngodon piceus*, grass carp *Ctenopharyngodon idellus*, silver carp *Hypophthalmich-*

Table 1 A list of non-native species introduced internationally into China. The native range, year of introduction, current distribution range, major negative effects in local environment and major reference for each species are shown. ^a The bolded species indicate contribution to aquaculture production in China

Species	Native range	Year of introduction	Distribution in China	Negative effects in local environment?	Production (ton) in China (2011)	Major reference
Ascidia – 1 species						
<i>Halocynthia roretzi</i> (Sea pineapple)	Japan & Korea	2005	Liaoning & Shandong Provs.	Unknown		Wang and Wang (2006)
Echinodermata – 2 species						
<i>Apostichopus japonicus</i> var. <i>red</i> (Red Japanese sea cucumber)	Japan	2004	Shandong Prov.	Unknown	–	Li (2009)
<i>Strongylocentrotus intermedius</i> (Japanese sea urchin)	Japan	1989	Liaoning & Shandong Provs.	Yes: destroy seagrass beds and aquaculture facilities, compete with native species for space and food	–	Chang et al. (2000)
Amphibia – 4 species						
<i>Rana catesbeiana</i> (Bull frog)	North America	1959	Nationwide	Yes: predation on native species, especially amphibians	–	Li and Xie (2004)
<i>Rana grylio</i> (Pig frog)	North America	1987	Jiangsu, Zhejiang, Fujian, Hubei, Hunan & Anhui Provs.	Unknown	–	Li and Xie (2004)
<i>Rana heckscheri</i> (American frog)	North America	1987	Guangdong & Hunan Provs.	Unknown	–	Li and Xie (2004)
<i>Rana tigrina</i> (Tiger frog)	Thailand	1995	South China	Unknown	–	Fang et al. (2002)
Testudines – 4 species						
<i>Annamemys annamensis</i> (Vietnamese leaf turtle)	Vietnam	1997	South China	Unknown	–	Li et al. (2002)
<i>Chelydra serpentina</i> (Alligator snapping turtle)	North America	1997	East & South China	Unknown	–	Lin and Zhou (2001)
<i>Morenia petersi</i> (Indian eyed turtle)	India & Bangladesh	Unknown	South China	Unknown	–	Li et al. (2007a)
<i>Trachemys scripta</i> (Red-eared slider)	America	1987	South China	Yes: exclude native species, predation on native species	–	Li et al. (2005)
Crustacea – 14 species						
Branchiopoda – 5 species						
<i>Artemia franciscana</i> (San Francisco brine shrimp)	America	1989	Coastal regions of China	Unknown	–	Tang and Lin (1993)
<i>Artemia monica</i> (Salt Lake brine shrimp)	USA	Unknown	Unknown	Unknown	–	Sun et al. (2000)

Table 1 (Continued)

Species	Native range	Year of introduction	Distribution in China	Negative effects in local environment?	Production (ton) in China (2011)	Major reference
<i>Artemia persimilis</i> (Argentinian brine shrimp)	South America	Unknown	Unknown	Unknown	–	Sun et al. (2000)
<i>Artemia tanisiana</i> (European brine shrimp)	Europe	Unknown	Unknown	Unknown	–	Sun et al. (2000)
<i>Artemia urmiana</i> (Iranian brine shrimp)	Iran	Unknown	Unknown	Unknown	–	Sun et al. (2000)
Decapoda – 9 species						
<i>Cherax destructor</i> (Australian crayfish yabby)	Australia	1998	Jiangsu & Zhejiang	Unknown	–	Li et al. (2007a)
<i>Cherax quadricarinatus</i> (Australian red claw crayfish)	Australia	1992	East & Southeast China	Unknown	–	Li et al. (2007a)
<i>Cherax tenuimanus</i> (Australian crayfish)	Australia	1986	Hubei	Unknown	–	Li et al. (2007a)
<i>Macrobrachium rosenbergii</i> (Malaysian prawn)	Indo-Pacific & Southeast Asia	1976	Nationwide	Unknown	122,933	Li et al. (2007a)
<i>Penaeus japonicus</i> (Kuruma prawn)	Indian & Pacific Oceans	Unknown	Southeast coastal regions	Unknown	50,991	Li et al. (2007a)
<i>Penaeus monodon</i> (Black tiger prawn)	Indian & Pacific Oceans	1986	Southern China	Unknown	60,691	Li et al. (2007a)
<i>Penaeus stylirostris</i> (Blue shrimp)	Latin America	1988	Nationwide	Unknown	–	Li et al. (2007a)
<i>Penaeus vannamei</i> (White-leg shrimp)	South America	1988	Nationwide	Unknown	665,588 (marine) 659,961 (freshwater)	Li et al. (2007a)
<i>Procambarus clarkii</i> ^b (Red swamp crayfish)	USA, Central & South America	1929	Nationwide	Yes: destroy dams, agriculture crop, and sessile communities.	486,319	Li et al. (2007a)
Algae – 16 species						
Blue-green algae – 2 species						
<i>Spirulina maxima</i> (N/A)	Mexico	1970s	Hainan, Guangdong & Yunnan Provs.	Unknown	–	Zhang and Yang (1997)
<i>Spirulina platensis</i> (N/A)	Africa	1985	Hainan, Guangdong & Yunnan Provs.	Unknown	–	Zhang and Yang (1997)
Brown algae – 6 species						
<i>Costaria costata</i> ^c (N/A)	Japan	Unknown	Liaoning Prov.	Unknown	–	Shao and Li (2000)
<i>Desmarestia ligulata</i> ^d (N/A)	Japan	1997	Liaoning Prov.	Yes: release sulphuric acid after death	–	Shao and Li (2000)

Table 1 (Continued)

Species	Native range	Year of introduction	Distribution in China	Negative effects in local environment?	Production (ton) in China (2011)	Major reference
<i>Laminaria japonica</i> (Kelp)	Pacific Ocean	1927	Liaoning, Shandong, Zhejiang & Fujian Provs.	Unknown	–	Liang and Wang (2001)
<i>Laminaria longissima</i> (Narrow-leaved tangle)	Pacific Ocean	1990	Liaoning & Shandong Provs.	Unknown	–	Zhang et al. (1998)
<i>Macrocystis pyrifera</i> (Giant kelp)	Mexico	1978	Jiangsu, Zhejiang & Shandong Provs.	Unknown	–	Liang and Wang (2001)
<i>Undaria pinnatifida</i> (Wakame)	Japan & Korea	1940s	Liaoning & Shandong Provs.	Yes: quick growth, reduce native seaweed diversity	134,175	Liang and Wang (2001)
Green algae – 3 species						
<i>Dunaliella salina</i> (Teodoresce)	Mediterranean	1986	High-salt Waters	Unknown	–	Sun (2000)
<i>Nannochloropsis oculata</i> (N/A)	Japan	1991	Jiangsu, Zhejiang & Shandong Provs.	Unknown	–	Liu et al. (1999)
<i>Tetraselmis</i> sp. (Green flagellate)	Canada	1996	Jiangsu, Zhejiang & Shandong Provs.	Unknown	–	Zou and Zhang (2003)
Red algae – 5 species						
<i>Eucheuma amakusaensis</i> (N/A)	Japan	1984	Guangdong Prov.	Unknown	–	Liang and Wang (2001)
<i>Eucheuma striatum</i> (N/A)	Asia	1985	South China	Unknown	–	Zeng (2001)
<i>Palmaria palmata</i> (N/A)	Atlantic & Pacific Oceans	2005	Lab only	Unknown	–	Pang (2005)
<i>Porphyra yezoensis</i> (N/A)	Japan & Korea	1986	Coastal provinces	Unknown	–	Mao (1988)
<i>Trichogloea lubrica</i> ^a (N/A)	Japan	1997	Liaoning Prov.	Unknown	–	Shao and Li (2000)
Mollusca – 27 species						
Pectinoida – 7 species						
<i>Argopecten irradians</i> (Bay scallop)	Atlantic Ocean	1982	Coast of North China	Unknown	800,000	Zhang et al. (1997)
<i>Argopecten purpuratus</i> (Peruvian scallop)	Peru	2007	Shandong Prov.	Unknown	–	Guo (2009)
<i>Chlamys asperima</i> (Doughboy scallop)	Australia	2001	Shandong Prov.	Unknown	–	Liu et al. (2003)
<i>Notovola meridionalis</i> (Tasmanian scallop)	Australia	2000	Shandong Prov.	Unknown	–	Liu et al. (2003)
<i>Patinopecten yessoensis</i> (Yesso scallop)	Japan, Korea & Russia	1980	North China	Unknown	250,000	Li et al. (2007a)
<i>Pecten maximus</i> (Great scallop)	English Channel & Iceland	1999	North China	Unknown	–	Li et al. (2007a)
<i>Placopecten magellanicus</i> (Giant scallop)	Canada	2005	Shandong Prov.	Unknown	–	Qin et al. (2009)

Table 1 (Continued)

Species	Native range	Year of introduction	Distribution in China	Negative effects in local environment?	Production (ton) in China (2011)	Major reference
Ostreoida – 4 species <i>Crassostrea gigas</i> (Pacific oyster)	Japan, Australia	1979	Nationwide	Yes: fouling species with high abundance on vessels and aquaculture facilities	–	Guo (2009) and Sun et al. (2010)
<i>Crassostrea nippona</i> (Iwagaki oyster)	Japan	Unknown	Shandong Prov.	Unknown	–	Teng (2009)
<i>Crassostrea sikamea</i> (Kumamoto oyster)	Japan	2007	Shandong Prov.	Unknown	–	Teng (2009)
<i>Crassostrea virginica</i> (American oyster)	East coast of North America	1986	Shandong Prov.	Unknown	–	Li et al. (2007a)
Unionoida – 2 species <i>Hyriopsis Schlegelii</i> (Biwa pearly mussel)	Japan	1997	Jiangxi & Zhejiang Provs.	Unknown	–	Li et al. (2007a)
<i>Potamilius alatus</i> (Pink heelsplitter)	America	2002	Jiangsu & Guangdong Provs.	Unknown	–	Li et al. (2007a)
Veneroida – 2 species <i>Mercenaria mercenaria</i> (Hard-shell clam)	USA	1997	Shandong, Liaoning, Jiangsu & Zhejiang Provs.	Unknown	–	Li et al. (2007a)
<i>Spisula solidissima</i> Atlantic Surfclam	East Coast, USA	2002	Shandong & Liaoning Provs.	Unknown	–	Guo (2009)
Mytiloida – 1 species <i>Mytilus galloprovincialis</i> (Mediterranean mussel)	Mediterranean, Black, Adriatic Seas	Unknown	Nationwide	Yes: fouling species with high abundance on vessels and aquaculture facilities	–	Li et al. (2007a)
Myoida – 1 species <i>Panopea abrupta</i> (Geoduck)	USA & Canada	1985	Shandong & Liaoning Provs.	Unknown	–	Li et al. (2007a)
Achatinoidea – 1 species <i>Achatina fulica</i> ⁹ (African giant snail)	Africa	1930	South China	Yes: pest in agriculture and horticulture, vector for disease-causing pathogens	–	Li et al. (2007a)
Neogastropoda – 1 species <i>Babylonia spirata</i> (Spotted baigai)	Indian Ocean & west Pacific	Unknown	South China	Unknown	–	Harasewych and Moretzsohn (2010)

Table 1 (Continued)

Species	Native range	Year of introduction	Distribution in China	Negative effects in local environment?	Production (ton) in China (2011)	Major reference
Haliotidae – 7 species						
<i>Haliotis discus discus</i> (Pacific abalone)	Japan	1996	Shandong & Liaoning Provs.	Yes: genetic introgression into local gene pools	–	Zhang et al. (2004)
<i>Haliotis fulgens</i> (Green abalone)	USA & Mexico	1985	South China	Unknown	–	Li et al. (2007a)
<i>Haliotis gigantea</i> (Japanese abalone)	Japan	1998	Shandong & Liaoning Provs.	Unknown	–	Sun et al. (2001)
<i>Haliotis iris</i> (Blackfoot paua)	West Pacific	1999	Unclear	Unknown	–	Liang and Wang (2001)
<i>Haliotis laevigata</i> (Smooth Australian abalone)	Australia	2000	Guangdong Prov.	Unknown	–	Yang and Cai (2002); Guo (2009)
<i>Haliotis refescens</i> (Red abalone)	USA & Mexico	1985	South China	Unknown	–	Li et al. (2007a)
<i>Haliotis rubra</i> (Blacklip abalone)	Australia	Unknown	South China	Unknown	–	Hou (1998)
Ampullariidae – 1 species						
<i>Pomacea canaliculata</i> ¹ (Apple snail)	South America	1977	Southern China	Yes: pest in agriculture, vector for disease-causing pathogens	–	Li et al. (2007a)
Fish – 111 species						
Acipenseriformes – 9 species						
<i>Acipenser baeri</i> (Siberian sturgeon)	Europe	1996	Nationwide	Unknown	–	Li et al. (2007a)
<i>Acipenser gueldenstaedtii</i> (Russian Sturgeon)	Europe	1993	Mainly in Xinjiang & Heilongjiang Provs.	Unknown	–	Li et al. (2007a)
<i>Acipenser nudiventris</i> (Bastard sturgeon)	Black, Caspian & Aral Seas	1993	Xinjiang	Unknown	–	Li et al. (2007a)
<i>Acipenser ruthenus</i> (Sterlet)	Europe	1997	Nationwide	Unknown	–	Li et al. (2007a)
<i>Acipenser stellatus</i> (Star sturgeon)	Europe	Unknown	North China	Unknown	–	Ren and Ma (2001)
<i>Acipenser transmontanus</i> (White sturgeon)	North America	Unknown	North China	Unknown	–	Ren and Ma (2001)
<i>Huso huso</i> (Beluga Sturgeon)	Europe	Unknown	Many provinces in coastal regions and middle China	Unknown	–	Ren and Ma (2001)
<i>Huso huso</i> ♀ × <i>Acipenser ruthenus</i> ♂ (Bester)	Created in Union of Soviet Socialist Republics	1998	North & Northeast China	Unknown	–	Li et al. (2007a)
<i>Polyodon spathula</i> (American paddlefish)	USA	1988	Nationwide	Unknown	–	Xiong et al. (2008a)
Anguilliformes – 4 species						
<i>Anguilla anguilla</i> (European eel)	Europe	1991	Southeast China	Unknown	–	Li et al. (2007a)
<i>Anguilla australis</i> (Shortfin eel)	Australia	2005	Jiangsu, Zhejiang, Fujian, Guangdong Provs.	Unknown	–	Li et al. (2007a)

Table 1 (Continued)

Species	Native range	Year of introduction	Distribution in China	Negative effects in local environment?	Production (ton) in China (2011)	Major reference
<i>Anguilla mossambica</i> (African longfin eel)	West Indian Ocean	2007	South China	Unknown	–	Fan et al. (2008)
<i>Anguilla rostrata</i> (American eel)	East coast of North America	1978	Jiangsu, Zhejiang, Fujian, Guangdong Provs.	Unknown	–	Li et al. (2007a)
Characiformes – 4 species						
<i>Colossoma brachypomum</i> (Freshwater spadefish)	South America	1982	Nationwide	Unknown	94,942	Li et al. (2007a)
<i>Piaractus mesopotamicus</i> (Pacu)	Brazil	1996	Mainly in Jiangsu & Zhejiang Provs.	Unknown	–	Li et al. (2007a)
<i>Prochilodus scrofa</i> (Shad)	South America	1996	Nationwide	Unknown	–	Li et al. (2007a)
<i>Pygocentrus nattereri</i> ¹ (Red bellied piranha)	South America	1990	Nationwide	Yes: predation on almost all native species, attack human beings	–	Li et al. (2007a)
Clupeiformes – 16 species						
<i>Alosa sapidissima</i> (American shad)	East coast of North America	2001	Guangdong, Shanghai, Zhejiang, Shandong, Jiangsu, Fujian Provs. Xinjiang	Unknown	–	Li et al. (2007a)
<i>Abramis brama orientalis</i> (European bream)	Caspian & Aral Seas	1949		Unknown	–	Li et al. (2007a)
<i>Barbodes schwanenfeldii</i> (Tinfoil barb)	Southeast Asia	1997	South China	Unknown	–	Song et al. (2012)
<i>Carassius auratus cuvieri</i> (Crucian carp)	Japan	1959	Many freshwater bodies	Unknown	–	Li et al. (2007a)
<i>Catla catla</i> (Catla)	South Asia	1973	Mainly in Guangdong, Guangxi & Hainan Provs.	Unknown	–	Li et al. (2007a)
<i>Chalcalburnus chalcoides</i> (Danube bleak)	Black, Caspian & Aral Seas	2001	Heilongjiang, Hebei	Unknown	–	Li et al. (2007a)
<i>Cirrhinus mrigala</i> (Mrigal)	Coast of Indian Ocean	1982	Shandong & Shanghai Pearl River basin & Hainan Prov.	Unknown	–	Li et al. (2007a)
<i>Cyprinus carpio</i> (Russian common carp)	Russian	1958	Northwest China	Yes: genetic introgression into local gene pools	–	Li et al. (2007a)
<i>Cyprinus carpio</i> var. <i>mirror</i> (Scattered mirror carp)	Ukraine	1958	Nationwide	Yes: genetic introgression into local gene pools	–	Li et al. (2007a)
<i>Cyprinus carpio</i> var. <i>specularis</i> (German mirror carp)	German	1982	Nationwide	Yes: genetic introgression into local gene pools	–	Li et al. (2007a)

Table 1 (Continued)

Species	Native range	Year of introduction	Distribution in China	Negative effects in local environment?	Production (ton) in China (2011)	Major reference
<i>Ictiobus cyprinellus</i> (Common buffalo)	USA & Canada	1993	Yangtze River & Pearl River basins	Unknown	–	Li et al. (2007a)
<i>Labeo calbasu</i> (Black Rohu)	Southeast Asia	1990	Guangdong Prov.	Unknown	–	Lou (2000)
<i>Labeo rohita</i> (Rohu)	Southeast Asia	1978	South China	Unknown	–	Li et al. (2007a)
<i>Leptobarbus hoevenii</i> (Mad barb)	Southeast Asia	1988	Taiwan & Guangdong Provs.	Unknown	–	Li et al. (2007a)
<i>Puntius gonionotus</i> (Java barb)	Southeast Asia	1986	Guangdong Prov.	Unknown	–	Li et al. (2007a)
<i>Tinca tinca</i> (Tench)	Europe	1998	Guangdong, Hubei, Jiangsu & Sichuan Provs.	Unknown	–	Li et al. (2007a)
Osteoglossiformes ¹ – 8 species						
<i>Arapaima gigas</i> (Paiche)	South America	1990	Guangdong & Shandong Provs.	Unknown	–	Lou (2000)
<i>Gnathonemus petersi</i> (Elephantnose fish)	Africa	1990	Guangdong Prov.	Unknown	–	Lou (2000)
<i>Notopterus blanchi</i> (Royal Clown Knife)	Southeast Asia	1990	Guangdong Prov.	Unknown	–	Lou (2000)
<i>Notopterus chitala</i> (Clown Knife)	Southeast Asia	1990	Guangdong Prov.	Unknown	–	Lou (2000)
<i>Osteoglossum bicirrhosum</i> (Silver arowana)	South America	1990	Guangdong Prov.	Unknown	–	Lou (2000)
<i>Osteoglossum ferreirai</i> (Black arowana)	South America	1990	Guangdong Prov.	Unknown	–	Lou (2000)
<i>Scleropages formosus</i> (Asian arowana)	Southeast Asia	1990	Guangdong Prov.	Unknown	–	Lou (2000)
<i>Scleropages leichardti</i> (Australian arowana)	Australia	1990	Guangdong Prov.	Unknown	–	Lou (2000)
Perciformes – 39 species						
<i>Bidyanus bidyanus</i> (Silver perch)	Australia	1999	Mainly in Fujian & Guangdong Provs	Unknown	–	Li et al. (2007a)
<i>Centropomus striata</i> (Atlantic seabass)	East coast of North America	2002	Shandong Prov.	Unknown	–	Li et al. (2007a)
<i>Channa micropeltes</i> (Giant snakehead)	Southeast Asia	1986	Shandong Prov.	Unknown	–	Li et al. (2007a)
<i>Channa striatus</i> (Snakehead)	Southeast Asia	1992	South China	Yes: predation on fish, amphibians and crustaceans	–	Li (1992)
<i>Cichlasoma</i> sp. (N/A)	Africa	1989	Guangdong Prov.	Unknown	–	Lou (2000)
<i>Gynoscion nebulosus</i> (Spotted seatrout)	North America	1997	Shandong, Zhejiang, Fujian, Beijing & Liaoning	Unknown	–	Li et al. (2007a)
<i>Eleotris fusca</i> (Dusky sleeper)	Southeast Asia	1999	Guangdong Prov.	Unknown	–	Li et al. (2007a)

Table 1 (Continued)

Species	Native range	Year of introduction	Distribution in China	Negative effects in local environment?	Production (ton) in China (2011)	Major reference
<i>Hephaestus fuliginosus</i> (Black bream)	Australia	1998	Guangdong, Hebei, Zhejiang & Jiangsu Provs.	Unknown	–	Li et al. (2007a)
<i>Lates calcarifer</i> (White sea bass)	Southeast Asia	1984	South China Sea & East China Sea	Unknown	–	Li et al. (2007a)
<i>Lepomis auritus</i> (Redbreast sunfish)	North America	1987	Hubei & Hainan Provs.	Unknown	–	Chen and Ye (1992)
<i>Lepomis cyanellus</i> (Green sunfish)	North America	1999	Guangdong, Hubei & Zhejiang Provs.	Unknown	–	Li et al. (2007a)
<i>Lepomis macrochirus</i> (Bluegill sunfish)	North America	1987	Hubei, Hunan, Zhejiang & Guangdong Provs.	Unknown	–	Li et al. (2007a)
<i>Lepomis megalotis</i> (Longear sunfish)	North America	1987	Hubei & Hainan Provs.	Unknown	–	Chen and Ye (1992)
<i>Lepomis nigromaculatus</i> (N/A)	North America	1989	Hubei Prov.	Unknown	–	Chen et al. (2010)
<i>Luciopeca luciopeca</i> (Pike-perch)	Europe	1960	Beijing, Tianjin & Hubei	Unknown	–	Li et al. (2007a)
<i>Maccullochella peelii peilii</i> (Murray cod)	Australia	2001	Zhejiang Prov.	Unknown	–	Li et al. (2007a)
<i>Macquaria ambigua</i> (Murray perch)	Australia	1991	South China	Unknown	–	Li et al. (2007a)
<i>Micropterus salmoides</i> (Largemouth bass)	USA & Canada	1983	Central & South China	Yes: compete with native fish for food and space	–	Li et al. (2007a)
<i>Morone chrysops</i> ♀ × <i>M. saxatilis</i> ♂ (Hybrid striped bass)	Created in USA	1993	Yellow Sea & East China Sea	Unknown	–	Li et al. (2007a)
<i>Morone saxatilis</i> (Striped bass)	USA & Canada	1997	Yellow Sea & East China Sea	Unknown	–	Li et al. (2007a)
<i>Oreochromis andersonii</i> (Threespot tilapia)	Africa	1987	Nationwide	Unknown	–	Chen and Ye (1994)
<i>Oreochromis aureus</i> (Blue tilapia)	Africa & Middle East	1981	Nationwide	Unknown	–	Li et al. (2007a)
<i>Oreochromis aureus</i> ♂ × <i>O. niloticus</i> ♀ (N/A)	N/A	Unknown	South China	Unknown	–	Chen and Ye (1994)
<i>Oreochromis mossambicus</i> (Mozambique tilapia)	Africa	1956	Nationwide	Unknown	–	Li et al. (2007a)
<i>Oreochromis mossambicus</i> ♂ × <i>O. niloticus</i> ♀ (N/A)	N/A	Unknown	Nationwide	Unknown	–	Chen and Ye (1994)
<i>Oreochromis niloticus</i> (Nilotica tilapia)	Africa	1978	Nationwide	Unknown	–	Li et al. (2007a)
<i>Oreochromis homorum</i> (Homorum tilapia)	Africa	2001	Nationwide	Unknown	–	Li et al. (2007a)
<i>Oxyeleotris lineolatus</i> (Sleepy cod)	Australia	1996	Pearl River basin	Unknown	–	Li et al. (2007a)
<i>Oxyeleotris marmorata</i> (Marble goby)	Southeast Asia	1988	Pearl River basin	Unknown	–	Li et al. (2007a)

Table 1 (Continued)

Species	Native range	Year of introduction	Distribution in China	Negative effects in local environment?	Production (ton) in China (2011)	Major reference
<i>Parachromis managuensis</i> (Jaguar guapote)	Central America	1988	Guangdong & Guangxi Provs.	Unknown	–	Li et al. (2007a)
<i>Perca flavescens</i> (Yellow perch)	USA & Canada	2003	Nationwide	Unknown	–	Li et al. (2007a)
<i>Sarotherodon galilaeus</i> (Tilapia galilaea)	Africa	1978	Hubei Prov.	Unknown	–	Li et al. (2007a)
<i>Sarotherodon melanothron</i> (Blackchin tilapia)	Africa	2002	Guangdong & Hebei Provs.	Unknown	–	Li et al. (2007a)
<i>Sciaenops ocellatus</i> (Red drum)	East coast of North America	1991	Shandong, Zhejiang, Fujian, Guangdong & Hainan Provs.	Unknown	64,838	Li et al. (2007a)
<i>Scortum barcoo</i> (Jade perch)	Australia	2002	Nationwide	Unknown	–	Li et al. (2007a)
<i>Sparus aurata</i> (Gilthead seabream)	France	2001	Tianjin	Unknown	–	Wang et al. (2010d)
<i>Stizostedion vitreum</i> (Walleye)	North America	1993	Heilongjiang Prov.	Unknown	–	Li et al. (2007a)
<i>Tilapia</i> sp. (Red tilapia)	Africa	1973	Guangdong, Fujian & Guangxi Provs.	Unknown	–	Li et al. (2007a)
<i>Tilapia zillii</i> (Zill's tilapia)	Africa	1963	Guangdong Prov.	Unknown	–	Li et al. (2007a)
Pleuronectiformes – 4 species						
<i>Paralichthys dentatus</i> (Atlantic flounder)	Atlantic Ocean	2002	Shandong, Jiangsu & Fujian Provs.	Unknown	–	Li et al. (2007a)
<i>Paralichthys lethostigma</i> (Southern flounder)	USA	2002	More than 10 provs.	Unknown	–	Li et al. (2007a)
<i>Scophthalmus maximus</i> (Black sea turbot)	Europe	1992	Bohai Sea	Unknown	–	Li et al. (2007a)
<i>Solea senegalensis</i> (Senegalese sole)	Europe	2001	North China	Unknown	–	Liu et al. (2008)
Salmoniformes – 16 species						
<i>Coregonus autumnalis migratorius</i> (Lake Baikal omul)	Europe	1998	Xinjiang	Unknown	–	Guo (2005)
<i>Coregonus lavaretus maraenoides</i> (Eurasian whitefish)	North America & Russia	1985	Heilongjiang Prov.	Unknown	–	Li et al. (2007a)
<i>Coregonus muksum</i> (Muskum)	Europe	2003	Xinjiang	Unknown	–	Guo (2005)
<i>Coregonus nasus</i> (Broad whitefish)	Europe	1987	Heilongjiang	Unknown	–	Li et al. (2007a)
<i>Coregonus peled</i> (Whitefish)	North America & Russia	1985	North China	Unknown	–	Li et al. (2007a)
<i>Coregonus sardinella</i> (Sardine cisco)	Europe	2003	Xinjiang	Unknown	–	Guo (2005)
<i>Coregonus tugun</i> (Tugun)	Europe	2003	Xinjiang	Unknown	–	Guo (2005)
<i>Oncorhynchus gorbusha</i> (Pink salmon)	North Pacific Ocean	1987	Heilongjiang Prov.	Unknown	–	Li et al. (2007a)
<i>Oncorhynchus keta</i> (Calico salmon)	North Pacific Ocean	1988	Heilongjiang	Unknown	–	Li et al. (2007a)
<i>Oncorhynchus kisutch</i> (Coho salmon)	North Pacific Ocean	1982	Liaoning	Unknown	–	Li et al. (2007a)

Table 1 (Continued)

Species	Native range	Year of introduction	Distribution in China	Negative effects in local environment?	Production (ton) in China (2011)	Major reference
<i>Oncorhynchus mykiss</i> (Rainbow trout)	West coast of North America	1959	Nationwide	Unknown	–	Li et al. (2007a)
<i>Salmo gairdneri</i> (golden trout)	Japan	1996	Nationwide	Unknown	–	Li et al. (2007a)
<i>Salmo salar</i> (Atlantic salmon)	Northern Atlantic Ocean	2000	Heilongjiang, Beijing, Hebei & Shandong Provs.	Unknown	–	Li et al. (2007a)
<i>Salmo trutta fario</i> (Brown trout)	Europe	1976	Tibet	Unknown	–	Lou (2000)
<i>Salvelinus fontinalis</i> (Brook trout)	Canada & USA	2005	Shandong Prov.	Unknown	–	Li et al. (2007a)
<i>Salvelinus leucomaenis pluvius</i> (Rain-speckled trout)	Japan	1996	Mainly in Heilongjiang & Beijing	Unknown	–	Li et al. (2007a)
Siluriformes – 10 species						
<i>Catfish batrachus</i> (Walking catfish)	Southeast Asia	1978	Guangdong Prov.	Unknown	–	Li et al. (2007a)
<i>Catfish lazera</i> (North African catfish)	Africa	1981	Nationwide	Unknown	–	Li et al. (2007a)
<i>Catfish macrocephalus</i> (Broadhead catfish)	Southeast Asia	1982	South China	Unknown	–	Li et al. (2007a)
<i>Catfish furcatus</i> (Blue catfish)	North America	1989	Hubei Prov.	Unknown	–	Lou (2000)
<i>Catfish nebulosus</i> (Brown bullhead)	North America	1984	Nationwide	Unknown	–	Li et al. (2007a)
<i>Catfish punctatus</i> (Channel catfish)	North America	1983	Nationwide	Unknown	–	Li et al. (2007a)
<i>Pangasianodon gigas</i> (Mekong giant catfish)	Southeast Asia	1986	Yunnan Prov.	Unknown	–	Li et al. (2007a)
<i>Pangasius sp.</i> (Iridescent shark)	Southeast Asia	2000	South China	Unknown	–	Li et al. (2007a)
<i>Pangasius sutchi</i> (Sutchi catfish)	Southeast Asia	1978	Nationwide	Unknown	–	Li et al. (2007a)
<i>Silurus glanis</i> (Wels catfish)	Europe	1991	Hubei Prov.	Unknown	–	Li et al. (2007a)
Tetraodontiformes – 1 species						
<i>Fugu (Takafugu) rubripes</i> (Tiger pufferfish)	Japan & Korea	1996	Mainly in Shandong & Liaoning Provs.	Unknown	–	Hao et al. (2005)

^aInformation, such as year of introduction and current distribution of non-native species, may vary in different references, mainly due to unclear records, multiple introductions, and frequent transfers.

For data accuracy, major/key journal articles and books are used to collect such information for this table. This also applies to Tables 2 and 3.

^b*Procambarus clarkii*: introduced via ballast water, but significant aquaculture in China.

^c*Costaria costata*: fellow traveller with introductions of *Undaria pinnatifida* from Japan.

^d*Desmarestia ligulata*: fellow traveller with introductions of *Undaria pinnatifida* from Japan.

^e*Trichogloea lubrica*: fellow traveller with introductions of *Undaria pinnatifida* from Japan.

^f*Mytilus galloprovincialis*: introduction vector unknown, but significant aquaculture in China.

^g*Achatina fulica*: introduction vector unknown, but significant aquaculture in China.

^h*Pomacea canaliculata*: introduced likely via hull fouling, but significant aquaculture in China.

ⁱ*Pygocentrus nattereri*: introduced illegally, mainly kept as pet but aquacultured for food in some regions of China.

^jOsteoglossiformes: mainly introduced as pets but aquacultured for food as well in some regions of China.

Figure 5 Aquaculture production in the category of 'shrimp, prawn, crayfish and lobster' from 2003 to 2011 (line graph), and production proportion of each major species in each year (pie chart) in China. Data from China Fisheries Yearbook (2004–2012).

thys molitrix, bighead carp *Aristichthys nobilis*) were introduced into major lakes in Yunnan Province. The introduction and release scale are extremely large, for example, the total number of released individuals of these four carp species reaches more than four million per annum in Lake Dian (Chen *et al.* 1998).

Risks

Established species may spread widely and become invasive at new locations (i.e. biological invasions), sometimes after a lag phase of many years in which populations remained small and localized (O'Dowd *et al.* 2003; Jeschke & Strayer 2005). Among 179 species introduced internationally into China, 17 (9.5%) have had negative effects on local environments (Table 1 and references therein). These negative effects include ecosystem degradation (e.g. sea grass beds destroyed by the Japanese sea urchin *Strongylocentrotus intermedius*, Liu *et al.* 2007a), loss of biodiversity and even species extinction (e.g. devastating predation on native amphibians by the bull frog *Rana catesbeiana*, Li & Xie 2004), and faunal homogenization (e.g. the red-bellied piranha *Pygocentrus nattereri* become dominant in many water bodies by excluding/killing/eating almost all native species, Li *et al.* 2007a). Moreover, some invasive species are associated with economic impacts, including increased operating costs (e.g. fouling by the Pacific oyster *Crassostrea gigas*, Sun *et al.* 2010) and lost revenue (e.g. agriculture crops destroyed by the apple snail *Pomacea canaliculata*, Li *et al.* 2007a). Although other species

have not had detectable negative effects, risks may still remain due to a lag phase of biological invasions.

When compared with the international transfer of non-native species, domestic translocation may possess even higher risks, mainly owing to easy transfer, time- and cost saving, a large number of propagules involved, and importantly lack of restriction regulations. The introduction of fish from the Yangtze River drainage into major lakes in Yunnan Province plays one of the most important roles for the loss of biodiversity. Yunnan Province is a hotspot of biodiversity for freshwater fish in China, with more than 430 endemic species in this province (Chen *et al.* 1998). Lake Dian, which is the biggest lake in Yunnan Province, had 23 native species based on historical records, 11 of which are endemic to this lake. After the introduction of fish from the Yangtze River drainage, especially the four major Chinese carps, the number of native species decreases extremely fast: from 23 to 15 in 1978, to eight in 1982, to two in 1997, and only one in 2007–2008, and all endemic species become extinct (Chen *et al.* 1998; Yuan *et al.* 2010). By contrast, both the number of non-native species and population size sharply increase. For example, 93.8% of species is non-native in Lake Dian in the survey conducted in 2007–2008 (Fig. 6). This decrease in native species and increase in non-native species also happened in other major lakes in Yunnan province. For example, the production of fish in Lake Erhai increased from less than 2500 ton in 2001 to more than 5000 ton in 2009, and all major captured fish were non-native (Fei *et al.* 2011). All endemic species in 7 of 9 lakes surveyed are extinct, and the

Table 2 Aquaculture species transferred from native range to where they naturally do not occur within China due to aquaculture activities. Species only with clear and available records are listed. The native range, introduced range, history of biological invasions, and major reference for each species are shown

Species	Native range	Introduced range	History of biological invasions	Major reference
Algae – 2 species				
Red algae – 2 species				
<i>Porphyra haitanensis</i> (–)	South China	North China	No	Li <i>et al.</i> (1992)
<i>Gracilaria lemaneiformis</i> (–)	Bohai and Yellow Seas	South China	No	Peng <i>et al.</i> (2007)
Amphibia – 2 species				
<i>Andrias davidianus</i> (Chinese giant salamander)	Mainly in Yangtze and Pearl River drainages	Many provinces such as Shandong	No	Liu (2004)
<i>Rana chensinensis</i> (Chinese wood frog)	Northeast China, Qinling-Daba mountains	South China such as Zhejiang Prov.	No	Qian and Chen (2003)
Crustacea – 3 species				
Decapoda – 3 species				
<i>Eriocheir sinensis</i> (Chinese mitten crab)	North to Liaoning, South to Fujian, West to Hubei Prov.	Almost all provinces	Yes	Ren and Shao (2004)
<i>Macrobrachium nipponense</i> (Oriental river prawn)	Wide distribution from Shandong to Fujian Provs.	Northeast provinces such as Heilongjiang	No	Chen (1997)
<i>Scylla serrata</i> (Giant mud crab)	South China	North China	Yes	Liu <i>et al.</i> (1995)
Fish – 61 species				
Acipenseriformes – 1 species				
<i>Acipenser schrenckii</i> (Amur sturgeon)	Heilongjiang, Songhua River, Wusuli River	More than 8 provinces such as Shandong, Guangdong	No	Wang <i>et al.</i> (2009b)
Anguilliformes – 1 species				
<i>Anguilla japonica</i> (Japanese eel)	Coastal provinces, rivers in Sichuan Prov.	Lakes in Yungui Plateau	No	Xiong <i>et al.</i> (2008b) and Wang <i>et al.</i> (2009b)
Belontiiformes – 1 species				
<i>Hyporhamphus intermedius</i> (Asian pencil halfbeak)	Nationwide except Yungui Plateau	Lakes in Yungui Plateau	No	Xiong <i>et al.</i> (2008b) and Wang <i>et al.</i> (2009b)
Cypriniformes – 25 species				
<i>Abbottina rivularis</i> (Chinese false gudgeon)	Nationwide except some water bodies such as Tarim River	Tarim River, Lakes in Yunnan Prov.	No	Wang (1995) and He <i>et al.</i> (2010)
<i>Acheilognathus chankaensis</i> (Khanka spiny bitterling)	Unclear	Lake Erhai in Yunnan Prov.	No	He <i>et al.</i> (2010)
<i>Carassius auratus gibelio</i> (Silver crucian carp)	Heilongjiang-Liaohu drainage	Nationwide	Yes	Wang <i>et al.</i> (2009b)
<i>Carassius carassius carassius</i> (Irtys River carp)	Irtys River	Tarim River	No	Wang (1995)
<i>Chanodichthys erythropterus</i> (Skygazer)	Nationwide except Yungui Plateau	Lakes in Yungui Plateau	No	Wang <i>et al.</i> (2009b)
<i>Ctenopharyngodon idellus</i> (Grass carp)	Mainly in Yangtze and Peal Rivers	Lakes in west plateau provinces, e.g. Yunnan and Xinjiang Autonomous Region	Yes	Wang <i>et al.</i> (2009b)
<i>Culter erythropterus</i> (Redfin culter)	Major rivers in East China	Lake Fuxian	No	Xiong <i>et al.</i> (2008b)
<i>Cyprinus carpio</i> (Common carp)	Nationwide	Introduced into enclosed lakes in many provinces such as Yunnan	Yes	Wang <i>et al.</i> (2009b)

Table 2 (Continued)

Species	Native range	Introduced range	History of biological invasions	Major reference
<i>Erythroculter dabryi</i> (Lake skygazer)	Nationwide except Yungui Plateau	Lakes in Yungui Plateau	No	Xiong et al. (2008b) and Wang et al. (2009b)
<i>Gobio gobio cynocephalus</i> (—)	Unclear	Tarim River	No	Wang (1995)
<i>Hemibarbus maculatus</i> (Spotted steed)	Yangtze River drainage	Tarim River	No	Wang (1995)
<i>Hemiculter leucisculus</i> (Sharpbelly)	Nationwide except Yungui Plateau	Lakes in Yungui Plateau	No	Wang et al. (2009b) and He et al. (2010)
<i>Hypophthalmichthys molitrix</i> (Silver carp)	Southeast China	Yunnan Prov.	Yes	Wang et al. (2009b)
<i>Hypophthalmichthys nobilis</i> (Bighead carp)	Northeast and north China	Qinghai, Yunnan, Guizhou, Liaoning Provs.; Xizang, Inner Mongolia Autonomous Regions	Yes	Wang et al. (2009b)
<i>Leuciscus baicalensis</i> (Siberian dace)	Irtys River and Ulungur River	Tarim River	No	Wang et al. (2010c)
<i>Leuciscus idus</i> (Golden ide)	Irtys River	Lake Ulungur	No	Karjan et al. (2006)
<i>Megalobrama amblycephala</i> (Wuchang fish)	Yangtze River drainage	Nationwide	No	Wang (1995)
<i>Magalobrama Terminalis</i> (Black Amur bream)	Rivers in Northeast China	Tarim River	No	Wang (1995)
<i>Misgurnus anguillicaudatus</i> (Oriental weatherfish)	Nationwide except Tibetan Plateau	Tibetan Plateau and Xinjiang Autonomous Region	No	Wang et al. (2010c)
<i>Mylopharyngodon piceus</i> (Black carp)	Mainly in Yangtze and Peal Rivers	Lakes in west plateau provinces, e.g. Yunnan and Xinjiang Autonomous Region	Yes	Wang et al. (2009b)
<i>Paramisgurnus dabryanus</i> (Chinese loach)	East and Northeast China	Lake Fuxian	No	Xiong et al. (2008b)
<i>Rhodeus nobilis</i> (—)	East China	Lake Fuxian	No	Xiong et al. (2008b)
<i>Rhodeus sinensis</i> (Chinese bitterling)	Nationwide except Yungui Plateau	Lakes in Yungui Plateau	No	Wang et al. (2009b) and He et al. (2010)
<i>Rutilus rutilus lacustris</i> (Siberian roach)	Irtys River and Lake Bosten in Xinjiang Autonomous Region	Tarim River, Lake Ulungur	No	Wang (1995) and Karjan et al. (2006)
<i>Xenocypris microlepis</i> (—)	Nationwide except some water bodies such as Tarim River	Tarim River	No	Wang (1995)
Esociformes – 1 species				
<i>Esox lucius</i> (Northern pike)	Irtys River in Xinjiang Autonomous Region	Yellow River drainage, Lake Ulungur	No	Karjan et al. (2006) and Li et al. (2008)
Gadiformes – 1 species				
<i>Lota lota</i> (Burbot)	Heilongjiang River	Lake Ulungur	No	Karjan et al. (2006)
Osmeriformes – 9 species				
<i>Hemisalanx brachyrostralis</i> (—)	Middle and lower reaches of Yangtze River	Three Gorges Reservoir	No	Ba and Chen (2012)
<i>Hypomesus olidus</i> (Pond smelt)	Heilongjiang and Tumenjiang Rivers	Yellow River drainage, Lake Ulungur	Yes	Karjan et al. (2006) and Li et al. (2008)

Table 2 (Continued)

Species	Native range	Introduced range	History of biological invasions	Major reference
<i>Hypomesus transpacificus nipponensis</i> (Asian pond smelt)	Liaoning Prov.	North China including Shandong, Heilongjiang, Jilin Provs.	No	Zhao <i>et al.</i> (2003)
<i>Leucosoma chinensis</i> (White muscle icefish)	Water bodies along East China and South China Seas	Yangtze River	No	Ba and Chen (2012)
<i>Neosalanx taihuensis</i> (Noodlefish)	Mainly in Lake Tai	North to Inner Mongolia, South to Yunnan Prov, West to Sichuan Prov.	Yes	Wang <i>et al.</i> (2009b)
<i>Plecoglossus altivelis</i> (Ayu)	Water bodies along the coasts of Bohai, Yellow and East China Seas	Many coastal provinces such as Shandong	No	Liu <i>et al.</i> (2003)
<i>Protosalanx chinensis</i> (Chinese icefish)	Mainly in Lake Tai	North to Inner Mongolia, South to Yunnan Prov, West to Sichuan Prov.	Yes	Wang <i>et al.</i> (2009b)
<i>Protosalanx hyalocranius</i> (Clearhead icefish)	Mainly in water bodies from Shandong to Zhejiang Prov.	Yellow River drainage	No	Li <i>et al.</i> (2008)
<i>Salanx prognathus</i> (—)	Lakes Poyang and Tai	Three Gorges Reservoir	No	Ba and Chen (2012)
Perciformes – 11 species				
<i>Hephaestus fuliginosus</i> (Sooty grunter)	Lower reaches of the Yellow River and other main river drainages	Middle and upper reaches of the Yellow River	No	Li <i>et al.</i> (2008)
<i>Hypseleotris swinhonis</i> (—)	Nationwide except Yungui Plateau	Lakes in Yungui Plateau	No	Wang <i>et al.</i> (2009b) and He <i>et al.</i> (2010)
<i>Lucioperca lucioperca</i> (Pike-perch)	Irtys river in Xinjiang Autonomous Region	More than 5 provs including Shandong, Hubei, Jiangsu	No	Karjan <i>et al.</i> (2006) and Wang <i>et al.</i> (2009b)
<i>Macropodus ocellatus</i> (Roundtail paradise fish)	Typically provinces in north of Yangtze River	Tarim River, Lake Erhai	No	Wang (1995) and He <i>et al.</i> (2010)
<i>Odontobutis potamophila</i> (Dark sleeper)	Yangtze, Qiantangjiang and Minjiang drainages	Tarim river in Xinjiang Autonomous Region	No	Wang <i>et al.</i> (2010c)
<i>Perca fluviatilis</i> (Eurasian perch)	Irtys river in Xinjiang Autonomous Region	Lake Bosten in Xinjiang Autonomous Region	Yes	Wang <i>et al.</i> (2009b)
<i>Plectropomus leopardus</i> (Coral trout)	South China Sea	North China such as Tianjin and Shandong Prov.	No	Zhang <i>et al.</i> (2011)
<i>Pseudosciaena crocea</i> (Large yellow croaker)	Typically from South Yellow Sea to South China Sea	North China such as Shandong Prov.	No	Kong and Xiong (2002)
<i>Rachycentron canadus</i> (Black kingfish)				
<i>Rhinogobius cliffordpopei</i> (—)	Mainly in Yangtze River drainage	Lakes in Yungui Plateau	No	Wang <i>et al.</i> (2009b)
<i>Siniperca chuatsi</i> (Mandarin fish)	Water bodies with altitude lower than 300 m	Tarim River, Yellow River drainage	No	Wang (1995)
Pleuronectiformes – 4 species				
<i>Platichthys stellatus</i> (Starry flounder)	North China	South China including Zhejiang, Fujian Provs & Guangxi Autonomous Region	No	Zhuang <i>et al.</i> (2009)
<i>Kareius bicoloratus</i> (Stone flounder)	Bohai Sea & Yellow Sea	Fujian Prov.	No	Zheng (2009)
<i>Cynoglossus semilaevis</i> (Tongue sole)	Mainly in Bohai Sea & Yellow Sea	South China, e.g. Zhejiang, Fujian, Guangdong, Hainan Provs.	No	Tang <i>et al.</i> (2007)
<i>Paralichthys olivaceus</i> (Olive flounder)	Coast from Pear River to Yalu River estuaries	Guangxi Autonomous Region	No	Yang <i>et al.</i> (2007)

Table 2 (Continued)

Species	Native range	Introduced range	History of biological invasions	Major reference
Salmoniformes – 1 species <i>Hucho taimen</i> (Siberian salmon)	Heilongjiang River	Lake Ulungur	No	Karjan et al. (2006)
Siluriformes – 5 species <i>Clarias fuscus</i> (Chinese catfish) <i>Pelteobagrus fulvidraco</i> (Yellow catfish)	South China Nationwide except west Plateau area	Lakes in Yungui Plateau Yunnan Prov.	No No	Wang et al. (2009b) Xiong et al. (2008b) and Wang et al. (2009b)
<i>Silurus lanzhouensis</i> (Yellow River catfish) <i>Silurus meridionalis</i> (Southern catfish) <i>Silurus soldatovi</i> (Northern sheatfish)	Yellow River from Ningxia to Shandong Prov. Provinces in south of the Yangtze River North China, mainly in Songhuajiang, Heilongjiang, Nenjiang Rivers	Shanghai Yellow River drainage Lakes in Yungui Plateau	No No No	Bian et al. (2010) Li et al. (2008) Xiong et al. (2008b) and Wang et al. (2009b)
Tetraodontiformes – 1 species <i>Fugu rubripes</i> (Torafugu)	Bohai, Yellow and East China Seas	Coastal provinces such as Shandong	No	Liu et al. (2003)
Mollusca – 5 species Arcoidea – 1 species <i>Arca inflata</i> (Blood cockle) Haliotoidea – 2 species <i>Haliotis discus hannai</i> (Pacific abalone)	North Yellow Sea Bohai Sea and North Yellow Sea Taiwan Prov.	South China South China such as Fujian and Guangdong Provs. South China	No No No	Chen (2007) Lin (2010) Su (2006)
<i>Haliotis diversicolor aquatilis</i> (–) Pterioidea – 2 species <i>Pinctada martensii</i> (Pearl oyster) <i>Pinctada maxima</i> (Large pearl oyster)	South China Hainan Island & Xisha Archipelago	North China Guangdong Prov. and Guangxi Autonomous Region	No No	Wei et al. (1997) Shen and He (1990)

Table 3 Successful inter-specific hybridization with non-native species involved in China. Names of non-native species are bolded. 'Adult hybrids successfully obtained' is used as an indicator of 'successful hybridization'

Taxonomic group	Hybridization setup	Major reference
Echinoderms	<i>Strongylocentrotus intermedius</i> (♀) × <i>S. nudus</i> (♂)	Wang <i>et al.</i> (2003)
Molluscs	<i>Argopecten purpuratus</i> (♀) × <i>A. irradians</i> (♂)	Wang <i>et al.</i> (2009a)
	<i>Argopecten irradians</i> (♀) × <i>A. purpuratus</i> (♂)	Zhang <i>et al.</i> (2012a)
	<i>Haliotis discus hannai</i> (♀) × <i>H. gigantea</i> (♂)	Wang (2006)
	<i>Haliotis gigantea</i> (♀) × <i>H. discus</i> (♂)	Wang (2006)
	<i>Haliotis discus hannai</i> (♀) × <i>Haliotis discus discus</i> (♂)	Wan <i>et al.</i> (2001)
	<i>Haliotis discus discus</i> (♀) × <i>Haliotis discus hannai</i> (♂)	Wan <i>et al.</i> (2001)
	<i>Haliotis fulgens</i> (♀) × <i>Haliotis discus hannai</i> (♂)	Fan (2012)
	<i>Haliotis discus hannai</i> (♀) × <i>Haliotis fulgens</i> (♂)	Fan (2012)
	<i>Haliotis refescens</i> (♀) × <i>Haliotis discus hannai</i> (♂)	Wang and Fan (1999)
	<i>Haliotis discus hannai</i> (♀) × <i>Haliotis refescens</i> (♂)	Wang and Fan (1999)
	<i>Crassostrea gigas</i> (♀) × <i>C. ariakensis</i> (♂)	Zhang <i>et al.</i> (2012b)
	<i>Crassostrea ariakensis</i> (♀) × <i>C. gigas</i> (♂)	Zhang <i>et al.</i> (2012b)
	<i>Crassostrea sikamea</i> (♀) × <i>C. gigas</i> (♂)	Teng (2009)
	<i>Crassostrea gigas</i> (♀) × <i>C. sikamea</i> (♂)	Teng (2009)
Algae	<i>Laminaria longissima</i> (♀) × <i>L. japonica</i> (♂)	Li <i>et al.</i> (2007b)
	<i>Laminaria japonica</i> (♀) × <i>L. longissima</i> (♂)	Zhang <i>et al.</i> (2007)
Fish	<i>Acipenser schrencki</i> (♀) × <i>A. ruthozus</i> (♂)	Wang <i>et al.</i> (2010a)
	<i>Acipenser schrencki</i> (♀) × <i>Huso huso</i> (♂)	Ren <i>et al.</i> (2012)
	<i>Huso dauricus</i> (♀) × <i>Acipenser baeri</i> (♂)	Liu <i>et al.</i> (2007b)
	<i>Huso huso</i> (♀) × <i>Acipenser baeri</i> (♂)	Gao <i>et al.</i> (2006)
	<i>Acipenser schrencki</i> (♀) × <i>A. gueldenstaedti</i> (♂)	Sun <i>et al.</i> (2009)
	<i>Acipenser schrencki</i> (♀) × (<i>Huso huso</i> ♀ × <i>Acipenser ruthenus</i> ♂) (♂)	Sun <i>et al.</i> (2009)
	<i>Acipenser gueldenstaedti</i> (♀) × <i>Huso dauricus</i> (♂)	Hu <i>et al.</i> (2008)
	<i>Acipenser baeri</i> (♀) × <i>Huso dauricus</i> (♂)	Hu <i>et al.</i> (2008)
	<i>Acipenser ruthozus</i> (♀) × <i>Huso dauricus</i> (♂)	Hu <i>et al.</i> (2008)
	<i>Acipenser gueldenstaedti</i> (♀) × <i>A. baeri</i> (♂)	Hu <i>et al.</i> (2008)
	<i>Acipenser baeri</i> (♀) × <i>A. schrencki</i> (♂)	Wang <i>et al.</i> (2010b)
	<i>Acipenser ruthozus</i> (♀) × <i>A. schrencki</i> (♂)	Wang <i>et al.</i> (2010b)
	<i>Acipenser schrencki</i> (♀) × <i>A. baeri</i> (♂)	Wang <i>et al.</i> (2010b)
	<i>Huso huso</i> (♀) × <i>Acipenser ruthozus</i> (♂)	Yang (2006)
	<i>Oxyeleotris marmorata</i> (♀) × <i>O. lineolatus</i> (♂)	Fan <i>et al.</i> (2009)
	<i>Oxyeleotris lineolatus</i> (♀) × <i>O. marmorata</i> (♂)	Fan <i>et al.</i> (2009)
	<i>Oreochromis niloticus</i> (♀) × <i>O. aureus</i> (♂)	Yang <i>et al.</i> (2006)
	<i>Oreochromis mossambicus</i> (♀) × <i>O. hornorum</i> (♂)	Yang <i>et al.</i> (2006)
	<i>Oreochromis aureus</i> (♀) × <i>Siniperca chuatai</i> (♂)	Yu <i>et al.</i> (2003)
	<i>Oreochromis mossambicus</i> (♀) × <i>O. niloticus</i> (♂)	Liu <i>et al.</i> (1985)
	<i>Oreochromis aureus</i> (♀) × <i>O. niloticus</i> (♂)	Xia <i>et al.</i> (1999)
	<i>Oreochromis niloticus</i> (♀) × <i>Sarotherodon melanothron</i> (♂)	Yan <i>et al.</i> (2007)
	<i>Sarotherodon melanothron</i> (♀) × <i>Oreochromis niloticus</i> (♂)	Yan <i>et al.</i> (2007)
	<i>Lepomis cyanellus</i> (♀) × <i>Lepomis macrochirus</i> (♂)	Chen and Su (2006)
	<i>Perca flavescens</i> (♀) × <i>P. schrenki</i> (♂)	Ding <i>et al.</i> (2012)
	<i>Hephaestus fuliginosus</i> (♀) × <i>Scortum barcoo</i> (♂)	Lu and Wang (2010)
	<i>Paralichthys olivaceus</i> (♀) × <i>P. dentatus</i> (♂)	Guan <i>et al.</i> (2007)
	<i>Paralichthys lethostigma</i> (♀) × <i>P. dentatus</i> (♂)	Gong (2009)
	<i>Fugu flavidus</i> (♀) × <i>F. rubripes</i> (♂)	Fan <i>et al.</i> (2011)
	<i>Oncorhynchus mykiss</i> (♀) × <i>O. kisutch</i> (♂)	Xu <i>et al.</i> (2006)
	<i>Oncorhynchus mykiss</i> (♀) × <i>Oncorhynchus masou masou</i> (♂)	Zhang <i>et al.</i> (2009)
	<i>Cyprinus carpio</i> var. <i>specularis</i> (♀) × <i>Megalobrama amblycephala</i> (♂)	Jin <i>et al.</i> (2003)
	<i>Carassius auratus cuvieri</i> (♀) × <i>Cyprinus carpio</i> var. <i>specularis</i> (♂)	He <i>et al.</i> (1995)
	<i>Carassius auratus cuvieri</i> (♀) × <i>Cyprinus carpio</i> var. <i>singuanensis</i> (♂)	Chen (2000)
	<i>Carassius auratus auratus</i> (♀) × <i>C. auratus cuvieri</i> (♂)	Lou <i>et al.</i> (1995)
	<i>Cyprinus carpio</i> var. <i>wananensis</i> (♀) × <i>C. carpio</i> var. <i>specularis</i> (♂)	Chi <i>et al.</i> (2010)
	<i>Cyprinus carpio</i> var. <i>specularis</i> (♀) × <i>C. carpio</i> var. <i>wananensis</i> (♂)	Chi <i>et al.</i> (2010)
	<i>Cyprinus carpio</i> var. <i>mirror</i> (♀) × <i>C. carpio</i> var. <i>specularis</i> (♂)	Liu <i>et al.</i> (1993)

Table 3 (Continued)

Taxonomic group	Hybridization setup	Major reference
	<i>Cyprinus carpio haematopterus</i> (♀) × <i>C. carpio</i> var. <i>mirror</i> (♂)	Ge <i>et al.</i> (2012)
	<i>Cyprinus carpio</i> var. <i>mirror</i> (♀) × <i>C. carpio haematopterus</i> (♂)	Ge <i>et al.</i> (2012)
	<i>Cyprinus carpio</i> var. <i>singunensis</i> (♀) × <i>C. carpio</i> var. <i>mirror</i> (♂)	Dong <i>et al.</i> (1999)
	<i>Cyprinus carpio</i> var. <i>mirror</i> (♀) × <i>C. carpio</i> var. <i>singunensis</i> (♂)	Dong <i>et al.</i> (1999)
	<i>Clarias macrocephalus</i> (♀) × <i>C. fuscus</i> (♂)	Wu <i>et al.</i> (1990)
	<i>Clarias fuscus</i> (♀) × <i>C. lazera</i> (♂)	Wu <i>et al.</i> (1990)
	<i>Clarias lazera</i> (♀) × <i>C. fuscus</i> (♂)	Zhang (1989)
	<i>Clarias macrocephalus</i> (♀) × <i>C. lazera</i> (♂)	Wu <i>et al.</i> (1990)

Figure 6 Number of species in different categories, including native, non-native and local endemic, in nine major lakes in Yunnan Province based on both historical records and survey conducted in 2007–2008 (bar chart), and proportion of native and non-native species in each lake in the survey of 2007–2008 (pie chart). Arrows indicate that all endemic species have been extinct based on the data from 2007–2008 survey. All data from Yuan *et al.* (2010).

majority of fish species in these lakes are non-native (Fig. 6). Although many factors, such as overfishing, reclamation of land from lakes, dam construction, pollution, and others may contribute to such loss of biodiversity (Chen *et al.* 1998), the fact is that both the number and production of non-native species increase. All evidence suggests that the introduction of non-native species plays a role for such loss of biodiversity.

Management solutions

A clear policy on the introduction of non-native species is needed as aquaculture expands, especially in developing countries. The policy must be clearly made based on the principle that all species are considered potentially harmful and therefore forbidden for introduction unless risk of invasiveness is acceptably low. The ICES Code of Practice on the Introductions and Transfers of Marine Organisms recommends effective procedures and practices to diminish potential risks. The most up-to-date version of this Code, published in 2005, covers all concerns expressed in former versions and follows the precautionary approach adopted from the FAO principles with the goal of reducing the spread of exotic species (ICES 2005). The ICES Code has become a well-recognized instrument, and its essential

components have been widely applied to the evaluation of species introductions.

Based on ICES Code, essential components for a sound management programme include the following:

- 1 Using multiple discipline procedures and the state-of-the-art technologies for scientific risk assessment and strictly applying a well-evaluated programme to every species proposed for introduction; this is the first priority to stop introductions of harmful species into local environments. Risk assessment relies on scientific methodologies to support decision-making. Methodology successfully developed for the Weed Risk Assessment (WRA, Pheloung *et al.* 1999) provides a good model to follow-up for the risk assessment of the introduction non-native aquatic species. Indeed, models and tools focusing on different taxonomic groups, such as Freshwater Fish Invasiveness Scoring Kit (FISK) and Marine Invertebrate Invasiveness Scoring Kit (MI-ISK), have been successfully developed based on WRA, and all these tools are made freely available at Centre for Environment, Fisheries & Aquaculture Science (Cefas) website (<http://www.cefas.co.uk/projects/risks-and-impacts-of-non-native-species/decision-support-tools.aspx>). Such tools and models can be adopted, modified and evaluated under various circumstances, such as characteristics

of different species and different condition of water bodies.

- 2 Developing new cost-effective tools (such as those based on remote sensing and global positioning system technologies) to monitor introduced species in order to rapidly respond to newly emerged negative effects; this serves as a supplement of recommendation (1) to response to problems caused by those not blocked by the procedure of risk assessment. Indeed, remote-sensing and global-positioning system technologies have been successfully used for detecting and mapping of invasive species, including aquatic invasive species (e.g. Maheu-Giroux & de Blois 2005). These provide good successful examples to follow-up for other species, although technical questions remain to be solved for wide application.
- 3 Establishing a legal authority specifically to perform comprehensive risk assessment and to monitor introduced species, especially those having high probabilities to escape, or to be released and discarded into local water bodies. In addition, such a legal authority should be responsible for providing research-based strategic management advice, such as (i) scientifically assessing culture methods (e.g. open *versus* enclosed) based on biological characteristics of transferred species and environmental conditions of different water bodies (e.g. coastal region, inland lakes, etc.); (ii) establishing a species-specific parameter for the number of escapees, that is a threshold for the establishment of self-sustaining populations and/or prevention of genetic changes to natural local populations, and subsequently using this parameter to strictly monitor escapees and all release events; (iii) developing sterile strains of transferred species/populations using safe manipulations.

In addition, sound management on non-native species used for aquaculture requires international effort, coordination and collaboration, mainly because some countries have less strict or no regulations on the introduction and use of non-native species. Negative impacts occur in such countries might spread larger areas, finally affecting neighbouring countries. The hazardous Substances and New Organisms Act (1996) implemented in New Zealand provides a common model that other countries could follow. Under this act, importers of non-native species must apply to an independent regulatory authority accountable to the Environment Ministry and Parliament for public approval.

Fellow travellers, accidental introductions

Background

Fellow travellers, or hitchhiking species, refer to species that inadvertently accompany the shipment of the species intended for introduction/transfer. Many countries have a long history of importing species for aquaculture and live

aquatic products from regional, national and international sources (De Silva *et al.* 2009; Peeler *et al.* 2011; De Silva 2012). Fellow travellers, attaching to the surface or inside of the body (e.g. gut, lung and mussel) of these desired species, are introduced into local environments, where they may become invasive and cause huge economic and environmental damages. For example, the European green crab (*Carcinus maenas*), a voracious predator and aggressive colonizer, is believed to have been introduced to the U.S. west coast in packing materials (seaweeds) of live food fish from the east coast (Yamada & Gillespie 2008). This crab species has had a strong influence through predation and aggression on biodiversity in invaded ranges (Grosholz & Ruiz 1995; Jamieson *et al.* 1998).

Fellow travellers in China

Despite the fact that micro-organism may be the major group of fellow travellers, we could not make a list in this review, mainly due to difficulties to track origins and poor historical records worldwide. Besides pathogens, a total of three species have clear records as fellow travellers (Table 1), two of which belong to brown algae (*Costaria costata*, *Desmarestia ligulata*), and the remaining one is red algae (*Trichogloea lubrica*; Table 1). All these three species were unintentionally transferred into China along with the introduction of *Undaria pinnatifida* from Japan (see Table 1 and references therein). It should be noted that the number of fellow travellers can be much larger than what we have known so far, because many fellow travellers remain inconspicuous at subthreshold densities.

Risks

One of the known examples in China is *Desmarestia ligulata*, which has become a harmful species in northern China after the introduction along with an aquaculture species *Undaria pinnatifida*. The length of this species usually reaches 1 m in China, which is much longer than 30–50 cm in its native ranges (Liu *et al.* 2007a). This brown algae release sulphuric acid after death, which can highly increase acidity of sea water. It is well known that ocean acidification has significantly negative impacts on marine ecosystems (see review by Fabry *et al.* 2008). An outbreak of this species not only can influence local water bodies in China, but also might threaten neighbouring areas after acid is advected and spread by marine currents in 'open' oceans.

Management solutions

Fast and correct identification of fellow travellers before introduction represents the first and also most important

step for the prevention of introduction of undesired harmful species. For large fellow travellers, especially those attached on body surface, identification might not be difficult, because large organisms could be easily detected by eye inspection and then eliminated. However, for small organisms such as micro-organisms and those at particular life stages such as eggs and immature individuals, huge challenges remain for fast and correct identification, not only because it poses immense technical difficulties to identify numerous extremely small organisms, but also a large number of micro-organisms often are unidentified hazards (e.g. Whittington & Chong 2007; Peeler *et al.* 2011). Unfortunately, currently applied risk assessment usually does not account for unidentified hazards.

There is little doubt that so far routine quarantine inspection has been the major method for the prevention of introduction of fellow travellers. Besides routine quarantine inspections and exams, several more recommendations can reduce/eliminate risks caused by fellow travellers: (i) introduction of fertilized eggs, instead of adults, should be encouraged to reduce the number of potential fellow travellers; (ii) it is essential to develop high-throughput and effective inspection tools, especially genetic tools based on newly emerged technologies, such as gene probe, microarray, and highly sensitive tools such as 454 pyrosequencing to effectively detect small organisms and low-density populations (Zhan *et al.* 2013). Indeed, some of these DNA-based methods have been available, pending only the initiative and investment of time and money to tailor tools to specific tasks (See reviews by Darling & Blum 2007; Darling & Mahon 2011). In addition, it should be noted that the impending benefits of DNA/RNA-based methods are vast, and worthy of continued effort and investment (Darling & Blum 2007; Darling & Mahon 2011).

Artificial hybridization

Background

Intra- and inter-specific hybridizations are widely employed in breeding programmes to improve economic properties of aquaculture species, that is, to obtain hybrid vigour or positive heterosis such as growth rate, disease resistance, harvestability and environmental tolerance (Bartley *et al.* 2001; Hulata 2001). Hybridization possesses many obvious advantages including simplicity of operation, time-saving, and immediate and significant improvement on performance of desired traits (Hulata 2001). Successfully created hybrids constitute a significant proportion of aquaculture production in several countries, such as hybrid striped bass (*Morone chrysops* × *M. saxatilis*) in the USA (Carlberg *et al.* 2000), hybrid catfish (*Clarias gariepinus* × *C. macrocephalus*) in Thailand (De Silva *et al.* 2006), and

hybrid tilapia (*Oreochromis niloticus* × *O. aureus*) in Israel (Milstein *et al.* 2001). Owing to these advantages, a large proportion of introduced non-native species is subjected to hybridization practice (see reviews by Bartley *et al.* 2001; Hulata 2001; Lou & Li 2006).

Hybridization practice in China

Hybridization is one of the most common practices in various breeding programmes in China. For intra-specific hybridization, it is common that different geographical populations of a species are introduced into local places where this species naturally occurs. One of the well-known examples is the introduction of Japanese stocks of the Pacific abalone (*Haliotis discus hannai*) into northern China to resolve the high-mortality problem (>90%) caused by diseases in 1994 (Zhang *et al.* 2004). The hybrids between Chinese and Japanese stocks, which highly improved survival rate (approximately 100%) and growth rate (approximately 30%), saved the abalone industry in China (Guo 2009).

For inter-specific hybridization, large-scale trials have been conducted both between native species and non-native species, and between two non-native species (Table 2). So far, at least 43 (24%) non-native species introduced internationally have been successfully subjected for inter-specific hybridization, yielding at least 63 successful crosses in echinoderms (1 cross), mollusks (14 crosses), algae (2 crosses) and fish (46 crosses; Table 2). Among these successful crosses, one of the successful examples is hybridization between two non-native species of sea kelps, *Laminaria japonica* and *L. longissima*, which were introduced from Japan in 1990s. Based on these two non-native species, more than ten varieties have been created and proven as new varieties with improved economic traits by the National Appraisal Committee of Aquatic Protospecies and Improved Varieties. The Dongfang No.2 (*L. longissima* ♀ × *L. japonica* ♂) variety improved yield more than 25% when subjected to large-scale cultivation at different locations (Li *et al.* 2007b). Now, almost all farmed kelps in China are hybrids.

Risks

Risks caused by hybrids are mainly genetic pollution (e.g. loss of genetic variation, breakdown of population structure) and species extinction (Huxel 1999; Bartley *et al.* 2001; Hails & Morley 2005). The observed diversity and distributions of species are formed by millions of years of evolution. Geographical isolation prevents hybridization and introgression, and species or local populations have been well adapted to local environmental conditions. Aquaculture and related activities

bring species into contact with their relatives from which these species have been historically isolated, and then further seek possible ways to produce hybrids with positive heterosis. In the absence of hybridization, invaders might be quickly eliminated due to low population density (i.e. Allee or stochastic effects). However, in the presence of hybridization, especially human-mediated hybridization aiming to produce vigorous offspring, non-native genetic materials could rapidly introgress into native gene pools, leading to genetic pollution to local populations and/or replacement of local gene pools. Using mathematical simulations, Huxel (1999) found that displacement of native gene pools could occur very rapidly: less than five generations. Indeed, quick replacement of local gene pools caused by both intra- and inter-specific hybrids has been observed in aquaculture species in China. The Pacific abalone (*Haliotis discus hannai*) in northern China and carps (genus *Cyprinus*) in Yunnan province represent good examples for intra- and inter-specific hybrids, respectively. As mentioned previously, hybrids between Chinese and Japanese stocks of the Pacific abalone successfully saved abalone aquaculture industry in the late 1990s in China; however, after several generations farming, 84.1% of individuals collected from the wild in northern China was identified as hybrids based on molecular markers and corresponding analyses (Wang 2011). Similarly, almost all carps from Lake Xingyun in Yunnan province are inter-specific hybrids, as revealed by both morphological and genetic surveys (Yang *et al.* 2011). 'Pure' native species do not exist in the wild, that is, species extinction genetically, the worst consequence caused by aquaculture-mediated hybridization. This type of extinction, which is different from 'traditional extinction' (i.e. permanent disappearance of a species), is largely 'invisible' to the human eye and cannot be detected without detailed investigations based on molecular analyses, leading to difficulties to generate an understanding in the public. Owing to a high rate of human-mediated introductions and hybridizations, Huxel (1999) suggested that hybridization alone may become a major cause for species extinction.

Management solutions

Although empirical studies have shown that some aquaculture-mediated hybrids are threatening local environments and biodiversity, there is still a lack of comprehensive programmes/systems for risk assessment and sound management of farmed hybrids. Several recommendations should be considered before hybrids are practically adopted and widely farmed. (i) Risk assessment, especially probabilities to breed with parental species and relatives in local sur-

rounding environments, must be carried out, and the results are used to develop species-specific (e.g. based on unique biological, genetic, physiological characteristics of each hybrid and parental species) and case-specific (e.g. intra- or inter-specific hybridization) performance standards. Although genetically modified organisms (GMOs) are defined by the international community and national governments as organisms created by recombinant DNA technologies, indeed, inter-specific hybridization represents a genetic modification wherein genetic materials from different species are combined in a single species (see review by Bartley *et al.* 2001 and references therein). The debate on whether or not inter-specific hybrids are GMOs is beyond the scope of this review, but risks caused by inter-specific hybrids may be as high as GMOs (Bartley *et al.* 2001). Consequently, risk assessment programmes for GMOs (e.g. Hill 2005) should be also applied to inter-specific hybrids, even to intra-specific hybrids, to approve whether or not these hybrids are environmentally safe enough to be widely farmed in aquaculture. (ii) Proper management of hybridization depends on knowledge of basic background of crossing, such as biological and genetic characteristics of parental species and resulting offspring hybrids, mechanisms of positive heterosis, genotype $\times$ environment interactions, etc. Consequently, intensive research should be performed to clarify these fundamental questions. According to the information obtained from these two recommendations, optimized management measures including culture method, facility design and operation management of the whole grow-out procedure should be advised and strictly followed by aquaculture managers. (iii) An oversight authority should set up surveillance programmes to monitor hybrids and launch quick response programmes for newly emerged negative effects.

Mass release of non-native species for ranching

Background

Mass release for ranching is a form of extensive aquaculture. Ranching refers to the release of cultured juveniles into unenclosed environments for harvest at a larger size in 'put, grow and take' operations (Bell *et al.* 2008). Now large-scale mass release of non-native for ranching has been performed for many aquaculture species in many countries (Shelton & Rothbard 2006). For example, approximately one-third of the capture harvest in the Caspian Sea was derived from stocked fish (Shelton & Rothbard 2006). Such aquaculture also supports important industries. For example, the caviar industry in the Black and Caspian Seas was maintained for decades by ranching transplanted sturgeon (McNeil 1979). Although mass release for ranching has been proven to have immediate improvement on

aquaculture production, adverse effects on local environments and native biodiversity are largely neglected in research and policy (Laikre *et al.* 2010).

Mass release of non-native species for ranching in China

Since the 1980s, large-scale release is intentionally performed in almost all major marine and freshwater water bodies in China (Li 2011; Tao & Wang 2011). The number of both species and released individuals increased rapidly in the past decade. Nationwide, the total number of released individuals increased from 8.9 billion in 2005 to 19.46 billion in 2007, while the value increased from 1.29 to 2.64 billion Chinese Yuan (Li 2011). Based on the National General Plan of Mass Release and Stock Enhancement for Aquatic Organisms (2011–2015), more than 34 billion individuals derived from 167 species are planned to be released into 356 water bodies in 2015. Species used for mass release for ranching in China are of three categories: (i) highly valued aquaculture species, including both native and non-native, of which native ones are the most commonly used in China; (ii) rare and endangered species; (iii) local-endemic species. Despite that the number of species and release scale for non-native species are not as large as those for native species, non-native species, which cover all major aquaculture species categories, have been successfully released for ranching, for example, mollusks such as the Japanese scallop *Patinopecten yessoensis*, echinoderms such as Japanese sea urchin *Strongylocentrotus intermedius*, fish such as turbot *Psetta maxima*, and crustaceans such as black tiger prawn *Penaeus monodon* and white-leg shrimp *Penaeus vannamei*.

Risks

High debate on the merits of large-scale release for ranching increases as the interest of such performance grows in aquaculture (see review by Mustafa 2003). Mass release poses the highest risk for the establishment of populations, mainly owing to a large number of individuals involved and direct release into suitable habitats. Sometimes establishment of populations in the wild may be beneficial to aquaculture; however, once non-native species become established, it is very difficult to control them (see review by Tyus & Saunders 2000). Established non-native species may become harmful after successfully localized. One representative example in China is the Japanese sea urchin *Strongylocentrotus intermedius* (Liu *et al.* 2007a). The established sea urchin populations have threatened local environments and biodiversity, such as destroying seaweed bed and aquaculture facilities, and competing with native species for food and space (Liu *et al.* 2007a).

Management solutions

Although mass release of aquaculture species in many countries is partially organized and/or supervised by local or central/federal governments, unfortunately scientific assessment was seldom employed to direct such large-scale releases. Assessment of risk-benefit trade-offs prior to mass release has proven to be most effective way for decision-making (Waples & Drake 2004; Barbour *et al.* 2008). Studies have indicated that taxa-specific risk-benefit assessment protocols are needed (Waples & Drake 2004; Barbour *et al.* 2008). To make effective taxa-specific assessment protocol, research gaps should be filled for species proposed to release, such as what is the observed and expected genetic structure of local populations before and after mass release respectively, how are individuals chosen to minimize genetic change to local populations, and what are biological and environmental consequences after release and how are these consequences properly assessed. All obtained information, including that derived from recommendations for risk assessment and management for each category of species, risk-benefit assessment and research results should be systemically combined and implemented into monitoring programmes. Finally, monitoring programmes need to be linked with management policy to point out outcomes from both mass release and associated monitoring, and management solutions/actions for each outcome.

Conclusions

Our dependence on non-native species for aquaculture likely becomes greater in the future as it supports increasing demands in aquatic food markets. It is therefore expected that the introduction and/or use of non-native species is more frequent and a common practice in aquaculture. For a practical and realistic perspective, sound management, coupled with good knowledge of possible risks and well prepared solutions for such negative effects, is the way for sustainable development of aquaculture. However, the aquaculture industry must now face the fact that accelerating introduction and/or use of non-native species for aquaculture remain unthoroughly unregulated, especially in developing countries, leading to high risks to ecosystems, economies, and even public health of inhabitants. Recent research adds increasing evidence on negative effects, threats and risks, which has fed back to affect sustainable development of aquaculture. In this review, we discuss observed and potential risks associated with unregulated introduction and irresponsible use of non-native species and recommend solutions for management based on high-risk aquaculture activities and related events employed in the past several decades.

The lack of risk assessment and sound management for non-native species is particularly true for the sustainable development of aquaculture, although risks and negative effects have been recognized and repeatedly stressed in literature in the past decades. Lessons from known disasters caused by non-native species are slowly learned compared with outbreak scale and spread speed of disasters. Numerous reasons are responsible for such slow pace, and the most important one is that short-term benefit is concentrated and long-term development is highly neglected. In addition, the aquaculture industry is the beneficiary of introductions of non-native species, but aquaculture industry is not made to pay the costs of environment damage once non-native species become invasive.

We stress that there is an extremely urgent need to consider risk assessment and sound management for the introduction and use of non-native species as aquaculture fast expands. Without proper management, negative effects can go extremely high degrees and large geographic scales, and in return, will certainly affect the sustainable development of aquaculture, and even lead to severe disasters to aquaculture. Meanwhile, we also suggest that policies should be put in place to make aquaculture industry pay for environmental damage. Finally, we call for effort and collaboration of researchers from academia, government and industry for responsible introduction and use of non-native species.

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