Management of Biological Invasions (2022) Volume 13, Issue 2: 406–434

Review

Systematic review of the Australian freshwater ornamental fish industry: the need for direct industry monitoring

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Citation: Millington MD, Holmes BJ, Balcombe SR (2022) Systematic review of the Australian freshwater ornamental fish industry: the need for direct industry monitoring. *Management of Biological Invasions* 13(2): 406–434, https://doi.org/10.3391/mbi.2022.13.2.09

Received: 23 February 2021
Accepted: 27 October 2021
Published: 14 March 2022

Handling editor: Alisha Davidson
Thematic editor: Joana Dias

Abstract

Invasive species represent one of the greatest biological threats to Australian ecosystems this century. Facilitated by global interdependence, increased connectivity, and established trade routes, the dissemination of non-native ornamental species has led to substantial establishments in Australian waterways. Despite this, recent and ongoing research into the trade and invasive potential of non-native ornamental fish species in Australia is lacking and well behind the global standard. Hampered by a shortage of adequate funding and an inability to make rapid policy-based decisions due to industry influence, restrictions on trade have been slow or non-existent in recent years. Further, the development and maintenance of accurate species trade lists as well as dedicated funding and a coordinated approach to compliance is currently inadequate across all Australian jurisdictions. Here we aimed to identify if existing ornamental freshwater fish records from scientific literature in Australia, including veterinary reports and zoonoses studies, were an appropriate alternative to direct industry monitoring necessary in producing comprehensive trade lists. To test this alternative approach, we identified and collated scientific literature that had recorded captive freshwater fish in the Australian ornamental industry. Our review identified a still inchoate scientific body of literature that is a poor substitute for direct survey approaches, with minimal reporting evident in Australia on the freshwater ornamental fish in trade. Assessment of available species records indicated unassessed, greylisted freshwater fish form a substantial part of the Australian ornamental industry. Nomenclature issues and potential exploitation by the ornamental fish industry were also identified. Given the paucity of contemporary literature on the presence and abundance of traded species within Australia, initiatives including pet store surveys and e-commerce monitoring are vital to collate a complete list of traded species necessary for management of this non-native community. We highlight key research priorities and provide recommendations on the future management needs of the Australian freshwater ornamental fish industry.

Key words: aquarium trade, aquatic invasive species, exploitation, freshwater fish, invasive species, pet fish

Introduction

One of the most current and enduring threats to Australian ecosystems this century is undoubtedly the presence and spread of invasive species (Kearney et al. 2018). The interconnectivity achieved through established trade and transport pathways as a result of global interdependence has

facilitated the spread and invasion of non-native species globally (Banks et al. 2015; Gallardo et al. 2015; Westphal et al. 2008). This is particularly so for the freshwater ornamental fish industry in Australia, whereby the global aquarium trade nexus has introduced and consequently disseminated diverse communities of non-native ornamental fish throughout the country (Ebner et al. 2020; Garcia-Diaz et al. 2018). As a by-product of this increased connectivity and the perpetual supply and trade of non-native ornamental species, establishments of ornamental fishes in Australia over the past 50 years continue to rise, most notably in the coastal northern regions of Queensland (QLD), the Northern Territory (NT), and Western Australia (WA) (Ebner et al. 2020; Garcia-Diaz et al. 2018). These northern states, with tropical and sub-tropical climates, provide suitable habitat for a large proportion of non-native warm water ornamental species that are prolific in trade (Corfield et al. 2008), and especially under a warming climate (Venezia et al. 2018; Rahel and Olden 2008). As a result, northern states maintain the highest number of exotic fish establishments in Australia (Garcia-Diaz et al. 2018; Corfield et al. 2008), including the most recent naturalisation of ornamental fish species (jaguar guapote – *Parachromis managuensis* (Gunther, 1867) (Holmes et al. 2020); *Cichla* sp. (Catchment Solutions 2019); Siamese fighting fish – *Betta splendens* (Regan, 1910) (Hammer et al. 2019)). While the impacts of these establishments in Australia are not yet understood (Holmes et al. 2020; Hammer et al. 2019), invasions of *Cichla* sp. in South America have resulted in substantial changes to the native fish community (Pelicice and Agostinho 2009), and similar impacts are projected following *P. managuensis* invasions in the Philippines (Agasen et al. 2006) and Brazil (Franca et al. 2017). With further ornamental fish invasions anticipated to be substantial in Australia (Chan et al. 2019), the freshwater ornamental fish industry poses a significant biosecurity threat to aquatic ecosystems in Australia. Management of this industry is key to reducing these impacts.

Despite a sizeable foundation of research highlighting the risks associated with the freshwater ornamental fish industry in Australia over the last 50 years (Ebner et al. 2020; Holmes et al. 2020; Harris 2013; Lintermans 2013; Corfield et al. 2008; Koehn and MacKenzie 2004; Lintermans 2004; Arthington 1986, 1989; Arthington et al. 1981, 1983), greater management of the industry is not recognised in biosecurity funding or action plans (e.g., Craik et al. 2017; Invasive Plants and Animals Committee 2017). Risk assessments aimed at determining an ornamental species' invasive potential languish behind other invasive terrestrial and agricultural pest and biosecurity priorities (e.g., Firn et al. 2015). Notably, while multiple models for these ornamental fish risk assessments have been developed and welcomed by ornamental researchers (e.g., Deveney 2018; Beyer and Fredberg 2010; Fredberg and McNeil 2010; Bomford and Glover 2004; Arthington et al. 1999), implementation of the suggested changes to invasive fish management regimes across the country remains to be seen. The immense pressure

placed on state and federal governments to be able to enforce any significant changes resulting from such assessments is often met with stakeholder resistance (Moore et al. 2010). As a result, there has been limited proactive management in this area, and there are currently no incentives to appropriately fund the necessary ornamental research required to address these biosecurity issues, particularly given the underperformance of earlier collaborations (e.g., Beyer and Fredberg 2010; Fredberg and McNeil 2010; Moore et al. 2010; O'Sullivan et al. 2008; Natural Resource Management Ministerial Council (NRMMC) 2006). Despite significant research efforts, these reports were unable to address the outstanding knowledge gaps regarding the diversity, abundance, or captive distributions of ornamental fish species traded in Australia (Moore et al. 2010; NRMMC 2006). Without such data to inform understanding on key trade pathways, particularly those involving invasive non-native species, effective management of the Australian freshwater ornamental fish industry is not achievable.

Until recently, knowledge on the ornamental fish species traded in Australia were sourced from unvalidated industry records supplemented by equivocal lists of risk assessed species in biosecurity or fisheries legislative schedules and regulations (Beyer and Fredberg 2010; Fredberg and McNeil 2010; O'Sullivan et al. 2008; Bomford and Glover 2004; McNee 2002). These legislations are state- and territory- specific and communicate trade decisions founded on invasive potential through risk assessments that evaluate the likelihood and resulting impact of established and self-sustaining non-native populations in Australia (Department of Agriculture, Water and the Environment n.d.). Separate legislation convey noxious species banned from trade and import (i.e. *blacklists*), while Commonwealth legislation indicate species approved for trade and import nationally (i.e. *whitelists*) (Supplementary material Table S1). The exact proportion of ornamental species on the black- and whitelists is difficult to extract, given that biosecurity and fisheries legislation indexes entire families and genera rather than list out individual species. While a necessary tool for industry to determine the legality of trade of particular ornamental fish, these black- and whitelists are an incomplete catalogue of ornamental species traded in Australia (McNee 2002) with a substantial number of ornamental freshwater fish species absent from either list (Moore et al. 2010). Such unassessed species are regarded as *greylisted*. Preliminary industry monitoring indicates greylisted species constitute a considerable proportion of ornamental trade in Australia (M. Millington *unpubl. data* 2020) owing to the confusion surrounding the legality of their trade that is perpetuated by conflicting biosecurity messaging. An example of this surrounds trade of the greylisted and invasive *P. managuensis* in QLD, with Biosecurity QLD (2017) stating *P. managuensis* may be kept for ornamental purposes in QLD; however, this is contradicted by Business QLD (2019) which states their import, trade, and possession is not

permitted. Given the recent naturalisation of *P. managuensis* in QLD (Holmes et al. 2020), clear messaging on the legality of greylisted species, and the recategorization of such high-risk species, remains crucial. Although no tangible list exists to define the extent of greylisted species in Australia, previous greylist suppositions indicate the number is considerable (e.g., Beyer and Fredberg 2010; Fredberg and McNeil 2010; Moore et al. 2010; McNee 2002) and quickly considered outdated – unable to encapsulate the burgeoning ornamental trade, with new species rapidly incorporated into trade as quickly as they are discovered (Dignall 2021; Ortega-Lara and Lujan 2020; Lujan et al. 2017). Indeed, industry representatives in Australia reported previous attempts at producing ornamental greylists are largely obsolete, with many in-trade species absent and a considerable proportion being of no interest to industry (M. Millington *pers. comm.* 2021). Thus, while the black-, white-, and greylists do give an indication of freshwater fish species considered to be in trade, these are far from comprehensive, and reliance on these as an adequate representation of the traded ornamental fish community is misguided.

Other methods used by international ornamental researchers in producing comprehensive species records includes utilising ornamental import and export lists (Costa Rica – Allen et al. 2017; India – Raghavan et al. 2013; USA – Chapman et al. 1997). However, the lack of reliable and publicly accessible data on industry statistics in Australia has hampered similar research. Data on the productivity and size of the sector continue to be grouped indiscriminately with various aquaculture activities (e.g., Mosby 2018; Mosby and Koduah 2017; Stephan and Hobsbawn 2014; Skirtun et al. 2013; Pham 2010; Wood et al. 2007; Szakiel et al. 2006; Langenkamp et al. 2002; Davies et al. 1999; Davies et al. 1998; Timcke and Campbell 1997; Schuele et al. 1996; Standen et al. 1995; Smith et al. 1993; Smith et al. 1991), despite an extensive and prolific ornamental industry in Australia. Current estimates indicate ornamental freshwater fish ownership in Australia is widespread, involving a substantial community of species, with 11.3 million (Animal Medicines Australia 2019) to 18.4 million fish kept across 1.1 million households in Australia (Hill 2010). However, highly extrapolated findings (Animal Medicines Australia 2019) and the application of growth rates to outdated fish population statistics (Australian Companion Animal Council 2010; O'Sullivan et al. 2008) confound the accuracy of current day estimates. Fish import figures, used exclusively in several industry assessments as estimations of freshwater ornamental fish industry size (Hill 2010; NRMMC 2006) are also unreliable, given the proportions of locally supplied species (L) compared with imported species (I) are considered vastly different between sources: NRMMC (2006) estimate 60(L):40(I), QLD ornamental fish industry representatives estimate 20(L):80(I) (S. Baines *pers. comm.* 2018), and O'Sullivan et al. (2008) estimate 30(L):70(I). Exacerbating this uncertainty is the poor standards of labelling provided with ornamental imports, with

fish imported under genus or family rather than by species (Allen et al. 2017; Smith et al. 2008). A persistent lack of understanding surrounds the origin and trade of freshwater ornamental fish species in Australia and as such import statistics are therefore unreliable in portraying the ornamental species in trade.

The consistent flawed theme in these past endeavours at compiling ornamental trade lists in Australia are the reliance upon indirect measures of traded species in lieu of direct monitoring. Instead, ornamental research in Australia must emulate the growing body of international targeted monitoring studies taking advantage of the data-rich ornamental fish industry, with specific taxon surveillance conducted on crustaceans (Germany – Chucholl and Wendler 2017), fish (Romania – Gavriloaie et al. 2016; Greece – Papavlasopoulou et al. 2013), and reptiles (USA – Stringham and Lockwood 2018), while broader ornamental monitoring identified rich communities involving a diversity of non-native fish, birds, small animals, and plants (Italy – Mazza et al. 2015; India – Soundararajan et al. 2015). These surveys acquire a wealth of information, enabling researchers to comprehensively understand species richness and abundance (Singapore – Yi 2014; Costa Rica – Allen et al. 2017), assess legislation compliance (USA – Diaz et al. 2012), examine the prevalence of accompanying parasites (Europe – Baska et al. 2009), diseases (Uruguay – Carnevia et al. 2013), and hitchhikers (Czech Republic – Patoka et al. 2020; New Zealand – Duggan et al. 2018; Singapore – Ng et al. 2016), and identify vendor locations, useful in mapping potential invasion hotspots (USA – Strecker et al. 2011). Further, the utilisation of these rich databases has proven vital in proactively managing non-native ornamental communities, specifically in quantifying trade pathways (USA – Strecker et al. 2011; Canada – Gertzen et al. 2008), identifying potentially invasive species (Mexico – Mendoza et al. 2015; Brazil – de Magalhaes and Jacobi 2013; Europe – Maceda-Veiga et al. 2013), approximating dispersal range once introduced (South Africa – Padayachee et al. 2019; Europe – Vranken et al. 2018; USA – Kramer et al. 2017) and in understanding the exploitation and illegal trade of ornamental species (Brazil – Gurjao and Lotufo 2018; Gurjao et al. 2018; India – Raghavan et al. 2013; Bangladesh – Faruk et al. 2012). However, such monitoring may not be cost-effective, given the considerable time (e.g., 580 hours – de Magalhaes and Jacobi 2013; multiple visits – Diaz et al. 2012), coordination, (e.g., 70 stores – Saba et al. 2020; 54 stores – Chang et al. 2009), and funding required (e.g., multiple funding sources – Gertzen et al. 2008), particularly for country-wide studies. One potential cost-effective alternative to these direct surveys is the utilisation of species records from past research that have directly surveyed the freshwater ornamental fish industry. Internationally, this type of literature review of ornamental data has aided in compiling traded species abundance (Biondo and Burki 2020; Mohanty and Measey 2019; Alas et al. 2015), and deftly illustrated major knowledge deficits in

the global trade of marine ornamental fish species (Biondo and Burki 2020). This cost-effective alternative shifts the emphasis onto "realised" presence rather than reliance on unvalidated industry lists and may allow for assessment of traded fish from multiple pathways and endpoints, including aquarium stores, private collections, wholesalers, and importers, as well as from non–traditional viewpoints including ornamental veterinarians and zoonoses reports, without the need for additional industry monitoring.

In this review, we systematically searched the scientific literature to identify and collate captive ornamental species records in order to understand whether such records would improve our understanding of the freshwater ornamental fish species traded in Australia without the need for additional industry monitoring. First, from these amalgamated species records we provide a stocktake of captive freshwater fish species reported as in the Australian ornamental industry. Second, we assess nomenclature accuracy and emphasise the need for improvements in identification methods and training to reduce nomenclature errors. Third, we evaluate the potential role of the Australian ornamental industry in trade–mediated exploitation of imperilled freshwater fish species, and reflect on the importance of surveillance and green certification in the ornamental industry to prevent unsustainable wild collection. Finally, we identify the invasive threat the Australian ornamental industry poses to native aquatic ecosystems through assessing biosecurity and fisheries legislation, and highlight the need for targeted industry monitoring, particularly surrounding online trade of greylisted and blacklisted ornamental species.

Materials and methods

Data search

A systematic literature review was carried out to identify, consolidate, and evaluate scientific records of captive freshwater fish species traded in the Australian ornamental industry reported from direct industry surveys. Encouraged for their repeatability due to transparent methods, systematic literature reviews are now the preferred form of initial topic exploration for researchers (Pickering et al. 2015). This comprehensive filtering and data categorisation of articles and information allows for the researcher to discern what is currently understood and deftly identify gaps in the literature (Ballantyne and Pickering 2015; Pickering and Byrne 2014). Following the Preferred Reporting Items for Systematic Review and Meta–Analyses (PRISMA) (Gammon et al. 2020; Moher et al. 2009), academic research and grey scientific literature that reported captive freshwater ornamental fish in Australia from direct industry surveys were sourced through extensive searches of the *SCOPUS* database, Google Scholar, and the Griffith University library database. Where articles were not retrievable from the databases, authors were contacted directly. Non-scientific literature, including

articles in hobbyist publications, were excluded from the review as the focus was on assessing the current academic knowledge of species in trade.

The literature searches (PRISMA – Identification stage) were performed from 1 May 2018 to 21 December 2018 when search results were deemed exhausted as per halt procedure guidelines, wherein 20 search results in a row were excludable. Search terms used the keyword *Australia* in all instances along with combinations of keywords from three lists: 1. *ornamental, aquarium, pet*, 2. *fish, owner, trade, species, home, hous*, captive*, 3. *zoonoses, fish parasite, fish disease*. Literature reviews were excluded; however, the references were searched to identify further relevant papers. Following the removal of duplicates, records were assessed and removed if direct industry surveys recording captive ornamental freshwater fish in Australia was not apparent from the title or abstract (PRISMA – Screening stage). Full-text articles were then downloaded or accessed, read for eligibility, and included in this review dependent upon the following criteria: 1) fish were held for ornamental purposes; 2) fish were identified to genus or species; 3) abundance or presence data were provided; and 4) the information was the result of a direct survey of the freshwater ornamental fish industry (PRISMA – Eligibility stage). Information from included papers were categorised in an Excel spreadsheet, with data recorded on the location in Australia, bibliographic details, research focus, species identified, fish stock source, containment type and location, and species richness (PRISMA – Included stage). As a result of data reporting inconsistencies between the publications, we assessed taxa presence rather than species abundance.

Species descriptors

Provided species names in the included literature were checked for accuracy using the online biodiversity database FishBase (Froese and Pauly 2019 Version (12/2019)) to identify currently accepted nomenclature. Where available, the synonyms list and common names list on FishBase (Froese and Pauly 2019) were examined to identify if scientific names provided by the included literature were merely *outdated* (i.e., were previously accepted as official nomenclature but are no longer current) rather than incorrect. Where nomenclature used in the included literature were too generic for identification correction or the fish was an undescribed species, the entry was deemed *unidentifiable*.

Information from FishBase (Froese and Pauly 2019) concerning the continent of origin (*the Americas, Australia, Asia, Europe, and Africa*), and commercial usage status (*highly commercial, commercial, public aquariums, minor commercial*) were recorded for each species. A precautionary approach was applied where commercial usage was not recorded or obsolete (i.e., *of no commercial use* and *public aquariums*), with these species categorised as *minor commercial*. The small sample size of included literature and the

inconsistency in reported abundance was insufficient in determining true commercial usage. Conservation status (*data deficient, least concern, near threatened, vulnerable, endangered, critically endangered, extinct*) were sourced for each species from the International Union for Conservation of Nature (IUCN) Red List of Threatened Species database (IUCN 2021a). Where information on conservation usage was unavailable, it was deemed *unidentifiable*.

Exploitation matrix

Minimal understanding on origins and trade pathways of ornamental species in Australia may potentially conceal the exploitation of imperilled species that are sourced from wild-caught or capture-based aquaculture. Given commercial use in the freshwater ornamental fish industry and conservation status compound and exacerbate ornamental species exploitation (Gurjao and Lotufo 2018; Raghavan et al. 2018; Raghavan et al. 2013; Raghavan et al. 2008), we developed a matrix to identify the potential level of exploitation a freshwater ornamental fish species may experience as a direct result of ornamental trade (Table S2). Species were allocated a level of risk (*low, moderate, high, extreme*) through overlaying information on commercial usage status (Fishbase: Froese and Pauly 2019) with conservation status (IUCN 2021a) in a matrix (Table S2). A precautionary approach was applied for species listed with no conservation status evaluated, whereby they were considered at *extreme* risk of exploitation regardless of commercial usage.

Invasive potential

Australian biosecurity and fisheries legislation (Table S1) were used as guides to determine invasive potential. Specific to each state and territory, the legislation communicate trade decisions founded on risk assessments that evaluate the likelihood and resulting impact of established and self-sustaining non-native populations in Australia (Department of Agriculture, Water and the Environment n.d.). Inclusion in blacklists indicated the species was potentially invasive, while inclusion in whitelists indicated the species was not considered potentially invasive. All remaining species absent from the black– and whitelists were considered greylisted.

Results

Eligible literature

From an extensive systematic search of the literature, 25 unique publications from an initial pool of 793 were identified that fulfilled the criteria of the systematic literature review – scientific literature that reported on captive freshwater ornamental fish within Australia. These were comprised of 21 peer-reviewed journal articles, one government report, two PhD theses, and one peer-reviewed editor letter (Figure S1, Table S3). Publication output

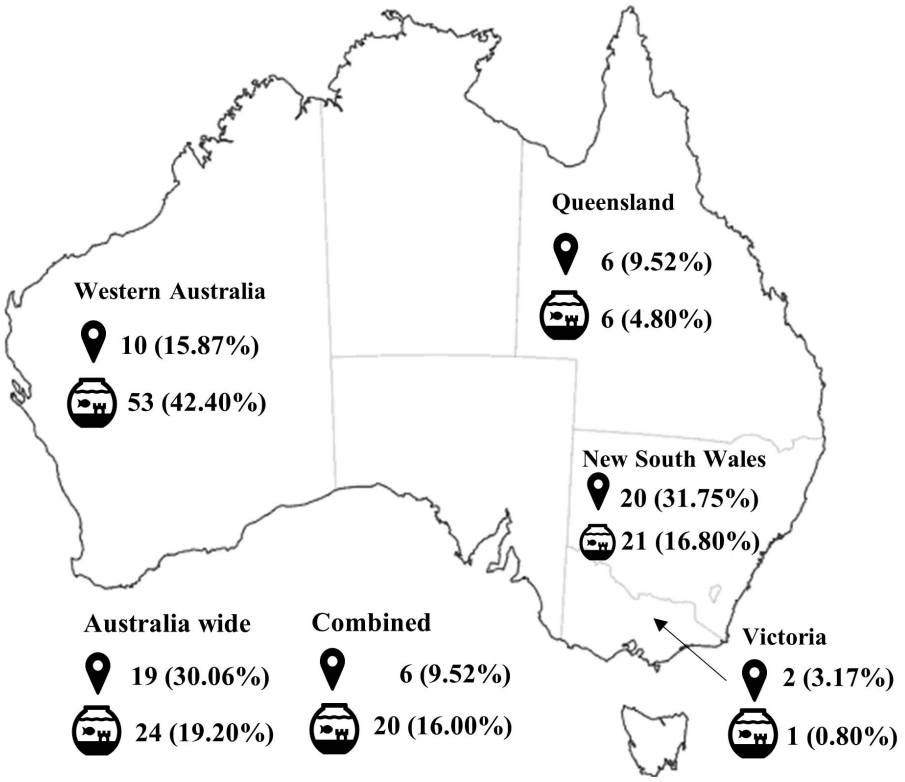

Figure 1. Summary of freshwater ornamental fish species records and survey sites by state and territory. Map of Australia detailing: Pin Icon – the total number of data collection events e specific to that state/territory (New South Wales, Queensland, Victoria, Western Australia) or amalgamated location group (Australia wide – unspecified locations within Australia, Combined – data collected across more than one state or territory provided in amalgamated datasets); Fishbowl Icon – the total number of ornamental fish species recorded across all sites visited specific to that state/territory or amalgamated location group. NOTE: No publications reported on ornamental species in the Australian Capital Territory, the Northern Territory, South Australia, or Tasmania in a state-specific dataset.

of the included literature increased consistently over time, with the first paper published by Ashburner in 1975 and the majority of research published in the most recent decade (1970–1980: one publication, 4.0%; 1980–1990: two publications, 8.0%; 1990–2000: three publications, 12.0%; 2000–2010: eight publications, 28.0%; 2010–2018: 12 publications, 48.0%).

Data in the included literature were collected from 63 research locations across Australia (Figure 1). The greatest number of direct industry survey records were sourced from New South Wales (NSW) with 20 data sources, followed by ten in WA, six in QLD, and two in Victoria (VIC) (Figure 1). An additional 19 species records were sourced from unspecified locations in Australia (Australia wide), and six inter-state datasets (Combined) (Figure 1). No publications reported on the trade of ornamental fish in the NT, South Australia (SA), Tasmania (TA), or the Australian Capital Territory (ACT). Taxa richness was greatest in WA with 53 taxa recorded (Figure 1) and lowest in VIC with just one species reported from two studies, followed by QLD with six taxa recorded from six surveys (Figure 1).

All studies were secondary data sources: their lists of captive ornamental species in Australia were a by-product of scientific research. Research aims

were varied and included reports on zoonosis infections from ornamental fish (Musto et al. 2006; Senanayake et al. 2004; Robson et al. 1998; Moulsdale et al. 1983), outcomes of ornamental fish surgery (Chin et al. 2017; O'Hagan and Raidal 2006; Raidal et al. 2006), welfare of captive fish (Sullivan et al. 2016; Sullivan 2014), and diseased fish assessments in 1.) import lots (Trujillo-Gonzalez et al. 2018; Nolan et al. 2015; Rimmer et al. 2015; Stephens et al. 2009; Evans and Lester 2001; Anderson et al. 1993; Humphrey et al. 1986; Ashburner 1975), 2.) fish farms (Mohr et al. 2015; Becker et al. 2014; Humphrey and Ashburner 1993), and 3.) pet stores (Palermo 2016; Morine et al. 2012; Wickins et al. 2011; Zanguee et al. 2010; Go et al. 2006). Data were predominately recorded from private collections (73.7%), with data also sourced from import and export lists (14.5%), pet stores (7.1%), wholesaler/ornamental fish dealers (4.5%), and public aquaria (0.2%) (Table S3). Only 14 of the 25 literature reported on the containment type and location ornamental fish were housed in, with the majority held in indoor aquaria (76.5%), and those held outdoors (23.5%) were kept in ponds (75.0%) or unspecified containers (25.0%) (Table S3).

Australian ornamental freshwater fish community

Overall, a total of 66 taxa were recorded, identifiable to 58 species with an additional eight taxa described at genus level only, from 14 families, notably Cichlidae (15 species), Cyprinidae (12 species), and Osphronemidae (nine species) (Table S4). Fish originated from the Americas (26 species), Asia (24 species), and Africa (8 species) (Table S4). No native species were reported from the included literature. Across the 25 publications, 244 occurrences of ornamental fish were recorded, with small tropical fish most often reported: 29 records of goldfish – *Carassius auratus* (Linnaeus, 1758) (11.9% of total occurrences), 19 records each (7.8%) of dwarf gourami – *Trichogaster lalius* (Hamilton, 1822) and three spot gourami – *Trichopodus trichopterus* (Pallas, 1770), 12 records each (4.9%) of southern platyfish – *Xiphophorus maculatus* (Günther, 1866) and pearl gourami – *Trichopodus leerii* (Bleeker, 1852), and 10 records each (4.1%) of kissing gourami – *Helostoma temminckii* (Cuvier, 1829) and guppy – *Poecilia reticulata* (Peters, 1859) (Table S4). Twenty-four species (9.8%) and three taxa (1.2%) were recorded singularly (Table S4).

Nomenclature

A full scientific and common name were recorded in 82.6% of ornamental fish entries, with the remaining entries either solely a common name (1.8%), species name (8.4%), or genus only (7.2%). Incorrect nomenclature were prevalent, with 65.3% of all names used in the reviewed literature being either outdated taxonomy, unaccepted synonyms, or unidentifiable. Where a species was recorded with both a common name and scientific

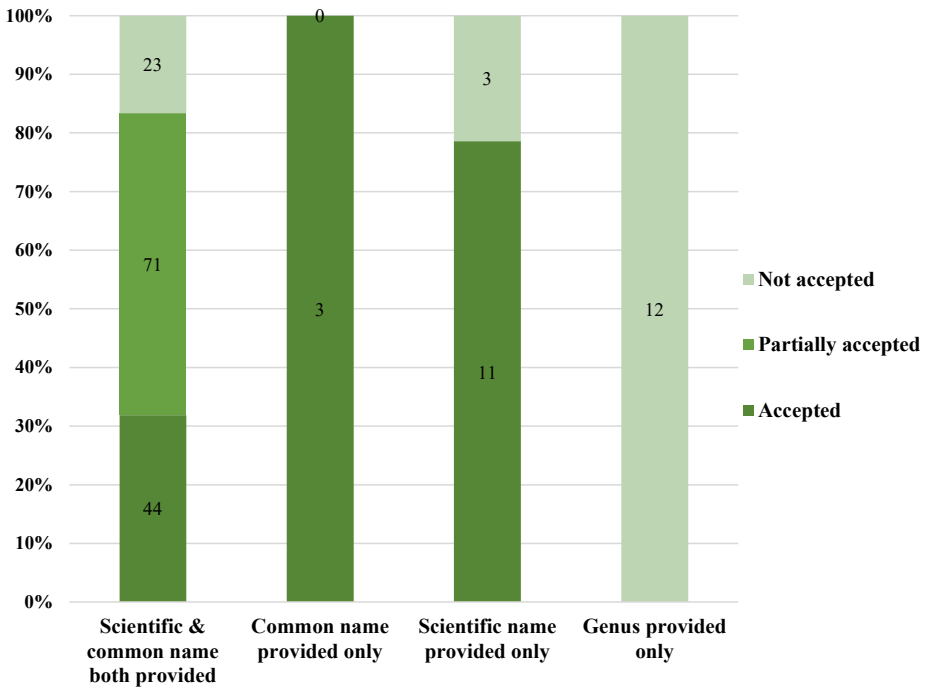

Figure 2. Nomenclature accuracy used in captive freshwater ornamental fish records in Australia. Entries have been divided into groups dependent on nomenclature provided – Scientific and common name both provided, Common name provided only, Scientific name provided only, and Genus provided only; with the legend indicating the proportion of accepted nomenclature used – Not accepted, Partially accepted, and Accepted, with data labels indicating the total number in each category.

name, 16.7% used incorrect nomenclature for both terms, and 51.4% used a combination of partially accepted common and scientific names (Figure 2). Fish listed with common name only used accepted nomenclature on all occasions, and fish with scientific name only were incorrect in 21.4% of entries (Figure 2). For eight taxa and six species, nomenclature used were incorrect on all occasions. Four species in particular, *T. trichopterus*, ram cichlid – *Mikrogeophagus ramirezi* (Myers and Harry, 1948), Sumatra barb – *Puntigrus tetrazona* (Bleeker, 1855), and southern platyfish – *Xiphophorus maculatus* (Günther, 1866), were consistently referred to by three or more unaccepted synonyms (Table S4). Contradictive nomenclature within reports referring to the same species (e.g., hornet cichlid and bumblebee cichlid in Zanguee et al. (2010) for *Pseudotropheus crabro* (Ribbink and Lewis, 1982)) were also recorded frequently (Table S4). All common and scientific names used in 10 of the 25 reports were correct on all occasions, although nine of these publications reported on singular species (one species: Palermo 2016; Sullivan et al. 2016; Becker et al. 2014; Musto et al. 2006; O'Hagan and Raidal 2006; Robson et al. 1998; Humphrey and Ashburner 1993; Moulsdale et al. 1983; Ashburner 1975; 10 species: Trujillo-Gonzalez et al. 2018).

Exploitation risk: conservation status and commercial usage

Of the 58 species identified in this review, 30 species (51.7%) were listed as highly commercial, 23 species (39.7%) as commercial, and five species as

Table 1. Exploitation matrix: potential risk of exploitation by trade in the Australian ornamental industry identified by overlaying information on ornamental trade status (column headers) (Fishbase: Froese and Pauly, 2019) (note precautionary approach converted Public aquariums and Of no commercial use to Minor commercial) with information on conservation status (row headers) (IUCN 2021c) in a matrix. Cell values indicate the total number of species for that row + column combination (e.g., 3 highly commercial and vulnerable species). Exploitation risk is then determined based on the cell colour (red – extreme risk: 23 species (39.7%); orange – high risk: 5 species (8.6%); yellow – moderate risk: 17 species (29.3%); green – low risk: 13 species (22.4%)).

	Highly commerical	Commercial	Minor commercial	TOTAL
Extinct in the wild	0	0	0	0
Critically endangered	1	0	0	1
Endangered	0	0	0	0
Vulnerable	3	2	0	5
Near threatened	1	0	0	1
Least concerned	16	10	3	29
Not evaluated	9	11	2	22
TOTAL	30	23	5	58

Extreme	Red	23	39,7%
High	Orange	5	8,6%
Moderate	Yellow	17	29,3%
Low	Green	13	22,4%
		58	

minor commercial (8.6%) in Fishbase (Froese and Pauly 2019). Four of the minor commercial species were a result of the precautionary principle enacted (Table 1, Table S2). Of the 58 species identified in this review, 22 species (37.9%) have not yet been evaluated by the IUCN (2021a) to determine their conservation status. IUCN conservation status for the 37 assessed species were determined within the previous 16 years and 51.4% had been evaluated within the previous five years (IUCN 2021a) (oldest assessments in 2006: vulnerable *Tropheus duboisi* (Marlier, 1959) and least concern Tanganyika tilapia – *Oreochromis tanganicae* (Gunther, 1894); most recent assessments in 2020: least concern *P. tetrazona*). One species (1.4%) was listed as critically endangered (redtail sharkminnow – *Epalzeorhynchos bicolor* (Smith, 1931)), five (8.6%) listed as vulnerable, one (1.7%) considered near threatened, 29 species (80.6%) were determined as least concern, and one species (1.7%) listed as data deficient (Table 1; Table S4). No species were listed as endangered or extinct in the wild (Table 1).

Potential ornamental exploitation risk was assessed using the exploitation matrix we developed, which overlays information on the conservation status data with that of commercial usage (Table S2). We identified 77.6% (45 species) of all freshwater ornamental fish species reported as in trade in Australia are at an extreme, high, or moderate risk of potential ornamental exploitation attributable to the ornamental industry (Table 1), with 23 species (39.7%) assessed as at extreme risk, 5 species (8.6%) at high risk, 17 species (29.3%) at moderate risk, and 13 species (22.4%) assessed as low risk of potential ornamental exploitation. Of those at-risk of potential ornamental exploitation, six species are of particular concern, experiencing a potent mix of high ornamental trade desirability and an at-risk conservation status: the critically endangered and highly commercial *E. bicolor*, the three vulnerable and highly commercial *B. splendens*, tricolor

sharkminnow – *Balantiocheilos melanopterus* (Bleeker, 1850), and cherry barb – *Puntius titteya* (Deraniyagala, 1929), and the two vulnerable and commercial *Tropheus duboisi* (Marlier, 1959) and common carp – *Cyprinus carpio* (Linnaeus, 1758) (Table 1, Table S4). A total of 22 species with no conservation status listed on IUCN were considered at an extreme risk of potential ornamental exploitation using the precautionary approach (Table 1, Table S2).

Threat to Australian ecosystems

Absence on state, territory, and Commonwealth biosecurity and fisheries legislation indicated more than half of the species identified in this literature review are considered greylisted. A total of 34 taxa (51.5%) currently await further assessment of their potential threat towards Australian biodiversity in all four surveyed states (NSW, QLD, VIC, WA) despite being reported as in trade (Table S1, Table S4). Of the remaining 32 taxa, federal legislation indicated 30 taxa (45.5%) are whitelisted and permitted for importation and keeping, and two taxa are blacklisted (Table S4) – *O. tanganicae* are not permitted in NSW, QLD, VIC, and WA (Table S4), and *C. carpio* are not permitted for trade or keeping in QLD and VIC. However, *C. carpio* are absent from biosecurity and fisheries legislation in NSW and WA and are considered greylisted in these states (Table S4).

Discussion

Trade in ornamental freshwater fish is a major global industry, encompassing several thousands of species (Yi 2014; Hensen et al. 2010), and connecting Australia to countries around the world with richly diverse communities of non–native ornamental fish through the global aquarium trade nexus (Ebner et al. 2020). This is in stark contrast to the relatively depauperate but highly endemic fish communities in Australia (Unmack 2013). Despite the long history of ornamental trade and research in Australia (Ebner et al. 2020; Holmes et al. 2020; Harris 2013; Lintermans 2013; Corfield et al. 2008; Koehn and MacKenzie 2004; Lintermans 2004; Arthington 1989, 1986; Arthington et al. 1981, 1983) and established international trade routes (Mosby 2018; Mosby and Koduah 2017; Stephan and Hobsbawn 2014; Skirtun et al. 2013; Pham 2010; Wood et al. 2007; Szakiel et al. 2006; Langenkamp et al. 2002; Davies et al. 1999; Davies et al. 1998; Timcke and Campbell 1997; Schuele et al. 1996; Standen et al. 1995; Smith et al. 1993; Smith et al. 1991), our systematic literature review identified a considerable knowledge gap, with minimal examples of direct industry monitoring available in Australian scientific literature for researchers and policymakers to understand the current species in trade. This knowledge gap is also geographical, with ornamental research failing to accurately represent trade Australia-wide as publications represented only four of the seven states and

territories. Further, utilisation of several species lists for state- or territory-specific research was not possible due to inter-state datasets, where data collected from more than one state or territory were available only in amalgamated format rather than attributed separately in the dataset to individual locations. Our review therefore concludes the utilisation of these ornamental records is an inadequate substitute to direct monitoring in producing comprehensive trade lists.

Nomenclature

It is evident from our review that a high level of inaccuracy and uncertainty surrounds nomenclature within the literature on the Australian freshwater ornamental fish industry. While considerable identification issues in the industry are recognised internationally (70.4% of imported stock – Allen et al. 2017) and suspected to be an issue at the Australian border (Morrisey et al. 2011; McNee 2002), those involved, including importers and retailers, are often not from scientific backgrounds. In contrast, the proportion of incorrect nomenclature we report here (44.5%) reveals an underlying flaw in the Australian ornamental scientific literature. While part of this problem is attributable to updates in taxonomy following more recent genetic research and/or taxonomic understanding post-publication, we identified human error, through the intentional choice of common name or genus instead of scientific name, frequent misspellings, and the use of synonyms, accounted for a substantial proportion. The expected pattern of increasing nomenclature accuracy in more recent literature was not evident when considering the literature by year published, suggesting erroneous nomenclature were applied at publication. Accurate published datasets are an important part of science, allowing for researchers to draw conclusions from these previous studies without investing considerable time or financial expenditure recollecting data. This is also particularly important regarding animal welfare, as repeated sampling or examining specimens that may cause stress to the animals may be avoided through access to existing accurate datasets. The high proportion of nomenclature issues identified through this systematic literature review, limits the ability for utilising datasets produced and draws into question the validity and value of such species records to future studies. Without accurate nomenclature, regulation of the freshwater ornamental fish industry is difficult. Indeed, correct species identification underpins many aspects of biosecurity management largely involving legislation compliance and enforcement (e.g., Diaz et al. 2012). Given our findings of persistent nomenclature issues in scientific literature, largely a result of human error, we recommend ornamental researchers make a commitment to ensuring adequate data management to allow for data utilisation. There is a wealth of resources and references that aid in ornamental freshwater fish species identifications (e.g., Jennings 2018; Hensen et al. 2010; Axelrod et al. 2007;

Hargreaves 2007), including highly detailed species profiles on hobbyist sites that meticulously describe species based on decades of breeding and observations (e.g., PlanetCatfish.com – Dignall 2021). Indeed, even older data-rich reference books (Sakurai et al. 1993; Axelrod et al. 1980) remain functional given the ability to easily verify nomenclature validity in Fishbase as a result of the comprehensive list of synonyms, common names, and outdated nomenclature listed on Fishbase species profiles (Froese and Pauly 2021).

Exploitation risk – Conservation status and commercial demand

Potential ornamental exploitation of traded species appears characteristic of the Australian freshwater ornamental fish industry. Overall, a considerable proportion of species included in this review were assessed as being potentially threatened by ornamental trade as a result of high desirability exacerbating an at-risk conservation status. We acknowledge our exploitation matrix relies upon accurate and up to date information that potentially disregards the voluntary nature of Fishbase upkeep as well as previous IUCN evaluation inaccuracies (e.g., murray cod – *Maccullochella peelii* (Mitchell, 1833)) were listed as critically endangered in 1996 until reassessment in 2019 recategorised the species as least concern (IUCN 2021b)). However, all conservation evaluations for the 37 assessed species were conducted within the previous 16 years, with half within the previous five years (IUCN 2021a), and recent mass evaluations by IUCN (2021a) even within the timeframe of this manuscript removed some of the uncertainty in our exploitation risk calculation (e.g., from no evaluation to least concern for molly – *Poecilia sphenops* (Valenciennes, 1846)), green swordtail – *Xiphophorus hellerii* (Heckel, 1848)), *P. tetrazona*, and coolie loach – *Pangio kuhlii* (Valenciennes, 1846)) (IUCN 2021a)), and also improved exploitation risk understanding (e.g., from endangered for *B. melanopterus* to vulnerable, and from near threatened for blue lyretail – *Fundulopanchax gardneri* (Boulenger, 1911)) to least concern (IUCN 2021a)). Despite the voluntary nature of Fishbase upkeep, all but four species were listed as of commercial interest to the freshwater ornamental fish industry, indicating such commercial assessments has some potential for indicating industry demand. However, it is not clear how demand level is assessed by Fishbase, and verification of their accuracy is currently not possible due to the lack of ornamental trade information available in Australia. Given demand level is a key part of the exploitation matrix, our assessment of exploitation is a potential indicator rather than determined risk until demand level is ascertained from direct industry monitoring. Revisions to conservation status and commercial usage are easily amended in the exploitation matrix developed, and thus further updates by IUCN (2021a) and Fishbase (Froese and Pauly 2021) will refine our understanding of potential exploitation risk to traded ornamental species.

We also acknowledge the potentially unfounded use of precautionary principles in instances where information on conservation status and commercial usage is unavailable may have inflated exploitation risk. However, as evident by the greylist management in Australia (e.g., Moore et al. 2010), indecision begets indecision, and setting aside species with no evaluation status from exploitation risk analyses disregards the potential for harm by the freshwater ornamental fish industry while such information is sourced. This is particularly so given the depauperate understanding of species origin. Wild-capture fisheries and captive-based aquaculture constitutes an important part of imported stock. Seven of the species we identified as at-risk of exploitation originate from continents involved in ornamental trade of wild fish (Asia: *E. bicolor*, *B. melanopterus*, *B. splendens*, *P. titteya*, *C. carpio*; Africa: *T. duboisi*, *O. mossambicus*) (Yi 2014), and may have been harvested from wild populations. Capture-based aquaculture continues to remain the only feasible and efficient means of production for a considerable number of top–traded ornamental species (Teletchea 2015). Indeed, an estimated 85% to 90% of the ornamental species produced in India are sourced from captive-based ornamental fisheries (Rani et al. 2013; Silas et al. 2011). Further, more than 70% of fish in the Singapore industry are harvested from wild populations in India, Asia, South America, and Africa (Yi 2014), and as Singapore is one of the leading exporters of freshwater ornamental fish and a main supplier to the Australian trade (O'Sullivan et al. 2008), these wild-caught fish will undoubtedly become part of the ornamental community in Australia. Demand for such fish remains high, as wild-type stock is championed by hobbyist groups over hybridised, line-bred progeny (M. Millington *unpubl. data* 2018). However, a ready supply of pure strain individuals is necessary to retain the wild type features that hobbyists' favour, and thus there continues to be a push by industry for further whitelisting of wild-caught species to supplement linebred stock (Toomes et al. 2020).

This desire for and supply of wild-caught fish over more sustainable captive-bred fish ensures continued impact on wild populations. Overfishing remains a key threat to sustainable wild-capture ornamental fisheries and the communities that rely on the income (Watson and Roberts 2015). Until 2011, *E. bicolor*, assessed as at extreme risk of ornamental exploitation in this review, were considered extinct in the wild (IUCN 2021a), with overharvesting for the ornamental trade one of the key threats identified (Vidthayonon 2011). Stress on these at-risk ornamental species is further exacerbated in native ranges where collection restrictions may be negligent (Raghavan et al. 2013), especially in lower income regions where wild collection contributes to a significant sector of the local economy (Phang et al. 2019; Raghavan et al. 2018; Ng and Tan 1997). The persistent pressure from unsustainable ornamental harvesting may result in non-sustainable declines occurring that cannot be restored by natural breeding and recruitment processes.

The onus to stop such degradation is on importing countries to enact trade protections. We make four recommendations for the Australian freshwater ornamental fish industry to reduce potential exploitation of traded species. First, we recommend generation of an ornamental industry exploitation assessment report detailing the origin and harvesting methods of freshwater ornamental fish species in trade in the Australian ornamental industry to ensure ethical and sustainable collection. Such research on the origin and collection methods of wild-caught species must be made a priority for future ornamental investigations to ensure exploitation concerns are managed. While the green certification of ornamental fish, that ensures their ornamental production is ethical and transparent, is already supported internationally (Silas et al. 2011), such an initiative for freshwater ornamental fish traded in Australia is not recognised. Information on origin and harvesting methods is currently not readily available and will require liaising with importers and international wholesalers. Given the potential coordination necessary, this report should initially focus on the 45 species identified in our review as at-risk of ornamental exploitation, before expanding to encompass imperilled species verified as in trade in Australia.

Second, while such research is amalgamated, we recommend that the import of the 45 species assessed as at-risk of ornamental exploitation must be halted until further research and investigation on harvesting methods is conducted to ensure Australian trade is not continuing to threaten ornamental populations in their native ranges. While availability of many ornamental fish may be founded on captive breeding, without records of such information there remains potential for wild-caught species entering trade in Australia. This moratorium on import of ornamental species should not impact the continuation of within-Australian ornamental breeding and trade, given such a mandate is focused on preventing future exploitation rather than addressing past exploitation. While it is unclear what proportion of ornamental imports these 45 species account for, the considerable value of ornamental imports in Australia (Mosby 2018; Mosby and Koduah 2017; Stephan and Hobsbawn 2014; Skirtun et al. 2013; Pham 2010; Wood et al. 2007; Szakiel et al. 2006; Langenkamp et al. 2002; Davies et al. 1999; Davies et al. 1998; Timcke and Campbell 1997; Schuele et al. 1996; Standen et al. 1995; Smith et al. 1993; Smith et al. 1991) will undoubtedly encourage importers to provide species origin and harvesting information to assessors, expediting the production of this report.

Our third recommendation is the green certification of importers whose ornamental stock are sustainably and ethically sourced. Environmental certification is already widely endorsed in Australia in multiple industries, including the Responsible Wood Certification Scheme (Australian Forestry Standard 2021), Green Star for infrastructure (Green Building Council of Australia 2021), and the Green Tick Certified scheme for products or services (Intellectual Property Australia 2021). With a familiar process that

promotes the sustainability and long-term retention of capture-based ornamental trade, such certification is anticipated to be welcomed by the industry. Indeed, wholesalers and retailers bearing such labels may find themselves at an advantage over others lacking certification, with eco-conscious consumers selecting those with sustainably and ethically sourced fish. The implementation of this scheme would also benefit remote communities involved in wild collection. Sustainable fishing methods, such as hand picking and diving, are already in use by many of these communities, with a focus on fish welfare to increase stock survival (Watson and Roberts 2015). The wild collection of ornamental fish constitutes a substantial part of the economy and workforce for some remote communities (Watson and Roberts 2015), and ornamental aquaculture has also enabled and empowered female-driven businesses internationally (Singh 2019). Thus, the sustainability, and green certification of these local industries is paramount in these communities. Receiving green certification would likely strengthen trade relationships with importers requiring ethically-sourced stock, and hence sustain the long-term continuation of these remote regional and low-impact ornamental fisheries.

Finally, in the event wild harvesting is deemed to threaten native population stability and self-sufficiency, we recommend these species be removed from whitelists and added to an exploitation-based blacklist to protect native populations from further exploitation. Captive-based aquaculture must be pursued and prioritised as a replacement for high-impact wild-caught fisheries to minimise further exploitation of the freshwater fish species by the Australian ornamental industry. This has been achieved in the past for ornamental species, including Boeseman's rainbowfish – *Melanotaenia boesemani* (Allen & Cross, 1980)). Following their intense collection for ornamental purposes in the 1980s that severely threatened population resilience (IUCN 2021c), a switch to captive-bred production removed this threat and the species is no longer considered exploited by ornamental trade (IUCN 2021c). While these trade protections may not substantially reduce within-native-range impact for all imperilled species, given the sizeable ornamental industries internationally (Yi 2014; Hensen et al. 2010), Australia must set a global example to encourage other countries to also remove exploited species from import. A united front on exploitation and investment in advancing captive breeding techniques has the potential to remove capture-based ornamental fisheries from the industry and reduce the industry's environmental impact.

Threat to Australian aquatic ecosystems

Unassessed, greylisted species form a substantial part of the freshwater fish industry, having not been allocated as approved for (whitelisted) or banned from import (blacklisted). While some species may eventually be assessed as low-risk in Australia, the current loophole enabling trade of potentially

high-risk greylisted species is at the expense of the freshwater community. Given the naïveté of Australian ecosystems to novel predators, the continued trade and movement of such high-risk non-native species in Australia may result in significant population declines and trophic shifts (Jolly et al. 2021; Banks and Dickman 2007; Cox and Lima 2006; Hamer et al. 2002). The persistence of the greylist and the continued trade of greylisted and blacklisted species within Australia must be prioritised as a biosecurity threat. We identify three key research priorities for the management of the Australian freshwater ornamental fish industry to reduce potential impact by greylisted species.

First, we recommend that there is a stronger emphasis on compliance and ornamental wildlife crime within Australia as opposed to the current external focus. The prioritisation of illegal ornamental trade in Australia remains on international imports (e.g., Henderson and Bomford 2011; Bricknell 2010; Alacs and Georges 2008). There is a clear need for a perspective shift in the existing ornamental biosecurity approach. Currently, invasive threats are largely perceived as externally sourced, with a focus on smuggling and unlawful imports across international borders. Minimal consideration is given to internal threats despite the extensive and largely unregulated import history prior to whitelist implementation (Mosby 2018; Mosby and Koduah 2017; Stephan and Hobsbawn 2014; Skirtun et al. 2013; Pham 2010; Wood et al. 2007; Szakiel et al. 2006; Langenkamp et al. 2002; Davies et al. 1999; Davies et al. 1998; Timcke and Campbell 1997; Schuele et al. 1996; Standen et al. 1995; Smith et al. 1993; Smith et al. 1991; McKay 1977) and the resulting availability of blacklisted species in the Australian ornamental industry (M. Millington *unpubl. data* 2020). This is particularly so online, with preliminary monitoring of ornamental groups identifying blatant trade of blacklisted species within Australia (M. Millington *unpubl. data* 2020). Currently, biosecurity monitoring and compliance activity is insufficient, and the industry is profiting from this inaction at the expense of freshwater environments, particularly in northern regions (Holmes et al. 2020; Catchment Solutions 2019; Hammer et al. 2019). Our second recommendation is thus the necessity for greater direct monitoring of ornamental trade in Australia with a focus on e-commerce where the connectivity and anonymity afforded has resulted in the establishment of extensive unregulated trade networks comprised largely of grey- and blacklisted species (M. Millington *unpubl. data* 2020). While only in its infancy in Australia (e.g., Stringham et al. 2020), online monitoring internationally is an established method in identifying illegal trade (Lavorgna and Sajeva 2020; Minin et al. 2019; Olmos-Lau and Mandujano 2016). Without information on what black- and greylisted species are in trade and where trade hotspots are, effective compliance measures and education programs are not feasible. There is strong potential for online monitoring to aid in identifying and reducing illegal ornamental trade in

Australia through informed compliance activities, and thus direct industry monitoring online must be made a priority for future ornamental research in Australia.

Given the intended notion of ornamental greylists to act as virtual holding areas rather than a permanent fixture (Burgiel and Perrault 2011), and the confusion on whether greylisted species are legally tradeable in Australia (e.g., trade of *P. managuensis* in QLD (Business QLD 2019; Biosecurity QLD 2017)), updated risk assessments resulting in actual policy change are long overdue. Our final recommendation therefore is for the recategorization of greylisted species to black- or whitelists resulting in the redundancy of the greylist, based on thorough assessments of invasive potential. Developments within this space are encouraging, with the recent establishment of a National Freshwater Vertebrate and Invertebrate Working Group, a sub-committee of the Commonwealth Environment and Invasives Committee, charged at overseeing the completion of > 500 greylisted freshwater ornamental fish risk assessments. The findings of these assessments will be supplied to Commonwealth with an aim to inform and expedite the currently arduous legislation amendment process (M. Millington *pers. comm*. 2021). Once an ornamental species has been determined by these assessments as an environmental, social, or economic threat, it is essential for all states and territories in Australia to unanimously list the species as a threat. The resulting trade restrictions will limit potential introduction pathways, and the clear and consistent messaging will enable industry comprehension of and adhesion to these new legislative measures.

Conclusions

Through a systematic review of scientific literature, this study revealed a largely depauperate reservoir of academic ornamental research in Australia that lacks the detail and breadth of information necessary to be an appropriate alternative to direct surveys of the ornamental industry. Invasive ornamental research in Australia continues to trail behind global standards, and there is the persistent need for industry data to inform key research needs. Direct industry monitoring to produce comprehensive trade lists must be prioritised, with an emphasis on data management and nomenclature accuracy to allow for database utilisation. In particular, monitoring must focus on the online trade pathways that are now prevalent in Australia and explore the potential for exploitation of freshwater fish species as a result of the ornamental industry. As such, there is a strong need for green certification in the industry and for an assessment of the role Australia has in the trade of wild-caught species; both essential in ensuring ornamental fish are sourced ethically and sustainably.

Acknowledgements

The authors would like to thank Professor Catherine Pickering and the Researcher Education and Development workshops at Griffith University for training in conducting a robust systematic literature review. We thank the two anonymous reviewers for valuable edits and feedback that greatly improved the manuscript.

Authors' contribution

MM, BH, and SB conceptualised the presented research idea. MM designed the methods, conducted the systematic literature review, collected the research articles, analysed the data, and interpreted the results. BH and SB supervised the findings of this work. MM took the lead in writing the manuscript. All authors provided critical feedback and contributed to the final version of the manuscript.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Biosecurity and fisheries legislation specific to each state, territory, or Commonwealth in Australia.
Table S2. Exploitation matrix results overlaying conservation status with commercial usage to indicate the potential level of exploitation experienced by freshwater fish in the Australian ornamental industry.
Table S3. Dataset detailing the date, location, source, containment type and location, and richness of each species recorded in the 25 included literature.
Table S4. Captive freshwater fish species and taxa reported as in trade in the Australian ornamental industry by the 25 reviewed literature.
Figure S1. PRISMA flow diagram detailing results of the systematic literature review.

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