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Risk and benefit assessment of alien fish species of the aquaculture and aquarium trade into India

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Abstract

There has been an increasing demand for alien fish species in India. However, environmental, socioeconomic and biodiversity issues are important considerations when regulating the unauthorized culture and spread of alien species. Information collected in the present review revealed the presence of over 300 alien species imported intentionally or illegally; 291 ornamental species, 31 aquaculture species and two larvicidal fishes. Field data demonstrated the widespread occurrence of some of the world's worst invasive species, for example, *Cyprinus carpio, Oreochromis niloticus, Aristichthys nobilis, Pygocentrus nattereri* and *Pterygoplichthys* spp., in inland waters; other species are emerging as a threat to aquatic biodiversity. The benefits and risks of alien species were analysed and the impact was quantified using a simple developed 'Fish Invasiveness Screening Test' (FIST). Our information suggests that alien species, despite possessing some attractive culture characteristics, generally reduce the availability of local species and establish in natural water bodies becoming invasive and consequently adversely affecting fish biodiversity and aquatic ecosystems. In light of the adverse ecological impacts of alien species, we developed strategic regulations and quarantine procedures and advised aquaculturists to strictly follow them to contain potential and plausible menaces.

Key words: alien species, culture, impact assessment, invasiveness, risks, unauthorized culture.

Introduction

India is endowed with a rich aquatic biodiversity of over 2319 finfish species, which includes 838 freshwater, 113 brackish water and 1368 marine fishes (Kapoor *et al.* 2002; Lakra *et al.* 2009). As these captive fishery resources are stagnating or declining, advancement in the aquaculture sector has been taking place to provide nutritional security. Thus, aquaculture is becoming increasingly important in developing countries, particularly as it can provide an affordable source of food and a nutritional diet to rural poor (Delgado *et al.* 2003). To augment fish production, a number of alien fishes have been introduced for aquaculture purposes throughout the world (De Silva *et al.* 2006, 2009) and such occurrences are common even today (Naylor *et al.* 2001; Lakra *et al.* 2008; Turchini & De Silva 2008). The mean yearly cultured alien freshwater finfish production from 2000 to 2004 amounted to 3.6 million tonnes or 16% of the global aquaculture production (De Silva *et al.* 2009). Over the past decade, alien finfish species have accounted for over 12.2% of total cultured finfish production and the proportion is as much as 35% when China is excluded (De Silva *et al.* 2006, 2009).

Alien fish species are non-native or exotic fishes that occur outside their natural ranges and have dispersal potential. Alien fish species have been brought into India intentionally or otherwise for the purposes of aquaculture, aquarium trade, therapeutic value, research and biological control (Singh & Lakra 2006; Lakra *et al.* 2008). In addition, to alien aquaculture species, over one billion ornamental fish comprising more than 4000 freshwater and 1400 marine species are also traded internationally each year, making it one of the most important components of the global fish trade (Whittington & Chong 2007; European Commission 2008). In India, hundreds of alien ornamental species form part of the aquarium trade (Lakra *et al.* 2008). The role of alien species in aquaculture and the ornamental trade has not yet been properly addressed in India.

Inland aquatic biodiversity offers several potential cultivable species for aquaculture development and also for aquarium purposes (Ghosh *et al.* 2003; Lakra *et al.* 2009). There have been incessant efforts to diversify aquaculture through alien fish species in India in recent years; total fish production has grown nearly 12-fold in the past five decades and stands at 6.9 million tonnes, of which 3.2 million tonnes is from the inland sector (Katiha *et al.* 2005). Over the past two decades, many alien fish species have been clandestinely brought into India by private aquaculturists, entrepreneurs and aqua-industrialists for immediate gains. Such unauthorized activities are causing indiscriminate spreading of alien species, with potentially adverse ecological consequences (Singh & Lakra 2006; Lakra *et al.* 2008). The use of aquatic alien species in aquaculture and in the ornamental fish trade is of increasing occurrence because of the social and economic importance of the fishery and aquaculture (Ross *et al.* 2008; De Silva *et al.* 2009). The unregulated transboundary movement of aquatic alien species into India in recent times has invited serious attention from scientists and policy makers (Singh & Lakra 2006; Lakra *et al.* 2008). In this review, we have endeavoured to collect scientific information on alien species in India and to assess the pros and cons of such introductions. At present, the status of alien fishes involved in aquaculture and in the aquarium trade in India is not available. Whatever information on alien fish species exists, in India, it is scattered and available only in the form of so-called 'grey' sources (i.e. reports, popular science magazines and newspapers). We have attempted to generate and synthesize information in order to update the status of alien fish species. Effort has also been made to document the historical perspective of the unauthorised culture of alien fish species under aquaculture and the aquarium trade and to examine the spread of such alien species in different aquatic environments throughout India. This paper is a review of the outcomes of our efforts over the past 10 years to generate field data on alien fish species in India and to assess their potential impacts, in terms of both benefits and risks. This information will provide a scientific basis for evaluations of the entry of a particular alien species into the country, restricting the spread of potentially invasive species and building up regulatory mechanisms to deal with safe aquaculture activities.

Historical perspective

We collected information on more than 300 alien fish species; 291 ornamental fishes, 31 aquaculture species and two species of larvicidal fish used for malaria control. The collected and generated information on the historical perspective of deliberate or illegal introductions are presented in Table 1.

Food fishes

The historical information on alien fish species and the purpose as well as the places where they were originally introduced to were generated from secondary sources and also through field studies and interaction with aquaculturists, scientists and state fishery officials. The information compiled on the historical perspective of alien species in India is summarized and presented in Table 1. Trout was the first alien fish introduced back in 1863 by the British for angling purposes. Rainbow trout, *Oncorhynchus mykiss* (Waulbaum 1792), and brown trout, *Salmo trutta fario* (Linnaeus 1758), were two important aquaculture species in upland waters, although other alien species of trout were brought into the country. Atlantic salmon, *S. salar* (Linnaeus 1758), was available in the trout hatcheries of Kashmir in 1960, but failed to establish. In the cold Himalayan region, brown trout is now so well established in Jammu and Kashmir State that the State is credited with some of the best trout streams in Asia. Some streams in Himachal Pradesh are known for rainbow trout (*O. mykiss*) and several kilometres of the tributaries of the Beas River are frequented by anglers and support a lucrative recreational fishery. More recently, these species have been re-established in the states of Uttarakhand, Arunachal Pradesh and in the Nilgiris in Tamil Nadu. Over the past decade, the development of infrastructure (hatcheries and farms) and human capacity coupled with the establishment of feed mills has given a new thrust to the commercial production of trout (Vass & Raina 2002). Recently brook trout, *Salvelinus fontinalis* (Mitchill 1814), has also been adopted for aquaculture in the Himachal Pradesh and Jammu and Kashmir states.

Tilapia, *Oreochromis mossambicus* (Peters), was first introduced into pond ecosystems in 1952 and thereafter stocked in several reservoirs of south India for production enhancement (Sugunan 1995). *Oreochromis mossambicus* is abundantly found in almost all reservoirs of Tamil Nadu, Kerala, Andhra Pradesh and in some reservoirs in Karnataka (Sugunan 1995; Lakra *et al.* 2008). This species is now found in almost every environment from Punjab to Assam and in the north-east through the Indo–Gangetic plains to down south. In India, four species of tilapia, *O. mossambicus*, *Oreochromis niloticus*, *Oreochromis urolepis* and *Tilapia zilli* are available. The first two species *O. mossambicus* and *O. niloticus* are predominantly available in the country.

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Table 1 Historical perspectives and status of alien fish species (reason for introduction, year and source and from where) in Indian aquaculture

Species (common name)	Reason	Year/source	From	Present status
Salmo trutta fario L. (Brown trout)	For planting in reservoirs and lakes	1863, England; 1908, Japan	Nilgiris (Tamil Nadu (TN)), Harwan in Kashmir (J&K), Kerala	Cultivated and bred in most of the hill states. Naturalized population exists in upland rivers, streams and lakes
Salmo levensis Pickens (Leven trout)	-do-†	1863, England	Nilgiris (TN)	Limited occurrence mostly in TN and J&K
Onchorhynchus mykiss Walbaum (Rainbow trout)	-do-	1909, Sri Lanka, Germany, New Zealand	-do-	Widely cultivated and bred in most of the hill states. Some are found in the wild
Salmo gairdneri irideus Ranae (Steelhead trout)	-do-	1867, Europe; 1940, England and Sri Lanka	Nilgiris (TN), Kashmir, Kerala	Limited occurrence
Salmo gairdneri shasta Ranae (Steelhead trout)	-do-	1941, England	Kerala	Limited occurrence
Salvelinus fontinalis Mitchill 1814 (Brook trout)	-do-	1959, 2007, Canada	-do-	Aquaculture of this species is now practiced in Himachal Pradesh
Salvelinus namaykush Walbaum 1972 (Splake trout)	For planting in reservoirs and lakes	1968, Japan	Nilgiris (TN)	Limited occurrence
Onchorhynchus nerka Walbaum (Sockeye salmon)	-do-	1968, 1970, Canada	-do-	Limited occurrence
Salmo salar Linnaeus (Atlantic salmon)	-do-	1968, North America	Kashmir	Limited occurrence
Carassius carassius L. (Golden carp/crusian carp)	Game fishery	1974, England	Nilgiri waters (TN)	Present at most freshwater farms. Some are also available in natural waters
Carassius auratus L. (Gold carp)	-do-	1974, England	Ooty lake and Nilgiri waters (TN)	-do-
Tinca tinca L. (Tench)	-do-	1870, England	-do-	Present in the states of TN, Kanataka, HP, J&K and Uttarakhand
Osphronemus gourami Lacepede (Gourami)	-do-	1856, Java	Kolkata, West Bengal (WB)	Present at most freshwater farms. Some are available in natural waters
Puntius gonionotus Bleeker 1850 (Tawes)	-do-	1972, Indonesia	West Bengal and Orissa	Cultured mostly in WB, Orissa and Andaman and Nicobar and are available in natural waters
Oreochromis mossambicus Peters (Mozambique tilapia)	-do-	1952, Sri Lanka; 1962, Sri Lanka	West Bengal, (Mandapam, TN) (Jaisamund Lake) Rajasthan	Natural population of the cultured species exists in rivers and reservoirs
Oreochromis urolepis urolepis Norman, 1922 (wami tilapia)	Aquaculture	Not known	Coastal waters of Andaman and Nicobar	Under aquaculture in Andaman and Nicobar

Table 1 (*Continued*)

Species (common name)	Reason	Year/source	From	Present status
Cyprinus carpio communis L. (common carp)	Aquaculture	1939, Sri Lanka; 1957, Bangkok	Cuttack	Widely cultivated. It is available in rivers, lakes and reservoirs
Cyprinus carpio specularis Lacepede (Mirror carp)	-do-	1939, Sri Lanka; 1957, Bangkok	Nilgiris, TN	Under aquaculture in hill states and are available in natural waters
Cyprinus carpio Bloch (Leather carp)	-do-	1939, Sri Lanka; 1957, Bangkok	Cuttack, Orissa	Under aquaculture in hill states and are available in natural waters
Ctenopharyngodon idella Val. (Grass carp)	-do-	1959, Japan, Hong Kong	Cuttack, Orissa	Widely cultured and are available in natural waters
Hypophthalmichthys molitrix Val. (Silver carp)	-do-	1959, Japan, Hong Kong	-do-	Widely cultured and some are available in natural waters

†'-do-' as mentioned in above column.

Three varieties of the Prussian (German) strain of common carp, namely the scale carp (*Cyprinus carpio* communis), the mirror carp (*C. carpio* specularis) and the leather carp (*C. carpio* nudus) were introduced from Ceylon (Sri Lanka) in 1939. Several high altitude ponds and lakes were stocked with these species in the 1950s. Later, in 1957, a Bangkok strain of the common carp and the Chinese silver carp, *Hypophthalmichthys molitrix* (Val.), were brought into the country with the objectives of broadening the species spectrum in aquaculture and increasing yields through better utilisation of vacant trophic niches. Of the alien carps, the common carp (*C. carpio* var communis) is now widely cultured all over the country in ponds and is deliberately stocked in lakes and reservoirs to enhance productivity. Fish are now found in several rivers including the Yamuna and the Ganga (Singh *et al.* 2010a,b).

Both silver carp (*H. molitrix*) and grass carp (*Ctenopharyngodon idella*) were introduced in 1959 for a specific purpose and have led to the development of a high yielding technology, 'Composite Fish Culture', after several years of experimentation. The grass carp (*C. idella*) was introduced in 1959, mainly to control weeds in natural water bodies. It is an important species used in 'composite fish culture' and is widely cultured throughout India, including in the hill states. Silver barb, *Puntius gonionotus* (Bleeker), alternatively known as *Barbonymus gonionotus* is an important species in many south-east Asian countries (Alam *et al.* 2004). This species was introduced into India in 1972 from Indonesia with a view to control aquatic weeds (Das *et al.* 1994). It is mainly cultivated in the West Bengal, Orissa, and Andaman and Nicobar states.

Ornamental fishes

The ornamental fish trade in India is dominated by alien fish varieties, such as goldfish, angel, guppy, swordtail, oscar, platy, gourami, arowana, piranha, pacu, koi carp and sucker mouth catfish; these varieties were introduced from different parts of the world, but mainly from Asia. Most of these species are freshwater species, although marine aquarium fishes have become popular in recent years. However, there are no records or information available documenting the timing and/or source of these imported species. The information collected revealed that more than 200 alien aquarium fish species are now bred in different parts of the country (Ghosh *et al.* 2003; Lakra *et al.* 2008), mostly in indoor small cement cisterns or earthen ponds and tanks for supply to the domestic markets or even for export purposes. The most commonly cultivated aquarium species are goldfish (*Carassius auratus* and *C. carassius*), gourami (*Trichogaster* spp.), koi carp (*Cyprinus carpio*), sutchi catfish (*Pangasianodon hypophthalmus*), red-bellied pacu (*Piaractus brachypomus*), Piranha (*Pygocentrus nattereri*), sucker mouth catfish (*Pterygoplichthys* spp.), guppy (*Poecilia reticulata*) and Oscar (*Astronotus ocellatus*). These species are flooding in markets and pet shops.

Larvicidal fishes

The most commonly occurring larvicidal fishes in India are *Poecilia reticulata* (Peters) and *Gambusia affinis* (Baird & Girard). These species were introduced in 1908 and 1928, respectively, to contain mosquito larvae in confined waters. However, the insecticidal value of these species is not well established. These species now occur in several natural aquatic environments in India.

Unauthorized or illegal fish introductions

Our neighbours, Bangladesh and Nepal, culture a number of alien species (Barua *et al.* 2001; Gurung 2005). Many alien species, such as *Clarias gariepinus, Pangasianodon hypophthalmus, Aistichthys nobilis, Oreochromis niloticus* and *Piaractus brachypomus*, have been surreptitiously smuggled into India and are being cultivated (Table 2). These unauthorized introductions have achieved popularity in aquaculture and in the aquarium trade. Some of these alien fish species were widely distributed across several states/union territories, for example, African catfish (*C. gariepinus*), bighead (*A. nobilis*) and Nile tilapia

Table 2 Illegal and unauthorised culture of alien fish species (reasons for introduction, year and source, and place of original introduction) in India

Species (common name)	Reason	Year/source	Place	Present status	Remarks
Oreochromis niloticus L. (Nile tilapia)	Aquaculture	Possibly 1987 from Thailand and Israel	Tamil Nadu, West Bengal, Rajasthan	Commercial culture production in Andhra Pradesh. Natural population exists in rivers and reservoirs	Government considered its regulated culture owing to increased demand. Adverse impact perceived
Tilapia zilli Gervais, 1848 (Red belly tilapia)	Aquatic weed control in irrigation systems	1986 Thailand	Indira Gandhi Canal, Rajasthan	Present in freshwater farms in addition to the Indira Gandhi Canal in Rajasthan	Impact not perceived, but introduction was unnecessary
Aristichthys nobils Richard. (Bighead)	Aquaculture	1980 Possibly Bangladesh and Nepal	West Bengal	Widely cultivated and some are present in natural waters	A banned species in aquaculture. Significant adverse impact perceived
Ictalurus punctatus Rafinesque, 1818 (Channel catfish)	-do-†	1990	Thanjavur (TN) West Bengal	Limited occurrence	Unauthorized trials were not successful
Clarias gariepinus Burch. 1822 (African catfish)	-do-	Possibly 1994	West Bengal	Widely cultured and some are present in natural waters	A banned species in aquaculture. Significant adverse impact perceived
Pangasianodon hypophthalmus Sauvage (Sutchi catfish)	Aquaculture and aquarium purpose	Possibly 1997	West Bengal	Cultured mostly in coastal states. Some are present in natural waters	Some adverse ecological impact perceived. However, government considered its regulated culture
Mylopharyngodon piceus Richardson (Black carp)	Aquaculture and mollusk control	Possibly 2005 from Bangladesh	24°N Parganas of West Bengal	Present mainly in West Bengal and have now spread throughout north India	Limited culture and impact not perceived
Myliopharyngodon idella Richardson (Mud carp)	Aquaculture	Possibly 2005 from Bangladesh	24°N Parganas of West Bengal	Limited occurrence	Limited culture and impact not perceived
Piaractus brachypomus Cuvier 1818 (Pacu)	Aquaculture and aquarium purpose	Possibly in 2004 from Bangladesh	West Bengal	Large-scale breeding in West Bengal and distributed in AP, Kerala, north-eastern region.	Used for both the aquaculture and aquarium trade
Litopaeneus vannamai Boone 1931 (White leg shrimp)	Aquaculture	2001 Probably from Thailand	Andhra Pradesh, Tamil Nadu	Under aquaculture mostly in Andhra Pradesh	Government has now considered its culture under bio-security

†'-do-' as mentioned in above column.

(*O. niloticus*), whereas others were localized in specific regions (e.g. sutchi catfish and red-bellied pacu). Bighead carp, a popular aquaculture species in India, was possibly introduced in 1987 from Bangladesh. It spread quickly and presently this alien species exists in most areas of freshwater aquaculture. Among the catfishes, the African catfish (*C. gariepinus*) was clandestinely introduced into the state of West Bengal possibly during 1994 and quickly spread throughout the country, including into cold regions as well as coastal areas. It is largely cultured in the states of West Bengal and Andhra Pradesh. However, seed production is mainly practiced in the state of West Bengal. Although its culture is unauthorized, these fishes have become popular among aquaculturists in the country. Hybrid catfish (*C. gariepinus* × *C. macrocephalus)* are a fast growing variety and hybrid seed is being produced in hatcheries in Bangladesh (Baruah *et al.* 1999; Khan *et al.* 2000) and then smuggled into the bordering north-eastern States, Assam and West Bengal and as far as Bihar, forming the basis of a flourishing trade in India. Hybrid catfish are more popular in Punjab and Haryana, owing to their fast growth. Hybrid catfish are very inexpensive to feed because recycled chicken and slaughterhouse wastes are generally used. Another catfish, *P. hypophthalmus*, has also become popular in aquaculture, particularly in West Bengal and Andhra Pradesh. This species has also been found in other coastal states including Kerala and is used both for aquaculture and aquarium keeping; thus, it has spread throughout the country. In India, there was also a trial by Hindustan Lever to culture the American channel catfish *Ictalurus punctatus* (Molur & Walker 1998). This company imported seed directly from the USA and began culturing. However, the trial failed to produce the desired results. Red tilapia (*O. niloticus*) was first introduced into West Bengal and became a popular species in sewage-fed fisheries. Later, Vorion Chemicals brought the species to Chennai and cultured it using distillery wastes and claimed high production of over 50 tonnes ha^{-1} (Singh & Lakra 2006). However, the project collapsed. Now some aquaculturists are demanding the importation of *O. niloticus* for culture purposes and the Indian Government has permitted importation by a couple of entrepreneurs in Andhra Pradesh. The introduction of *Tilapia zilli* was for weed control in the Indira Gandhi Canal in Rajasthan. This introduction was unnecessary as many locally available weed-controlling species, such as *Puntius pulchellus* or even grass carp, were present in the country. An alien shrimp species, *Litopenaeus vennamei* (Boon 1931), has also recently been incorporated into brackish-water aquaculture, possibly in 2001 (Lakra *et al.* 2008). Many farmers started culturing this alien shrimp species, particularly in Andhra Pradesh and Tamil Nadu. Farmers are of the opinion that this shrimp species has huge potential for culture because of great demand in international markets. The Indian Government has allowed a small number of farmers to culture this shrimp species using specific pathogen free (SPF) stock. Culture and breeding of red-bellied pacu (*P. brachypomus*) was clandestinely started in the state of West Bengal in 2001 and has become popular (Lakra *et al.* 2008; Chatterjee & Mazumdar 2009), particularly in the states of Andhra Pradesh, Kerala, Maharashtra and Orissa, and in some areas of the north.

Risk assessment

Risk assessment of alien fish is one of the core elements for protecting fish biodiversity and food safety today. The benefits and risks of alien fish species in India have been assessed for ecological functions, within which they are embedded. A science-based simple risk assessment protocol named here as the 'Invasiveness Screening Test' (FIST), which includes screening of potential biological features such as growth, culture level, history of establishment, breeding in the wild, phenotypic plasticity (tolerance to a range of salinities and temperatures), ability to live off a wide range of food types, competition with local species, diseases, dispersal ability (propagule pressure) (Table 3) and other characteristics attributable to invasiveness (Kolar & Lodge 2001; Kolar & Lodge 2002; Ricciardi & Kipp 2008), was used in the present evaluation. The cumulative value percentage (CV %) for each screening criteria was statistically analysed using Statistix Version 8.1 software (Informer Technologies Inc) and a ranking for each criteria was determined based on the CV %. The frequency distribution percentage value (FD %; +++) of screened criteria for each species was calculated. The risk level for the assessed species was classified on the basis of the value calculated for FD %. Species with FD% values of +++ for overall screened criteria (i.e. above 50%) were classified as high-risk species, species between 30 and 50% were classified as medium-risk species, and species below 30% were classified as low-risk species (Table 3). The potential biological characters of the alien species that were attributable to invasiveness were assessed through an analysis of dietary intake and environmental tolerance and also from the history of establishment success (Kolar & Lodge 2001; Kolar & Lodge 2002). A lack of data is generally a constraint in risk assessment. Therefore, we also consulted the Database of Introduced Aquatic Species (DIAS) (http://www.fao.org/figis/servlet/static?dom=root&xml=introsp_s.xml), a Food and Agriculture Organization (FAO) database on the introduction of aquatic species (DIAS 2004), Fish Base (http//:http://www.fishbase.org), Global Invasive Species Database (GISD) (http://www.issg.org/database/welcome) and the database on National Biological

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Table 3 Invasiveness screening test (FIST) of alien fish species to determine the risk level

Invasiveness screening criteria	Species invasiveness assessment														Ranking of the screened criteria based on CV%
	1§	2§	3†	4§	5†	6†	7‡	8§	9†	10†	11§	12§	13§	CV%	
Culture level	+++	+++	++	+++	++	++	++	+	++	++	+++	+++	+++	36.4	4
Growth	+++	+++	+++	++	+++	+++	+++	++	+++	++	+++	+++	+	63.6	7
Propagule pressure (transportation)	+++	+++	+++	+++	+++	+++	++	+	+++	++	+++	+++	+++	81.8	9
History of establishment	+	+++	+	+++	+++	++	+++	+++	+	–	++	++	+++	72.7	8
Ability to live off a wide range of food	+++	++	+++	++	++	++	+++	++	++	++	+++	+++	+++	18.2	2
Tolerance to temperature	+++	+++	+	+++	++	+++	++	+++	++	+++	+++	++	+++	100.0	11
Tolerance to salinity	+++	+	++	++	+	+	+++	++	++	+++	+++	+++	++	90.9	10
Tolerance to dissolved oxygen	+++	++	++	++	+	+	++	+++	+	++	+++	+++	+++	54.5	6
Ability to breed in the wild	+	++	+	+++	++	++	+++	+++	+	+	++	+++	+++	9.1	1
Competition with local species	+++	+++	++	+++	++	+	+++	+++	++	++	+++	+++	+++	27.3	3
Diseases	+	++	+++	+	+	+	+	+	+	++	+	++	+	45.5	5
Frequency distribution % (FD%) for +++	72.7	54.5	45.5	54.5	27.3	27.3	45.5	54.5	27.3	27.3	72.7	72.7	72.7	–	–

1, *Clarias gariepinus*; 2, *Aristichthys nobilis*; 3, *Pangasianodon hypophthalmus;* 4, *Cyprinus carpio;* 5, *Hypophthalmichthys molitrix;* 6, *Ctenopharyngodon idella;* 7, *Oreochromis niloticus;* 8, *O. mossambicus;* 9, *Piaractus brachypomus;* 10, *Litopenaeus vennamei;* 11, *Pygocentrus nattereri;* 12, *Pterygoplichthys spp.;* 13, *Poecilia reticulata)*; CV %, cumulative value %; +, low; ++, moderate; +++, high.

†Species with an FD % for +++ below 30 are considered to be low-risk species.

‡Species with an FD % for +++ between 30 and 50 are considered to be moderate-risk species.

§Species with an FD% value for +++ above 50 are considered to be high-risk species.

The assessed *Pterygoplichthys* spp. were *Pterygoplichthys perdalis* and *Pterygoplichthys disjuntivus*.

Information Infrastructures in the USA (http://www.invasivespecies.nbii.gov) during the risk assessment process.

The risk assessment process covered two major components: 'probability of establishment' (i.e. the invasion of an alien species) and 'consequence of establishment' (i.e. the impact of alien species). The invasion process was significantly facilitated by propagule pressure and environmental factors (e.g. temperature and salinity). The main predictor of establishment for various aquatic alien species depended on propagule pressure, which was the number or frequency of alien species released (Fausch *et al.* 2009) and depended on human interest in any alien species. Hence, unauthorised culture of alien species by public aquaculturists has been burgeoning in recent years. Alien species once established often quickly spread depending on environmental factors such as temperature and salinity (Moyle & Light 1996; Bomford *et al.* 2010). Invasive species are alien fishes that can colonize through naturally breeding populations or have the potential to establish. Such invasive species are mostly capable of causing adverse ecological impacts, although in some cases they do not; for example, there are hardly any reports on the adverse ecological impacts of gold fish (*C. auratus*) and freshwater jellyfish (*Craspedacusta sowerbyi*), although these species are known to be invasive worldwide (Ricciardi & Cohen 2007; Valery *et al.* 2008).

Impact of alien food fishes

An impact assessment of alien fish species was conducted for the Yamuna, Ganga and Periyar Rivers, backwaters of Kerala, Jaiselmer Lake (Rajasthan), Ramgarh Lake (Uttar Pradesh) and Kolleru Lake (Andhra Pradesh). The ecological impact of *Oreochromis mossambicus*, *O. niloticus*, *Pangasianodon hypophthalmus*, *Litopenaeus vannamei*, *Clarias gariepinus*, *Cyprinus carpio*, *Hypophthalmichthys molitrix*, *Ctenopharyngodon idella*, *Aristichthys nobilis* and some ornamental fish species such as *Piaractus brachypomus*, *Pterygoplichthys* spp. and *Pygocentrus nattereri*, which commonly occur in culture and breeding, was conducted following the risk assessment protocols and approaches. It is noteworthy that the invasiveness and impacts of some alien species are fully apparent within a short timeframe (within 2 years) in some cases (e.g. African catfish and Piranha), whereas for other species it can take decades (e.g. common carp) (Strayer *et al.* 2006; Arthur *et al.* 2010; Singh *et al.* 2010a). We present the overall impacts of various species below.

Impact assessments of tilapia have shown that it can make up a substantial part (up to 25%) of the catch in many reservoirs of Kerala, resulting in stunting, poor growth or even elimination of some indigenous species, such as the Gangetic carps, *Puntius dubius* and *Labeo* *kontius*, in the southern region of the country (Lakra *et al.* 2008). The growth of *Chanos chanos* was restricted to less than 100 g $year^{-1}$ compared with the usual 500 g $year^{-1}$ in many water bodies in Tamil Nadu when tilapia were present. Its prolific breeding habit and parental care help it to multiply every 3 weeks, causing space overlap with local species, particularly carps. Tilapia now form part of the fish fauna in the Godavari, Krishna, Cauvery, Yamuna and Ganga Rivers (Lakra *et al.* 2008). Tilapia and Indian economic local species share a common food niche, the success of one in competition with the other can be determined by the ability of this fish to breed and propagate. Given the propensity of tilapia for auto-stocking, indigenous species that breed in the ecosystem have to struggle to coexist with tilapia. Released tilapias as a result of anthropogenic activities tend to establish in waters that have deteriorated or in quasi-natural water bodies such as reservoirs, rivers and irrigation systems. The ecological consequences of the invasion of tilapias and their establishment in such waters bodies can be serious (Canonico *et al.* 2005; Lakra *et al.* 2008). An interesting example of tilapia invasion was noted from Jaisalmund Lake in Rajasthan, where it out-competed many local species and resulted in a phenomenal reduction in the average weight of Indian major carps (Lakra *et al.* 2008). Tilapia was introduced into this lake during 1988 and started appearing in commercial catches in 1990. Since 1998 it has constituted more than 90% of the catch (Lakra *et al.* 2008). Despite this, the growing popularity of Nile tilapia in aquaculture for food production has attracted some aquaculturists in India who are willing to culture it mainly for export purposes; it is not in high demand domestically. *Oreochromis niloticus* is cultured in relatively poor quality waters, in sewage-fed ponds in West Bengal or under commercial culture operations in Andhra Pradesh. Recent efforts to culture Genetically Improved Farmed Tilapia (GIFT) tilapia introduced to Central Institute of Freshwater Aquaculture (CIFA), Bhubaneswar, and study its performance and prospects have not provided any recommendation on its culture and propagation.

The common carp (*Cyprinus carpio*) is a very popular fish in aquaculture and has considerably added to the total yield from pond culture. However, its pond-breeding habit upsets the population balance leading to severe competition for food and space, resulting in the production of small-sized individuals. Three varieties of common carp (scale carp, leather carp and mirror carp) have formed naturalized populations in rivers, lakes and reservoirs (Lakra *et al.* 2008; Singh *et al.* 2010a). The naturally bred mirror carp and leather carp have not only been observed in upland waters, but have also been observed approximately 200 km downstream in the plains of Uttar Pradesh. Increased populations of carp in natural water bodies have negatively impacted on catches of the local mahseer species *Tor putitora*, snow-trout *Schizothorax richardsonii* and some other species, such as carps and catfishes, in different ecosystems (Petr 1999; Singh & Lakra 2006; Lakra *et al.* 2008). Its over population has been found to critically reduce the endemic fish species *Osteobrama belangiri* from Loktak Lake (Manipur) (Singh & Lakra 2006). It has recently invaded the Ganga River System after 50 years of existence in pond aquaculture (Fausch *et al.* 2009; Singh *et al.* 2010a). At present both *C. carpio* and *O. niloticus* have been found to dominate commercial catches in the Ganga River (Singh *et al.* 2010a). Catches of local fishes, particularly Indian major carps and some others, have declined by 72% at Allahabad and Varanasi, whereas the catch of alien fishes (mainly *C. carpio* and *O. niloticus*) increased 237.1% in 2009 (Fig. 1). This increasing trend in the catch of alien fishes was noticed from 2004 onwards. A similar phenomenon was found in the Yamuna River, where commercial catches were dominated by the presence of alien fishes, particularly *C. carpio*, *Oreochromis* spp. (both *O. niloticus* and *O. mossambicus*) and also some *C. gariepinus* at most sampling stations (Singh *et al.* 2010b).

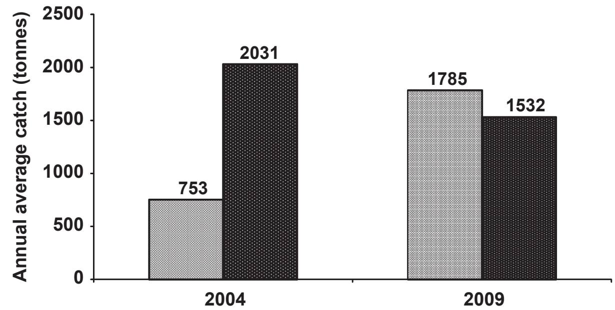

Figure 1 Increased occurrence of alien species in the Ganga River (2004 and 2009). (▨) Exotics; (■) local.

Occurrences of common carp, tilapia and African catfish in the Yamuna River have been mapped for an approximately 900-km-long river stretch using a Geographical Information System (GIS) tool for the period 2003 and 2008 (Fig. 2). *Cyprinus carpio*, *Oreochromis mossambicus* and *O. niloticus* were found to colonize naturally breeding populations in this river and the presence of all reproductive stages was confirmed in our studies. Some of the river stretches of the Yamuna were full of tilapia only and hardly any other local fish species were caught (Singh *et al.* 2010b).

Both silver carp (*Hypophthalmichthys molitrix*) and grass carp (*Ctenopharyngodon idella*) have increased farmer yields and, although not commensurate with their income, are still a welcome addition so long as the

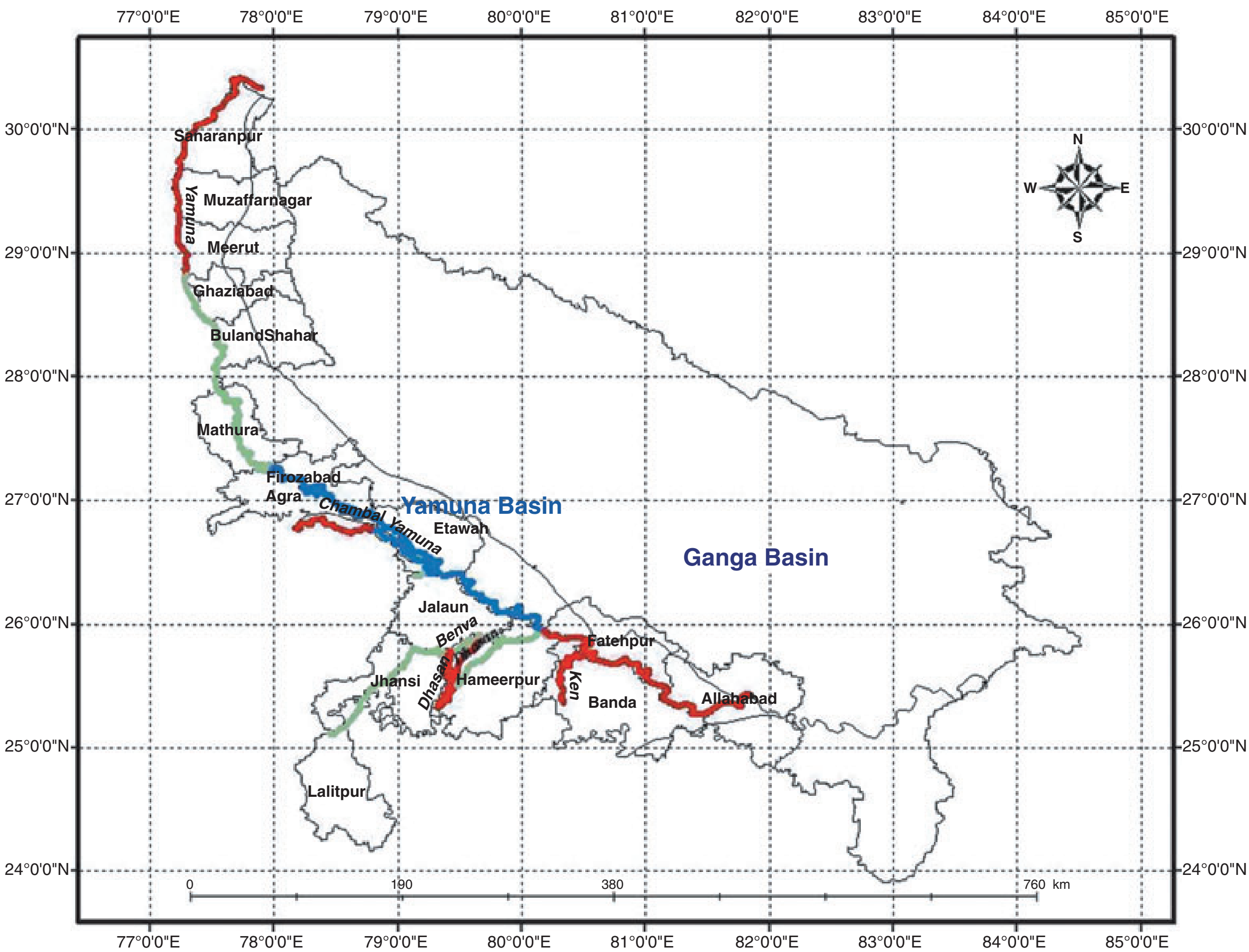

Figure 2 Mapping of the occurrences of alien fish species in the Yamuna River using a Geographical Information System tool. (----) No data; (----) *Cyprinus carpio*, *Clarias gariepinus*, *Oreachromis* spp.; (----) *Cyprinus carpio*, *Oreachromis* spp.

proportions of the different species are maintained as suggested to avoid competition with indigenous species (Jena *et al.* 2002). However, in an interesting example, a few specimens of silver carp escaped into the Gobindsagar Reservoir (Himachal Pradesh) during transportation and this species has now become the most dominant fishery in the reservoir, accounting for over 80% of the total catch (Singh & Lakra 2006; Lakra *et al.* 2008). The abundant population of silver carp in the Govindsagar Reservoir (Himachal Pradesh) and similarly in the Kulgarhi Reservoir (Madhya Pradesh) has changed the trophic structure significantly (Singh & Lakra 2006; Lakra *et al.* 2008). These alien carps have further established in many rivers. Available data suggest that this species possesses invasive characters, such as good survival, growth and competition with local fishes and is able to establish breeding populations in the wild. In a field study of 18 grow-out farms in a cluster, *Aristichthys nobilis* negatively impacted the overall average pond production in polyculture by 24.6%, whereas growth of *Catla catla* was reduced by 17.0%. The specific growth rate (% day^{-1}) of *C. catla* was also affected and it was less than that of *A. nobilis* in the same environment and on the same diet. One major reason for such an adverse impact could be the indiscriminate and irregular stockings of bighead in established composite culture farms. Both *C. catla* and *A. nobilis* were found to occupy the same ecological niche and they had similar feeding habits in the wild. Bighead have the potential to hybridize with *C. catla* and silver carp (*H. molitrix*) under farm conditions (Lakra *et al.* 2006, 2008). Its hybrid with silver carp (*H. molitrix*) is very common at many farms (Mia *et al.* 2005; Singh & Lakra 2006). In our field studies, we recorded the occurrence of 23.6% hybrid stocks of *A. nobilis* and *H. molitrix* in culture farms. An F_1 hybrid between bighead *A. nobilis* and silver carp *H. molitrix* showed beneficial properties in terms of growth, food conversion and disease resistance. However, further uncontrolled hybridization in later generations might result in the loss of the acquired beneficial traits (Mia *et al.* 2005). Invasion of *A. nobilis* into several rivers, reservoirs and lakes has been shown to adversely affect the local fishes because it is a voracious feeder and depends mostly on naturally available planktonic food on which many local fishes thrive (Lakra *et al.* 2008; Sampson *et al.* 2009). Invasive impacts of this species have also been reported from some countries where bighead carp (*A. nobilis*) are reported to form established natural populations causing adverse ecological conditions (Taylor *et al.* 2005; Sampson *et al.* 2009).

Aquaculture of *Puntius gonionotus* is commonly practiced in West Bengal, Orissa and also in Andman and Nicobar. This species has been incorporated into pond culture systems and its growth ranges from 200 to 500 g year^{-1} in different areas. However, a lack of information on its compatibility, growth performance and interaction with local species of culture has been a major limitation in risk assessment. A recent study on the compatibility of silver barb with other local species used in polyculture reported that silver barb had a higher level of competition with *Labeo rohita* than *C. catla*. However, this species may be a potential candidate species of aquaculture and is a preferred fish species in paddy-cum-fish culture (Jena *et al.* 2007).

In India, monoculture of African catfish (*Clarias gariepinus*) has shown a wide range in growth when integrated with slaughter house and chicken wastes and improvised feed with 40% protein (Singh & Mishra 2001), and production under monoculture was estimated to range from a few kg to over 20 t ha^{-1} year^{-1} at different farms (Singh & Lakra 2006; Lakra *et al.* 2008). There was a loss to the carps in the range of 78.2–86.3% when *C. gariepinus* was cultured under polyculture with carps (Baruah *et al.* 1999; Lakra *et al.* 2008). An average growth of 1.63 mm day^{-1} was observed in managed grow-out ponds. This species was found to possess a highly carnivorous feeding habit on live fish, insects, snails, earthworms, plankton, plants and fruits and also rotting flesh. African catfish (*C. gariepinus*) exist in fishponds, lakes, streams and other natural water bodies, including river stretches both deep and shallow. This species tolerates harsh environmental conditions and is distributed over a wide range of temperatures (12–36 ± 1°C) and salinities (<14 p.p.t.), which is why it is widespread throughout the country. It occurs in coastal areas, freshwater ponds, tanks, lakes, reservoirs, aquatic bodies of foot-hills in cool environments and even in some rivers, such as the Godavari, Yamuna, Gomti and the Ganga Rivers, with different pristine diversity (Lakra *et al.* 2008, 2009). African catfish culture has occurred in all areas where local *C. batrachus* naturally exist. *Clarias gariepinus* has the potential to hybridize with local *C. batrachus* (Rahman *et al.* 1995; Sahoo *et al.* 2003), suggesting the possibility of genetic pollution when escapee fish breed in the wild. Gene introgression has already been reported in the local species *C. macrocephalus* in Thailand as a result of escapee *C. gariepinus* (Na-Nakorn *et al.* 2004; Senanan *et al.* 2004). Its spread in different aquatic ecosystems has negatively impacted on the existence of local magur *C. batrachus*, in addition to other native species. African catfish are easy to culture and seed is readily available throughout the year. In Western ghat, a biodiversity-rich hotspot, farmers culture *C. gariepinus* over the endemic yellow catfish (*Horabagrus brachysoma*), which has now critically declined (Lakra *et al.* 2008). African catfish grow fast, culture management is easy and farmers prefer it to local species. African catfish have been shown to possess attractive culture characteristics, such as fast growth (approximately 600 g in 6 months), and acceptability of cheap feed, such as slaughterhouse and chicken waste. This species is disease resistant and easy to breed. At the same time it also possesses some characters attributable to invasiveness, such as survival in different agro-climatic conditions, superior growth over local species, carnivorous and aggressive behaviour, acceptability of a wide range of feed, including live fish and other aquatic animals, and attaining maturity in different water bodies. A critically declining bird, the Moorhen *Gallinula chloropus*, was recently found in the gut of a 67-cm-long fish caught from the Bharatpur bird sanctuary in Rajasthan (Anoop *et al.* 2009). Low culture management practice, tolerance of a harsh environment, acceptability of a variety of feed, including slaughterhouse wastes, and fast growth mean that farmers have begun to culture it in small pits and cement cisterns as well as in large ponds and reservoirs. However, this obnoxious predator has become far more inimical to indigenous species as it has now gained unsolicited entry into mighty rivers, such as the Ganga, Yamuna, Sutlej and Godavari, which are the pride of India for their precious and specific gene pool (Kapoor *et al.* 2002; Lakra *et al.* 2009). The threat of *C. gariepinus* and its invasion into a river in South Brazil have also been reported (Vitule *et al.* 2006). Considering the threats posed by African catfish, the Ministry of Agriculture, Government of India, ordered killing of this alien catfish *en masse* and has imposed a ban on its culture. However, it is still bred and cultured even today in different parts of the country.

Aquaculture of *Pangasianodon hopophthalmus* has been booming in recent years in the coastal states. This species shows fast growth and can be farmed intensively, thus attracting aquaculturists. In cases of polyculture with carps it has been shown to harm other local culture species. Intensive monoculture of *P. hypophthalmus* was found to be associated with heavy disease infestation. Some diseases, particularly haemorrhagic septicaemia, bacillary diseases, *Flavobacterium columnarae* and *Trichodina*, that have been found at a number of farms are a serious concern (Lakra & Singh 2010). As this species is farmed in areas that have also been used for carps and shrimp, there are concerns with regard to biodiversity and socioeconomic conditions (Lakra & Singh 2010). The production of *P. hypophthalmus* is estimated to be over 200 000.0 tonnes at present (Lakra & Singh 2010) and the production rate of this catfish exceeded carp production. However, this alien catfish is not preferred locally and is rated as a low-price fish in the domestic market compared with carps and other major local fishes. The unit cost of production of this catfish is greater than that of carps owing to excessive feeding and the additional expense of sanitizers and antibiotics (Lakra & Singh 2010). In general, intensive feeding results in eutrophic conditions in farms and there are frequent outbreaks of disease. These culture conditions adversely impact marginal farmers, consumers, culture environments and socioeconomic conditions (Lakra & Singh 2010). However, the prospect of culturing *P. hypophthalmus* has recently been reviewed and its culture under regulated conditions as per the developed guidelines has been permitted.

In India, trout are regarded to be important culture species in hill states. However, our field observations have found that brown trout that have established in some of the natural water bodies have competed with local snow-trout and other native stocks, leading to their decline (Singh & Lakra 2006; Lakra *et al.* 2008). Trout have been reported to hybridize with genetically similar indigenous species in some countries (De Silva *et al.* 2009). Alien sport fish, such as rainbow trout, can be major predators of eggs and young ones of native species (Petr 1999). These reports beg further investigations on the impact of alien trout fish species in Indian waters as detailed studies are still lacking. Whatever the negative aspects of its culture, there is no more important culture species than trout in the coldwater aquaculture sector. At present, the aquaculture production of trout is estimated to reach up to 500 tonnes per annum.

In recent times, the shrimp industry in India has been pessimistic with production at 80 000 tonnes in 2009 as a result of a reduction in farming areas, stocking density (5–10 post larvae m^{-2}) and number of crops as well as failures through diseases, particularly White Spot Syndrome Virus (WSSV) (Lakra *et al.* 2008; Senanan *et al.* 2009). As disease outbreaks occurred among locally cultured shrimp species, *Penaeus monodon*, aquaculture of *L. vannamei* has recently attracted Indian farmers because of its fast growth, low incidence of native diseases, availability of domesticated strains and also international market demand. The Ministry of Agriculture has authorised pilot-scale culture of this alien shrimp at a few private farms, but there is increasing demand from other private farmers for its culture. The Coastal Aquaculture Authority has registered more than 24 farms for *L. vannamei* culture. Although some farmers have shown great interest in the culture of *L. vannamei*, others have vehemently opposed it. Our risk assessment study revealed that this alien shrimp species has the potential to cause some ecological impacts, such as reducing aquatic biodiversity or spreading alien pathogens (Lakra *et al.* 2008; Senanan *et al.* 2009). Socioeconomic issues are also being raised with regard to the culture of *L. vannamei* (Lakra *et al.* 2008; Senanan *et al.* 2009). However, field data are still lacking to quantify the real impact of introduced shrimp species. At present the greatest threat appears to be from a devastating pathogen, Taura syndrome virus (TSV), which has not yet been reported from India, although it has been reported from other Asian countries (Senanan *et al.* 2009). Recent efforts to culture this alien shrimp have been considered under biosecurity by using specific pathogen free (SPF) stock.

In general, we have demonstrated a decline in indigenous fish catches with a concurrent increase in alien fish catches, particularly in rivers such as the Ganga. This does not necessarily imply a cause–effect relationship, particularly when one considers that over time the river ecosystems as a whole have degenerated through anthropogenic influences, both direct and indirect. Perhaps, in a deteriorated environment alien species are often better equipped to gain dominance, and this has been clearly demonstrated for tilapia species in the Asia–Pacific region (De Silva *et al.* 2004).

Impact of alien ornamental fish species

Many alien aquarium fish species have been found in natural water bodies in different parts of India. Four popular species of aquarium pets, guppy (*Poecilia reticulata*), three-spot gourami (*Trichogaster trichopterus*), platy (*Xiphophorus maculatus*) and sucker catfish (*Pterygoplichthys multiradiatus*), were found in the inland waters of Kerala State, a biodiversity hot-spot region of the country (Raghavan *et al.* 2008; Krishnakumar *et al.* 2009). The presence of three-spot gourami, an opportunistic carnivore with territorial and aggressive behaviour, could prove harmful to native species. The sucker catfish (*P. multiradiatus*) was found in Vembanad Lake apart from water bodies of Vylathur village in Thrissur and the Chackai canal in Thiruvananthapuram. As this fish is an algae eater, its presence might reduce food and physical cover for aquatic insects as a result of its algae-devouring habits (Raghavan *et al.* 2008; Krishnakumar *et al.* 2009). Its presence in rivers has been shown to adversely affect the benthic fish fauna. *Trichogaster trichopterus* was sporadically observed in catches and this species is an opportunistic carnivore with territorial and aggressive behaviour that could prove potentially harmful to native fish species such as *Pseudosproneus cupanus* and *Aplocheilus lineatus.* The insectivorous feeding habit of platy (*X. maculates*) was assessed because they may be potential competitors with indigenous barbs such as *Puntius fasciatus*, *Puntius ticto* and *Puntius vittatus*, as well as with killifish such as *A. lineatus*, *A. punchax* and *A. dayi*. As is the case for *P. reticulata*, *X. maculatus* also attains sexual maturity after 3–4 months and reproduces easily in the wild, becoming a potential pest. *Aplocheilus punchax* and *A. dayi* are popular native ornamental fishes and have been found to exist with *X. maculates*. Furthermore, *P. multiradiatus*, *P. disjuntivus* and *P. perdalis*, native to South American drainages, are popular aquarium pets. *Pterygoplichthys multiradiatus* has been recorded in the rivers and canals of Kerala, whereas *Pterygoplichthys disjunctivus* and *P. perdalis* have been recorded in the wetlands, rivers and lakes of West Bengal, Andhra Pradesh and Uttar Pradesh. These omnivorous species attained large sizes (up to 300 mm) and exhibited territorial behaviour. They were capable of tolerating low oxygen levels because of their air-breathing ability. *Pterygoplichthys disjunctivus* and *P. perdalis* are highly invasive fish species (Gibbs *et al.* 2008) and thousands of live specimens of *P. disjunctivus* and *P. perdalis* were captured from wetlands of West Bengal, and individuals were also recorded from lakes, rivers and reservoirs in Andhra Pradesh, West Bengal, Bihar and Uttar Pradesh. *Pterygoplichthys disjunctivus* and *P. perdalis* are multispawners and are highly fecund. Escapee fish have the potential to adversely affect the local fauna and have been observed to create serious negative impacts on periphyton feeding and bottom-spawning fishes such as *Etroplus suratensis.* These species can breed naturally in different drainages and are capable of establishing in the wild. *Pterygoplichthys disjunctivus* and *P. perdalis* were assessed as high-risk species on the basis of our risk analysis study and also because they have existed in different ecosystems for more than 5 years, bred there naturally and adversely impacted the local ichthyo-fauna at more than one location. These species have invaded a number of ecosystems in southern USA (Gibbs *et al.* 2008). During our recent survey study, we captured some live specimens of red-bellied pacu (*P. brachypomus*) from the Periyar River in Kerala. Specimens were also reported from the Dimbhe Reservoir near Pune, Maharashtra, and there were incidences of people being bitten when they entered the reservoir for their day-to-day work. Pacu are capable of causing economic losses to fishers by damaging gear, particularly cast nets and gill nets. Pacu can tolerate temperatures ranging from 23 to 28°C and pH levels of 4.8–7.5 under grow-out conditions. Although carnivorous, farmers are culturing pacu in polyculture with carps. It is an opportunistic fish preying on insects, zooplankton and small fish. Piranha fish are hardy and breed occasionally in aquaria. The risk assessment study for the highly carnivorous *P. natterei* revealed that it had strong potential to breed and establish in natural water bodies, thus damaging local species. Swarms of piranha confined to small water bodies in Kerala have attacked large animals and even humans with their sharp teeth. Piranhas are also the bane of fishers because they devour other fish caught in the nets (Gopalakrishnan & Ponniah 1999; Lakra *et al.* 2008). As it is an original inhabitant of South America, which has a similar tropical humid climate to Kerala, it is likely to have reproductive populations and may create a major ecological catastrophe (Gopalakrishnan & Ponniah 1999). In view of its highly invasive potential, the Ministry of Agriculture, New Delhi, has already declared it a banned species.

The koi carp is a very common and popular aquarium pet and is usually available in freshwater farms culturing carps. The major problem of this aquarium fish is that it is a carrier of the koi herpes virus (KHP). Fortunately this virus has not yet been reported in India.

A lack of field data was a big constraint in determining the risks of alien ornamental fish species. As a result the possible threats of alien ornamental fishes were assessed by way of organising a workshop of expert scientists and aquarium fish culturists. A list of 51 low-risk alien aquarium species was prepared and submitted to the Ministry of Agriculture to consider the demand-based cases of import of ornamental fish species (Singh & Lakra 2006). The volume of trade and propagule pressure of the ornamental fish species was understood to be a significant factor in the probability of their establishment. Marketing and trade in alien ornamental fish species was significantly related to their occurrence and establishment in the wild. Fish species sold in high volumes (high propagule pressure) in the aquarium trade were more likely to be sighted in the wild.

Discussion

In India, the use of alien species has been practiced since the middle of the 19th century for fisheries and aquaculture diversification (Singh & Lakra 2006; Lakra *et al.* 2008). Trout were first introduced into lakes and reservoirs for recreational purposes and thereafter Chinese carps, *Hypophthalmichthys molitrix*, *Ctenopharyngodon idella* and the common carp *Cyprinus carpio*, were introduced in a planned way after a decade-long study and were found to contribute significantly to aquaculture production (Jena *et al.* 2002; Lakra *et al.* 2008), whereas others have resulted in highly publicized failures, generating controversy over the protection of native biodiversity and the spread of pathogens and diseases (Lakra *et al.* 2008;

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Peter & Mohan 2009). Alien fish species in many countries have caused damage to aquatic biodiversity with consequent ecological problems (De Silva *et al.* 2006, 2009; Garcia-Berthou 2007; Lakra *et al.* 2008). In recent years, there has been an alarming increase in the number of alien fish species being detected in the rivers, lakes and reservoirs of India (Lakra *et al.* 2008; Raghavan *et al.* 2008). Most escapee alien species were from unauthorized culture species and moved into open waters inadvertently or because farmers were unaware and/or lacked knowledge of the potential adverse effects. At the same time, ornamental fishes, although confined to aquarium tanks, were still released into natural habitats. The growth and culture conditions of most alien food fishes are superior to local species and their invasiveness can cause serious impacts (Lakra *et al.* 2008). The rich fish biodiversity of India is subjected to growing pollution by sewage and industrial wastes, excessive use of fertilizers, pesticides, over-fishing and environmental aberrations (Sarkar & Bain 2006; Lakra *et al.* 2009). Globally also, freshwaters are experiencing declines in biodiversity as a result of overexploitation of both water and organisms, water pollution and habitat destruction and degradation, including modification of natural flow regimes (Dudgeon *et al.* 2006). However, unauthorised culture of alien species and their unintentional or deliberate spread is emerging as one of the greatest threats to the biodiversity of aquatic ecosystems. The impacts are typically greater in systems already affected by human activity (Vaughn 2010). Increased appearance of alien species particularly in degraded aquatic environments has further significantly aggravated threats to biodiversity (Lakra *et al.* 2008). Escapees have been found to establish in the wild and cause ecological damage in several natural aquatic systems, including the Ganga River, the largest river in the country (Lakra *et al. 2008;* Singh *et al.* 2010a). In the case of ornamental species, we have come across two major invasion threats. First, the gene pool of alien ornamental species is continually expanding as the industry searches for new, potentially popular species/strains to market. Second, because most aquarium species are of tropical or subtropical origin, the probability of their establishment in Indian agro-climatic conditions is relatively high; this would increase further with climatic warming (Bomford *et al.* 2010; Leprieur *et al.* 2009; Vaughn 2010). A series of invasions by many freshwater aquarium fishes has already taken place in India over the past decade and many more may be expected to occur (Lakra *et al.* 2008; Raghavan *et al.* 2008; Krishnakumar *et al.* 2009).

The spread of alien fishes is associated with a drop in local fish biodiversity and significant losses to aquaculture production through competition and increased incidences of disease (Lakra *et al.* 2008; Khan & Panikkar 2009; Peter & Mohan 2009). Private aquaculturists in India believed that the use of alien species in aquaculture would help them bring in vast economic returns and provide huge employment opportunities. Production data on alien fishes have never appeared on the national production figures (De Silva *et al.* 2006), indicating their contribution to production enhancement. The role of alien species in aquaculture has been dealt with on global (Gozlan 2008) and regional scales (De Silva *et al.* 2006, 2009; Turchini & De Silva 2008). Very few reports emphasize the importance of alien species in aquaculture production enhancement on a sustainable basis. Most reports have highlighted irreparable losses that can adversely impact on fish production and food security at large (Casal 2006; Simberloff 2007; Subasinghe *et al.* 2009; Peter & Mohan 2009). Harmful alien species and the control of their spread are international issues with potential impacts that span economic, social, health and ecological concerns (Pimentel *et al.* 2005; Lakra *et al.* 2008; De Silva *et al.* 2009). Introducing species accidentally or intentionally from one habitat into another is a risky business (Lakra *et al.* 2008; Chang *et al.* 2009; De Silva *et al.* 2009). Aquatic invasive alien species do not respect geopolitical borders and have the potential to cause significant negative impacts (De Silva *et al.* 2006, 2009; Garcia-Berthou 2007; Lakra *et al.* 2008). India is a signatory of the United Nations Convention on Biological Diversity (UNCBD), so it is bound to follow the convention, but very little has been done to empower the protocol on biosafety and control of alien species.

In view of the adverse environmental, socioeconomic and biodiversity impacts, there is an urgent need to regulate the illegal entry of alien species into the country. Some countries, notably New Zealand, Australia, USA, Hungary and several island states, have developed and are implementing comprehensive biosecurity policies to markedly reduce the threats of alien species (http://www.issg.org/database/welcome; http://www.invasivespecies.nbii.gov). In contrast, India lacks a regional policy and needs to address the issue of alien species at a regional as well as national level. However, with our sustained endeavour to regulate the culture of alien species in the country, we have now developed a set of strategic national plans and guidelines for the import of alien aquatic organisms (Lakra *et al.* 2006). As there is pressure from private aquaculturists to import alien species, the developed set of national guidelines will regulate imports for safe aquaculture and aquarium trade. There is a pressing need to follow scientifically sound methods and approaches in the field of risk assessment for alien species so as to pick only safe and profitable species of aquaculture (Anderson *et al.* 2004; Hill & Zajisek 2007; Copp *et al.* 2009). For all import proposals, our developed impact assessment protocol 'FIST' will help to screen invasive and dangerous alien fish species for decision support. At present, the available risk assessment modules cannot absolutely determine whether or not an alien species will establish and if it does what impact it will have. It means that there is: (i) uncertainty in the process (methodology); (ii) uncertainty in the assessor(s) (human error); and (iii) uncertainty about the organism (biological and environmental unknowns) (Bomford *et al.* 2010; Leprieur *et al.* 2009). Because sufficient information on critical aspects of an aquatic species' biology is often lacking, decisions on most alien introductions may often be based on incomplete information, resulting in controversy, debate and criticism. Decisions regarding the import of any controversial alien species can follow a precautionary approach (Bartley & Minchin 1996). Therefore, while assessing the invasiveness of any new introduction, uncertainty should also be acknowledged when required data are not available. Where critical data are lacking, a precautionary approach will provide risk analysts with the additional time required to generate information.

At the national level, quarantine and health certification programmes have also been initiated as an integral part of much broader strategies aimed at protecting the natural environment and fauna from the deleterious impacts of alien fish species and pathogens. Fish species-specific guidelines have been developed particularly for the introduction of *Oreochromis niloticus*, *Pangasianodon hypophthalmus* and *Litopenaeus vannamei* and some aquarium fishes. Recently, the Ministry of Agriculture, Department of Animal Husbandry, Dairying and Fisheries, Government of India, has given clearance to a few private aquaculturists to culture tilapia (*O. niloticus*) and *L. vannamei* as well as some aquarium fishes using the developed guidelines. Based on the performance of approved introductions under regulated conditions, the role of some successful alien fish species in aquaculture development can be evaluated. Enactment of the guidelines for quarantine of any new consignment was usually constrained owing to absence of proper quarantine infrastructural facilities. To handle the problem of free import and culture of alien species, public awareness about the adverse consequences of alien species and the requirements of quarantine was campaigned in different parts of the country. As legislation is not in place, a viable alternative approach to properly implement the guidelines is private–public partnership. Considering the negative impacts of existing alien species on biodiversity, it should be made mandatory for all alien species to pass through a risk assessment trial. After any alien species is approved for import following the risk assessment trial, aquaculturists and farmers should comply with the available regulatory mechanisms and follow the quarantine protocol along with strict conditions of sanitary and phyto-sanitary standards.

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