

Sustainability of threatened species displayed in public aquaria, with 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 exhibit numerous threatened species globally, and in the modern context of these institutions as conservation hubs, it is crucial that displays are ecologically sustainable. Elasmobranchs (sharks and rays) are of particular conservation concern and a higher proportion of threatened species are exhibited than any other assessed vertebrate group. Many of these lack sustainable captive populations, so comprehensive assessments of sustainability may be needed to support the management of future harvests and safeguard wild populations. We propose an approach to identify species that require an assessment of sustainability. Species at risk of extinction in the wild were considered to be those assessed as threatened (CR, EN or VU) 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. We defined sustainable captive populations as self-maintaining, or from a source population that can sustain harvest levels without risk of population declines below sustainable levels. The captive breeding and wild harvest records of at risk species displayed by Australian aquaria were examined as a case study. Two species, largemouth sawfish *Pristis pristis* and grey nurse shark *Carcharias taurus*, were found to have unsustainable captive populations and were identified as high priorities for comprehensive sustainability assessments. This review highlights the need for changes in permitting practices and zoo and aquarium record management systems to improve conservation outcomes for captive elasmobranchs.

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

Introduction

Conservative estimates suggest that approximately one million fish from >3,500 species are exhibited by major zoos and public aquaria worldwide (WAZA 2009; ZSL 2014). Fish stocks are often sourced from the ornamentals trade (Tlustý et al. 2013) where high proportions (including $\geq 90\%$ of marine species) are harvested from the wild (Murray and Watson 2014). However the World Association of Zoos and Aquariums (WAZA) regards environmental sustainability as a core value (WAZA 2009) and many zoos and public aquaria have redefined their traditional roles (as primarily recreational facilities) to that of modern conservation hubs (Zimmermann et al. 2007; WAZA 2009; Beri et al. 2010). In this context, it is vital that aquarium displays are ecologically sustainable (i.e., do not represent a risk to the viability of wild populations). Sustainability is particularly imperative for species at risk of extinction in the wild, including species listed in threatened categories (Critically Endangered, CR; Endangered, EN; or Vulnerable, VU) 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 assessed species are considered to be threatened (CR, EN, or VU), while data is considered inadequate to assess extinction risk for a further 449 species (Data Deficient, DD) (IUCN 2016). Many species are harvested for meat, fins, liver, gill rakers, oil and skin; and population pressures also occur due to incidental catches, habitat loss, persecution and climate change (Last and Stevens 2009; Dulvy et al. 2014). Unsustainable targeted and incidental catches have caused the decline of many populations and even local or regional extinctions (Dulvy et al. 2014). Further, general elasmobranch life history traits, such as slow growth, low fecundity and high longevity, limit the capacity for many species to resist or recover from population depletions (Stevens et al. 2000).

Since the inception of public aquaria in the 1870's, elasmobranchs have been an integral part of many displays, and most individuals are harvested from the wild (Smale et al. 2012; Murray and Watson 2014). Although aquaria have not been identified as a major impact on the sustainability of elasmobranch fisheries, the cumulative impact of various threatening processes has contributed to an increased extinction risk for many species (Dulvy et al. 2014). It is therefore possible that harvests for aquaria can negatively impact at risk

populations of elasmobranchs. Although several attempts have been made to assess the sustainability of marine aquarium fisheries as a whole (Tissot and Hallacher 2003; Okemwaab et al. 2016), few attempts have been made to assess the sustainability of individual harvested species (Roelofs and Silcock 2008), and none of these have incorporated the potential conservation benefits of associated displays. Stakeholders, including public aquaria and government agencies responsible for enacting threatened species legislation, can contribute to safeguarding wild populations and fulfil their conservation commitments by undertaking targeted and comprehensive assessments of sustainability for species that may be negatively impacted by harvests for aquaria.

Here, we propose an approach to identify species that require assessments of sustainability with regards to wild harvests for aquarium display purposes (Fig. 1). Initially, the taxonomic composition and conservation status of elasmobranchs exhibited globally is reviewed to identify species at risk of extinction in the wild. Australia is used as a case study to determine whether at risk species have sustainable captive populations, as this region has a relatively comprehensive database of species and individuals collected for display. In the context of this review, captive populations are considered sustainable if identified as self-maintaining (i.e. not requiring supplementation), or sourced from a population able to withstand harvests without declines below sustainable levels (Lees and Wilcken 2011, Simpfendorfer and Dulvy 2017). Species at risk of extinction in the wild, and with unsustainable captive populations, are identified as urgently requiring comprehensive assessments of sustainability.

Methods: literature and data review

Currently recognised elasmobranch taxonomy was sourced from the Catalogue of Fishes (Eschmeyer et al. 2016) and a literature review. Species listed in a threatened category (CR, EN, or VU) on the IUCN Red List (IUCN 2016) were considered to be at risk of extinction in the wild. We also examined DD species in this review as a precautionary measure (Fig. 1), given that Dulvy et al. (2014) estimated that 68 of 396 IUCN listed DD chondrichthyan species (sharks, rays and chimaeras) were likely to be threatened due to life history traits and habitat associations that may lead to low intrinsic rates of population growth or exposure to fisheries. Data Deficient species on display were considered to be at risk of extinction in the wild if they were identified as potentially threatened by Dulvy et al. (2014).

Information on elasmobranch collections in zoos and public aquaria globally was collated using industry databases and internet resources. Data was accessed from Species 360 [formerly International Species Information System (ISIS)] animal records database Zoological Information Management System (ZIMS) (ISIS 2015a), the American Elasmobranch Society Captive Elasmobranch Census (AES CEC) (AES 2008), and the Zootierliste (a current list of vertebrates held in European zoos and aquaria) (Zootierliste 2017). Web sites of the World Association of Zoos and Aquaria (WAZA) and its member zoo and aquarium associations (see Online Resource 1) were browsed for links to studbooks (comprising detailed records of all individuals in managed captive populations), yearbooks (publications aimed at the dissemination of information within the zoo and aquarium industry) or censuses. The internet search engines Google Search and Google Scholar were used to search for combinations of the following terms: ‘threat*’, ‘elasmobranch’, ‘shark’, ‘ray’, ‘public aquari*’, ‘aquari*’, and ‘~bred’ to identify species that have previously bred in aquaria.

Within Australia, a review of captive breeding successes and proposed wild harvests was used to identify self-maintaining captive populations. The Zoo and Aquarium Association (ZAA) Australasian Species Management Program (ASMP) Regional Census and Plan (ZAA 2015) (hereafter the ZAA Census) provided collection planning information for nine zoos and public aquaria, while the current stock numbers were accessed via the ZAA Collection Planning Online System (CPOS) (hereafter the ZAA CPOS) (ZAA 2016). Internet searches using Google Search included the terms listed above, and ‘Australia’. This method identified a further seven Australian public aquaria that did not participate in the ZAA Census. Due to data accessibility restrictions, the websites and other photographic databases relating to these aquaria (including Facebook and tripadvisor® Australia) were examined and elasmobranchs were recorded as follows: a) an identifiable species with the number of individuals given by the source: recorded as total number of individuals given; b) an identifiable species, no number of individuals given: recorded as one individual; c) an identifiable species, photographic record of several individuals: recorded as the maximum count of individuals in a single photograph; or, d) not an identifiable species: not recorded.

For species in Australian aquaria without self-maintaining captive populations, current and proposed stocking information was used to determine if future wild harvests are likely. If so, we considered whether this could occur without population declines below sustainable levels. Wild harvests of species not listed as threatened on the IUCN Red List were assumed to be sustainable (Simpfendorfer and Dulvy 2017). For threatened species, the

risk of population declines below sustainable levels was considered with reference to the species' local conservation status (IUCN Red List regional assessments and Australian Commonwealth *Environment Protection and Biodiversity Conservation Act* listings), where harvests are most likely to occur. Captive populations that were 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); the remaining species were identified as requiring assessments of sustainability.

The following taxonomic and nomenclatural assumptions were made regarding species held in Australian aquaria: (a) records of *Rhynchobatus djiddensis* referred to *Rhynchobatus australiae* as the former does not occur in Australian waters and was unlikely to be displayed by any Australian aquaria; (b) records of *Himantura uarnak* referred to *Himantura australis* for similar reasons; (c) *Trygonorrhina* sp. recorded in ZAA affiliated aquaria were *Trygonorrhina fasciata* based on visual confirmation at the holding aquaria (K. Buckley pers. obs.); (d) *Myliobatis australis* was 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 were recorded locally and on the IUCN Red List as *N. kuhlii*. The term *N. australiae/trigonoides* was used here although *N. trigonoides* likely represented the bulk of holdings, given that is very common along the Australian east coast (where most major aquaria occur).

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 currently recognised families (refer to Online Resource 2). Notably, two taxa 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 distribution of species among IUCN Red List categories was similar for elasmobranchs in general, and for those displayed in aquaria (Fig. 2). For example, more species were listed as DD than any other category; and more DD species were displayed than any other category. Despite DD and Least Concern (LC) species numerically dominating displays, a smaller proportion of all DD

and LC species were displayed by public aquaria (14.5 % and 20.8 %, respectively) than Near Threatened (NT) and threatened species (between 30.0 % and 37.4 %) (Fig. 3). Consequently, while 18.1 % of assessed elasmobranch species were threatened, 28.3 % of exhibited elasmobranchs were threatened (IUCN 2016) (Online Resource 2a).

The 67 threatened species displayed represent 35.6 % of all threatened elasmobranchs. However, a further ten threatened species were identified 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 (Tlustý et al. 2013), up to 41.0 % of elasmobranchs that are now considered threatened have probably been exhibited historically. Further, 65 species (27.4 % of all species displayed) were 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 found in public aquaria, 34.6 ± 23.7 % (\pm standard deviation; SD) of recognised species were 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 %) of species from the Pristidae (sawfishes), Trygonorrhinidae (banjo rays), Heterodontidae (bullhead sharks), and Ginglymostomidae (nurse sharks) were exhibited (Fig. 4).

The family Dasyatidae (stingrays) is both large (94 species) and had a high proportion of species exhibited (36.2 %) (Fig. 4). In terms of absolute numbers of species, the Dasyatidae, Rajidae (hardnose skates) and Carcharhinidae (requiem sharks) dominated displays, followed by the Triakidae (houndsharks), Scyliorhinidae (catsharks) and Potamotrygonidae (river stingrays) (Table 1, Fig. 4). These six families comprised more than half (51.1 %) of all species displayed by public aquaria.

The Dasyatidae and Potamotrygonidae had a notably high proportion of threatened or DD species on display. Of the Dasyatidae, 13 species displayed (38.2 %) were threatened and nine species (26.5 %) were DD (Table 1). Three of the nine DD species are considered to be potentially threatened (Dulvy et al. 2014). Ten (71.4 %) of 14 displayed Potamotrygonidae (river stingrays) species were DD, although none are considered potentially threatened by Dulvy et al. (2014).

Six CR elasmobranch species were displayed by 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

Australian zoos and public aquaria exhibited at least 739 individuals from 46 elasmobranch species during 2016 (Online Resource 3). Within each IUCN Red List category, the number of species displayed was broadly proportional to the number of individuals (Fig. 5). The greatest proportion of exhibited species was LC; while the greatest proportion of exhibited individuals was from VU species. Approximately one third of species and individuals (30.4 % and 35.0 %, respectively) were threatened and a small proportion was DD (6.5 % and 2.2 %). One of the DD species, *Carcharhinus cautus* (Bennett and Kyne 2003), is considered to be potentially threatened (Dulvy et al. 2014). Two taxa, *N. australiae/trigonoides* and *H. australis*, have not yet been evaluated.

Prior records of breeding behaviour or successful breeding in captivity exist for 58.7 % of the species exhibited by Australian aquaria, which exceeds the global figure of 47.4 % (Online Resource 2a and 2b). For species with reported breeding activity, significantly more individuals (24.4 ± 25.5 SD) were displayed than for species with no reported activity (4.3 ± 3.6 SD); (two-sample Students' *t* test assuming unequal variances, $t = 3.96$, $df = 27$, $p = <0.001$). In Australia, breeding activity was reported for similar proportions of threatened and potentially threatened DD species, compared to non-threatened species (Table 2). The highest percentage of past breeding activity was reported for VU (69.2 %) and NT (77.8 %) species.

Australian aquaria displayed 16 species that are either threatened, or DD and 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 differs from the global assessment and they are not considered threatened in Australian waters (Table 3). The four species displayed considered as threatened or potentially threatened in Australian waters were the speartooth shark *Glyphis glyphis*, estuary stingray *Hemitrygon fluviorum*, grey nurse shark *Carcharias taurus*, and largetooth sawfish *P. pristis*.

The EN *G. glyphis* (Compagno et al. 2009) is assessed as critically endangered in Australian Commonwealth waters (EPBC Act) (Table 3). Three individuals, originally collected as part of a planned breeding program, are displayed by Australian public aquaria (L. Squires, Cairns Marine, pers. comm.). No breeding activity has been reported for these individuals and there is no intention to collect further stock from the wild (ZAA 2015).

There are at least 113 individual *H. fluviorum* displayed by three Australian public aquaria (ZAA 2016, Online Resource 3). One aquarium hosted 111 of these individuals in 2016 (ZAA 2016) and this captive population was a large breeding group (R. Jones, Merlin Entertainments, pers. comm.). In 2015, one public aquarium intended to acquire ten female individuals to join a single male on display (ZAA 2015), but the source of the acquisition was not specified.

There are 15 *C. taurus* displayed in Australian public aquaria (Online Resource 3), and in 2015 the ZAA Census reported that wild harvests were intended (ZAA 2015) as brood stock to support a captive breeding program (Smith et al. 2013). However, Australian captive populations have had limited breeding success and, although individuals have mated and pupped several times, in nearly all cases the pups were stillborn (ZAA 2015). From a total of eight pups born in captivity in Australia since 1995 (NSW Primary Industries 2005), two have survived and are displayed by aquaria (Smith et al. 2013). Since 2002 there has been a moratorium on harvests for public aquaria, as the Recovery Plan for Grey Nurse Shark (reviewed in 2014) identifies this as a ‘secondary threat’ to wild populations (DOE 2014). Regional wild populations of *C. taurus* in Australian waters are CR on the east coast and NT on the west coast (Table 3).

The eleven *P. pristis* in Australian public aquaria are not intended for breeding purposes, and future wild harvests are proposed (ZAA 2015, ZAA 2016, D. Wedd, Territory Wildlife Park, pers. comm.). Although this species 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), individuals may still be harvested locally in the Northern Territory of Australia and Queensland for display purposes only. Specifically, the Northern Territory Director of Fisheries has the discretion to issue a permit to collect *P. pristis* for the purpose of public aquarium displays, while in Queensland permits may be issued to collect for the purpose of public display or public education (DOE 2015). Not all harvested individuals remain in captivity: in the Northern Territory at least 13 juveniles were released

into their natal river system after outgrowing local public aquaria. The fate of released individuals is unknown, but is the focus of a separate study (authors, unpublished data).

Discussion

Compared to other faunal groups, a high proportion of threatened elasmobranchs were displayed in aquaria globally. In addition, several displayed DD species may have an elevated risk of extinction due to distribution or life history traits. Captive Australian populations of two threatened species, *C. taurus* and *P. pristis*, are not self-maintaining and future wild harvests are proposed. Wild populations of these species may be susceptible to declines below sustainable levels and comprehensive sustainability assessments are needed to formally consider both the conservation benefits and potential ecological impacts. Improved public aquarium record keeping and/or accessibility to records will facilitate the identification of other species that require comprehensive assessments of sustainability.

Global review of patterns in taxonomic composition and conservation status

Globally, the number of threatened elasmobranch species displayed by aquaria declined with increasing IUCN Red List threat category, a pattern consistent with zoo displays of threatened mammals and birds recorded by ISIS (Conde et al. 2011). This pattern is likely to reflect collection management based on availability (e.g. due to rarity and species protection measures). In contrast, the proportion of threatened elasmobranchs displayed in aquaria (at least 35.6 %), out of all threatened elasmobranchs, was much higher than the proportion of threatened birds (15.6 %), mammals (23.0 %), reptiles (22.2 %), or amphibians (29.2 %) displayed (Conde et al. 2013). Further, a greater proportion of threatened species were displayed (out of all species on display), than the overall proportion of threatened species (out of all elasmobranchs species) (28.3 % and 18.1 %, respectively) (IUCN 2016).

The choice of threatened species for displays may be influenced by a range of factors. For example, historical factors such as established ease of husbandry and static collection planning could result in continuous display of species despite declines in wild populations. Novel and charismatic species, such as manta rays (family Mobulidae) and sawfishes, are likely to be exhibited due to marketability considerations; and ‘flagship species’ (which are often threatened in the wild) may be chosen to educate the public, raise funds, or support

conservation efforts. Although the display of many individual species is understandable based on these considerations, it remains unclear why proportionally more threatened elasmobranchs were displayed than other faunal groups or whether such displays are sustainable.

As many elasmobranchs are particularly susceptible to population declines (Dulvy et al. 2014, Stevens et al. 2000), it is necessary to examine the risks posed to wild populations from cumulative impacts (including harvests for public aquaria). Sixty-seven (67) threatened elasmobranch species and 15 DD listed species considered to be potentially threatened due to life history traits and habitat associations (Dulvy et al. 2014) were displayed by public aquaria (Online Resource 2a). None of these species are likely to withstand cumulative impacts without population declines below sustainable levels (see Simpfendorfer and Dulvy 2017). Additionally, six species on display were CR (*D. batis*, *P. horkelii*, *P. pristis*, *P. pectinata*, *P. zisron*, and *S. squatina*), and any impacts on wild populations may be highly detrimental to these species.

Several elasmobranch families are notable for the high proportion species exhibited, with many of these being threatened, or DD and potentially threatened. For example, the Ginglymostomidae comprises four species, three of which were displayed. Two of these species are threatened, being the tawny nurse shark *Nebrius ferrugineus* (VU) (Pillans 2003) and the shorttail nurse shark *Pseudoginglymostoma brevicaudatus* (VU) (Nel et al. 2004). The third species, *Ginglymostoma cirratum*, is DD (Rosa et al. 2006) but potentially threatened (Dulvy et al. 2014). Both species from the two monospecific families (Rhincodontidae and Stegostomidae) are threatened, being the whale shark *Rhincodon typus* (EN) (Pierce and Norman 2016) and the zebra shark *Stegostoma fasciatum* (EN) (Dudgeon et al. 2016). Finally, the Pristidae is considered to be one of the most threatened elasmobranch families (Dulvy et al. 2014) and all three species displayed are CR.

The Dasyatidae and Rajidae dominated 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. The Dasyatidae is one of seven families considered to be 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 displayed have been identified as potentially threatened (Dulvy et al. 2014). The Rajidae are similarly considered to be highly susceptible to extinction (Dulvy and Reynolds 2002), although none of the DD species displayed have been identified as potentially threatened.

The Potamotrygonidae had an extremely high proportion of DD species on display, with ten of the 14 species displayed being DD. Although none of these species are considered as potentially threatened by Dulvy et al. (2014), all species are of concern for conservation due to a complete restriction to freshwater habitats (de Araújo et al. 2004). Notably, the publicly displayed and previously DD *Potamotrygon tigrina* was recently reassessed as EN (García Vásquez et al. 2016).

Considering the risks to wild populations and the high proportional representation in public aquaria discussed above, it is a priority to determine if sustainability assessments are required for captive populations of threatened and potentially threatened species from the families Ginglymostomidae, Rhincodontidae, Stegostomidae, Pristidae, Rajidae, Dasyatidae and Potamotrygonidae.

Australian case study of captive populations

In the context of this review, captive populations were considered sustainable if they were sourced from a wild population able to withstand harvests without declines below sustainable levels, or were self-maintaining (i.e. not requiring supplementation) (Lees and Wilcken 2011, Simpfendorfer and Dulvy 2017). Species at risk of extinction in the wild, with unsustainable captive populations and planned future wild harvests, were identified as requiring comprehensive assessments of sustainability due to cumulative risks to their wild populations, including harvests for aquarium displays (Fig. 1).

In 2016, a higher proportion of threatened elasmobranchs were displayed in Australian zoos and public aquaria (30.4 % of species on display) than globally (28.0 % of species on display) (IUCN 2016). Proportionally, Australian aquaria displayed a higher proportion of VU species and a smaller proportion of DD species (Fig. 2, Fig. 5). Notably, more LC species were displayed in Australia than any other category, possibly reflecting the relative local availability for wild harvests of these species. Sixteen species on display in Australia were threatened, or DD but considered to be potentially threatened by Dulvy et al. (2014).

Due to the challenges presented in transporting large elasmobranchs (Smith 1992) and the relative ease and cost-effectiveness of collecting local specimens, most harvests for Australian public aquaria occur locally. Any assessment of the potential impact of aquarium harvests to wild populations of at risk species should therefore consider the conservation status at the point of harvest. Since that four of the threatened and potentially

threatened species displayed in Australia may also be regionally threatened, we regard them as having source populations that cannot sustain harvests without population declines below sustainable levels. These species are *G. glyphis*, *H. fluviorum*, *C. taurus* and *P. pristis* (Table 3). Future acquisitions are proposed for all of these species except *G. glyphis*, for which an assessment of sustainability is therefore not required unless future acquisitions are proposed.

Based on our findings, we conclude that assessments of sustainability for self-maintaining species such as *H. fluviorum* are not currently required unless future wild harvests are proposed. Captive populations of *H. fluviorum* in Australian aquaria are principally comprised of a large breeding group (R. Jones, Merlin Entertainments, pers. comm.). Captive breeding of aquarium fish can reduce or eliminate the need to harvest stock from the wild (Tlustý 2002) and it is likely that the captive *H. fluviorum* population is self-maintaining. Consequently, future proposed acquisitions would likely occur by transfers between aquaria rather than wild harvests, although this is not specified. It is pertinent to note that a high proportion of VU, NT and DD species in Australian aquaria have historically displayed breeding activity in captivity, and currently have slightly higher stocking levels than would be expected given the proportion of species that they represent. The positive relationship between the number of individuals on display in Australian aquaria and a history of breeding activity is significant, and the high stocking levels of many VU, NT and DD species is therefore likely to be a result of captive breeding successes and indicative of the potential for other self-maintaining captive populations.

Assessments of sustainability for the display of species of conservation concern, such as *C. taurus*, that are subject to wild harvest is clearly required. Without population supplementation it is predicted that the captive Australian population of *C. taurus* will be lost within 30 years and exceptions to the current moratorium on wild harvests are proposed to prevent this (Smith et al. 2013). While the CR status of the wild east coast population indicates that it is unlikely to tolerate harvests without population declines below sustainable levels, the IUCN regional assessment of the west coast population is NT. It is less likely that harvests for public aquaria would put this population at risk of decline below a sustainable level. One of the top priority actions in the recovery plan for *C. taurus* (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). It is possible that a self-maintaining captive *C. taurus*

population could be established, given that self-maintaining populations of elasmobranchs already occur in Australian aquaria as a result of captive breeding; but breeding success for this species is currently unreliable. Considerations of priority conservation actions, the potential for establishing a self-maintaining captive population, local conservation status and possible conservation benefits of displays should all be considered in a comprehensive assessment of sustainability of *C. taurus*.

An assessment of sustainability for the display of any CR species with ongoing wild harvests for aquarium displays, such as *P. pristis* in Australian aquaria, is urgently required to support the management of wild stocks. Due to the species' CR status, wild populations are unlikely to sustain harvests without population depletion. Further, there is no captive breeding program for the species, although Objective 7 of the Sawfish and River Sharks Multispecies Recovery Plan recommends research be undertaken on captive breeding opportunities (DOE 2015). A successful *P. pristis* breeding program would prove challenging due to the species' complex euryhaline life cycle and the large size of adults (Last and Stevens 2009), although the congeneric smalltooth sawfish *Pristis pectinata* has bred in captivity with four surviving offspring (Online Resource 2a). Unusually, *P. pristis* have been released from public aquaria to the wild and this could significantly influence the impact of wild harvests. A comprehensive assessment of sustainability should consider recovery plan recommendations, the potential for establishing a self-maintaining captive population, possible conservation benefits of displays and the survivorship of released individuals.

Future directions

The approach (Fig. 1) described above allowed the identification of species requiring comprehensive assessments of sustainability to support the management of wild harvests for display purposes. Additionally, the approach provided a way of identifying priority species based on the level of urgency for assessments. For example, in Australian public aquaria assessment of sustainability is of low priority for the VU *H. fluviorum*, whereas the VU *C. taurus* and CR *P. pristis* require assessments of sustainability, and in the case of *P. pristis* this is considered to be urgent.

To date there have been no comprehensive assessments of sustainability for harvests of threatened elasmobranchs for public aquarium displays. However, the need for such assessments is strongly reflected by Australian State and Territory Fisheries permit requirements, as wild harvests for the purposes of public

aquarium display commonly require some form of justification in terms of educational or conservation benefits and sustainability of harvest (Online Resource 4). Our findings suggest that it would be beneficial for responsible agencies to formalise their justification processes, so that at risk species with unsustainable captive populations (such as *C. taurus* and *P. pristis* in Australia) require comprehensive assessments of sustainability prior to permitting wild harvests.

Comprehensive assessments of sustainability for zoo and aquarium displays must consider both *in-situ* and *ex-situ* conservation approaches (Redford et al. 2012; Lacy 2013; Conde et al. 2013). This is due in part to the large number of prevailing conceptions of ‘sustainability’ (Bond et al. 2012). 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). Assessments of sustainability that incorporate educational or conservation benefits of displays and ecological impacts of harvests would provide fisheries management agencies or other regulatory bodies with a consistent and defensible basis for decision making and would provide public aquaria with clear strategies and targets to attain sustainable displays.

Data complications

The large number of DD elasmobranchs complicated the identification of species at an elevated risk of extinction in the wild. Data Deficient species were incorporated into the analyses by identifying potentially threatened DD species, although there is statistical uncertainty in this process (Dulvy et al. 2014). Considerable future research effort is needed to provide the ecological knowledge required for accurate IUCN Red List assessments of these species, and a precautionary approach to wild harvests is needed in the meantime.

The lack of comprehensive and current databases of elasmobranch stocks in zoos and public aquaria also precluded an accurate assessment of global species holdings. Although ZIMS is considered to be the most comprehensive database of animals held in zoos and aquaria globally (ISIS 2015a) and has been used to examine the taxonomic composition of terrestrial vertebrates in captivity (Conde et al. 2011), it is voluntary and was only redesigned to cater for aquarium collections in 2012. Consequently ZIMS recorded only around 3,000 individual elasmobranchs in 2015 (ISIS 2015b) compared to the 9,578 elasmobranchs recorded by the AES

CEC seven years previously (AES 2008). Participation in the 2008 AES CEC census was also voluntary and only 129 of the estimated 315 public aquaria globally participated (AES 2008, WAZA 2009). The voluntary nature of censuses and the rapid growth in the number of aquaria globally (WAZA 2009) mean that many aquaria remain uncensused, leading to uncertainty in the status of captive elasmobranch populations.

The most current Australasian regional elasmobranch database is the ZAA CPOS (ZAA 2016) in which participation was voluntary. Several Australian aquaria were not participants and institutional restrictions prevented direct access to stocking information. Data was gathered from publicly available sources but the lack of comprehensive stocktakes for these aquaria determined that the extent of Australian holdings for some species was uncertain. Further to these issues, several species identifications in the ZAA records required clarification and the possible duplication of data in some instances led to further uncertainty in stock numbers. Finally, the intended source/s of future acquisitions is currently not identified in the ZAA CPOS, which compromised our ability to identify the source of intended acquisitions.

There is a need for current and comprehensive regional zoo and aquarium databases that use currently accepted taxonomic nomenclature and include detailed acquisition records. These databases could be effectively supported by regional zoo and aquarium associations which often already have access to detailed stocking information. Effective regional databases could provide data to ZIMS, supporting its' continuing development as a comprehensive global database. This is a vital step towards effective global management of threatened elasmobranch species.

Conclusions

Many elasmobranchs exhibited by zoos and public aquaria are at risk of extinction in the wild and yet wild harvests for displays continue. This review demonstrates that a progressive analysis of aquarium stocks can identify species needing comprehensive assessments of sustainability to support the management of wild harvests. This includes identifying species at an elevated risk of extinction in the wild, without self-maintaining captive populations, and for which harvests are proposed from wild populations that are vulnerable to population declines below sustainable levels.

Management agencies that formalise the process of justifying wild harvests by requiring comprehensive assessments of sustainability for targeted species will be able to provide defensible rationalization for any permits issued. Further, such assessments will enable zoos and aquaria to identify strategies and targets to achieve sustainable displays and in so doing uphold their core conservation values. Comprehensive assessments of sustainability should address individual species of concern, incorporate conservation benefits of the displays and consider the potential ecological impacts of wild harvests. The development of comprehensive regional databases for zoos and public aquaria, with participation strongly encouraged for all institutions, could meet the need for improved data quality and accessibility; thereby improving conservation outcomes for threatened species.

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Fig. 1 A new approach for the identification of elasmobranch species displayed by public aquaria which require comprehensive assessments of sustainability using the example of the largetooth sawfish *Pristis pristis*. Figure created with Mind the Graph.

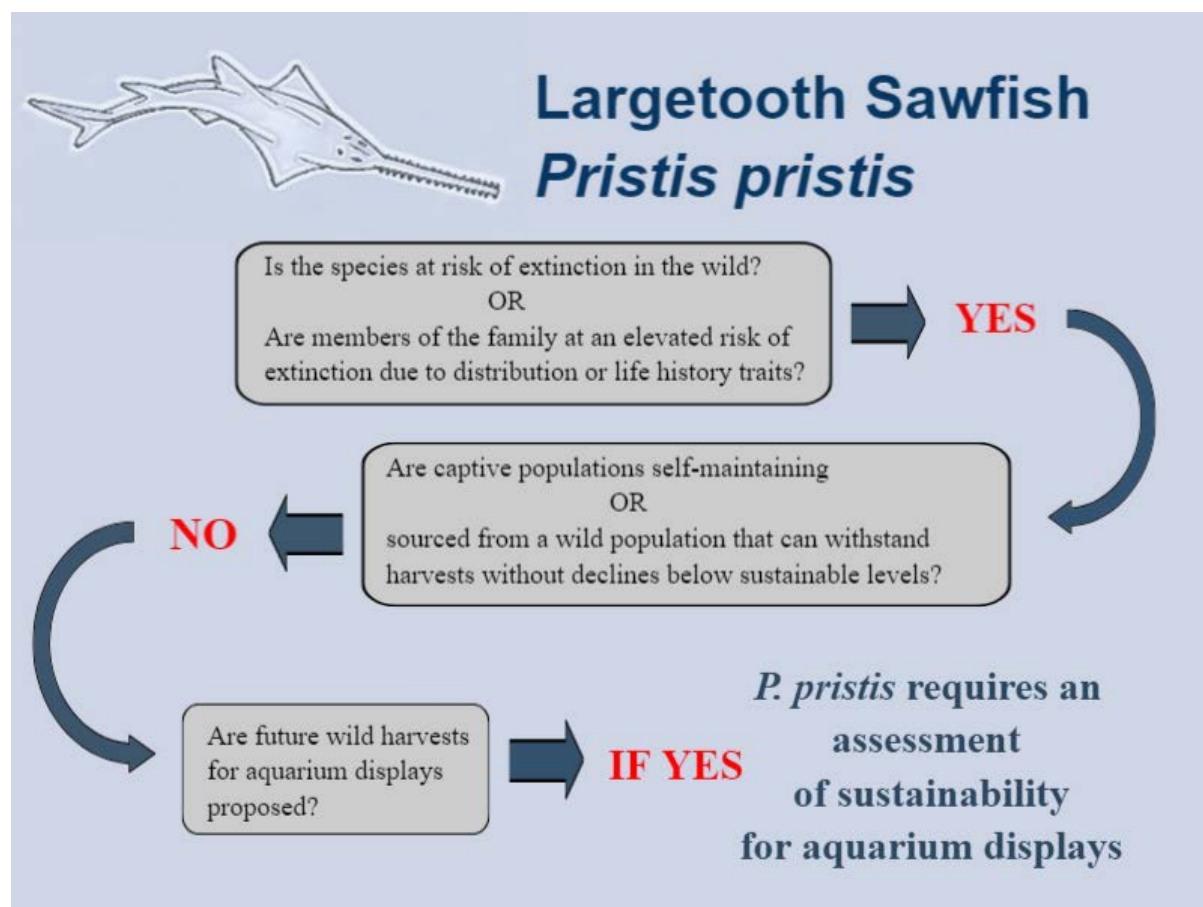
Fig. 2 The status of elasmobranch species according to IUCN Red List of Threatened Species categories. Black bars represent assessed elasmobranch species displayed in zoos and public aquaria globally. Grey bars represent all assessed elasmobranch species. Number of species listed at top of each bar. IUCN Red List categories: CR, Critically Endangered; EN, Endangered; VU, Vulnerable; NT, Near Threatened; LC, Least Concern; DD, Data Deficient (IUCN 2016).

Fig. 3 The proportion of elasmobranch species in each IUCN Red List of Threatened Species category that are displayed by public aquaria globally. IUCN Red List of Threatened Species categories: CR, Critically Endangered; EN, Endangered; VU, Vulnerable; NT, Near Threatened; LC, Least Concern; DD, Data Deficient (IUCN 2016).

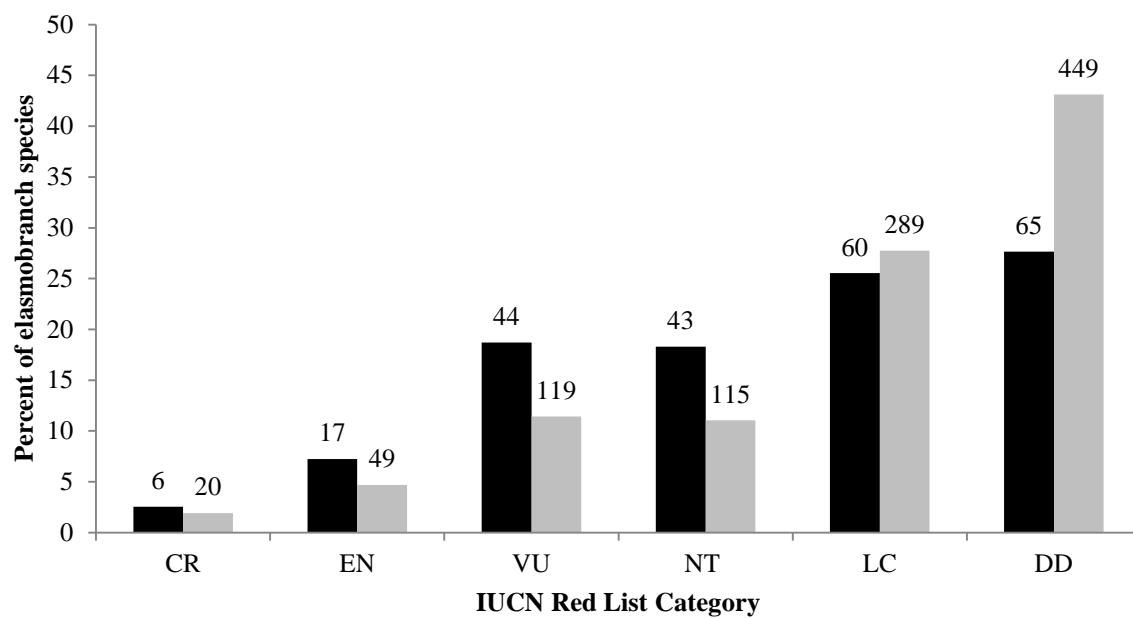
Fig. 4 The number of species in each of the 40 elasmobranch families displayed in public aquaria globally plotted against the proportion of species in the family displayed in public aquaria. Numbers in parentheses indicate points representing more than one elasmobranch family. The following source data are available for Figure 1: Online Resource 2(a) Elasmobranchs displayed in public aquaria and recorded breeding or mating in captivity.

Fig. 5 The proportion of elasmobranch species and individuals in each IUCN Red List of Threatened Species category that are displayed by Australian zoos and public aquaria. Black bars represent species. Grey bars represent individuals. Number of species and individuals listed at top of each bar. IUCN Red List categories: CR, Critically Endangered; EN, Endangered; VU, Vulnerable; NT, Near Threatened; LC, Least Concern; DD, Data Deficient (IUCN 2016).

19 Figure 1

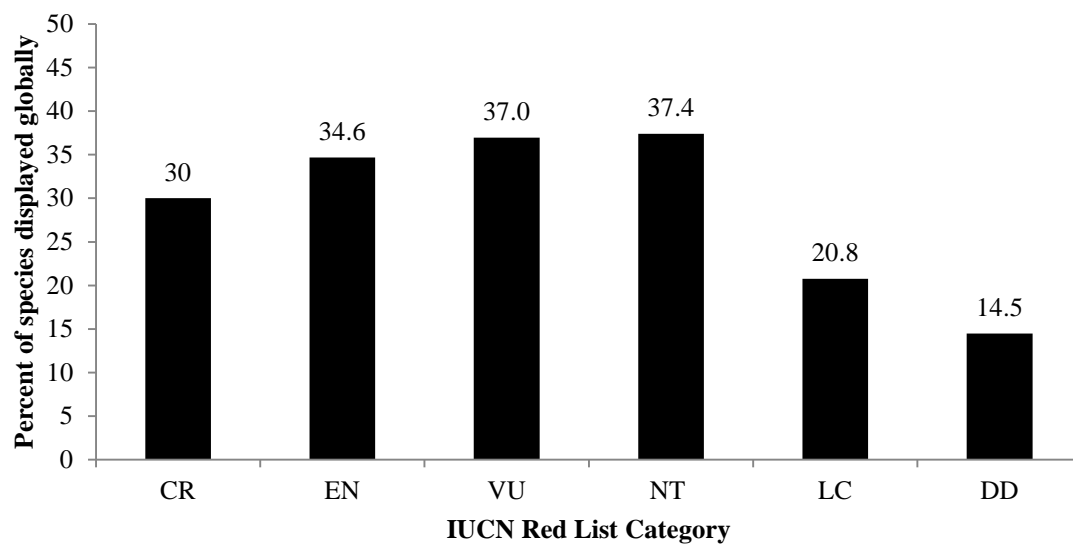
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22 Figure 2



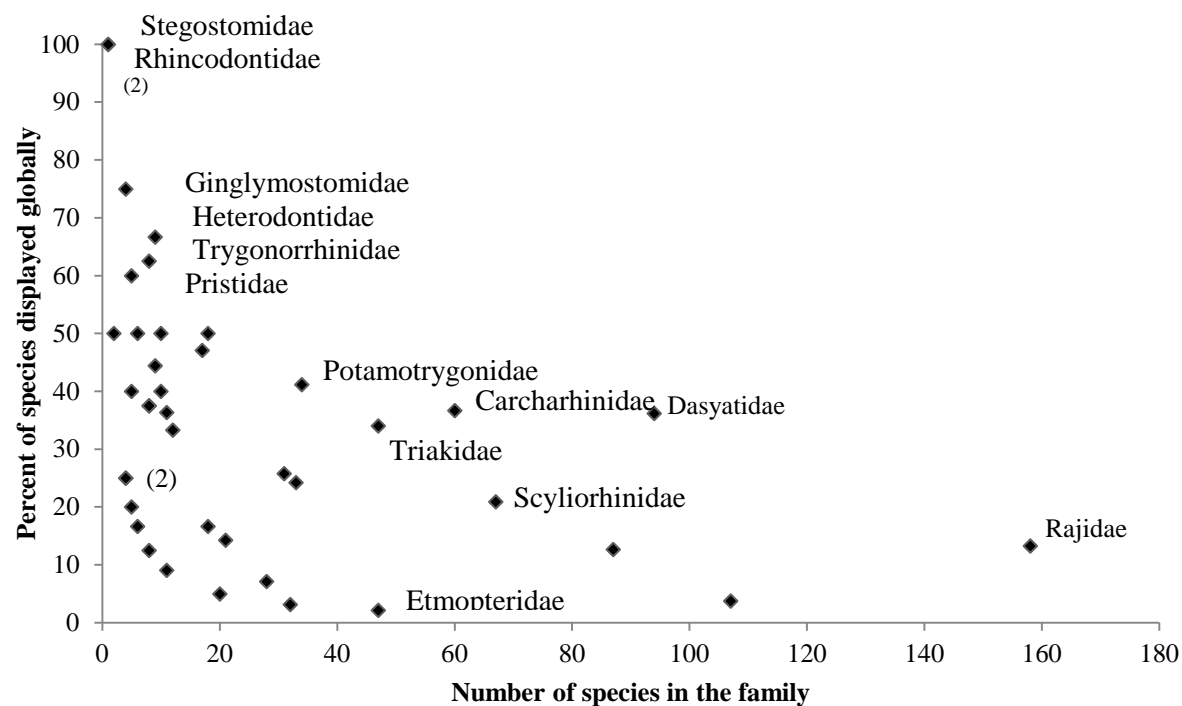
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24 Figure 3



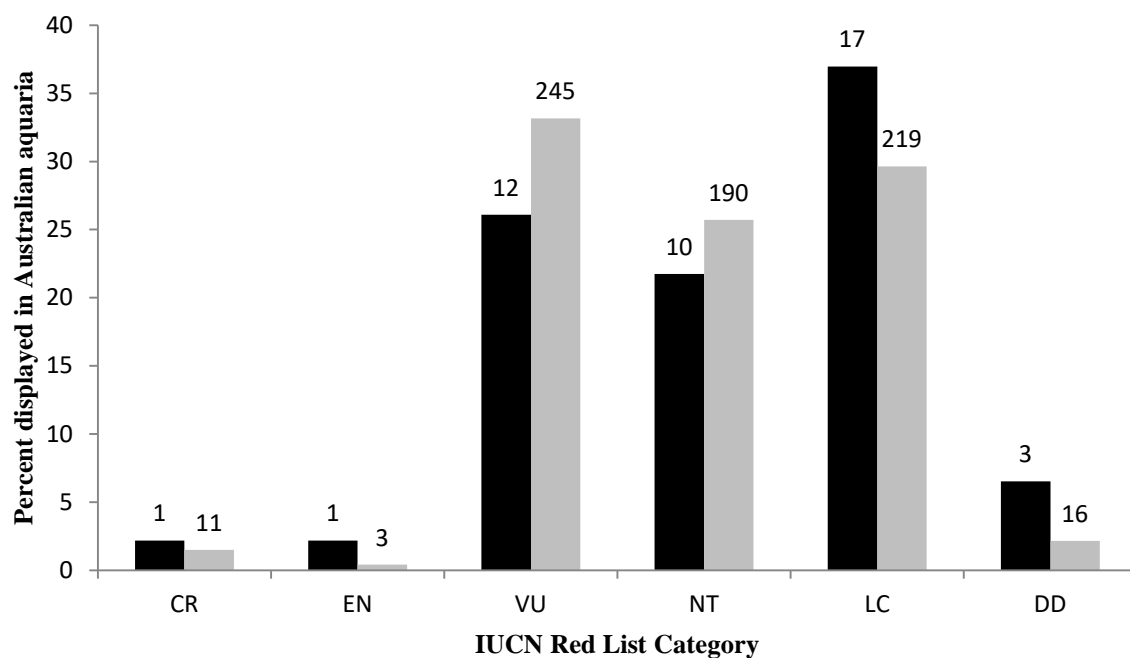
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26 Figure 4



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29 Figure 5



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Table 1 Families of elasmobranchs that dominate public aquarium displays globally in terms of absolute number of species displayed, and the threatened or DD status of those species according to the IUCN Red List of Threatened Species.

| Family | Number of species in Family | Number of species on display | Number (and percentage) of threatened* species on display | Number (and percentage) of DD species on display | Total percentage of species on display that are threatened or DD |
|------------------------------------|-----------------------------|------------------------------|---|--|--|
| Stingrays (Dasyatidae) | 94 | 34 | 13 (38.2 %) | 9 (26.5 %) | 64.7 % |
| Hardnose skates (Rajidae) | 158 | 21 | 7 (33.3 %) | 3 (14.3 %) | 47.6 % |
| Requiem sharks (Carcharhinidae) | 60 | 22 | 5 (22.7 %) | 1 (4.5 %) | 27.3 % |
| Houndsharks (Triakidae) | 47 | 16 | 2 (12.5 %) | 4 (25 %) | 37.5 % |
| Catsharks (Scyliorhinidae) | 67 | 14 | 1 (7.1 %) | 4 (28.6 %) | 35.7 % |
| River stingrays (Potamotrygonidae) | 34 | 14 | 1 (7.1 %) | 10 (71.4 %) | 78.6 % |

The following source data are available for Table 1: Online Resource 2(a) Elasmobranchs displayed in public aquaria and recorded breeding or mating in captivity. *IUCN Red List categories: Threatened encompasses: Critically Endangered, Endangered, and Vulnerable; DD, Data Deficient.

Table 2 Historical breeding records of elasmobranch species kept in Australian public aquaria during 2016, and their threatened status according to the IUCN Red List of Threatened Species and Dulvy et al. (2014).

| | Threatened or potentially threatened DD species* | | Species that are not threatened or potentially threatened | | All species | |
|--|--|-----------------|---|-----------------|-------------|-----------------|
| | <i>Bred</i> | <i>Not Bred</i> | <i>Bred</i> | <i>Not Bred</i> | <i>Bred</i> | <i>Not Bred</i> |
| Number of species | 9 | 7 | 18 | 12 | 27 | 19 |
| Number of individuals | 231 | 34 | 427 | 47 | 658 | 81 |
| Mean number of individuals per species (\pm SD) | 25.7 (32.1) | 4.9 (2.9) | 23.7 (21.5) | 3.9 (3.8) | 24.4 (25.5) | 4.2 (3.6) |

The following source data are available for Table 1: Online Resource 2(a) Elasmobranchs displayed in public aquaria and recorded breeding or mating in captivity and Online Resource 3: Species and numbers of elasmobranchs identified present in Australian public aquaria. *IUCN Red List categories: Threatened encompasses: Critically Endangered, Endangered, and Vulnerable; DD, Data Deficient; (IUCN 2016); Potentially threatened DD species as listed by Dulvy et al. (2014); SD, standard deviation.

Table 3 Elasmobranchs displayed in Australian public aquaria that are threatened according to the IUCN Red List of Threatened Species (CR, EN, VU)* or for which there is insufficient information available to accurately assess their status (DD)* but they are considered to be potentially threatened by Dulvy et al. (2014). Australian legislation listings (Commonwealth *Environment Protection and Biodiversity Conservation Act*; EPBC Act) are specified. Grey highlighted species are at risk of extinction (threatened) in Australian waters. Species marked with an asterisk have previously displayed breeding behaviour in captivity.

| Family | Species | Stock held in Australian public aquaria | IUCN Red List category (global) | IUCN Red List category (Australian waters) | Australian EPBC Act status |
|--------------------|---|---|---------------------------------|--|---|
| CARCHARHINIDAE | <i>Carcharhinus cautus</i> (nervous shark) | 1 | DD | LC | - |
| CARCHARHINIDAE | <i>Carcharhinus obscurus</i> (dusky shark)* | 11 | VU | NT | Ineligible for listing (data deficient) |
| CARCHARHINIDAE | <i>Carcharhinus plumbeus</i> (sandbar shark)* | 6 | VU | NT | - |
| CARCHARHINIDAE | <i>Glyphis glyphis</i> (speartooth shark) | 3 | EN | - | CR |
| CARCHARHINIDAE | <i>Negaprion acutidens</i> (sharptooth lemon shark) | 6 | VU | LC | - |
| DASYATIDAE | <i>Hemirhamphys fluviorum</i> (estuary stingray)* | 113 | VU | - | - |
| DASYATIDAE | <i>Himantura leoparda</i> (leopard whiplay) | 5 | VU | LC | - |
| DASYATIDAE | <i>Taeniurops meyeri</i> (blotched fantail ray)* | 33 | VU | LC | - |
| DASYATIDAE | <i>Urogymnus granulatus</i> (mangrove whiplay) | 5 | VU | LC | - |
| GINGLYMOSTOMATIDAE | <i>Nebrius ferrugineus</i> (tawny nurse shark)* | 14 | VU | LC | - |
| GLAUCOSTEGIDAE | <i>Glaucostegus typus</i> (giant shovelnose ray)* | 24 | VU | NT | - |
| ODONTASPIDIDAE | <i>Carcharias taurus</i> (grey nurse shark)* | 15 | VU | CR (East coast) NT (West coast) | CR (East coast) VU (West coast) |
| PRISTIDAE | <i>Pristis pristis</i> (largetooth sawfish) | 11 | CR | - | VU |
| RHINIDAE | <i>Rhina ancylostoma</i> (shark ray)* | 1 | VU | NT | - |
| RHINIDAE | <i>Rhynchobatus australiae</i> (bottlenose wedgefish) | 3 | VU | NT | - |
| STEGOSTOMIDAE | <i>Stegostoma fasciatum</i> (zebra shark)* | 14 | EN | LC | - |

The following source data are available for Table 3: Online Resource 2(a) Elasmobranchs displayed in public aquaria and recorded breeding or mating in captivity and Online Resource 3: Species and numbers of elasmobranchs identified present in Australian public aquaria. *IUCN Red List categories: CR, Critically Endangered; EN, Endangered; VU, Vulnerable; NT, Near Threatened; LC, Least Concern; DD, Data Deficient.