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REVIEW PAPER

New Australian frontier in freshwater fish invasion via Torres Strait Islands

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Abstract

All continents, excluding Antarctica and the Artic, have been affected by incursion from alien freshwater fish species. Australia has not been spared. Four hundred and fifty species have now been declared on the ornamental importation list, making management a real challenge. With approximately 25 non-native species documented, Papua New Guinea (PNG) has likely some problems with invasive freshwater fish. Many of these species have been intentionally introduced to increase access to food as a protein source for remote communities or have spread naturally from western parts of Java and Indonesia, and now constitute a large biomass on some floodplain areas in PNG. The Torres Strait is located between PNG and northern Queensland and was previously a land bridge, though now under higher sea levels the region exists as a series of approximately 300 islands. The threat of further range extension of freshwater fish from PNG into northern Queensland via the Torres Strait Islands is significant, with two invasive fish species already recorded on northern islands of the Torres Strait (climbing perch, *Anabas testudineus* which has been continually recorded for the past decade; and recently the GIFT tilapia, *Oreochromis niloticus*). Here we present a case to control further spread of invasive freshwater fish species towards Australia, using a Land and Sea Ranger program, where Rangers are trained to be confident in the identification of pest fish species and to implement strategies to protect their borders from potential future incursions. The success of this program relies on Rangers to continue partaking in surveillance monitoring of coastal waters, checking and controlling for any new invasive species moving from PNG into Australian waters. We outline the biosecurity obligation under Article 14 of the Treaty between the two nations, which identifies the importance of conservation and protection of coastal floodplains from invasive species, and the spread between both nations.

Keywords Torres Straits · *Channa striata* · *Anabas testudineus* · Papua New Guinea · Community monitoring · Pest species

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Introduction

The world is highly connected, large ocean ships and air travel have become major pathways to the expansion of invasive species distribution, enabling the colonisation of new areas (Casal 2006; Simberloff 2009). With the exception of climate-mediated biological invasion—where managing natural range spread of species into new areas is difficult (Walther et al. 2009), the prevention of invasive species from human action has contributed to heightened biosecurity policy, quarantine checks and strategic management frameworks to protect the spread of invasive species into new areas and threaten the local fauna community in many places (Oreska and Aldridge 2011; Smith et al. 2014). Examples where these management processes have been implemented, indicate that although it is possible to maintain invasive species to acceptably low densities, or even complete eradication (Simberloff 2009; Epanchin-Niell et al. 2010; Ruiz-Navarro et al. 2013), it is costly (Luque et al. 2014). A further management avenue showing promise is empowering and educating communities to identify invasive species (Pernat et al. 2021), to be more aware of the ecological impact of moving species from place to place or indeed eradicating invasive species when observed (Crall et al. 2010; Genovesi 2011; Maistrello et al. 2016).

All continents, with the exception of Antarctica and the Artic, have been affected by incursions of invasive freshwater fish species (Casal 2006). The spread of invasive fish species continues to cost local communities and government agencies funding to eradicate them or on expensive media and community educational campaigns. Australia is not invulnerable, despite being an island nation, to invasive freshwater fish introductions. In a review of available fish data, 450 species have been declared on the Australian ornamental importation list. Of these, 34 freshwater species have established feral populations and colonised Australian freshwater rivers (Corfield et al. 2007). Twenty two of the 34 established species have been intentionally introduced, including the European carp (*Cyprinus carpio*) (Shearer and Mulley 1978), tilapia (*Oreochromis mossambicus*) (Arthington et al. 1984) and mosquitofish (*Gambusia affinis*) (Howe et al. 1997); with each now widespread across tropical and temperate river systems (Corfield et al. 2007). These three fish species have contributed to wide scale habitat destruction, poor water quality (King et al. 1997; Koehn 2004), predate on local native species (Doupe et al. 2009) and have spread disease (Koehn 2004). In fact, the European carp now account for more than 90% of the total biomass in some south-east Australian rivers, creating difficulties for the management of this species by authorities (Harris and Gehrke 1997).

Here we outline a new frontier of invasive freshwater fish that, if left unmanaged, could reach the near-pristine freshwater rivers and wetlands of northern Australian, which support incredible diversity in aquatic fish, turtles, crustaceans and migratory birds (Pusey et al. 2004; Burrows and Perna 2009). Furthermore, we suggest that success in protecting Australia from the threat of these invasive fish species hinges on a strong community educational program, supported by on-going surveillance of coastal wetlands, a robust regulatory framework and implementation of advancing technologies to detect new species.

Papua New Guinea and invasive freshwater fish

Papua New Guinea (PNG) has a rich indigenous culture, with communities in remote parts of the country still participating in traditional forms of hunting and gathering to provide sustenance for village communities. It is a nation with strong economic potential built on large mineral deposits and resources (Williamson and Hancock 2005), aquaculture enterprise (Smith 2007), forestry farming (Koczberski and Curry 2005) and sports fishing/tourism (James et al. 2012). The country has striking river systems that deliver substantial freshwater flow to connected coastal floodplain wetlands and lakes, and main river channels (Milliman and Farnsworth 2011). Amazingly, there are more than 5000 wetlands and lakes documented along the PNG coastline (Chambers 1987), that collectively support an incredible diversity of aquatic species (Berra et al. 1975; Hyslop 1999), including over 500 known freshwater fish species (Allen 1991).

Despite supporting a high number of endemic freshwater fish species, an emerging challenge for PNG authorities is invasive freshwater fish (Gerke et al. 2010). Based on a review of available literature, 25 invasive freshwater fish species have been described as present in PNG Rivers and coastal wetlands (Allen 1991; Polhemus et al. 2004; Busilacchi et al. 2014; Manangkalangi et al. 2020). However, Allen (1991) acknowledges that this list is not exhaustive given the remoteness of PNG highland river catchments, and the difficulty in accessing these areas to complete comprehensive field surveys. Mechanisms contributing to the incursion of freshwater fish are numerous and likely to have occurred over a number of decades, either through escape from aquaculture ponds (Glucksman et al. 1976; Smith and Morris 1992; Powell and Powell 1999; Smith 2007), via direct introduction to river catchments explicitly to increase access to food and protein for the community (Glucksman et al. 1976), or spread through natural range expansion across the New Guinea border between Papua and PNG (Mack and Alonso 2000; Tweedley et al. 2013). Evidence has emerged that many invasive fish species are now well established in Western Province (Gerke et al. 2010), the Fly River floodplain (Smith and Hortle 1991; Storey et al. 2002, 2009), and in eastern PNG river catchments (Coates 1987). In fact, surveys of coastal communities on the floodplains near to Daru have shown that many of the fish species commonly caught in the artisanal catch that appears in the local market have been replaced with large catches of tilapia (Cichlidae), climbing perch (Anabatidae), and snakeheads (Channidae) (Busilacchi et al. 2014).

Ecological niche theory (Shea and Chesson 2002) posits that presence and distribution of organisms is mediated by intrinsic biological traits that dictate whether a species will successfully exist or be resilient to local environmental vagaries (Sternberg and Kennard 2013). This concept is particularly interesting when considering invasive species (Casal 2006), where non-native species must possess certain traits acquiescent to the local conditions for successful establishment (Ruesink 2005; Dudgeon et al. 2006). For those invasive freshwater fish species recorded in PNG, we attempt to elucidate the characteristics that have allowed them to thrive in environments outside their natural range. In doing so, we utilised the FishBase (www.fishbase.org) and FAO Fisheries and Agriculture (http://www.fao.org/fishery/dias/en) websites (accessed August 2020), to produce a summary of the physical and biological traits for each species, to understand how each may have become established in PNG Rivers. Of the listed invasive freshwater fish species, it is difficult to determine which poses more ecological risk to natural fish populations and river habitats (see Casal 2006); to do so would require a specific and detailed biogeographic assessment of river catchments, including assessment of the underlying environmental conditions,

Table 1 Fish species in river regions within PNG

Scientific name	Common name	Originating location (date first recorded PNG)#	Picture of specimen	Summary of biological traits
Anabas testudineus	Climbing perch*	Indonesia (1985)	 Photo—Waltham, N.—James Cook University	Omnivore feeding on aquatic plants, detritus, fish, insects, crustaceans; Fresh to brackish waters, slow or still flowing waters; Migrates overland to new waterhole, specialised respiratory structure above gills to breath air, aestivates in mud during dry season; Spines on gill plate which can lodge in throat of predators; and Grows to 25 cm, 0.8 kg
Aplocheilus panchax	Blue panchax	Unknown	 Photo—Appleby, C—Fishbase	Occurs in lowland wetlands to estuaries and peats. Found in ponds and ditches canals, reservoirs and mangrove creeks Prefers clear water in areas with dense growth of rooted or floating macrophytes. Sometimes occurring in hypersaline waters Feeds mainly on insect Grows to 10 cm
Barbodes binotatus	Spotted barb	Unknown	 Photo: Baird, I. G.—Fishbase	Occurs sealevel to at least 2000 m above sea level, commonly below waterfalls in streams and stagnant water bodies Mid-water to benthic dweller in shallow water Feeds on zooplakanton, insect larvae and plants Considered harmless Grows to 20 cm

Table 1 (continued)

Scientific name	Common name	Originating location (date first recorded PNG)[#]	Picture of specimen	Summary of biological traits
Barbonymus gonionotus	Java barb	Malaysia (1970)	 Photo: Balaram Mahalder, Indonesia	Freshwater; benthopelagic; potamodromous; Feeds on plant matter, but also macroinvertebrates May travel upstream during rain and river flow to spawning habitats; and Grows to 45 cm
Channa striata	Snakehead	Unknown	 Photo: Reyes, R. B.—FishBase	Aggressive, territorial, ambush predator (eats fish, frogs, snakes, insects, crustaceans, birds, mammals); Found in slow flowing waters, swamps; Migrates overland to new waterhole, specialised respiratory structure above gills to breath air, aestivates in mud during dry season; and Grows to 1 m, 3 kg
Clarias batrachus	Walking catfish	Unknown	 Photo: Baird, I.—University of Wisconsin-Madison—Department of Geography	Aggressive, territorial, ambush predator (eats fish, frogs, snakes, insects, crustaceans, birds, mammals); Found in slow flowing waters, swamps; Present in Western Providence and found in artisanal fisheries Migrates overland to new waterhole, specialised respiratory structure above gills, aestivates in mud during dry season; and Grows to 47 cm, 1.2 kg

Table 1 (continued)

Scientific name	Common name	Originating location (date first recorded PNG)#	Picture of specimen	Summary of biological traits
Cyprinus carpio	Common carp	Unknown	 Photo: Lorenzoni, M.—Università di Perugia—Dipartimento di Biologia Animale ed Ecologia	Freshwater; brackish; benthopelagic; Adults inhabit warm, deep, slow-flowing and still waters such as lowland rivers and large, well vegetated lakes; Thrive in large turbid rivers; Adults often undertake considerable spawning migration to suitable backwaters and flooded meadows; Both adults and juveniles feed on a variety of benthic organisms and plant material; Females are known to lay more than a million eggs in a season; and Grow 120 cm, 41 kg, 38 years old
Gambusia affins	Mosquitofish	Unknown (1930)	 Photo—Aland, G, 2008, FishBase	Freshwater; brackish; benthopelagic; Pelagic and surface predatory fish, feeds on zooplankton, small insects and detritus; Adults inhabit standing to slow-flowing water; most common in vegetated ponds and lakes, backwaters and quiet pools of streams; and Grows to 5 cm

Table 1 (continued)

Scientific name	Common name	Originating location (date first recorded PNG)[#]	Picture of specimen	Summary of biological traits
Monopterus albus	Asian swamp eel	Unknown	 Photo: Shao, K. T.—Fishbase	Found in hill streams to lowland wetlands, ephemeral waters, but also rivers and estuaries Benthic and can burrow in moist sediment in dry season Nocturnal predators devouring fish, worms, crustceans and other aquatic animals Protandrous hermaphrodites, obligate air-breathing species Grows to 100 cm, commonly 40 cm
Neolissochilus hexagonolepis	Copper mahseer	Nepal (1993)	 Photo: Laloo, B, India	Freshwater; benthopelagic; potamodromous; Occupy's fast flowing regions over gravel, stone benthos; Feeds on plant material, but also macroinvertebrates; Migrates upstream to freshwater regions to spawning; Males mature at approx. 9 cm; and Grows to 120 cm, 11 kg
Oncorhynchus mykiss	Rainbow trout	New Zealand (1952)	 Photo: (McDowall 1990)	Marine; freshwater; brackish; benthopelagic; anadromous; Feed on plants, macroinvertebrates and small fish; Male mature 2 years, females at 3 years; Lay eggs in stream sediments, freshwater regions; and Grows to 120 cm, 24krs, and 11 yr old max

Table 1 (continued)

Scientific name	Common name	Originating location (date first recorded PNG)$^{\#}$	Picture of specimen	Summary of biological traits
Oreochromis niloticus	GIFT tilapia*	Unknown	 Photo: Stiassny, JIJ, Fishbase	Freshwater habitats like lakes, rivers, lakes, brackish but not pure saltwater tolerant Feed on phytoplankton and benthic algae, also insects Mouthbrooder—female carries up to 200 eggs in mouth where larvae hatch, males dig pits in shallow water Grows to 60 cm, 4kgs
Oreochromis mossambicus	Mozambique tilapia	Malaysia (1954)	 Photo—Cumming, G, North Queensland	Occurs in fresh, brackish and marine waters, prefers slow to standing water; Seasonally migrates across floodplains; Reported impacts included competition for food, habitat, inhibition of spawning in native species; Occupies poor water quality, and contributes to high turbidity; Maternal mouthbrooder, highly fecund; and Grows to 39 cm, 1.1 kg, 11 years old
Osphronemus gouramy	Giant gourami	Unknown (1957)	 Photo—Aquarium Tropical du Palais de la Porte Dorée http://www.palais-portedoree.org/	Aggressive, feeding on fish, crustaceans, insects, some plant and detritus; Fresh to brackish waters, slow or still flowing, lowland streams, often in turbid vegetated waters; Migrates overland to new waterhole; Specialised respiratory structure above gills to breath air, aestivates in mud during dry season; and Grows to 70 cm

Table 1 (continued)

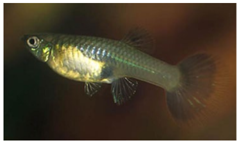
Scientific name	Common name	Originating location (date first recorded PNG)[#]	Picture of specimen	Summary of biological traits
Piaractus brachypomus	Pacu	Malaysia (1995)	 Photo—Lovshin, L. L	Freshwater species, occurs in lowland rivers and lakes but migrates in large schools up tributary rivers into flooded forests; very powerful swimmer; Powerful jaws with large well-developed teeth; grows to 85 cm and 20 kg; Native range tropical/equatorial; 23° N—11° S; Amazon and Orinoco River; Known to bite humans; and Grows to 88 cm, 25 kg, 28 years old
Poecilia reticulate	Guppy	Unknown	 Photo—Jensen, J 2000, FishBase	Freshwater; brackish; benthopelagic; Found in various habitats, ranging from highly turbid water in ponds, canals and ditches at low elevations to pristine mountain streams at high elevations; Feeds on zooplankton, small insects and detritus; Males mature at 2 months and females at 3 months of age; and Grows to 5 cm
Prochilodus lineatus	Streaked prochilod	Brazil (1996)	 Photo: Timm, Cláudio Dias, Universidade Federal de Pelotas (UFPel)—Faculdade de Veterinária	Freshwater, benthopelagic, potamodromous; Males thought to remain near nest; and Grows 80 cm, 7.2 kg

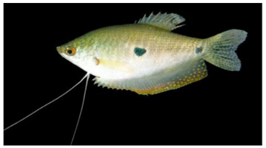
Table 1 (continued)

Scientific name	Common name	Originating location (date first recorded PNG)[#]	Picture of specimen	Summary of biological traits
Salmo trutta	Brown trout	Australia (1949)	 Photo: Scarola J., New Hampshire Fish and Game Department	Marine, freshwater, brackish, pelagic-neritic, anadromous, prefer cold water in higher catchment regions; Feeds on aquatic and terrestrial insects, small fish; Spawning usually in swift flow regions of rivers; Migration to lower river catchments, outlets, to spawn; Spawning occurs more than once each year; and Grows 140 cm, 50 kg, 35 years old
Salvelinus fontinalis	Brook trout	Australia (1974)	 Photo: Scarola J., New Hampshire Fish and Game Department	Marine; freshwater; brackish; demersal; anadromous; Occurs in clear, cool, well-oxygenated creeks, small to medium rivers, and lakes; Feeds on macroinvertebrates, small fish; Lay eggs in gravel of channels; and Grows to 86 cm, 8 kg, 24 years old
Schizothorax richardsonii	Common snowtrout	Nepal (1995)	 Photo: Johnson, J.A., Wildlife Institute of India	Freshwater species, demersal, potamodromous; Adults inhabit maintain streams and rivers; Herbivores feeding on algae, aquatic plants and detritus; and Grows to 60 cm

Table 1 (continued)

Scientific name	Common name	Originating location (date first recorded PNG)#	Picture of specimen	Summary of biological traits
Tilapia rendalli	Red-breast tilapia	Unknown	 Photo: Seegers, L.—Royal Museum for Central Africa, Tervuren, Belgium	Freshwater; brackish; benthopelagic; Prefer quiet, well-vegetated water along river littorals or backwaters, floodplains and swamps; Juveniles feed on plankton. Adults feed mainly on higher plants and also algae, insects and crustaceans; Prefers a sloping spawning ground near the marginal fringe of vegetation, builds nest in shallow water where both parents guard the eggs and young; and Grows 45 cm, 2.5 kg, 7 years old
Tilapia mariae	Spotted tilapia	Unknown	 Photo—Waltham, N; James Cook University	Freshwater; brackish; demersal; Live in still or flowing waters in rocky or mud-bottom areas; Feeds on plant material; Parents prepare nest site on logs, leaves and other debris; Eggs guarded by parents and hatch in 1 to 3 days; and Grows 33 cm, 1.3 kg
Tor putitora	Golden mahseer	India (1995)	 Photo—Bakalial, B., Dibrugarh University, India	Freshwater, benthopelagic, potamodromous; Omnivorous —ish, zooplankton, dipteran larvae, plant material; Breeds over gravel and stone stream reaches, returning to higher altitudes; and Grows to 2.75 m, 54 kg

Table 1 (continued)

Scientific name	Common name	Originating location (date first recorded PNG)#	Picture of specimen	Summary of biological traits
Trichogaster pectoralis	Snakeskin gourami	Malaysia (1954)	 Photo—Reyes, R. B.—FishBase	Found in shallow sluggish or standing-water habitats with a lot of aquatic vegetation; Feeds on aquatic plants and detritus; Specialised respiratory structure above gills capable of breathing air directly from the atmosphere and to migrate across flood-plains; Males provide some parental care towards eggs; and Grows to 25 cm, 0.5 kg
Trichogaster trichopterus	Three-spot gourami	Unknown	 Photo—Ratmuangkhwang, S.; Thailand	Feeds on zooplankton, aquatic insects, plant material and detritus; Occupies heavily vegetated, shallow low flow to standing freshwater; Specialised respiratory structure above gills to breath air on land; Tolerant of poor water quality; and Grows to 15 cm
Xiphophorus helleri	Swordtail	Mexico (1935)	 Photo—McDowall, R 1998, FishBase	Freshwater; brackish; benthopelagic; Adults are found mainly in rapidly flowing streams and rivers, preferring heavily vegetated habitats; Feed on worms, crustaceans, insects and plant; Female produces 20 to 200 young after a gestation period of 24 to 30 days; Can undergo sex reversal (from female to male) under certain environmental conditions; and Grows to 14 cm

*Indicates species already present in Australian waters on northern most islands in the Torres Strait. #Originating location of each species according to FAO Fisheries and Aquaculture Department (http://www.fao.org/fishery/introsp/search) and date first recorded in Papua New Guinea, if known, in parentheses risks and interactions between native and invasive species (Olden and Poff 2004; Keck et al. 2014).

Of the invasive freshwater fish species listed in Table 1, the species of most concern are those that display high aggression towards native fish. As a case in point, the snakehead (*Channa striata*) is a territorial, ambush predator that will eat a diverse range of prey including fish, crustacean and herpetofauna (Courtenay and Williams 2004). The snakehead has a highly specialised phenotype, including a labyrinth organ (a common feature of the invasive fish species listed in Table 1). This organ effectively allows a species to surface respire (i.e., breath air on land), which can be beneficial during terrestrial locomotion, enabling it to relocate from one water hole to another when conditions become unfavourable. This terrestrial locomotion may assist in the range extension of invasive species, spreading through more coastal wetland environments.

Another interesting introduction to PNG Rivers is the black mangrove cichlid or mozambique tilapia (*Oreochromis mossambicus*). This species was intentionally introduced into PNG river systems in the mid 1950's to provide sustenance for remote communities and has become an important source of protein in these regions (Glucksman et al. 1976). This intentional introduction has been exacerbated by the unintentional escape of tilapia from aquaculture ponds (Powell and Powell 1999). Data from Australia, where *O. mossambicus* is now a widespread pest fish, has shown that this species disrupts successful breeding of native fish species (Doupe et al. 2009). It is unknown whether *O. mossambicus* afflicts the same disruption to breeding in native PNG freshwater fish. Since the 2000's one of the main target species for inland aquaculture in PNG was GIFT tilapia (*O. niloticus*) (Sammut et al. 2021). *O. niloticus* has since entered water systems due to poor maintenance of fishponds or released voluntary by people in villages, with *O. niloticus* likely more prevalent in water systems in some parts of PNG (Smith et al. 2016). Eradication of tilapia from PNG river catchments is challenging, it presents a social dilemma for government authorities: a decision that would need to consider food security, along with biodiversity and conservation protection.

For the other freshwater fish species listed in Table 1, there is currently no data available that has specifically examined their ecological consequences on PNG freshwater ecosystems. For example, the golden masher (*Tor putitora*) and the snow trout (*Schizothorax richardsonii*) have only recently been sighted in the head waters of the Fly River catchment (A. Storey per. comms.) and may occur more broadly in other altitude river systems however it is difficult to know the full extent given the remoteness of some river systems. The exact incursion pathway leading to both these species occurring in the head waters of the Fly River catchment is uncertain.

A new frontier of freshwater fish invasion

The Torres Strait (the Straits) are a chain of approximately 300 islands that spread the entire 200 km stretch of water between PNG and Cape York in northern Australia (Fig. 1). During times of lower sea levels, approximately 5 million years before present, the Straits formed part of a land bridge between PNG and Australia. This land bridge was an important geological feature and explains the genetic similarity of several freshwater species that are found in southern PNG and northern Australia (McGuigan et al. 2000). At present sea levels, the proximity of the northern Torres Strait islands to PNG means they may become

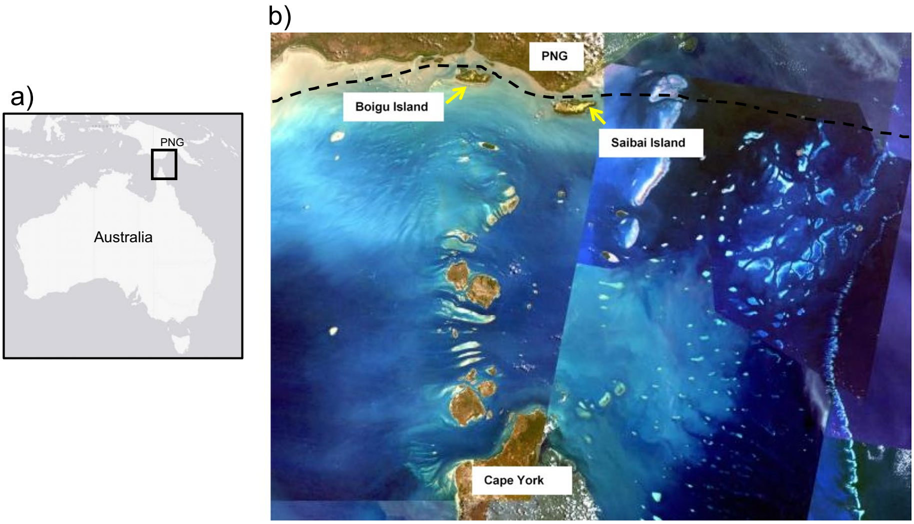


Fig. 1 Location map of **a** Australia and Papua New Guinea (PNG); and **b** Torres Strait (including Boigu and Saibai Islands), the island chain separating Cape York (Australia) and PNG. Dashed line indicates the approximate Australian Protection Zone border with PNG

a conduit for fish incursions into the pristine freshwater wetlands and rivers of northern Australian mainland.

Unfortunately, some invasive freshwater fish species known to occur in PNG have already reached the outer most islands of the Straits (Hitchcock 2008; Waltham et al. 2014, 2018). On both Boigu and Saibai Islands, located four kilometres from the PNG coastline, the climbing perch (*Anabas testudineus*) continues to be recorded in the wetland swamps (Waltham et al. 2018). *Anabas testudineus* is native to SE Asia, from India and spread to western Indonesia (Khatun et al. 2019) and has likely been brought to Papua Province of Indonesia (the western part of New Guinea) with the transmigration of people across Indonesia (Hitchcock 2008). This species is regularly traded by villagers as a food source, and it is through this anthropogenic movement that *A. testudineus* is believed to have been transported to new river catchments (Hitchcock 2002). Like snakeheads, climbing perch possess a labyrinth organ and, therefore, the capacity for surface respiration (Davenport and Matin 1990). Another advantageous feature of climbing perch is a highly mobile operculum and strong spines, which assist with terrestrial locomotion particularly during the wet season (Waltham et al. 2014), and enables the ability to climb, as the name suggests, over or past obstacles that would be a barrier to or restrict movement of other fish species (Davenport and Matin 1990). This adaptation, which allows terrestrial locomotion, effectively means that *A. testudineus* is capable of colonising new locations (e.g., isolated wetlands areas) under its own means (Waltham et al. 2014). This is the likely invasion pathway for this species into southern PNG (Storey et al. 2002).

The climbing perch has a main defence mechanism: if swallowed by a large predator, such as a fish or bird, it will splay its' strong gill cover outwards, locking it in place and lodging in the throat or stomach of the predator. Birds that have a diet which includes fish, such as pelicans and cormorants, have been observed to choke on climbing perch in this manner (Hitchcock 2008), as have other fish and reptile species (Storey et al. 2002). Further, climbing perch have several adaptations that make them tolerant to a wide range of environmental conditions, including an accessory air-breathing organ on the dorsal area behind their head, allowing them to tolerate low dissolved oxygen concentrations and to survive out of water (reportedly up to 6 days) (Allen 1991). It is also thought that this species will burrow into the mud of drying wetlands and aestivate during the dry season until water returns (Das 1927). In addition, although considered a freshwater species, climbing perch can tolerate hypersaline wetland waters up to 75 salinity (Waltham et al. 2014). These adaptations make this freshwater fish species very tolerant and hardy, demonstrating the serious risk it poses should this species reach the near-pristine freshwater ecosystems in northern Queensland.

In 2022, the GIFT tilapia (*Oreochromis niloticus*) was captured on Saibai Island, which had not been previously recorded during the 2014 surveys (Waltham et al. 2014). This recording was not a single individual, but there was a school of tilapia caught. Discussions with Rangers confirmed that this species was known in the wetlands on the island for the 12mths prior to this documentation. Whether this species was released on the island, swam across the narrow waters between Saibai and PNG, or was washed over during large flood plumes is unclear. This new recording confirms the need for a close check of the wetlands to not only understand the impacts that these invasive species have on local native fauna, but to be proactive should other invasive fish species establish on these islands, adjacent to PNG.

Border protection in Australia

A Treaty between Australia and the Independent State of Papua New Guinea concerning Sovereignty and Maritime Boundaries in the area between the two Countries, including the Torres Straits, was brought into force 15 February 1985. This Treaty captures the agreed position of each Nation with respect to the importance of protecting the traditional way of life and livelihoods, protecting the marine environment and conservation and management of fisheries resources. Specifically, Article 14 (Protection of fauna and flora) outlines that each Party shall, in the vicinity of the Protection Zone, use its best endeavours to: (a) identify and protect species of indigenous fauna and flora that are or may become threatened with extinction; (b) prevent the introduction of species of fauna and flora that may be harmful to indigenous fauna and flora; and (c) control noxious species of fauna and flora. Further, the Treaty also outlines that a Party may implement within its area of jurisdiction measures to protect species of Indigenous fauna and flora which are or may become threatened with extinction. It also states that Parties shall as appropriate and necessary exchange information concerning species of Indigenous fauna and flora that are or may become threatened with extinction and shall consult on the measures that each may take to give effect to species protection. To this end, the Treaty is clear with the intent to manage the risk of invasive species from PNG reaching Australian waters through the Torres Straits (source http://www.austlii.edu.au/au/other/dfat/treaties/1985/4.html).

To regulate the spread of invasive fish across the Torres Strait, many of these pest species have been declared noxious under the Land Protection Act 2002. This declaration is an important step in protecting Australia from further incursions of invasive freshwater fish. Managing pests is also a key objective of the Queensland State Government and was reflected in the Queensland State Pest Management Strategy (the Strategy). The Queensland Government has an *Operational Strategy for the Control of Pest Fish in Queensland Freshwaters 2011–2016* (DEEDI 2011) where the primary goal was providing a framework for preventing the spread of existing pest fish. The Strategy made specific reference to the Torres Strait as a conduit for the invasion of pest fish into Queensland. Explicitly mentioned in the Strategy as species of concern due to their aggressive nature and ability to colonise wetlands through terrestrial locomotion, are climbing perch and snakeheads. Additional invasive species listed in the Strategy that are present in PNG are the walking catfish (*Clarias batrachus*), gambusia (*Gambusia holbrooki*), pacu (*Piaractus brachypomus*) and tilapia (*Oreochromis mossambicus*)—all other species recorded in PNG have not yet been included on this list. Under the Quarantine Act 1908, DAFF Biosecurity (Australia) has the responsibility for preventing invasive fish introductions into Australian waters, although their mandate does not include control once they arrive. DAFF Biosecurity (Australia) have staff located on most Torres Strait Islands, with their role to prevent any declared species, including freshwater fish, from reaching Australia via human transportation.

An important aspect within the Strategy is the recognition that prevention of pest fish can be achieved through community engagement. In fact, community empowerment is a core feature in three of the six priority actions in the Strategy. Given the low population density of the Torres Strait and proximity to mainland Australia, community education in pest fish identification and mitigation is achievable. The concern is not that these invasive fish will traverse the region and spread to the northern parts of mainland Australia naturally, rather the ease and regularity that the island communities move between islands (using personal watercrafts), creates a risk in translocating pest fish throughout the Straits. The ability of snakeheads and climbing perch to air breathe

Fig. 2 **A** Traditional Rangers completing surveillance surveys for invasive fish species in wetlands on Saibai and Boigu Islands of the Torres Straight; **B** Remains of climbing perch (*Anabas testudineus*) in wetland; **C** Undertaking community education awareness information sessions in local halls; and **D** Education program within schools to familiarise students with invasive fish identification

means these fish species could easily survive in the hull of vessels, or in a bucket or basket, to later be released at another location, such as Cape York, Australia (Waltham et al. 2014).

A community education program has been established through the Torres Strait Regional Authority Land and Sea Program (Waltham et al. 2014). Under this program, Torres Strait traditional owners are appointed as Land and Sea Rangers, an appointment requiring them to work closely with land holders, schools and community groups to achieve environmental outcomes, and to raise awareness of the importance of looking after country (Fig. 2). To date, Rangers on Boigu and Saibai islands have been trained to identify the invasive species listed in Table 1, and more broadly in wetland ecology and management. Under the auspices of the Ranger program, the Boigu and Saibai Island communities need to have the basic skills with which to distinguish invasive fish species from local species. Importantly, with this confidence in identification, the community will have the aptitude to immediately destroy invasive fish if caught in their local swamps (Waltham et al. 2014). The collective sum of community observation in the swamps will increase the capacity of surveillance campaigns for pest fish species and function as an early warning (see Simberloff 2009), for new invasive species threats. This activity is an important and necessary response; however, it does raise an important point that under the Treaty between the two nations, PNG has an obligation to advise Australia of any biosecurity threat to indigenous fauna and flora, and it must also exercise measures to control noxious species and their spread (Article 14).

In addition to community-based observation and physical detection of non-native fish species, the Torres Strait Regional Authority have implemented emerging technology for detecting invasive fish species through environmental DNA (eDNA): DNA that has been passively released into the environment through natural biological processes such as excretion, shedding of skin cells and hair, decay etc. (Valentini et al. 2009). Torres Strait Island Land and Sea Rangers have been trained in collecting water samples for subsequent eDNA analysis at the TropWATER eDNA laboratory, James Cook University. Since 2018, islands thought to be at greater risk of incursions, due to their proximity to PNG and to the Australian mainland, have been surveyed for the presence of eDNA of invasive freshwater fish species including climbing perch, snakehead and tilapia, with the aim of monitoring their current distribution for management purposes, or to prove continued absence of these species on each island. The implementation of new technologies such as eDNA detection methods (Jerde et al. 2011), will augment existing surveillance methods for invasive fish species, to monitor the continued absence of unwanted species and to provide early detection of new threats. Environmental DNA monitoring also contributes to capacity building of Rangers, raises awareness in the community on the threats that invasive fishes pose to the environment and empowers traditional owners to sustainably manage and benefit from their land. Results from eDNA sampling can comprise an early warning tool that can trigger further on-ground actions to prevent the establishment of invasive fish species in those islands.

Environmental DNA analyses of water samples collected from the wetlands on Boigu and Saibai Island detected the presence of climbing perch in the years 2018 and 2019 (Villacorta-Rath et al. 2019; Villacorta-Rath and Burrows 2020). The 2020 sampling campaign detected Mozambique tilapia eDNA at Saibai (Villacorta-Rath 2021), though a physical specimen was not observed for confirmation of the eDNA results. Snakehead eDNA has not been detected on either island (Villacorta-Rath 2021).

Importance of community engagement in border protection

The series of islands that form the Torres Strait make a distinct and geographically definable entry point for incursions of non-native fish into Australia. Boigu and Saibai Islands, given their proximity, must be the line in the sand for biological invasion from PNG towards Australia. The ability for these fish species to be spread past Boigu and Saibai Islands, reaching islands further south in the Torres Strait and subsequently into northern Australia, is unlikely to occur under their own locomotion—the distance to swim is too far. The risk of spreading further south and reaching northern Australia is, however, very possible with the assistance of anthropogenic translocation. A framework preventing fish arriving in Australia is currently in place, with Australian Biosecurity stations located on most islands in the Torres Strait, where inspection of goods and humans is undertaken to prevent the entry of invasive fish. The predominant risk outlined here relates to the community moving pest fish from island to island. We advocate that the most critical preventative action lies in continued training of Rangers in identification of invasive species and potential threats, implementation of new technologies such as eDNA detections and, importantly, the ongoing communication and education of the Torres Strait community. We also refer to the Treaty between both nations and the emerging biosecurity risk under Article 14, and the need for appropriate conservation management responses to protect northern Australia from invasive species.

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Declarations

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