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ORIGINAL PAPER

Ornamental fish in the South African pet shop trade: potential risk to natural aquatic ecosystems

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Abstract The aquarium pet trade is one of the leading pathways for the introduction of invasive species into natural ecosystems. In 2018, we surveyed pet shops across South Africa to obtain a checklist of ornamental fish species in the aquarium pet shop trade and to assess their invasion potential using sourced data (e.g., natural environment, native range, introduction status, impact status and climatic zone). We evaluated selected common aquarium fish species with high invasion potential according to previous invasion history. We highlighted the need for the development of a management strategy for the aquarium pet trade in South Africa. We identified 312 fish species belonging to 77 families and 182 genera. Most pet shops were in Gauteng Province (n = 38), with few in Limpopo Province (n = 3). Gauteng had the highest number of fish species (n = 271), while North West Province had the lowest number (n = 95). Pet shops were dominated by freshwater species (68%), followed by marine species (22%), while the origin of 30 species (10%) was transitional aquatic ecosystems. Most freshwater taxa were native to South America and Asia, while most marine species were from the Pacific and Indo-Pacific Oceans. Most (88%) species were tropical, 10% subtropical, and 1% temperate. Several (n = 28) species had more than 50% frequency of occurrence, representing the most popular ornamental fishes. Several (n = 13) species are invasive in South Africa and other parts of the world. The system of importation of ornamental fish in South Africa is not clear. Although there is a recommendation that these importations must be regulated according to the whitelist and blacklist in South

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Africa, it is not clear how this is implemented in practice. We demonstrated a high risk of alien fish species introduction in South Africa through the aquarium pet shop trade.

Keywords Alien species · Aquatic systems · Aquarium trade · Introduction pathways · Invasions · South Africa

Introduction

The pet trade is identified as a billion-dollar growing business globally (Pimentel et al. 2005; King 2019; Gippet and Bertelsmeier 2021; Dickey et al. 2023). Trade is stimulated by free trade policies (Jenkins 1996), globalised markets (Margolis et al. 2005; King 2019; Guilder et al. 2022) and an increase in online shopping and options (Kay and Hoyle 2001; Borges et al. 2021). The nature of the business has aided the simple and fast trade of species between distant locations, increasing the risk of the introduction and establishment of alien species and disease spread (Dehnen-Schmutz et al. 2007; Lockwood et al. 2019; Guilder et al. 2022). Although there is trade in many taxa, freshwater and marine fish species make up the majority of animals being traded as pets and ornamentals (Smith et al. 2009; Farrah et al. 2019; Gippet and Bertelsmeier 2021). About 150–256 invasive fish species in natural ecosystems worldwide are linked to the aquarium trade (Padilla and Williams 2004; Farrah et al. 2019). In freshwater ecosystems, invasive fish species can alter ecosystem processes, modify community structure through competition with, and predation on native species and can alter the structure and function of the invaded system, leading to the displacement, decline and, in some cases, extinction of the native fish species (Gurevitch and Padilla 2004; Moorhouse and Macdonald 2015; Bellard et al. 2016; Hammer et al. 2019; Burnett et al. 2023). Furthermore, invasive fish species can clog waterways (Schardt 1997) and introduce pathogens that may pose threats to human health (Ciruna et al. 2004; Padilla and Williams 2004). Apart from the impacts on the receiving systems, there are also effects associated with aquarium trade on the donor areas during collection (Papavlasopoulou et al. 2014). Although about 90% of the freshwater aquarium fish are cultured in captivity (Tlusty 2002), the majority of supplies of marine fish species come from wild sources, which usually involve illegal/ destructive fishing practices which severely damage endangered fish species and fragile aquatic systems (Papavlasopoulou et al. 2014).

Aquarium fish species are generally tolerant to the stressful conditions of collection and transportation and display physiological plasticity that enables them to survive and reproduce in aquariums (Padilla and Williams 2004). Such traits may allow these fish species to survive and establish themselves in new aquatic environments (Padilla and Williams 2004). Aquarium fish species are often introduced into the wild through intentional release by owners who dump unwanted fish species (Gertzen et al. 2008) as well as the ritualistic release of species during religious practices (Severinghaus and Chi 1999; Wasserman et al. 2019). Unintentional releases of fish species are often through escape from the tanks and breeding farms, and drainage of water-containing organisms from tanks and public aquariums (Dickey et al. 2022). Intentional releases from the aquarium trade are a significant pathway for spreading alien fish species (McDowall 2004), with fish species from the aquarium trade comprising one-third of the world's aquatic invasive species (Padilla and Williams 2004). Prevention of species introductions is the foundation for managing invasive fish species (Vander Zanden and Olden 2008; Weyl et al. 2020). However, there are difficulties in developing and implementing integrated approaches to manage invasion vectors because pathways to aquatic species introductions are diverse, dynamic over time and vary geographically and taxonomically (Moyle and Marchetti 2006). Consequently, improved biosecurity measures are required upon entering a country (Collins et al. 2012).

In terms of biosecurity control, there are two main approaches used by authorities to address threats from aquarium fishes; these include the implementation of blacklists and whitelists. Blacklists consist of a small group of known high-risk taxa and is subject to strict regulations (Copp et al. 2010). Whitelists are implemented only when manageable fish are permitted (Whittington and Chong 2007; Mäkinen et al. 2013). Overall, these suggested biosecurity controls of permitted lists are usually outdated, with the aquariums and trade in aquarium and ornamental fish species generally being an unregulated industry globally (Padilla and Williams 2004), with the most

popular and beautiful species being traded irrespective of their "listing" (Gippet and Bertelsmeier 2021). In general, the ornamental fish trade lacks reliable record-keeping of the type and number of fish species involved (Smith et al. 2008; Chang et al. 2009). For instance, South Africa utilised a 'whitelist' containing over 1000 species of alien ornamental fish until 2014 when the new 'blacklist' (invasive alien species lists and regulations) was implemented (Republic of South Africa *National Environmental Management: Biodiversity* Act 2014) (Republic of South Africa 2014; Wilson and Kumschick 2024). Since the implementation of the blacklist, no substantial regulations or improvements to this list have been undertaken. Consequently, little is known in the country regarding the extent of the aquarium trade and the associated diversity and abundance of fish in its trade market. Additionally, there is a high possibility that some species on both lists may pose significant risks to inland aquatic systems if accidentally or deliberately released (Mäkinen et al. 2013; Marr et al. 2017; Weyl et al. 2020; Evans et al. 2022).

The ornamental fish trade constitutes a steadily growing proportion of fish introductions into South African waters (Van der Walt et al. 2017; Faulkner et al. 2020). Although relatively few species, such as the guppy (*Poecilia reticulate*), goldfish (*Carassius auratus*), sailfin catfish (*Pterygoplichthys disjunctivus*), butterfly koi (*Cyprinus carpio*), and largemouth bass (*Micropterus salmoides*), have naturalised in South Africa's freshwater systems (Jones et al. 2013; Mäkinen et al. 2013; Ellender and Weyl 2014; Marr et al. 2017; Weyl et al. 2020; Evan et al. 2022; Burnett et al. 2023), the potential introduction and naturalisation of other ornamental fish species into the wild persist.

While the number of alien fish species introduced through aquaculture in South Africa is known (Weyl et al. 2020; Zengeya and Wilson 2020), uncertainties exist regarding what was legally brought into the country and whether the imported population still exists. This study represents the first comprehensive examination of the national-level ornamental fish pet trade in South Africa. The country's generally warmer temperatures, accompanied by a large and growing human population, present numerous opportunities for introducing and establishing aquarium fish species.

A study previously conducted on ornamental fishes in South Africa only covered three big cities from only three provinces where 114 taxa whose common names could be linked directly to an inferred scientific name through DNA barcoding were recorded (van der Walt et al. 2017). Our study aimed to provide a checklist of ornamental fish species present in the aquarium pet trade across South Africa. We further collected qualitative data pertaining to various aspects of recorded ornamental fish species (e.g. natural environment, native range, introduction status, impact status, and climatic zone). Our specific objectives of this study were to: (a) compile a list of ornamental fish species present in the aquarium trade in South Africa; (b) predict which species have a high risk of invasion in South African aquatic systems based on traits and previous invasion history in their global invasion range; (c) estimate the "propagule pressure" based on occurrence frequency for each species in the pet shops; and (d) highlight the need for the development of a management strategy for aquarium pet trade in South Africa.

Methods

We surveyed pet shops in South Africa from October to December 2018 to document ornamental fish species in the pet trade. We made 96 on-site visits to pet shops in eight provinces around the country (Table 1). To get the number and location of pet shops in each province, we searched the web using the Google© search engine (www.google.com) and the keywords "pet shops", "pet stores", "aquarium stores", and provincial names and names of towns or cities within a province, e.g. for KwaZulu–Natal Province the search string was "pet stores in KwaZulu–Natal" or "pet shops in KwaZulu–Natal" or "aquarium stores in KwaZulu–Natal". We used Google Earth© to determine each shop's global position system (GPS) geographical location coordinates. The Northern Cape was the only province in the country excluded from the survey. This was because Google Earth and the Google search engine did not retrieve any information about the pet shops in this province. Depending on the number of pet shops present, a maximum of 3 days was spent in each province. The common names and/or species names were recorded in each pet shop and verified using FishBase's taxonomic backbone (www.

Table 1 The number of pet shops and aquarium fish species recorded in eight provinces of South Africa in 2018 (n = 312 total fish species identified as there was overlap between provinces)

Province	No. of pet shops	No. of freshwater fish species	No. of marine fish species	No. of transitional aquatic ecosystem species	Total no. of fish species
Free State (FS)	4	86	10	8	104
KwaZulu-Natal (KZN)	12	98	40	9	147
Limpopo (LP)	3	86	11	4	101
Mpumalanga (MP)	7	125	11	8	144
North West (NW)	6	81	8	6	95
Gauteng (GP)	38	202	50	19	271
Eastern Cape (EC)	11	100	9	6	115
Western Cape (WC)	15	123	44	10	177

One province was not assessed as no pet shops were identified

fishbase.org; Froese and Pauly 2021). The list from Strecker et al. (2011) was also used to convert common names to species names. On a few occasions, some common names (n = 12) resulted in no scientific names, so these fishes were excluded. Species whose scientific classification was recorded at a class or order level in the pet shops (n = 3) were excluded since family, genus, and natural environment could not be assigned. No molecular work was conducted to confirm species.

We obtained information on a fish species native range, natural environment and invasion status (introduction history and impacts) in its global introduction range and in South Africa from literature and databases such as Global Invasive Species Database (GISD) (http://www.issg.org) and FishBase (www.fishbase.org). The natural environment was classified as freshwater (FW), marine (M), freshwater-brackish (F-B), marine-brackish (M-B), and freshwater-marine-brackish (F-M-B), following Papavlasopoulou et al. (2014). The F-B, M-B and F-M-B environments are hereafter called transitional aquatic ecosystems. The native range was classified into continents and sub-continents for freshwater species and oceans for marine species, while basic climatic zones were classified into tropical, subtropical and temperate following the Köppen-Geiger climate classification system (Kottek et al. 2006). We determined spatial patterns of popularity by occurrence frequency. We calculated the occurrence frequency for each taxon as a proportion of pet shops in which that particular taxon was present across the country (Duggan et al. 2006). We used occurrence frequency as a proxy measure for propagule pressure, and this could provide a better proxy of 'frequency' than of 'numbers' released (Adopted from Duggan et al. 2006).

One of the other objectives of this study was to determine the number and status of alien aquatic species legally imported into the Republic of South Africa using the permit records. It was difficult to get records for freshwater species permits from the National Department of Forestry, Fisheries and the Environment (DFFE) because it was not easy to get access, and where access was granted, permit records were not digitised, which made processing the information difficult. We also contacted provincial and regional authorities in all the provinces and experienced challenges similar to those experienced by the national departments. These objectives were, therefore, not addressed in this present study but are aimed to be addressed in future studies.

Results

Composition of the fish species observed

In the present study, we identified 312 fish species belonging to 77 families and 182 genera (Figs. 1 and 2). Freshwater taxa were represented by 46 families, of which the most abundant were Cichlidae (49 species), Cyprinidae (36 species) and Characidae (28 species), which together accounted for 36% of observed species (Fig. 1). Marine taxa were represented by 31 families, with the most abundant families being Acanthuridae (14 species), Gobiidae (8

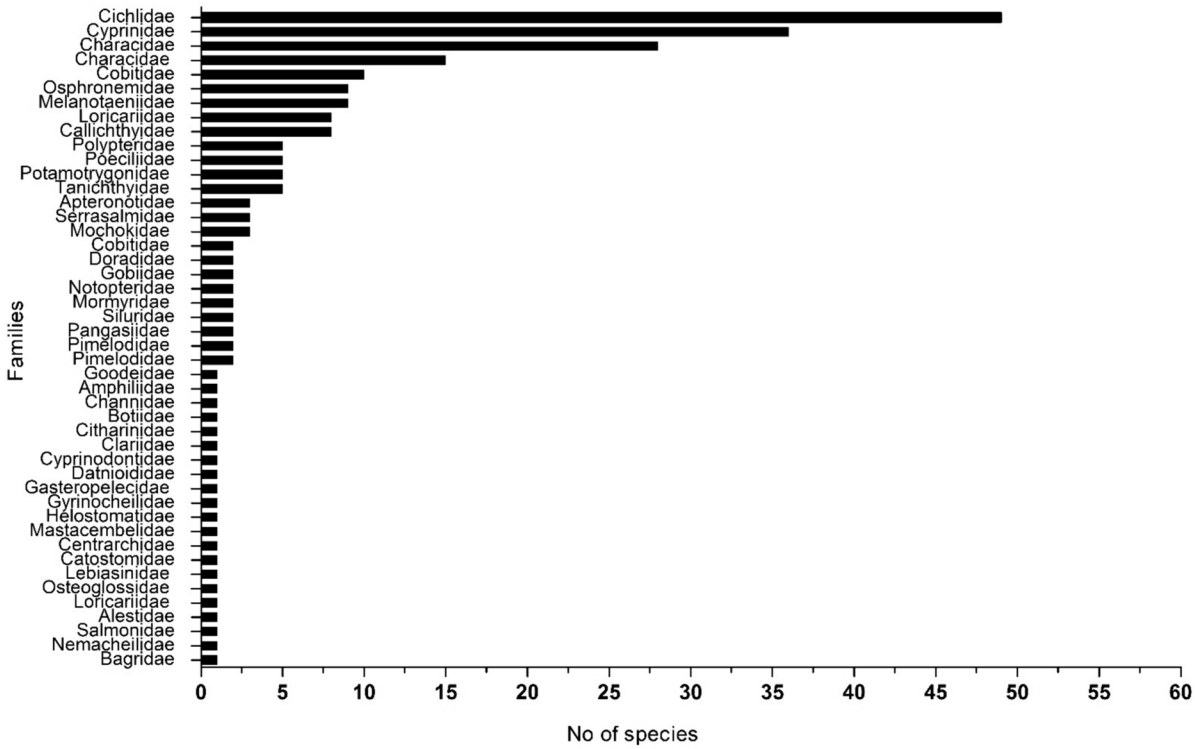

Fig. 1 Number of freshwater aquarium fish species from respective families in South African pet shops in the present study

species) and Labridae (7 species), together accounting for 9% of the observed taxa (Fig. 2).

Frequency of occurrence

The highest number of pet shops selling fish was recorded in the Gauteng Province (n = 38), while the lowest number was recorded in Limpopo (n = 3) (Table 1). In turn, the highest number of species was recorded in Gauteng Province (n = 271) and the lowest number in North West (n = 95) (Table 1). Pet shops across the country were dominated by freshwater fish taxa (214 species), representing 68% of the total number (Table 1, Fig. 3), while marine taxa consisted of 69 species, representing 22% of the total number (Table 1, Fig. 3), and 30 species (10% of the total number) were from transitional aquatic ecosystems (Table 1, Fig. 3).

Several (n = 28) species had an overall occurrence frequency greater than 50%, and these represented the most popular ornamental fishes among the pet shops across the country (Table 2). The five most popular species, sold in all provinces, were *Carassius auratus* (89%), *Poecilia reticulata* (83%), *Callopleisops altivelis* (79%), *Poecilia* spp. (78%), and *Betta splendens* (77%), of which four were freshwater species and one was a marine species (Tables 2 and 3). The freshwater guppy *P. reticulata* displayed the high occurrence frequency (> 80%) in all the provinces except for the Free State and Western Cape provinces (Table 3). Generally, the most popular fish species displayed an occurrence frequency of more than 80% in all provinces except for the Free State, while Mpumalanga and Limpopo provinces displayed an occurrence frequency of 100% for all five popular fish species (Table 3).

Native regions

Overall, the native region of most species was the tropics (88%), and a few species were from subtropical (10%) and temperate (1%) regions. Only 1% of species were located in the transitional climatic regions. For freshwater fish taxa (n = 214), most species were native to South America (36%), Asia (35%), and Africa (20%) (Fig. 4a). For

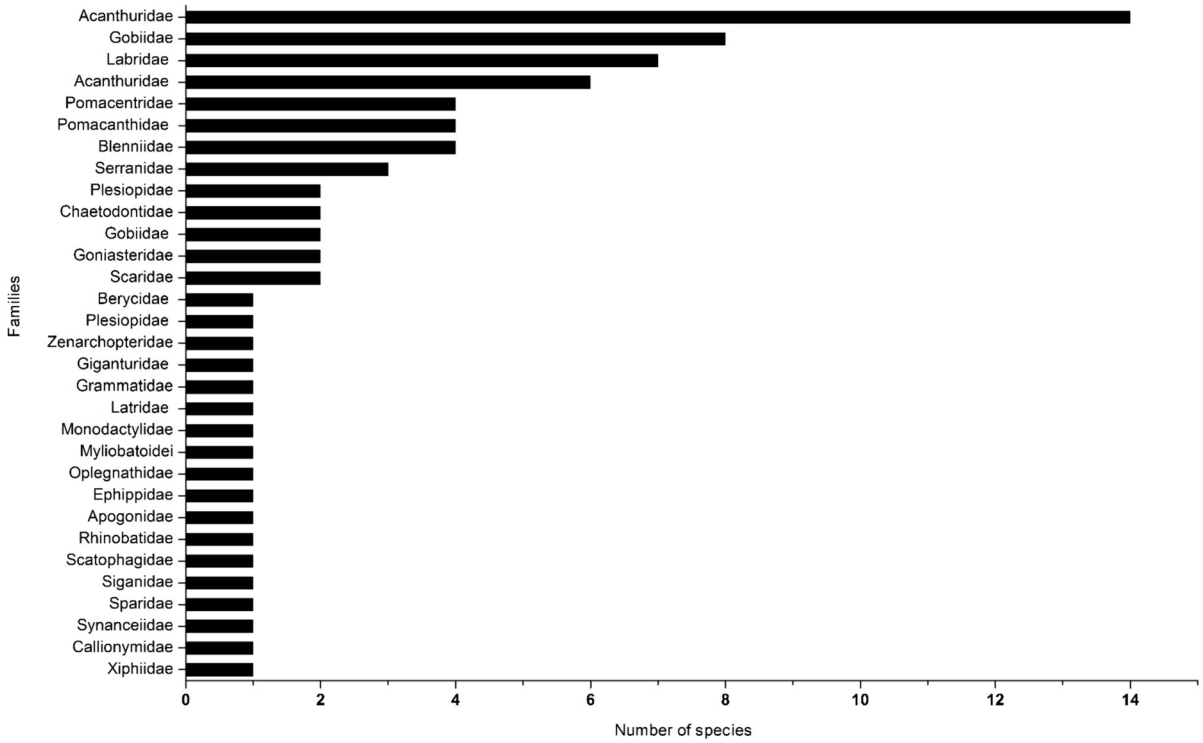

Fig. 2 Number of marine aquarium fish species from respective families in South African pet shops in the present study

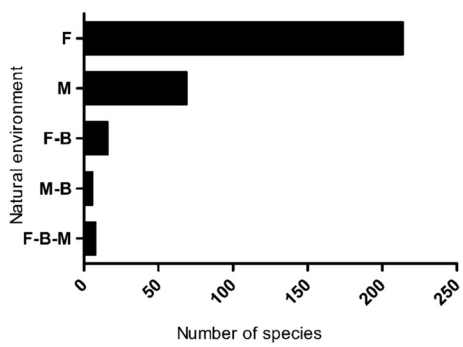

Fig. 3 Number of aquarium fish species recorded in South African pet shops according to their natural environment (*Note*: F = Freshwater, M = Marine, B = Brackish)

marine fish taxa (n = 69), the majority of the species were native to the Pacific Ocean (45%) and Indo–Pacific range (24%) (Fig. 4b). Only two species (*Sebastes* spp. and *Xiphias gladius*) had native ranges that occurred across more than one ocean, and *Gigantura indica* was circumglobal (Fig. 4b).

Invasion history

A total of 13 fish species recorded during the present study are reported to be invasive in their global introduction distribution range (Table 4). Of these, six species are known to have been introduced in South Africa. Their introduction status varied from introduced but not naturalised (*Serranochromis robustus*), naturalised but not invasive (*Pangasius sanitwongsei* and *Xiphophorus maculatus*), and invasive (*C. carpio*, *M. salmoides, C. auratus* and *P. reticulata*) (Supplementary Table S1). The majority (n = 9) of the invasive species were of freshwater origin, while three species were from transitional environments (Table 4). There was limited information on the impacts caused by the 13 invasive species on the global invasive range. Only one species (*M. salmoides*) had recorded impacts in South Africa and was assigned as causing major impacts, while the rest were assessed as "data deficient" (Table 4).

Table 2 Ornamental fish species with occurrence frequency greater than 50% across South Africa in the present study

Family	Species	Natural environment	% Occurence frequency
Cyprinidae	*Carassius auratus*	F	89
Poeciliidae	*Poecila reticulata*	F	83
Plesiopidae	*Calloplesiops altivelis*	M	79
Poeciliidae	*Poecilia* spp.	F	78
Osphronemidae	*Betta splendens*	F	77
Characidae	*Hyphessobrycon herbertaxelrodi*	F	73
Poeciliidae	*Xiphophorus maculatus*	F	72
Characidae	*Gymnocorymbus ternetzi*	F	71
Cichlidae	*Cyrtocara moorii*	F	70
Gyrinocheilidae	*Gyrinocheilus aymonieri*	F	70
Osphronemidae	*Trichogaster lalius*	F	68
Callichthyidae	*Corydoras aeneus*	F	67
Cyprinidae	*Cyprinus carpio*	FB	67
Cyprinidae	*Danio rerio*	F	66
Xiphiidae	*Xiphias gladius*	M	64
Cyprinidae	*Epalzeorhynchos frenatum*	F	63
Characidae	*Paracheirodon innesi*	F	63
Cyprinidae	*Pethia conchonius*	F	63
Helostomatidae	*Helostoma temminckii*	F	59
Callichthyidae	*Corydoras paleatus*	F	56
Cyprinidae	*Puntigrus tetrazona*	F	56
Characidae	*Moenkhausia sanctaefilomenae*	F	55
Characidae	*Hemigrammus erythrozonus*	F	54
Characidae	*Hyphessobrycon pulchripinnis*	F	54
Chaetodontidae	*Chaetodon* spp.	M	53
Osphronemidae	*Trichopodus trichopterus*	F	53
Cichlidae	*Pseudotropheus demasoni*	F	51
Cyprinidae	*Trigonostigma heteromorpha*	F	50

Natural environment (F = freshwater; M = marine; F-B = freshwater-brackish; M-B = marine-brackish; F-M-B = freshwater-marine-brackish)

Table 3 Percentage occurrence frequency for popular ornamental fish species recorded in each province in the present study

Species	% Occurrence frequency							
	Free State	KwaZulu-Natal	Limpopo	Mpumalanga	North West	Gauteng	Eastern Cape	Western Cape
Carassius auratus	75	75	100	100	83	89	64	93
Poecila reticulata	50	83	100	100	83	89	82	67
Calloplesiops altivelis	50	33	100	100	83	89	73	73
Poecilia spp.	50	50	100	100	83	82	73	80
Betta splendens	75	50	100	100	83	79	100	60

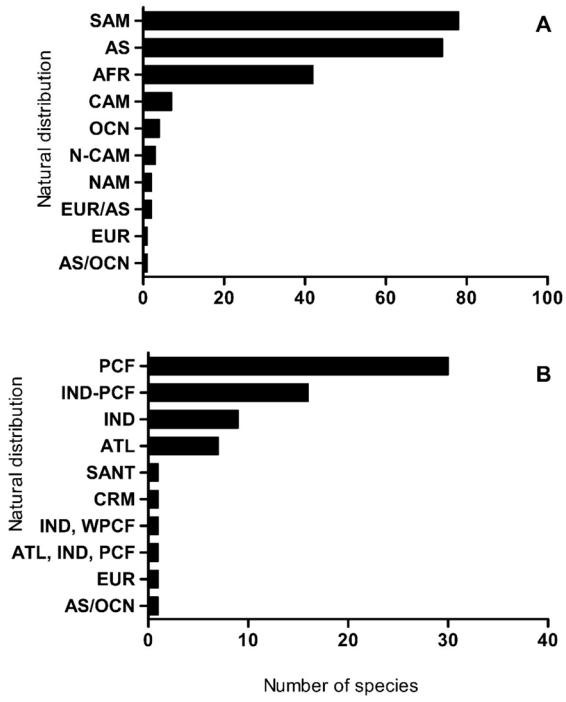

Fig. 4 Native distributional range of ornamental fish species recorded in the pet shops of South Africa: **A** freshwater species in each continent-subcontinent (Note: AS/OCN = Asia and Oceania; EUR = Europe; EUR/AS = Europe and Asia; NAM = North America; N-CAM = North and Central America; OCN = Oceania; CAM = Central America; AFR = Africa; AS = Asia; SAM = South America) and **B** marine species in each ocean (PCF = Pacific; IND-PCF = Indo-Pacific; IND = Indian; ATL = Atlantic; SANT = Subantarctic; CRM = Circumglobal; IND, WPCF = Indian and Western Pacific; ATL, IND, PCF = Atlantic, Indian and Pacific; EUR = Europe; AS/OCN = Asia and Oceania)

Discussion

Checklist of alien fish in the ornamental trade

The number of ornamental fish species (n = 312) recorded in the South African pet shops during this survey was much higher than that previously recorded (n = 114), although the latter species were only recorded from three provinces (van der Walt et al. 2017). The number of fish species recorded during the present survey was similar to the numbers recorded in pet shops in Europe, e.g. Greece (n = 326) (Papavlasopoulou et al. 2014); North America, e.g. Canada and the United States (n = 308) (Duggan et al. 2006) and Laurentia (n = 308) (Rixon et al. 2005). The most common fish species recorded in the present survey (e.g., *C. auratus* and *P. reticulata,* among others) were generally popular in similar surveys conducted around the world (Rixon et al. 2005; Duggan et al. 2006; Gertzen et al. 2008; Chang et al. 2009; Strecker et al. 2011; Papavlasopoulou et al. 2014; Borges et al. 2021).

Although one province was not sampled during the present study, the eight provinces that were sampled covered the largest proportion of the country's aquarium trade market. As such, the aquarium species diversity obtained during the present study is believed to accurately reflect the actual status of the South African aquarium pet trade since most pet shops controlling the national market chain were surveyed. The species diversity in South African pet markets is likely to be attributed to the tradition of fish keeping, aquaculture-based ornamental fish sector as well as improved living standards. The dominance of the freshwater fish species in the South African aquarium trade could be attributed to the moderate environmental conditions, feeding preferences, ease of maintaining home aquaria with freshwater as well as relatively low prices coupled with high affordability compared to marine fish species as found in other studies (Rixon et al. 2005; Duggan et al. 2006; Gertzen et al. 2008; Chang et al. 2009; Strecker et al. 2011; Papavlasopoulou et al. 2014; Borges et al. 2021). Although the small-sized and low-priced fish species such as *Poecilia* sp., *P. reticulata* and *X. maculatus* dominated the South African aquarium trade, some bigger fishes with relatively high prices such as *Helostoma temminckii* and *C. carpio* were also recorded especially in the pet shops with breeding/rearing facilities within the premises (pers. obs.).

Similar to South Africa, farming of freshwater fish species such as gouramis (e.g., *Trichogaster* spp.), goldfish, guppies, swordtails (*Xiphophorus* spp.), platies, Siamese fighting fish (*B. splendens*), koi (*Cyprinus* spp.) and mollies (*Poecilia* spp.) is an established industry in other countries such as Singapore (Sales and Janssens 2003), Thailand (Monvises et al. 2009; Kipouros et al. 2011), and Japan, all with a long and strong history of domestication through controlled fry production and artificial selection processes (Papavlasopoulou et al. 2014). Furthermore, many freshwater aquarium fish species, such

Table 4 Ornamental fish species recorded to be invasive in South Africa and other parts of the world

Family	Species	No. of pet shops where present	Provinces where present	Natural environment	Global impact status	References
Osphronemidae	*Betta splendens*	74	KZN, FS, LP, MP, NW, GP, EC, WC	F	DD	Hammer et al. (2019)
Cyprinidae	*Carassius auratus**	85	KZN, FS, LP, MP, NW, GP, EC, WC	F	DD	GISD, Luskova et al. (2010), Wouters et al. (2012), Esmaeili et al. (2014), Elender and Weyl (2014), Marr et al. (2017)
Cyprinidae	*Carassius gibelio*	1	FS	F	DD	Tsoumani et al. (2006), Tarkan et al. (2012), Bulut et al. (2013), Kirankaya and Ekmecki (2013), Esmaeili et al. (2014), Agdamar and Tarkan (2019)
Notopteridae	*Chitala ornata*	9	FS, MP, NW, GP	F	DD	Shiranta (2016), Kumudinie and Wijeyaratne (2005), Castro et al. (2018), Castro et al. (2019)
Cyprinidae	*Cyprinus carpio**	64	KZN, LP, MP, NW GP, EC, WC	F, B	DD	GISD, Marambe et al. (2011), Ellender and Weyl (2014), Esmaeili et al. (2014), Marr et al. (2017), Brosse et al. (2021)
Cichlidae	*Herichthys cyanoguttatus*	1	GP	F	DD	Lorenz (2008), Lorenz et al. (2010), Lorenz et al. (2015), Lorenz and Connell (2011)
Cichlidae	*Heros efasciatus*	6	WC	F	DD	Brosse et al. (2021)
Loricariidae	*Hypostomus plecostomus*	25	KZN, FS, LP, MP, NW, GP, WC	F	DD	Marambe et al. (2011)
Centrarchidae	*Micropterus salmoides**	2	WC	F	MR	Ellender and Weyl (2014), Esmaeili et al. (2014), Marr et al. (2017), Zengeya et al. (2017)
Poeciliidae	*Poecilia latipinna*	24	KZN, FS, GP, EC, WC	F, B, M	DD	Koutsikos et al. (2018), Ghazwan (2020)
Poeciliidae	*Poecilia reticulate**	80	KZN,FS, LP, MP, NW, GP, EC, WC	F	DD	GISD, Marambe et al. (2011), Ellender and Weyl (2014), Marr et al. (2017)., Brosse et al. (2021)
Poeciliidae	*Poecilia sphenops*	5	NW, GP	F, B	DD	Ramírez-García et al. (2018)
Cyprinidae	*Rasbora borapetensis*	20	KZN, FS, LP, MP, GP, EC, WC	F	DD	Pallewatta et al. (2003)

Natural environment: F = freshwater, B = brackish, M = Marine. Global impact status: DD = data deficient, MR = major impact. GISD = Global Invasive Species Database. An asterisk indicates species that have been introduced and established in South Africa. (See Table 1 for province abbreviations)

as cichlids and cyprinids can spawn under aquarium conditions (Papavlasopoulou et al. 2014). On the contrary, the maintenance of marine ornamental fish is relatively complicated as it requires extra care and demands more expensive basic and auxiliary equipment (Ng and Tan 1997). In addition, these fish

species are collected in the wild with traditional and generally mortality escalating techniques, which eventually affect the prices (Ng and Tan 1997). In the present study, the majority of fish species were of tropical origin as a result of increased biodiversity and endemism in the tropics, the peculiarity of body forms of these fishes and their living modes, as well as impressive colour patterns (Wabnitz et al. 2003; Papavlasopoulou et al. 2014). The dominance of marine fish species of tropical origin could be attributed to the attractiveness of the reef-associated species as well as to the historic fishing tradition of capturing ornamental fish in communities along the Indian Ocean (Wood 2001; Bruckner 2005).

Invasion risk

Although the aquarium pet trade has economic value through the generation of jobs and revenue, it has been reported as a major driver for the introduction of non-native fishes into the wild, especially for freshwater species (Duggan et al. 2006; Copp et al. 2010; Farrah et al. 2019). About 4% of the recorded species during this survey have been introduced and become invasive outside their native range, with nine species reported to be invasive in other parts of the world with no invasion records in South Africa (e.g. *Carassius gibelio*, *Chitala ornata*, *Herichthys cyanoguttatus* and *Heros efasciatus* among others). The presence of these species in South African pet shops poses a risk to South African aquatic ecosystems as these species are likely to be released into the wild by owners dumping unwanted species, escapes from the tanks and breeding farms, drainage of water containing organisms from tanks and public aquariums as well as ritualistic release of species during religious practices. The high occurrence frequency of these species thus increases the possibility of introducing these species in natural ecosystems, thus presenting invasion debt. Generally, all the eight provinces surveyed during the present study are at invasion risk since three historically invasive species occurred in pet shops across all the eight provinces surveyed. The presence of subtropical ornamental fish species, especially with an invasion history in South African pet shops, raises concerns about introducing and establishing these species in the wild. A typical example of this concern was the new record of the giant pangasius (*P. sanitwongsei)* captured in the Breede River in South Africa (Mäkinen et al. 2013). This specimen displayed a genetic match of juveniles purchased from the ornamental pet trade, and most likely originated through release by an aquarist. This species is not on the list of fishes permitted to be imported into South Africa, and it has been reported to be invasive in Bangladesh (Barua et al. 1999). The likelihood of it becoming invasive in South Africa is high. The presence of this fish in the pet trade in South Africa demonstrates complications associated with preventing illegal introductions.

In the present study, the species with the high occurrence frequency (> 80%) included the species previously reported to be established and invasive in South Africa and other parts of the world, e.g. *C. auratus and C. carpio*. The relationship between the occurrence frequency of fish in pet shops and their introduction and establishment has been previously reported (Duggan et al. 2006; Farrah et al. 2019). This relationship suggests that popular and readily available species to aquarists/ hobbyists are introduced faster and in higher numbers than less popular or rare species (Duggan et al. 2006; Farrah et al. 2019). Species with global invasion history recorded during the present study pose a threat to the aquatic ecosystems of South Africa since most of the historically invasive species occur in all the provinces surveyed coupled with high occurrence frequency with particular concern in Gauteng and Western Cape provinces. Similar to the present study, *C. auratus and C. carpio* were reported to have been extensively introduced into the river basins of Australia and are now widespread throughout the continent (Brumley 1991). These highly invasive species are associated with environmental degradation and reductions in endemic species in waterways where they have been introduced (Tapia and Zambrano 2003; Pinto et al. 2005). In this regard, popularity could serve as an important determinant of invasions from aquarium releases. High propagule pressure is increasingly recognised as one of the paramount correlates of establishment success (e.g. Forsyth and Duncan 2001; Lounibos 2002; Duggan et al. 2006).

The more individuals are introduced and available in the region, the more likely the establishment will occur (Hulme 2009). Furthermore, Courtenay and Stauffer (1990) stated that any aquarium fish has the potential to be released at some point. It is predicted that with the ever-increasing human population and

the associated growth of the aquarium hobby, introduction frequency and subsequent establishment by this vector is likely to increase with time, as found in other studies (Duggan et al. 2006). Although, caution is required when assuming that propagule pressure is important, especially in taxa that exhibit behavioural plasticity (Hulme 2009). The dominance of species from the sub-tropical origin that are known to be invasive elsewhere in the pet shops of South Africa remains a concern because of suitable climatic conditions for the species establishment in the country. Some of the species recorded during the present study have already naturalised (e.g. *P. sanitwongsei* and *X. maculatus*), and some have become invasive (e.g. *C. carpio*, *M. salmoides, C. auratus* and *P. reticulata*) in South Africa (Weyl et al. 2020; Burnett et al. 2023). The presence of species with a known history of becoming naturalised and invasive in the global range in South Africa but still restricted in captivity (pet shops) might be a big problem in the future. It is, however, still recommended that all the species recorded as invasive in the present study be thoroughly assessed for their risk of invasion. For example, the invasion risk posed by the species could be assessed using the Risk Analysis for Alien Taxa framework (RAAT, Kumschick et al. 2020a, b). The framework outlines a normative process to assess an alien taxon's likelihood of invasion, realised and potential impacts, and options for management in a given area.

From the 312 species recorded during this study, only 77 species belonging to 57 genera are on the whitelist of South Africa, which contains the list of freshwater fish species for aquarium purposes allowed for importation into the country (DEA 2015). This comprised only 25% of the recorded species during the present survey, granting a relatively high uncertainty on the prohibited species (blacklist) as this could not be obtained from the national, provincial and regional authorities. There is a gap in understanding the number/ proportion of prohibited aquarium species that are present in the South African pet trade, which poses a further threat to the natural aquatic systems in the country. The use of a list of permitted (white list) and prohibited (blacklist) species to regulate the aquarium trade is not always successful (Strecker et al. 2011). This might be caused by a lack of updated data or records of fish species in the country and a lack of risk assessment studies. This situation is true in South Africa, where there is no monitoring of ornamental fish importation/international trade in place, and data as well as records of ornamental fish species in the country are not being systematically collected, curated and readily accessible.

In addition, blacklists of prohibited species can be difficult to enforce given the sparsity of data and knowledge about the ecological effects of most aquarium species. The rationale for a species being included on either list is not based on a formal risk analysis process that can stand up to peer review and legal challenges. The lack of information on most aquarium fish is a common problem and should be addressed as a research priority (Strecker et al. 2011; Weyl et al. 2020). This may include research on the negative and beneficial impacts of the species used in the aquarium trade. Apart from the impacts, more information on areas likely to be susceptible to establishment is needed, e.g. temperature tolerances, given the importance of temperature in invasion success.

Challenges with regulating the ornamental trade in South Africa and possible solutions

Although the diversity of ornamental fish in South African pet shops was determined during the survey, comparing these numbers with importation records was impossible. In South Africa, it is unclear which government department is responsible for the management of aquarium fish importation records. The importation of alien fish in South Africa is governed by the National Environmental Management: Biodiversity Act (NEM:BA) (Republic of South Africa 2004) and its related invasive alien species lists and regulations (Republic of South Africa 2014; Wilson and Kumschick 2024) as well as the Animal Diseases Act No 35 of 1984 (Republic of South Africa 1984). During the present survey, there was ambiguity regarding the control of fish importation records as the Department of Agriculture, Fisheries and Forestry (DAFF) (some components of which have now merged with the Department of Environmental Affairs (DEA) to form the National Department of Forestry, Fisheries and the Environment (DFFE)) which was mandated to control the records of fish importations into the country mentioned that they are only responsible for freshwater fishes particularly for aquaculture and further stated that the marine

fish species importation records were supposed to be controlled by Department of Agriculture, Land Reform and Rural Development (DALRRD). During this survey, we contacted DALRRD as well as other provincial and regional authorities, to request data on freshwater and marine fish permit records, but these records were not available. Although DALRRD did have some records of freshwater fish imports for aquaculture, these records were not easily accessible as they were in hard copies and not digitised. Such uncertainty in responsibility and poor cooperation between the government departments pose further difficulty in regulating aquarium trade in South Africa, which further threatens biodiversity. As a result of the problems encountered in obtaining permit records for the fish species imported into the country, our objective to determine the number of fish species legally introduced into the country and identify important introduction pathways could not be achieved.

Although the legislation instrument guiding the management of alien species in South Africa is in place (NEM: BA), this instrument does not seem to be effective in controlling the aquarium trade as a pathway of invasions in South Africa. Focused legislative and regulatory control of alien aquatic species in the aquarium trade is required. A possible solution is for the risk posed by fish species traded in the aquarium trade to be assessed through a formal risk analysis process (e.g. Kumschick et al. 2020a, b). The fish species should then be listed and regulated under appropriate categories under the NEM:BA A&IS regulations to restrict the importation of high-risk species, regularise the movement and use of species, assess eradication feasibility for species that occur in low numbers over limited areas, contain invasions, and to reduce the extent and impact of well-established invaders. This process needs stakeholder engagement across the national, provincial and local departments, as well as the general public. Stakeholder engagement is required to minimise conflict and encourage compliance (Novoa et al. 2018). All these concerned departments and authorities need to have a clear and equal understanding of policies, procedures, rules and regulations on importing alien fishes into the country for the aquarium trade and develop a readily available/retrievable database when needed.

On the contrary, other countries practice stringent regulations to control imports of ornamental fish species. For example, in Australia, regulatory measures include using the list of permitted species, a case-by-case risk assessment process for species not on the list, health certification requirements as well as quarantining of imported stock to minimise transboundary disease spread (Morrisey et al. 2011; Whittington and Chong 2007).

The present study represents one of the relatively few surveys on the diversity of fish in the ornamental pet trade in South Africa, and this can be used to inform policy and management strategies to reduce the threat posed by alien fish in the aquarium trade. Although it might not be easy to assess all the fish species identified in the aquarium trade through risk analysis, the present survey list could inform the prioritisation process, e.g., targeting species with a global invasion history first for risk analysis. The prioritisation process may also include targeting species with known impacts, most commonly traded species, and species commonly misidentified and traded under the incorrect name. Although the study focused on fish, other aquatic organisms were recorded during the present survey (e.g. shrimps, sponges, snails, frogs, sea urchins, corals, tubeworms, anemones and feather stars). It is recommended that these other animal taxa be also assessed for their invasion risk, given the unprecedented growth in the aquarium trade and lack of proper monitoring of the aquarium trade in South Africa.

Non-indigenous fish species prevention and public awareness programs where experts, citizen scientists, government organisations, and the general public participate must be developed and implemented to control the trade of high-risk species and ultimately protect the natural aquatic systems. These may include education/awareness of possible ecological and legal consequences of release as well as the ability to return unwanted organisms to pet shops or National Zoological Gardens. These may also include programmes that supply educational materials such as pamphlets and stickers to pet shops as well as plastic bags with the message “Do not release fish, rather return it to the pet shop”, and such material should reach the widest audience including the vast internet trade of ornamental fish. The benefits of returning unwanted live fish to the pet shop may include receiving store vouchers, discounts, or any other form of financial incentive for the aquarists. It is acknowledged that reselling the returned fish may raise concerns regarding disease transmission, limiting this

recommendation. However, as a solution, the returned unwanted live fish can be euthanised humanely. Additionally, educational campaigns targeting aquarium enthusiast individuals, including those that belong to aquarium societies and associations, must be established. This could be the initial step towards educating aquarists about the harm of releasing live fish into the wild.

Conclusions

Our study demonstrated that the aquarium pet trade is an important pathway for the introduction of alien fish in South Africa. Although greater attention has been given to other introduction pathways, such as aquaculture and fishing sports, this study has presented a need for a greater appreciation of the ornamental pet trade as a potential source of alien species introductions. From the present study, it was assumed that the high risk of alien fish species introductions through the aquarium trade could be associated with urban areas and, by association, high numbers of aquarium pet shops and aquarists, with Gauteng Province being a typical example. These regions need to be targeted and prioritised for educational and legislative activities efforts. With the high trade in e-commerce within the country, even the regions in rural communities are susceptible to alien fish invasions via the aquarium pet trade. Thus, a more comprehensive plan of action is required.

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Data availability The data that supports the findings of this study are available in the supplementary material of this article or from the authors.

Declarations

Conflict of interest The authors declare no conflict of interest.

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