Sustainability of threatened species displayed in public aquaria, with a case study of Australian sharks and rays

Buckley, Kathryn A.; Crook, David A.; Pillans, Richard D.; Smith, Liam; Kyne, Peter M.

Published in:
Reviews in Fish Biology and Fisheries

DOI:
10.1007/s11160-017-9501-2

Published: 01/03/2018

Document Version
Peer reviewed version

Sustainability of threatened species displayed in public aquaria: a case study of Australian sharks and rays

Kathryn A. Buckley • David A. Crook • Richard D. Pillans • Liam Smith • Peter M. Kyne

K.A. Buckley • D.A. Crook • P.M. Kyne

Research Institute for the Environment and Livelihoods, Charles Darwin University, Darwin, NT 0909, Australia

R.D. Pillans

CSIRO Oceans and Atmosphere, 41 Boggo Road, Dutton Park, QLD 4102, Australia

L. Smith

BehaviourWorks Australia, Monash Sustainable Development Institute, Building 74, Monash University, Wellington Road, Clayton, VIC 3168, Australia

Corresponding author: K.A. Buckley, Research Institute for the Environment and Livelihoods, Charles Darwin University, Darwin, NT 0909, Australia; Telephone: +61 4 2917 4554; Fax: +61 8 8946 7720; e-mail: Kathryn.Buckley@nt.gov.au

Abstract Zoos and public aquaria globally display numerous threatened vertebrate species and in the modern context of these institutions as conservation hubs it is crucial that displays are sustainable. Elasmobranchs (sharks and rays) are a taxonomic group of particular conservation concern. In this review, we examined the taxonomic composition and conservation status of elasmobranchs displayed globally and found a higher proportion of threatened elasmobranch species displayed than any other assessed vertebrate group. It is therefore critical to identify elasmobranchs that require assessments of sustainability for aquarium displays. We propose a new approach to identify sustainable captive populations of threatened elasmobranch species, defined as either self-maintaining or from a source population that can sustain harvest levels without risk of population declines below sustainable levels. We determined which displayed species are at risk of extinction in the wild – those assessed as threatened on the IUCN Red List of Threatened Species, or Data Deficient (DD) species that may be at an elevated risk of extinction due to life history traits and habitat associations. Captive breeding and wild harvests of at-risk species displayed by Australian aquaria were examined to determine if the captive populations are sustainable. Two species currently displayed in Australian aquaria do not have sustainable captive populations and were identified as needing comprehensive assessments of sustainability for their aquarium display. Such a sustainability assessment would incorporate the conservation benefits of the displays and the ecological impacts of wild harvests. This review also highlights that change in public aquarium record management systems are needed to improve conservation outcomes for captive elasmobranchs.

Keywords elasmobranch; zoos; aquarium display; conservation benefits; sustainability assessment

Introduction

The display of fishes in zoos and public aquaria has grown rapidly in recent decades, with conservative estimates suggesting that approximately one million fish from >3,500 species are held by major aquaria worldwide (WAZA 2009; ZSL 2014). Display stocks are often sourced from the ornamental fish trade (Tlusty et al. 2013) where high proportions (including 90% or more of marine species displayed) are sourced solely from the wild (Murray and Watson 2014). As the World Association of Zoos and Aquariums (WAZA) identifies environmental sustainability as a core value for public aquaria (WAZA 2009), it is vital to ensure that public aquarium fish displays are sustainable. This is imperative for the many species displayed that are considered to be at risk of extinction, such as those species listed in threatened categories on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (hereafter referred to as the 'IUCN Red List') (IUCN 2016).

Elasmobranchs (sharks and rays) are a taxonomic group of particular conservation concern. Currently, 188 (18.1 %) of the 1041 elasmobranchs assessed on the IUCN Red List fall into a threatened category (Critically Endangered, CR; Endangered, EN; or Vulnerable, VU). Data is considered inadequate to assess extinction risk, and thereby accurately assign a category, for a further 449 species (Data Deficient, DD) (IUCN 2016). Elasmobranchs are harvested for products such as meat, fins, liver, gill rakers, oil and skin, and further pressures are placed on populations due to incidental catches, habitat loss, persecution and climate change (Last and Stevens 2009; Dulvy et al. 2014). Further, the general life history traits of elasmobranchs include slow growth, low fecundity and high longevity which results in a limited capacity to resist or recover from population depletion (Stevens et al. 2000).

Since the inception of public aquaria in the 1870's, elasmobranchs have been an integral component of many displays. Although collection for public aquarium displays has never been identified as a major driver of elasmobranch fisheries, most exhibited individuals are harvested from the wild (Smale et al. 2012; Murray and Watson 2014). The cumulative impact of various threatening processes have contributed to the increased extinction risk for many species, and unsustainable targeted and incidental fisheries catches have caused regional or local extinctions and the decline of many shark and ray populations (Dulvy et al. 2014). It is therefore critical to identify elasmobranch species that are vulnerable to population declines below sustainable

harvest levels due to harvests for public aquaria and which therefore require comprehensive assessments of sustainability.

We propose a new approach (Fig. 1) for the identification of elasmobranch species that are vulnerable to population declines below sustainable levels due to wild harvests for public aquaria. First, we examine the taxonomic composition and conservation status of elasmobranchs displayed globally to identify species at risk of extinction in the wild. We then use the Australian case study to determine whether at-risk species have sustainable captive populations, as it has a relatively comprehensive database compared to most regions and a long history of displaying elasmobranchs dating back to a shark display at the Manly Aquarium (Sydney) in 1886 (SMH 1886). In the context of this review, captive populations were considered sustainable if they were identified as self-maintaining, or sourced from a population able to withstand harvests without declines below sustainable levels (Lees and Wilcken 2011, Simpfendorfer and Dulvy 2017). At-risk species identified as not having sustainable captive populations urgently require comprehensive assessments of sustainability for aquarium displays.

Methods: literature and data review

Currently recognised elasmobranch species and families were identified using both the Catalogue of Fishes (Eschmeyer et al. 2016) and a literature review. We identified captive elasmobranch species at risk of extinction in the wild using the IUCN Red List (IUCN 2016) to identify threatened species (CR, EN or VU) on display. In the absence of an accurate extinction risk assessment due to insufficient available information we also considered DD species alongside threatened species (Fig. 1). This is a precautionary approach taking into consideration that Dulvy et al. (2014) estimated that 68 of 396 IUCN listed DD chondrichthyan species (sharks, rays, and their close relatives, the chimaeras) were likely to be threatened due to life history traits and habitat associations which may lead to low intrinsic rates of population growth or exposure to fisheries. Data Deficient species on display were considered to be at risk if they were identified as potentially threatened by Dulvy et al. (2014).

Information on current elasmobranch collections in public aquaria globally was collated using industry databases and internet resources. Species 360 [formerly International Species Information System (ISIS)] animal records database Zoological Information Management System (ZIMS) was accessed for data recovery (ISIS

92 2015a) and the web sites of the World Association of Zoos and Aquaria (WAZA) and its member zoo and
93 aquarium associations (see Online Resource 1) were browsed for links to studbooks, yearbooks or censuses. The
94 American Elasmobranch Society Captive Elasmobranch Census (AES CEC) (AES 2008) and the Zootierliste (a
95 current list of vertebrates held in European zoos and aquaria) (Zootierliste 2017) provided further information
96 on elasmobranch stocks in zoos and aquaria globally. The internet search engines Google Search and Google
97 Scholar were used to search for combinations of the following terms: 'threat*', 'elasmobranch', 'shark', 'ray',
98 'public aquari*', 'aquari*' and the additional term '~bred' to identify additional elasmobranch species that have
99 been displayed and bred in aquaria.

100 In order to determine whether captive populations of elasmobranch species at risk of extinction in the wild are
101 self-maintaining within Australian public aquaria, current stocks including captive breeding successes and
102 proposed wild harvests were reviewed. The Zoo and Aquarium Association (ZAA) Australasian Species
103 Management Program (ASMP) Regional Census and Plan (ZAA 2015) (hereafter the ZAA Census) publishes
104 elasmobranch stock and collection planning information for nine participating zoos and public aquaria in
105 Australia, while the most current stock numbers were accessed via the ZAA Collection Planning Online System
106 (CPOS) (ZAA 2016) (hereafter the ZAA CPOS). Internet searches were also conducted using the search engine
107 Google Search including the terms listed above, and including the term 'Australia' which identified a further
108 seven Australian public aquaria which display elasmobranchs but do not supply publicly available stocktakes.
109 The institutional websites (including their Facebook pages where relevant) and other photographic databases
110 (such as tripadvisor® Australia) relating to these aquaria were searched to identify elasmobranch species on
111 display. Species detected within photographic databases were recorded as follows: a) an identifiable species
112 with the number of individuals given by the source: recorded as total number of individuals given; b) an
113 identifiable species, no number of individuals given: recorded as one individual; c) an identifiable species,
114 photographic record of several individuals: recorded as the maximum count of individuals in a single
115 photograph; or, d) not an identifiable species: not recorded.

116 Elasmobranch species at risk of extinction in the wild that do not have self-maintaining captive populations in
117 Australian aquaria were examined to determine whether stock is sourced from wild populations that can
118 withstand harvests without population declines below sustainable levels. Harvests of species not listed as
119 threatened on the IUCN Red List were assumed to be sustainable by this definition (Simpfendorfer and Dulvy

2017). We reviewed the stocking levels and proposed wild harvests of each species to determine if future stock is to be sourced from the wild. If future wild harvests are expected, the local conservation status of each species was used to assess the potential risk of harvests to wild populations. This status is more relevant in the context of elasmobranch harvests for Australian public aquaria than the IUCN Red List global assessment as most elasmobranch harvests for Australian public aquaria occur locally. Local conservation statuses that were considered were IUCN Red List regional assessments (if available for a particular species) and Australian legislative listings (Commonwealth *Environment Protection and Biodiversity Conservation Act*; EPBC Act). Captive populations identified as self-maintaining or harvested from a source population that can sustain harvests without population declines below sustainable levels were considered sustainable (Lees and Wilcken 2011, Simpfendorfer and Dulvy 2017); while the remaining species were identified as requiring comprehensive assessments of sustainability.

For the purposes of this review, the following taxonomic and nomenclatural assumptions are made regarding species held in Australian aquaria: (a) records of *Rhynchobatus djiddensis* refer to *Rhynchobatus australiae* as the former does not occur in Australian waters and is very unlikely that this species is held in any Australian aquaria; (b) records of *Himantura uarnak* refer to *Himantura australis* for similar reasons; (c) *Trygonorrhina* sp. recorded in ZAA affiliated aquaria are *Trygonorrhina fasciata* based on visual confirmation at the holding aquaria (K. Buckley pers. obs.); (d) following recent taxonomic revision, *Myliobatis australis* is considered a junior synonym of *Myliobatis tenuicaudatus* (White 2014); and, (e) resolution of the *Neotrygon kuhlii* species-complex has resulted in the occurrence of two species in Australian waters: *N. australiae* (northern and western Australia) and *N. trigonoides* (eastern Australia) (Last et al. 2016). However, these are recorded locally and on the IUCN Red List as *N. kuhlii*. The term *N. australiae/trigonoides* is used here until such time that Australian aquaria holdings can be identified. Given that *N. trigonoides* is very common along the Australian east coast (where most major aquaria occur) it likely represents the bulk of holdings.

Results

Global review of taxonomic composition and extinction risk status

Records were found for a total 237 elasmobranch species exhibited globally in an unspecified number of public aquaria, from 40 of the 61 elasmobranch families currently recognised (refer to Online Resource 2). The

distribution of assessed species among IUCN Red List categories is proportionally similar for elasmobranchs in general, and elasmobranchs displayed in aquaria (Fig. 2). More elasmobranch species are considered to be DD than any other category; and more DD species are displayed by aquaria than any other category. A similar proportion of Least Concern (LC) species is displayed as DD species. Despite their numerical dominance in public aquaria, LC and DD species are still underrepresented for their category, compared to Near Threatened (NT) and threatened species (Fig. 3). Only 20.8 % and 14.5 % of all assessed LC and DD species, respectively, are displayed by aquaria compared to between 30.0 %, and 37.4 % of all assessed CR, EN, VU and NT elasmobranchs. Consequently, although only 18.1 % of all assessed elasmobranch species are considered to be threatened more than a quarter (67 or 28.3 %) of exhibited elasmobranch species is listed in a threatened category on the IUCN Red List (IUCN 2016) (Online Resource 2a). Notably, two taxa referred to here found in public aquaria, *N. australiae/trigonoides* and *H. australis*, have not yet been evaluated (Not Evaluated, NE) by the IUCN due to recent taxonomic revisions.

The 67 threatened elasmobranch species displayed in public aquaria represent 35.6 % of all threatened elasmobranchs. However, a further ten threatened elasmobranch species were identified here as either historically occurring in public aquaria and/or occurring in the ornamentals trade (see Online Resource 2b). As public aquarium stocks are often sourced from the ornamentals trade (Tlusty et al. 2013), up to 41.0 % of elasmobranchs that are now considered threatened have at some stage probably been displayed in zoos and public aquaria. A further 65 species of elasmobranchs on display (27.4 % of all species displayed) are DD, and 15 of these are considered to be potentially threatened in the wild (Dulvy et al. 2014, Online Resource 2a).

For each elasmobranch family in public aquaria, an average (± standard deviation; SD) of 34.6 ± 23.7 % of recognised species are displayed, however this ranged broadly from 2.1 % for the Etmopteridae (lantern sharks) to 100 % for the monospecific families Rhincodontidae (whale shark) and Stegostomidae (zebra shark) (Fig. 4). A high proportion (60.0 % or more) of species in the families Pristidae (sawfishes), Trygonorrhinidae (banjo rays), Heterodontidae (bullhead sharks), and Ginglymostomidae (nurse sharks) are also displayed by public aquaria (Fig. 4).

Notably, the family Dasyatidae (stingrays) is both large (94 species) and has a high proportion (36.2 %) of species exhibited in public aquaria (Fig. 4). In terms of absolute numbers of species, the Dasyatidae, Rajidae

(hardnose skates) and Carcharhinidae (requiem sharks) dominate aquarium displays, along with the Triakidae (houndsharks), Scyliorhinidae (catsharks) and Potamotrygonidae (river stingrays) (Table 1, Fig. 4). These six families comprise more than half (51.1 %) of all species displayed in public aquaria.

Two of the six elasmobranch families dominating public aquarium displays are also notable for the very high proportion of exhibited species that are listed as threatened or DD on the IUCN Red List. Of the family Dasyatidae, 13 species (38.2 %) occurring in public aquaria are considered to be threatened and nine species (26.5 %) are DD (Table 1). Of the nine DD species, three are considered to be potentially threatened (Dulvy et al. 2014). Ten (71.4 %) of the 14 displayed species from the family Potamotrygonidae (river stingrays) are classified as DD, although none are considered potentially threatened by Dulvy et al. (2014).

Six CR elasmobranch species are currently kept in public aquaria globally: the blue skate *Dipturus batis* (Dulvy et al. 2006), Brazilian guitarfish *Pseudobatus horkelii* (Lessa and Vooren 2007), largetooth sawfish *Pristis pristis* (Kyne et al. 2013), smalltooth sawfish *Pristis pectinata* (Carlson et al. 2013), Green sawfish *Pristis zijsron* (Simpfendorfer 2013), and angelshark *Squatina squatina* (Ferretti et al. 2015).

Australia: a case study of captive populations

Records indicate that Australian zoos and public aquaria exhibited at least 739 individual elasmobranchs from 46 elasmobranch species during 2016 (Online Resource 3). Approximately one third of these species (30.4 %) and individuals (35.0 %) fall within threatened categories (CR, EN or VU). A small proportion of displayed species and individuals were DD (6.5 % and 2.2 %, respectively) with one of these, *Carcharhinus cautus* (Bennett and Kyne 2003), considered to be potentially threatened (Dulvy et al. 2014). Two taxa displayed by Australian aquaria, *N. australiae/trigonoides* and *H. australis*, have not yet been evaluated. Of all categories, species that are assessed as LC comprise the greatest proportion of species exhibited while the greatest proportion of individuals is from VU species (Fig. 5). Within each IUCN Red List category, the number of individuals displayed was broadly proportional to the number of species on display (Fig. 5).

In Australian public aquaria, 58.7 % of the elasmobranch species identified as exhibited during 2016 have at some time presented breeding behaviour or have successfully bred in public aquaria. This is a relatively high success rate, as captive breeding activity has been identified in only 47.4 % of elasmobranch species displayed

by public aquaria globally (Online Resource 2a and 2b). In Australian aquaria, there were significantly more individuals on display for species for which breeding activity has previously been recorded in captivity (24.4 ± 25.5 SD) than for those that have not (4.3 ± 3.6 SD); t-test, $t(27) = 3.96$, $p = <0.001$. Breeding activity in captivity has been recorded for similar proportions of threatened and potentially threatened DD species compared to other species in Australian aquaria (Table 2), with the highest percentage of past breeding activity reported for VU (69.2 %) and NT (77.8 %) species.

Australian public aquaria currently display 16 species that are either listed within a threatened category (CR, EN, VU), or are DD species considered to be potentially threatened by Dulvy et al. (2014) (Online Resource 3, Table 3). However, the regional IUCN Red List assessment for 12 of these species varies from the global assessment and the species is not considered threatened in Australian waters (Table 3). Consequently, only four of the 16 species identified above may be considered as threatened or potentially threatened in Australian waters. These species are the speartooth shark *Glyphis glyphis*, estuary stingray *Hemitrygon fluviorum*, grey nurse shark *Carcharias taurus*, and largetooth sawfish *P. pristis.*

Glyphis glyphis

Three individuals of the Endangered *G. glyphis* (Compagno et al. 2009) are displayed by Australian public aquaria. In Australian Commonwealth waters this species is assessed as critically endangered (*EPBC* Act) (Table 3). The three individuals were originally collected as part of a planned breeding program (L. Squires, Cairns Marine, pers. comm.), although to date no breeding activity has been reported. There is no intention to collect further stock from the wild (ZAA 2015).

Hemitrygon fluviorum

There are at least 113 individual *H. fluviorum* displayed by three Australian public aquaria (ZAA 2016, Online Resource 3). One aquarium hosts 111 of these individuals (ZAA 2016) and this captive population is a large breeding group (R. Jones, Merlin Entertainments, pers. comm.). In 2015 the ZAA Census recorded the intent by one public aquarium to acquire ten female individuals to join a single male on display (ZAA 2015).

Carcharias taurus

There are currently 15 individual *C. taurus* present in Australian public aquaria (Online Resource 3) and in 2015, the ZAA Census reported that Australian public aquaria intended to acquire more individuals from the wild (ZAA 2015) as brood stock to support the *C. taurus* breeding program (Smith et al. 2013). However, in contrast to *H. fluviorum*, Australian captive populations of *C. taurus* have had limited breeding success. Although *C. taurus* have mated and pupped several times in Australian aquaria, in nearly all cases pups were stillborn (ZAA 2015), and currently only two on display in Australia are captive bred (Smith et al. 2013). Wild populations of *C. taurus* in Australian waters are considered to be Critically Endangered on the east coast and Near Threatened on the west coast (Table 3). Since 2002 there has been a moratorium on collection of *C. taurus* for display in public aquaria as the Recovery Plan for Grey Nurse Shark (reviewed in 2014) continues to identify collection for public aquaria as a 'secondary threat' to *C. taurus* populations (DOE 2014).

Pristis pristis

The eleven *P. pristis* currently held in Australian public aquaria are not intended for breeding purposes, and at least one public aquarium intends to undertake future wild harvests (ZAA 2015, ZAA 2016, D. Wedd, Territory Wildlife Park, pers. comm.). Although *P. pristis* is listed on Appendix I of the Convention on International Trade in Endangered Species (CITES) (which restricts international trade) and on Appendix I of the Convention on Migratory Species (which prohibits harvests with very limited exceptions), *P. pristis* may still be harvested from the wild in both the Northern Territory of Australia and Queensland. Specifically, the Northern Territory Director of Fisheries has the discretion to issue a permit for the collection of *P. pristis* for the purpose of public aquarium displays; while in Queensland a permit may be issued to collect *P. pristis* for the purpose of public display or public education (DOE 2015). Not all of the harvested *P. pristis* remain in captivity: in the Northern Territory at least 13 wild harvested *P. pristis* have been released into their natal river system after outgrowing local public aquaria. The survivorship of the released individuals is unknown, but is the focus of a separate study (K. Buckley et al. unpublished data).

Discussion

Compared to other faunal groups, a high proportion of threatened elasmobranchs are displayed globally and, considering their conservation status and life history traits, a number of these species have wild populations that may be vulnerable to population declines below sustainable levels in part due to aquarium harvests. These

252 species warrant comprehensive sustainability assessments for aquarium displays incorporating conservation
253 benefits and ecological impacts. On a local Australian level, two species urgently require such assessments of
254 sustainability: *C. taurus* and *P. pristis*. Improved record keeping and/or accessibility to records maintained by
255 public aquaria are necessary to facilitate the identification of all species displayed which require comprehensive
256 assessments of sustainability.

257 Global review of patterns in taxonomic composition and conservation status

258 This review found that the number of elasmobranch species displayed globally by zoos and public aquaria and
259 listed as threatened (CR, EN, VU) on the IUCN Red List declines with increasing threat category, a pattern
260 consistent with that of zoo displays of threatened mammals and birds recorded by ISIS (Conde et al. 2011). This
261 pattern is likely to reflect aquarium collection management based on availability (e.g. rarity and species
262 protection measures). In contrast, the proportion of all assessed threatened elasmobranchs that are displayed by
263 aquaria, at least 35.6 %, is much higher than the proportion of threatened birds (15.6 %), mammals (23.0 %),
264 reptiles (22.2 %) or amphibians (29.2 %) displayed by zoos (Conde et al. 2013). This indicates a trend by
265 aquaria to display a higher proportion of threatened elasmobranch species than would be expected from a
266 comparison with other vertebrate animal groups. Further, a slight preference to display threatened rather than
267 non-threatened species is indicated by the higher proportion of threatened elasmobranch species on display, out
268 of all displayed species (28.3 %) than the overall proportion of elasmobranchs that are threatened (18.1 %;
269 IUCN 2016).

270 While there are many factors which may contribute to the notably high proportion of threatened elasmobranchs
271 displayed in public aquaria globally, this does not explain why, proportionally, more threatened elasmobranchs
272 are displayed than other faunal groups. For example, historical factors such as established ease of husbandry and
273 static collection planning (i.e. commencing a pattern of display well prior to a species' threatened listing) could
274 result in the continuous display of a species despite the recognition of declines in wild populations. For more
275 novel and charismatic species, collection planning based on marketability considerations is probable for species
276 such as manta rays and sawfishes, all of which are now listed as threatened. Further, modern zoos and public
277 aquaria have redefined themselves from their traditional role as primarily recreational facilities to conservation
278 hubs, and this new role is now widely recognised (Zimmermann et al. 2007; WAZA 2009; Beri et al. 2010).

279 Threatened elasmobranch species may therefore be chosen for display as 'flagship species' to educate the
280 public, raise funds, support in-situ conservation efforts or for ex-situ breeding programs. Although the display of
281 many threatened elasmobranch species may well be explicable, it does highlight the need to consider whether
282 displays are sustainable in the context of modern aquaria as conservation hubs.

283 Species listed as threatened on the IUCN Red List are considered to have an elevated risk of extinction in the
284 wild (IUCN 2001) and it is therefore important to identify particular species that are vulnerable to population
285 declines below sustainable levels due to wild harvests for public aquaria. However, a number of species that are
286 not listed as threatened may also be at risk of extinction in the wild. For example, Dulvy et al. (2014) calculated
287 that 68 of 396 (17.3 %) DD listed chondrichthyans are potentially threatened due to life history traits and habitat
288 associations which may elevate their risk of extinction; and fifteen of these species occur in public aquaria
289 (Online Resource 2a). As a precautionary measure, our approach to identifying species vulnerable to population
290 declines below sustainable levels due to wild harvests for public aquaria therefore incorporates consideration of
291 threatened species and DD species that are potentially threatened due to distribution or life history traits, as
292 identified by Dulvy et al. (2014) (Fig. 1). These species may not be able to withstand harvests without
293 population declines below sustainable levels (see Simpfendorfer and Dulvy 2017). If captive populations of
294 these species are not self-maintaining, and future wild harvests are proposed, comprehensive assessments of
295 sustainability for their aquarium display are warranted (Fig. 1).

296 A number of elasmobranch families on display in public aquaria have both a high proportion of species
297 displayed, with many of these species assessed as threatened on the IUCN Red List or DD species that have
298 been identified as potentially threatened. For example, two of the three species on display from the family
299 Ginglymostomidae are threatened, including the tawny nurse shark *Nebrius ferrugineus* (VU) (Pillans 2003) and
300 the shorttail nurse shark *Pseudoginglymostoma brevicaudatus* (VU) (Nel et al. 2004). The third species,
301 *Ginglymostoma cirratum*, is considered to be DD (Rosa et al. 2006) but is a potentially threatened species
302 (Dulvy et al. 2014). Both species from the two monospecific elasmobranch families Rhincodontidae and
303 Stegostomidae are assessed as threatened, being the whale shark *Rhincodon typus* (EN) (Pierce and Norman
304 2016) and the zebra shark *Stegostoma fasciatum* (EN) (Dudgeon et al. 2016). Finally, the Pristidae is considered
305 to be one of the most threatened elasmobranch families (Dulvy et al. 2014) and all three of the sawfish species
306 on display are assessed as CR. Considering both their proportionally high levels of representation in public

aquaria and their elevated risk of extinction in the wild, it is a priority to determine if captive populations of all threatened and potentially threatened species from the families Ginglymostomidae, Rhincodontidae, Stegostomidae and Pristidae are self-maintaining or sourced from a wild population populations that can withstand harvests without population declines below sustainable levels. As no individuals on display from the families Rhincodontidae (whale shark) and the Pristidae (sawfishes) are captive bred, we know that all have been sourced from the wild.

Two elasmobranch families, the Dasyatidae and Rajidae, dominate aquarium displays in terms of total number of species on display, with a high proportion of displayed species (38.2 % and 33.3 %, respectively) being threatened. Further, the Dasyatidae is one of seven elasmobranch families at highest risk of extinction due to life history sensitivity (low intrinsic rates of population growth) and exposure to fisheries, and three of the nine DD species on display have been identified as potentially threatened (Dulvy et al. 2014). Although none of the DD species on display have been identified as potentially threatened, members of the family Rajidae are similarly considered to be highly susceptible to extinction (Dulvy and Reynolds 2002). Threatened species, and DD species that may be at an elevated risk of extinction due to distribution or life history traits, from the families Rajidae and Dasyatidae warrant an examination of captive populations to determine if they are self-maintaining or sourced from a wild population that will not be depleted below sustainable levels.

The Potamotrygonidae has the highest proportion of DD species on display in public aquaria of any elasmobranch family with ten of the 14 species on display (71.4 %) considered to be DD. Although none of these DD species are considered to be potentially threatened by Dulvy et al. (2014), the Potamotrygonidae is the only elasmobranch family to be completely restricted to freshwater habitats and all species are considered to be of concern for conservation and management (de Araújo et al. 2004). In addition, one displayed species, the previously DD *Potamotrygon tigrina*, was recently reassessed as EN (García Vásquez et al. 2016). In order to minimise potential risk to wild populations an examination of captive populations of all threatened and DD species from the Potamotrygonidae is warranted to determine if they are self-maintaining or sourced from a wild population that can sustain harvests without depletion below sustainable levels.

Unless captive populations are self-maintaining, assessments of sustainability are required for wild collections of all CR species on display in public aquaria (Fig. 1). Critically Endangered species face an ‘extremely high

risk of extinction in the wild' (IUCN 2001) which is often the result of cumulative risks to their wild populations, which may include harvests for aquarium displays. It is therefore unlikely that any wild populations of CR species could sustain harvests without depletion below sustainable levels. The CR species present in public aquaria globally and needing an examination of their captive populations are: *D. batis*, *P. horkelii*, *P. pristis*, *P. pectinata*, *P. zijsron*, and *S. squatina*.

Australian case study of captive populations

In 2016, a higher proportion of threatened elasmobranch species were displayed in Australian zoos and public aquaria (30.4 % of species on display) than globally (28.0 % of species on display) (IUCN 2016). Regional trends in the proportions of species assigned to each IUCN Red List category cannot account for the high proportion of threatened elasmobranchs on display in Australia. Both globally and within the Indo-Australasian region, the proportion of species within an IUCN threatened category decreases as the threat category grows more severe (White and Kyne 2010). In contrast, Australian aquaria display a higher proportion of VU species than NT species. Additionally, while the proportion of DD species in the Indo-Australasian region is 29.2 % (White and Kyne 2010), the proportion of DD species on display is much less at only 6.5 %. It is unknown why Australian aquaria display relatively more VU species and fewer DD species, but the trend highlights the importance of ensuring public aquarium collections are sustainable. Notably, more LC species are displayed than any other IUCN Red List category, possibly reflecting the relative local availability for wild harvests of these species.

In Australian aquaria there is both a high proportion of VU, NT and DD elasmobranch species that have displayed breeding activity in captivity, and slightly higher stocking levels than would be expected given the proportion of species that they represent. There is also a significant positive relationship between the number of individuals on display and a history of breeding activity in captivity, and therefore it is expected that the high stocking levels of VU, NT and DD species on display is a result of captive breeding successes for these species. Captive breeding of aquarium fish can greatly reduce or even eliminate the need to harvest stock from wild populations (Tlusty 2002). As successful captive breeding increases the size of captive elasmobranch populations in Australian aquaria, some populations are expected to become self-maintaining thereby reducing or negating the need for wild harvests.

Due to the combination of challenges presented in transporting large elasmobranchs (Smith 1992) and the relative ease and cost-effectiveness of collecting specimens close to the destination aquarium, most elasmobranch harvests for Australian zoos and public aquaria likely occur locally. The appropriate management of local wild populations is an important consideration when undertaking harvests of elasmobranchs (Smith 1992) and it is therefore appropriate to use the local conservation status at the point of harvest for each species to assess the potential risk of harvests to wild populations. In total this review identified 16 species on display in Australian public aquaria that are considered as globally threatened on the IUCN Red List, or for which there is insufficient information available to accurately assess their status (DD) but are considered to be potentially threatened by Dulvy et al. (2014). Of these species, four were found to be regionally threatened on the IUCN Red List: *G. glyphis*, *H. fluviorum*, *C. taurus* and *P. pristis* (Table 3). These four species may be regarded as having source populations that may not be able to sustain harvests without population declines below sustainable levels. However, no future acquisitions for aquaria are proposed for *G. glyphis* and therefore an assessment of sustainability for existing aquarium displays is not required unless future harvests from the threatened wild populations are proposed.

It is likely that captive populations of *H. fluviorum* are self-maintaining in Australian aquaria as the existing stock is principally comprised of a large breeding group (R. Jones, Merlin Entertainments, pers. comm.). Consequently, any future acquisitions would likely occur by transfers between aquaria and future wild harvests for the purposes of aquarium display in Australia are unlikely, at least in current aquaria. We consider that an assessment of sustainability for *H. fluviorum* is therefore not required unless future wild harvests are proposed.

Without population supplementation it is predicted that the captive Australian population of *C. taurus* will be extinct by the year 2044 (Smith et al. 2013). Only two *C. taurus* on display are captive bred (Smith et al. 2013), from a total of eight pups born in captivity in Australia since 1995 (NSW Primary Industries 2005). One of the top priority actions identified in the Recovery Plan for Grey Nurse Shark (DOE 2014) is to ‘Determine whether it is feasible and appropriate for management protocols to enable captive breeding and investigate survivorship in captivity, to maintain a sustainable captive population without further collection from the wild’ (DOE 2014). Given that high stocking levels and self-maintaining captive populations of several elasmobranch species do already occur in Australian aquaria as a result of captive breeding successes, it is possible that a self-maintaining captive *C. taurus* population may be established in the future. However, achieving reliable success in breeding

C. taurus presents many challenges despite ongoing research into artificial insemination options for the species (ABC News 2016). Supplementation from the wild may be the only option to support the breeding program and prevent the loss of a captive *C. taurus* population in in Australian aquaria. The CR status of wild *C. taurus* populations on the east coast of Australia indicate that they are unlikely to tolerate harvests without the risk of population declines below sustainable levels. The *Carcharias taurus* population on the west coast are not considered to be threatened and it is less likely that harvests for public aquaria would put the population at risk of decline below a sustainable level. A comprehensive assessment of sustainability for the aquarium display of *C. taurus*, taking into account the potential to establish a self-maintaining captive population, would assist stakeholders to meet their conservation commitments and would help inform the current moratorium on collection.

The CR *P. pristis* population in captivity is not intended for breeding purposes and it is unlikely that this would occur in the near future. *Pristis pristis* may attain seven metres total length and has a complex euryhaline life cycle (Last and Stevens 2009) which makes the establishment of a *P. pristis* breeding program problematic. In addition, although the congeneric smalltooth sawfish *Pristis pectinata* has bred in captivity, no offspring survived (Henningsen et al. 2004). Nevertheless, Objective 7 of the Sawfish and River Sharks Multispecies Recovery Plan (which aims to 'Reduce and, where possible, eliminate any adverse impacts of collection for public aquaria on sawfish and river shark species') recommends action to research captive breeding opportunities (DOE 2015) and a comprehensive assessment of sustainability could incorporate consideration of the establishment of a breeding program. An important consideration for an assessment of sustainability for *P. pristis* is the success of releases from public aquaria to the wild, as this could significantly influence the impact of wild harvests. Current research examining the survivorship of aquarium released *P. pristis* (K. Buckley et al. unpublished data) will provide vital information to inform this assessment. As a limited wild harvest is currently allowed for domestic public aquaria, *P. pristis* urgently requires a comprehensive assessment of sustainability to support the management of ongoing wild harvests.

Future directions

Two species have been identified in this review as needing urgently requiring comprehensive assessments of sustainability for Australian aquarium displays: *C. taurus* and *P. pristis*. As yet there have been no assessments

of sustainability for an Australian public aquarium display of a threatened elasmobranch species. The need for comprehensive assessments of sustainability prior to harvesting elasmobranch species at risk of population decline below sustainable levels is reflected by State and Territory Fisheries permit requirements for public aquarium collections of elasmobranchs in Australian waters, which commonly require some form of justification in terms of educational or conservation benefits and sustainability of harvest (Online Resource 4).

Many authors agree that both in-situ and ex-situ conservation approaches must be considered in comprehensive assessments of sustainability of zoo and aquarium displays (Redford et al. 2012; Lacy 2013; Conde et al. 2013), due in part to the large number of prevailing conceptions of 'sustainability' (Bond et al. 2012). For example, within the zoo and aquarium industry, definitions of sustainability range from the maintenance of captive population viability (in terms of genetic, physiological, behavioural, and morphological traits) (Lacy 2013) to sustainable collection practices (WAZA 2009; ZAA 2014) and the commitment to undertake conservation activities associated with threatened species on display (IUCN 2002). Comprehensive assessments of sustainability incorporating both educational or conservation benefits of displays and ecological impacts of harvests would provide regulatory bodies with a consistent and defensible basis for decision making, particularly as Australian permit requirements to collect elasmobranchs for display in aquaria usually identify educational or conservation benefits as a justification for the harvests. Additionally, assessments would provide public aquaria with clear strategies and targets, such as elasmobranch captive breeding and longevity goals, or public education and field conservation projects, which can be met to achieve sustainable displays.

The large number of DD elasmobranch species complicated the identification of captive elasmobranch species at an elevated risk of extinction in the wild. These species were able to be incorporated into the analyses by identifying DD species that have been identified as potentially threatened in the wild, although there is a level of statistical uncertainty in this process (Dulvy et al. 2014). Considerable future research effort is needed to provide the ecological knowledge required for an accurate IUCN Red List assessment of all current DD elasmobranch species. As a taxonomic group of particular conservation concern, a precautionary approach to wild harvests of DD elasmobranch species should be undertaken until the necessary research is complete.

The lack of a comprehensive and current database of elasmobranch stocks in zoos and public aquaria precluded an accurate assessment of global species holdings. Although the database ZIMS is considered to be the most

443 comprehensive database of animals held in zoos and aquaria globally (ISIS 2015a) and has been used to
444 examine the taxonomic composition of terrestrial vertebrates in captivity (Conde et al. 2011), ZIMS is voluntary
445 and was only redesigned to cater for aquarium collections in 2012. In 2015, ZIMS recorded approximately 3,000
446 individual elasmobranchs in public aquaria (ISIS 2015b) compared to the 9,578 elasmobranchs recorded by the
447 AES CEC seven years prior (AES 2008). Despite the relatively comprehensive results of the 2008 AES CEC,
448 participation in this census was also voluntary and only 129 of the estimated 315 public aquaria globally
449 participated (AES 2008, WAZA 2009). Further, the rapid growth in the number of aquaria globally (particularly
450 in high growth areas such as China) (WAZA 2009) mean that many aquaria remain uncensused to date, leading
451 to considerable uncertainty in the status of captive elasmobranch populations.

452 Within Australian public aquaria, the most current Australasian regional elasmobranch database is the ZAA
453 CPOS (ZAA 2016) in which participation is voluntary. Several Australian aquaria are not members of the ZAA
454 and institutional restrictions prevented direct access to stocking information. Some data was gathered from
455 publicly available sources (such as public aquarium websites and tourism web sites) but the lack of
456 comprehensive species lists and numbers of individuals held ultimately determined that this data may be
457 incomplete and that the stocking levels of some species are uncertain. Further to these issues, several species
458 identifications in the ZAA records required clarification and the possible duplication of data in some instances
459 led to further uncertainty in stock numbers. Finally, the intended source/s of future acquisitions is currently not
460 identified in the ZAA CPOS, which compromises our ability to identify species intended to be harvested from
461 wild populations.

462 The uncertainty in species and numbers of elasmobranchs displayed globally and regionally indicates the need
463 for current and comprehensive regional databases for threatened elasmobranch species held by zoos and aquaria.
464 Regional databases could be effectively supported by regional zoo and aquarium associations which often
465 already have access to detailed stocking levels of threatened species within their region. Data recorded would
466 include details of proposed acquisitions (whether from wild harvests, breeding programs or transfers from other
467 aquaria) and would use currently accepted taxonomic nomenclature to alleviate species identification issues.
468 Participation in a regional threatened elasmobranch database would be strongly encouraged for all institutions
469 that harvest threatened elasmobranchs from the wild for display purposes, and the regional databases could
470 provide data to ZIMS, supporting its' continuing development as a comprehensive global database. This would

be a vital step towards effective global management of these species by facilitating the identification of threatened elasmobranch species on display that are vulnerable to declines of wild populations below sustainable levels.

Conclusions

Many elasmobranchs exhibited by public aquaria are at risk of extinction in the wild and yet continue to be harvested from the wild for displays. This review demonstrates that a progressive analysis of aquarium stocks can identify elasmobranch species that do not have sustainable captive populations. This includes identifying species at risk (or potentially at risk) of extinction in the wild, without self-maintaining captive populations, and for which harvests are proposed from wild populations that cannot withstand harvests for public aquarium displays without population declines below sustainable levels.

Elasmobranch species that do not have sustainable captive populations, and that are at risk or potentially at risk of extinction in the wild, urgently require comprehensive assessments of sustainability for aquarium displays prior to future harvests. Defensible sustainability assessments that address individual species and incorporate both conservation benefits of the displays as well as the potential ecological impacts of wild harvests will ensure that the conservation commitments of stakeholders are upheld. For example State and Territory Fisheries agencies will be able to demonstrate robust justification for harvest permits issued, in terms of educational or conservation benefits and sustainability of harvests, while public aquaria will identify strategies and targets to achieve sustainable displays and thereby meet their core conservation values.

As a result of this review, we identify the need for an improvement in data management of threatened elasmobranch species in zoos and public aquaria to ensure that harvests for display purposes are not causing unsustainable declines to wild populations. This could be achieved by the establishment of comprehensive regional databases for zoos and public aquaria, with participation strongly encouraged for all institutions that harvest threatened species from the wild.

Acknowledgements

We gratefully acknowledge the support of the Marine Biodiversity Hub and the Northern Australia Hub, collaborative partnerships supported through funding from the Australian Government's National Environmental Research Program and National Environmental Science Program; the Northern Territory Government (Territory Wildlife Park and NT Department of Primary Industries and Resources); National Geographic; the Oceania Chondrichthyan Society/Passions of Paradise; and the Australasian Society of Zoo Keeping.

References

ABC News (2016) Australian-first artificial insemination experiment hopes to save shark species. ABC News, 7 October 2016. http://www.abc.net.au/news. Accessed 20 January 2017

AES (2008) The American Elasmobranch Society (AES) International Captive Elasmobranch Census (AES CEC) 2008. The American Elasmobranch Society, Dade County, Florida

Bennett MB, Kyne PM (2003) *Carcharhinus cautus*. The IUCN Red List of Threatened Species. Version 2016.3. http://www.iucnredlist.org. Accessed 5 January 2017

Beri V, Tranent A, Abelson P (2010) The economic and social contribution of the zoological industry in Australia. Int Zoo Yearbook 44:192-200. doi:10.111/j.1748-1090.2009.00104-x

Bond A, Morrison-Saunders A, Pope J (2012) Sustainability assessment: the state of the art. Impact Assessment and Project Appraisal 30:53-62

Carlson J, Wiley T, Smith K (2013) *Pristis pectinata*. The IUCN Red List of Threatened Species. Version 2016.3. http://www.iucnredlist.org. Accessed 5 January 2017

Compagno LJV, Pogonoski J, Pollard D (2009) *Glyphis glyphis*. The IUCN Red List of Threatened Species. Version 2016.3. http://www.iucnredlist.org. Accessed 5 January 2017

Conde DA, Colchero F, Gusset M, Pearce-Kelly P, Byers O, Flesness N, Jones OR (2013) Zoos through the lens of the IUCN Red List: a global metapopulation approach to support conservation breeding programs. PLoS ONE 8: e80311 doi:10.1371/journal.pone.0080311

Conde DA, Flesness N, Colchero F, Jones OR, Scheuerlein A (2011) An emerging role of zoos to conserve biodiversity. Science 331:1390-1391. doi:10.1126/science.1200674

521 de Araújo MLG, Charvet-Almeida P, Almeida MP, Pereira H (2004) Freshwater stingrays (Potamotrygonidae):
522 status, conservation and management challenges. CITES Information Document AC20 (8):1-6.
523 http//www.cites.org/common/cttee/animals/20/E20-inf-08.pdf. Accessed 25 June 2015
524 DOE (2014) Recovery Plan for the Grey Nurse Shark (*Carcharias taurus*). Department of the Environment
525 (DOE), Commonwealth of Australia, Canberra
526 DOE (2015) Sawfish and River Sharks Multispecies Recovery Plan. Department of the Environment (DOE),
527 Commonwealth of Australia, Canberra
528 Dudgeon CL, Simpfendorfer C, Pillans RD (2016) *Stegostoma fasciatum*. The IUCN Red List of Threatened
529 Species. Version 2016.3. http://www.iucnredlist.org. Accessed 5 January 2017
530 Dulvy NK et al. (2014) Extinction risk and conservation of the world's sharks and rays. eLife 3: e00590
531 doi:10.7554/eLife.00590
532 Dulvy NK, Notarbartolo di Sciara G, Serena F, Tinti F, Ungaro N, Mancusi C, Ellis J (2006) *Dipturus batis*. The
533 IUCN Red List of Threatened Species. Version 2016.3. http://www.iucnredlist.org. Accessed 5
534 January 2017
535 Dulvy NK, Reynolds JD (2002) Predicting extinction vulnerability in skates. Conserv Biol 16:440-450
536 Eschmeyer WN, Fricke R, van der Laan R (eds) (2016) Catalog of Fishes.
537 http://researcharchive.calacademy.org/research/ichthyology/catalog/fishcatmain. Accessed 5 January
538 2017
539 EPBC Act (1999) Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) List of
540 Threatened Fauna. Office of Legislative Drafting and Publishing (OLDP), Commonwealth of
541 Australia, Canberra
542 Ferretti F, Morey G, Serena F, Mancusi C, Fowler SL, Dipper F, Ellis J (2015) *Squatina squatina*. The IUCN
543 Red List of Threatened Species. Version 2016.3. http://www.iucnredlist.org. Accessed 5 January
544 2017
545 García Vásquez A, Sánchez Riveiro H, Valverde D, García Dávila C, Ortega Torres H, Reyes Ramírez C,
546 Reategui Ocampo D, Perea Sicchar C, Panduro M, Moya Vásquez L, Moncada Gallardo T, Chavez
547 Mendoza G, Correa E (2016) *Potamotrygon tigrina*. The IUCN Red List of Threatened Species.
548 Version 2016.3. http://www.iucnredlist.org. Accessed 5 January 2017

549 Henningsen AD, Smale M, Gordon I, Garner R, Marin-Osorno R, Kinnunen N (2004) Captive breeding and
550 sexual conflict in elasmobranchs. In: Smith MD, Warmolts D, Thoney D, Hueter R (eds) The
551 Elasmobranch Husbandry Manual: Captive Care of Sharks, Rays and their Relatives. Ohio Biological
552 Survey, Colombus, pp 237-248
553 ISIS (2015a) International Species Information System (ISIS). World Wide Web online database.
554 http://www2.isis.org/AboutISIS/Pages/About-ISIS. Accessed 25 June 2015
555 ISIS (2015b) ZIMS for Aquariums. International Species Information System (ISIS).
556 http://www2.isis.org/products/Pages/zims-for-aquariums. Accessed 25 June 2015
557 IUCN (2001) Red List Categories and Criteria: Version 3.1. Second edition. International Union for
558 Conservation of Nature (IUCN), Gland, Switzerland and Cambridge, UK
559 IUCN (2002) Technical guidelines in the management of ex-situ populations for conservation. International
560 Union for Conservation of Nature (IUCN) Species Survival Commission, Gland, Switzerland and
561 Cambridge, UK
562 IUCN (2016) International Union for Conservation of Nature (IUCN) Red List of Threatened Species Version
563 2016.3. http://www.iucnredlist.org. Accessed 20 January 2017
564 Kyne PM, Carlson J, Smith K (2013) *Pristis pristis*. The IUCN Red List of Threatened Species. Version 2016.3.
565 http://www.iucnredlist.org. Accessed 5 January 2017
566 Lacy RC (2013) Achieving true sustainability of zoo populations. Zoo Biol 32:19-26. doi:10.1002/zoo.21029
567 Last PR, Stevens JD (2009) Sharks and Rays of Australia, Second Edition. CSIRO Publishing, Collingwood
568 Last PR, White WT, Séret B (2016) Taxonomic status of maskrays of the *Neotrygon kuhlii* species complex
569 (Myliobatoidei: Dasyatidae) with the description of three new species from the Indo-West Pacific.
570 Zootaxa 4083:533-561
571 Lees CM, Wilcken J (2011) Towards sustainable population management. World Association of Zoos and
572 Aquariums (WAZA) Magazine. Vol 12. Agentura NP, Czech Republic
573 Lessa R, Vooren CM (2007) *Rhinobatos horkelii*. The IUCN Red List of Threatened Species. Version 2016.3.
574 http://www.iucnredlist.org. Accessed 5 January 2017
575 Murray JM, Watson GJ (2014) A critical assessment of marine aquarist biodiversity data and commercial
576 aquaculture: identifying gaps in culture initiatives to inform local fisheries managers. PLoS ONE 9:
577 e105982 doi:10.1371/journal.pone.0105982

578 Nel R, Yahya S, Jiddawi N, Semesi S (2004) *Pseudoginglymostoma brevicaudatum*. The IUCN Red List of
579 Threatened Species. Version 2016.3. http://www.iucnredlist.org. Accessed 5 January 2017
580 NSW Primary Industries (2005) World's first "test tube" sharks to be bred in NSW laboratories. Media Release
581 Archives, NSW Primary Industries, NSW Government. http://www.dpi.nsw.gov.au. Accessed 20
582 January 2017
583 Pierce SJ, Norman B (2016) *Rhincodon typus*. The IUCN Red List of Threatened Species. Version 2016.3.
584 http://www.iucnredlist.org. Accessed 5 January 2017
585 Pillans R (2003) *Nebrius ferrugineus*. The IUCN Red List of Threatened Species. Version 2016.3.
586 http://www.iucnredlist.org. Accessed 5 January 2017
587 Redford KH, Jensen DB, Breheny JJ (2012) Integrating the captive and the wild. Science 338:1157-1158.
588 doi:10.1126/science.1228899
589 Rosa RS, Castro ALF, Furtado M, Monzini J, Grubbs RD (2006) *Ginglymostoma cirratum*. The IUCN Red List
590 of Threatened Species. Version 2016.3. http://www.iucnredlist.org. Accessed 5 January 2017
591 Simpfendorfer CA (2013) *Pristis zijsron*. The IUCN Red List of Threatened Species. Version 2016.3.
592 http://www.iucnredlist.org. Accessed 5 January 2017
593 Simpfendorfer CA, Dulvy NK (2017) Bright spots of sustainable shark fishing. Current Biology 27:R97-R98
594 Smale MJ, Booth AJ, Farquhar MR, Meÿer MR, Rochat L (2012) Migration and habitat use of formerly captive
595 and wild raggedtooth sharks (*Carcharias taurus*) on the southeast coast of South Africa. Mar Biol
596 Res 8:115-128
597 SMH (1886) News of the day. The Sydney Morning Herald (SMH), December 23 1886. Page 7
598 Smith MFL (1992) Capture and transportation of elasmobranchs, with emphasis on the Grey Nurse Shark
599 (*Carcharias taurus*). Mar Freshwater Res 43:325-343
600 Smith MFL et al. (2013) The role of aquaria in the recovery of Australian grey nurse shark populations.
601 Presentation at the Grey Nurse Shark Symposium, September 2013. Brisbane, Australia.
602 https://sites.google.com/site/elasmobranchhusbandry/gns. Accessed 25 June 2015
603 Stevens JD, Bonfil R, Dulvy NK, Walker PA (2000) The effects of fishing on sharks, rays, and chimaeras
604 (chondrichthyans), and the implications for marine ecosystems. ICES J Mar Sci 57:476-494
605 Tlusty MF (2002) The benefits and risks of aquacultural production for the aquarium trade. Aquaculture
606 205:203-19

607 Tlusty MF et al. (2013) Opportunities for public aquariums to increase the sustainability of the aquatic animal
608 trade. Zoo Biol 32:1-12
609 WAZA (2009) Turning the Tide. A Global Aquarium Strategy for Conservation and Sustainability. World
610 Association of Zoos and Aquaria (WAZA). Berne, Switzerland. http://www.waza.org. Accessed 25
611 June 2015
612 White WT (2014) A revised generic arrangement for the eagle ray family Myliobatidae, with definitions for the
613 valid genera. Zootaxa 3860:149–166
614 White WT, Kyne PM (2010) The status of chondrichthyan conservation in the Indo-Australasian region. J Fish
615 Biol 76:2090-2117
616 ZAA (2014) Zoo Aquarium Association (ZAA) Code of Ethics. http://www.zooaquarium.org.au. Accessed 17
617 January 2015
618 ZAA (2015) The Australasian Species Management Program (ASMP) Regional Census and Plan. Zoo
619 Aquarium Association (ZAA), Australia
620 ZAA (2016) Zoo Aquarium Association (ZAA) Collection Planning Online System (CPOS). Accessed 20
621 November 2016
622 Zimmermann A, Hatchwell M, Dickie L, West CE (2007) Zoos in the 21st century: catalysts for conservation?
623 Cambridge University Press, New York
624 Zootierliste (2017) Zootierliste: a current and former vertebrate inventory of European zoos and other public
625 collections. http://www.zootierliste.de/en. Accessed 28 January 2017
626 ZSL (2014) Zoos and aquariums of the world. The Zoological Society of London (ZSL). International Zoo
627 Yearbook 48:250-406
628