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 (Tlusty 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.

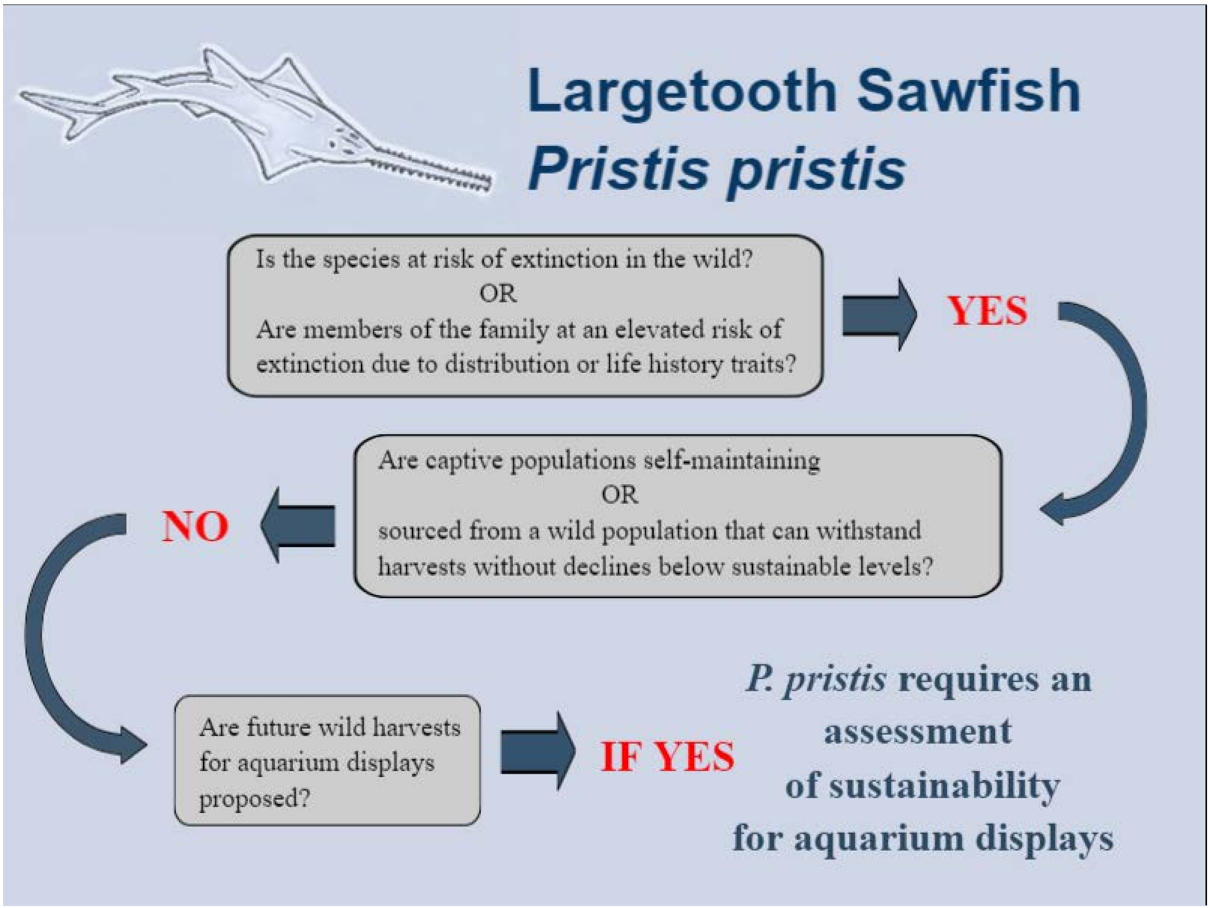
Fig. 2 The status of elasmobranch species according to IUCN Red List of Threatened Species categories. Black bars represent assessed elasmobranch species displayed in zoos and public aquaria globally. Grey bars represent all assessed elasmobranch species. Number of species listed at top of each bar. 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



20
21

Figure 2

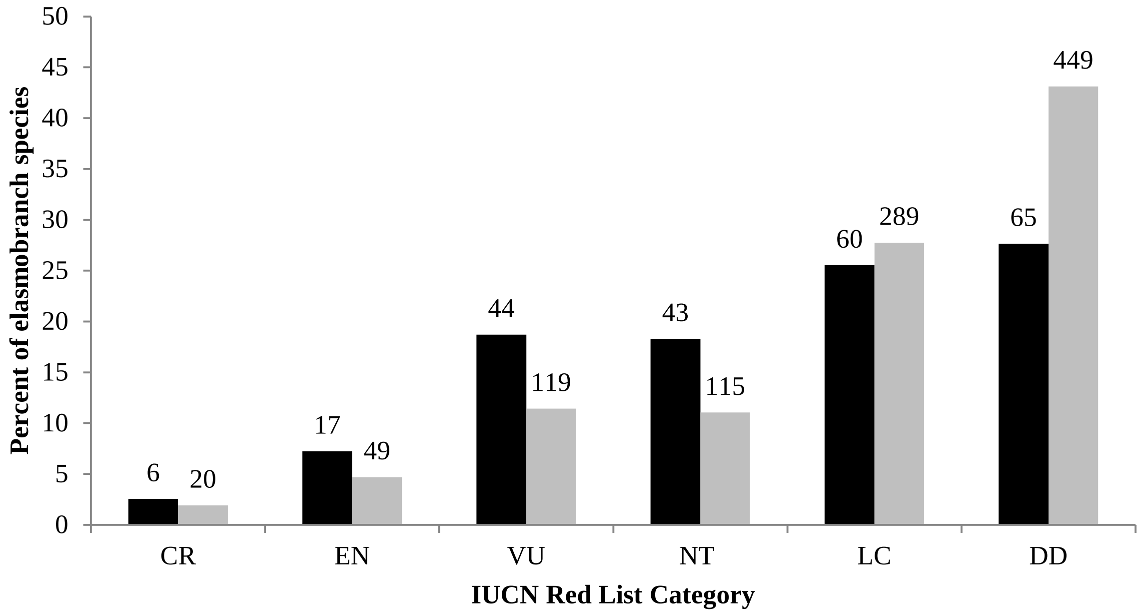

Percent of elasmobranch species
0
5
10
15
20
25
30
35
40
45
50
6
20
17
49
44
119
43
115
60
289
65
449
CR
EN
VU
NT
LC
DD
IUCN Red List Category

Figure 3

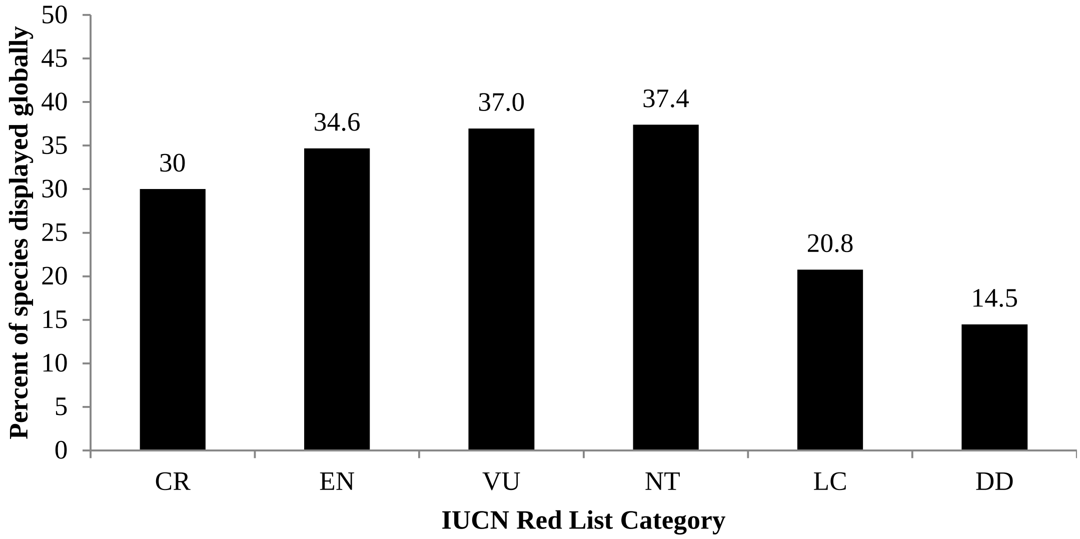
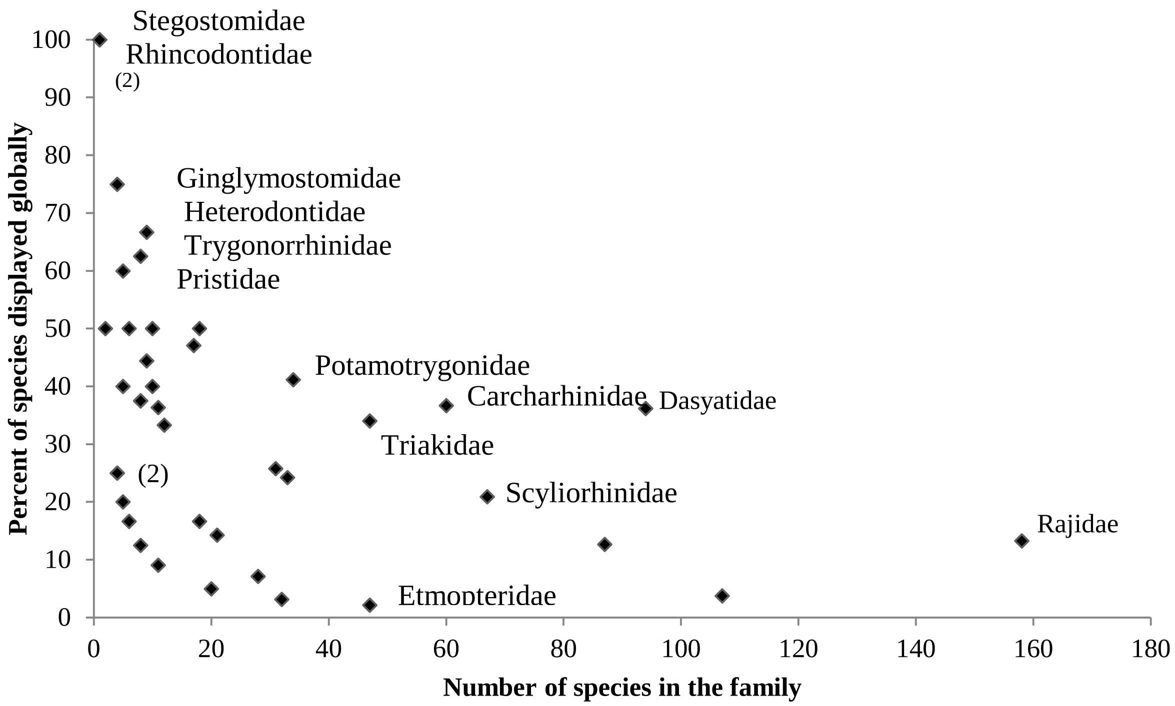
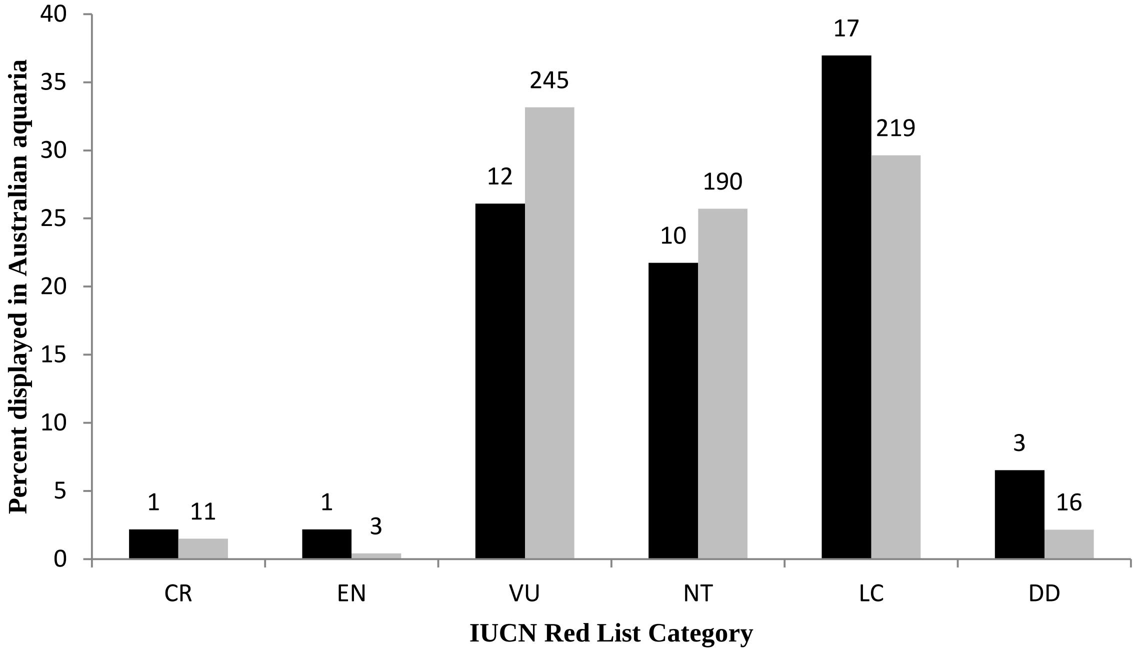

Percent of species displayed globally
50
45
40
35
30
25
20
15
10
5
0
30
34.6
37.0
37.4
20.8
14.5
CR
EN
VU
NT
LC
DD
IUCN Red List Category

Figure 4


Stegostomidae
Rhincodontidae
(2)
Ginglymostomidae
Heterodontidae
Trygonorrhinidae
Pristidae
Potamotrygonidae
Carcharhinidae
Dasyatidae
Triakidae
(2)
Scyliorhinidae
Rajidae
Etmopteridae
Percent of species displayed globally
0
10
20
30
40
50
60
70
80
90
100
0
20
40
60
80
100
120
140
160
180
Number of species in the family

29 Figure 5



30

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	
	Bred	*Not Bred*	*Bred*	*Not Bred*	*Bred*	*Not Bred*
Number of species	9	7	18	12	27	19
Number of individuals	231	34	427	47	658	81
Mean number of individuals per species (± 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 asterix 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	*Carcharhinus cautus* (nervous shark)	1	DD	LC	-
CARCHARHINIDAE	*Carcharhinus obscurus* (dusky shark)*	11	VU	NT	Ineligible for listing (data deficient)
CARCHARHINIDAE	*Carcharhinus plumbeus* (sandbar shark)*	6	VU	NT	-
CARCHARHINIDAE	*Glyphis glyphis* (speartooth shark)	3	EN	-	CR
CARCHARHINIDAE	*Negaprion acutidens* (sharptooth lemon shark)	6	VU	LC	-
DASYATIDAE	*Hemitrygon fluviorum* (estuary stingray)*	113	VU	-	-
DASYATIDAE	*Himantura leoparda* (leopard whipray)	5	VU	LC	-
DASYATIDAE	*Taeniurops meyeni* (blotched fantail ray)*	33	VU	LC	-
DASYATIDAE	*Urogymnus granulatus* (mangrove whipray)	5	VU	LC	-
GINGLYMOSTOMATIDAE	*Nebrius ferrugineus* (tawny nurse shark)*	14	VU	LC	-
GLAUCOSTEGIDAE	*Glaucostegus typus* (giant shovelnose ray)*	24	VU	NT	-
ODONTASPIDIDAE	*Carcharias taurus* (grey nurse shark)*	15	VU	CR (East coast) NT (West coast)	CR (East coast) VU (West coast)
PRISTIDAE	*Pristis pristis* (largetooth sawfish)	11	CR	-	VU
RHINIDAE	*Rhina ancylostoma* (shark ray)*	1	VU	NT	-
RHINIDAE	*Rhynchobatus australiae* (bottlenose wedgefish)	3	VU	NT	-
STEGOSTOMIDAE	*Stegostoma fasciatum* (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.