Scoping the biosecurity risks and appropriate management relating to the freshwater ornamental aquarium trade across northern Australia

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Executive Summary

The global aquarium trade nexus is the human-mediated connection of aquatic biota between biogeographically separate ecosystems as a function of the ornamental trade industry. It is arguably the greatest biosecurity threat to freshwater ecosystems. It is not just a potential source of single invasive species in isolation, rather it is a constant supplier of harmful and potentially harmful species and pathogens from evolutionarily distinct biogeographic waterways. Understanding and dealing with this continual threat from a biological, ecological, economic and societal (including cultural) perspective has major ramifications for the planet.

The global aquarium trade nexus is especially relevant to those receiving tropical biogeographic provinces and sub-tropical provinces in northern Australia, where many unique aquatic ecosystems are currently devoid of alien species. On a certain level, the ornamental industry serves as a beneficial societal endeavour with multiple economic, human health and lifestyle values. The hyper-diverse tropical communities of biota from multiple continents, islands and oceans provide spectacular resources for recreation, as pets and exhibits, and trade. However, there are many examples whereby the transfer of these biotas has had catastrophic environmental consequences for receiving ecosystems, and the potential threat for further and continued incursions is high. Aesthetically pleasing fauna and flora, particularly fishes, invertebrates and plants, are transported on a global scale to wholesaler, retailer, private and public aquaria, and ornamental ponds.

The global aquarium trade includes the legal, illegal and incidental transport of biota and biological agents including large-bodied species that are familiar to the public, and microscopic size material including diseases and pathogens which are often the working domain of a small subset of specialists (e.g. plankton biologists, microbiologists, pathologists, veterinarians). The global aquarium trade nexus also encompasses the overharvest of endemic species and impacts to receiving ecosystems. Most notably, the global aquarium trade nexus refers to the transport of substantial components of fauna and flora from one biogeographic province to another, creating challenges far beyond the more tangible single-species pest problems that are traditionally grappled with at a local scale and for that matter as single pest species issues from local through to international scales of biosecurity. The global trade comprises both marine and freshwater biota, with the freshwater trade and the receiving tropical freshwater ecosystems in northern Australia the focus of the current report. To summarise, global aquarium trade nexus refers to an extensive and complex human driven transport network for biosecurity risk that involves the transport of species, assemblages and essentially an entire spectrum of biota. Its global biosecurity risk and relevance to native northern Australian waterways is substantial and remarkably it has been unaddressed.

The current scoping study provides for a preliminary understanding of the numerous existing and potential pathways for incursions from the aquarium trade into freshwater ecosystems in tropical Australia, encompassing the lands and waterways north of the Tropic of Capricorn. Climatic conditions including water temperature play a major role in sustaining species in tropical regions and therefore much of the biota from the tropics do not threaten temperate climates (e.g. Bomford et al. 2010). From an Australian perspective, where European settlement has been most intense in the temperate (southern) parts of the country, there are major ramifications for the global aquarium trade nexus in northern Australia as human developments unfold.

A finding of this desktop project is the lack of consolidated information relevant to tropical Australia in terms of biotic incursion of even the better documented taxa (e.g. freshwater fishes) and a lack of information on most taxa in the aquarium trade (e.g. shrimps, molluscs, diseases in the wild). This is the consequence of the extent and scale of the aquatic biosecurity task as well as *ad hoc* biological sampling, under-resourcing of ecological surveys, monitoring and reporting in the grey or published literature, all of which is compounded by the remoteness of much of tropical northern Australia. Major knowledge gaps exist in terms of: a) the knowledge of the social and biophysical processes and agents including institutional networks in tropical Australia in regard to the aquarium trade, b) unbiased survey data of propagule and colonisation pressure from the aquarium trade, and c) risks and composition of aquatic fauna particularly at the modified habitat level. In terms of the latter, ecological data, let alone unbiased and independent ecological data, is severely lacking in relation to farm dams, public dams and water transfer schemes across much of tropical Australia. This is pertinent to private and public management of land and water not the least because such dams have the capability of acting as footholds for propagule production and entry to catchments.

Biosecurity is very much a human endeavour. It involves the management of biotic materials dispersed by human and non-human agents. At a fundamental level there are single species problems that become the focus of management. In contrast, the global aquarium trade represents a source of a myriad of such single species problems, not to mention their interactions. For instance, an aquarium plant can be a potentially invasive species while also acting as a host to snails and their embryos and associated parasites and pathogens. Not surprisingly, best practice in such ecologically and societally complex circumstances is likely to require multijurisdictional responses inclusive of governmental, societal and industry participation and practice. It is emphasised that the term industry is used here to refer to the aquarium trade (including internet trading of products and biota) and importantly extended further to industries that are not necessarily intuitively thought of being relevant to the aquarium industry. The latter includes major industry and recreational practices in northern Australia (e.g. agricultural practices including water storage and transfer, recreational angling sector, and the fly in fly out workforce more generally). There is also considerable informal trade of aquarium biota not yet well documented or understood.

Using translational ecology principles to engage tropical communities of people is the key to ensuring that the general public is being made aware of the risks, is informed of best practice methods, and can be involved in aquatic biosecurity. By definition, translational ecology draws on a cross section of representation from local council, government, non-government organisations (NGOs) and community groups. Federal and state agencies, the Commonwealth Science and Industry Research Organisation (CSIRO), universities and NGO's all have roles to play in this process, however, attention needs to be paid to local societal ownership and responsibility for aspects of the biosecurity process. Given two of the relevant states have administrative capitals (Perth, Western Australia (WA); Brisbane, Queensland (Qld)) well south of the tropical region and this presents real challenges for resourcing and informed decision making associated with biosecurity and biodiversity value, whereas, the Northern Territory has its capital positioned in the tropics.

Key Recommendations

The primary recommendation of this report is that the federal government and the Australian people develop behaviour that protects freshwater ecosystems in tropical Australia from the biosecurity threats posed by the freshwater aquarium trade. This will entail getting the issue into mainstream public discourse, generating funding models and properly resourcing preventive risk actions and protective actions on the ground. This resourcing is not just in terms of dollars, but in ensuring that staffing appointments to key roles in the biosecurity process are not diluted with other tasks such as fisheries compliance, agricultural biosecurity or human safety matters. Dedicated expertise and focus (in compliance, communication, coordination and scientific and social science) are required to deal with the aquarium trade related biosecurity issues.

To this end, we provide four overarching recommendations, with more detailed context and specific recommendations for action provided elsewhere in the report.

1. Establish a national focus on biosecurity in freshwater by instating a Freshwater Pest Sectoral Committee to the level equivalent to that of the Marine Pests Sectoral Committee.

The justification for this is rooted in the sheer magnitude and hyper-diversity of biota being formally and informally traded, the relatively pristine state of many of the potential recipient ecosystems in tropical settings especially, and the continually increasing human development in tropical Australia and its inevitable interaction with water resource use.

2. Effectively inform and educate community and government about the magnitude of current and future biosecurity risks from tropical aquarium trade and the consequences for northern Australian freshwater ecosystems and society.

Opportunities exist in school curriculum, broadcast media, social media and marketing approaches to develop a public awareness of the importance of aquatic biosecurity in Northern Australia. Adequate resourcing of established roles within industry, government agencies and establishing coordinator roles within the natural resource management sector are key requirements to achieving effective extension and on-ground action, including promoting healthy choices in the aquarium and ornamental trade.

3. Develop an independent understanding of the human networks that lead to impact including future potential impact to tropical aquatic ecosystems in tropical Australia.

These networks include understanding within-industry market drivers, characteristics and trends including social science investigations of incidental and intentional illegal trade including via the unregulated and internet components of the aquarium, pet and ornamental trades (Note: The aquarium industry is not a trade in static products, it also deals in a continual and emerging novelty biota). Recently, analogous social network analysis has been achieved regarding marine pests in Australia. In the freshwater pest context, the mindset of the hobbyists, traders and collectors is central to interpreting any social analysis and this should be paired with an inventory of the aquarium trade species including parasites and pathogens currently in the country.

4. Develop regional solutions to protecting aquatic ecosystems. Specifically, this is termed 'translational ecology' whereby partnerships are formed to develop ongoing solutions to address aquarium trade specific biosecurity risks aimed at catchment and regional scales in northern Australia.

As a matter of urgency this should include resourcing and appointing regional coordinators through existing NRMs and resourced pilot programs to galvanise indigenous ranger, local council, university and state and federal agency staff and NGOs, including pet shop retailers, in championing best practice and undertaking aquatic biosecurity.

Notably, long-term officers, specifically dedicated to the aquarium trade biosecurity matters at state and federal government level are required to champion effective biosecurity in this complex social, biological and ecological arena. Funding an analysis of the freshwater pest network including the aquarium trade and ornamental pond sector akin to Stenekes *et al.* (2019) (regarding the marine pest sector), is an urgent priority providing a platform for shaping the long-term priorities of regional coordinators and key state and national decision makers including the Chief Environmental Biosecurity Officer, The Threatened Species Commissioner, the Freshwater Pest Sectoral Committee, Biosecurity Queensland, the Western Australian Department of Primary Industries and Regional Development, and the Northern Territory Government. Major land management organisations and employers in Northern Australia are also relevant (e.g. mining sector, Defence Force). Active or activating NGOs in this space is key consideration. A preliminary list of immediate tasks is provided in Appendix-B.

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1. BACKGROUND

Throughout history it has never been so easy for humans to trade foreign biota across the globe as it is currently. Information and transport networks, including those associated with the internet, have created unprecedented connectivity, often with dire consequence in terms of reconfiguring ecosystems. The current era of technology and consumer choice has fuelled intercontinental human communication regarding wild and captive biota to consumers, hobbyists and traders in biota, especially regarding the garden nursery industry and the aquarium trade which are both hyper-diverse in the number of species that are internationally traded.

1.1 Global aquarium trade nexus

The global aquarium trade nexus is the human-mediated connection of aquatic fauna and flora between biogeographically separated ecosystems as a function of the ornamental trade industry. It is especially relevant to receiving tropical biogeographic provinces because of the hyper-diversity and volume of fauna and flora in the tropics and invading via the aquarium trade. Aesthetically pleasing fauna and flora, particularly fish, invertebrates and plants, are transported on a global scale to wholesaler, retailer, private and public aquaria and ornamental ponds (Figure 1) (Liang et al. 2006, Peres et al. 2008, de Derraik and Phillips 2010, de Magalhaes and Jacobi 2013, Mazza et al. 2015, Ng et al. 2016). The ornamental industry creates multiple economic, human health and lifestyle values. However, it can have catastrophic environmental consequences for receiving ecosystems (Whittington and Chong 2007, Peh 2010). The global aquarium trade includes a mixture of legal, illegal and incidental transport of biota and biological agents including large-bodied species that are familiar to the public, as well as microscopic size taxa including parasites which are often the domain of a small subset of specialists (e.g. plankton biologists, microbiologists, pathologists and veterinarians) (Figure 1).

The trade also encompasses the overharvest of endemic species which can have profound effects on the ecosystem from where they are sourced (Moreau and Coomes 2007, Raghavan et al. 2013), and conversely can involve translocations of native species causing alteration to recipient ecosystems within another country or continent (Arthington 1991, Burrows 2004). Most notably, the global aquarium trade nexus encompasses the transport of the ingredients of substantial components of ecological communities from one biogeographic province to another, creating challenges far beyond the more tangible single-species pest problems that are traditionally grappled with at local scale, and for that matter, as single pest species issues from local through to international scales of biosecurity. In many cases, where large catchments and waterways are the recipient systems, established aquatic pests represent intractable and irreversible cultural, economic and environmental problems.

The advent and global adoption of the internet has facilitated unprecedented rates of information exchange. YouTube videos, commercial websites, chat forums etc., have aided awareness of the existence, availability and keeping (including breeding) requirements of focal species. For the everyday consumer or hobbyist this has led to a far wider choice of species to trade and keep, and notably for intercontinental exchange of alien species (Liang et al. 2006, Peres et al. 2008, Mazza et al. 2015). It has also led to the ongoing emergence of new species and hybrids for trading as hobbyist demand for non-native and rare species persists and evolves. This dynamic process creates a major biosecurity risk as the potential biotic invasion propagules being shipped rapidly change in not only type (with associated genetic and taxonomic detection issues) but also in quantity, whilst the number of species posing risk is cumulatively increasing as a function of consumer choice and market direction.

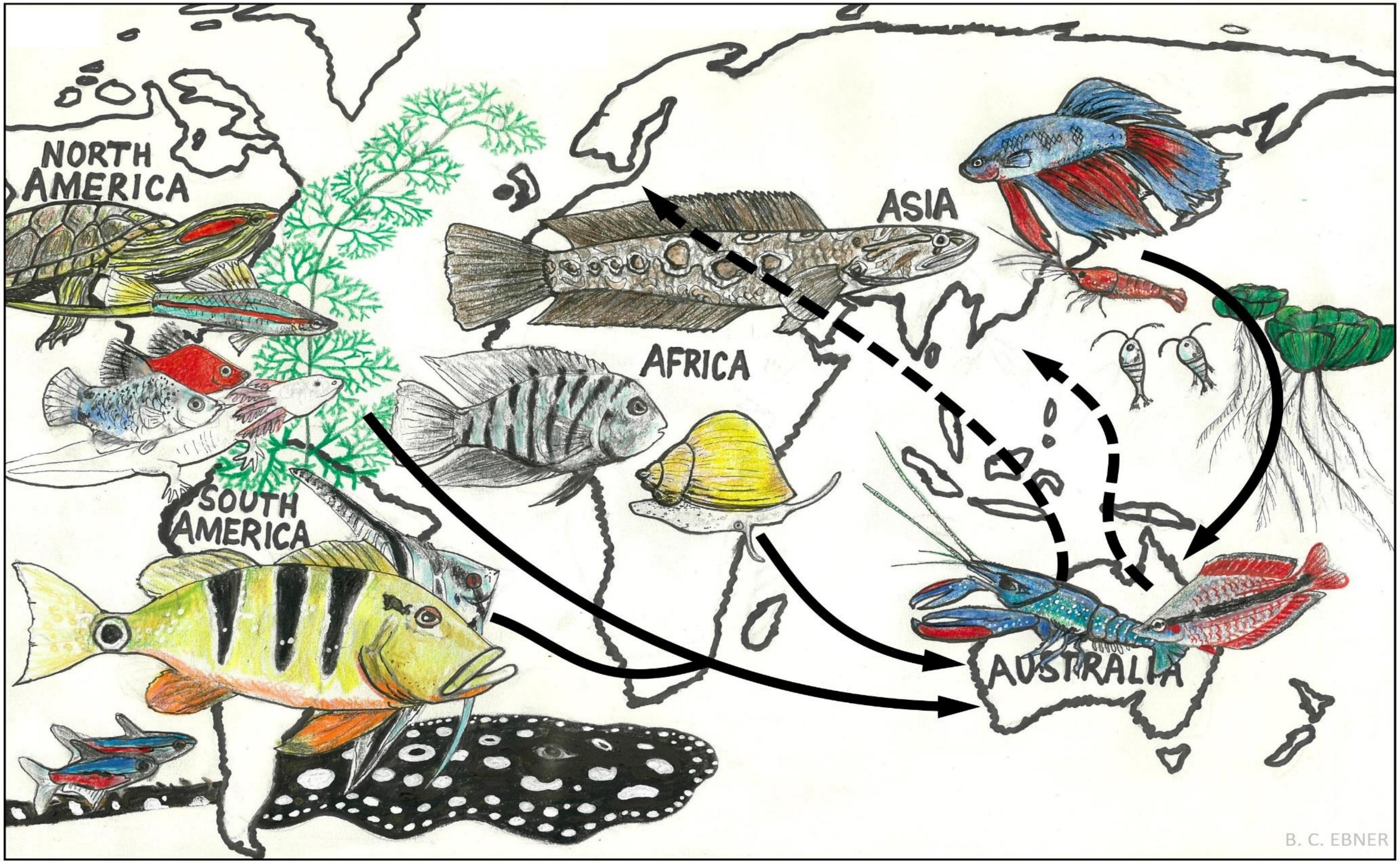

Figure 1: An illustration of a small subset of tropical freshwater species transported intercontinentally with Australia via the global trade.

1.2 Connectivity, incursion and impact

The global aquarium trade is substantial, providing major economic and recreational benefits alongside high environmental impact and risk (Tlusty 2002, Olivier 2003, Shuman et al. 2004, Whittington and Chong 2007, Raghavan et al. 2013). The trade comprises many operators and hobbyists with variable appreciation of their local aquatic biogeography and ecological sustainability principles; who also sometimes have substantial ecological knowledge of species husbandry and taxonomy (Maceda-Veiga et al. 2016). Unlike the marine aquarium trade which is mostly reliant on wild harvest, the freshwater component of the trade is built considerably on captive breeding and propagation practices (Tlusty 2002) though wild harvest is by no means trivial (Moreau and Coomes 2007, Raghavan et al. 2013). The continual selection for freshwater species that are bred in captivity can pose additional biosecurity risk if selective genes render a species more likely to establish in wild environments and thus become more invasive. Furthermore, plant fragmentation, and faunal free-embryos (referred to as eggs) and larvae present special challenges to biosecurity containment (e.g. overflowing aquaculture ponds, treatment of wastewater, incidental transport of plants and wood with demersal eggs, deliberate concealment of small eggs and plant fragments). Invertebrates that reproduce via parthenogenesis and live bearing fishes where a single pregnant individual can lead to the colonisation of a waterway are also problematic vectors to manage. Furthermore, selection of prolific breeding species with minimal requirements to complete their life cycle, can produce a subset of species that are predisposed to be effective colonisers.

The global aquarium trade comprises a wide array of taxa. Perhaps most prominently are the thousands of species of fishes and numerous other vertebrates such as freshwater stingrays, turtles and other reptiles, amphibians such as salamanders (including axolotls) and frogs (Toomes et al., 2020), as well as focal invertebrates particularly crayfish, crabs and shrimps (Faulkes 2015, Patoka et al. 2018), and molluscs including snails and mussels (Keller et al. 2007). Aquatic plants are a major component of the trade for display in indoor aquaria and outdoor ponds (Patoka et al. 2018) and can have substantial impacts on receiving ecosystems due to their functional roles in providing structure for organisms and influencing chemical and trophic processes (Strayer 2010, Carey et al. 2018, Peres et al. 2018). Broadly speaking, aquatic plants include floating plants, floating attached plants, submersed plants and emergents. There are also additional novel and cryptic taxa in the global aquarium trade including microcrustaceans and molluscs (especially snails) with some kept as attractions in their own right whilst others are kept for controlling algae, used as food for other aquarium pets or inhabitants or are obtained incidentally (Duggan 2010, Ng et al. 2016, Duggan et al. 2018). Significantly, aquatic snails serve as intermediate hosts in parasite life cycles having implications for the health of humans, companion animals and livestock (Arthington and Blühorn 1995).

Globally, biosecurity threats and risk to receiving freshwater ecosystems from the aquarium trade is considerable (Tlusty 2002, Peh 2010, Faulkes 2015). It includes displacement of native species by competition, predation and hybridisation, the introduction, spread and proliferation of disease, and in some cases total transformation of the structure and function of ecosystems (Whittington and Chong 2007, Peh 2010). These regime shifts also commonly occur in association with other stressors of freshwater ecosystems including water extraction, changes to flow regimes, pollution and reduced water quality, exploitation or loss of aquatic fauna and flora, climate change, habitat destruction and loss (Reid et al. 2013). The impacts are especially pronounced in human occupied and managed catchments, in urban, and agricultural settings, and at the centre of major trade routes (Ng et al. 1993, 2016; Rahel 2007, Olden et al. 2008). However, human-occupied catchments and seemingly more remote 'pristine' ecosystems, including those declared as national parks or nature reserves, can also suffer disproportionately from the establishment of alien species especially if they take on keystone or transformative roles in receiving ecosystems (Peh 2010, Faulkes 2015).

The latter is of serious concern and arises from human assisted dispersal of species across evolutionarily distinct biogeographic regions.

1.3 Australian aquarium trade and tropical incursions

As a function of Australia's isolation in geologic and evolutionary time, its freshwater fauna and ecosystems are unique and can be endemic (found nowhere else) at small spatial scales (Unmack 2001, 2013; Munasinghe et al. 2004, Abell et al. 2008, Buhlmann et al. 2009, Unmack et al. 2016). However, human occupation and development have led to the reconfiguration of the composition of fish assemblages and of ecosystems particularly in the past century in southern and north-eastern Australia (Lintermans 2004, Koehn and MacKenzie 2004, Olden et al. 2008). Initial 'alien' fish species incursions in Australia were related to the introduction of angling and sport fishes during the 1920s-1950s as part of the goals held by the numerous acclimatisation societies (Lintermans 2004). From the 1970s, the aquarium trade became the primary contributor in terms of alien fish incursions in Australia (Lintermans 2004, Webb 2007). From 2010-2016 it was estimated that 1075 alien freshwater fish species were legally imported into Australia though it is conceded that the taxonomic resolution of consignments is a major limitation of this estimate (Trujillo-González and Militz 2019).

Over a decade ago the ornamental aquarium fish trade was estimated to be worth approximately $350 million annually with a retail value of $65 million (DAFF 2007). Sixty percent of aquarium fish in the Australian market were thought to be domestically bred as opposed to directly imported (DAFF 2007). O'Sullivan et al. (2008) also provided estimates of aquarium trade economics in an Australian context including $129.1 million in ornamental fish sales, $170.6 million accessories sales, and $4.1 million in other sales (live rock, coral, plants).

McNee (2002) provides a staggering figure of 1181 species of alien freshwater fish recorded within the Australian aquarium industry over a 40-year period. In more recent times, it is likely that the internet trade has added to this list including in terms of fishes and other taxa, though this is not easily quantified (e.g. Martin and Coetzee 2011, Peres et al. 2018). There has been substantial invasion of freshwater ecosystems by alien species particularly in southern (temperate) Australia (Lintermans 2004). To a large extent this corresponds with areas of high human population density and period of human occupancy in the post-European settlement era. There has also been substantial invasion of tropical Australian freshwater ecosystems by alien species including via the aquarium trade concentrated mostly in north-eastern Australia (García-Díaz et al. 2018) well south of Cape York Peninsula. Road transport pathways have been a major agent for this spread of ornamental fishes (García-Díaz et al. 2018).

The global aquarium trade relies heavily on tropical marine and freshwater species, many of which have evolved in tropical settings. The current study focusses on the tropical freshwater component of this trade. Many tropical freshwater species are naturally suited to and have life-history characteristics that render them a suitable climatic match for northern Australian waters, and the deliberate or unintentional releasing of these species from aquarium stock can result in successful new establishments in tropical Australia. Generally, there is less trade in temperate freshwater species that may only be a climatically suitable match for the cooler ecosystems in southern Australia. There is however suitable 'sub-tropical' habitat across much of central Australia that is also providing suitable habitat for both warm and cool-water alien species that do not cohabitate across their native ranges [e.g. the Mozambique tilapia (*Oreochromis mossambicus*), and European carp (*Cyprinus carpio*) in southern Queensland]. This is partly owing to the natural adaptability and plasticity of invasive species that, over time and successive generations, can tolerate cooler and/or warmer conditions, adding to their range extensions into new waterways. This is also a result of shifting climatic conditions which is particularly important to understand, given the current warming climate and what it means for predicting future establishments of new species and the displacement of native species (cf. Bomford et al. 2010, James et al. 2017).

Northern Australia contains globally significant landscapes in terms of relatively undisturbed ecosystems and vast wilderness (Bowman et al. 2010). The spatial context for the current report is Australia and Australian territories north of the tropic of Capricorn (i.e. latitude 23° South). This equates to southern townships of Rockhampton in Queensland, Alice Springs in the Northern Territory and Exmouth in Western Australia. Northern Australia is tropical, and the coastal areas generally experience an annual monsoonal wet season (Finlayson et al. 2005, Bowman et al. 2010) whereas, the vast arid interior receives less consistent rain. The streams and rivers of the region thus include a wide range of surface water environments in terms of flow regime and permanence (Kennard et al. 2010, Boulton 2014, Steward et al. 2018). These freshwater ecosystems are still being explored ecologically, though are seemingly diverse and species rich in terms of some groups including fishes, turtles, frogs, crabs, crayfish, prawns (Palaemonidae) and shrimps (e.g. Atyidae), microcrustaceans and aquatic plants (Shiel and Koste 1986, Horwitz 1990, Whiting et al. 2000, Georges and Thomson 2010, Capon et al. 2016, Naser et al. 2018, Shelley et al. 2019, Short et al. 2019). Australia entirely lacks certain aquatic groups such as newts and salamanders, has few freshwater mammals, and has few obligate freshwater elasmobranchs (sharks and rays) in comparison to for instance South America. There are also major differences in the families of fish present and absent from within Australia's diverse ecosystems (Levêque et al. 2007). These faunal composition disparities have ramifications for potential invasion by species for which we do not have ecologically functional equivalents given we do not yet understand which elements of our fauna are susceptible to invasion by overseas comparative species and the impacts via competition, hybridisation and spread of novel pathogens and diseases.

Some of the recognised aquatic pests in temperate Australia have already proven costly to society from a research and management perspective. A focus on Weeds of National Significance (WoNS) has seen major benefits in focussing on 32 key weeds species including agricultural, aquaculture and aquarium trade derived or partly derived (e.g. *Salvinia*, *Cabomba*, *Alternanthera philoxeroides*, *Eichhornia crassipes*, and *Sagittaria*) alien species (WoNS 2019). Attempts to resource and achieve European carp (*Cyprinus carpio*) control serves as a substantial long term example spanning decades in south eastern Australia and especially in the Murray-Darling Basin (MDB) (Shearer and Mulley 1978, Roberts and Tilzey 1997, Koehn 2004, Koehn and MacKenzie 2004). In the MDB, European carp are estimated to represent 29–76% of fish biomass according to catchments within the country's largest river basin (Kopf et al. 2019). There are many other examples of fish incursions and impacts including those from the aquarium trade specifically (Arthington 1991, Lintermans 2004, Morgan et al. 2004) and there are some documented failures to achieve eradication (e.g. Jack Dempsey cichlids https://www.dpi.nsw.gov.au/fishing/pests-diseases/freshwater-pests) with aquatic pest problems in their comparative infancy in northern Australia.

The number of species that pose a threat to freshwater ecosystems in northern Australia is theoretically much greater than it is for temperate Australia. There are increasing reports of incursions in tropical Australia (e.g. Hammer et al. 2019, Holmes et al. 2020) and particularly in north-eastern Queensland (Holmes, B., pers. obs.). However, a few high-profile pests still dominate societal and scientific thinking (Koehn and McKenzie 2004, see Finlayson et al. 2005). In general, government investment has targeted aquaculture-related invasive fishes (e.g. European carp, Mozambique tilapia) in contrast to a lack of targeted investment in the much greater threat of aquarium species, with arguably a few vertebrate exceptions [e.g. goldfish (*Carassius auratus*), eastern gambusia (*Gambusia holbrooki*), Oriental weatherloach (*Misgurnus anguillicaudatus*), red-eared sliders (*Trachemys scripta elegans*)] and aquarium derived invertebrates have attracted limited resourcing.

The current review serves to provide some form of consolidation and update of the current status of aquarium trade related or inferred incursions into freshwater ecosystems in tropical Australia. There have been Australia wide (e.g. freshwater fishes: Lintermans 2004, García-Díaz et al. 2018) or regional (Burrows 2004) summaries relating to incursions of select taxa in the past decade, whereas, the emphasis here is on the collective of taxa in the aquarium trade and the risk to northern Australian aquatic ecosystems, specifically. There have also been major shifts in real urban growth, mining and agricultural development as well as tourism practices (e.g. the grey nomad boom) in northern Australia in the past two decades which have the potential to have influenced transport and establishment of aquatic pests. Additionally, there have been rapid assessments of select scenarios for large scale development in agriculture and water resource use across the tropical savannas and semiarid rangelands (Petheram et al. 2018a, b, c, d). However, aquatic biosecurity in relation to these scenarios warrants at least similar levels of scoping work in terms of risk assessment and predictive modelling (e.g. Della Venezia et al. 2018). Furthermore, one of the great unrecognised obstacles to ecologically sustainable development in northern Australia is overcoming the lack of resourcing for ongoing and targeted education and compliance in this differentially more susceptible part of the country with respect to the global aquarium trade nexus.

1.4 Key definitions

For the purpose of this report the tropics is defined as the area between the Tropic of Capricorn and the Tropic of Cancer. Since this report is prepared for the (Australian) Department of Agriculture, Water and the Environment, the Australian tropics refers to the areas of the Australian states and territories north of the Tropic of Capricorn. The terms 'alien' and 'alien species' are consistently used to refer to a source or origin outside of Australia (including its territories). The management of alien species is a primary focus of this scoping study. The term 'endemic' is used to refer to species (or pathogens, viruses, diseases) with long-term evolutionary origins in Australia. The term translocated native species is used to refer to endemic Australian species that have been moved by humans or human processes into new locations within Australia outside of their historically realised or potential range. While translocated native species are not the primary focus of this report, they are an important consideration in relation to ornamental aquarium trade behaviour and activity and especially relevant to water transfer schemes and the interaction with the agriculture, aquaculture and recreational angling sectors. For detailed treatment of translocations pertaining to fishes in northern Australia see Arthington (1991), Burrows (2004) and Lintermans (2004). 'Ecologically sustainable development' is also distinguished from 'sustainable development'. The former refers to human development that has given broad consideration for and has acted in accordance with ensuring that ecosystems remain functioning as they would naturally, whereas, sustainable development focusses on the establishment, perpetuation and success of the human development or industry specifically. A glossary containing definitions of technical terms is also provided in Appendix 2.

1.5 An ecologically sustainable tropical Australian aquarium trade

Certain aspects of aquatic biosecurity in northern Australia are best considered through a tropical lens and an appreciation of the remoteness of much of this part of the country. As has been mentioned earlier, tropical climates including relevant annual temperature regimes, provide idyllic conditions for many alien species stemming from similar climates. The flow regimes of rivers across northern Australia vary and can be catchment and sub-catchment specific (see Kennard et al. (2010) for an excellent continental scale assessment of this topic). Additionally, the flooding and drying regimes of tropical Australia are overwhelming dominated by an annual monsoonal wet season cycle, particularly in the north and north-east (Warfe et al. 2011). However, much of the central and mid-west tropical regions are essentially desert, and rivers may only flow following episodic rainfall events (Morgan et al. 2014). The implications for this highly dynamic mosaic of aquatic and terrestrial environments are many and in relation to aquarium trade related biosecurity issues include:

- Small surface water storage sites (e.g. farm dams) on farms in remote areas serve multiple purposes for human water consumption and use, to produce food (e.g. fish, crayfish) and recreation, as refuge for native biodiversity and act as a potential reservoir for aquatic and semi-aquatic pests.

- Regular spilling of dams, ornamental ponds and outdoor tanks through seasonal rainfall maxima, providing propagule and colonisation pressure via regular opportunity for incursions of aquarium trade sourced pests.

- Wet season related logistical challenges that prevent field-based access, detection, eradications and control of incursions leading to interruptions in biosecurity planning and logistics including pest detection, monitoring and control for significant parts of the year (in some cases 6-9 months each year).

- In areas where habitats contract to small refuge pools for extensive dry periods, thus restricting connectivity to more favourable habitat, alien fishes can have severe impacts on similarly marooned native fishes.

- Issues related to the use of non-native fish for mosquito-wriggler control associated with alleviating mosquito-borne diseases, which forms a substantial mechanism for human behaviour relating to private and public waterways use including in very small water containers (e.g. garden pots) (Jacups et al. 2008, Snr et al. 2011).

- In providing large water storage schemes, large public and private waterways (e.g. dams, channel systems) inevitably provide habitats that tend to serve as establishment and release sites and/or refuges for alien pests including aquatic weeds (Khattab and El-Gharably 1986, Bowmer et al. 1995). However, large water storage and transfer schemes present irreversible logistical challenges for aquatic biosecurity as a function of the scale and interconnectivity of the systems (Kolar and Lodge 2002).

- Seasonal aquatic connectivity across broad landscapes comprised of wetlands and floodplain during the monsoon require a whole-of-catchment and/or intra-catchment approach to managing biosecurity risk be used.

Northern Australia presents as a great global opportunity for conservation and nature appreciation case studies in near pristine landscapes of substantial scale. Maintaining some balance with the intrinsic value of the tropical parts of Australia and various industries including tourism (Anderson et al. 2015) and agriculture is a major challenge. Furthermore, there are multiple human developments in the region. Various forms of urban, residential, and mining activity rely on water and interact with surface and groundwater processes. With human development of northern Australia, whether it be extractive or renewable industries, nature tourism and the accompanying growth of tropical cities and use of regional lands, clearly improved planning, monitoring and management of aquatic biosecurity is required. The aquarium trade as the primary source of current and potential invasion by aquatic pests in tropical Australia should be front and centre in the design and planning of natural resource use and management, and in societal thinking in tropical Australia.

2. AN INTEGRATED FRAMEWORK FOR RESEARCH & MANAGEMENT

Integrated pest management principles bring together economic and ecological considerations in controlling pests (Barzman et al. 2015). Integrated pest management makes use of informed strategy by monitoring and evaluating progress through adaptive management principles. Where single pest species are the focus, these principles enable effective management of available resources in managing the pest at scale (e.g. Westcott et al. 2016). Integrated pest management principles have also evolved to focus on targeting best returns for effort by understanding the ecology of pests in the context of the wider ecosystem (Westcott et al. 2016).

Since the global aquarium trade nexus involves myriad pest species and pathways, presently it is difficult to design and optimise an integrated pest management strategy at the scale and extent of waterways across tropical Australia. Nevertheless, the principles remain the same. Prevention, monitoring and evaluation, whether it be of alien species incursions or surrogate information, remains central to best practice. A major message in the current report is to remain aware of and be proactive in managing pathways for introduction and establishment of multiple alien species across diverse taxa groups (e.g. vertebrates, invertebrates, plants, diseases, viruses) via the aquarium trade and in relation to human behaviour including industry sectors that are not necessarily associated with or readily considered part of the aquarium trade. Furthermore, it is useful to consider the different phases of pest species establishment since this has bearing on investment opportunity (section 2.1.1) since there are significant trade-offs in managing multiple pests and potential pests along a continuum of phases of invasion.

2.1 Incursion

An incursion has been initiated when an alien (or translocated native) species is transported and established outside of its natural range into areas once impenetrable due to geographic or evolutionary barriers.

2.1.1 Phases of incursions by taxa

Biological invasion is a process in which alien species are transported and introduced to a new community (in an ecosystem), and then become established and propagate. At every stage, would-be invaders will be filtered out by unsuitable abiotic and biotic conditions, and only a relatively small proportion will likely ultimately become 'invasive' (Figure 2). Alien species that are intentionally brought to Australia, such as via the aquarium trade, have better chances of surviving and establishing should they be released to the environment because they have already been assisted in surviving during transport, and may be released in locations with suitable habitat and environmental conditions. High propagule pressure readily assists in the initial incursion stage. The continued release of individuals (or infrequent large numbers of individuals) of a species increases the genetic diversity of the group thus increasing the likelihood of individuals findings suitable niches and a population establishing.

Biosecurity is relevant at all stages of invasion (Figure 2). The earlier in the invasion stage that an introduced species is detected, generally the more cost-effective it will be to prevent its impacts (Lovett 2008; Figure 3). This is because invasive species typically can rapidly increase their population size due to taking advantage of favourable breeding conditions or as a result of high propagule pressure, and control costs generally increase with the size of the population or area infested. Preventing the transport, introduction, or establishment of a potential invader is the most desirable and cost-effective form of biosecurity. Eradication is most likely to be economically feasible if the invader is detected relatively early following establishment when the population(s) is (are) small or localised and the risk of further introductions can be minimised or removed. With invasive fishes, successful eradications have generally been from small waterbodies such as dams or smaller reaches of creeks (see review of Lintermans 2004, p493). Eradication may still be feasible and desirable in larger waterbodies though logistically and financially challenging (e.g. carp control in Lake Sorrell, IFS 2020). If the invader has become very abundant or has a large novel range, eradication may no longer be feasible, and containment might be considered. The goal of containment is to keep the invader from further spreading beyond a defined invaded area. Until recently, containment of tilapias [specifically Mozambique tilapia and spotted tilapia (*Pelmatolapia mariae*)] from the Gulf of Carpentaria has been a goal, with initial incursions receiving resourcing for localised eradication in the upper Mitchell River catchments. There has been no resourcing to control this incursion. Because containment requires ongoing management, it can be more difficult to obtain funding for containment than for eradication. If the invader has become extremely widespread, containment will no longer be relevant, and long-term management is the only option for minimising impacts. Protection of high priority biodiversity assets is a key part of long-term management of invasive species by this stage.

A major challenge for considering which option is feasible is determining where on the curve the invasion population is. There are no absolute rules. Decisions about what is feasible will require considering population size and extent, likelihood of reinvasion should eradication be attempted, and whether there are suitable and effective methods for decreasing populations.

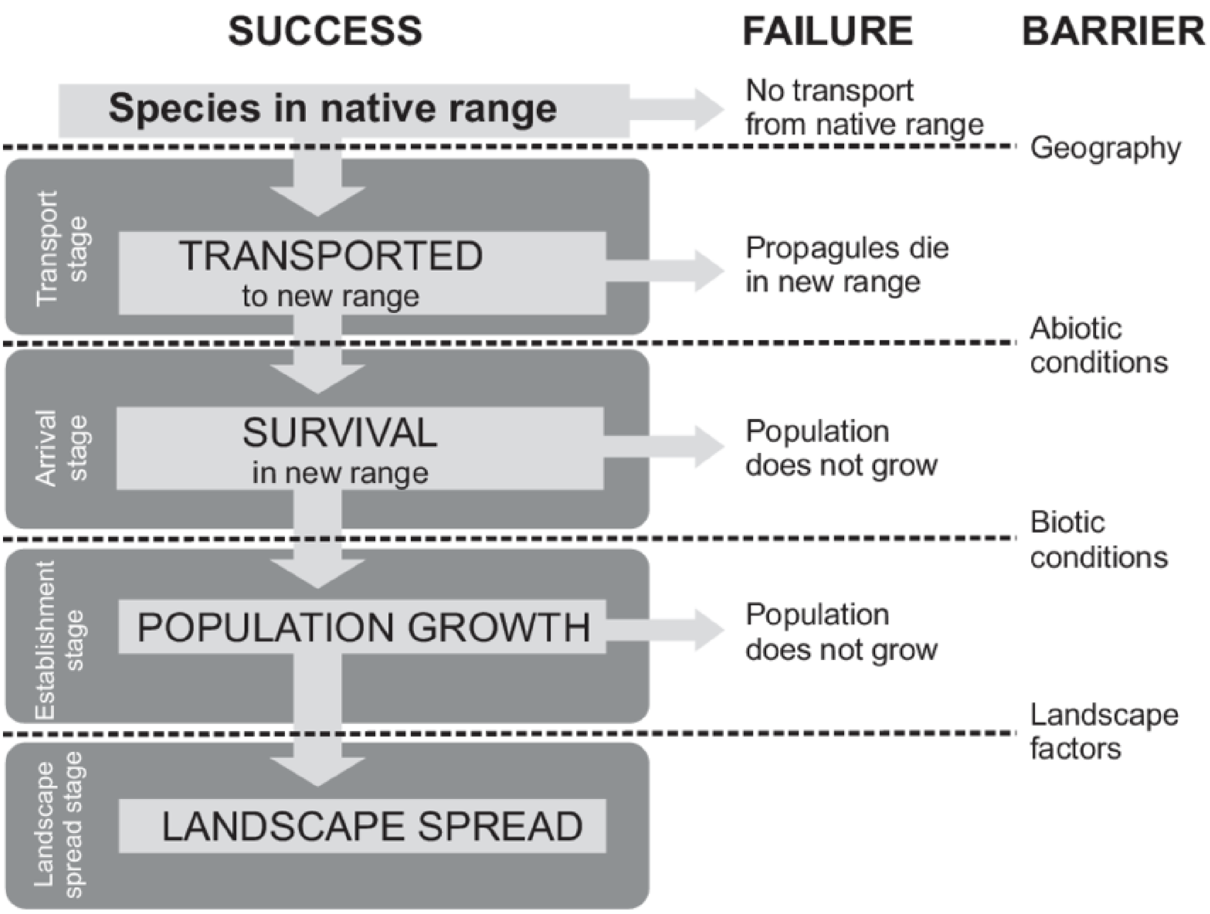

Figure 2: Species invasion outlining the transition steps between the four stages of invasion (reproduced from Darrigran and Damborenea 2015).

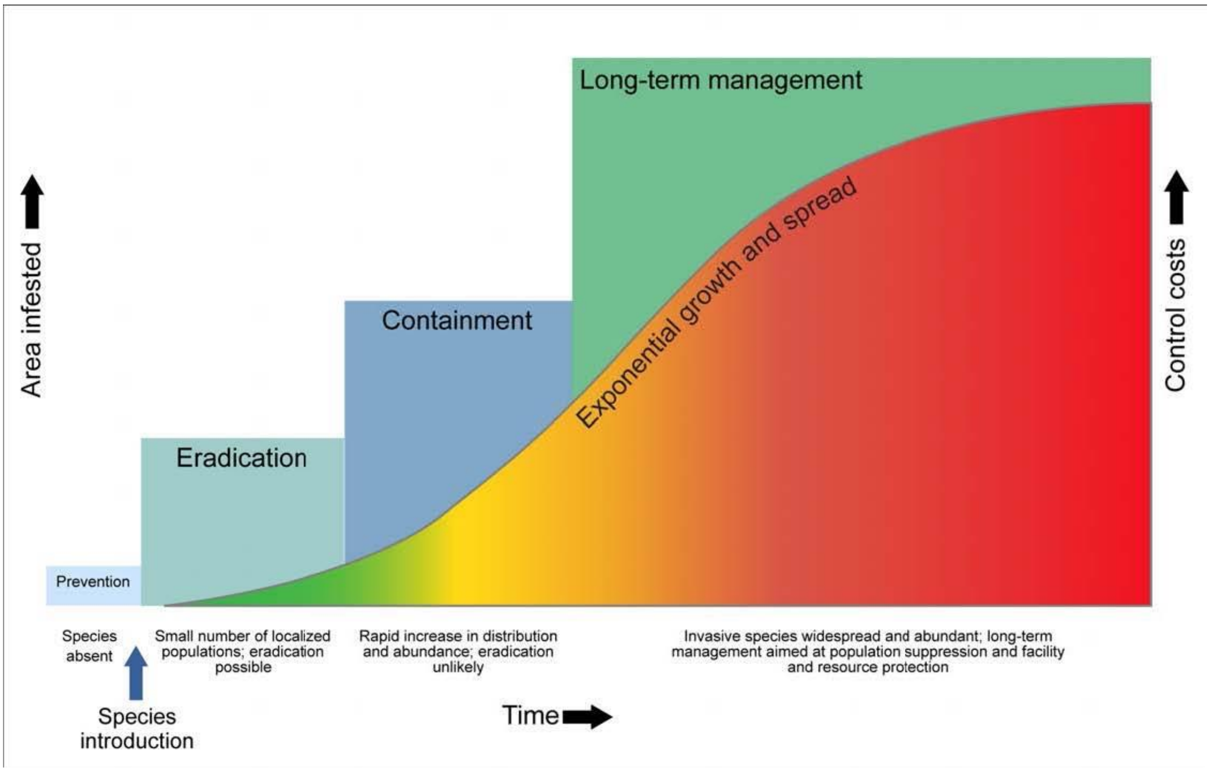

Figure 3: Conceptualisation of an invasive species and the relevant management options available with increasing time (Courtesy of Andrew Cox, the Invasive Species Council).

2.1.2 Published incursions in tropical Australia

Below is a summary of each of the various species incursions that are related, at least originally, to the introduction of species via the aquarium trade. The records are based on available published and unpublished literature and relevant national archives (e.g. Atlas of Living Australia, herbariums, museums). These records pertain to states that have jurisdictions north of the Tropic of Capricorn, and only includes incursions in waterways north of those lines. The following account is separated into summaries of aquarium fish, reptiles and amphibians, crustaceans, molluscs, co-invading parasites and diseases and ornamental plants.

Aquarium fish

It is clear most of the aquarium fish introductions into northern Australia occurred from around the early 1970s (Figure 4). While goldfish became established in northern Queensland (QLD) as early as 1914 in the Norman River (Queensland Museum_I2205), a further three species established in 1977, including swordtails (*Xiphophorus helleri*) in Gladstone, platys (*Xiphophorus maculatus*) and pearl cichlids (*Geophagus brasiliensis*) in Rockhampton, while the eastern gambusia is first represented in collections in 1978 in Cairns (the latter species was spread for mosquito control, but has also been widely used in the aquarium trade including as a feeder fish). Further incursions of other species followed in Townsville in 1978 (Mozambique tilapia); in Cairns in 1982 (spotted tilapia) and in 1985 (jewel cichlid, *Hemichromis bimaculatus*), and three spot gourami (*Trichogaster trichopterus*) in 1996 in the Burdekin River. Since the turn of the century, a further four species have been recorded in databases, including the red devil cichlid (*Amphilophus labiatum*) at Port Douglas in 2001, blue-eyed cichlid (*Cryptoheros spilurus*) in 2004 at Ayr and black sharkminnow (*Labeo chrysophekadion*) in the Ross River in 2010. Many of these alien fish species have since been recorded at multiple locations, in more catchments, predominantly around major towns (e.g. Kroon et al. 2015). Most recently (2014, 2016 and 2018), several cichlids have been reported from the Mackay-Whitsundays area (Holmes et al. 2020, T. Power, unpublished data).

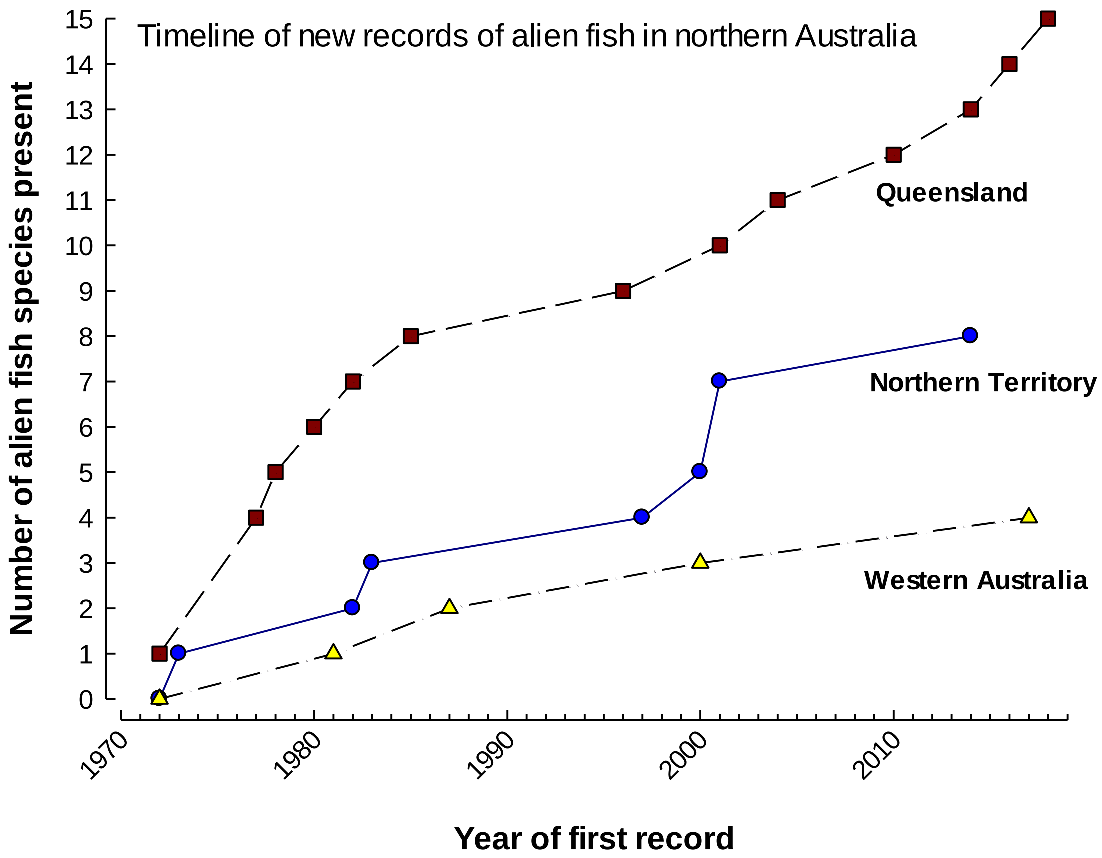

Figure 4: Cumulative number of alien fish species established in northern Queensland, the Northern Territory and northern Western Australia above the Tropic of Capricorn (~23.5°S). Data derived from: Atlas of Living Australia, Australian museums, Unmack 2001, Morgan et al. 2004, 2014, Morgan and Gill 2004, Larson et al. 2013, Thorburn et al. 2018, Hammer et al. 2019, unpublished databases.

The clear trend in aquarium species being strongly associated with townships is also consistent with experiences in northern Western Australia (WA) and the Northern Territory (NT). For example, the first introduced aquarium fish that was recorded in northern WA was Mozambique tilapia in 1981 (near Carnarvon), followed by eastern gambusia and guppies (*Poceilia reticulata*) (1981) near Exmouth, and sailfin molly (*Poecilia latipinna*) near Newman (2017) (Morgan et al. 2004, 2014, Morgan and Gill 2004, Thorburn et al. 2018) (Figure 4). The territories of Christmas Island and Cocos-Keeling also recorded guppies from 1987 (WAMP29332.001). Within the NT, most species are found around Darwin or Alice Springs; the first introduced fish, one-spot livebearer (*Phalloceros caudimaculatus*) was identified in 1973 (Unmack 2001, Larson et al. 2013) near Alice Springs (Trephina Gorge); although Hammer et al. (2019) noted that eastern gambusia was reported in drains around Darwin from the 1950s. Golden perch (*Macquaria ambigua*) and guppies (MAGNT S.12360-001) were recorded there in 1982 and 1983, respectively (Unmack 2001, Larson et al. 2013). Golden perch represent a translocation from another basin. In 1997, the jewel cichlid (*Hemichromis* *bimaculatus*) was discovered in Racecourse Creek (Darwin) (NTM S.15238-005) while eastern gambusia (MAGNT S.15207-001) was discovered in Alice Springs in 2000, swordtails were found in Alice Springs in 2001 (MAGNT S.12274-001), and platys in 2001 in Darwin (MAGNT S.15500-001). Siamese fighting fish (*Betta splendens*) had established in the Adelaide River by 2014 following moderate flooding, although this species had been occasionally detected as early as 2010 (Hammer et al. 2019). A number of other species are known to exist in ornamental ponds in the major townships of northern Australia, and represent a potential invasion source (e.g. Hammer et al. 2019).

Most records in WA and the NT are restricted to a single catchment or small section of a catchment, with most catchments free from feral fish, perchance a result of the small and isolated townships in these tropical regions. In contrast, the records of incursions of alien aquarium fishes in northern QLD number in the thousands, and from these initial incursions, many species listed above have now spread to many catchments across a wide geographic area in recent times. García-Díaz et al. (2018) note the change in introduction pathways of alien fishes into Australia since the 1970s, with 69% of new invasions a result of the ornamental industry. The establishment of feral populations in the regions may also act as stepping-stones for invasion to other regions via human-mediated transfers (see Beatty et al. 2019). Although all fish invasions have been restricted to the teleosts, there is the possibility of the introduction of freshwater or euryhaline elasmobranchs which currently exist in several boutique ornamental hobby collections. For example, multiple species of neotropical stingrays from South America are exploited in the aquarium trade, including species of *Potamotygon* (de Carvalho 2016). Often brightly coloured or ocellated, they are kept in Australia, but are not yet known to have escaped captivity, their rarity and thus associated high value probably precluding frequent illegal dumping into waterways at a rate which is sufficient to foster successful establishment. Currently, under Federal Government Legislation, only two elasmobranch species are deemed suitable for live importation for the ornamental trade, and both these are marine species, and interestingly, both naturally occur in northern Australia. In contrast, over 260 teleost fishes are listed as suitable for live import, and many of these species pose a high risk to northern Australian ecosystems.

Reptiles and Amphibians

Overall, herpetofauna (reptiles in particular) are considered high risk as a source of invasive species due to their predicted ability to establish in Australia (Henderson and Bomford 2011) and prominence in the illegal pet trade (Toomes et al. 2020). Australia severely restricts the importation of alien reptiles and amphibians at the federal level under a number of legislative acts including (but not limited to) the *Environment Protection and Biodiversity Conservation (EPBC) Act 1999* (EPBC ACT), the *Biosecurity Act 2015* and under its treaty obligations as a member of the *Convention on International Trade of Endangered Species* (CITES). As a direct result of these restrictions, increasingly high numbers of alien herpetofauna are intercepted at the border by Australian Biosecurity authorities every year (Henderson and Bomford 2011). Despite these efforts, there exists a burgeoning black-market trade in alien reptiles and amphibians within Australia since in general, only native reptiles and amphibians can be kept, with various state-based permitting systems in place to regulate trade. Effective control measures are dependent not only on stringent border biosecurity to prevent the arrival of novel species, but also effective management and control of high-risk species already present in domestic captivity (Toomes et al. 2020).

To date, there have been no naturalised incursions involving alien reptiles and/or amphibians in tropical Australia as a direct result of the aquarium trade and the few documented naturalised incursions have been almost exclusively been restricted to a subset of southern states [New South Wales (NSW), Southern Australia (SA) and Victoria (VIC)] and subtropical regions of QLD and WA (Tingley et al. 2015; Robey et al. 2011). For example, at least four species of caudate salamanders have been available in the Australian in the last 100 years (Tingley et al. 2015). However, none has been known to establish wild populations here until 2011, when an individual European newt (*Lissotriton vulgaris*) was discovered in an outer suburban waterway of Melbourne (Tingley et al. 2015). Although declared a 'controlled pest animal' in 1997 under the *Catchment and Land Protection Act 1994* and later upgraded to 'prohibited' in 2010, it has not been declared an 'established' pest despite several clearly established viable populations remaining in Victoria (Tingley et al. 2015).

In a similar context, the axolotl (*Ambystoma mexicanum*) which is listed as Vulnerable on the IUCN Red List (Shaffer et al. 2004) is a species of caudate salamander native to Mexico that is widely available in the aquarium trade in all Australian states and territories excluding Tasmania (TAS) and the NT. A cold-water species, axolotls cannot withstand temperatures over ~22°C which largely precludes the risk of naturalisation over much of tropical Australia. So far, they have not been cited as an invasive species anywhere in the world despite their widespread use in laboratory studies. Like the European newt (mentioned above) however, axolotls have a high potential for being inadvertently released into wild systems and there is a serious concern regarding the risk of spreading aquarium borne diseases, such as the chytrid fungus (*Batrachochytrium dendrobatidis*) for the time that they are able to survive in tropical waterways (Berger et al. 1999; Tingley et al. 2015).

Currently only one species of alien reptile is known to have established populations in Australia that have been directly attributed to the keeping of alien species (McFadden et al. 2017). Considered by the IUCN as one of the top 100 most invasive animals, naturalised populations of the red-eared slider now exist on every continent except Antarctica (Csurhes and Hankamer 2016). This turtle, which is native to the southern USA and northern Mexico, was once widely available in the pet trade in Australia until the early 1960's (McFadden et al. 2017). Naturalised populations and individual detections are associated with large urban areas (Burgin 2006; Burgin and Lunney 2007) and now exist in NSW, ACT and QLD while individuals have been detected in VIC and WA (Perth). Despite being banned from possession and sale in QLD in 1985 (Csurhes and Hankamer 2016), e-commerce is acknowledged and established populations are present in the greater Brisbane area, centred on the Pine River Catchment and have been subject to ongoing eradication programs since 2004 (Robey et al. 2011, Csurhes and Hankamer 2016). The most recent incursion of this species was reported further north in the Wide Bay Region in May 2019. It remains unknown if the single specimen detected has spread from the Pine River Catchment population, or if the turtle that was found was another potentially dumped pet, indicating that there are remaining captive specimens still able to act as potential colonisers if released (https://www.abc.net.au/news/2019-05-03/turtle-red-ear-slider-turtle-bundaberg-qld/11078602).

Most of the Australian species of freshwater turtles that are available in the aquarium trade are obtainable under licence through private breeders. However, a few species are classed as 'commercial' and can be sold in various states, on licence, to the general public within the aquarium trade. There is growing concern with the high potential for translocation since turtles have a high potential for being 'dumped' (Cadie et al. 2008), can walk out of ornamental ponds or aquariums and can hybridise (see Georges et al. 2011) with other closely related but regionally distinct species existing in Australia (see Georges et al. 2018; Todd et al. 2013). In QLD, under the *Nature Conservation Act 1992*: Schedule 4, part 3 of the Nature Conservation (Wildlife Management) Regulation (2006) freshwater turtle species that are classed as commercial species include: Eastern long-necked turtle (*Chelodina longicollis*), Krefft's River turtle (*Emydura m. krefftii*), Murray River turtle (*Emydura m. macquarii*), and saw-shelled turtle *Muychelys (Wollumbinia) latisternum.* A native of southeast QLD, NSW and VIC, the Murray River turtle (Georges et al. 2010) is probably the most commonly available species seen in aquarium stores throughout Australia and has been implicated in a number of translocations in coastal NSW and at least one instance where hybridisation has occurred (Bellinger River; see Georges et al. 2011). Not much is known about the extent of translocation of native turtle species in tropical Australia though dedicated investigations are required, perhaps utilising emerging technologies in environmental DNA (eDNA) detection. Murray River turtle has been detected in Mareeba and in Lake Eacham on the Atherton Tablelands in the Wet-Tropics bioregion of North QLD (Ebner, B.C., unpublished data, Figure 5). There is only a single endemic turtle species in the Pilbara region of WA, the dinner plate turtle (*Chelodina steindachneri*), although a south-western Australian endemic species, the oblong turtle (*Chelodina oblonga* previously *Chelodina colliei*, Shea et al. 2020), has been translocated into the southern range of the dinner plate turtle where it is believed to have become dominant in numbers. There is no evidence for any alien turtles in the NT or Kimberley region of WA, noting that each region supports multiple endemic turtle species.

Figure 5: Murray River turtle (*Emydura m. macquaria*) observed in Lake Eacham.

Crustaceans

There are several decapod crustaceans that have been spread by humans within Australia, which has occurred through a combination of vectors including aquarium escapees, use as bait, and aquaculture rearing in outdoor ponds. Within northern Australia, the most common is the redclaw (*Cherax quadricarinatus*), a crayfish, which has recently been moved from its natural range in northern QLD and the NT, to the east Kimberley (Ord River) in 2000, and more recently to the Pilbara (2010), where it continues to be spread by irresponsible recreational fishers (Doupé et al. 2004, Beatty et al. 2019). It poses a huge threat to these ecosystems which do not naturally house crayfish (see Morgan et al. 2014). Redclaw have also been introduced into many east coast drainages of northern QLD (Ebner, B.C., unpublished data) and in subtropical drainages and overseas (Belle et al. 2011, Leland et al. 2012).

A number of alien crayfish have been seized (and tested for pathology) from aquarium hobbyists in Australia which is of concern especially from the perspective of protection against disease (Diéguez-Uribeondo and Söderhäll 1993, Hood 2017, Holmes, B., unpublished data). These include species like the Mexican dwarf crayfish (*Cambellarus spp*.) and the red swamp crayfish (*Procambarus clarkii*), both invasive species in their own right, but also carriers of the potentially deadly crayfish plague disease, caused by the fungus *Aphanomyces astaci*. This disease is rampant in the United States where it originated, and is now destroying crayfish stocks in Europe where it was introduced by importing infected crayfish. It has potential to decimate Australian native crayfish populations, as well as aquacultured crayfish here, which currently remain free of the disease.

Freshwater prawns and shrimps are readily available in the global aquarium trade (e.g. De Grave et al. 2015). Atyid shrimps especially have become prominent in the hobby in conjunction with the rise of microscale exhibits including nano-aquaria (small decorative aquaria) which also involves keeping small plants including mosses (Geck and Schliewen 2010, De Grave et al. 2015). Prawns and shrimps are also used as live feed for predatory aquarium subjects. While alien atyids have been reported from the wild in southern Australia, they are not known currently in tropical Australia. An increase in their online trade is likely to lead to new incursions throughout the north. Atyids play specific roles in consuming meiofauna and have become invasive species on multiple continents (Weber and Traunspurger 2016). Atyid shrimps, along with freshwater crabs, are known to be potential hosts or vectors for the spread of freshwater crayfish pathogens (Mrugała et al. 2019).

Alien freshwater crabs also have the ability to impact trophic webs through higher leaf litter decomposition than native crustaceans and higher rates of litter consumption, increased production of smaller leaf fragments, fine particulate organic matter and dissolved organic carbon (Dohery-Bone et al. 2018). Currently, there are no reports of alien freshwater crabs released or established in tropical Australia.

Native microcrustacean taxonomy and ecology has generally received little attention in tropical Australia and therefore it is unsurprising that there is little published information on alien microcrustacean incursions from the area (though parasitic crustaceans are treated to some extent in a subsequent section dealing with parasites). This aligns with a global trend toward limited attention being given to invasion ecology of microcrustaceans via the aquarium trade despite its likely prevalence. Duggan (2010) provides an informative study from New Zealand whereby alien zooplankton species were detected with minimal effort. It is highly likely that lack of taxonomic resolution and an absence of systematic attempts to investigate prevalence and species richness of microcrustaceans in the aquarium trade (let alone incursions in the wild) is underscoring invasion pathways relating to this group (Shiel and Koste 1986, Pearson and Duggan 2018). Similar logic almost certainly applies to other microscopic or cryptic groups including protozoa, and sponges which are not specifically reviewed in this report.

Molluscs

Molluscs occur in the freshwater aquarium trade in some cases as ornaments, are acquired for their tank cleaning (algae eating gastropods, water filtering bivalves) capability, are used as live food for other species (e.g. cichlids, pufferfishes, stingrays) or are incidentally acquired (for instance on wood and plants) (Ng et al. 2016). Alien bivalve invasions have caused extraordinary and costly impacts in some countries including in the Great Lakes System in Northern America (Burlakova et al. 2012). Data is lacking on invasive molluscs in tropical Australia and represents a priority area for biosecurity work at the wholesaler, retailer and consumer level in conjunction with researchers of native and alien species in tropical Australia.

Although several freshwater molluscs (predominantly Gastropoda) derived from the aquarium trade have been introduced into south-western Australia, south-eastern Australia and Tasmania, few have been reported from northern Australia. Ponder et al. (2016) provide a review of Australian freshwater molluscs, and note that many species that could pose a serious biosecurity threat to Australia are regularly intercepted by Australian biosecurity officers, and others are currently within aquarium shops and pose a real future threat. The spike-top apple snail (*Pomacea bridgesii*) is one such species that has been traded widely in Australia for >20 years. Not surprisingly, in recent years the Brazilian native has established wild populations in water bodies in Brisbane (2008), Hervey Bay, and Townsville (2014) (Biosecurity Queensland, unpublished data). As a generalist herbivore, it is unknown what impact the species will have on the native flora and fauna, or its trajectory for range-expansion throughout connected ecosystems. Acute bladder snail or fountain snail (*Haitia acuta*) is native to north-eastern North America and has been widely introduced throughout the world, including temperate Australia and near Darwin in the NT and northern QLD (Ponder et al. 2016). Seminole rams horn (*Planorbella duryi*) is another North American (Florida) gastropod aquarium species that is found in a few localities of southern Australia, and in a least one northern Australian location near Darwin. Another species found in the Northern Territory (*Taiwanassiminea bedaliensis*) is known only from the Daly River, and there is conjecture as to whether this represents a native population of a south-east Asian species, is an undescribed species or whether it is alien. Due to the morphological similarities of many aquatic gastropods and indistinguishable features, it is unknown if some common aquarium species are present in Australia (e.g. *Haitia mexicana* and *Physella gyrina*), and surveillance of tropical systems (and elsewhere) is urgently needed. Aquatic gastropods are hosts of the liver fluke (*Fasciola hepatica*), a parasite that infects humans and livestock and compete with native gastropods for food and habitat, while also preying on native species.

The most recently detected gastropod in the aquarium trade and one of most concern is the tropical assassin snail [*Anentome* (*Clea*) *Helena*]. This species is a freshwater snail native to south-east Asia. It is popular for use in home aquariums as a predator for other unwanted snails and has recently been detected in aquaria in Queensland for the first time. As Australia has no native carnivorous freshwater snails, the deliberate or accidental release of this species is of significant concern. A lack of information on the ecology of the species in general makes predictions on its pest potential difficult to quantify. Another species of concern is the quilted melania (*Tarebia granifera*) – an invasive freshwater snail of SE Asian origin that can reduce native benthic macroinvertebrate biodiversity once introduced (Jones et al. 2017). Not yet in Australia, it also has the potential for introduction via aquarium trade (Ponder et al. 2016).

Co-invading parasites and diseases

We use the term parasites in this document to include both prokaryotic pathogens (viruses and bacteria) and eukaryotic parasites (protozoa, platyhelminths, nematodes, arthropods). Parasites are integral components of natural ecosystems and play key roles in maintaining ecosystem function (Marcogliese 2004, Hudson et al. 2006). Invasive free-living species, however, may alter normal host/parasite interactions in multiple ways. First, parasite transmission may occur from native hosts to alien hosts, leading to an increase in infection of natives if aliens amplify transmission (spillback) or a decrease in infection of natives if aliens reduce transmission (dilution). Second, if alien hosts introduce new parasites (co-invaders), then these may be transmitted to native hosts, leading to the emergence of new disease in the natives (spillover). Co-invading parasites present a particular problem in aquatic habitats. Lymbery et al. (2014) found from a literature survey of 98 examples of co-invasions, that fishes made up 55 % of the total alien hosts with co-invading parasites, with 81% of these fish hosts being either freshwater species or diadromous.

Many co-invading parasites have been detected in introduced fishes held in quarantine facilities throughout Australia (Whittington and Chong 2007), and in both native and alien fishes in natural waterways in south-western and south-eastern Australia and as far north as southern QLD (Dove 2000; Dove and Fletcher 2000; Marina et al. 2008; Lymbery et al. 2010; Boys et al. 2012). There have been almost no surveys of the parasite fauna (either native or alien) of freshwater fishes in natural waterways in northern Australia, although the bacterium *Edwardsiella ictaluri* was recently discovered in a northern Queensland River and is believed to have entered the river through an alien fish introduction (Lymbery et al. 2016, Kelly et al. 2018). Wilson et al. (2018) investigated the parasites of the invasive Mozambique tilapia in Townsville, and found four species of exotic parasites that were likely co-introduced with this teleost (three monogeneans and one trichodinid), or from other introduced exotic fishes in the region. This study highlights the need for significantly more research into alien parasites in tropical Australia, including investigations on whether these parasites are now also using native species as hosts, and what impact they may have on the life history traits and survivability of Australian endemic fishes.

Co-invasive parasites are frequently more virulent in native hosts in their new range than in the alien host with which they were introduced and presumably co-evolved (Lymbery et al. 2014). The greater virulence of co-invasive parasites in native hosts is usually ascribed to the lack of coevolved resistance or tolerance in the new, naïve host (Mastitsky et al. 2010, Fassbinder-Orth et al. 2013). For example, the swim bladder nematode *Anguillicoloides crassus* is a common parasite of Japanese eels (*Anguilla japonica*) in east Asia, but is generally found at low intensities, with no obvious adverse effects on the host (Nagasawa et al. 1994). The parasite was introduced to Europe with Japanese eels in the 1980s and colonised European eels (*A. anguilla*), in which it is much more virulent, causing thickening and fibrosis of the swim-bladder wall, haemorrhages, secondary bacterial infections and acute inflammatory responses (Kirk 2003).

The paucity of baseline studies on parasitic diseases in Australian freshwater fishes means that there are only a few epizootic events that can be definitively associated with co-invading parasites. Dove and Fletcher (2000) found Asian fish tapeworm (*Schyzoctyle* (*Bothriocephalus*) *acheilognathi*), whose principal host is European carp (*Cyprinus carpio*), in five native fish species sympatric with European carp in sites throughout VIC, NSW and southern QLD. Although pathology was not recorded in this study, Asian fish tapeworm can cause significant intestinal damage, including occlusion, pressure necrosis, and perforation and rupture, leading to death (Scholtz et al. 2012). Marina et al. (2008) reported infections of anchor worm, *Lernaea cyprinacea*, on native fishes in south-western Australia, all with extensive haemorrhages and ulcerations at attachment sites; this parasite was almost certainly introduced with ornamental cyprinids, such as goldfish (*Carassius auratus*) or *Cyprinus carpio*. Boys et al. (2012) found *Aphanomyces invadans*, the causative agent of epizootic ulcerative syndrome, in fishes in the Murray-Darling River system; all infected fish had severe ulcerations. The vector responsible for transmission of *A. invadans* to the Murray-Darling is unknown. *Aphanomyces invadans* has a very wide host range, and is present in north QLD but has not been recorded from the Pilbara or Kimberley regions of WA (Ebner and Morgan pers. obs.).

The presence and impacts of co-invading parasites in northern Australian waterways are largely unknown. The only extensive survey of native fishes for parasitic disease in this region is that of plotosid and ariid catfishes for *Edwardsiella ictaluri* by Kelly et al. (2018). Catfish were sampled from 15 sites across Queensland, the Northern Territory and Western Australia, and the bacterium was detected in the tropical tandan (*Tandanus tropicanus*) from the Tully River at a prevalence of 40% (95% CI 21-61%). *Edwardsiella ictaluri* is the causative agent of enteric septicaemia of catfish (ESC). The disease was first observed in cultured channel catfish (*Ictalurus punctatus*) in the USA (Hawke et al. 1981), with acute clinical signs of ulcers and pin point haemorrhages externally, with diffuse internal septicaemia and tissue necrosis (Evance et al. 2011). There is also a chronic form of disease, where fish exhibit meningoencephalitis (Newton et al. 1989), and some fish can be infected asymptomatically (Chen et al. 1994). The bacterium has now been detected from multiple fish species (catfish and non-catfish) throughout the world. Infected fishes from the Tully River (North QLD) showed no clinical signs, either behaviourally or from histopathological examination. While the origin of the bacterium in the Tully River is not known, at least one alien ornamental fish species, platys (*Xiphophorus maculatus*), were present at the same site as infected catfish (Kelly et al. 2018).

Ornamental plants

Study of aquatic weeds has received at best patchy treatment across the vast remote areas of northern Australia. However, there are some good examples of co-ordinated control and eradication attempts at specific localities. Perhaps the longest standing of these is yellow burrhead (*Limnocharis flava*), which since 2001 has been the target of a national cost-shared eradication program, managed by Biosecurity Queensland with financial support from other states and the federal government. Beyond this example of a national eradication program, there are multiple examples of eradication objectives at a state or local government level for many other ornamental invasive plants.

Despite the high diversity of ornamental plants globally, only a few species appear to be restricted from importation. In WA, the following aquatic ornamental plants are declared weeds and must be reported to the Department of Agriculture and Food, Western Australia (DAFWA) for eradication: leafy elodea (*Egeria densa*), hydrocotyl (*Hydrocotyle ranunculoides*), parrot's feather (*Myriophyllum aquaticum*), sagittaria (*Sagittaria platyphylla*), salvinia (*Salvinia molesta*), senegal tea (*Gymnocoronis spilanthoides*), water hyacinth (*Eichhornia crassipes*) and water lettuce (*Pistia stratiotes*).

Within WA, the *Biosecurity and Agriculture Management Act 2007* (BAM Act) was enacted in 2013 to prevent new animal and plant pests and diseases from entering, while also managing the impact and spread of those pests already present in the state. Many of these species are declared weeds in the NT, as well as additional species including alligator weed (*Alternanthera philoxeroides*). Three infestations found in the NT have since been eradicated. The absence of surveillance for aquatic weeds in large parts of northern Australia hinders our ability to report on the distribution of incursions.

Within Queensland the *Biosecurity Act 2014* regulations identify both prohibited and restricted biosecurity matters. In the basic application of the legislation, prohibited matters are those not yet established within the state (although they may be present elsewhere in Australia) and restricted matter are present within the state and subject to conditions. Prohibited invasive plants identified in schedule 1 include anchored water hyacinth (*Eichhornia azurea*), Eurasian water milfoil (*Myriophyllum spicatum*), fanworts (*Cabomba* spp. other than *C. caroliniana*), floating water chestnuts (*Trapa* spp.), horsetails (*Equisetum* spp.), lagarosiphon (*Lagarosiphon major*), Peruvian primrose bush (*Ludwigia peruviana*), salvinias (*Salvinia* spp. other than *S. molesta*) and water soldiers (*Stratiotes aloides*). Restricted invasive plants listed in schedule 2 include alligator weed (*Alternanthera philoxeroides*), cabomba (*Cabomba caroliniana*), hygrophila (*Hygrophila costata*), yellow burrhead (*Limnocharis flava*), sagittaria (*Sagittaria platyphylla*), salvinia (*Salvinia molesta*), water hyacinth (*Eichhornia crassipes*), andwater lettuce (*Pistia stratiotes*). There are other notable aquatic weeds from outside of the ornamental plant trade such as pond apple (*Annona glabra*), water mimosa (*Neptunia oleracea* and *N. Plena*) and mimosa pigra (*Mimosa pigra*).

In addition to the *Biosecurity Act 2014* local governments within Queensland can locally declare a species and limit its sale and distribution under relevant local laws.

The Weeds of National Significance (WoNS) approach has provided a way of prioritising terrestrial and aquatic weeds from the multitude of invasive plants in Australia (Lizzio et al. 2010, Hennecke 2012). Criteria for listing of species at the national level include degree of invasiveness, impact, potential for spread and socio-economic and environmental values (Lizzio et al. 2010, Hennecke 2012). The process provides profile to specific weeds for resourcing on-ground biosecurity actions. An equivalent process does not exist in Australia for prioritising field responses to, for instance, pest freshwater fishes or invertebrates.

2.1.3 Suspected and unpublished incursions

The introduction of new species into aquatic ecosystems is inherently difficult to monitor given that infestation and subsequent establishment occurs out of human sight. Unlike land-based spread of an invasive species which is often obvious, alien fish and invertebrates often have the advantage of proliferating significantly before being detected, for instance by the public (e.g. recreational anglers, amateur naturalists). This is further hampered in remote areas like northern Australia, where waterways may be infrequently visited, and where spread of alien species may be assisted through regular annual flooding events that occur as part of the wet season in the tropics. As with incursions detected in populated centres, alien fishes are often found in remote waterways that neighbour adjacent high-use recreational areas, such as popular riverside campsites. It is unknown whether this is coincidental, in that the increased fishing effort in these areas increases the chance of detection of an alien fish, or rather that these areas are the incursion sites themselves (most likely where alien fish have been used for bait or similar). More research into these pathways for initial incursion is sorely needed.

Reporting of alien fish catches is also paramount. Currently in QLD, the Department of Agriculture and Fisheries (DAF) has an online ‘report a pest fish’ page, where the public is encouraged to report suspect fish, with photographs and location details. Alternatively, the DAF call centre can also be contacted. Continual education and public reports have been paramount in the early detection of most new incursions identified in north Queensland. Indeed the 2007 ‘Stop the Spread’ campaign road show undertaken by DAF to stakeholders in north Queensland led to the reporting and discovery of the spotted tilapia incursion at Eureka Creek in the Mitchell River Catchment in 2008. The quick response and eradication efforts contained the population spread until around 2017, when a new population was discovered in Chillagoe, around 100 km west. It is unknown if this new population was facilitated by the Eureka Creek supply, or from a new introduction to the system. In Western Australia people are encouraged to report aquatic pests and diseases via the FishWatch and WA PestWatch websites, or through phone numbers and apps provided by the Department of Primary Industries and Regional Development. These mechanisms have resulted in the identification of a number of alien species incursions in wild systems and also includes species translocated from other regions of Australia. https://www.fish.wa.gov.au/Sustainability-and-Environment/Aquatic-Biosecurity/Pages/Biosecurity-Alerts.aspx. The Northern Territory has a relatively active aquatic biosecurity program including a community pest reporting system which has provided several important leads and observations as and is facilitated by The Northern Territory Aquatic Biosecurity Unit (Hammer et al. 2019; https://nt.gov.au/marine/for-all-harbour-and-boat-users/biosecurity/aquatic-pests-marine-and-freshwater/freshwater-pests).

There are numerous active investigations of suspected ornamental fish incursion underway in QLD, WA (Figure 6) and the NT. Generally, limited human and financial resources are available to mount a full response, and resources are severely limited in this space for ‘investigative’ work. While this can lead to delayed intervention of newly established alien species, the impact on the environment can be very destructive. Often, collaborations are required between state and local government, university staff, NRM and local community groups are required to undertake investigations, particularly in remote areas. Facilitating these groups, ascertaining funding and/or in-kind support, and coordination of tasks requires a consolidated approach which is often difficult to achieve in the current limited resource environment. It highlights the critical need for a fully funded, formal program in northern Australia to tackle not only existing, but emerging priorities at and within state and national borders.

Figure 6: An example of government signage for reporting of aquatic pests and suspected incursions in Western Australia.

2.1.4 Environmental and economic impacts

Estimating the financial cost of investing and not investing in aspects of aquatic biosecurity is an especially important process from environmental and economic management perspectives. There is a wide range of risk posed by the global aquarium trade nexus and in the context of northern Australia this includes risk to subsistence fishing by indigenous people, recreational fishing including for local community recreation and tourism purposes, biodiversity loss, human heath (liver flukes, mosquitos) and agricultural impacts. However, there are several reasons why relevant estimates of economic impacts of aquatic biosecurity are rarely available (Lovell et al. 2006, Oreska and Aldridge 2011). To some extent the technical challenges and resources required to perform such valuations are stumbling blocks (Oreska and Aldridge 2011) and partly the complexity of responses by naïve ecosystems to alien species is unpredictable and requires resourcing for economic analyses to have a meaningful basis. Economic analyses are also often associated with cases of single pest species, or industries that deal with one or few commodities, whereas the aquarium trade comprises a myriad of biota and products often each of small economic value but many of which with potential to have far reaching environmental impact (i.e. the global aquarium trade nexus). There is a feedback loop here between conducting cost-benefit analysis and performing biosecurity.

Estimation of the order of magnitude of economic costs of environmental management and loss of economic revenue including ecotourism impacts is required to justify spending on biosecurity (e.g. Lovell et al. 2006, Oreska and Aldridge 2011) and this may be achieved by estimating biosecurity needs associated with individual invasive species (e.g. Oreska and Aldridge 2011). However, even this process makes use of hindcasting. Therefore, in addition to recommending the prioritisation of individual alien species for containment, control and eradication akin to a WoNS program, and evaluating resourcing such species-specific biosecurity (e.g. Oreska and Aldridge 2011), it is argued here that some form of predictive costing is required to anticipate biosecurity requirements in the future and to value prevention of invasion in regard to the aquarium trade at the species level and at a higher taxonomic or sector level (e.g. outdoor pond biota, nanoaquarium biota). CSIRO has conducted analogous predictive work modelling water harvesting scenarios in northern Australia (e.g. Petheram et al. 2018d, Pollino et al. 2018) that could be adapted to suit biosecurity needs. It would be useful to involve biosecurity specialists, aquarium trade consumers, retailers and wholesalers in deriving models that explore scenarios of aquarium trade to maximise benefit to protect freshwater ecosystems and human economics in northern Australia.

There has been research into the ecological impacts of specific aquatic pest fauna in tropical Australia including tilapia (e.g. Morgan et al. 2004, Maddern et al. 2010, Russell et al. 2012), pigs (e.g. Fordham et al. 2006) and cane toads (e.g. Letnic et al. 2008). There are numerous research papers available on the impacts and management of each of these species in this context, although the impact of cichlid species in QLD has been largely lab and desktop based with dedicated field monitoring discontinued following termination of government research presence in Cairns almost a decade ago. Research into tilapia in the Gascoyne River (WA), however, demonstrated dietary comparisons with native fishes in dry season refuge pools and demonstrated their aggressive behaviour in guarding nests (Maddern et al. 2004). Strikingly, in comparison there has been negligible lab or field-based study of the impacts by aquarium trade incursions on northern Australian ecosystems despite numerous recognised incursions of taxa, notably fish and plants and in some cases species that have been in the wild for decades.

In part, the lack of research focus on the impact of aquarium trade related incursions in tropical Australia may be a function of the lack of visibility of the small-bodied alien fauna (e.g. platys, swordtails, guppies) and the lack of visibility of submerged aquarium plants, to the public. This is probably exacerbated when colourful aquarium fishes rapidly lose the colour gained via selective breeding when in wild systems over several generations, making them less identifiable to experts and public alike. In contrast, semiaquatic fauna and especially large-bodied and/or repugnant species (e.g. cane toads, pigs) and floating or emergent weeds (e.g. salvinia) are more obvious and prominent in the minds of people. The lack of public profile for aquarium trade escapee species is a major impediment for managing and resourcing protection against their environmental and economic impacts. Additionally, the lack of underwater accessibility for the public in many freshwater habitats in northern Australia arises from the risks associated with estuarine crocodiles (*Crocodylus porosus*) and represents a major obstacle to generating community connection with underwater freshwater fauna and flora, and ultimately in gaining political support for aquatic biosecurity in this part of the country.

Alien aquatic plants that escape from aquariums, ponds and farm dams can become highly invasive and cause a range of socio-economic and environmental impacts (Petroeschevsky et al., 2011; Stiers et al., 2011). Aquatic weed infestations interfere not only with recreational activities (e.g. boating, fishing and swimming) (Verhofstad and Bakker, 2019), but also reduce water quality and quantity (drinking and irrigation water) (Bunn et al., 1998) and alter aquatic habitat complexity thus leading to changes in community composition including the potential loss of valuable angling species in some invaded waterways. There is also a public health concern linked to the proliferation of mosquitoes in dense aquatic vegetation such as water hyacinth. From an environmental perspective, aquatic weeds are of concern as they have the ability to alter entire ecosystems and cause a decline in biodiversity (Kovalenko and Dibble, 2011; Kuehne et al., 2016). Lastly, invasive aquatic weeds incur high management costs aimed or occur in complex management scenarios that make the challenge of managing or ameliorating their impacts expensive or complex to the point of impossible once established.

Aquatic plants come in four different growth forms: submersed, free floating, floating attached and emergent. Respective invasive examples would be Carolina water shield (*Cabomba caroliniana*), water hyacinth, blue lotus (*Nymphaea caerulea*) and sagittaria. Of all the invasive aquatic plants, the free floating forms are the most environmentally damaging because of their potential to completely change the way freshwater systems function (Figure 7) (Brendonck et al. 2003, Scheffer et al. 2003, Feuchtmayr et al. 2009, Fontanarrosa et al. 2010, Villamagna and Murphy 2010). Healthy water ways are characterised by clear water that allows penetration of sunlight and exchange of gases through the surface. The system is based on primary production, i.e. photosynthesis of submersed macrophytes and phytoplankton drive the ecosystem and are the basis of the food web. The submersed native aquatic plants play an important role in providing habitat structure and refuge for other organisms (Carpenter and Lodge 1986, Jeppesen et al. 1998, Meerhoff et al. 2003). Once invasive floating plants cover the entire water surface, the ecosystem will be dramatically altered as a result [see Figure 8a as an example of a farm dam covered by the popular aquarium plant, Amazon frogbit (*Limnobium laevigatum*)] (Scheffer et al. 2003, Perna and Burrows 2005, Perna et al. 2012). The dense surface cover prevents gas exchange and light penetration leading to a loss in photosynthesis production and changes in dissolved oxygen levels. The decay of organic material and thick roots of floating plants, of both native species being outcompeted and the natural lifecycle of invading aquarium plants, will release large amounts of CO_2 into the water, altering water chemistry to become more acidic, to a level not favoured by native ecosystems. Overall, under a dense cover of floating alien plants, such as water hyacinth, the water becomes anoxic and the pH can be as low as 4. These conditions are completely unsuitable for most native aquatic biota. The ecosystem previously driven by primary production shifts to one that is based on detrital decomposition. Once this happens it is very difficult to restore the system to its original state without a large scale management effort (Scheffer et al. 2003, Jeppesen et al. 2007, Feuchtmayr et al. 2009), resulting in a total loss of established species.

2.1.5 Managing invasive aquatic plants

There is limited published information available or accounts of successful eradication of alien species incursions from the aquarium trade in tropical Australia. However, many local governments, catchment groups and state agencies are involved in continual management of a range of escaped aquarium or ornamental aquatic weeds, often in large or complex landscape scale management scenarios. Species which fit this bill include the weeds of national significance: salvinia, water hyacinth, water lettuce, and Carolina water shield. Other notable aquarium escapes under management include glush weed (*Hygrophilla costata*), stream bogmoss (*Mayaca fluviatilis*) and Amazon frogbit. Aquatic plant management is in many ways much more complex than it is for land-based weeds. Generally, the weed management strategies and technologies developed for a terrestrial context are not suitable or transferable for use in aquatic situations. Access for management activities in tropical waterways and floodplains is highly seasonal and has the added complexities of requiring specialised aquatic craft or contending with significant hazards such as estuarine crocodiles. Aquatic systems are also frequently fragile ecosystems with high natural and social-economic values that are easily upset by management options (Morris et al. 2003, Scheffer et al. 1993, van Nes and Scheffer 2005).

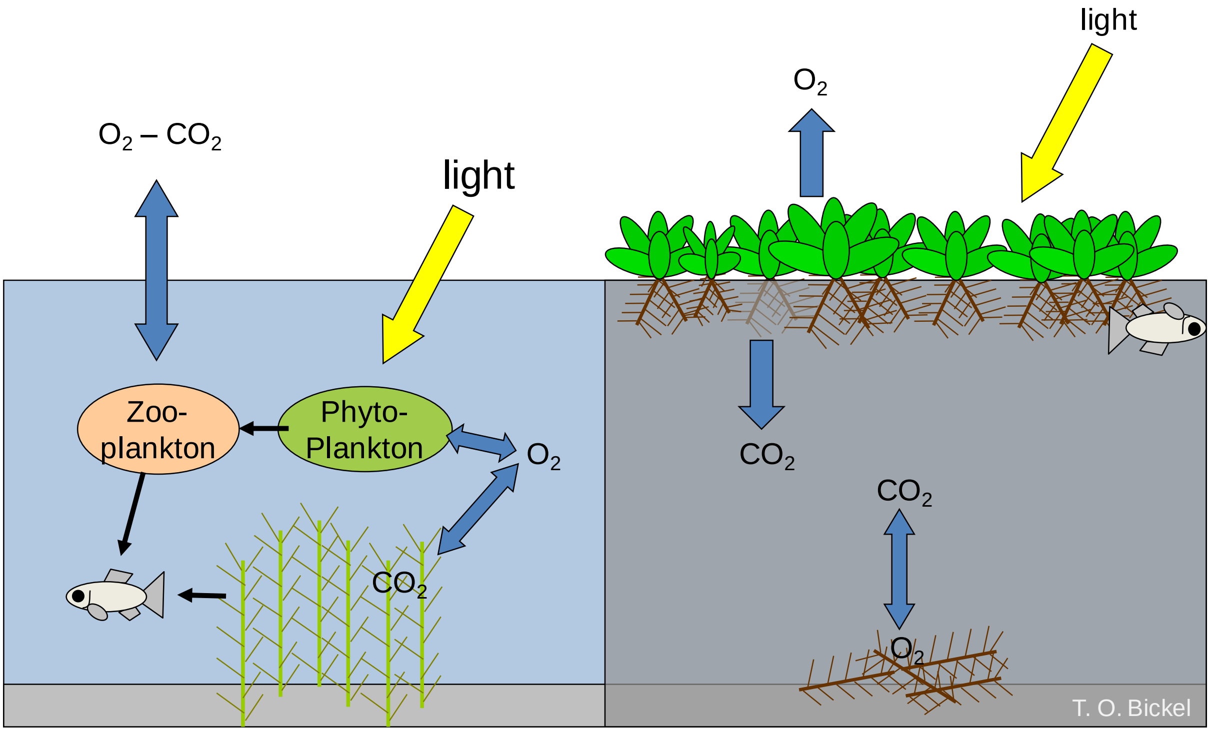

Figure 7: Simplified conceptual diagram of a healthy and diverse aquatic ecosystem driven by primary production and the shift to a detrital system after the invasion by floating plants. The shift also profoundly affects the water physio-chemical environment: the water becomes anoxic, acidic (low pH), and deprived of photosynthetically active radiation.

Essentially there are four distinct types of aquatic plant control methods: 1) chemical control with herbicides, 2) physical controls relying on machinery or manual removal, 3) biological control with species-specific plant predators or pathogens and 4) habitat manipulation, such as draining or nutrient management (Hussner et al. 2017). All these methods have advantages and disadvantages - the situation will determine which tool to choose (Clayton 1996). Herbicides and physical methods are the most widely used tools. Herbicides are able to control large areas at a relatively low cost, and are an excellent tool to remove surface cover of floating plants in farm dams (Figure 8a, b). However not all aquatic weeds have effective herbicide control tools available (e.g. stream bog moss), or the control tools can only be applied in limited situations (e.g. Carolina water shield). Mechanical devices are often used because there is a perception that they are more environmentally friendly than herbicides. However, the long-term environmental impact of invasive plants will in most cases far outweigh any potential short-term impacts of herbicides used in freshwater systems. Mechanical devices can work very well to remove unwanted biomass from water-bodies (Figure 8b), but the running costs are typically high and the machines are often restricted in where they can be used, based on water depths and submerged hazards for example. For some species, such as salvinia and water lettuce, there are excellent biocontrol agents available that can achieve a high degree of control with little input (Figure 8c). Due to the complexity of aquatic plant control, success often depends on the expertise when applying the control tools to achieve management goals. Management of invasive aquatic plants is frequently a long-term commitment, incurring recurring and high financial burdens on managers. Therefore, prevention of invasion in the first place is the most cost effective management solution and highlights the importance of preventing release of alien aquarium plants into the wild (Ricciardi and Rasmussen 1998).

2.1.6 Climate change considerations

Rapid shifts in the distribution of fauna and flora via self-dispersal, is becoming commonplace for a subset of species and especially for mobile species in marine, terrestrial and freshwater environments (Pecl et al. 2017). In the context of freshwater ecosystems, climate change has major ramifications for human and ecosystem water availability, fisheries, native aquatic species and endemic ecosystems (Ficke et al. 2007, James et al. 2013, 2016, 2017; Hilbert et al. 2014). Furthermore, tropical mosquito borne diseases including malaria and Ross River virus are predicted to increase in range because of climate change and other human related mechanisms (Pecl et al. 2017). There is also likely an increasing demand for human use of water in countering bushfires and fulfilling urban and agricultural demand for water notwithstanding population growth.

Climate change is likely to have effects on obligate freshwater fauna including semi-aquatic taxa in Australia (James et al. 2013, 2017, Hilbert et al. 2014). James et al. (2013) provide an initial projection of impacts of climate change on freshwater biodiversity at a continental scale. However, monitoring of indicator populations and comprehensive research and adaptive management of tropical freshwater taxa is clearly lacking in northern Australia. Scientific comment to date is commendable but has been largely speculative and rudimentary (e.g. Rayner et al. 2008, Morrongiello et al. 2011). Diadromous species have the capacity to disperse via marine connections between catchments, however, focus on endemic species with restricted ranges including wholly freshwater species with an inability to migrate between latitudes requires urgent attention. The highly restricted nature of several endemic species of freshwater taxa including fish and/or crustaceans in parts of the Pilbara, Kimberley, Northern Territory and the Australian Wet Tropics points toward those regions as important areas for cases studies and adaptive management at least in terms of safeguarding from alien fishes and crustaceans (Choy and Marshall 1997, Pusey et al. 2004, Unmack et al. 2016, Hammer et al. 2018, Shelley et al. 2018, 2019, Choy et al. 2019, Short et al. 2019, Ebner, B. C. and Donaldson, J. A., unpublished data). The Australian Wet Tropics is probably the most urgent of these given the rate at which alien species from the aquarium trade are emerging in that region.

A key compounding threat for wholly aquatic species with restricted ranges is that they are vulnerable to climate change rendering habitat unsuitable and having no ability to migrate elsewhere, combined with the threat of human delivery of alien and translocated species to the restricted range of the endemic species. Highly restricted endemic species do not have the luxury of the more widespread species for which declining distribution or abundance is possibly detected by coarse monitoring programs. Since human behaviours provide the vectors for alien and translocated native species dispersal, the subregions where range-specific endemic freshwater taxa inhabit could be targeted for raising awareness and in some cases forming the basis of rescue populations via captive breeding programs or translocation strategies. These approaches require consideration, potential approval and a sense of urgency within scientific, government and societal input. Existing public facilities and visitor sites are potential key locations for maintaining high profile freshwater species and in raising the profile of others (e.g. Malanda rainbowfish, Unmack et al. 2016), in conjunction with educating and promoting healthy choices in the aquarium and ornamental pond sector and in farms dams.

Figure 8: Examples of aquatic plant management: a) a farm dam infested with Amazon frogbit; there is no visible water, b) two months after treatment with a herbicide there is an open water surface and several bird species start using the dam again; c) harvest of salvinia with a mechanical harvester in Dogwood Creek, Miles; QLD (note areas with woody structures in the river that can't be accessed by the harvester were treated with herbicides); d) Draining of Lake Benalla, VIC to control Carolina water shield; e) salvinia infestation in a weir before, and f) one year after integrated control using a biocontrol agent, herbicides and a mechanical harvester [photos: a)-c) Tobias Bickel; d) Tony Dugdale, VIC DPI; e) & f) Craig Hunter, QDAF].

For completeness, it should also be mentioned that locations historically considered to be sub-tropical are generally becoming more inhabitable to tropical invasive species, as a function of climate change (e.g. Lough 2008, Pecl et al. 2017). In Australia, on the eastern coast this equates with major human population centres that are expanding (e.g. south-eastern QLD) which comes with associated risk of aquarium species incursion and establishment.

3. OPPORTUNITIES

Whilst there is an inevitability of further incursions by aquarium trade related biota into our waterways and endemic freshwater ecosystems, there are multiple opportunities for safeguarding tropical ecosystems. These opportunities exist at each level of the biosecurity process, namely prevention, preparedness, early detection, eradication and control. As mentioned earlier there are compelling reasons for focussing on the 'prevention end' of this progression. Vast tracts of land in tropical Australia are under Native Title, freehold tenure to pastoralists, Crown Land and National Parks and the various state government agencies manage the land, water and flora and fauna. Therefore, clearly these multiple land and water managers are central to prevention and early detection of incursions in tropical freshwater ecosystems.

However, if the roll out of a successful and ongoing 'prevention' campaign has been successful, there is rarely a yardstick to determine success – in that the only measure of success is that there are no new establishments of aquatic alien species. In the current resourcing climate, this alone traditionally makes securing ongoing committed funding very difficult, particularly when there are often new incursions of other high-risk terrestrial species (i.e. ants) or other agricultural biosecurity species of concern (i.e. fall army worm, fruit flies) that often take up the resources or minimal 'slush funds' available to such responses. This again highlights the need for a long-term committed funding model that is not able to be removed when the next biosecurity issue arises.

Raising societal awareness of potential or existing problems surrounding risks of purchasing and maintaining aquarium and ornamental pond species is critical. However, communication exercises centred on pest control confront serious obstacles that are not easily overcome with simplistic initiatives such as producing a flyer or series of brochures (Kruger et al. 2009, Gilmour et al. 2011). Gaining public attention is not the least of these considerations. Building trust (Gilmour et al. 2011) and understanding target audiences, including aquarium industry-centric demographics and non-industry aware demographics is also important. For instance, people purchase and stock small aquarium fishes into pots, ponds and dams for mosquito control or for the perceived value of mosquito control without necessarily having knowledge of the relative predatory effectiveness (Martinez-Ibarra et al. 2002, Hurst et al. 2004, Willems et al. 2005), nor biosecurity risk to freshwater ecosystems (Figure 9). Furthermore, the choice of aquatic plants and their management can influence mosquito production (Greenway et al. 2003). The health considerations of mosquito control hold a substantial role in human formal and informal behaviour in the tropics (Martinez-Ibarra et al. 2002, Benelli 2015, Horword et al. 2018) given the prevalence of mosquito-borne diseases within these regions. This extends to international, state and local government and non-government activity, advice and regulation relating to household practice with water management (Russell 1999, Mutero et al. 2000, Jacups et al. 2008).

This also demonstrates that it is not just keen recreational aquarists, retailers and wholesalers that are a focal demographic for communicating aquarium trade biosecurity concerns. The aquatic biosecurity risk and biodiversity information needs relate to land owners and managers including those mentioned previously and practitioners ranging from ecologists, medical practitioners, landscape gardeners, council environmental officers and human health officers, to fly-in and fly-out mining workers, to ordinary citizens including grey nomads and politicians. With regard to the latter, there is a clear need for our political leaders to understand and champion the global aquarium trade nexus to federal parliament noting that it encapsulates challenges of both a human health and economic nature but also of ecological concern, and that these concerns at least nationally, are most pronounced for Northern Australia.

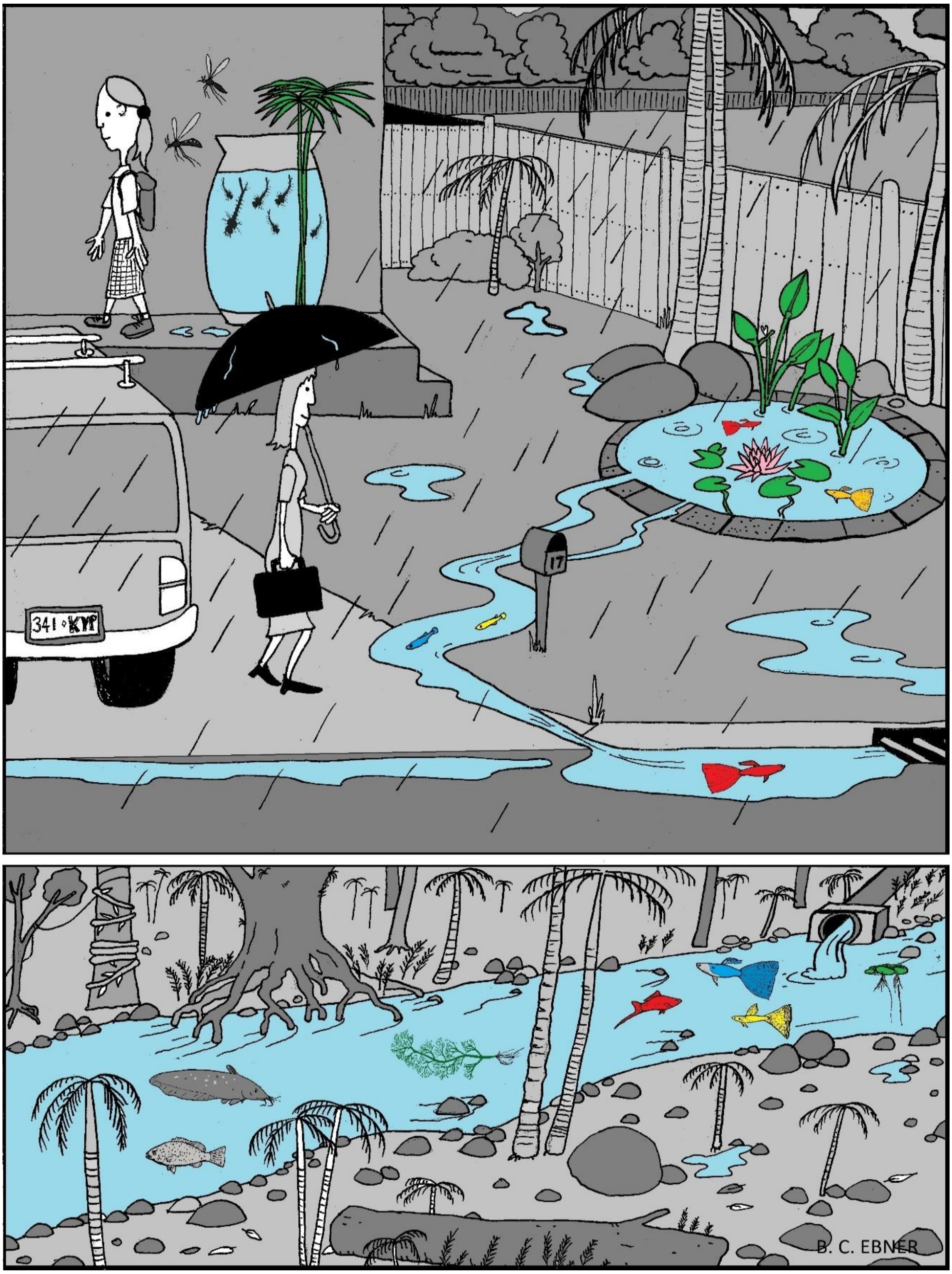

Figure 9: In Tropical locations, including suburban developments, mosquitos represent important vectors for human health related issues including Ross River virus, dengue fever and malaria. Small ornamental fishes represent a common strategy in responsible care of still water features including ornamental pots and ponds to prevent mosquito pupae proliferating. However, these underly numerous pathways for ornamental plants and animals (alien and native species) to enter local ecosystems. Shown here is the effect of torrential rain in spilling a pond to a roadside drainage network.

On a more fundamental level, is broad societal awareness and willingness to act in response to the global aquarium trade nexus. A major recommendation of this report is to pursue an approach that clearly provides wholesalers, retailers and consumers including those consumers that do not necessarily identify as aquarists with clear and transparent information regarding the choices they are making in transactions involving aquarium trade and ornamental pond related purchases of biological material.

3.1 Establish a national focus on biosecurity in freshwater

Water resource use is one of the leading and most contentious issues for Australian society. This arises from its immediate value for human survival including water consumption, agricultural production, culture, recreation and biodiversity (Leybourne and Gaynor 2006). Societal and institutional behaviour plays a major role in biosecurity related matters in waterways, and on private and public land. However, in tropical Australia with emerging and unique cities, diverse land and water use, diverse tourism, recreational activities, and evolving institutional structures, it is difficult to conceptualise, quantify and understand this complexity (Woinarski et al. 2007, Luckman et al. 2009). This includes the reality that most Australians do not live in the tropics and that many northern catchments are relatively pristine by world standards (Zander et al. 2010). It requires detailed investigation of human dimensions and institutional arrangements including preliminary assessment akin to that achieved in the marine pest sector (Stenekes et al. 2019) with a focus on human behaviour in northern Australian settings (e.g. Cridland 2008, Close et al. 2014, Mahadevan 2014). An immediate task that is recommended is funding an analysis of the freshwater pest network.

The National Biosecurity Committee (NBC) was formally established under the Intergovernmental Agreement on Biosecurity (IGAB) in January 2019. Operating under the NBC are the four sectoral committees namely: Animal Health, Plant Health, Marine Pest Sectoral and the Environment and Invasives Committee. (IGB 2019, p90). This arrangement does not prioritise freshwater ecosystems and water resource development to the level warranted, with the only dedicated sub-committee (the Freshwater Vertebrate and Invertebrate Working Group) sitting underneath the Environment and Invasives Committee. A major recommendation of this report is that a Freshwater Pest Sectoral Committee, to the level equivalent to that of the Marine Pest Sectoral Committee, should be instated.

The primary pathway for legal and illegal transport of aquatic vertebrates and invertebrates into Australia is via the aquarium trade. The freshwater component of the trade has a much lengthier history of pest establishment than does the marine sector. However, the impacts to freshwater ecosystems are far better studied and resourced in southern Australia (see for instance Lintermans 2004, Vilizzi and Copp 2013) and even today the national focus remains heavily Murray-Darling Basin centric (e.g. IGB 2019, p.35). In part it can be argued that aquatic pests have had pronounced impact in the Murray-Darling Basin where the nation has a major focus on irrigated agricultural production. However, as this agricultural focus expands to areas including northern Australia there is clearly a need to focus biosecurity attention on existing and developing waterway management. Aquatic biosecurity has not featured highly in prominent water infrastructure planning initiatives, rather the ecological focus has been on quantity of water extracted in relation to predicted ecological responses (Petheram et al. 2018a, b, c, Pollino et al. 2018). Part of the reason for this is that the primary source of aquatic pest and potential pests including those from the aquarium trade is poorly appreciated and seemingly treated as separate from the proponent industries in the agricultural sector.

Most importantly, the rate at which urban centres are developing in northern Australia and agricultural water is being used in regional and remote tropical Australia is occurring with minimal transparency or knowledge of biosecurity risks to the aquatic environment. The focus on major damming and water extraction initiatives is centred on how much water can be harvested in relation to environmental trade-offs. The inevitable establishment of pathways for moving pests, including the myriad of aquarium and ornamental species and their raft of co-invaders including to farm dams, has received next to no attention or resourcing.

The lack of detailed ecological information regarding private dams is a major national knowledge gap that requires specific targeted work in tropical Australia (despite some attention in southern Australia, e.g. Hazell et al. 2001, Hazell 2003, Brainwood and Burgin 2009). Clearly, it will require participation from private landholders and private water corporations. Furthermore, the political rhetoric that exists in an economic and predevelopment climate is a societal and political 'urgency' to develop land and water resources, with little appreciation or regard for the inadequacy or availability of ecological baseline data nor the time and cost that it takes to obtain it. This creates a disconnect between what is considered transparent process and informing the public of the true risk and best practice requirements of developing waterways in tropical settings.

One of the goals of a Freshwater Pest Sectoral Committee would be to work with the Department of Agriculture, Water and the Environment to establish reliable baseline information on freshwater ecosystems and biosecurity strategies for large scale water resource and agricultural development in line with the principle of Ecologically Sustainable Development (*cf.* Craik et al. 2017). A number of additional initiatives are proposed below which would clearly benefit from the instating and input of a Freshwater Pest Sectoral Committee and notably with a strong tropical representation and resourcing commensurate with where the risk and opportunity is positioned, in what are generally less impacted landscapes.

3.2 Support translational ecology

Translational ecology is an approach that embodies intentional processes in which ecologists, stakeholders, and decision makers work collaboratively to develop ecological research via joint consideration of the sociological, ecological, and political contexts of an environmental problem. This will ideally result in improved environment-related decision making (Enquist et al. 2017). Collaborations and adaptive management (applied learning and experimentation) are already happening in aquatic biosecurity in tropical Australia. However, there is substantial scope for resourcing and facilitating translational ecology in this context by broadening the involvement to a wider array of specialists, managers and local communities including via formal and informal education. Specifically, in resourcing synergies among multiple contributors and expertise, we gain the ability to showcase adaptive management to the public and involve a wider society in taking ownership of the problems and solutions rather than resourcing research projects that are detached from society.

Tropical cities and towns are arguably the first place to invest in translational ecology for aquatic biosecurity in tropical Australia since this is where many key government agencies and relevant non-government institutions have a presence. Importantly, this provides opportunity for aquarium trade and ornamental pond retailers to be involved in the biosecurity process.

The role of traditional owners and indigenous ranger programs should be a core part of the translational ecology dynamic including in voicing culture value, exploring economic opportunities and championing the natural state of the waterways and endemic biodiversity. Interaction between retailers, researchers, waterway and environmental managers, and town planners is important in this regard. Local councils that are already controlling pests including weeds, insects and pigs may well be overwhelmed by the concept of taking on yet another biosecurity issue; however, they are on the front line for many relevant parts of the puzzle including early detection, since local staff are on the ground and are well suited to observing change in waterways (e.g. riparian and floating weed management). NRMs are also well positioned to provide a conduit between council and the wider regional priorities in northern Australia. Communication to the point of influencing popular culture in the tropics will be touched upon in subsequent sections, but needless to say hubs for environmental education (e.g. botanic gardens, public aquaria, schools, and universities; Figure 10) including in the arts and education (including school curricula) are important considerations in this regard (e.g. Azevedo-Santos et al. 2015).

Of course, cities and towns are not the only place where translational ecology can take place. However, given resource limitations and the density of aquarium trade related activity (including by hobbyists) in cities, these are the most likely place to start initiatives including pilot programs.

Specific recommendations are made in subsequent subsections that develop upon this theme of translational ecology. The scoping work regarding the social structure of human networks in tropical Australia in relation to aquarium trade and aquatic biosecurity (refer back to section 3.1), should also serve for planning, modelling and testing initiatives that bring about human behavioural change for bio-secure tropical freshwater ecosystems, human endeavour and health. It is recommended that any actions be conducted with a feedback loop based on measures or indicators of freshwater ecosystem protection and human behavioural change.

3.2.1 Inform society of the magnitude of the risk

A key component of effective translational ecology is in informing society of the magnitude of the risk of established and potential tropical aquarium trade related incursions and the heightened consequences for northern Australian freshwater ecosystems and regional development. Single pest species issues, especially concerning large-bodied species or those with pest characteristics, tend to gain traction in both funding, media and public perception. There is a clear need for effective communication of the disproportionate risk that smaller and less charismatic species in the aquarium trade pose for the introduction of a substantial number of pests, damaging tropical industries and biodiversity, and the irreversibility of such invasions post early-detection. This communications challenge should be seen and resourced as an ongoing national priority (rivalling or superseding single pest species priorities including high profile aquatic pest species management issues in tropical and more southerly parts of Australia), in alignment with the rationale for preventing and minimising future national biosecurity costs.

This communication will likely be achieved through multiple mechanisms. One of the more important mechanisms is through on-ground action itself. Translational ecology solutions provide local communication through word of mouth and site-based display and public discussion of natural and modified ecosystems (Enquist et al. 2017). A second communication mechanism is through improved educational materials and communication led by the Department of Agriculture, Water and the Environment. In this regard, it is recommended that communication strategies be designed to capture a wide cross section of the Australian public particularly in northern Australia. High profile personalities will likely be useful in championing communication of the global aquarium trade nexus and specifically current developments in finding solutions or healthy choices (Figure 11).

Figure 10: Botanic garden signage of waterbird information could be extended to improve awareness of alien aquarium species and native aquatic biodiversity.

There is also opportunity to empower local industries including retailers, wholesalers and indigenous rangers in marketing products that provide market driven solutions (healthy choices) and effective eco-labelling (Boström and Klintman 2008). Industry-driven transparent labelling of the origins and risks of biotic products represents an important communication mechanism to consumers in the aquarium and gardening sectors. Opportunities relating directly to mosquito control, home-renovation and landscaping industry and popular marketing on mainstream television serves as ripe areas for improved communication and raised profile of aquatic biosecurity. Communication through formal education at primary, secondary and tertiary education levels also warrants substantial resourcing in terms of raising public awareness and skilling future generations in aquatic biosecurity (Landos et al. 2007, Mueller 2011, Smith et al. 2011, Phillips and Zavros 2013).

Figure 11: International cricket celebrity Andrew Symonds was engaged in a campaign aimed at raising awareness of prawn disease spread. (Image courtesy of Department of Agriculture and Fisheries, QLD)

3.2.2 Improving detection upon arrival into the Australia aquarium trade

Detection of potential species arriving into the country is a clear priority for biosecurity. The arrival of considerable pest threat comes from illegal elements of trade although relevant data on this insidious behaviour is not readily available or achievable at scale (but see Hendersen et al. 2011 for terrestrial vertebrate pests arriving into Australia). Taxonomic identification remains a major challenge for biosecurity agencies especially in aquatic fauna, flora and disease (e.g. Trujillo-González and Militz 2019). There is significant scope for bolstering national taxonomic identification and detection capacity for aquatic pests through a translational ecology approach involving the Department of Agriculture, Water and the Environment, museum and university based taxonomic experts and researchers, and hobby and industry operators. This would see regular workshopping with existing national societies and scientific expertise (e.g. the Alien Fishes Committee of the Australian Society for Fish Biology, The Australian Herpetological Society, Australian Society for Limnology, Ecological Society of Australia) and could benefit immensely from harnessing the expertise and operating knowledge of aquarium trade workers (e.g. pet shop retailers) and hobbyists and related societies (e.g. Australia and New Guinea Fish Association). It is our recommendation that this synergy is not diluted initially by coupling it to terrestrial and marine pest initiatives, since clearly freshwater ecosystems and pest issues have been under-resourced. It should focus on efficient ways to ensure accurate identification of species rich and cryptic biotic groups that are central to the aquarium trade (e.g. cichlids, shrimps, submerged plants) and co-invaders (e.g. gastropods, zooplankton, parasites). It could make the focus of a joint ecological society's conference as a means of attracting and harnessing existing societal expertise and ensuring collaboration with biosecurity agency staff and aquarium industry personnel. Efficiency would likely come from embracing new technologies including eDNA techniques and investing in application of techniques that enable rapid screening of biotic material from water samples.

Workshops and working groups targeted at the appropriate scale to involve the mix of private sector and public roles as well as community with an emphasis on empowering local capacity.

Development and application of rapid biotic identification methods including eDNA.

3.2.3 Strengthen translational ecology at key border control sites

In addition to consignments of aquarium fauna and flora being inspected by ship and air transport there are physical borders where aquarium trade occurs. One example relates to the tip of Cape York Peninsula which is a key gateway for boat and small aircraft traffic transport and trade, human disease vectors and human assisted and natural migration of fauna and flora via the Indo-Papuan conduit (e.g. McCallum et al. 2008, Horwood et al. 2018). Vessel and aircraft traffic from external biosecurity zones (e.g. the Torres Strait Protected Zone and Permanent Biosecurity Monitoring Zone) is regulated as far as possible. Local air and seaports on mainland Cape York peninsula are not gazetted for other international arrivals. Human disease issues are a key challenge for border control across this conduit. Providing long-term support to existing initiatives aimed at educating, detecting and managing disease and pathogens is to be encouraged, as is building on aquatic biodiversity protection in that region. Recent concerns regarding arrival of Covid-19 into Australia provide a high-profile example of a human health concern that gained entry into Australia despite biosecurity efforts, with devastating results. Similarly, the freshwater biodiversity and ecosystem relevance (including potential benefits) warrants survey and ongoing monitoring (e.g. Freeman et al. 2016, Negus et al. 2017).

A project is recommended that centres on understanding the societal processes impacting on private and public water use, mosquito control and freshwater ecosystems in Far North Queensland biosecurity zone 1 (under Queensland biosecurity zoning). This includes the greater Jardine River catchment area including nearby the townships of Bamaga, Injinoo, New Mapoon, Seisia and Umagico and the Torres Strait Islands. It should also extend to key Zone 2 locations including Weipa and New Mapoon. The specific focus being aquarium trade related biota and practices, including pathways for arrival and establishment of alien species. The existing location of the Department of Agriculture, Water and the Environment laboratory and staff in Seisia provides a useful resource and the project would seek to resource the Apudthuma Land and Sea Ranger program as well as leveraging off existing human health initiatives including those that combine human health and biodiversity priorities. An example of this would be the culling of feral pigs for human health, economic and biodiversity outcomes. Currently the Jardine River catchment appears to represent a near pristine catchment with no evidence of alien fish or aquatic plant incursions while the freshwater ecosystems of Cape York Peninsula more widely are considered to be in good condition with the exception of widespread pig damage (Figure 12) (Negus et al. 2017, Waltham and Schaffer 2017, Ebner and Freeman 2018) and ponded pasture species (olive hymenachne, *Hymenachne amplexicaulis* and para grass, *Urochloa mutica*).

Notwithstanding, recent reports of invasive fish species Mozambique tilapia and climbing perch (*Anabas testudineus*) also making their way south from mainland PNG into Australian territory, via deliberate or incidental spread across the northern most Torres Strait Islands, are concerning. In 2006, climbing perch was first detected on Saibai Island in the northern Torres Strait (Hitchcock 2008; Burrows and Perna 2009), followed by Boigu Island in 2010 (Burrows 2010). This aggressive species can withstand days on land due to its specialised gill chambers and has spread prolifically through Indonesia and Papua New Guinea (PNG) over the past 40 years. In 2018, Mozambique tilapia was also reported for the first time on Saibai and Boigu Islands in the Torres Strait, indicating they, like climbing perch, have been able to move across open saltwater from mainland PNG and nearby islands (they can tolerate full marine conditions), or they have been deliberately moved. Either way, the proximity of the Cape York Peninsula to these islands renders it a hotspot for the landing of these species and others (see Waltham et al. 2014) in Australia. Clearly the Torres Strait Islands and tip of Cape York Peninsula is an important region for establishing ongoing aquatic surveillance to detect incursions at early stage.

The risk and value of native aquatic plants and aquatic ecosystems from the tip of Cape York Peninsula warrants specific ecological monitoring and social science attention in the context of bolstering aquatic biosecurity. Local community engagement might for instance be achieved though focussing on prospective flagship species and indicator species of the region such as Jardine River turtle, the northern saratoga, local rainbowfishes and aquatic plants (Ebner et al. 2016a, Freeman and Ebner 2020, Figure 13). This could build on existing efforts to manage pigs for environmental gain and using pigs as sentinels for human disease. Monitoring of aquatic fauna and flora would target waterways north of the Jardine River as well as in the catchment itself. The small waterways neighbouring the townships of Cape York Peninsula warrant specific monitoring as possible sites for unwanted aquarium species (Copp et al. 2005).

Figure 12: A selection of near pristine waterways of the Jardine River catchment and Heathlands National Park (HNP) surveyed for fishes and turtles with no feral incursions of aquatic vertebrates detected other than semi-aquatic cane toads and pigs. A wide variety of flowing water habitats were surveyed for fishes during the expeditions. Shown here are: small perennial streams, a) Mistake Creek, b) a wide reach of upper Gunshot Creek, and c) a narrow run in upper Gunshot Creek; major tributary streams: d) lower Sam Creek, e) Eliot Creek, Fruit Bat Falls, f) Eliot Creek immediately downstream of Eliot Falls; and g) a mid-reach of the Jardine River (Reproduced from Ebner and Freeman 2018).

This monitoring should be combined with extension work in local communities to develop an understanding of aquarium and ornamental pond ecology from a hobbyist and mosquito wriggler control perspective. This should centre on townships and involve local council and school directed learning teaching the strategic relevance of the local region in terms of a) the biosecurity importance of the local freshwater ecosystems, b) the regional and national value of local freshwater ecosystems, c) how to make healthy aquatic biodiversity choices in local communities, d) examining opportunities for employment in the healthy choices for aquarium and ornamental pond use and biosecurity arena, e) specific recognition of the northward transport of risks to and from the tip of Cape York Peninsula, and f) co-investment with local indigenous communities in the production of freshwater biota for the aquarium and ornamental products trade both locally, nationally and potentially internationally.

Figure 13: Flagship species from freshwater ecosystems at the tip of Cape York Peninsula: a) a rare hatchling of the Jardine River turtle a species which represents a prospective flagship species for engaging the local community and the wider Australian public in considering pest issues including feral pig impacts in northern Australia, b) the northern saratoga a popular angling and aquarium species, and c) the lotus lily, a stunning example of a native aquatic plant suitable for ornamental ponds.

3.2.4 Improved knowledge of propagule and colonisation pressure

Since its original conceptualisation in 1996 (Williamson 1996), propagule pressure has formed the foundation of invasion science, assisting in predicting species invasion success and in identifying high risk species (e.g. Gertzen et al. 2008; Strecker et al. 2011; Duggan et al. 2006). Propagule pressure focuses on the intensity (propagule size) and frequency (propagule number) of individuals from one species entering the same location, with repeated introduction events increasing the gene pool diversity and heightening the likelihood of sexually mature individuals coupling thus overcoming issues with small founder populations (Lockwood et al. 2005). Greater propagule pressure also increases the likelihood of an individual being released into favourable conditions and establishing

(Lockwood et al. 2005). In an ornamental setting, propagule pressure relates to the intentional release of unwanted individuals, or the escape of species from captivity into waterways during flood events or through a lack of proper maintenance of enclosures. Continued monitoring of a disconnected pond in Eppings Forest, England, clearly demonstrates the overwhelming influence of propagule pressure on whether establishment is deemed successful or a failure with what is regarded as a highly invasive non-native species, the topmouth gudgeon (*Pseudorasbora parva*) (Copp et al. 2007). A site of repeated release of ornamental fish, the Goldings Hill Pond was subjected to high colonisation pressure, with a diverse community of native and non-native abandoned ornamental fish recorded across all monitoring periods. Despite this, the low propagule pressure of the invasive topmouth gudgeon was key to their failure to establish with low numbers of individuals unable to overcome the restrictions of a smaller founder population. Further introductions of topmouth gudgeon, especially sexually mature individuals (i.e. a greater propagule pressure), may have assisted in establishing a self-reproducing population and thus have been deemed as successfully invading in this case study.

While propagule pressure is a key theme throughout invasion science, the acknowledgement of colonisation pressure as a key concept is relatively new (MacIsaac and Johansonn 2017). Indeed, Lockwood et al. (2009) argue the idea has long been incorrectly allotted under propagule pressure rather than considered a concept in its own right. While related, colonisation pressure is distinguished through assessing the diversity of species invading the same location (Lockwood et al. 2009). Further, colonisation pressure highlights the idea of co-invasion; a disturbed community assemblage with heightened diversity as a result of an increase in invaders becomes not only more susceptible to but facilitates the successful establishment of additional alien species (Xiong et al. 2020). The inclusion of both these measures of incursion is necessary to fully anticipate the potential impacts to waterways.

The availability, diversity, and intensity of propagules and the identification of high risk pathways to establishment (e.g. farm dams acting as footholds for propagation on floodplains) is acknowledged as key information for managing and predicting incursions (e.g. Duggan et al. 2006, Gertzen et al. 2008). Baseline survey data of hobbyists and industry trade, behaviour and beliefs are relevant. This includes data relating to incidental hobbyists (e.g. those inheriting properties with existing alien species in farm dams, ornamental ponds, cattle troughs, and those using aquarium species for human health purposes such as mosquito wriggler control, or as live bait in angling).

It is proposed that a major plank of this work would rely on independent data obtained via a mixture of phone surveys combined with targeted public and industry specific interviews (Martin-Smith and Vincent 2006, Morrisey et al. 2011). However, we recommend obtaining substantial and representative samples equivalent akin to state and national recreational angling surveys (Henry and Lyle 2003, Sutton 2007, Lynch et al. 2019, Taylor and Ryan 2019). This benchmarking should be used to measure not only propagule and colonisation pressure, but societal attitudes and behaviour in order to gauge any changes that might arise from regional initiatives including those proposed herein.

In turn, quantitative data on propagule and colonisation pressure and societal behaviour in the aquarium trade within tropical Australia could be instructive for communicating best practice within and beyond the aquarium industry in terms of customising messaging for healthy choices and product labelling (section 3.2.6). Eco-labelling and education should reflect a knowledge of colonisation propagule pressure issues including which species are likely to establish with minimum propagule pressure (e.g. species that reproduce by fragmentation) (Louback-Franco et al. 2020). It would also provide a basis for targeting messaging and regulating retailer and consumer behaviour in and adjacent to high value environmental areas, in collaboration with key environmental managers in National Parks, Indigenous Protected Areas, and World Heritage Areas. For instance, it is illegal to maintain overseas aquarium biota in communities in Kakadu National Park though notably not in and adjacent to the Australian Wet Tropics. This thinking should be extended to areas where inter-basin water transfer schemes and major dams are relevant due to increased risk of spreading and establishment of alien (and translocated native) biota (sections 3.2.7, 3.2.8).

Recommendation: Establish and maintain quantitative data on propagule pressure and pathways of incursion in tropical Australian regions

Recommendation: Resource aquatic biosecurity coordinator roles within NRMs associated with major tropical cities. Coordinators would serve to establish and maintain cross-sector working groups, gather independent data on regional propagule pressure from the aquarium trade and seek funding for on-ground biosecurity initiatives.

3.2.5 Internet trade

Several cities including Rockhampton, Mackay, Townsville and Cairns in Queensland, Broome, Karratha and Port Hedland in Western Australia, and Darwin in the Northern Territory represent locations for recreational aquarium keeping at enough scale to support local aquarium retailers and in some cases wholesalers. Recent fish incursions appear to be occurring in Mackay especially [e.g. ornamental jaguar cichlids (*Parachromis managuensis*) (Holmes et al. 2020), peacock bass (*Cichla* spp.) (Holmes, B., unpublished data) and convict cichlids (*Amatitlania nigrofasciata*) (Power, T., unpublished data)] in a city populated by more than 172000 inhabitants (ABS 2019, Proctor 2019). Similarly, the Townsville (with a population size in the order of Mackay) has an especially high record of aquarium fish incursions in the Ross River (Burrows 2004) and is locally known as the most alien fish diverse waterway in Australia. This may be a function of discard practices of a historically large transient workforce (including Defence Force) and tertiary education role of this city. Increasing human population sizes in major tropical cities is fuelling greater aquarium trade and high propagule pressure of non-native alien aquarium species.

Still, few regions in Australia are defined by high human population densities, the tropics being no exception. Although Mackay has 172000 inhabitants, over 90000km^2 this equates to 1.91 people/km^2 with just four independent pet stores trading in ornamental freshwater fish (Yellow Pages 2020), while the Far North region where Cairns is located, has a population density at just 1.04 people/km^2 (ABS 2019, Proctor 2019) and nine independent freshwater fish pet stores (Yellow Pages 2020). In comparison, the Brisbane region in South East Queensland has a population density of 175.78 people/km^2 (ABS 2019, Proctor 2019) and 67 independent aquarium stores (Yellow Pages 2020). There are two or fewer pet stores in all the major towns of northern WA, and there are far fewer alien fish incursions as a comparison. Given the low densities of both pet stores and the human population in northern Australia, the high incidence of alien aquatic incursions and establishment, are probably a function of high suitability of tropical alien fishes to the receiving ecosystems and is likely connected to high turnover of aquarium product via pet shops and the internet trade.

The proliferation of internet, and resulting e-commerce trade, throughout the Australian community has facilitated connections across considerable distances, with the ability to attain ornamental species and products at the click of a mouse and from the comfort of the home. Thus, focus must now shift from exclusively a traditional shop-front trade route, to also focussing on the internet trade. Tropical cities where large numbers of internet consumers live provides some surrogate for areas of likely incursion, however, remotely located hobbyists are arguably now more of concern then historically has been the case.

Accessibility appears to be key to the widespread usage of the internet for trade of ornamental species. Considering more than 85% of households have internet access (ABS 2018), and the wide availability of connected computers in public spaces, and the advent of portable smart phones – online trade is now more accessible than the traditional store front, affording pet stores and plant nurseries a considerably larger consumer pool (Chucholl 2013). Indeed, e-commerce introduces a novel avenue for dispersal of non-native species. Studies in Poland indicate online sales disperse seeds of invasive ornamental plants considerably greater distances than in-store purchases (Lenda et al. 2014). However, greater dispersal is accompanied by more frequent opportunities for release and thus establishment, with introduced non-native species significantly more likely to have been listed online (Chucholl 2013).

In Australia, this novel dispersal and incursion pathway has received limited research and management attention. There has been negligible published evidence of relevant documentation of the online trade, although in 2008, industry representatives reported a limited number of freshwater fish groups were regularly traded online involving several prohibited species (O'Sullivan et al. 2008). These include tiger or shovel-nosed catfish (*Pseudoplatystoma fasciatum*), prohibited in Queensland and Western Australia, and alligator gar (Lepisosteidae family) prohibited in Queensland and the Northern Territory and numerous prohibited aquatic plants (Biosecurity Act 2014, GWA 2015, NTG 2020, Bickel, T., pers. obs.).

Prohibited and grey listed species are regularly observed for trade on online forums (Millington, M., Griffith University, unpublished data 2019). The internet trade being essentially unregulated, has opened avenues for trade well beyond the traditional aquarium shop-front model, facilitating widespread trade among the public without the applicability of licencing, visible premises or tax involvement. Many have taken advantage of a supplemental income through the establishment of basement breeding ornamental species, with little probability of encountering government compliance officers. Furthermore, there is no guarantee of effective quarantining before shipment from backyard breeders, further spreading diseases and hitchhikers. Conventional plant nurseries and pet stores partaking in internet trade have also been found to inadequately quarantine species before shipment, with live passenger biota found on a range of plant species bought online, especially on broad-leaved plants (Keller and Lodge 2007). Novel protozoans and a *Salmonella* serotype were detected on illegally traded reptiles seized from e-commerce in New Zealand (Derraik and Phillips 2010), and parasites, viruses and diseases are regularly identified from ornamental fish in pet stores and waterways in Australia (Dove and Ernst 1998, Evans and Lester 2001, Becker et al. 2014, Trujillo-Gonzalez et al. 2018). Harmful zoonoses acquired from post-quarantined fish are also problematic in the aquarium trade industry (Kelly 1976, Iredell et al. 1992, Lehan and Rawlin 2000).

Since the O'Sullivan et al. (2008) report, research into the Australian online ornamental trade has stalled. In the meantime, a globally and extensive online community has evolved, trading regularly in highly invasive, endangered, and prohibited ornamental species including those harmful to human health, generally listed at affordable and thus accessible prices (Chucholl 2013, Mazza et al. 2015). The paucity of data in Australia results in the inability to contrast with global understanding nor assess the extent of aquarium trade until all trade avenues have been considered. An online presence and clear messaging from an aligned state and national biosecurity perspective is required in relation to the risks of the aquarium trade including the internet trade for tropical Australian ecosystems. This issue would also benefit immensely from some form of buy-in from the online aquarium industry and it seems that a workshop bringing together government and NGOs is required to develop solutions as a matter of urgency.

Internet surveillance of trade by dedicated national compliance officers is vital to achieve biosecurity compliance in line with national and state legislation in Australia. Without it, state-based biosecurity and fisheries officers are unlikely to affect change in culture of the mainstream freshwater hobbyists in tropical Australia. *Ad hoc* interdepartmental searches of the internet trade are unsuitable based on observation of government process in New Zealand (Derraik and Phillips 2010). There are major logistical issues associated with the 24/7 capabilities and connections of the global on-line aquarium trade. This includes a continuous stream of sales and purchaser data, reviews and chatroom dialogue. Reliable peaks and troughs in online trade where monitoring would be most effective have not yet been identified. In Australia there is also no one main online marketplace where trade occurs, with a range of private and public sources available for vendors to show their wares. With the recent ban on the sale of live animals on Facebook, hobbyists have moved further underground to less accessible sites. These lesser known sites thus require an active search using specific, and potentially purposefully deceiving, keywords with access not guaranteed. Surveillance is further hampered by the anonymity afforded, with no assurance personal information shared by the customer or stockist will be accurate, leading to difficulties in finding and prosecuting those partaking in trade of prohibited species. Indeed, there is also no guarantee the surveyors will be able to accurately identify what or when species are being sold. Purposefully misleading code words are used frequently in the trade, especially surrounding species not on the approved List of Specimens Taken to be Suitable for Live Import (Live Import List).

However, familiarisation with online trade allows for a dictionary of code words to be generated and learnt, allowing access and thus monitoring of this unregulated and unknown trade pathway. Surveillance, although potentially time consuming and fraught with challenges, has been successful overseas, with monitoring of a popular angler forum in Portugal identifying invasive European perch (*Perca fluviatilis*). This information aided prioritisation of waterway surveys that confirmed perch incursions and will lead to eradication programs before establishment (Banha et al. 2015). Such information on non-native species traded online in Australia is crucial in formulating a list of species that may then be assessed for invasive potential and a status on admissibility determined, emulating successful overseas studies in Brazil (de Magalhaes and Jacobi 2013), Europe (Maceda-Veiga et al. 2013) and Taiwan (Liang et al. 2006). This in turn will lead to a clearer understanding of the laws surrounding the trade of these species and deter their continued trade at least among a proportion of the public with a compliant mind set.

3.2.6 Prioritise discrete waterbodies

A central tenet of pest control is that eradication is favoured by early detection and action. Additionally, successful eradication exercises have demonstrated that pest species eradication is favoured under circumstances of a small bound extent of pest distribution. Prominent examples come from eradications of vertebrate pests from small islands (e.g. rabbits, rats, cats) (Griffiths 2011), discrete waterbodies (Rayner and Creese 2006, Britton et al. 2008) or fenced areas (Young et al. 2013). Discrete waterbodies offer opportunity for delivery of specific control agents (e.g. rotenone poisoning, dewatering) intensively and in some cases across the entire waterbody (e.g. Copp et al. 2007), whereas, many of these control options become increasingly impractical in large scale waterbodies (Britton et al. 2008). The complexity of structure in a waterbody also plays an important role in dictating potential for control and eradication (e.g. Rayner and Creese 2006). Sustained efforts to eradicate carp appear to be nearing a successful endpoint in a lake in Tasmania despite late detection and establishment of the pest and the relatively large size and complexity of the waterbody (e.g. IFS 2020).

In tropical Australia there are multiple cases of pests and pest impact that exist at vast extent and scale in aquatic ecosystems which are currently considered beyond resourcing for eradication. Examples include widely spread cane toads and their impact on native predatory and prey species (e.g. Letnic et al. 2008), and pigs and ensuing damage to wetland ecosystems and stream and riverbanks (e.g. Fordham et al. 2006). Tilapia (Mozambique tilapia and spotted tilapia) have now reached this stage of being widely spread in eastern Queensland and having become established in the Mitchell River catchment in the Gulf of Carpentaria (Ovenden et al. 2015; Holmes, B., Ebner B. C. and Vallance, T., unpublished data) with Mozambique tilapia established in three rivers in north-western Australia (Morgan et al. 2004). This illustrates the need for early detection and eradication of new aquatic pest species in northern Australia, but also warrants consideration in terms of which waterbodies warrant priority monitoring and protection against established and future incursions of alien species.

Briefly, these opportunities relate to issues of exceptional high value, be it cultural, economic, recreational or environmental, and are set against the achievability of pest management (e.g. feasibility of detection of pest incursion and re-incursion, likelihood of eradication/containment). Importantly there is also an interplay between these two broad requirements, in that society is more likely to invest in management practices where there is a reasonable chance of success and the benefits of the management have perceived or tangible value. Successful exercises of this kind are also likely of high value in terms of obtaining or maintaining a level of societal confidence in biosecurity (e.g. Petroeschevsky et al. 2011) where losses to cultural, biodiversity, and economics conditions, as well as psychological fall out to biosecurity practitioners and society general are inevitable. There is also some evidence that multiple invasive species eradication programs are more efficient than single species programs where terrestrial vertebrate control has been undertaken on islands (Griffiths 2011, Young et al. 2013). This is worth considering in terms of pilot work in small waterways (e.g. upper stream catchments above natural or artificial barriers, or in city ponds such as botanic gardens).

There are opportunities to protect specific and somewhat discrete freshwater ecosystems (which contrast large catchments and highly connected waterways of substantial extent) including high diversity ecosystems and locations with highly localised endemic species (Figure 14). By way of some examples, in the Australian Wet Tropics as a consequence of geology, topography and water availability there are freshwater ecosystems which are small and discrete where a subset of incursions of aquarium trade sourced species might be detected early or at least if detection is late it is at least potentially feasible to achieve eradication (or long-term control with measurable benefit). These ecosystem types include crater lakes and short-steep-coastal-streams. In the crater lakes there are occurrences of translocated native species (e.g. a freshwater crocodile *Crocodylus johnstoni*, and Murray River turtle) including locally established species (e.g. redclaw; fishes: *Glossamia aprion, Amniataba percoides, Melanotaenia splendida, Toxotes chatareus*) and alien species (spotted tilapia) in Lake Barrine or Lake Eacham, and localised extinctions of endemic species (e.g. Lake Eacham rainbowfish *Melanotaenia eachamensis*; Figure 14) whereas, Lake Euramoo is currently pest fish free and populated by a healthy population of Lake Eacham rainbowfish (Ebner, B.C, Unmack, P. and Hammer, M., unpublished data). There are no examples of eradication of any of these aquatic incursions from the crater lakes, however, the authors are unaware of any well-resourced attempts to do so (acknowledging that the Parks Service currently organises annual volunteer spearfishing events for tilapia in Lake Barrine).

Figure 14: Discrete waterbodies housing high value native species represent sites for targeted biosecurity focus including for communication, prevention, detection, control and eradication of pests. Shown here is a) a short-steep-coastal-stream at Cape Tribulation, home to b) Birdsongs cling goby, c) entrance to a subterranean cave in the Pilbara, home to d) the blind cave gudgeon, and e) the popular crater lake, Lake Eacham, previously home to f) Lake Eacham rainbowfish. (Photographs courtesy of Ebner, Morgan and Visser).

A focus on restoration of the two larger crater lakes in the Wet Tropics, namely Lake Barrine and Lake Eacham would face numerous obstacles but could be improved through emulating the learnings of successful carp management in TAS. The Carp Management Program in Lake Sorrel, TAS provides an example of a long term commitment (since 1995) to carp control in a discrete waterbody, and makes use of monitoring of a nationally threatened fish (Golden galaxias) in terms of remaining focussed on environmental benefits (Hardie et al. 2006, IFS 2020). In addition to a number of locally extinct species which might form the focus of rehabilitation exercises, both Lake Eacham and Lake Barrine are high profile tourism and local recreational areas which lends itself to potential value in terms of communicating the risks and opportunities for protecting tropical aquatic ecosystems from alien species.

In the past decade, short-steep-coastal-streams have received research attention (Thuesen et al. 2011, Ebner et al. 2016b). These catchments are small and have high underwater visibility, thus favouring a complete survey of the area for pest detection and importantly for verifying the absence of pests (Ebner et al. 2016b). These streams can be of high aesthetic value (Figure 14) adjacent to resorts, caravan parks, and idyllic beaches, and contain threatened fish species. Currently, pig damage and cane toad tadpoles represent potential biosecurity issues in a subset of these streams, and this opportunity for societal interest in the biodiversity and biosecurity opportunity in this ecosystem type would be highly advantageous. Furthermore, eradication of aquarium trade related incursions is likely to be feasible in these systems as a function of their extent and attributes including water clarity which aids rapid surveillance. Field surveys involving indigenous rangers have been conducted previously in remote short-steep-coastal-streams (Ebner et al. 2016b), however, a focus on the status of native and alien composition of suburban catchments warrants attention in the future.

Understanding the geographical context of an invasive species can help inform the management action required and provide significant motivator for on-ground action. Beginning in 2008 the small farming community of Lakeland, South Cape York Catchments (SCYC) and the Laura Rangers worked to eradicate salvinia from the waterways associated with Honey Dam, upstream of Lakefield (Rinyirru) National Park. The original infestation spread over 340 hectares and included 2 dams, 14km of rivers and 13 swamps. http://capeyorknrm.com.au/sites/default/files/2018-09/2014_19_August.pdf. The infestation was the northern most infestation in Queensland and threatened the adjoining wetlands of the Rinyirru National Park and greater Cape York region. Monitoring has continued since the last detection in 2011.

Similarly, discrete waterbodies worthy of mention also exist beyond northern Queensland. For example, the invasive pest fish, eastern gambusia was eliminated by Larrakia Traditional Owners from One Mile Dam in the Northern Territory (Anonymous 2017)(https://www.sbs.com.au/nitv/nitv-news/article/2016/12/15/traditional-owners-eradicate-toxic-fish-darwin).

A prioritisation process is required to order investment. However, values and starting points inevitably affect the outcome. For instance, emphasis can be put on any manner of things including surrogates for biodiversity, feasibility of control methods and known or expected interactions between species (e.g. Courtois et al. 2018, Osunkoya et al. 2019). In the aquatic realm, Ramsar sites provide one means of indicating priority; however, these wetlands do not provide an adequate representation of high aquatic biodiversity value across the extent of tropical Australia. We argue that building culture amongst aquarists specifically and society generally is a key objective in the prioritisation process. Therefore, in the short-term, it would be remiss not to focus on resourcing and commencing on-ground pilots involving selected societally driven projects at some locations in urban, and regional settings or where human visitation rates are high or marked by high cultural value.

Community sites for adaptive management is not a new idea and is aimed at empowering communities by removing the disconnect between people and nature. There are severe challenges associated with maintaining public engagement in pest control when eradication is frequently impossible in large catchments (Boys et al. 2014). However, demonstration sites can range from being extremely useful to failures and there is a specific need to capture learnings from key personnel that have been involved with demonstration reaches and sites elsewhere (e.g. Boys et al. 2014). It is recommended that key personnel be resourced in the urban and water scheme pilots that are recommended in this report. Potential sites include high profile urban and regional waterways that are relatively discrete for local pest control and native aquatic biota rehabilitation and build on existing initiatives or infrastructure. Examples include, Kakadu and the Botanic Gardens in Darwin, the Cairns Botanic Gardens (nested within the Saltwater Creek catchment, where a current Cairns Regional Council healthy waterways initiative is underway), Crater Lakes within the Atherton Tablelands, selected short-steep-coastal streams, and township waterways at the tip of Cape York Peninsula.

It is also worth revisiting climate change vulnerable endemic species in a discussion of discrete water bodies. In addition to expecting shifts in dominant species composition and distribution with tropical regions, there is opportunity to focus translational ecology learnings on high priority endemic species of freshwater taxa with restricted ranges. This includes wholly freshwater species with an inability to migrate between latitudes, which require urgent attention (Figure 14). A healthy choices project could be developed squarely around public displays (e.g. at Botanic gardens, public aquaria, council chambers, etc.) and private holdings (e.g. ornamental ponds) of aquatic taxa with restricted distributions. This would require genuine participation of government agencies in embracing the risks of species loss without societal participation and in overcoming the logistical constraints of a more conservative rhetoric of legally restricting public collection and keeping of threatened or potentially threatened species. In this regard such a project would benefit from being transparent about risks of loss to freshwater ecosystems with and without proactive societal and industry involvement in maintaining threatened species populations (e.g. rainbowfishes, shrimps, turtles, plants). Landscape scale prioritisations could also be incorporated into this initiative (e.g. Bush et al. 2014).

3.2.7 Develop healthy choices (aquaria and ornamental ponds)

Eco-labelling is somewhat analogous to more familiar product labelling to promote healthy choices and labelling of human foods including transparency on sugar and salt content, and foreign origin of products, or with cigarette and alcohol labelling in terms of health warnings (e.g. Sonnenberg et al. 2013). This is not a new concept even within the aquarium industry and is not without its challenges in terms of industry including consumer and retailer participation and willingness to change (as is the case with any industry faced with regulatory mandates or change).

Indeed, selected online ornamental fish retailers have already independently undertaken aspects of 'eco-labelling', providing a premise to the launch of such a program (M. Millington, unpublished data 2020). Key information is provided underneath a species advertisement detailing the longevity, total maximum length, habitat requirements, and aggressiveness or an indicator of suitable fish communities as a surrogate for temperament. This information is particularly important for pre-emptively reducing the incidence of owners releasing unwanted or unsuitable species by arming the consumer with necessary information for a successful pairing between pet and owner (Stringham & Lockwood 2018). Independent uptake is currently low, especially surrounding longevity (M. Millington, unpublished data 2020). Given selected ornamental fish may persist for a decade or longer [e.g. goldfish were indicated by one retailer to have a lifespan between 10-15 years, while a 10 year lifespan was indicated for albino bristlenose catfish (*Ancistrus cirrhosus*) by a second online retailer], it would be beneficial for consumers to be made aware before purchase of the long-term commitment such a fish requires. Considering the frequent dissemination of this key information already, retailer uptake of providing such information as a routine part of ornamental species advertisements is thus expected to be widespread, at least within the ornamental fish trade. It is currently unknown what key information is provided in other ornamental species advertisements and thus success of such a program in these industries is unclear.

Given the relevant risk to endemic freshwater ecosystems it is our recommendation that an important goal is progressing beyond the negative connotations of regulation and labelling (e.g. Austin and Garrett 2011). Investigations into effective communication means and testing of labelling are required (e.g. O'Hegarty, et al. 2006) and an awareness of healthy biodiversity options in the aquaria, ornamental pond and farm dam arenas warrants directed resourcing and applied research attention (i.e. translational ecology).

This 'healthy choices' approach warrants a scoping study specifically. Initial thoughts include borrowing from societal case studies and approaches that have worked at scale and with an appreciation for nation specific context including specifically with indigenous people requirements considered (e.g. Cummins and Macintyre 2006, Austin and Garrett 2011, Jackson et al. 2014). Indigenous people should be provided opportunity to be central in the process. This includes their input and use of commodities that are directly relevant to regional communities of people (e.g. Jackson et al. 2014). Indigenous representation and involvement should be encouraged early in the process for both developing business ventures from aquatic native fauna and flora (e.g. Zander et al. 2014) and in biocontrol involving indigenous ranger groups including protecting local catchments and high value freshwater ecosystems and threatened species (e.g. Austin and Garrett 2011). There are some valuable win-wins to be had in this space including collecting and propagating valuable endemic species of aquarium plants, fish and invertebrates (e.g. O'Reilly et al. 2009) and enhancing public education through ecotourism experiences.

Australian rainbowfishes provide good examples of successful high-profile aquarium species (Ebner et al. 2016a). For instance, the Malanda rainbowfish is a species currently facing extinction and is a striking small-bodied rainbowfish (Figure 15b) from the Atherton Tablelands that might be ideal for ponds, and aquaria. Captive breeding and possibly line-breeding could be used to negate overharvest from the wild and to further enhance colour of the fish, thereby providing an aesthetically pleasing alternative to the more common alien fish while serving to involve people in protecting a species and learning about the conservation of aquatic ecosystems.

Part of this healthy choices program should also focus on promoting the sale of species and taxa that are alien but are highly unlikely to pose risk in tropical Australia, over species with an unknown or higher risk of establishment if released. This concept is not new in invasive species regulation, with such a notion supported in the ornamental mollusc (Yanai et al. 2017) and fish trade (Maceda-Veiga et al. 2013, Mendoza et al. 2015, de Magalhaes and Jacobi 2013). Species-specific examples include species with water quality requirements that are not found in Australia: some of the discus cichlids (*Symphysodon discus*) and neon tetras (*Paracheirodon innesi*) have a proven record of frequent and long-term trade in Australia with nil reports of wild incursions and establishment, providing some indication of their future invasion potential and highlighting such species as those considered 'healthy choices' for the future of Australian aquatic ecosystems. There also likely select small shrimps that have unusual water quality requirements (e.g. shrimps from Lake Puso and Lake Matano in Sulawesi that require very warm water and soft but alkaline water unavailable in tropical Australia). A select number of such species could even be tested in captivity for their unsuitability to Australian wild conditions as part of the healthy choices process. Obviously, quarantine for disease and pathogens would still be relevant.

It is also vital to include industry leaders and hobbyists in discussions on suitable replacements from a list of approved species. Although it may be determined select species from the white list are appropriate alternatives to those on grey lists, these may not possess the features that make collection and ownership of such species a popular hobby. Understanding the needs of the hobbyist may be complex, as a purely aesthetic consideration of ornamental species is naïve. Rather, hobbyists may be attracted to a species for its rare behaviour [such as the archerfish (*Toxotes* spp.)

and it's unique feeding behaviour], playfulness [for example Siamese fighting fish (*Betta splendens*) that may be trained to jump hoops], or other less understood features. Involving and considering the ideas and non-scientific opinions of those heavily involved in the ornamental industry will ensure the widespread acceptance of species considered 'healthy choices' and the campaign as a whole.

There is a real risk that this kind of argument also preaches to the converted. The next step is to encourage innovation in ecological sustainability in the aquarium trade and in the outdoor ornamental pond industry. This could see societal recreational and corporate values of ecological sustainability fostered by encouraging uptake of sponsorship, purchasing and selling native species (or vetted alien species) which ultimately provide excellent functional substitutes for existing alien species, and provide a functional use in the landscape gardening and home improvement sector. Through high profile recognition of healthy choices promoted by key celebrities and innovators in regard to our valuable endemic fauna and flora there is a strong likelihood to successfully reach and integrate such a concept into mainstream corporate sector and social culture (Figure 11). This has been done successfully before in Queensland using famous sporting personalities to promote responsible bait practices after the white spot virus decimated southern Queensland prawn aquaculture farms. By way of background, the virus was traced back to imported prawns for sale in supermarkets carrying the disease, and these prawns were bought and subsequently used as bait in native environments.

Eco-labelling and promoting native plants over alien species have potential to reduce risk of wild incursions of alien species from aquaria, ponds, and farm dams. In turn this would ease the burden of how many species require weed control in the wild. A range of common potentially invasive plants available in the trade today can be replaced with suitable native species without the need to make sacrifices in terms of diversity of choice or decorative effect. Numerous native aquatic plants are available to decorate aquaria. The following tables provides an example of suggested alternative species as a how to guide in replacing invasive or potentially invasive aquatic plants with functionally similar native species. The choice of species somewhat differs between aquaria (Table 1), ornamental ponds (Table 2) and farm dams (Table 3). This is mainly due to the different functions that plants play in these situations; aquarists use predominantly submersed plants to create attractive underwater landscapes in their aquaria or to provide cover for fish; emergent and floating attached plants are more important for ornamental ponds; while emergent plants to form the fringes of the pond and floating attached plants are chosen for their beautiful flowers (e.g. *Nymphaea* species). The function of aquatic plants in farm dams is usually to restrict nutrient inflow and bank erosion, therefore, emergent wetland plants are the most appropriate plants. Additionally, the 'Grow Me Instead' project led by the Nursery and Garden Industry Australia provides a useful template and demonstration of an industry led initiative to achieve an ecologically sustainable outcome (http://www.growmeinstead.com.au/).

Figure 15: Popular aquarium and outdoor pond fish include a) the fantail guppy, which is widely kept in Australia due to its beauty, ease of breeding and for mosquito control, b) however there are less well known alternatives such as this undescribed rainbowfish from the Atherton Tablelands which is on the verge of extinction. c) The zebra shrimp (*Caridina zebra*) is an endemic to the Australian Wet Tropics which serves as an attractive shrimp for the nano aquarium market. d) An Australian bulrush (*Eleocharis* sp.) serves as a suitable outdoor ornamental pond plant as do e) the native *Myriophyllum* species.

Table 1: Healthy choice aquarium plants separated by growth form, this is not an exhaustive list and only shows some examples. (It is recognised that while some genera are native to Australia and/or other countries, here we advocate use of examples of species that are native to Australia)

GROWTH FORM	ALIEN SPECIES	NATIVE ALTERNATIVE	COMMENTS
SUBMERSED	*Cabomba caroliniana*	*Lymnophila wilsonii* *Lymnophila brownie* *Ceratophyllum demersum* *Myriophyllum* spp.	Native ambulias (*Lymnophila*) are aesthetically pleasing submersed plants that are an attractive addition to any aquarium
	Sagittaria platyphylla (submersed form)	*Vallisneria nana* *Vallisneria caulescens*	*Vallisneria* spp. are easy to grow and come in a range of shapes and colours
	Echinodorus sp.	*Aponogeton* spp. *Ottelia ovalifolia* *Damasonium* spp. *Blyxa* spp	*Echinodorus* plants are an emerging weed in some tropical rivers
	Egeria densa *Elodea canadensis* *Lagarosiphon major* *Myriophyllum aquaticum*	*Hyrdrilla verticillata* *Ericaulon* spp. *Myriophylum* spp.	
FLOATING	*Salvinia* spp. *Limnobium laevigatum*	*Lemna* spp. *Azolla* spp.	*Lemna* spp. are a good food source for some fish species (e.g. rainbowfish)

Briefly it is noted that some freshwater plants that are used in the aquarium trade also serve as human food (e.g. Romanowski 2007). Indigenous people have long used native aquatic plants for food and some alien species function as livestock feed including for cattle and buffalo (Finlayson et al. 1997, Clarke 2011, Pettit et al. 2012). In several countries aquatic plants are commonly cultured for culinary purposes and form a staple practice historically and currently in parts of Asia for instance (Crawford 2006). Australia as a multicultural nature is embracing more and more elements of international cuisine in our household cooking and restaurant dining practices (Wahlqvist 2002, Hall and Mitchell 2003). In parallel there are some signs of alien plants that are in the aquarium trade being deliberately cultivated in waterways in northern Australia for culinary purposes, including kan kong (*Ipomea aquatica*) and water hyssop, (*Bacopa caroliniana*) in Darwin (Wilson, D., pers. obs.) and yellow burrhead and water mimosa (*Neptunia* sp.) in the Cairns region (Sydes, T., pers. obs.). This demonstrates another example of the complexity of pathways for incursion and establishment of alien species via intersections between the aquarium trade and society. This issue might be addressed to some extent in conjunction with the restaurant sector in select tropical cities, and perhaps by engaging ethnically diverse celebrity chefs as champions of ecologically sustainable practices.

Table 2: Healthy choice plants for ornamental ponds separated by growth form, this is not an exhaustive list and only shows some examples.

GROWTH FORM	ALIEN SPECIES	NATIVE ALTERNATIVE	COMMENTS
FLOATING ATTACHED	*Nymphae mexicana,* *N. caerulea* *N. alba*	*Nymphaea nouchalii* *Nymphoides indica*	There is a range of native *Nymphaea* species that are extremely attractive and are readily available in the trade
FLOATING	*Salvinia molesta,* *Eichhornia crassipes*	*Nymphaea* spp. *Nymphoides* spp.	Free floating plants are not recommended for ornamental ponds in general because of their dense growth. Native *Nymphaea* spp. have extremely attractive flowers that match *Eichhornia* spp.
SUBMERSED	*Egeria densa* *Elodea canadensis* *Lagarosiphon major*	*Hydrilla verticillata* *Potamogeton* spp.	There is a range of native submersed plants that can be used in ornamental ponds
EMERGENT	*Sagittaria platyphylla*	*Damasonium* spp. *Lepironia* spp. *Schoenoplectus* spp. *Eleocharis* spp. *Juncus* spp.	
	Alien *Myriophyllum* spp.	Native *Myriopyllum* spp.	

Table 3: Healthy choice farm dam plants separated by growth form, this is not an exhaustive list and only shows some examples.

GROWTH FORM	ALIEN SPECIES	NATIVE ALTERNATIVE	COMMENTS
FLOATING ATTACHED	*Nymphaea mexicana* *N. caerulea* *N. alba*	*Nymphaea* spp. *Nymphoides* spp.	There is a range of native *Nymphaea* spp. that are extremely attractive and are readily available in the trade
FLOATING	*Salvinia molesta* *Eichhornia crassipes*	Native *Nymphaea* or *Nymphoides* spp.	Free floating plants are not recommended for farm dams as they increase water loss. Native *Nyphmaea* spp. have extremely attractive flowers that rival *Eichhornia* spp.
EMERGENT	*Sagittaria platyphylla* *Cyperus involucratus*	*Damasonium* spp. *Lepironia* spp. *Schoenoplexus* spp. *Eleocharis* spp. *Juncus* spp. *Marsilea* spp.	There is a wide range of native shoreline vegetation that is useful to limit nutrient transfer and for stabilising banks

3.2.8 Major agriculture initiatives and water transfer schemes

Proximate causes of incursion by alien species include deliberate release of fauna and flora, and incidental escape of pets or garden plants. Ultimate causes of incursion include human overpopulation, human development and occupation of catchments. In this case, it can be informative to consider three human demographics, namely those that are directly involved in and identify with the aquarium trade/hobby, those not involved in the aquarium trade and those that do not identify as being part of the aquarium trade but in fact are a silent participant. The distinction of this third demographic is important as was seen in the example of a suburban household using ornamental fishes to control mosquito larvae for human health reasons (Figure 9).

All three of these demographics are important and especially the third at institutional and policy levels for achieving effective biosecurity. For instance, large scale resource development is planned and costed regarding economic, cultural and environmental benefit and loss, sometimes without understanding important elements of biosecurity. Ecological impacts of large-scale water resource development for agriculture has recently been investigated for water extraction with specific simulations based around water resource trade-offs for aquatic species and ecosystems. To some extent this line of enquiry is to be commended as society shifts toward predictive understanding in ecological and environmental processes (e.g. Pollino et al. 2018, Stratford et al. 2018, Della Venezia et al. 2018) in addition to more traditional before and after monitoring of environmental impacts (e.g. Underwood 1997). This type of predictive modelling requires adequate resourcing in underpinning decision making about large scale resource use and likely change to ecosystems, arguably more so in pristine/near pristine catchments and wilderness areas.

Nevertheless, it is important to broaden the scope of predictive modelling to incorporate biosecurity issues. Repeatedly as humans disperse and occupy near pristine catchments and wilderness areas, they contaminate these ecosystems through a combination of incidental, accidental and intentional mechanisms. It is for this reason and specifically from a human health perspective that headwaters of catchments are protected from human occupation and activity in water supply catchments (Lowe and Likens 2005, Hill et al. 2014). Furthermore, from a biodiversity protection perspective, water transfer schemes between catchments alter native species distributions and present biosecurity challenges (e.g. Waters et al. 2002, Crook et al. 2015), although, this may be concealed or overlooked and rarely acted upon from a truly ecologically sustainable perspective. The tell-tale signs are at best desperately simplistic engineering solutions and at worst in total disregard of ecologically sustainability principles. Water transfer schemes tend to be progressed in ignorance of complex aquatic ecological processes including microscopic scale processes such as bacterial, disease and plankton transfers (*cf.* Oidtmann et al. 2011).

By way of specific examples, the Snowy River Hydro Scheme provided a hallmark of economic and engineering conquest in the 1960's and yet from an environmental perspective it compromised aspects of the ecology of both eastern and western catchments in south-eastern Australia (e.g. Waters et al. 2002). In tropical Australia, the Tinaroo Water Transfer Scheme situated on the Atherton Tablelands poses similar problems, though the propensity for natural spread of alien and translocated species from the Tablelands into the Mitchell catchment and connected neighbouring catchments is even greater than the southern example. Specifically, there is natural and relatively regular connectivity of adjacent catchments in the lowlands of the Gulf of Carpentaria as a function of torrential annual rains and floodplain behaviour. In this regard, recent alien fish species incursions in the upper Walsh River catchment are cause for environmental concern (i.e. Mozambique tilapia and spotted tilapia). With a complex irrigation channel network, and myriad farm dams, combined with human propensity for keeping aquaria, comes risk of spreading ornamental species, bait and aquaculture species, and contaminated tank water. There is a real need to understand the full extent of interactions between society and the environment in the Atherton Tablelands area. The considerable human occupation of these tableland communities is likely a key ingredient in the incursion of aquarium trade species. To date, the scale of the biosecurity challenge in this region is not widely appreciated. This is partly because aquatic pests have not spread on a scale that impacts economic or local biodiversity values as perceived by the local communities. The irreversibility of environmental damage once aquatic pests establish in large waterways is also typically not appreciated until it is too late (Kolar and Lodge 2002).

There are several inter-catchment water transfer schemes in northern Australia. However, the scheme on the Atherton Tablelands including current and proposed water transfers in that region warrants aquatic biosecurity focus that embraces translational ecology principles including public education. Considerable investment in social science, testing and understanding communication strategies within the regional community and extension work is required in relation to aquarium trade related use of home aquaria, ornamental ponds, farm dams, and pet shops and in relation to other sectors such as the irrigation industry and the recreational angling sector (including bait and angling practices in the area) and school education. This should be viewed as a national priority given existing documented, undocumented, and currently unknown aquatic biotic incursions.

Synthesis of existing published information is to be supported in the initial research and project formation stage, but should not serve as a substitute for collection of accurate up to date baselines of the distribution and condition of endemic biodiversity and alien species, diseases and pathogens in the relevant waterways of and adjacent to the Atherton Tablelands. Future proofing of these waterways and planning for agricultural development in the region should specifically seek to accrue reliable and transparent baseline information (minimum 3-5 years of annual sampling of key indicator taxa such as fishes, plants, invertebrates, parasites) to establish best practice given the severity of the risk between major biogeographic provinces (e.g. across the great dividing range) including in relation to the Wet Tropics World Heritage Area and in relation to major commercial and recreational fisheries in the Gulf of Carpentaria.

Regarding national biodiversity conservation there is also a clear need for investment in fast tracking the ecological and the *Environmental Protection and Biodiversity Conservation (EPBC) Act 1999* related aspects of environmental protection in northern Australia. The lack of focussed scientific expertise and resourcing for taxonomic and ecological study of freshwater endemic species in the region (e.g. studying molluscs, crabs, sponges and even fish) has led to a lack of listed species despite signs that this is paramount. There is a growing number of new species discoveries but a major lag phase to description of these species (due to a national shortage of taxonomists) and a failure to recognise this lag, let alone resourcing and time requirements for listing these species under protective legislation (e.g. plight of the Malanda rainbowfish - Unmack et al. 2016). This is a challenge in providing informed industry development choices in relation to the current and proposed water transfer schemes locally and across northern Australia.

Traditional owner groups and their ranger programs should play a key role in this process as should regional National Resource Management agencies (NRMs) and catchment management groups. Additionally, given the complexity of the social, ecological and cultural issues involved in the Atherton Tablelands scenario, regional councils, Barron Catchment Care, Northern Gulf NRM, Terrain and SunWATER all have potential roles to play in future work. In this regard, engagement with farmers, water providers, local council, pet shop owners, hobbyists (including in terms of internet trade and private exchanges of aquarium biota) are all fundamental demographics warranting consideration. Given the complexity of the task, success will require strong project management governance achievable through the installation of a Freshwater Pest Sectoral Committee, and warrants strong national leadership involving the Department of Agriculture, Water and the Environment, and university input, recognising key state agency involvement (e.g. Biosecurity Queensland, Fisheries). Learnings from this case study are likely to have interstate and national ramifications for water transfer schemes across tropical Australia, with the strong potential for a global standard in ecologically and invasive species minded water transfer schemes for other nations to then emulate.

3.2.9 Dams, including farms dams

Understandably, the common perception regarding farms and biosecurity is production centric. It centres on agents including weeds, and disease and pathogens of the agriculture crops and livestock on which the farm is based for economic reasons. However, ecological data from waterways on farms and specifically the aquatic ecology of farm dams in Australia is scarce and patchy. A review by James et al. (1999) concluded that human-modified or artificial watering points positioned in the landscape have profound effects on native flora and fauna in arid Australian environments including in the tropics. However, this evidence was based mostly on, terrestrial mammals, birds, and insects with a life history phase reliant on water. More recent research has further highlighted the importance of these farm dams facilitating non-native species invasion, with cane toads found to be utilising such created watering points to move deeper into the dry Australian outback (Letnic et al. 2014). While not necessarily colonising such water holes, cane toads instead utilised these aquatic refuges as steppingstones for continued range expansion, potentially arriving in isolated and relatively pristine ecosystems unreachable without such watering points. In tropical Australia, it is less understood how such farm dams may assist in invasive species establishment; however, if comparisons may be drawn with the results of eDNA testing of farm dams in temperate Australia, these artificial water impoundments host a community rife with invasive species (https://www.envirodna.com/static/uploads/files/edna-farm-dam-report-landcare-july2019-wflgqwjoaxwc.pdf).

Our understanding of the aquatic ecology of farm dams (and furthermore roadside construction ponds and ornamental ponds) at the extent of tropical Australia is rudimentary at best, bearing in mind the unquantified and undoubtedly increasing number of these dams for water security. In functional terms there is not a clear distinction between farm dams and aquaculture ponds, with land owners and managers including farmers frequently stocking aquatic species (e.g. food fish, bait, and species that perform both roles such as crayfish) into private dams (Horwitz 1990, Lintermans 2004, Romanowski 2007). Dams and outdoor ponds pose as reservoirs for alien and translocated species incursion including of an incidental nature (during regular or extreme flooding) (Lintermans 2004, Romanowski 2007) and specifically may serve as important footholds for pests to accumulate in numbers to promote propagule pressure that enhance the likelihood of establishment in the receiving catchment (cf. Gertzen et al. 2008). The substantial magnitude of flooding in tropical catchments during the monsoonal wet season places disproportionately high emphasis on the prospects for escape of alien and translocated species from farm dams in the tropics. Data on the biotic composition of farm dams remains a major knowledge gap for biosecurity and biodiversity protection in Australia and specifically in protecting freshwater ecosystems in tropical Australia.

Figure 16: In addition to providing drinking, amenity and agricultural water supply, dams provide multiple functions for recreation, biodiversity and biosecurity in terms of risk and opportunity including: a) recreational angling (Tinaroo Dam, Qld), b) pubic interest relating to angling and aquatic pest fish management initiatives (Gooseponds, Mackay, Qld), c) private dam on a dairy farm being checked for pest fish prior to being stocked with a threatened fish species (Malanda, Qld), d) environmental consultants responding to reports of pest fish incursion (Mackay, Qld), e) Indigenous rangers performing biodiversity monitoring of irrigation offtake (Fitzroy catchment, WA), f) private dams and nature tourism (Mareeba, Qld), g) and h) ponds in Botanic Gardens being cleared of aquatic pests (Darwin, NT).

By way of relevant context, site based data used to gain an appreciation for aquatic biota in tropical Australia is heavily biased toward public access sites in rivers and streams and natural lakes and wetlands rather than farm dams (Finlayson et al. 2005, Lukacs and Finlayson 2010, Cann and Sadlier 2017, Pusey et al. 2017). This possibly arises from researchers biasing site selection via conscious or unconscious bias towards more pristine settings. The biodiversity within these artificial watering points may not have even been considered as a potential field site given the lack of government mandated records of farm dams located on private land. This is not to say that there has been a total absence of biotic survey of farm dams or that these habitats are devoid of endemic biodiversity (Hazell et al. 2001, Hazell 2003, Brainwood and Burgin 2009). In fact, developing a working knowledge of farm dams as sites for high aquatic endemic biodiversity value and production (e.g. Brainwood and Burgin 2009) is a fertile area for building landholder confidence in the positives of ecologically sustainable waterway management (Markwell and Fellows 2008) in amongst the negative elements of biosecurity, and in achieving landscape scale biodiversity conservation including threatened species protection in the face of limited water availability and climate change (Hazell 2003, Beatty et al. 2017; Figure 16). Clearly, functioning relationships with landholders is an important aspect of any plans to systematically survey and maintain appropriate native biodiversity in farm dams (Figure 16, Figure 17). More importantly, programs centred on working specifically with landholders to understand the ecology of farm dams has the potential to activate more effective waterway management including deriving solutions to these challenges in conjunction with landholders.

It is recommended that field survey of biota in farm dams be conducted to develop an unbiased assessment of this key aquatic habitat in the tropics. This would serve to develop, a) an inventory of alien, pest and translocated native species, b) endemic species, and c) opening up lines of communication with landholders regarding the aquatic biosecurity and biodiversity opportunities in these habitats.

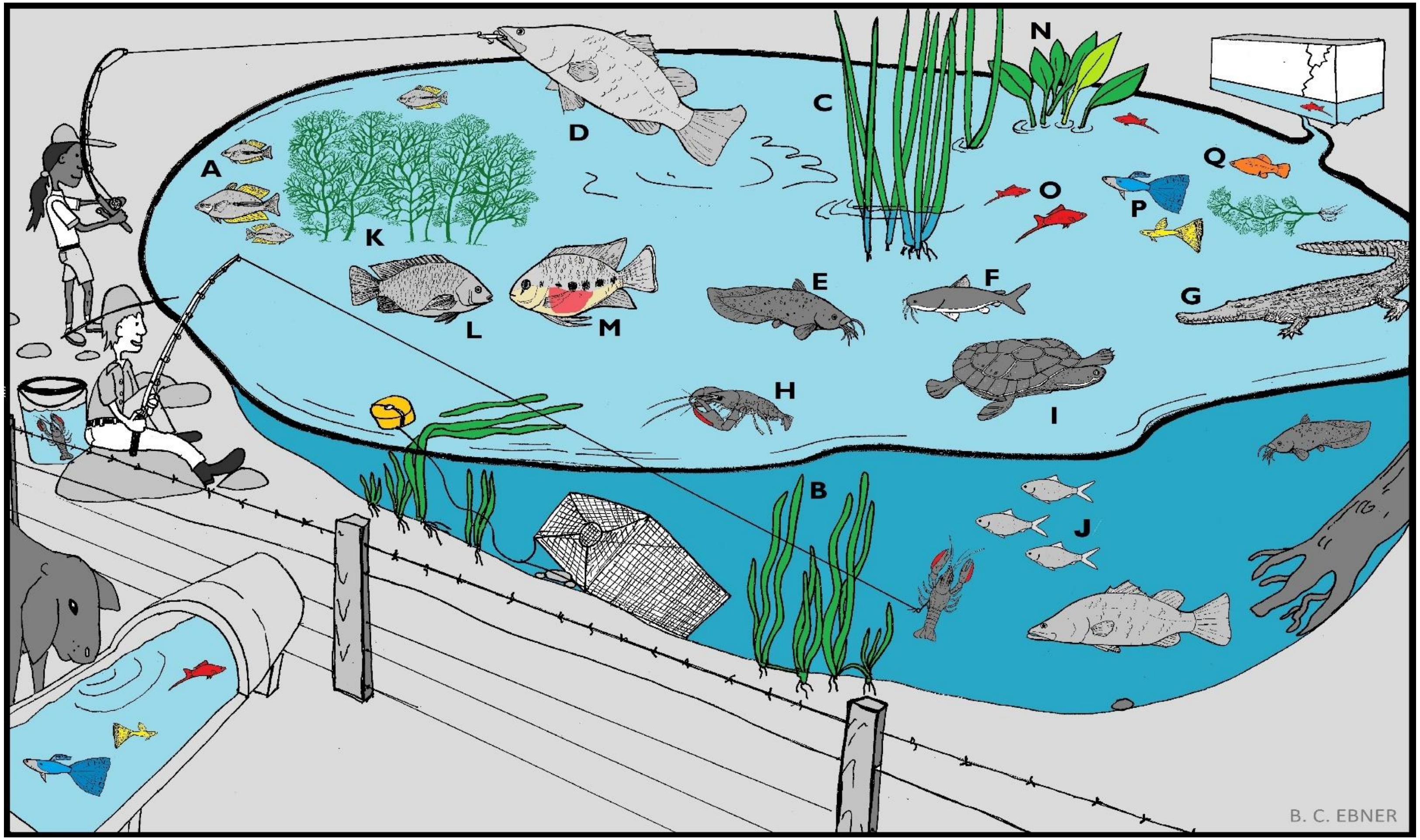

Figure 17: Conceptualisation of a farm dam in the mid Barron River catchment on the Atherton Tablelands demonstrating the biodiversity value and biosecurity risk of aquatic flora and fauna. Processes and behaviours leading to the movement and establishment of different species include, a discontinued aquarium that housed a penny turtle before it grew too large, and small tropical aquarium fishes and plants; fishes used to control algae and mosquitos in cattle trough, crayfish used as a source of live bait and as human food. Endemic species: A) eastern rainbowfish, B) ribbonweed, C) common rush; Translocated native species: D) barramundi, E) eel-tailed catfish (*Tandanus tandanus*), F) fork-tailed catfish, G) freshwater crocodile, H) redclaw, I) Murray River turtle, J) bony herring; and alien species: K) cabomba, L) Mozambique tilapia, M) spotted tilapia, N) yellow sawah lettuce, O) swordtail, P) guppy, Q) platy.

3.2.10 Transient work force in tropical Australia

Within the tropics of northern Australia substantial transient workforces operate in the mining, agricultural and tourism sectors (Perry and Rowe 2015) and in the Defence Force. There is also a transient tertiary education sector that should be acknowledged in this regard. It is recognised that extractive industries (i.e. mining) are frequently associated with negative environmental, social, and cultural repercussions for regional communities (Perry and Rowe 2015), and implications from inadequate biosecurity surrounding aquatic ornamental species is a mostly unrecognised aspect of this form of development in the Australian tropics. The social impacts of industry in northern and remote parts of Australia are not easily quantified nor represented (Wright and Bice 2017) and similarly environmental consequences can be difficult to quantify, predict or manage. This includes fly-in fly-out (FIFO) workforces that regularly transport in a proportion of their workers from home residences in tropical and subtropical cities (e.g. Mackay, Brisbane, Perth) (Perry and Rowe 2015). This workforce includes individuals with high disposable income that are regularly visiting holiday or home destinations in domestic locations (e.g. city pet shops) and international locations (e.g. Bali, Singapore) with opportunity to purchase and smuggle biota including pets and biotic fragments of small size (e.g. snails, shrimps, plant seeds and fragments) into tropical Australia. The transient nature of these workforces also provides opportunity for the discard and dispose of biota including low financial value pets (e.g. fish, shrimps) as workers shift residency. Furthermore, transient individuals may be less prone to appreciating which biota are native and foreign to their new and shifting places of residence.

Low initial cost of an ornamental pet was one of the key features of species with a high likelihood of release into the environment in the USA (Stringham and Lockwood 2018), and a similar pattern likely exists in Australia. Given the average price of an ornamental fish on online retailer sites in tropical and subtropical Queensland is between \$3.79/cm and \$4.62/cm, although selected species may be listed at as little as \$0.16/cm (M. Millington, unpublished data 2020), it is highly likely these transient workers may choose to release such inexpensive pets, and the plants, hitchhikers, and potentially contaminated water, directly into the environment rather than deal with the complications of selling or moving their aquatic pets long distances once their housing situation changes. These worksites may act as hotspots for ornamental establishment, and the locations of such employment may be used to determine the priority of waterways for invasive species investigations.

The behaviour of these transient workforces is an important consideration for the social network assessment of the freshwater aquarium trade in tropical Australia proposed in the current report and ultimately in tailoring effective communication of aquatic biosecurity to key members of the public. Relevant to this is the idea of exploring the issue of social licence (Wright and Bice 2017) in developing corporate and regional community responsibility for local ecosystems and ecosystem services (e.g. Greiner et al. 2009, Adams et al. 2014).

3.2.11 Resourcing effective regulation, compliance and enforcement

Revisiting the compliance and enforcement processes undertaken by the Federal government at the Australian border is critically needed. There have been several cases in recent years where loopholes in border protection processes between the Department of Environment and Energy – who managed the *EPBC Act 1999* – and the Department of Agriculture and Water Resources – who managed border enforcement and the List of Specimens Taken to be Suitable for Live Import (Live Import List), resulted in ineffective responses to non-permitted aquatic species being brought into the country. Once here, traders of alien freshwater species have then proliferated the trade of potentially invasive species as being 'progeny' of animals already in Australia – one of the loopholes to effective compliance and enforcement across the country. Substantial action is required regarding the lack of compliance around the importation and/or smuggling of alien aquatic species initially, including a systematic review of penalties for infringements. Often once aquatic species are let 'through the gate' the biosecurity responses are pushed back onto the state and territories to facilitate the compliance and enforcement activities. The recent merger of the two aforementioned departments into the Department of Agriculture, Water and the Environment provides an opportunity for effective treatment of this issue.

Each state or territory facilitates its own biosecurity response system, and historically aquatic biosecurity has never received the level of funding that is required to mitigate the level of risk that these activities pose both environmentally and economically. Despite best efforts to manage noxious species lists between jurisdictions, discrepancies between the state or territory permitted species lists still exist. Often it is these differences between the state and territories, or the loopholes in licensing systems or paperwork requirements for progeny of fish already in Australia, that is exploited by illegal traders. In addition, most state and territory management agencies do not currently utilise the Commonwealth legislation to enforce the provisions of the *EPBC Act 1999*. Currently only the Northern Territory links its *Fisheries Act 1988* and *Fisheries Regulations 1992* to the *EPBC Act 1999* and will enforce the provisions of that Act as it relates to possession of fish not on the Live Import List managed under DAWE. Queensland is in the process of following suit but is facing difficulties in dealing with the resources required to work with industry on the species not permitted, but already widely in circulation across the state (B. Holmes, pers. obs.). Recently the Western Australian government enforced provisions of the *EPBC Act 1999* in relation to imported (smuggled) shrimps that are currently very popular in the aquarium trade, in particular cherry shrimps (*Neocaridina davidi*) which are available in many aquarium retailers in other states and territories, as well as online from various sources. These sorts of challenges are widespread, but should not negate the federal, state and territory management authorities from disregarding the very real threats to Australian environment.

For the states and territories to enforce the Commonwealth legislation in relation to possession of species not on the Live Import List, particularly those already here in trade, it will require significantly more investment and resourcing for each jurisdiction to undertake such complex activities. There are numerous species now in the aquarium trade that have turned up since the introduction of the *EPBC Act 1999*, and therefore imported illegally. Currently, the National Environment and Invasives Committee (EIC) sub-committee, and the Freshwater Vertebrate and Invertebrate Working Group (FVIWG), are working towards implementing an approved rapid risk assessment process to determine which species, including those already in circulation, pose low, moderate or high risks using a detailed range of applicable economic, social and environmental considerations in the models (see Deveney 2018). Once completed however, significant work on how these assessments translate into policy changes in each state and territory remains an immense task. In short, to deliver on these responsibilities a new model of committed long-term funding is vital, along with elevating the management and apportioning of funds via a stand-alone Freshwater Aquatic Pest Sectoral Committee or Cooperative Research Centre (CRC), that is represented by all jurisdictions, is required.

3.2.12 Unregulated trade

Unregulated trade may involve the covert sale of noxious species, but also encompasses all aquarium species that are traded by persons or groups that are not governed by state or federal business legislation. The term hobby business also falls under unregulated trade, meeting business guidelines set by the Australian Taxation Office (2016) including selling items online, making or intending to make a profit, creating an online trading or auction site, and regularly participating in sales. The issues with unregulated aquarium trade lie in the lack of reporting requirements, with information regarding revenue, the species involved, quantities moved, and locations distributed to going unrecorded. Consequently, there is no clear trail for investigating species movement through buyers and sellers. This can be especially important for tracing disease and parasite outbreaks. Additionally, it is likely that the pool of species relevant to unregulated trade includes listed noxious species and is especially likely to involve high risk species to Australian ecosystems and their native biodiversity. For this reason, above all other, specialist investment is warranted in a specific program focused on illegal and unregulated trade and this has been recognised as an important and ongoing issue in Australia (McNee 2002) radiating through multiple branches of the aquarium trade network (O'Sullivan et al. 2008) and should also extend to the government biosecurity process itself including the import quarantine process.

Illegal trade refers to the buying, holding, advertising, or selling of species determined by the *Biosecurity Act 2014* as noxious 'those species perceived to threaten the environment, society and economy, and hence are high-risk'. While the smuggling of wildlife by organised criminal networks is acknowledged in Australia (Alacs and Georges 2008), the prevalence of illegal trade in the aquarium industry is debated by industry representatives, with contradicting reports indicating illegal trade is viewed as pervasive by some but limited by others (McNee 2002, O'Sullivan et al. 2008). Regardless of frequency, the illegal movement of even a small number of noxious species into and around Australia through the aquarium trade poses a considerable threat given the vulnerability of Australian native flora and fauna through their naïve evolutionary history. Their release, whether incidental, accidental, or purposeful, could lead to irreversible damage to native communities, loss in societal value of an aquatic environment, and damage to fisheries production.

Ornamental species being smuggled illegally into the country is of genuine concern. Note the difficulty and uncertainty associated with this aspect of biosecurity monitoring and management, with the lack of quarantine and hence disease or parasite prevention a noteworthy issue. Inconsistency in legislation within Australia and the lack of screening of movement between borders also contributes to illegal trade, with certain species permissible in one state or territory (e.g. koi are legally allowed to be kept in NSW) but differing legislation within another bordering state or territory (e.g. koi are a noxious species in Qld) creating perfect conditions for illegal trade to develop and prosper. This has been a major complication for the protection of the endangered Denison barb (*Sahydria denisonii*) in India, where state-wide restrictions on the trade of this species had minimal effect due to surrounding territories not enforcing these regulations, and hence allowing for a thriving black market in neighbouring states (Raghavan et al. 2013). Given the overexploitation of this species through wild collection that resulted in severe population declines (Raghavan et al. 2013), the inability for much needed regulations to be respected by bordering regions to protect an endangered species calls into question the role Australia plays in the decline of species given the current ignorance on illegal trade in Australia.

Although there have been suggestions that part of the problem stems from a lack of understanding by consumers on what species are approved (e.g. Alacs and Georges 2008, O'Sullivan et al. 2008, Hoveka et al. 2016), online monitoring of aquarium trade in fish has identified many situations where the illegal nature of the sale, including the suggested smuggling of noxious species into Australia, and associated penalties was acknowledged and understood by all parties involved (M. Millington, unpublished data 2020). McNee (2002) identified some of the issues associated with smuggling fish illegally into the country. Preliminary findings from an online monitoring project of ornamental trade in Queensland has indeed detected high-risk illegal species (according to *Queensland Biosecurity Act 2014*) being listed for sale, including the restricted noxious species spotted alligator gar (*Lepisosteus oculatus*), eastern gambusia, and black pacu (*Colossoma macropomum*), and the prohibited noxious species redtail catfish (*Phractocephalus hemioliopterus*) also being advertised (M. Millington, unpublished data 2020). These few species do not represent the full extent of current high risk species in the state, rather it reflects the inability for covert trade of illegal species to be accessed and monitored, as this illegal trade network likely encompasses a substantial community of noxious fish, reptiles, invertebrates and other aquatic ornamental species.

Northern Queensland, and especially Townsville, appears to be most at-risk of noxious species being released and establishing, with several advertisements listing restricted noxious spotted gar documented within the past year (M. Millington, unpublished data 2020). This species is not to be sold, bought or moved, and its possession must be reported (*Biosecurity Act 2014*). Although it is unclear whether these individuals were legally imported before legislation changed, or were smuggled interstate or internationally, it is of note that Townsville represents one of the four priority ports in Queensland (Queensland Resources Council n.d.) and transports 1.79 million passengers annually via the Townsville domestic and international airport (Townsville Airport 2020).

Given the apparent failure of regulations to limit the trade of high-risk aquarium species in other countries such as Brazil (de Magalhaes and Jacobi 2013), the UK (Hill 2012), South Africa (Hoveka et al. 2016), US (Diaz et al. 2012), and India (Raghavan et al. 2013), it is vital for the protection of Australian society, environment and economy, as well as the continuation of the Australian aquarium industry, for complementary management to be established alongside consistent legislation in each state.

The necessary instating of a Freshwater Pest Sectoral Committee to the level equivalent to that of the Marine Pests Sectoral Committee is a vital first step in addressing illegal trade. This committee should address illegal trade by facilitating and supporting national, state and regional level messaging and compliance activities (Alacs and Georges 2008, O'Sullivan et al. 2008, Hoveka et al. 2016). Legislation must also be strengthened considering findings from a study of 13 years of criminal proceedings concerning wildlife seizures in Australia which found prosecutions were negligible (1%), and when legislation was forced the resulting fine was much less than the species worth (Alacs and Georges 2008). Evidently prosecutors are misinformed on the appropriate punishments regarding illegal trade, and emphasis should be placed on the fines acting as a clear warning for the parties and others involved in illegal trade through accurate valuation of the species seized and hence a more accurate fine based on that information.

Gray et al. (2017) emphasised the importance of understanding not only the species illegally traded, but also the criminal networks involved. A key function of the Freshwater Pest Sectoral Committee should be to establish and maintain quantitative data on propagule pressure and pathways of incursion within the aquarium trade and in private waterways by independent data obtained through illegal trade data collection. This database will act as guidance towards not only understanding for the first time the illegal trade community, but also act as a benchmark to determine management's next step and, when necessary, the strengthening and redefining of legislation.

The complexity of the unregulated trade needs to be thoroughly investigated and articulated including through the social networking assessment proposed earlier. In turn, this assessment should be used as a key resource for the National Freshwater Pest Sectoral Committee and relevant agencies and industry operators to shape best practice including curbing incidental and deliberate illegal trade. Workshops targeting these issues separately are recommended since the former can be commenced at a regional scale, whereas, the latter will require significant government resolve, including commitment to state and federal government intelligence and enforcement capacity. A focus of this second workshop should be scoping resourcing requirements and preparing costings for parliamentary consideration, since the scale of dedicated intelligence and compliance resourcing required to affect change in the illegal including incidental trade of prohibited aquarium species in tropical Australia is substantial. We offer no estimates here, although at times we have alluded to some practical considerations. These include resourcing dedicated aquarium trade compliance officers in each tropical state and territory, NRM aquatic biosecurity coordinators, and purchasing time from pet shop owners to participate in regional initiatives.

4. SUMMARY

Tropical Australia is a vast area containing numerous near-pristine freshwater ecosystems that hold resources of high cultural, economic and biodiversity value. However, this is changing rapidly with the establishment and expansion of a few high-profile pest ornamental species, and the incursion and establishment of multiple other ornamental taxa. The global aquarium trade nexus is the primary threat to tropical Australian waterways since it underlies the transport and propagation of hyper-diverse fauna, flora and their parasites from biogeographically distinct provinces (often from other continents), with risk of entering and establishing at large spatial scales generally unchecked. The diversity of tropical species being traded is (for some taxa) at least an order of magnitude greater than the biodiversity that naturally occurs in tropical Australia with respect to specific taxa (e.g. for freshwater fishes).

Many aquatic pest incursions are irreversible once the species has established in a large waterway. In aquatic biosecurity terms, this underlies the reasoning why substantially more investment in prevention and early detection is needed. Surveillance and reporting by the public is often a key element for early detection for land-based weeds and fauna. However, underwater surveillance capability is limited in tropical Australia partly as a function of remoteness and the presence of crocodiles. Effective biosecurity also relies on the public having a broader vision and understanding of invasive freshwater ornamental species and knowing where and how to report suspected alien taxa if seen or captured in the wild. To this end, the current scoping study contends that investment in translational ecology and integrated pest management principles are vital in improving the biosecurity continuum in Australia.

There is a critical need for substantially greater national resources to be directed at freshwater biosecurity in tropical Australia than has been historically the case. Drastically raising the profile and national significance of aquatic biosecurity challenges in the region is a critical priority. Identifying key community groups, traditional owners and other land users is an important step in developing and tailoring engagement activities to appropriate audiences. Education in relation to ornamental fish importation, trade and keeping is paramount, along with providing information on the risks that deliberate release and establishment of non-native aquatic species causes to Australian native waterways. Communication campaigns should be achieved with popular culture and societal attention firmly in mind. Establishing a National Freshwater Pest Committee at the level of the Marine Pest Committee is one of the steps in adequately resourcing and treating freshwater biosecurity at an adequate level.

In optimising resource allocation, we recommend building on existing institutional strengths in tropical Australia but investing heavily in piloting and developing cross institutional and societal connections. Undoubtedly NRM agencies, indigenous ranger programs and local councils among others, have key roles to play in this process. We have provided recommendations as to how on-ground pilot work might look at key sites. Pilot studies that focus on issues of healthy choices for backyard mosquito control, aquarium and ornamental pond keeping and farm dam use by individuals, is at the heart of not limiting biosecurity to purely involving the institutional level. In this regard there is a recognised interplay between establishing substantially larger resourcing for this issue and an informed and empowered tropical society actively reporting pest incursions and improving aquarium trade and related practice.

The disbenefits of not managing this major impact pathway have not been costed in the current study, as this is not a straightforward process (Lovell et al. 2006). However, a predictive costing framework will likely be required if this major biosecurity risk is to be resourced adequately. That tropical society needs to be engaged and active in the aquatic biosecurity space in tropical Australia for cultural, economic and biodiversity benefit, is undeniable.

Our intention is that the current document serves to promote rather than close discussions aimed at finding ways forward in making informed decisions regarding society and freshwater ecosystems in northern Australia. This report provides some expert advice on ways forward, while acknowledging that substantial investment, thinking, and action remains ahead with input and involvement by others including regional biosecurity workers, indigenous groups, private industry (within and outside of the aquarium trade), levels of government, NRMs and a public acknowledging variable awareness of the magnitude of these issues.

5. RECOMMENDATIONS

The primary recommendation of this report is that the federal government and the Australian people develop behaviour that protects freshwater ecosystems in tropical Australia from the biosecurity threats posed by the freshwater aquarium trade. This will involve getting the issue into mainstream public discourse, generating funding models and properly resourcing preventive risk actions and protective actions on the ground. This resourcing is not just in terms of dollars, but in ensuring that staffing appointments to key roles in the biosecurity process are not diluted with other tasks such as fisheries compliance, agricultural biosecurity or human safety matters. Dedicated expertise and focus (in compliance, communication, coordination and scientific and social science) are required to deal with the aquarium trade related biosecurity issues.

To this end, four overarching recommendations are provided here with more detailed context and specific recommendations for action provided elsewhere in the report.

1. Establish a national focus on biosecurity in freshwater by instating a Freshwater Pest Sectoral Committee to the level equivalent to that of the Marine Pests Sectoral Committee.

The justification for this is rooted in the sheer magnitude and hyper-diversity of biota being formally and informally traded, the relatively pristine state of many of the potential recipient ecosystems in tropical settings especially, and the continually increasing human development in tropical Australia and its inevitable interaction with water resource use.

2. Effectively inform and educate community and government about the magnitude of current and future biosecurity risks from tropical aquarium trade and the consequences for northern Australian freshwater ecosystems and society.

Opportunities exist in school curriculum, broadcast media, social media and marketing approaches to develop a public awareness of the importance of aquatic biosecurity in northern Australia. Adequate resourcing of established roles within industry, government agencies and establishing coordinator roles within the natural resource management sector are key requirements to achieving effective extension and on-ground action, including promoting healthy choices in the aquarium and ornamental trade.

3. Develop an independent understanding of the human networks that lead to impact including future potential impact to tropical aquatic ecosystems in tropical Australia.

These networks include understanding within-industry market drivers, characteristics and trends including social science investigations of incidental and intentional illegal trade including via the unregulated and internet components of the aquarium, pet and ornamental trades (Note: The aquarium industry is not a trade in static products, it also deals in a continual and emerging novelty biota). Recently, analogous social network analysis has been achieved regarding marine pests in Australia. In the freshwater pest context, the mindset of the hobbyists, traders and collectors is central to interpreting any social analysis and this should be paired with an inventory of the aquarium trade species including parasites and pathogens currently in the country.

4. Develop regional solutions to protecting aquatic ecosystems. Specifically, this is termed ‘translational ecology’ whereby partnerships are formed to develop ongoing solutions to address aquarium trade specific biosecurity risks aimed at catchment and regional scales in northern Australia.

As a matter of urgency this should include resourcing and appointing regional coordinators through existing NRMs and resourced pilot programs to galvanise indigenous ranger, local council, university and state and federal agency staff and NGOs including pet shop retailers in championing best practice and undertaking aquatic biosecurity.

Notably, long-term officers, specifically dedicated to the aquarium trade biosecurity matters at state and federal government level are required to champion effective biosecurity in this complex social, biological and ecological arena. Funding an analysis of the freshwater pest network including the aquarium trade and ornamental pond sector akin to Stenekes et al. (2019) (regarding the marine pest sector), is an urgent priority providing a platform for shaping the long-term priorities of regional coordinators and key state and national decision makers including the Chief Environmental Biosecurity Officer, The Threatened Species Commissioner, the Freshwater Pest Sectoral Committee, Biosecurity Queensland, the Western Australian Department of Primary Industries and Regional Development, and the Northern Territory Government. Major land management organisations and employers in northern Australia are also relevant (e.g. mining sector, Defence Force). Active or activating NGOs in this space is a key consideration. A preliminary list of immediate tasks is provided in Appendix-B.

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7. APPENDICES

Appendix A: Glossary of relevant terms

Alien species
Terminology surrounding invasive species definitions has been an area of debate, with multiple phrases such as exotic, invasive, non-native, high-risk, and introduced species used. Ricciardi and Cohen (2007) suggested terminology should refrain from including negative connotations. Guided by this, we define alien species as species, sub-species or varieties whose native range does not include any part of Australia and that have established naturally occurring, self-sustaining populations under human-means, whether deliberate, unintentional or incidental, in at least one drainage in Australia (Copp et al. 2005, García-Díaz et al. 2014).

Biogeographic province
Biological subdivisions of ecosystems characterised by species similarities and difference (Oxford Reference, Encyclopaedia Britannica, Udvardy 1975).

Cichlids
A grouping referring to fishes of the species rich Cichlidae family with centres of diversity in Africa, Central America, and South America.

Climate change
Climate change is now agreed upon by all leading scientists and research bodies as an anthropogenically driven substantial increase in greenhouse gases, namely carbon dioxide, in the upper atmosphere to levels which greatly exceed those measured since the last interglacial period (IPCC 2013, NASA 2015). Altered atmospheric composition is recognised as a significant threat to global biodiversity due to the effects altered climatic conditions convey upon population densities and distributions (Gilman et al. 2010; Araujo et al. 2007), with an overall impact upon community structure as a result (Brooker et al. 2007). Aquatic environments, in particular, are thought to be more susceptible to these impacts, and this has been realised, with considerable disadvantages attributed to climate change that have been measured more often in aquatic environments than in terrestrial (McClure et al. 2013).

Colonisation
Considered the second phase of a species integrating itself into a native community, colonisation refers to the established founding population of a self-sustaining alien species increasing its abundance to form a colony, and begins expanding its range (Copp et al. 2005).

Colonisation pressure
A recent definition that has historically and incorrectly been grouped with propagule pressure. Colonisation pressure is distinct in that it is a community-level aspect of introduction, assessing the diversity of species invading the same location (Lockwood et al. 2009). Colonisation pressure highlights the idea of co-invasion; a disturbed community assemblage with heightened diversity as a result of an increase in invaders becomes not only more susceptible to but facilitates the successful establishment of additional alien species (Xiong et al. 2020).

Ecological sustainability
Emphasises conserving the productivity of the natural environment and maintaining its essential functions and processes. This is distinct from sustainability as it disregards the industry perspective of productivity.

E-commerce
The trading of species, products, and services conducted on an online platform such as a website or private chat forum.

Endemic range

The area in which an endemic species (as per the definition below) is naturally distributed and confined to by physical barriers that inhibit natural range expansion.

Endemic species
Native species (as per the above definition) that are found only in one particular region. For example, the Threadfin rainbowfish (*Iriatherina werneri*) is a native species in Australia and Papua New Guinea but not an Australian endemic species, while the koala is native to only Australia, and is therefore an Australian endemic species.

Exotic species
Typically used as a synonym for alien species; however, this term implies positive attributes, including aesthetically pleasing and enticing characteristics, which overshadow the high-risk nature of such non-native species to the ecosystem they invade and establish in. This term has been thus avoided within this report to convey the lack of connotations surrounding such a species.

Establishment
Considered the first phase of a species integrating itself into a native community, establishment refers to the founding individuals of an alien species forming a self-sustaining population in a region outside of its native range, transported there under human influence (Copp et al. 2005).

Extinction
The International Union for Conservation of Nature (IUCN) is the global authority on the conservation status of species via their Red List of Threatened Species and defines extinction as an irreversible process whereby no individuals of a species persist or are thought by experts to exist.

Farm dam
A natural or human-made depression for collection of surface water and precipitation for the sole purpose of increased water security. These dams may inadvertently act as pathways for alien species between waterways during flooding, and refuges after flood waters subside.

Global Aquarium Trade Nexus
The human mediated connection between biogeographically separated freshwater ecosystems as a function of the ornamental trade industry. It is especially relevant to receiving tropical biogeographic provinces.

Introduction
The deliberate or unintentional release of species into a novel ecosystem by direct or indirect human agency (Copp et al. 2005). This is distinguished from natural range expansion or reestablishment of an area once colonised by a species through the anthropogenic influence.

Live bearers
Species in the Poeciliidae family, characterised by their bearing of live young.

Native species
Crees and Turvey (2015) explored the definition of what constitutes a species as native, but instead found a complex history of evidence from a range of sources, including zooarchaeological and molecular techniques is necessary for this determination. In this report, native species are defined as species that have naturally established a self-sustaining population in Australia prior to human colonisation and without human influence. Note: species that require stocking for population maintenance may also be considered native.

Noxious species
Although a founding term used throughout the *Biosecurity Act 2014* to designate an alien species as a pest, no exact definition was provided. However, recent reports from the Department of Agriculture and Fisheries (2016) and Biosecurity Queensland (2018) suggest noxious species are those deemed to threaten and disrupt native aquatic ecosystems. Noxious species are further classified by the *Biosecurity Act 2014* into restricted and prohibited. Depending on risk assessment of their perceived threat, restricted noxious species are subject to 7 categories wherein it is an offence for individuals to be sold or bought (Category 3), moved (Category 4), possessed (Category 5), or fed (Category 6), species must be euthanised if caught while fishing (Category 7),

and knowledge of individuals being held, carried or possessed must be reported to an authorised Biosecurity Officer (Category 2).

Pest species
An alien species (as per the above definition) declared noxious, whether prohibited or restricted, under state or federal legislation (*Biosecurity Act 2014*, DAF 2016).

Poeciliidae
Fishes in the family Poeciliidae, also referred to as livebearers, and include the well-known aquarium species guppy, molly, platy, and swordtail.

Propagule pressure
Propagule pressure focuses on the intensity (propagule size) and frequency (propagule number) of individuals from one species entering the same location, with repeated introduction events increasing the gene pool diversity and heightening the likelihood of sexually mature individuals coupling thus overcoming issues with small founder populations (Lockwood et al. 2005). Greater propagule pressure also increases the likelihood of an individual being released into favourable conditions and establishing (Lockwood et al. 2005).

Retailer
Acts as an intermediary supplier between wholesalers and the public, selling goods, services, and in this instance, ornamental species and their products for a profit.

Sustainability
Refers to ensuring a business model or project maximises production while also meeting the needs of the present society without compromising the ability for future generations to meet their needs. Although used interchangeably with ecological sustainability, the term has been degraded and reshaped to prioritise industry desires rather than sustainability focused on the persistence of a natural environment.

Translational ecology
An approach that embodies intentional processes in which ecologists, stakeholders, and decision makers work collaboratively to develop ecological research via joint consideration of the sociological, ecological, and political contexts of an environmental problem that ideally results in improved environment-related decision making (Enquist et al*.* 2017).

Translocated native species
Species introduced under human-means from one catchment where it is native into a catchment where it has historically not established under natural means due to the presence of natural barriers (Copp et al. 2005).

Vagrant species
Species that unsuccessfully undertake range expansion through naturally distributing themselves into a novel ecosystem but failing to establish a self-sustaining population (Copp et al. 2005).

Water transfer scheme
The distribution or diversion of water from one catchment with an abundance to another experiencing water shortages, for improved regional water security. These water transfers may incidentally transport microorganisms, fish fry, and plant fragments capable of regeneration into novel ecosystems where previously physical barriers prevented range expansion, potentially resulting in species establishment, reducing diversity between ecosystems.

Wholesaler
Acts as an intermediary supplier between importers and retailers, trading bulk goods, services, and in this instance, ornamental species and their products at a reduced price due to their ability to buy in bulk.

Appendix B: A preliminary list of tasks for aquatic biosecurity regarding the freshwater aquarium trade in tropical Australia

a. Resourcing targeted field-based survey of the aquatic biota composition including pathogens and parasites in private dams in tropical Australia as potential reservoirs for aquatic pests (acknowledging that this might be considered by some to be beyond the bounds of the aquarium trade sector).

b. Building surveillance and control plans into indigenous ranger programs and up-skilling in identification of alien species and removal methods (e.g. at the tip of Cape York Peninsula in the Indo-Papuan conduit, e.g. where consignments arrive for import clearance at airports).

c. Resourcing northern NRMs to establish regional coordinators and extension officers dedicated exclusively to the freshwater pest sector relating to communicating the complexity of in and outside aquarium trade related incursions in tropical Australian waterways.

d. Establish and maintain quantitative data on propagule pressure and pathways of incursion within the aquarium trade and in private waterways by independent data obtained from i) phone survey data (akin to national recreational angler survey), ii) targeted surveys of wholesaler and retailer stock, iii) internet trade surveillance, iv) illegal trade data collection, and v) substantial bolstering of aquatic pathology surveillance within the aquarium trade including upon import.

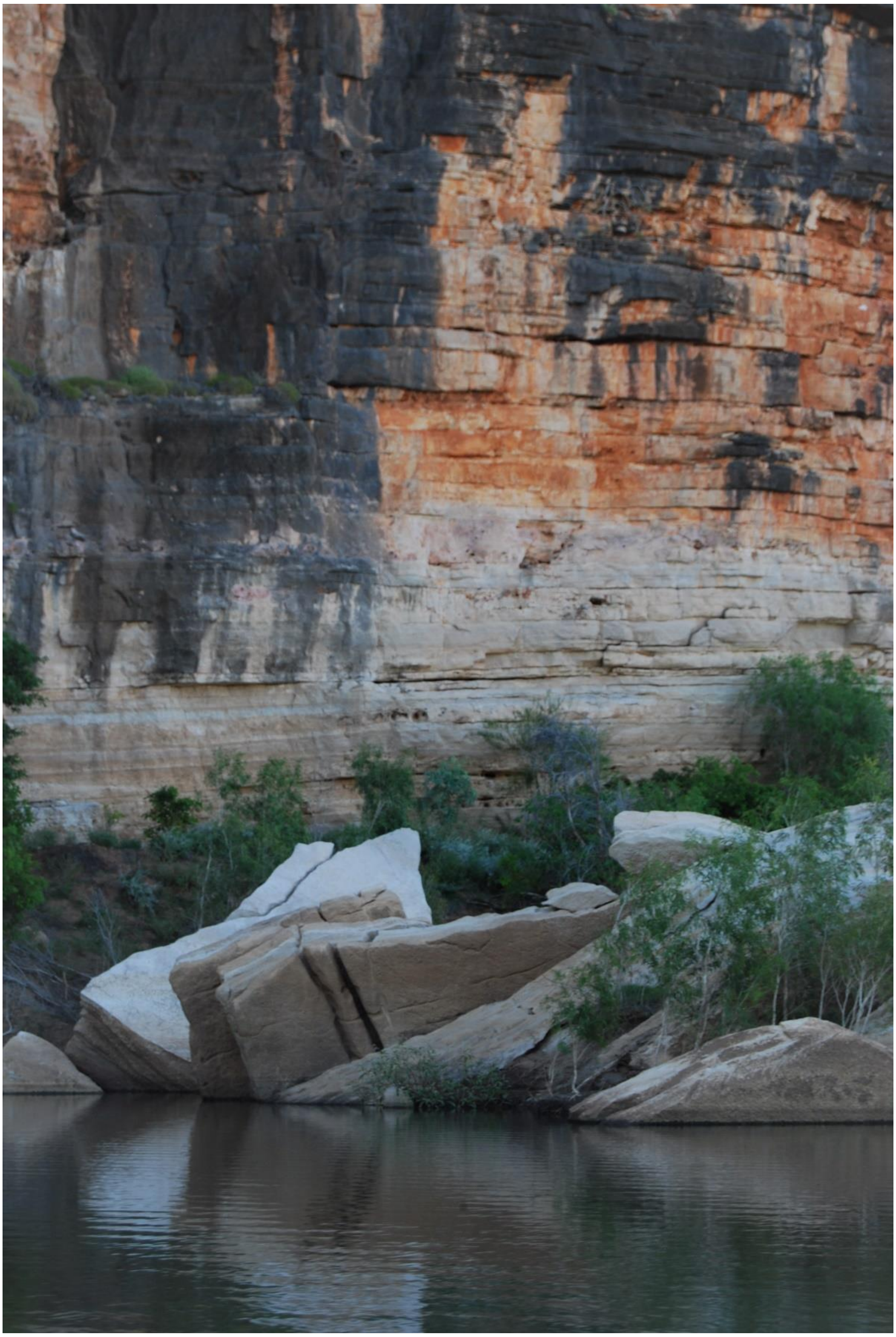
e. Establish NRM, indigenous ranger and pet shop owner working relations on matters of aquatic biosecurity. Conduct small but well-resourced and targeted workshops that maximise attendee contribution in deriving these local solutions (representation such as indigenous rangers, pet shop owners, ornamental pond wholesalers and retailers, council, NRM, State agencies responsible for biosecurity, aquatic specialist(s) from Department of Agriculture, Water and the Environment, ecologists/university researchers, social scientist, non-government organisations (NGOs)). Importantly, retailer stipends should be commensurate with the time taken out from their businesses to accommodate working group involvement.

f. Engaging town planners prior to and during the development of new tropical suburbs to produce community spaces that are resilient to aquarium and ornamental pond releases of biota. Adequate and ongoing resourcing for this is a major issue but might gain traction initially through targeted integration of town planners in e) above.

g. A focus on resourced best practice for water transfer schemes especially at major biogeographic boundaries (e.g. Atherton Tablelands) where alien and translocated native species pose great risk of impacting the structure and function of natural ecosystems. Furthermore, preventing the dispersal of aquatic parasites, pathogens and viruses (including native and alien forms) should be prioritised and resourced in all future water transfer scoping and implementation.

h. Apply a biosecurity focus at selected small and discrete high-value waterbodies for societal engagement and biodiversity benefit in tropical Australia partly by transferring learnings from demonstration site initiatives in the Murray-Darling Basin. (Note: small and discrete waterbodies provide societal and ecological benefits because of logistical issues associated with early detection and removal of alien species in the way that pest management has been possible on small islands in the terrestrial pest management space).

i. In terms of developing an informed national culture regarding responsible farm dam aquatic biosecurity, one recommendation that would be useful from an on-ground management perspective is the genetic sequencing of all exotic fish species on the import list, and others known to be in the aquarium trade in Australia. Priority could be given to species that pose a higher risk of establishment and ecological impact. If this program was funded well enough it should also include the development of primers that can be used for eDNA surveillance. The limiting factor in field surveillance is sensitivity and the inability to make confident management decisions due to the possibility of false negatives.



Geike Gorge, WA.