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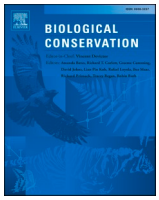

Perspective

Conservation challenges for the most threatened family of marine bony fishes (handfishes: Brachionichthyidae)

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ABSTRACT

Marine species live out-of-sight, consequently geographic range, population size and long-term trends are extremely difficult to characterise for accurate conservation status assessments. Detection challenges have precluded listing of marine bony fishes as Extinct on the International Union for Conservation of Nature (IUCN) Red List, until now (March 2020). Our data compilation on handfishes (Family Brachionichthyidae) revealed them as the most threatened marine bony fish family, with 7 of 14 species recently listed as Critically Endangered or Endangered. The family also includes the only exclusively marine bony fish to be recognised as Extinct – the Smooth handfish (*Sympterichthys unipennis*). Ironically, some of the characteristics that threaten handfishes with extinction have assisted assessments. Poor dispersal capabilities leading to small, fragmented populations allow monitoring and population size estimation for some shallow water species. Evidence that the Smooth handfish is now Extinct included no sightings over 200 years in an area subject to numerous scientific surveys, inferred shallow habitat and moderate abundance at time of original collection, and major habitat transformation through fishing, aquaculture, rising sea temperature, and urban development. Contemporary threats to extant handfish species include habitat degradation, introduced species, loss of spawning substrate, climate change, and demographic risks associated with small, fragmented populations. Multifaceted conservation efforts are needed, including addressing threats to habitat quality, bolstering wild population numbers, and implementing novel techniques to find and monitor populations. Expanded monitoring, including application of eDNA methods, represent critical steps towards overcoming the challenges in studying wild populations of rare marine species. Ongoing investigation will likely reveal numerous other threatened species for which little is known.

1. Introduction

Accurate reporting of the conservation status of marine fishes is generally extremely difficult, resulting in relatively few status assessments compared to other marine vertebrates and terrestrial animals (Reynolds et al., 2005). In addition to the usual monitoring challenges for rare species, search effort for marine species is limited by sea-state, vessel availability, and depth. For small, sea floor-dwelling marine animals, finding an individual can be akin to finding a needle in a haystack. This is no doubt a key reason for a lack of recognised extinctions in the marine realm (Edgar et al., 2017; McCauley et al., 2015; Reynolds et al., 2005), and high proportion of Data Deficient listings of marine species in the International Union for Conservation of Nature's (IUCN) Red List of Threatened Species.

Recent updates of the IUCN Red List have attempted to reduce this under-representation of marine threatened species, particularly fishes. The Red List now covers 20,341 of 35,423 described freshwater and marine fish species (Superclass Pisces; IUCN, 2020), of which 2721 (13% of assessed species) are considered threatened, and 74 are listed as Extinct or Extinct in the Wild. Until the 2020 update, none of the Extinct species was a marine bony fish.

The recent update covered all 14 species in the Family Brachionichthyidae (handfishes), a small group of marine fishes with distribution restricted to south-eastern Australia. Before this Red List update,

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only a single species from this family, the Spotted handfish (*Brachionichthys hirsutus*) had been assessed. Originally assessed in 1996, it was one of the first marine fishes to be listed as Critically Endangered, the highest level of extinction risk (Hudson and Mace, 1996). Excluding families that have not yet been completely assessed (and those in which only a single species has been assessed), the handfishes are now the most threatened marine bony fish family included on the IUCN Red List (Fig. 1), with 57% of its species listed as Critically Endangered, Endangered or Extinct. Brachionichthyidae is the 11th most threatened fish family containing largely marine members (only shark and ray families have a greater proportion of threatened members, Fig. 1). The primary goals of this study were to review the state of knowledge on the handfishes, including characteristics that have contributed to their extreme vulnerability, document the information basis for the Red List assessments, and discuss future directions for the conservation of handfishes and other small and inconspicuous marine species.

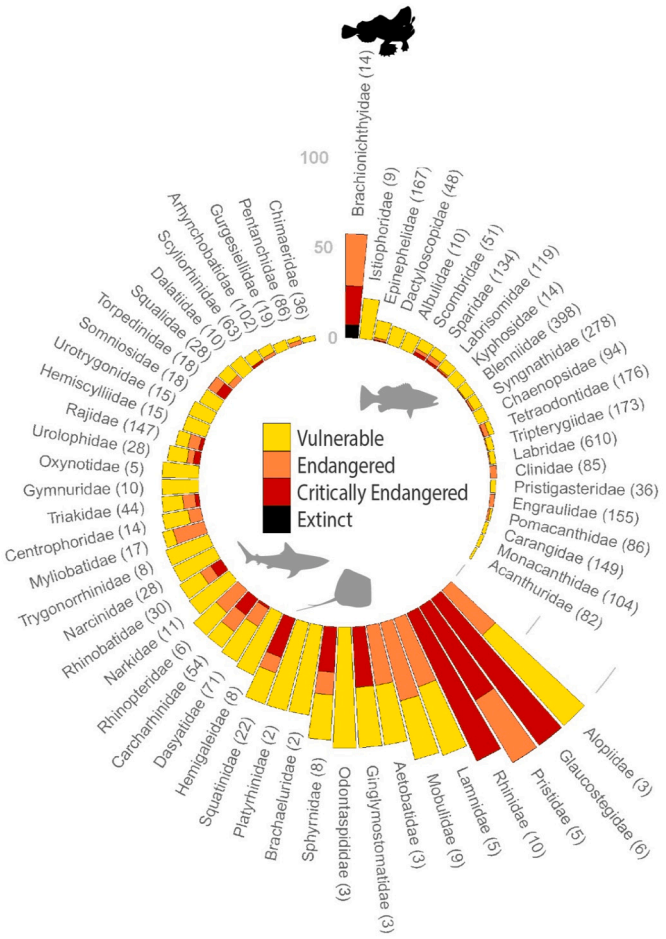

Fig. 1. The percentage of threatened (and Extinct) species in all fully assessed predominantly marine fish families (i.e. with more than 50% classified as marine). Four families with only a single assessed member listed as threatened are not included, and all assessed families with no threatened members (228) are also not shown. Families in the class Chondrichthyes (sharks and rays) are shown on the left and lower portions of the plot, and in the class Actinopterygii (bony fishes) on the top right, colour ranked within family by the total percentage of members classified in IUCN categories CR (Critically Endangered), EN (Endangered), VU (Vulnerable). The Smooth handfish (the only exclusively marine fish classified as Extinct) has been included in the proportion threatened for the family Brachionichthyidae (shown as black). The number of assessed species in each family is shown in parentheses after the family name. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1.1. The handfishes (Family Brachionichthyidae)

Handfishes are relatively small (60–151 mm) marine fishes with distributions restricted to the temperate waters of south-eastern Australia, predominantly concentrated in Tasmania (Last and Gledhill, 2009). The fossil record documents handfishes as well represented in the Eocene period (from 56 to 33 million years ago) in the Monte Bolca area of Italy, indicating that the family once occupied a vastly different, and likely larger, range of marine realms (Carnevale and Pietsch, 2010). Their very small present-day range in south-eastern Australia has been suggested as a residual distribution resulting from a range shift between West Tethyan and Indo Australian Archipelago hotspots (Carnevale and Pietsch, 2010).

Brachionichthyidae are the most speciose of the marine fish families entirely endemic to Australia, with almost half of the species exhibiting the narrowest geographic distributions of any of the 4000+ fish species found throughout the region (Bruce et al., 1998; Pogonoski et al., 2002; Fig. 3). The family comprises of 14 species (Last and Gledhill, 2009), most of which are poorly studied, particularly those restricted to greatest depths. The phylogenetic lineage has changed little morphologically since the early fossil records (Edgar et al., 2017; Last and Gledhill, 2009); they are demersal, generally cryptic in nature, with pectoral fin extremities reminiscent of human hands – hence their name (Carnevale and Pietsch, 2010; Whitley, 1949). Lacking a swim bladder, they prefer to use their 'hands' to 'walk' across the sea floor, rather than swim (although can do so over short distances when disturbed).

In the marine realm, the majority of listed threatened fishes belong to the class Chondrichthyes (sharks and rays), often because of life history characteristics that make them vulnerable, such as slow growth rates, delayed maturity, and smaller clutch/brood sizes (Musick, 1999). To date, no species of shark or ray is listed as Extinct, although several species have been extirpated from large parts of their range, and one species (the Clown wedgefish, *Rhynchobatus cooki*) is listed as Critically Endangered (Possibly Extinct) (Dulvy and Forrest, 2009; Simpfendorfer et al., 2011). Sawfishes (Pristidae), wedgefishes (Rhinidae) and giant guitarfishes (Glaucostegidae), which are targeted for their high-value fins, are among the most threatened families within the sharks and rays as well as across marine fish families of the world (Kyne et al., 2019).

2. Extinction risk of handfish species

2.1. Extinct – no reasonable doubt that the last individual has died

In 2020, the Smooth handfish (*Sympterichthys unipennis*), an Australian endemic marine species not seen in over 200 years, was the first marine bony fish worldwide to be formally classified as Extinct. This

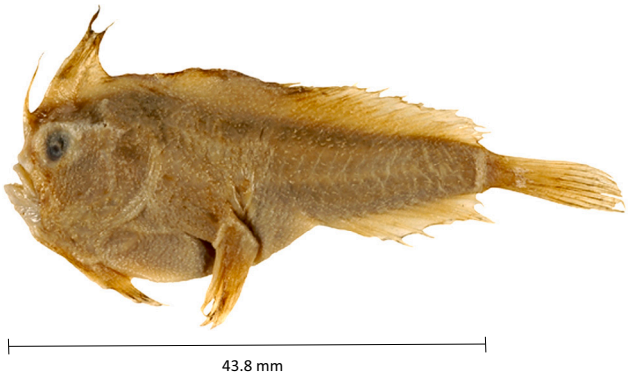

Fig. 2. The Extinct Smooth handfish, *Sympterichthys unipennis* - MNHN A 4630, holotype, 43.8 mm SL, preserved specimen.
(Photo: Australian National Fish Collection, CSIRO.)

species is known from only the holotype individual (Fig. 2) obtained by French zoologist François Péron during an expedition to Australia in the early 1800s (Last and Gledhill, 2009). It is among the first endemic fish species described from Australia. This species was likely impacted by mortality through habitat change (via the scallop fishery operating in the region until 1967; Edgar and Samson, 2004), fisheries bycatch, and climate change, combined with the general life history characteristics of handfishes that increase their vulnerability and susceptibility to rapid population declines (e.g. restricted dispersal).

Since the first Red List was published in 1964, 878 species have been classified as Extinct, and none of these were marine bony fishes until 2020. This is likely an artefact of scarcity of knowledge of the marine realm and consequent underestimated recognition of extinction and extirpation (Edgar et al., 2005; Mora et al., 2011; Powles et al., 2000). According to Red List guidelines, a species can only be listed as Extinct when exhaustive surveys have been undertaken in all known or likely habitat throughout its historical range, and there is "no reasonable doubt that the last individual has died" (IUCN, 2019). This subjective benchmark provoked considerable discussion during Red List assessment and review of the threat status category for the Smooth handfish, with ongoing debate among fish experts as to the extent of doubt.

Doubt is atypically low for the Smooth handfish compared to other fish species that have not been seen for many years because: (1) the species was presumably common when collected as it was one of the first 25 fish species observed and formally named from the continent of Australia, (2) the French naturalists who collected the type specimen were only able to deploy simple sampling gear (seine net, hand dip net, baited line) in shallow (<8 m) habitats that have been extensively sampled over the past century, and (3) shallow habitats across the south-eastern Tasmanian region where the initial specimen was likely collected, have transformed with major loss of biodiversity (Edgar and Samson, 2004). It is notable that the 20 other fish species lodged in the National Natural History Museum, Paris, after collection on the same voyage, are all common shallow-water species, other than the Critically Endangered Spotted handfish, which also has a small range but with >235 subsequent observations (Atlas of Living Australia website: https://bie.ala.org.au/species/urn:lsid:biodiversity.org.au:afd.taxon:fa0c82af-92b0-4988-82f5-c0a261ac6fb5#overview). If the Smooth handfish had been one of the first terrestrial mammal, bird, reptile, or plant species discovered in Australia and not seen for 200 years, rather than a marine species, extinction would have been recognised many years ago.

More broadly, due to difficulties associated with sampling under the sea surface, marine fish extinctions are likely underestimated (Edgar et al., 2005; Roberts and Hawkins, 1999). The Galápagos damselfish (*Azurina eupalama*), which is currently listed as Critically Endangered (Possibly Extinct), has not been seen since the 1980s when common. The New Zealand Grayling (*Prototroctes oxyrhynchus*) is listed as Extinct but is not considered a fully marine species as it largely occurs in freshwater and estuarine habitats. It is likely that other small cryptic fishes with highly localised ranges (including in the families Gobiidae and Blenniidae) have also disappeared without documentation or official recognition.

2.2. Critically Endangered – facing an extremely high risk of extinction

The Spotted handfish (*Brachionichthys hirsutus*), Ziebell's handfish (*Brachiopsilus ziebelli*), and Red handfish (*Thymichthys politus*) are facing an extremely high risk of extinction and are listed as Critically Endangered. All three species were previously more widely distributed, but each have undergone severe population declines in the last 35 years. All are known from small, fragmented populations, with Ziebell's handfish not seen since ~2005. The Spotted handfish is restricted to the urbanised Derwent Estuary and associated waterways in fragmented pockets with fewer than 2000 mature individuals remaining. Less than 100 mature Red handfish individuals are currently known to exist, from only two small patches of rocky reef in Frederick Henry Bay, near Hobart.

2.3. Endangered – facing a very high risk of extinction

Four out of the remaining 13 brachionichthyids are now classified as Endangered (i.e. facing very high extinction in the wild; IUCN, 2012); the Cockatoo handfish (*Pezichthys amplispinus*), Narrowbody handfish (*Pezichthys compressus*), Pink handfish (*Brachiopsilus dianthus*), and Moulton's handfish (*Sympterichthys moultoni*). Of these, only the Pink handfish is a shallow water species (and also restricted to Tasmania), with the other three deeper water species found mostly in south-eastern mainland Australia in areas overlapping with trawl and dredge fisheries (Table 1).

2.4. Data Deficient – inadequate information to make a direct, or indirect, assessment

Five of the extant handfish species are known from fewer than five specimens/records, and seven species have not been seen for between 15 and 36 years (see Table 1 and Fig. 3). Five species are listed as Data Deficient, with assessment of population status not possible with current available information: Humpback handfish (*Brachiopsilus dossenus*), Eltanin handfish (*Pezichthys eltanini*), Longfin handfish (*Pezichthys macropinnis*), Eyelash handfish (*Pezichthys nigrocilium*) and Warty handfish (*Thymichthys verrucosus*). There is some taxonomic uncertainty with the Warty handfish, which is represented in museum collections by multiple morphs and may constitute an unresolved species complex (Last and Gledhill, 2009). Further sampling is required to be able to resolve the nature of this variability. Of the Data Deficient species, only the Warty and Humpback handfish have been found in <25 m (although both have ranges extending to over 200 m depth). More sampling effort is needed in deep water to adequately assess distributions and population trends. Given the high percentage of handfishes listed in threatened categories, some of these Data Deficient species are probably also threatened as well.

2.5. Least Concern – the Australian handfish

Red List assessments regard only a single handfish species – the Australian handfish (*Brachionichthys australis*) – as 'Least Concern', meaning that it does not reach the quantitative thresholds to qualify as Threatened or Near Threatened. It has the widest distribution and presumed largest population size of all handfish species (from southern Queensland to south eastern Tasmania). Although taken as bycatch in fisheries that dredge the sea floor in parts of its range, population declines are not considered to be approaching 30% at a global level at this time. Regardless, estimation of population trends is extremely difficult, and this handfish could be declining at an unknown level.

3. Threats

Brachionichthyids have relatively few eggs (~50–150 for the three species for which this is known) and no planktonic larval stage, instead hatching as fully metamorphized juveniles that are inferred to directly recruit; consequently, dispersal is severely limited. Limited capture-mark-recapture work and genetics for the most extensively studied of the species, the Spotted handfish (*B. hirsutus*), also suggests very limited adult movements and genetic isolation between local populations, even within the same estuary (Bessell, 2018; Lynch et al., 2020; Lynch et al., 2019).

The combination of poor dispersal potential with highly localised distributions and generally low population numbers means that they are highly susceptible to local disturbance events and broader environmental change (Bruce et al., 1998; Last and Gledhill, 2009; Last et al., 1983). These threats are compounded with a number of significant human-mediated threats; declines in benthic habitat quality due to

Table 1
Threats to handfishes (IUCN Red List categories: LC: Least Concern, DD: Data Deficient, EN: Endangered, CR: Critically Endangered, EX: Extinct). General threats occur across all species, and include warming seas associated with climate change particularly for shallow water species (although impacts on deep water species are unknown), limited dispersal capabilities, small subpopulations and impacts from invasive species, sea floor fishing activities, habitat loss and pollution; as assumed on the basis of those impacting better-studied species. Shallow water species are considered as those that live primarily in <20 m (note, SA: South Australia, TAS: Tasmania, NSW: New South Wales, VIC: Victoria).

Species	IUCN Listing	Current extent	Status	# localities (specimens observed)	Depth range (m)	Threats
Brachionichthys australis (Australian handfish)	LC	S & E AUS (incl TAS)	Declines not yet detected	Several localities	18–277	Degradation of soft-bottom habitat from destructive bottom fishing practices, also mortality from bycatch.
Brachionichthys hirsutus (Spotted handfish)	CR	TAS	Declines detected 1980s	Several localities (<2000 individuals)	1–60	Declines in habitat quality: predation on preferred spawning substrate by Northern Pacific seastar, historical scallop dredging, pollution, marine moorings (urban development & heavy metals)
Brachiopsilus dianthus (Pink handfish)	EN	SE TAS, 3 localities	Last recorded in 1999	3 localities (5 specimens)	15–38	Habitat degradation, bycatch (scallop fishery), pollution, and invasive species
Brachiopsilus dossenus (Humpback handfish)	DD	SE AUS from VIC & TAS	Last recorded in 1984	3 localities (3 specimens)	20–226	Specific threats are poorly understood.
Brachiopsilus ziebelli (Ziebell's handfish)	CR	TAS	Last recorded in 2005	Several localities	3–20	General threats, and possibly historical shellfish fishing impacts, pollution, spawning habitat degradation, invasive species, habitat loss, and potentially the illegal aquarium trade.
Pezichthys amplispinus (Cockatoo handfish)	EN	SE AUS	Last recorded in 1996	5 localities (7 specimens)	74–121	Prolonged trawl and dredge effort within its range possibly causing both habitat destruction and direct mortality.
Pezichthys compressus (Narrowbody handfish)	EN	SE VIC	Last recorded in 1996	2 localities (2 specimens)	112–218	Prolonged trawl and dredge effort within its range possibly causing both habitat destruction and direct mortality.
Pezichthys eltanini (Eltanin handfish)	DD	TAS	Last recorded in 1984	2 localities (2 specimens)	135–520	Specific threats are poorly understood.
Pezichthys macropinnis (Longfin handfish)	DD	SA	Last recorded in 2000	1 locality (1 specimen)	145	Specific threats are poorly understood.
Pezichthys nigrocilium (Eyelash handfish)	DD	W TAS	Last recorded in 2004	1 locality (1 specimen)	176	Specific threats are poorly understood.
Sympterichthys moultoni (Moulton's handfish)	EN	SE AUS (incl TAS)	Last recorded in 2003	5 localities (5 specimens)	125–211	Prolonged trawl and dredge effort within its range possibly causing both habitat destruction and direct mortality.
Sympterichthys unipennis (Smooth handfish)	EX	TAS (inferred)	Extinct. Last recorded in 1802	1 locality (1 specimen)	10	Scallop and oyster fisheries in Tasmania from late 19th century until collapse in the D'Entrecasteaux Channel in 1967 probably contributed to decline (habitat destruction & bycatch), also potentially habitat loss, invasive species, and pollution.
Thymichthys politus (Red handfish)	CR	TAS	Declining	2 localities (<250 individuals)	1–20	General threats, likely including extreme population fragmentation, degradation of shallow reef habitat quality through increasing urchin densities (possibly as a result of predator release from depletion of Rock lobsters). Remaining colonies in urban areas, with possible impacts on habitat through nutrient runoff, pollution, siltation and turbidity. Poaching is a potential threat.
Thymichthys verrucosus (Warty handfish)	DD	S and E AUS (incl TAS)	Last recorded in 2000	Several localities	8–230	Prolonged trawl and dredge effort within its range possibly causing both habitat destruction and direct mortality.

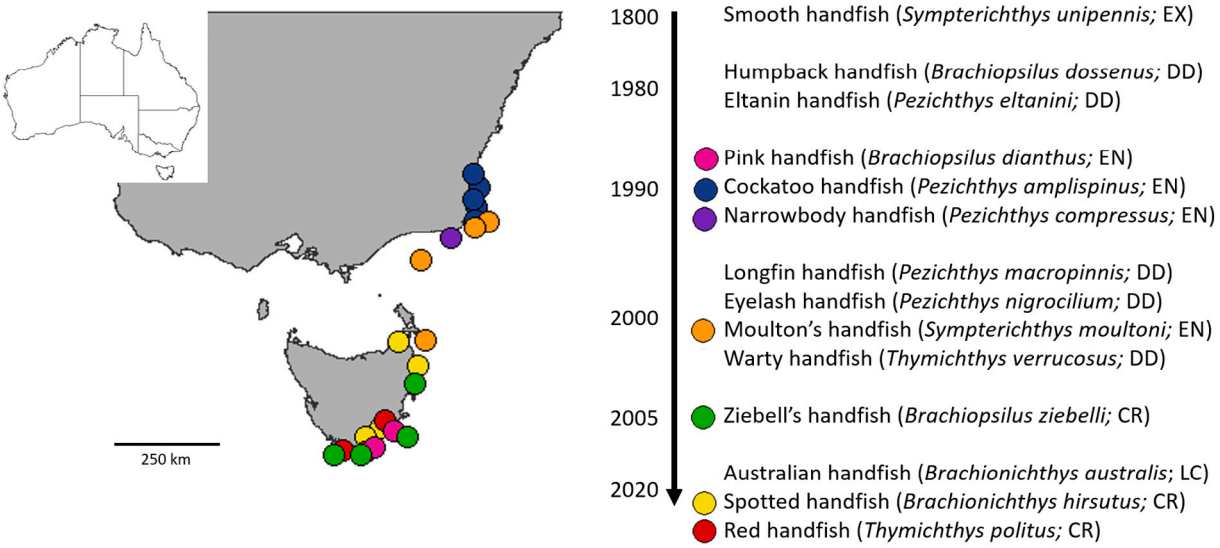

Fig. 3. Map of south-eastern Australia (left) showing recent distributions of threatened handfishes (location of all records since 1970s; (Atlas of Living Australia, website, 2020). Note: points are 'jittered' to minimise overlap, so are not precise), and (right) timeline of last recorded sightings for all fourteen handfish species in Australia. The Smooth handfish is the only species listed as Extinct, and the only four species observed in the last 20 years include the Red, Spotted, Ziebell's, and Australian handfishes. IUCN categories in parentheses (EX: Extinct, DD: Data Deficient, LC: Least Concern, EN: Endangered, CR: Critically Endangered).

cumulative historic and contemporary anthropogenic pressures are likely significant contributors to the current downward population trends of handfishes (Bruce et al., 1998; Edgar et al., 1982; Edgar et al., 2005; Jackson, 2008; Jackson et al., 2001; Last et al., 1983). Specific threats most important for each species are not well-understood, with different threat levels likely for shallow and deep water handfishes (see Table 1). While less is known about the handfishes found in the deeper continental shelf waters and beyond, these deeper regions have been subject to fishing activities that have potentially caused population declines directly through bycatch, and indirectly through impacts of destructive scallop dredging and trawl fisheries on their habitat (e.g. by direct disturbance or as a result of shifts in turbidity, water and sediment quality).

Increasing water temperatures associated with climate change are considered a significant threat to all handfishes. Sea surface temperatures off the east coast of Tasmania have warmed by 0.20 °C decade^{-1} over the last 70 years (Ridgway, 2007; Shears and Bowen, 2017), approximately four times that of the global ocean average (Holbrook and Bindoff, 1997; Ridgway, 2007), and no continental extension exists poleward of Tasmania for the handfishes to retreat to. Consequently, they are among a number of Tasmanian endemic marine species which may be 'pushed over the edge' into global extinction by ocean warming (Last et al., 2011). The remaining populations of all shallow water species are now confined to those parts of Tasmania which experience the coolest winter sea temperatures (due to local effects), suggesting warming seas may also have played a role in historical range contractions. The temperature ranges tolerated or required for handfish reproduction have not yet been studied, but spawning occurs in winter/spring when seas are coolest, and spawning and embryonic development have recently been suggested to be the life stages most vulnerable to changing temperature for fishes (Dahlke et al., 2020). Thus, reduced reproductive success along warming coasts may be a key mechanism leading to population fragmentation and decline.

Pressures posed by warming seas are exacerbated for the shallow water species by a combination of other threats, including loss of spawning substrata, habitat degradation and loss, water pollution (urban development and heavy metals), siltation, spread of invasive species (which impact their spawning habitat), and the cumulative impacts of fishing (Lynch et al., 2015). The illegal aquarium trade is also considered a potential threat for shallow water species. This threat has recently been acknowledged by the Tasmanian state government with fines of up to AUD110,000 for taking of these species.

Specific threats to Spotted handfish include habitat degradation, such as pollution, urban and industrial development, heavy metals, and historical scallop dredging. The decline of Spotted handfish in the Derwent Estuary was first reported in the mid 1980's, which coincided with the establishment of the Northern Pacific Seastar (*Asterias amurensis*) in Tasmania (Bruce et al., 1999). Well known as an opportunistic predator, this seastar consumes a diverse range of epifauna (Ross et al., 2003), including stalked ascidians (*Sycozoa* spp.) – the preferred natural spawning habitat of Spotted handfish (Wong et al., 2018). The seastars may also destroy microhabitat complexity through grazing. Combined with this, the scallop-dominated benthic community, which the Spotted handfish is adapted to and camouflaged in, has also failed to recover following exploitation (Edgar and Samson, 2004). Direct degradation of habitat quality may also occur from the heavy chains that moor hundreds of vessels within the sheltered bays inhabited by Spotted handfish (Lynch et al., 2015).

The Red handfish is restricted to two small localities in south-eastern Tasmania, with an observed population size of fewer than 100 adults. This species is one of the only marine fishes to qualify for a threatened category under criterion C (small population numbers), which was possible only because of the monitoring of the two current populations by Reef Life Survey volunteer divers facilitated by a community sighting (www.reeflifesurvey.com; Edgar and Stuart-Smith, 2014), and the extensive biodiversity monitoring undertaken on similar shallow reef habitats around Tasmania since the early 1990s (Edgar and Barrett, 2012; Edgar et al., 1997; Stuart-Smith et al., 2010). This survey effort has resulted in more than 7653 underwater transects (each 50 m) surveyed by scientific divers on Tasmanian reefs (including the Bass Strait islands) between 1991 and 2019 (contained within the National Reef Monitoring Network of the Integrated Marine Observing System, imos.org.au). These survey methods use systematic standardised methods that involve a close search of the substrate (including in crevices), and recording any handfishes observed (combined Reef Life Survey and Australian Temperate Reef Collaboration, atrc.org.au; Edgar and Barrett, 2012). The key current vulnerabilities for Red handfish include their small, fragmented populations, and local increases in density of native Purple urchins (*Heliocidaris erythrogramma*) which overgraze the seaweed habitat required for shelter and spawning. Increases in urchin

Fig. 4. From L-R: Spotted (*Brachionichthys hirsutus*), Red (*Thymichthys politus*), and Ziebell's (*Brachiopsilus ziebelli*) handfishes. (Image credit: Spotted and Red: R. Stuart-Smith; Ziebell's A.J. Green; taken in 1997.)

density are likely due to multiple factors, including release from predation by rock lobsters (*Jasus edwardsii*), which are a primary target of the local fisheries. The close vicinity of urban development increases the risk of nutrient runoff, pollution, siltation, and turbidity, resulting in habitat degradation through smothering of the Red handfish's preferred seaweed habitats (via increased filamentous algal and sediment loads). Causes for historical declines in Red handfish are unclear, but most likely include a combination of local anthropogenic impacts and warming seas. Population fragmentation has likely been a critical mechanism by which localised impacts have further contributed to overall population declines.

4. Conservation measures

Species extinctions result in the loss of biodiversity and natural heritage values, but may also have potential ecological consequences (Hooper et al., 2012; Ling et al., 2009). It is impossible to speculate on any potential ecological impacts associated with the loss of handfishes from the south-eastern Australian seascape, given the lack of ecological information about most species and their extreme contemporary rarity.

The IUCN Red List represents the most comprehensive information source on the extinction risk status of species worldwide. Listing provides a powerful tool for (1) informing the public, policy makers, managers, and researchers, (2) catalysing action for management and conservation, and (3) leveraging support (IUCN, 2020). However, limitations to monitoring and data collection for small, rare marine species may limit accurate assessment of extinction risks and the ability for the timely categorisation in these species.

4.1. Current management

Current management strategies exist only for Spotted, Ziebell's, and Red handfishes (Fig. 4) via a National Recovery Plan (Commonwealth of Australia, 2015). Activities are directed by the National Handfish Recovery Team (NHRT), which guides the research and conservation priorities for handfishes. Since no Ziebell's handfish have been seen for ~15 years, the management options for this species will first involve locating any remnant colonies. Hence, targeted searches in known historical sites and likely habitat represent the most useful initial steps. Spotted handfish management is more advanced than for any other handfish species due to the early recognition of population decline (Barrett et al., 1996). This has included captive breeding trials, release of captive-bred juveniles into wild populations, ongoing species and habitat surveys since 1998, development and planting of artificial spawning habitat (ASH) to replace loss of the native ascidians used by adults as spawning substrata, and increasing biological and ecological knowledge (Bruce et al., 1997, 1999; Lynch et al., 2015; Wong and Lynch, 2017; Wong et al., 2018). A recent conservation initiative has also included the provision of boundary maps of locations of Spotted handfish colonies to state and council planning authorities. This increased consideration of the potential for any adverse overlap of development applications with handfish colonies in the planning process and facilitated negotiation to avoid impacts on this species. In addition, work investigating development and implementation of environmentally-friendly moorings to protect Spotted handfish habitat in the Derwent Estuary is underway (Wong and Lynch, 2017).

Conservation effort for Red handfish has increased in recent years, with ongoing monitoring by citizen scientists through the Reef Life Survey program since 2010. Field surveys also led to the discovery of a second population in 2018, more than doubling the estimated global population size at the time. In 2018, the Handfish Conservation Project (handfish.org.au) was established to provide opportunity for promotion/awareness for all three species, and to provide an avenue through which the NHRT could drive action and seek public support. Initial work has included habitat management intervention through native urchin (*H. erythrogramma*) removals, ongoing species and habitat monitoring, development of an environmental DNA assay to allow for investigating improved search techniques for new colonies; head-starting (and planned release) of captive-reared juveniles, and increasing biological/ecological data via capture-mark-recapture at both known population sites.

No conservation strategies are currently in place for other handfish species.

4.2. Priorities and recommendations

Filling key biological and ecological information gaps is an important first step for improving conservation of handfishes. This should include establishing a non-invasive method to differentiate sexes for captive breeding trials, determining environmental cues for mating that can be applied in captivity to establish effective breeding programs, understanding micro-habitat use and movement, determining age and growth parameters, and seasonal patterns in behaviour.

Although Spotted handfish numbers appear stable, continued ASH deployment and captive breeding is considered essential to maintain their numbers. Local populations are not connected so are all at peril of stochastic processes that can lead to serial local extinctions. Captive breeding and repopulation in the wild, which are likely critical for the survival of Red handfish (and probably Ziebell's handfish, if a population is located), could effectively be trialled through experimental aquaculture approaches with Spotted handfish.

For the Red handfish, immediate intervention in multiple directions is essential for preventing imminent extinction. Conservation and restoration of habitat are unlikely on their own to bolster populations for Red handfish. Human assistance is needed to increase numbers through captive breeding and headstarting, while concurrently protecting habitat and reducing present and possible future environmental and human stressors. Increasing public awareness to leverage funding and support is essential to enable the full range of activities needed to occur. These should accompany an investigation of options for habitat

protection, *ex situ* cultivation (captive breeding/headstarting), and dedicated searches.

A key issue for the handfishes found in deeper waters is the reduced search effort in these habitats following scallop stock collapses and scaling back of dredge and trawl fisheries, as well as reduced scientific effort in collecting fisheries-independent data for these fisheries. Added to this, reporting of handfishes in bycatch by fishers has probably decreased due to concerns about management responses if the fishery is determined to be a threatening process for handfishes, thus further limiting the flow of information for these species. Expanded monitoring is therefore needed, including focussed sampling of deeper offshore waters to better assess distribution and population trends.

Conservation of other handfish species is heavily reliant on firstly improving knowledge of their current distributions, as well as aspects of their biology and ecology. This is relevant to other small, rare marine taxa where accurate listings are often constrained by the ability to find and study populations. Conservation effort will likely heavily depend on successful development of eDNA techniques to assist in finding remnant populations. Lacking crucial biological and ecological information makes effective conservation difficult, for handfishes and other rare micro-endemic marine species. An increase in tactical resourcing is paramount to improving this situation, with targeted action to minimise anthropogenic impacts and by enlisting public support for safeguarding species, all essential in developing strategies for conservation of marine threatened species.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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