Invasion Risks of Aquarium Fish Trade to the Natural Environment in Sri Lanka

Udaya Priyantha Kankanamge Epa*, Madalusse Gedara Maheshika Udayangani Piyathissa, Sangasinghe Devage Achila Eshani Ranasinghe, Yahani Gayara Ranasinghe and Rathnayaka Mudiyanselage Kalhari Harsha Rathnayaka

ABSTRACT

Sri Lanka, one of the world's biological hotspots, exports wild-caught and farm-bred aquarium fish species to more than 70 countries. This study evaluated the potential for invasiveness of aquarium fish species now raised and traded in Sri Lanka's Gampaha, Kandy, and Polonnaruwa districts. A questionnaire survey of 40 hobbyists, 20 retailers and ten breeders of aquarium fish in each selected district was conducted to assess the causes of aquarium fish releases. The invasion potential was evaluated using a model consisting of species thermal tolerance, propagule pressure and invasion history. Overall, 59 non-native fish species belonging to 14 families (Acanthuridae, Callichthyidae, Characidae, Cichlidae, Cyprinidae, Helostomatidae, Loricariidae, Notopteridae, Pimelodidae, Poeciliidae, Osphronemidae, Osteoglossidae, Salmonidae, and Scombridae) were recorded from the aquarium trade in the country. Out of 17 species with high to moderate invasive potential, six have already been established in the environment in Sri Lanka. Therefore, *Astronotus ocellatus, Barbonymus schwanenfeldii, Carassius auratus, Hypostomus plecostomus, Pangasianodon hypophthalmus, Poecilia latipinna, P. sphenops, Puntigrus tetrazona, Trichopodus microlepis, Xiphophorus helleri,* and *X. maculatus* are identified as potential invaders in Sri Lanka. The reasons for the intentional release of aquarium fish into the environment were excessively large size, aggressiveness, diseases and high reproductive rates. The number of fish of each species released into the natural environment is positively correlated to the number kept in home aquaria. A well-coordinated institutional mechanism to control unwanted fish introductions through the aquarium fish trade in Sri Lanka is urgently needed.

Keywords: Introduction, Invasive, Non-native, Propagule pressure

INTRODUCTION

In 2020, aquarium fish was the world's 3,110th most traded product, with a total trade of US $330 million (OEC, 2023). Currently, this sector trades more than 5,300 species and is responsible for more than 150 species invasions globally (Padilla and Williams, 2004). It is considered one of the top five pathways for introducing non-native species worldwide (Strecker *et al*., 2011; Magalhães *et al*., 2020). The detrimental impacts of these fish introductions around the world have long been documented, i.e., displacing native species (Arthington, 1989; Elvira and Almodóvar, 2001; Bambaradeniya, 2002; Lockwood *et al*., 2009; Rahim *et al*., 2013; Magalhães and Jacobi, 2013a), carrying pathogens (Ye *et al*., 2009; Gozlan *et al*., 2010; Ebner *et al*., 2020), preying on native species (Fuller *et al*., 1999; Liang *et al*., 2006; Knight 2010; Silva *et al*., 2016), causing changes in nutrient cycling (Capps and Flecker, 2013), and presenting dangers to humans (Papavlasopoulou *et al*., 2010; Xiong *et al*., 2015).

Department of Zoology and Environmental Management, University of Kelaniya, Kelaniya, Sri Lanka
*Corresponding author. E-mail address: epa@kln.ac.lk
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The aquarium industry in Sri Lanka started as a small-scale cottage industry in the 1930s (Ekaratne, 2000; Wijesekara and Yakupitiyage, 2001) and has now transformed into one of the country's major export-oriented industries. Sri Lanka exports farm-bred and wild-caught fish with striking fin and body color patterns to over 70 countries, including the USA, the United Kingdom, Canada, Japan, Holland, Germany, France, Italy, Singapore, Hong Kong and Saudi Arabia (NAQDA, 2023). Aquarium fish exports from the country earned foreign exchange worth US $7.3 million in 2012 and increased to US $19.6 million in 2022 (NAQDA, 2023). This industry has now become a significant income source for several fish retailers, breeders and exporters scattered in the rural and urban areas of the island. Irrespective of this economic and social significance, the aquarium industry is considered a poorly monitored and controlled industry in Sri Lanka.

Non-native species introduced by the aquarium trade and aquaculture have created serious management issues regarding the conservation of native aquatic species on the island (Bambaradeniya, 2000; Marambe *et al*., 2003; Epa, 2006; Wijethunga and Epa, 2008; Epa, 2014). Nine out of 20 animal species that have invaded natural environment in Sri Lanka are fish species introduced through the aquaculture or aquarium industry, i.e., *Pterygoplichthys pardalis, Oreochromis mossambicus, Chitala ornata, Poecilia reticulata, Oncorhynchus mykiss, Osphronemus goramy, Trichopodus pectoralis*, *Helestoma temminkii* and *Cyprinus carpio* (Bambaradeniya, 2000; 2002; Marambe *et al*., 2003; Silva and Kurukulasuriya, 2010; Epa, 2014; MMDE, 2015). Similarly, aquarium and aquaculture industries are the primary vectors responsible for the introduction of invasive fish species into freshwater habitats of North America (Fuller *et al*., 1999), Great Britain (Keller *et al*., 2009), Singapore (Ng and Tan, 2010), Malaysia (Rahim *et al*., 2013), China (Xiong *et al*., 2015) and India (Sandilyan, 2016).

The management of the introduction of aquarium fish species and their distribution in many countries is stalled, as it is uncertain whether the species are being traded and released into the environment (Magalhães and Jacobi, 2013a; Rahim *et al*., 2013; Epa, 2014). The lack of this information hinders policy development to control and prevent the future introduction of aquarium species to new environments. In most cases, risks and damages of the introduction of non-native species outside of their native ranges received attention only after they had established themselves in a new environment (Padilla and Williams, 2004; Rixon *et al*., 2005; Papavlasopoulou *et al*., 2010; Strecker *et al*., 2011; Magalhães and Jacobi, 2013b). Therefore, assessment of the invasion potential of species is critical to improve policy actions, guide integrated management strategies, and enhance educational campaigns aimed at reducing the threat of future invasions. This study aimed to provide a provisional checklist of aquarium fish species, find reasons for deliberate and accidental releases of aquarium fish species to the environment, and assess the invasion potential of aquarium fish species reared and traded in Sri Lanka.

MATERIALS AND METHODS

Study area

Gampaha (Western Province), Kandy (Central Province) and Polonnaruwa (North Central Province) districts were selected to conduct the study, as the highest number of commercial aquarium fish breeders in Sri Lanka are found in these three districts (Figure 1). The average temperature of the Gampaha, Kandy and Polonnaruwa districts are 28.4, 25.7, and 29.1 °C, respectively.

Preparation of species checklist and questionnaire survey

Name lists of privately owned aquarium fish retailers and breeders were acquired from extension officers of the National Aquaculture Development Authority (NAQDA) of each selected district. Ten commercial aquarium fish breeders and 20 aquarium retailers from each district were randomly selected from the list provided by NAQDA. The retail sector primarily caters to people who keep ornamental fish in home aquaria and institutes such as banks, hospitals, restaurants, hotels and military camps that maintain aquaria for decorating purposes. Forty aquarium hobbyists were randomly selected from the information gathered from selected retailers in each district. Fish retailers and breeders were visited monthly, while hobbyists were visited twice during the study period of eight months from February to September 2019. Species of aquarium fish kept in homes, retail shops and breeding centers were identified and recorded during the visits. Photographs of live specimens of each fish species/type were taken to confirm the identification using Fishbase.org (Froese and Pauly, 2017). Some fish species that could not be identified up to the species level using photographs were identified based on morphometric and meristic characteristics. In such cases, fish were anesthetized using tricaine methanesulfonate (MS-222), and morphological parameters such as the number of lateral line scales, number of fin rays, and number of spines were counted. The IUCN Red List Category was recorded to assess the conservation status of each fish species (IUCN, 2022).

A questionnaire survey was conducted to gather the following information: (1) aquarium fish species that were released to the environment in the last ten years; (2) if released, the type of receiving aquatic habitat; and (3) the reason for the release. Respondents were interviewed face-to-face to fill out the questionnaire.

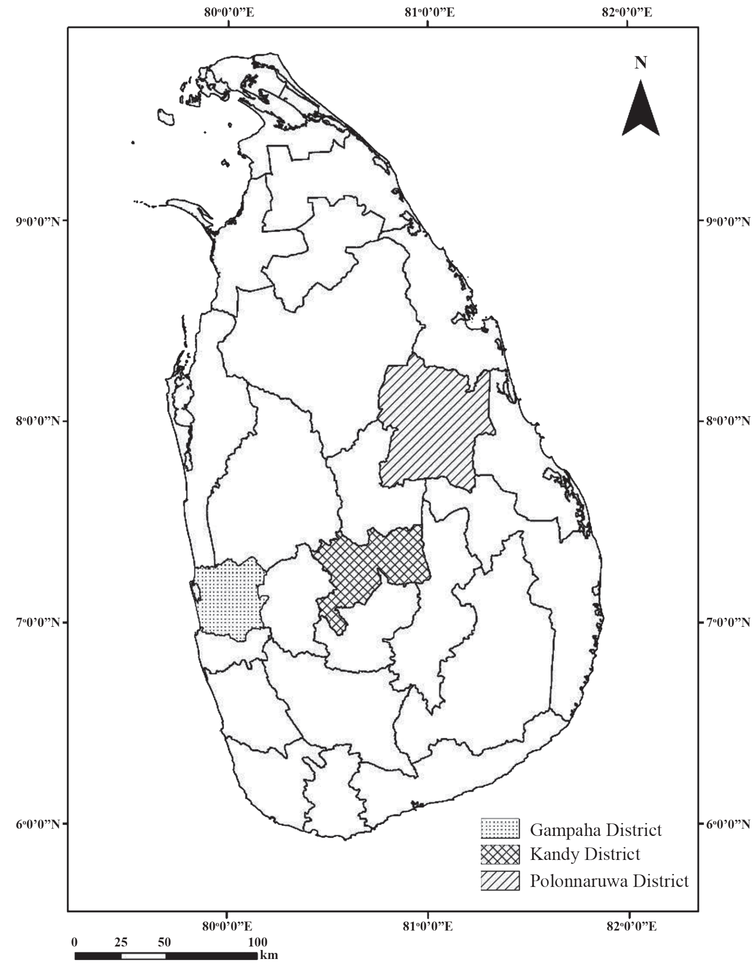

Figure 1. Map showing Gampaha, Kandy and Polonnaruwa districts, Sri Lanka.

Estimation of the invasive potential of aquarium fish species

In this study, the term non-native implies species that have been successfully introduced into a country from other countries or regions, either intentionally or accidentally. At the same time, the term invasive implies the establishment of a breeding population/s of a non-native species in a new environment. This definition is used as there are not enough studies to confirm whether the establishment of a particular species in a new habitat negatively affects the new environment or not (Biju Kumar, 2000; Ye *et al*., 2009; Capps and Flecker, 2013; Xiong *et al*., 2015).

The invasion risk of each nonnative aquarium fish species recorded was assessed through a model comprising four variables: (i) invasiveness (thermal ranges), (ii) propagule pressure, and (iii) history of invasions (establishment in a new environment) (Modified after Rixon *et al*., 2005). Based on the assumption that popular species have more opportunities to be released, the frequency of occurrence in aquarium retail shops, breeding centers and home aquaria was considered a proxy for propagule pressure. The temperature tolerance and invasion history of fish species were recorded from the literature available in the European Alien Species Information Network (EASIN, 2017) database and Fishbase (Froese and Pauly, 2017). The invasive potential of fish species was evaluated according to the following flow chart (Figure 2). Further, a Google survey was conducted using the species name and the terms 'invasion,' 'invasive' and 'non-native' as search words.

According to the results of the questionnaire survey, each fish species was given a rank (from one to nine) to quantify propagule pressure based on their presence in home aquaria, retail shops and breeding centers in three selected districts. If a fish species was present only in one site in one district, it was scored as one. A fish species was scored as five if it occurred in home aquaria in two districts, retail shops in two districts and a breeding center in one district. Likewise, a fish species that was present in all the sites (home aquaria, retail shops and breeding centers in three selected districts) was scored as nine. Finally, the fish species that had

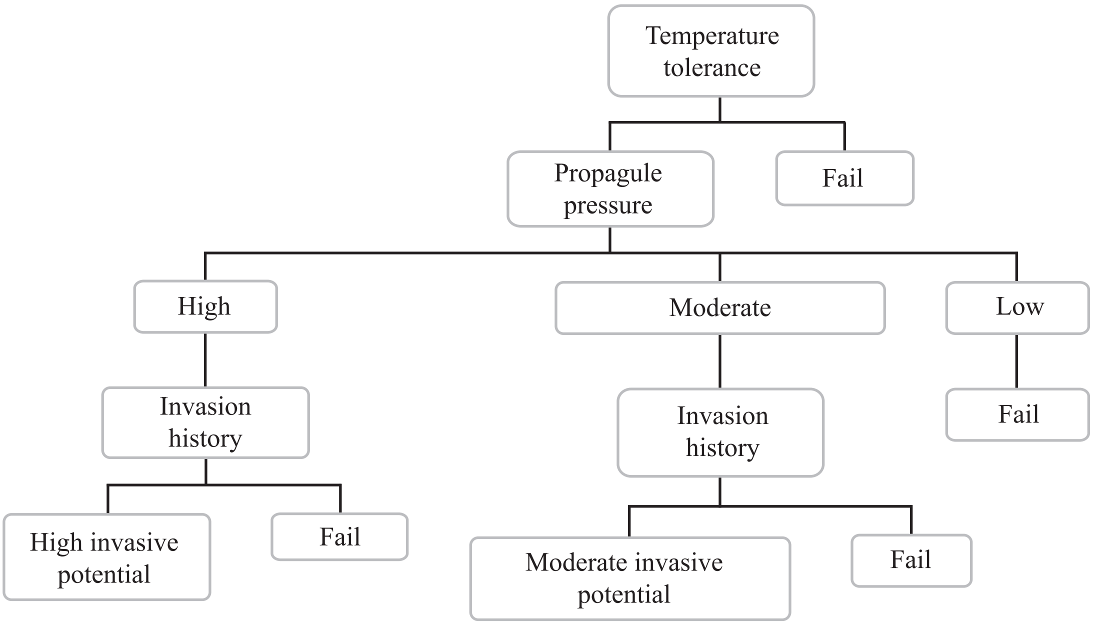

Figure 2. Flow chart used to assess the invasive potential of ornamental fish species (Modified after Rixon *et al*., 2005).

high propagule pressure (7–9), moderate propagule pressure (4–6) and low propagule pressure (1–3) were identified. For this study, species varieties were assigned to a species level when possible (e.g., the carp variety Kohaku was given as *Cyprinus carpio*). Hybrids recorded in each site were not categorized into species, i.e., hybrid swordtail fish.

Correlation between the number of fish released and the number of fish kept in home aquaria

The Spearman correlation test was conducted to assess the relationship between the number of fish of each species kept in home aquaria with the number of those fish species released into the natural environment by hobbyists from October 2018 to September 2019. The statistical test was performed using Minitab version 12.

RESULTS AND DISCUSSION

Provisional checklist of aquarium fish species traded in Sri Lanka

This study identified 59 fish species belonging to 14 families currently in the aquarium trade, representing the minimal aquarium fish species pool for Sri Lanka (Table 1). Most species recorded in the study were classified under the Families Cichlidae, Cyprinidae, Characidae, Osphronemidae and Poeciliidae (Figure 3) and were tropical; the rest originated from sub-tropical regions, without any single species from temperate waters. None of the native freshwater or marine aquarium fish species were kept in home aquaria and breeding centers and traded in retail shops. Although Sri Lanka exports more than 50 native aquarium fish species (Gunasekara, 2011), none of these species were produced in the breeding facilities examined in this study. The majority of Sri Lankan native fish species that are being traded in the international aquarium markets may be collected from the wild environment (Ekaratne, 2000; Wijesekara and Yakupitiyage, 2001; Goonatilake, 2012). However, aquarium fish breeders in Sri Lanka breed *Epalzeorhynchos bicolor, Balantiocheilos melanopterus, Pangasianodon hypophthalmus, Pseudotropheus saulosi, Maylandia lombardoi, Cyprinus carpio* and *Betta splendens,* which have all been listed under the Threatened category in the IUCN Redlist (IUCN, 2022). The breeding of these species in captivity for aquarium purposes may reduce the collection pressure on wild fish stocks in their native ranges.

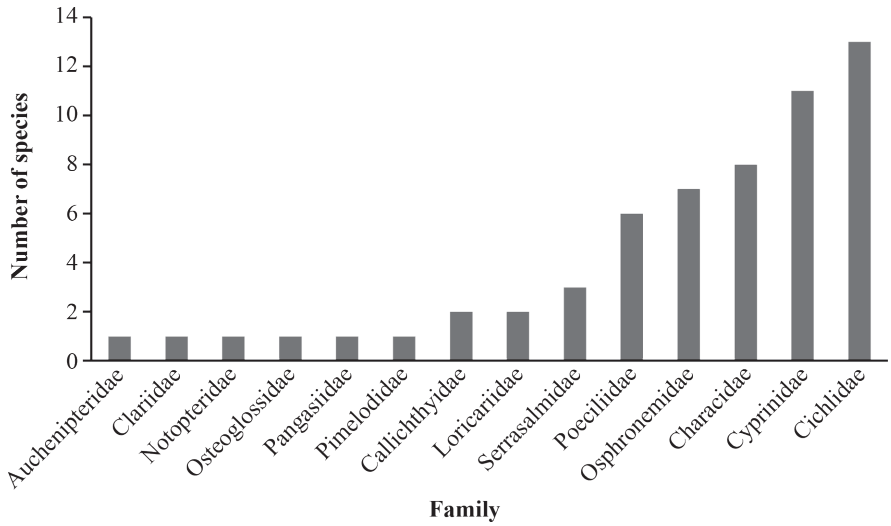

Figure 3. Number of aquarium fish species and their families recorded in Sri Lanka.

Table 1. Families, species, common names and thermal tolerance of aquarium fish species recorded in Sri Lanka.

Family/Species with authority	Common name	Thermal tolerance (Source from Froese and Pauly, 2017)
Auchenipteridae		
Trachycorystes trachycorystes	Black catfish	Tropical; 22–26 °C
Callichthyidae		
Corydoras panda	Panda corydora	Tropical; 20–25 °C
Corydoras paleatus	Peppered corydora	Subtropical; 18–23 °C
Characidae		
Paracheirodon innesi	Neon tetra	Tropical; 20–26 °C
Hyphessobrycon herbertaxelrodi	Black neon tetra	Tropical; 23–27 °C
Hyphessobrycon pulchripinnis	Lemon tetra	Tropical; 23–28 °C
Paracheirodon axelrodi	Cardinal tetra	Tropical; 23–27 °C
Gymnocorymbus ternetzi	Black tetra	Subtropical; 20–26 °C
Hyphessobrycon columbianus	Colombian tetra	Tropical; 22–26 °C
Hyphessobrycon eques	Jewel tetra	Tropical; 22–26 °C
Hyphessobrycon rosaceus	Rosy tetra	Tropical; 24–28 °C
Cichlidae		
Astronotus ocellatus	Oscar	Tropical; 22–25 °C
Pterophyllum scalare	Angelfish	Tropical; 24–30 °C
Pseudotropheus saulosi	Malawi	Tropical; 23–27 °C
Amphilophus citrinellus	Midas cichlid	Tropical; 23–33 °C
Astronotus labiatus	Red devil	Tropical; 28–33 °C
Maylandia lombardoi	Kenya cichlid	Tropical; 24–26 °C
Hemichromis bimaculatus	Jewelfish	Tropical; 21–23 °C
Melanochromis auratus	Golden mbuna	Tropical; 22–26 °C
Labidochromis caeruleus	Blue streak hap	Tropical; 23–26 °C
Amatitlania nigrofasciata	Convict cichlid	Tropical; 20–36 °C
Symphysodon discus	Red discus	Tropical; 26–30 °C
Callochromis macrops	Bunker fish	Tropical; 24–26 °C
Symphysodon aequifasciatus	Blue discus	Tropical; 26–30 °C
Clariidae		
Clarias batrachus	Marble catfish	Tropical; 10–28 °C
Cyprinidae		
Cyprinus carpio	Carp	Subtropical; 3–35 °C
Carassius auratus	Goldfish	Subtropical; 0–41 °C
Danio rerio	Zebra danio	Tropical; 18–24 °C
Puntius tetrazona	Tiger barb	Tropical; 20–26 °C
Pethia conchonius	Rosy barb	Subtropical; 18–22 °C
Pethia gelius	Golden barb	Subtropical; 18–22 °C
Barbonymus schwanenfeldii	Tinfoil barb	Tropical; 22–25 °C
Trigonostigma heteromorpha	Harlequin rasbora	Tropical; 22–25 °C
Balantiocheilos melanopterus	Tricolor shark minnow	Tropical; 22–28 °C
Epalzeorhynchos bicolor	Redtail shark minnow	Tropical; 22–26 °C
Epalzeorhynchos frenatus	Rainbow shark minnow	Tropical; 24–27 °C

Table 1. (Continued)

Family/Species with authority	Common name	Thermal tolerance (Source from Froese and Pauly, 2017)
Loricariidae		
Pterygoplichthys pardalis	Amazon sailfin catfish	Tropical; 23–28 °C
Hypostomus plecostomus	Suckermouth catfish	Tropical; 20–28 °C
Osphronemidae		
Trichopodus leerii	Pearl gourami	Tropical; 24–28 °C
Trichopodus microlepis	Moonlight gourami	Tropical; 26–30 °C
Osphronomus goramy	Giant gourami	Tropical; 20–30 °C
Helostoma temminckii	Kissing gourami	Tropical; 22–28 °C
Trichogaster lalius	Dwarf gourami	Tropical; 25–28 °C
Trichogaster trichopterus	Three spot gourami	Tropical; 22–28 °C
Betta splendens	Siamese fighting fish	Tropical; 24–30 °C
Osteoglossidae		
Osteoglossum bicirrhosum	Arowana	Tropical; 24–30 °C
Pangasiidae		
Pangasianodon hypophthalmus	Striped catfish	Tropical; 22–26 °C
Poeciliidae		
Xiphophorus hellerii	Green swordtail	Tropical; 22–28 °C
Xiphophorus maculatus	Southern platy fish	Tropical; 18–25 °C
Poecilia latipinna	Sailfin molly	Subtropical; 20–28 °C
Poecilia reticulata	Guppy	Tropical; 18–28 °C
Poecilia sphenops	Molly	Tropical; 18–28 °C
Poecilia velifera	Yucatan molly	Tropical; 25–28 °C
Serrasalmidae		
Metynnis hypsauchen	Silver dollar	Tropical; 24–28 °C
Piaractus mesopotamicus	Pacu	Subtropical; 15–28 °C
Serrasalmus natterreri	Red piranha	Subtropical; 23–27 °C
Notopteridae		
Chitala ornata	Clown featherback	Tropical; 24–28 °C
Pimelodidae		
Phractocephalus hemioliopterus	Redtail catfish	Tropical; 20–26 °C

Conservation status of aquarium fish species

Out of all the aquarium fish species surveyed in this study, 28 species have Not been Evaluated, 21 species are of Least Concern, two species are Near Threatened, four species are Vulnerable, two species are Endangered and only a single species is categorized under Critically Endangered and Data Deficient categories (IUCN, 2022). Figure 4 illustrates the percentages of IUCN categories of aquarium fish species recorded from Sri Lanka. Eight aquarium fish recorded in the study were classified under threatened categories in the IUCN Red list, i.e., *Epalzeorhynchos bicolor* (Critically Endangered), *Balantiocheilos melanopterus*, *Pangasianodon hypophthalmus* (Endangered) and *Pseudotropheus saulosi, Maylandia lombardoi. Cyprinus carpio, Bettta splendens* (Vulnerable) in their native ranges.

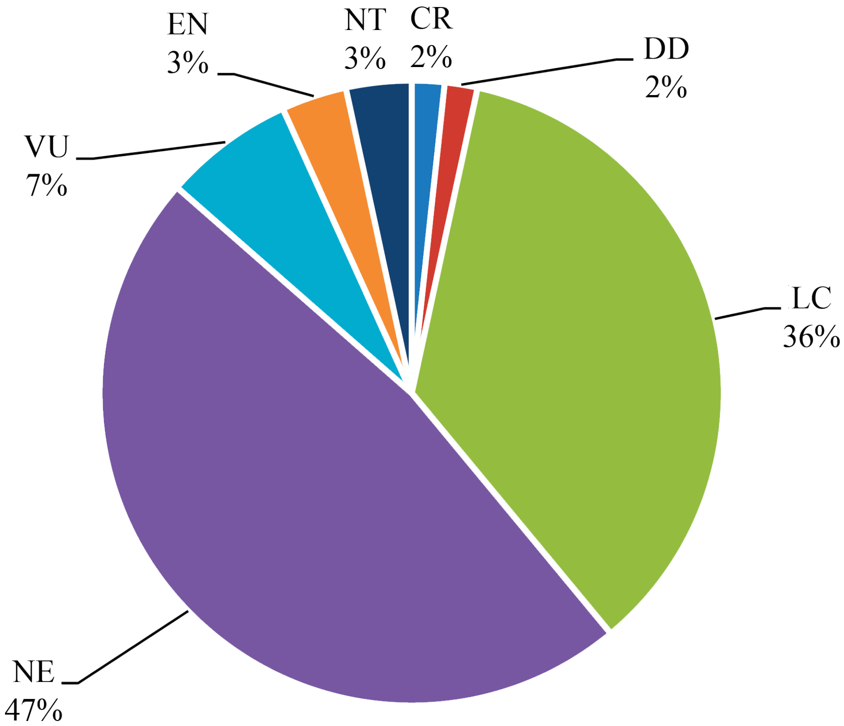

Figure 4. Percentages of IUCN (2022) threat categories of aquarium fish species recorded in Sri Lanka.

Note: NE = Not Evaluated; DD = Data Deficient; LC = Least Concern; NT = Near Threatened; VU = Vulnerable; EN = Endangered; CR = Critically Endangered

Propagule pressure of aquarium fish species

The propagule pressure of aquarium fish species recorded in the study is given in Table 2. Of 59 aquarium fish species recorded, 28 have moderate to high propagule pressure.

Invasive potential of aquarium fish species

Aquarium fish species that have shown high to moderate success in becoming invasive in Sri Lanka based on their thermal tolerance, propagule pressure and invasion history are given in Table 3. Six of 17 aquarium fish species with invasive potential already have established populations in the environment in Sri Lanka. Therefore, the number of aquarium fish species that can potentially be invasive in Sri Lanka is 11.

Seventy-one percent of aquarium fish species recorded did not have invasive potential in the country due to low propagule pressure and lack of invasion history. Species of particular concern are *Astronotus ocellatus, Barbonymus schwanenfeldii, Carassius auratus, Hypostomus plecostomus, Pangasianodon hypophthalmus, Poecilia sphenops, Puntius tetrazona, Trichopodus microlepis, Poecilia latipinna, Xiphophorus hellerii* and *Xiphophorus maculatus*. These species have yet to be established in the environment in Sri Lanka. They have appropriate thermal tolerance, high to moderate propagule pressure and invasion histories elsewhere in the world. Therefore, there is a high possibility of establishing these non-native fish species in the environment in Sri Lanka unless necessary precautions are taken to prevent their introduction to the environment. According to the results, Poeciliidae and Cyprinidae had the highest number of species with invasive potential in Sri Lanka. These families were also highlighted by Bomford and Glover (2004), who identified poeciliids and cyprinids among the highest-risk taxa based on invasive potential in the Australian tropical region. Currently, six poeciliids and five cyprinids are among the 31 invasive fish species found in Australia (Lintermans, 2004). Magalhães and Jacobi (2013a), who used a model consisting of biological traits, invasion history, popularity, availability and abiotic features of the environment to assess the invasive potential of aquarium fish, have also predicted the invasive potential of *Carassius auratus, Xiphophorus hellerii, Xiphophorus maculatus, Poecilia reticulata,* and *Poecilia latipinna* in rivers in southeastern Brazil.

Temperature tolerance, which has been an important factor in determining the success of fish invasion (Rixon *et al*., 2005), was the first criterion used in the present study in assessing the invasiveness of fish species. As all the fish species recorded in this study were native to tropical and subtropical regions, they could permanently survive all year round in the environment of Sri Lanka. *Poecilia sphenops, Poecilia reticulata* and *Xiphophorus helleri*, which have high invasive potential in Sri Lanka, were unable to establish themselves in the environment in the Czech Republic, mainly due to thermal differences in their new habitat (Lusk *et al*., 2010). Most aquarium fish of tropical origin cannot survive or reproduce in Europe due to temperature variations (Maceda-Veiga *et al*., 2013). Therefore, the survival of species recorded in the present study is more likely in environments of other countries with tropical climatic conditions if enough fish are released or escaped.

Except for *Chitala ornata*, all the aquarium fish species with well-established populations in the environment in Sri Lanka (Silva and Kurukulasuriya, 2010; Epa, 2014; MMDE, 2015) were categorized

Table 2. Propagule pressure of aquarium fish species recorded from Sri Lanka.

Propagule pressure	Number of species	Fish species
Low (1-3)	31	*Corydoras paleatus, Hyphessobrycon pulchripinnis, Astronotus labiatus, Hemichromis bimaculatus, Melanochromis auratus, Amatitlania nigrofasciata, Callochromis macrops, Symphysodon aequifasciatus, Pethia gelius, Balantiocheilos melanopterus, Epalzeorhynchos frenatus, Trachycorystes trachycorystes, Hyphessobrycon herbertaxelrodi, Paracheirodon axelrodi, Gymnocorymbus ternetzi, Hyphessobrycon columbianus, Hyphessobrycon eques, Hyphessobrycon rosaceus, Pseudotropheus saulosi, Symphysodon discus, Trigonostigma heteromorpha, Helostoma temminckii, Trichogaster lalius, Poecilia velifera, Piaractus mesopotamicus, Amphilophus citrinellus, Epalzeorhynchos bicolor, Chitala ornata, Phractocephalus hemioliopterus, Serrasalmus natterreri*
Moderate (4-6)	14	*Corydoras panda, Paracheirodon innesi, Labidochromis caeruleus, Puntius tetrazona, Pethia conchonius, Barbonymus schwanenfeldii, Trichopodus leerii, Trichopodus microlepis, Betta splendens, Osteoglossum bicirrhosum, Poecilia latipinna, Maylandia lombardoi, Osphronomus goramy, Metynnis hypsauchen*
High (7-9)	14	*Astronotus ocellatus, Pterophyllum scalare, Danio rerio, Hypostomus plecostomus, Clarias batrachus, Cyprinus carpio, Carassius auratus, Pterygoplichthys pardalis, Trichogaster trichopterus, Pangasianodon hypophthalmus, Xiphophorus maculatus, Poecilia reticulata, Xiphophorus hellerii, Poecilia sphenops*

Table 3. Aquarium fish species that have high to moderate potential to become invasive in Sri Lanka based on their thermal tolerance, propagule pressure and invasion history.

Species	Invasion history
Moderate invasive potential	
Trichopodus microlepis	Colombia (Welcomme, 1988), Malaysia (Ang *et al*., 1989), Singapore (Low and Lim, 2012)
Puntius tetrazona	Singapore (Ng and Tan, 2010), Mexico, USA, Puerto Rico, Colombia, Brazil and Australia (Nico *et al*., 2018)
Barbonymus schwanenfeldii	Singapore (Ng and Tan, 2010), Malaysia (Shafiq *et al*., 2014), USA (Nico *et al*., 2018)
Poecilia latipinna	Australia (Arthington, 1989), Greece (Papavlasopoulou *et al*., 2010), Iran (Esmaeil *et al*., 2017), USA (Nico *et al*., 2018), Australia (Ebner *et al*., 2020)
*Osphronomus goramy**	India (Shetty *et al*., 1989; Knight, 2010; Sandilyan, 2016), Sri Lanka (Pethiyagoda, 1990; Bambaradeniya, 2000), Singapore (Ng and Tan, 2010)
High invasive potential	
Astronotus ocellatus	Malaysia (Ang *et al*., 1989), Australia (McKay, 1989), USA (Courtenay and Stauffer, 1990), Spain (Elvira and Almodóvar, 2001)
*Poecilia reticulata**	Australia (Lindholm *et al*., 2005), India (Sandilyan, 2016), Sri Lanka (Marambe *et al*., 2011), Germany (Jourdan *et al*., 2014), Rwanda (Gomes-Silva *et al*., 2020), French Guiana (Brosse *et al*., 2021)
Pangasianodon hypophthalmus	Colombia (Castellanos-Mejía *et al*., 2021), India (Sandilyan, 2016)
Hypostomus plecostomus	China (Li *et al*., 2007), Spain (Elvira and Almodóvar, 2001), French Guiana (Brosse *et al*., 2021)
*Clarias batrachus**	Taiwan (Liao and Liu, 1989), Sri Lanka (Bambaradeniya, 2002), China (Li *et al*., 2007)
*Cyprinus carpio**	Australia (Arthington, 1989), India (Shetty *et al*., 1989; Biju Kumar, 2000; Sandilyan, 2016), Indonesia (Eidman, 1989), Sri Lanka (Marambe *et al*., 2011)
Carassius auratus	Indonesia (Eidman, 1989), Australia (McKay, 1989), Greece (Papavlasopoulou *et al*., 2010), India (Sandilyan, 2016)
*Pterygoplichthys pardalis**	Singapore (Ng and Tan, 2010), USA (Strecker *et al*., 2011), Taiwan (Wu *et al*., 2011), Thailand (Chaichana and Jongphadungkiet, 2012), Sri Lanka (Epa, 2014), India (Sandilyan, 2016), Bangladesh (Hossain *et al*., 2018)
*Trichogaster trichopterus**	Malaysia (Ang *et al*., 1989), Indonesia (Eidman, 1989), Taiwan (Liao and Liu, 1989), Singapore (Ng and Lim, 1996; Li *et al*., 2016), Sri Lanka (Pethiyagoda, 1990; Bambaradeniya, 2000), China (Mu *et al*., 2008), United States (Courtenay and Stauffer 1990), Australia (Ebner *et al*., 2020)
Xiphophorus maculatus	Australia (McKay, 1989), India (Raghavan *et al*., 2008), Australia (Ebner *et al*., 2020)
Xiphophorus hellerii	Australia (McKay, 1989), India (Sandilyan, 2016), Australia (Ebner *et al*., 2020)
Poecilia sphenops	Singapore (Li *et al*., 2016), China (Liang *et al*., 2006)

Note: * Fish species that already have breeding populations in the environment in Sri Lanka.

as species with invasive potential in the present study. Therefore, the possibility of reintroducing aquarium fish species already established in the environment is high in Sri Lanka, as observed in Brazil (Patoka *et al*., 2018) and French Guiana (Brosse *et al*., 2021). As such, an increase in population size and further expansion of the existing range of these species could be expected in the future. Red piranha, *Pygocentrus nattereri*, is banned from sale in Sri Lanka but was available in small numbers in aquarium retail shops. The law enforcement authorities of the country need to pay attention to the presence of *Pygocentrus nattereri* in the aquarium trade, as this voracious carnivore has already established itself in rivers, lakes, ponds and other inland freshwater bodies in neighboring India (Biju Kumar, 2000).

Reasons for aquarium fish release and releasing pathways

Four pathways that hobbyists and industry release aquarium fish into the environment were reported in this study (Table 4). Fish were intentionally released to dug wells and other water bodies, while unexpected floods and heavy rain caused unintentional fish releases. None of the aquarium fish retailers and breeders intentionally released fish into the environment. However, many fish breeding centers have been subjected to floods within the last ten years, releasing many non-native fish into the environment. *Pterygoplichthys pardalis, Cyprinus carpio* and *Carassius auratus* have been introduced to the environment through all the pathways reported in this study. The highest number of species were released due to unexpected floods in the farming areas.

The causes of the introduction of non-native aquarium fish by hobbyists to the environment and the species they introduced within the last ten years are given in Table 5.

Flooding and excessive rain were the two main vectors that accidentally introduced non-native fish species to the environment in Sri Lanka, a previously observed situation in Bohemia (Lusk *et al*., 2010) and India (Sandilyan, 2016). In some cases, healthy females of some species (e.g., rosy barb *Pethia conchonius*) are intentionally released into the environment because they are less colorful than male individuals (Magalhães and Jacobi, 2013a), a practice that was not observed in the present study. Several aquarium hobbyists claimed

Table 4. Percentages of hobbyists, retailers and breeders who released aquarium fish to the environment and the names of species released within the last ten years (H-hobbyists, n = 40; R-retailers, n = 20; B-fish breeders, n = 10).

Pathway	Site			Species
	% H	% R	% B	
Intentional				
Release to natural water bodies	22	22	22	*Pterygoplichthys pardalis, Cyprinus carpio, Carassius auratus, Poecilia reticulata, Xiphophorus maculatus, Corydoras panda, Clarias batrachus*
Release to dug wells	15	15	15	*Pterygoplichthys pardalis, Cyprinus carpio, Carassius auratus, Poecilia reticulata, Trichogaster trichopterus*
Unintentional				
Escapes during flood	15	33	44	*Pterygoplichthys pardalis, Cyprinus carpio, Carassius auratus, Pangasianodon hypophthalmus, Hypostomus plecostomus, Clarias batrachus, Xiphophorus maculatus, Xiphophorus hellerii, Poecilia sphenops, Poecilia reticulata*
Escapes during heavy rain	7	33	22	*Pterygoplichthys pardalis, Cyprinus carpio, Clarias batrachus, Pangasianodon hypophthalmus, Poecilia reticulata*

Table 5. Reasons for hobbyists' intentional introduction of aquarium fish to the environment in Sri Lanka.

Reason	Species released
Aggressive behavior on other fish	*Clarias batrachus, Trichogaster trichopterus, Xiphophorus maculatus, Betta splendens, Pangasianodon hypophthalmus, Corydoras panda*
Diseases	*Cyprinus carpio, Carassius auratus, Corydoras panda, Xiphophorus maculatus, Xiphophorus hellerii*
Excessive numbers due to high reproduction rate	*Poecilia reticulata, Xiphophorus hellerii, Xiphophorus maculatus*
Excessive growth of fish/too large to be kept in the aquarium	*Pterygoplichthys pardalis, Cyprinus carpio, Helostoma temminkii*

that the Buddhist practice of releasing captive animals into the wild environment played a role in deciding to release unwanted fish, even knowing its ecological consequences. Therefore, though this practice is founded on the good intention of protecting living organisms, it represents a potential pathway for introducing non-native species into aquatic ecosystems (Everard *et al*., 2019).

Correlation between the number of fish released and the number kept in home aquaria

Aquarium hobbyists in the Kandy, Gampaha and Polonnaruwa districts released 12 fish species, including *Carassius auratus, Clarias batrachus, Cyprinus carpio, Corydoras panda, Hypostomus plecostomus, Pangasianodon hypophthalmus, Pterygoplichthys pardalis, Poecilia reticulata, Poecilia sphenops, Trichogaster trichopterus, Xiphophorus hellerii* and *Xiphophorus maculatus* between October 2018 and September 2019. According to the Spearman correlation test, the number of fish of each species released into the natural environment by aquarium hobbyists was positively correlated ($r = 0.92$; $p<0.05$) to the number of individuals of that fish species kept in home aquaria (Figure 5). As such, the propagule pressure, which significantly contributes to fish introduction to the natural environment, was correlated to the number of fish kept in home aquaria. Rixon *et al*. (2005) and Duggan *et al*. (2006) indicated that popularity, as measured by the frequency of stores selling a species, was important in determining propagule pressure.

As already accepted, once an invasive species has ben fully established and naturalized, it is difficult to completely remove it from its new range (Padilla and Williams, 2004; Lusk *et al*., 2010; Rahim *et al*., 2013, Magalhães *et al*., 2020). Therefore, the most effective way to prevent the negative impacts of such introductions is to not release them into the environment. To develop the aquarium fish export industry, the Sri Lankan government encourages individuals and corporate sector organizations to introduce and cultivate non-native aquarium fish species. Implementing this policy without proper monitoring and control mechanisms not only has introduced new fish species into Sri Lanka from other countries, but also has increased the production and transfer of non-native fish from Sri Lanka to the rest of the world.

According to the observations made during this study, we recommend developing and enforcing a positive list of aquarium organisms that the aquarium fish industry may import, conducting an initial environment examination (IEE) and environmental impact assessment (EIA) for all future intentional releases of non-native fishes, and enforcing existing laws and regulations through the intervention of the government. The importation of *Penaeus vannamei* in June 2018 to develop the shrimp culture industry without proper impact assessment shows the weakened efficiency of legislative norms, connected with the desire to support commercial development while disregarding the possible long-term impacts of such introductions

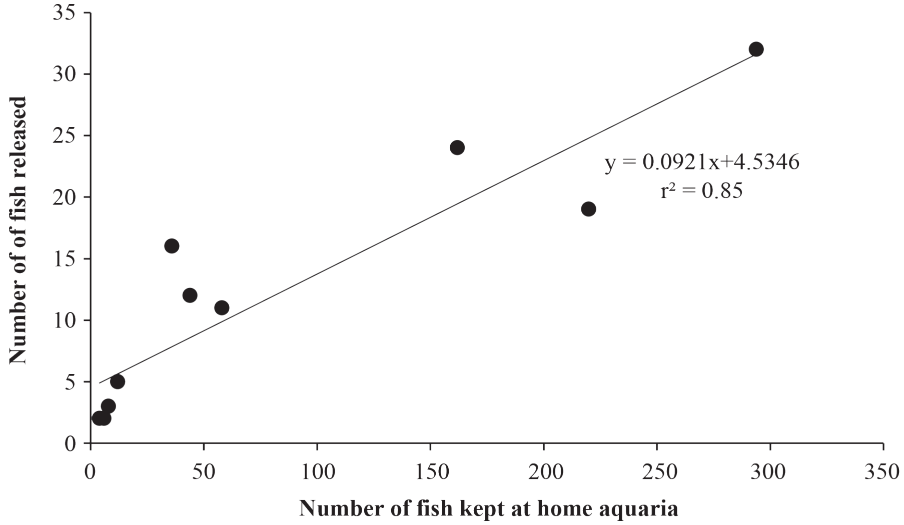

Figure 5. Correlation between the number of fish released and the number kept in home aquaria. (Each data point represents a different fish species with reported releases.)

on aquatic ecosystems of the country. Education, training and extension should be used to inform workers in the aquarium industry and the general public of the dangers of the unregulated release of nonnative species. Implementation of the recommendations given in this article should be done solely to prevent unnecessary introductions of aquarium fish species to the environment but not to affect the development of the aquarium industry.

CONCLUSION

In Sri Lanka, fish from at least 59 different species in 14 different families are traded. Of these, 48 species are native to tropical regions, and 11 species are native to subtropical regions. There are six established populations of the 17 aquarium fish species that have the potential to become invasive in Sri Lanka. *Astronotus ocellatus, Barbonymus schwanenfeldii, Carassius auratus, Hypostomus plecostomus, Pangasianodon hypophthalmus, Poecilia sphenops, Puntius tetrazona, Trichopodus microlepis, Poecilia latipinna, Xiphophorus hellerii,* and *Xiphophorus maculatus* are among the aquarium fish species that can potentially be invasive in the country. The number of fish of a species kept in home aquaria is positively correlated to the number of that fish species released into the natural environment. In Sri Lanka, there is an urgent need for a well-coordinated institutional structure to regulate the introduction of non-native aquarium fish into the environment.

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