Journal for Nature Conservation 48 (2019) 1–11

Contents lists available at ScienceDirect

Journal for Nature Conservation

journal homepage: www.elsevier.com/locate/jnc

Assessing the conservation potential of fish and corals in aquariums globally

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A R T I C L E I N F O

Keywords:
Animal records
Animal records
Species360/ZIMS
Data sharing
Collection planning
Species vulnerable to climate change
Zoo

A B S T R A C T

Aquatic ecosystems are indispensable for life on earth and yet despite their essential function and service roles, marine and freshwater biomes are facing unprecedented threats from both traditional and emerging anthropogenic stressors. The resultant species and ecosystem-level threat severity requires an urgent response from the conservation community. With their care facilities, veterinary and conservation breeding expertise, re-introduction and restoration, and public communication reach, stand-alone aquariums and zoos holding aquatic taxa have great collective potential to help address the current biodiversity crisis, which is now greater in freshwater than land habitats. However, uncertainty regarding the number of species kept in such facilities hinders assessment of their conservation value. Here we analyzed, standardized and shared data of zoological institution members of Species360, for fish and Anthozoa species (i.e. Actinopterygii, Elasmobranchii, Holocephali, Myxini, Sarcopterygii and Anthozoa). To assess the conservation potential of populations held in these institutions, we cross-referenced the Species360 records with the following conservation schemes: the Convention on the International Trade of Endangered Species of Fauna and Flora (CITES), the IUCN Red List of Threatened species, climate change vulnerability, Evolutionary Distinct and Globally Endangered (EDGE) and The Alliance for Zero Extinction (AZE). We found that aquariums hold four of the six fish species listed by the IUCN Red List as ‘Extinct in the Wild’, 31% of Anthozoa species listed by Foden et al. (2013) as vulnerable to climate change, 19 out of the 111 Anthozoa EDGE species, and none of the species prioritized by the AZE. However, it is very likely that significant additional species of high conservation value are held in aquariums that do not manage their records in standardized, sharable platforms such as Species360. Our study highlights both the great value of aquarium and zoo collections for addressing the aquatic biodiversity crisis, as well as the importance that they maintain comprehensive, standardised, globally-shared taxonomic data.

1. Introduction

Healthy aquatic ecosystems are essential for biodiversity and humanity alike, but freshwater and marine biomes are experiencing increasingly severe threats to their species and at ecosystem level (Millennium Ecosystem Assessment, 2005; The Ocean Conference, 2017). Freshwater habitats cover less than 1% of the world's surface and yet contain 7% (126 000) of the estimated 1.8 million described species, including 25% of the estimated vertebrates (Vié, Hilton-Taylor, & Stuart, 2009). This vertebrate component includes ~40% of the known global fish diversity (Allan, Palmer, & Poff, 2005) with new species being discovered each year. Despite their important ecosystem service roles and biological richness, freshwater habitats are being degraded by human activity, which is leading to an extinction crisis. The United Nations Environment Program's (UNEP) Millennium Ecosystem Assessment report (Millennium Ecosystem Assessment, 2005) states that inland water ecosystems are in worse condition overall than any other broad ecosystem type, and estimates that about half of all freshwater wetlands (excluding lakes, rivers, and reservoirs) have been lost since 1900. The degradation and loss of inland water habitats and species is driven by water abstraction, infrastructure development, land conversion in the catchment, overharvesting and exploitation, introduction of exotic species, eutrophication and pollution, and global climate change (Hassan, Scholes, Ash, & Condition and Trends Working

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https://doi.org/10.1016/j.jnc.2018.12.001
Received 31 July 2018; Received in revised form 3 December 2018; Accepted 3 December 2018

Group, 2005). These stressors are increasingly threatening the viability of entire freshwater systems and their dependent biodiversity (Dudgeon et al., 2006; Dudgeon, 2010; Kundzewicz et al., 2007).

The marine biome is also severely impacted by human activities, which are observable at species, ecosystem, and biophysical levels. Reid et al. (2009) detail the many and diverse direct and indirect anthropogenic impacts acting on the marine environment and their consequences for biodiversity and human well being. These include habitat alteration and loss, disturbances leading to mortality of marine life, pollution, disease translocation, nutrient overloading, changes in salinity, sea-level raise, ocean heat content and sea-ice coverage decrease, deoxygenation, and ocean acidification. A dramatic example of a disturbed environment is the Florida Reef coral disease outbreak, which is the result of a combination of more than one stressor. The warmer water temperatures associated to climate change combined with opportunistic pathogens have affected nearly 390 km^2 of Florida's reefs only in the last four years (Precht, Gintert, Robbart, Fura, & Van Woesik, 2016; Wright, 2018).

Addressing the aquatic biodiversity crisis requires concerted engagement across all relevant agencies and organizations. Stand-alone aquariums and zoos holding aquatic taxa (from here on both are included in the term aquarium) fill a diverse range of roles (Barongi, Fisken, Parker, & Gusset, 2015; Conde, Flesness, Colchero, Jones, & Scheuerlein, 2011; Fa, Funk, & O'Connell, 2011; Gusset & Dick, 2010; Penning et al., 2009; Pritchard, Fa, Oldfield, & Harrop, 2012; Zimmermann, Hatchwell, Dichie, & West, 2007). With more than 700 million visitors worldwide every year, technical expertise, physical and financial resources, these organizations are uniquely placed to help protect and understand biodiversity (Gusset & Dick, 2011).

Like the wider zoo community, aquariums range from leading research and conservation facilities to purely commercial organizations. In addition to their potential for public awareness-raising and policy influencing, there are many specialist conservation and research possibilities including species threat assessments (Conde et al., 2011), conservation breeding, assisted colonization and reintroduction programmes (Conway, 2011; Gilbert & Soorae, 2017), bio-banking (Starek, Conde, Siriaroonrat, Ryder & Hvilsom, 2018), ecosystem monitoring and conservation support.

Current freshwater fish conservation initiatives, such as FishNet (Koldewey, Cliffe, & Zimmerman, 2013), highlight the potential of aquariums for providing both in situ and ex situ species conservation assistance. Aquarium based research into coral propagation is another example of the valuable contribution that these facilities can provide (Craggs et al., 2017). However, an appreciation of their conservation role needs to be better understood and acted upon if their full potential is to be realized (Gilbert & Soorae, 2017). Aquariums can provide important information on basic biology and life history traits as well as genetic reservoirs for species threatened with extinction in the wild (Moss, Jensen, & Gusset, 2015). These institutions have the potential to be important contributors to bio-banking initiatives such as the Frozen Ark cryopreservation program (http://www.frozenark.org/). Moreover, aquarium staff often possess wide-ranging species knowledge which, coupled with in situ and ex situ conservation management expertise and institutional financial commitment, allows the creation of diverse partnerships that makes the aquarium community well placed to respond to aquatic conservation challenges. For instance, aquarists' knowledge on life histories of species can inform threat evaluation of species for which data on wild populations is not available.

The conservation potential of aquarium populations is compromised by a current lack of readily available information of the total number of species held. Although one population in a single aquarium can have a critical role for the conservation of a species, the interaction among different institutions through standardized shared animal records is often essential for optimal population management and for informing the prioritization for species conservation assistance (Reid, Contreras MacBeath, & Csatádi, 2013). For terrestrial species, Conde et al. (2011) showed that zoo members of the Species360 network hold one in every seven threatened species (15%), but the same kind of information is currently unavailable for aquatic species. Addressing this knowledge gap is essential for a comprehensive assessment of the importance of aquariums for ex situ conservation. The conservation potential of animals held in aquariums can be optimized when combined with species threat assessments and prioritization schemes, such as (1) their CITES designation (CITES, 1973), (2) their IUCN threat status (Baillie, Hilton-Taylor, & Stuart, 2004), (3) their vulnerability to climate change (Foden et al., 2013), (4) their evolutionary distinctiveness (EDGE, 2017), and (5) their prioritization in the Alliance for Zero Extinction (AZE, 2018). To further inform the conservation potential of populations held in aquariums and demonstrate the importance of global standardized shared animal record keeping, here we analyzed how many species of the Chondrichthyes and Osteichthyes fishes and the Anthozoa corals and anemones (hereafter 'corals and anemones' refers to corals and anemones of the class Anthozoa) are represented among those species prioritization schemes. Based on our results, we provide recommendations to support the decision-making process for current and potential new ex situ species and collection planning for conservation programs in aquariums.

1.1. *Aquatic species under human care*

Populations of high conservation value are usually managed in studbooks to ensure their genetic variability and demographics (collection of continuously updated data relevant to the captive population of a species (WAZA, 2018)). However, aquariums have generally been slower to manage their populations due to the complexities and lack of protocols for group management in the way that most aquatic species are kept. For instance there are only 26 studbooks for two classes of fish species (i.e. Actinopterygii and Elasmobranchii) and none for corals or anemones, while there are 704 studbooks for the mammals, birds, reptiles and amphibians across five regions [i.e. EAZA (European Association of Zoos and Aquaria), AZA (American Association of Zoos and Aquariums), PAAZA (African Association of Zoos and Aquaria), ALPZA (Latin American Zoo and Aquarium Association), and ZAA (Australasian region Zoo and Aquarium Association)] (Hedeager, 2018). In the case of fish, coral and anemone species, the collection of wild specimens by aquariums is still a relatively common practice (Tlusty et al., 2013). There are a number of reasons for this, including difficulties in breeding some species in captivity, added costs associated with captive breeding and the wide availability of animals via established commercial ornamental fisheries. For many aquariums the requirement to establish managed programs for aquatic species was shadowed by efforts to learn technologies to aid aquarium system management. An increasing number of aquariums are realizing significant ex situ breeding success across a wide range of taxa and developing managed programs for several species of threatened fish. Gradually, aquariums are also beginning to follow best practices for sustainable harvesting of wild animals that can provide in situ conservation benefits. For example, the project Piaba in Brazil (Piaba, 2017) aims to create a sustainable supply of wild-caught ornamental fishes, which provides a livelihood for local communities and encourages good management of fish stocks. However, zoos focusing on terrestrial species have been significantly more restricted to ensuring the genetic viability of their populations by not importing animals from the wild. This is partly the result of increased numbers of zoos focusing on conservation goals and the strict regulations imposed by the Convention on International Trade of Endangered Species of Wild Fauna and Flora (CITES). On the other hand, aquariums have not faced the same limitations partly due to a historical focus on terrestrial species by CITES.

1.2. Convention on International Trade of Endangered Species of Fauna and Flora (CITES)

To help address overexploitation of natural populations and ensure species survival in the wild, several states and regional economic integration organizations (referred to as Parties) joined in 1973 to create CITES. Today 183 Parties are bound by CITES, an international agreement to regulate international trade in plants and animals and their products. CITES lists a species when it is either endangered with extinction or when the international trade affects its population's sustainability. However, to date, there are only 147 aquatic species listed in CITES (CITES, 2017). This is of concern since the sustainability of many aquatic species is threatened by international trade. This includes some species of sharks and tuna, which are currently unsustainably harvested and traded (Clarke et al., 2006). Here we analyzed which species in aquariums are indexed in CITES and its overlap with other prioritization schemes, such as the IUCN Red List.

1.3. International Union for Conservation of Nature (IUCN) Red List

The International Union for Conservation of Nature's (IUCN) Red List assesses the threat status of species by their extinction risk. Although Red List assessment of aquatic taxa is still incomplete, of the 67 assessed bony fish, six were found to be 'Extinct in the Wild' (EW) (IUCN, 2017). The representation of these species in aquariums illustrates the conservation role that aquariums have in preventing species extinction and providing the opportunity for such species to be safely returned to the wild. However, other threatened criteria are important, such as populations of species described as 'Critically Endangered' (CR), which, if managed properly, could support conservation programs in the wild. While exploring the representation of other IUCN Red List categories is crucial, we would like to emphasize the importance of species listed as 'Data Deficient' (DD) in aquariums. This is because there are a great number of aquatic species that have been reviewed by the IUCN Red List, but a lack of knowledge prevents an accurate listing for these species. This is partly due to taxonomic uncertainty (Butchart & Bird, 2010), which prevents cataloguing a species in a threatened status. Some of these species might already be threatened and at risk of extinction before there is enough information to list them under a threatened category. For example, Bland, Collen, Orme, and Bielby (2015) estimated that 63.5% of all DD mammals were threatened with extinction and have smaller geographical ranges than species with sufficient data for the IUCN Red List assessment. The same was shown for amphibians, in which DD species are more threatened with extinction than their data sufficient counterparts (Howard & Bickford, 2014). Therefore, here we analyzed the number of species in aquariums within the IUCN Red List categories and highlighted not only the number of threatened species but as well those listed as DD.

Despite the importance of the IUCN Red List to explore the conservation potential of populations held in aquariums, there are other criteria that should be considered. For example, a species listed as 'Least Concern' (LC) may not be given immediate conservation attention, despite being at risk from climate change if it has not been reassessed in recent years or is susceptible to rapid declines or thresholds. Failure to identify such species threatens their survival and undermines the role that aquariums can play in protecting them (Martin et al., 2012; Pearce-Kelly, Khela, Ferri, & Field, 2013).

1.4. Species' vulnerability to climate change

IUCN's trait-based assessment of species' vulnerability to climate change (VCC) (Foden et al., 2013) estimates the relative vulnerability of all birds, amphibians, and corals globally. Relative scores of high and low vulnerability were based on the species' exposure to climatic change (e.g. ocean temperature and acidity changes), in combination with their inherent sensitivity (i.e. their ability to persist and cope) and adaptive capacity (i.e. their ability to escape or adapt). Sensitivity and adaptive capacity were assessed based on the species-specific ecological, distribution, morphological and life history traits that exacerbate or mitigate the impacts of climate change (Carr, Outhwaite, Goodman, Oldfield, & Foden, 2013; Foden & Young, 2016; Gardali, Seavy, DiGaudio, & Comrack, 2012; Young et al., 2012). Populations of species that are vulnerable to climate change and are held in aquariums can provide valuable information on biological traits (e.g. demography, physiology, reproductive biology and environmental tolerances), including through observations of their sensitivity to environmental stresses. These may in turn inform conservation responses and provide important 'insurance' populations. Here we assess how many Anthozoa species in Species360 member aquariums have formally been assessed as highly vulnerable to climate change.

1.5. Evolutionary Distinct and Globally Endangered (EDGE)

When looking at conserving evolutionary uniqueness, the EDGE score of a species is critical. The EDGE score represents both the amount of evolutionary history and the threat level of a species (Isaac, Turvey, Collen, Waterman, & Baillie, 2007; Isaac, Redding, Meredith, & Safi, 2012). EDGE species are those that in addition to having been formally assessed as threatened ['Vulnerable' (VU), 'Endangered' (EN) and 'Critically Endangered' (CR)] by the IUCN Red List assessment process are phylogenetically distinct from their closest related surviving species (EDGE 2017). EDGE relative score has only been developed for the classes Mammalia, Amphibia, Aves, Reptilia (Gumbs, Gray, Wearn, & Owen, 2018) and Anthozoa. Here we looked at EDGE species, but also species with high Evolutionary Distinctiveness (ED) that are 'Least Concerned' or 'Near Threatened'.

1.6. Alliance for Zero Extinction

Species at the tipping point of extinction are those assessed by the Alliance for Zero Extinction (AZE). AZE is a consortium of conservation-oriented organizations with the goal to ensure the survival of 'Critically Endangered' (CR) and 'Endangered' (EN) species that are restricted to single sites (Ricketts et al., 2005). There are 920 species in the AZE list distributed among 588 sites globally for mammals, birds, amphibians, reptiles, conifers and reef-building corals. There are only two AZE listed coral species: *Porites pukoensis* from Molokai Island, US and *Siderastrea glynni* from Uraba Island, Panama (AZE, 2018).

1.7. Aquariums and Anthozoa

Tropical coral reef ecosystems occupy less than 0.1% of the ocean floor but provide habitat for at least 25% of known marine species (Fisher et al., 2015; Hoegh-Guldberg, Poloczanska, Skirving, & Dove, 2017). Although corals play a key role in the maintenance of marine biodiversity, in 1998 58% of the global corals were threatened by human actions (Bryant, Burke, McManus, & Spalding, 1998). Furthermore, 25% of corals have been destroyed or severely damaged by the effects of climate change (Heron et al., 2017; Roberts et al., 2002). The loss of corals severely impacts associated biodiversity, including sharks, bony fishes, sea turtles and sponges (Munday, 2004). Climate change, intensive fisheries, pollution, and the wildlife trade present major threats to corals. From 2003 to 2013, corals constituted 98% of the total trade of live animal specimens from Indonesia to the Netherlands (Janssen & Blanken, 2016). Aquariums are already playing a key role by providing knowledge and expertise in coral reproduction and restoration techniques in natural habitats. Some examples include the SECORE International initiative (SECORE, 2017) in which a collaboration between aquariums and researchers are working to re-establish 'Critically Endangered' (CR) stony corals in the Caribbean Sea and also the work of Taronga Zoo, Australia (Hagedorn et al., 2012) with the cryopreservation of two species with enough genetic material for the production of over 200 million colonies. Craggs et al. (2017) provide a further example of the important role aquariums can play in advancing coral spawning capability and associated production of potentially more climate change resilient populations. However, an assessment of the overall value of aquariums for coral conservation is seriously compromised by a current lack of available information on total species numbers held worldwide. Because of the current concern on coral reefs, we gave a special focus to this group to better explore and identify the potential of aquariums to help conserve these taxa.

2. Materials and methods

To assess the number of aquatic species in aquariums, we used data from the Species360 organization that manages the Zoological Information Management System (ZIMS) (ZIMS, 2017), a real-time international database used by 1 111 aquariums and zoos (Species360, 2017). We analyzed species holdings of the 594 member institutions that report to have species belonging to the fish classes of Actinopterygii (ray-finned fishes), Elasmobranchii (cartilaginous fishes such as sharks and rays), Holocephali (chimeras), Myxini (hagfishes), Sarcopterygii (lobe-finned fishes) and to one class from the Cnidaria phylum, Anthozoa (corals and anemones). We excluded 6% of the records (2 819 out of 44 884) because they referred to groups of individuals. Of these, 2 441 records referred to species (1 343 different species), 315 to genus, 25 to families, 19 to subspecies, 8 to order, 7 to domestic, 3 to subclass, and 1 to class. Only for Anthozoa, we excluded a total of 13% of the records, comprising 276 species due to reporting only at a group level without precise counting of number of individuals.

In order to determine the conservation potential of aquariums we compared the species from the selected aquatic taxa in ZIMS with the (1) CITES Appendices or species index (CITES, 1973), (2) the IUCN Red List (IUCN, 2017), (3) Vulnerability to climate change (Foden et al., 2013), (4) EDGE (EDGE, 2017) and (5) AZE (AZE, 2018). We further calculated the total number of individuals in the entire Species360 network. For some species, the number of individuals is not recorded because they are managed as groups or colonies, ranging from approximately two to hundreds of thousands of individuals, depending on the species and management strategies. Due to the complexities to interpret the number of individuals by groups we did not include groups in our analysis.

2.1. *Convention on International Trade of Endangered Species of Fauna and Flora (CITES)*

Species listed in CITES were indexed in three different appendices. In the Appendix I are species that are threatened with extinction and in which trade is not permitted, except in special circumstances such as scientific research. In Appendix II are species which trade should be controlled in order to promote sustainable trade, and in the Appendix III are species protected in at least one country and, consequently, should be treated with special concern from all parties (CITES, 1973). Here we analyzed the number of species in each appendix for each of the target assessment classes.

2.2. *International Union for Conservation of Nature (IUCN) Red List*

The IUCN Red List status provides a species-specific indication of the globally threatened status, by listing species in different categories (Baillie et al., 2004). Species that no longer exist as their last individual has died are categorized as 'Extinct' (EX) and species that have disappeared from the wild but still have representatives in captivity are classified as 'Extinct in the Wild' (EW). Species in the categories of 'Critically Endangered' (CR), 'Endangered' (EN) or 'Vulnerable' (VU) are referred as threatened. Species that are close to meeting a threatened threshold but evaluated to have a low risk of extinction are considered as 'Near Threatened' (NT), and 'Least Concern' (LC). Species can also be catalogued as 'Data Deficient' (DD) when there is not enough information for their evaluation (IUCN, 2017). In this study we analyzed the number of species in each threat category.

2.3. *Climate change vulnerability/EDGE/AZE*

Most of the data for marine species assessed for vulnerability to climate change by Foden et al. (2013) were of the Scleractinian order. Although the IUCN Red List investigates threats related to climate change, the Foden et al. (2013) assessment identified species that might not yet be threatened but can potentially become at risk in a near future due to climate change. We looked at whether focal species were categorized as of high and low vulnerability to climate change.

Data for species listed in EDGE and AZE were only available for the Scleractinian corals of the class Anthozoa. We considered as EDGE all the species with an evolutionary distinctiveness (ED) score equal or bigger than the mean (5.176730086) of all assessed species, according to EDGE (2017), independently of the species IUCN Red List category.

2.4. *Taxonomic standardization*

To standardize taxonomic names across the six different data sources, we used the accepted scientific name according to Catalogue of Life (CoL) (Roskov et al., 2015). Subspecies for which the accepted scientific name (i.e. genus and epithet) were not found or when the species was not specified in the database were not considered in this study. We automatically retrieved the IUCN threat status (IUCN, 2017) and scientific names using the *taxize* (Chamberlain & Szöcs, 2013) *R* package (R Core Team, 2016), which searches for accepted names based on synonyms and fuzzy matching names. We manually searched for the species names that could not be retrieved automatically.

We mapped aquarium geographical locations by their associated species IUCN threat category using the R package *ggmap* (Kahle & Wickham, 2018). In the case of aquariums holding more than one species, only the species with the highest IUCN Red List threat status (more threatened with extinction) was plotted to give an overview of the geographical location of the institutions that hold threatened species. We generated a Venn diagram with the web tool from Bioinformatics and Evolutionary Genomics (2018). For the rest of the maps and plots we used *R* (R Core Team, 2016).

2.5. *Recommendations for species prioritization*

For fish, we generated a list of targeted species for species prioritization, based on their overlap between the IUCN Red List status and Species360. We put special focus on those that are already being managed as a studbook in the regional association of EAZA (European Association of Zoos and Aquaria), AZA (American Association of Zoos and Aquariums), PAAZA (African Association of Zoos and Aquaria), ALPZA (Latin American Zoo and Aquarium Association) and ZAA (Australasian region Zoo and Aquarium Association). For corals and anemones, the prioritization consisted on species based on the IUCN Red List, as well as how many of the species from the different threat categories overlap with a high Evolutionary Distinctiveness, AZE, and their vulnerability to climate change. For fish, we provided a list of conservation potential based on the number of species listed in CITES and with an active studbook.

3. Results

The ZIMS database has records of 3 511 aquatic species for the six studied taxonomic classes. For this analysis, we were only able to retrieve the accepted scientific names of 96% of the species (3 370), due to a combination of taxonomic conflict issues and genus level only taxa being recorded. The most represented taxa by the number of individuals in aquariums are that of the cartilaginous fishes (Elasmobranchii)

Table 1
Number of aquatic species held in aquariums of the Species 360 network. Total number of species in the different classes, number of described species according to Catalogue of Life (CoL), and percentage of species in aquariums from the described number in Catalogue of Life.

Class	N° of species in Aquariums	N° of species in CoL	% in Aquariums
Actinopterygii	2978	32 024	9.30
Elasmobranchii	126	1 181	10.67
Holocephali	1	51	1.96
Myxini	3	78	3.85
Sarcopterygii	5	8	62.5
Anthozoa	257	6 407	4.01

although not the most species-rich (Table 1). The class with the highest number of species in aquariums is the ray-finned bony fish (Actinopterygii), with almost 3 000 species, representing ~9% of all the described species in this class. The Holocephali and Myxini, on the other hand, had the lowest percentage of the described species present in aquariums (Table 1).

As shown in Fig. 1, most of the aquariums are geographically located in temperate zones in Europe and America, while the natural distribution of many fish and corals is located in tropical areas. We found that 62% (367/594) of the institutions in this analysis have at least one threatened species under their care.

3.1. Fish in aquariums

From the fish species (of the classes Actinopterygii, Elasmobranchii, Holocephali, Myxini and Sarcopterygii) described in Catalogue of Life, 14% (3113/33342) are represented in Species360's aquariums. Of the fish species listed in CITES, 34% (16/47) are within Species360 aquarium's members (Table 2). Divided by IUCN Red List threatened categories we found that these aquariums hold four of the six (67%) fish species listed as 'Extinct in the Wild' (*Cyprinodon alvarezi*, *Cyprinodon longidorsalis*, *Ameca splendens*, *Skiffia francesae*), which have a mean population size of 637.75 (SD: 1044.025), with the biggest population of 2 200 individuals, for the butterfly splitfin (*Ameca splendens)*. However, aquariums do hold additional species whose assessments need

Table 2
Species in the different CITES appendices. Total number of species described by Catalogue of Life and in aquariums in each CITES appendix and taxonomic class.

	Appendix I	Appendix II	Appendix III	Total in CoL
Elasmobranchii				
Total described (CoL)	6	20	18	1 181
In aquariums	3	4	8	126
Sarcopterygii				
Total described (CoL)	2	1	0	8
In aquariums	0	1	0	5
Anthozoa				
Total described (CoL)	0	1701	3	6 407
In aquariums	0	158	0	257

CoL: Catalogue of Life (Roskov et al., 2015).

updating that are also 'Extinct in the Wild', such as *Cyprinodon veronicae*. From the fish in aquariums, 8% (256 out of the 3 113 fish species in aquariums) are considered threatened by the IUCN Red List (i.e. 'Vulnerable', 'Endangered' and 'Critically Endangered'). Of the 'Critically Endangered' (CR) listed species 15% (56/387) are in aquariums, which represents only 2% (56 CR species out of the total 3113 species hold) of their fish collections. The largest populations of 'Critically Endangered' species are of blackfin tilapia (*Sarotherodon linnellii*) and the *Tilapia deckerti,* with 570 and 560 individuals, respectively. Aquariums collections are constituted of 2% (56/3113) of 'Endangered' species and 5% (126/3113) 'Vulnerable' species (Fig. 2). The most represented IUCN Red List category is 'Least Concern'– 100% of the Holocephali and Sarcopterygii, 78% of the Actinopterygii, 67% of the Myxini, and 30% of the Elasmobranchii. Also, it is important to notice the proportion of 'Data Deficient' species in aquariums – 33% of the Myxini, 17% of the Elasmobranchii and 5% of the Actinopterygii (Fig. 2), with a mean population size of 102.9364 individuals (SD: 475.1134). There are 1 249 species not yet assessed by the IUCN Red List and they have the species with the highest population numbers recorded in aquariums (mean: 100.823 SD: 427.755) (Fig. 3). For example, the guppy, *Poecilia reticulata,* not yet assessed by the IUCN Red List, is the species with the largest population registered in aquariums with 410 328 individuals.

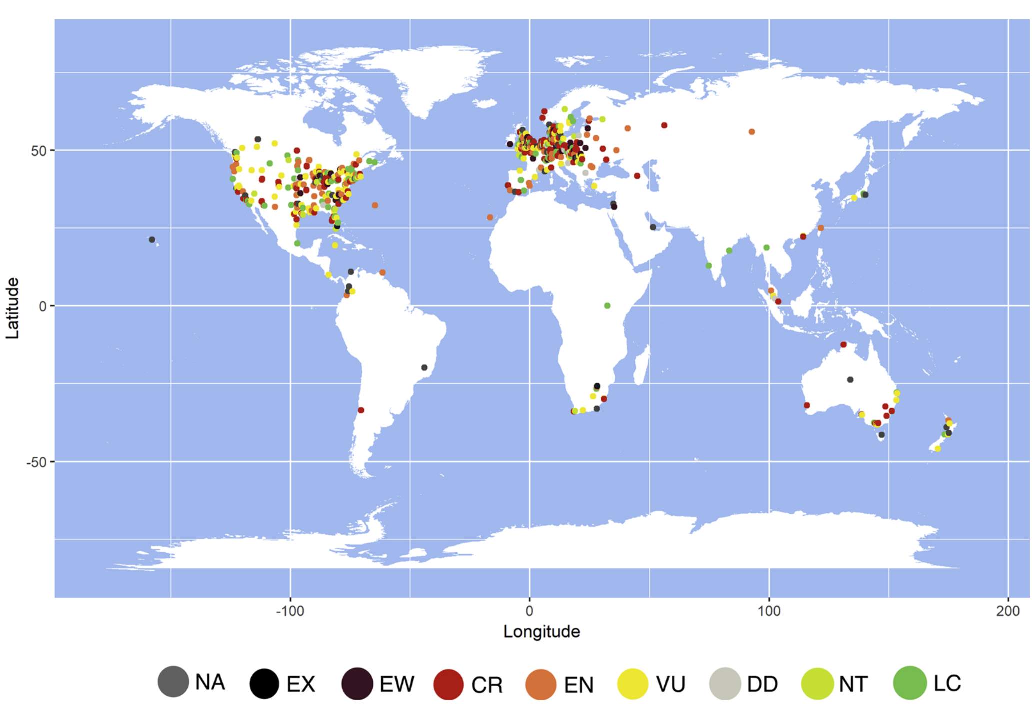

Fig. 1. Geographical distribution of aquariums of the Species360 network holding fish and corals taxa of the classes Actinopterygii, Elasmobranchii, Holocephali, Myxini, Sarcopterygii and Anthozoa species. Each point represents the most threatened species in an institution. The colours represent its IUCN Red List category - NA: not assessed; EX: extinct; EW: extinct in the wild; CR: critically endangered; EN: endangered; VU: vulnerable; DD: data deficient; NT: near threatened; LC: least concern.

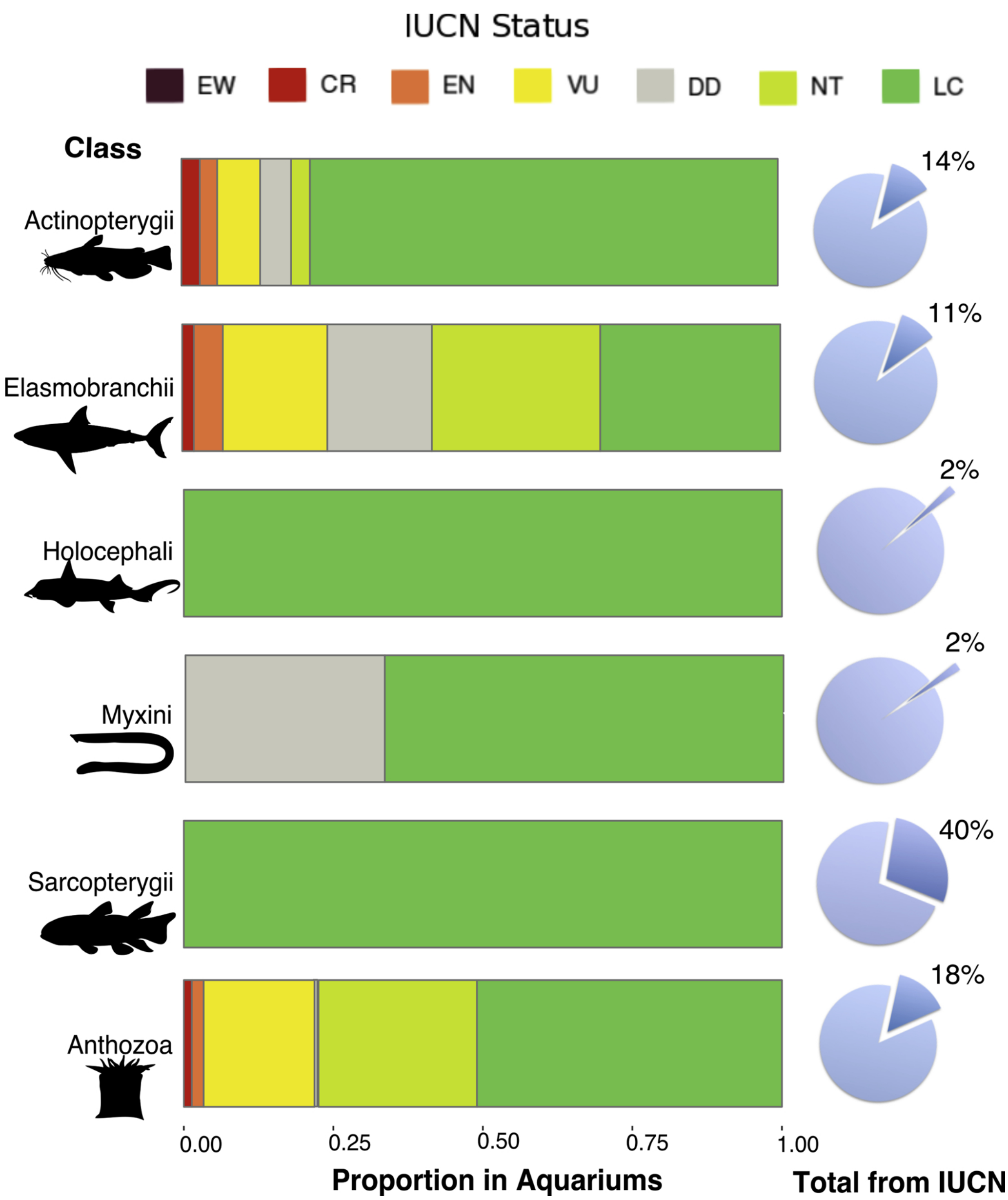

Fig. 2. Proportion of species holdings in each IUCN Red List category by Species360's members. EW: extinct in the wild; CR: critically endangered (15% of the species in all classes); EN: endangered (10% of the species in all classes); VU: vulnerable (14% of the species in all classes); DD: data deficient (4% of the species in all classes); NT: near threatened (19% of the species in all classes); LC: least concern (17% of the species in all classes). The pie charts indicate the percentage of species that are in aquariums from the IUCN Red List assessed species. Species not yet assessed by the IUCN Red List are not represented here. Image: Holocephali by Tambja (vectorized by T. Michael Keesey) https://creativecommons.org/licenses/by-sa/3.0/.

3.2. Corals and anemones in aquariums

Aquariums hold, at least, 4% of the 6 407 coral and anemone species of the class Anthozoa described in Catalogue of Life (Table 1). CITES lists 27% (1 704/6 407) of the described Anthozoa, of which 9% (158/1 704) are in Species360's aquariums. There are 234 threatened coral and anemone species of which 14% (33/234) are in aquariums, accounting for 13% (33/257) of their Anthozoa collection. Two of the six species of 'Critically Endangered' species are in aquariums (i.e. *Acropora palmata* and *Acropora cervicornis*). Aquariums also hold 11% (3/28) and 14% (28/199) of all the species assessed as 'Endangered' and 'Vulnerable', respectively. For non-threatened species, aquariums hold 23% (40/174) of 'Near Threatened', 26% (77/292) of the 'Least Concerned' and less than 1% of the 'Data Deficient' Anthozoa species. Furthermore, 24% of the 611 coral and anemone species assessed as vulnerable to climate change are at least in one aquarium. Broken down by the two categories of high and low vulnerability zoos hold 23% and 24%, respectively, with the highest percentage of those listed as 'Least Concerned' [33% (74/224)] (Table 3). Aquariums in the Species360 network hold 19 out of the 111 Anthozoa coral species listed as evolutionary distinct.

3.3. Recommendations for prioritization

From the five zoological regions (i.e. EAZA, AZA, PAAZA, ALPZA and ZAA), only institutions part of EAZA and AZA have active studbooks for Elasmobranchii and Actinopterygii. We found that aquariums in the Species360 network have 88% (23) of the 26 species with a studbook in the two mentioned regions. Of the species with a studbook that are not part of the Species360 network, one of them (*Pristis pectinata*) is listed in Appendix I of CITES. Seven species with a studbook are considered 'Critically Endangered' by the IUCN Red List, with population sizes ranging from two to 406 individuals. The least represented IUCN Red List status in a studbook is of an 'Endangered' species (tiger river stingray- *Potamotrygon tigrina*) which has a population of 11 individuals. The biggest population with a studbook is of the 'Vulnerable' lined seahorse (*Hippocampus erectus*), with 1 746 individuals.

Aquariums have 21% (17) of the 82 coral and anemone species listed both as ED and vulnerable to climate change (Fig. 4). Moreover, aquariums hold one species assessed as vulnerable to climate change (*Montastraea curta*) that has not yet been assessed by the IUCN Red List. Species of concern not yet represented in aquariums are the two species listed by AZE (i.e. *Porites pukoensis*, *Siderastrea glynni*) and the 65

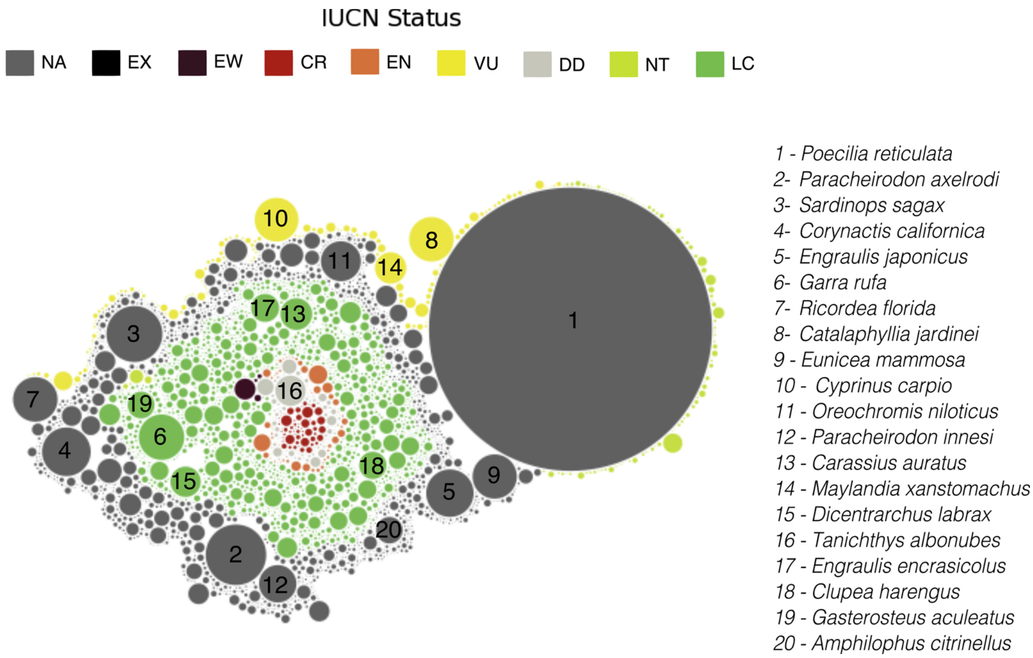

Fig. 3. Population sizes of fish and corals. Number of individuals of the classes Actinopterygii, Elasmobranchii, Holocephali, Myxini, Sarcopterygii and Anthozoa across all aquariums of the Species360 network. Each species is represented by a bubble colored by its IUCN global threatened status - NA: not yet assessed by the IUCN Red List; EX: extinct; EW: extinct in the wild; CR: critically endangered; EN: endangered; VU: vulnerable; DD: data deficient; NT: near threatened; LC: least concern. The size of the bubbles is proportional to the population size which ranges from a maximum of 410 328 individuals to 1 individual (mean 250, SD: 7103.5). The 20 species with biggest population sizes are numbered and listed.

Table 3
Number of Anthozoa species assessed as of high, low, and unknown climate change vulnerability (based on Foden et al. (2013)). Number of species described in Catalogue of Life and in aquariums grouped by its IUCN Red List categories: NA: not assessed; CR: critically endangered; EN: endangered; VU: vulnerable; DD: data deficient; NT: near threatened; LC: least concern. Numbers in brackets denote the percentage of the total of species in each of the vulnerability categories.

	NA	CR	EN	VU	DD	NT	LC	Total
High vulnerability								
Total described (CoL)	0	0	8	31	12	14	36	101 (100%)
In Species360 aquariums	0	0	1	3	1	2	16	23 (23%)
Low vulnerability								
Total described (CoL)	5	2	8	132	47	128	188	510 (100%)
In Species360 aquariums	0	2	0	25	0	37	58	123 (24%)
Unknown vulnerability								
Total described (CoL)	4	1	2	3	19	11	19	59 (100%)
In Species360 aquariums	2	0	1	0	0	0	3	6 (10%)

CoL: Catalogue of Life (Hopkins et al., 2015).

species listed as both vulnerable to climate change and evolutionary distinct (Fig. 4, Table 4). Furthermore, none of the species indexed in Appendices III or I by CITES overlap with another prioritization scheme. However, the two AZE species are indexed in CITES Appendix II and 81 species listed in Appendix II are considered evolutionary distinct and Vulnerable to Climate Change. Of the 17 species held by aquariums listed as ED and assessed as vulnerable to climate change, the biggest population is of *Catalaphyllia jardinei*, with 10 042 individuals recorded, while the species with the least number of individuals (only one) is of *Cyphastrea ocellina*. Of those, more than half (10 species) have more or equal to 20 individuals. Out of the 107 species held by aquariums that have not been assessed by the IUCN Red List yet, the biggest population is of the species *Corynactis californica* with 12 057 individuals, followed by *Ricordea florida* with 10 113. Moreover, 12 of those 107 species (including the *Montastraea curta* that is also vulnerable to climate change according to Foden et al. (2013)) have only one individual under human care and another 11 species only have two individuals in ex situ collections. Active management of these species should be considered a priority conservation action. We draw attention to the conservation potential of species listed in different prioritization schemes in Table 4.

4. Discussion

Given the current biodiversity crisis, coral and fish populations held in the world's aquariums will certainly play an increasingly critical conservation role. Still, the potential of these populations in captivity to respond to the extinction crisis has not been fully explored. Here we helped to fill this gap by i) assessing the number of described fish and corals recorded in Species360's aquariums network, ii) highlighting targeted species of concern based on different prioritization schemes to inform the development of management programs (i.e., studbooks and wider collection planning), and iii) showing the value of aquariums sharing real-time standardized animal records globally to better respond towards the current biodiversity crisis. We found that at least 14% of the described fish and 4% of Anthozoa corals and anemones are held in aquariums. However, we strongly expect that there are significantly more species not yet recorded, and therefore we urge aquariums to increase their standardization and sharing of animal record keeping for species under their care to maximize their conservation potential as a global network.

In 2014, the IUCN shark specialist group revealed that 25% of more than one thousand species of sharks, rays and chimaeras were threatened with extinction due to overfishing, whether targeted or accidental (Dulvy et al., 2014). Yet, only ~4% of all described Elasmobranchii are listed in CITES and therefore considered threatened by international trade, from which 34% are in aquariums. Given the high volume of fisheries trade, it is highly likely that more species need to be listed. These reflect a combination of historical policy inertia and inadequate formal species risk assessments resulting in the trade of aquatic species continuing to be poorly regulated in many countries, with resultant pressures on wild populations (Vincent, de Mitcheson, Fowler, & Lieberman, 2014). With the species they hold, aquariums are ideally placed to influence public opinion and policymakers so that more species threatened by international trade are included on CITES. Furthermore, aquariums' populations of species can provide important information on demographic traits and ecological thresholds to inform fishing quotas and coral harvesting, as well as climate change vulnerability. Nevertheless, estimating species vital rates such as age at first reproduction, reproductive lifespan and recruitment, can only be possible when the population size is big enough. Therefore, to reach statistically reliable numbers to estimate these, aquariums' shared data on the species they hold is essential. This is of particular importance not

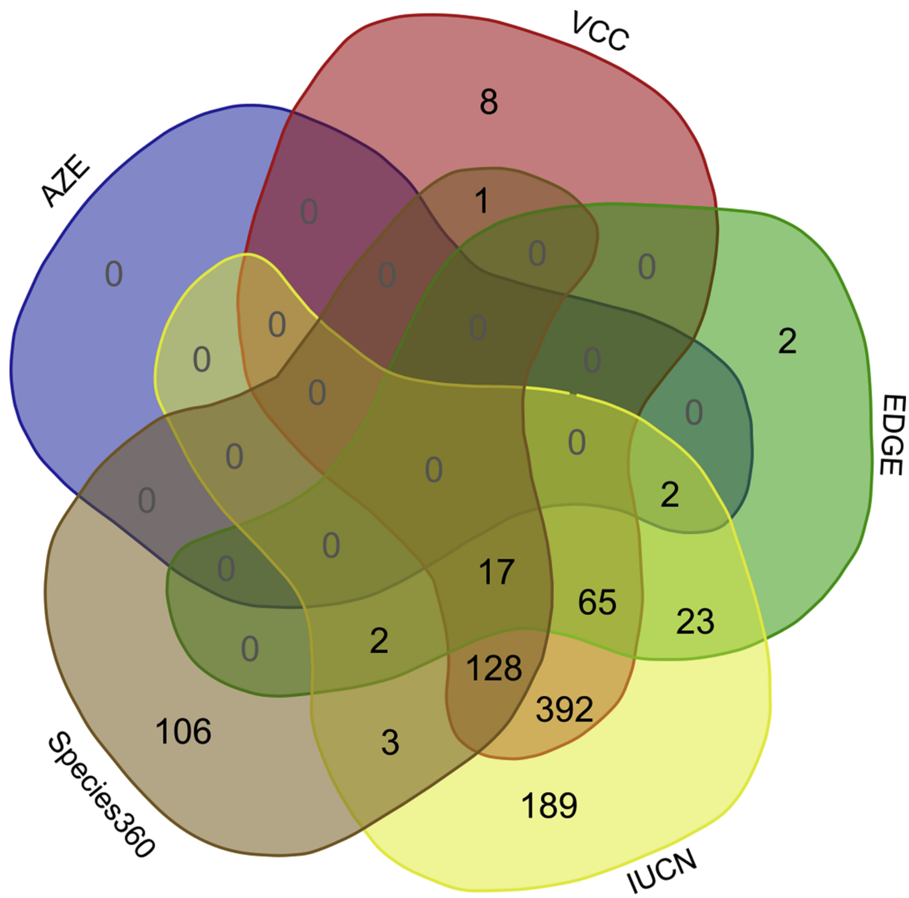

Fig. 4. Number of Anthozoa species in each prioritization scheme and its overlaps (VCC: Vulnerable to Climate Change, EDGE: Evolutionary Distinct and Globally Endangered, IUCN: International Union for Conservation of Nature, AZE: Alliance for Zero Extinction).

Table 4
Number of targeted species for management recommendations. Number of species listed in different prioritization schemes and key recommendations for their conservation management. ZIMS: Zoological Information Management System from Species360; EDGE: Evolutionary Distinct and Globally Endangered; VCC: Vulnerable to climate change; AZE: Alliance for Zero Extinction; IUCN: International Union for Conservation of Nature Red List of Threatened Species.

	Species Prioritization scheme	Species number	Conservation potential
Anthozoa	**ZIMS** not assessed by IUCN	106	Can support the IUCN Red List assessment with data on life history traits
	ZIMS/EDGE/VCC/IUCN	17	Consider on prioritization for studbooks
	ZIMS/VCC	1	Special attention on management
	EDGE/VCC/IUCN	65	Consider on prioritization assessments for new collections or in record digitalization
	AZE/EDGE	2	
Fish	**ZIMS** not assessed by IUCN	1 352	Can support the IUCN Red List assessment with data on life history traits
	ZIMS/CITES	16	Special attention on management
	Species with an active studbook that are threatened with extinction	14	Special attention on management programs that already exist

only for species endangered by international trade but also assessed as threatened by the IUCN Red List and other formal assessment and prioritization schemes.

Here we showed that more than half (62%) of the aquariums worldwide hold at least one species considered to be threatened with extinction by the IUCN Red List, which underlines the potential value of aquariums' husbandry data for saving species of concern from extinction. One of every seven fish species assessed by the IUCN is threatened with extinction and 8% of these are currently in aquariums. At the tipping point of extinction are species listed as 'Extinct in the Wild' (EW), for which aquariums hold four of the six EW species, with populations ranging from 47 up to 2 200 individuals. At least one of these EW listed species needs updating, the butterfly goodeid *Ameca splendens*, since it has been found in the wild, in Mexico (López-López et al., 2004). Ensuring viable populations of these species is crucial to prevent their extinction. Unfortunately, there are more species believed to be EW not yet updated by the IUCN Red List, that exist in aquariums of the Species360 network. For example, the pupfish *Cyprinodon veronicae,* which has not yet been formally reassessed by IUCN (Miller, Minckley, & Norris, 2005). Species listed as 'Data Deficient' (DD) are usually afforded conservation program assistance, however, 111 species are recorded being held in aquariums and data collected on them can provide important information on species' vital rates to support IUCN assessments (i.e., with a population averaging 100 individuals). As shown by previous studies, species identified as DD have a high probability of being threatened or of becoming extinct even before we are able to notice that they were threatened (Bland et al., 2015; Butchart & Bird, 2010; Howard & Bickford, 2014).

The potential of populations in aquariums to contribute to conservation should not only be seen in the light of the IUCN Red List but within other assessments or prioritization schemes. However, fish have been relatively neglected by these assessments, for example, from 1976 to 2002, no marine fish was listed in CITES (Vincent et al., 2014). Likewise, fish classes are not yet assessed under EDGE, species vulnerability to climate change and AZE. This is mainly due to the lack of data and taxonomic uncertainties. However, filling this gap is essential, not least because fish sources provide 17% of the protein intake globally (The Ocean Conference, 2017) and the reduction of fish populations would lead to high economic and social pressures. Conversely, corals are included in more assessments, as the conservation outlook is bleak for almost a quarter of the species in class Anthozoa currently formally assessed by IUCN. Our findings showed 77 coral and anemone species listed as 'Least Concern' in aquariums, and consequently may currently not receive the conservation focus they should. However, 74 of these are listed as vulnerable to climate change and therefore justify better conservation attention. Moreover, with 17% of the evolutionary distinct corals already held in aquariums, these institutions have high potential to support conservation efforts (including bio-banking) as the extinction threat facing the Anthozoa group is so severe.

The alignment of different conservation prioritization schemes is of special importance for the decision making of future collection planning. For fish, we would draw attention to the importance of those species threatened by international trade, which are already being managed through studbooks, such as the smalltooth sawfish (*Pristis pectinata*). In total, aquariums intensively manage 26 fish species through a studbook, and 14 of those are considered threatened by the IUCN Red List. The knowledge on the ex situ population sizes of species with active studbooks might help the establishment of new management programs and the development of existing ones. Regarding corals and anemones, aquariums hold 17 species severely susceptible to extinction by being indexed as vulnerable to climate change and evolutionary distinct for which conservation programs have yet to be developed. These species are distinctive candidates for initiating a studbook, in which research into their husbandry, culture and management can be improved in the aquarium and their population viability assured while these species are being attentively managed as possible insurance populations for their wild counterparts.

Conservation actions highly depend on collaboration between diverse institutions and the integration of different prioritization schemes. The management of populations across institutions as a metapopulation invariably means better changes of successful conservation outcomes. Population size demographics are of extreme importance, due to genetic variability and robustness, which can influence the repopulation success. We found that 4% of the species in our targeted analysis taxa have more than 500 individuals, which is considered a minimum population size to uphold a genetically sustainable population with minimal loss of genetic diversity (Frankham, Briscoe, & Ballou, 2002). The biggest population with an active studbook in aquariums has more than 500 individuals and represents a 'Vulnerable' species, according to the IUCN Red List. Due to group management difficulties, the precise count of individuals is frequently not possible. Although challenging, identifying useful data management techniques for this group of colony living animals in conservation programs is crucial for conservation dependent species. Additionally, we need to highlight that corals are likely to be represented by many more species than the ones covered in this analysis. On the other side, for corals, the number of individuals is highly challenging and underestimated due to the enormous difficulty in identifying a single individual in a colony for many polyp species. The findings in this study also unveil the issue of taxonomy and the challenge of species identification. We expected a higher number of species than the ones recorded by aquariums due to identification issues and taxonomic compatibility. A prime example of these dual challenges are the Anthozoan corals and anemones, as the number of species in this class would be at least 55% (257/467) higher accounting for the reported unidentified species that were not considered due to the lack of identification to species level. Recent initiatives, such as the CORALZOO (Osinga et al., 2012) are helping to address this identification issue.

The employment of a standard, shared animal record databases is key to optimizing the ex situ conservation breeding program success for almost all species. For example, the now 'Extinct' (EX) pupfish *Megupsilon aporus* could potentially have been saved from extinction. This species naturally occurred in the same spring habitat in Mexico as the EW pupfish *Cyprinodon alvarezi*. Due to anthropogenic impacts, the spring disappeared and both species became EW in the 1990's (Liu & Echelle, 2013; Miller et al., 2005). Remnant populations of both species, however, were maintained in aquarium collections, when in 2013 the population of *Megupsilon aporus* dropped to dangerously low levels and was only recorded in a few institutions. By the time the remaining holders realized the fragmented metapopulations had only one remaining female, it was too late. It is believed the last fish died in 2014 and the species became 'Extinct' (Lozano-Vilano & La Maza-Benignos, 2017; Miller et al., 2005). Therefore, it could be strongly argued that the integration of captive data in conservation projects could have raised the alert for this species before it reached critical levels and a coordinated effort could have saved the species from extinction.

At the moment, conservation practitioners, demographers and scientists in general struggle to get good quality data, especially for species on the brink of extinction. The wealth of data collected by standardized databases such as ZIMS, maintained by Species360, can provide invaluable practical management assistance and also deeper insights of significance to both ex situ and in situ species conservation. By contributing information on life history traits, behavior, water quality requirements and other environmental and biological information of species (including those that have disappeared from their natural environments) member institutions are making invaluable contributions to global conservation knowledge and capability. Captive standardized data might also help to generally improve conservation assessments such as the IUCN Red List and climate change vulnerability assessments since wild species-specific data is scarce, hard to obtain and usually biased towards regions, habitats and environmental domains. Even if we rethink our approach to fill gaps in the available knowledge by targeting strategically chosen biases, there is a strong possibility that the gaps will not be entirely filled in a timely manner, delaying action for species in need and posing a dilemma for both conservationists and policymakers, who might not be able to wait years for sufficient data (Hortal et al., 2015). Even though aquariums keep only a small proportion of all described species, they are in an ideal position to provide important information on species that occur in areas where an in situ study is difficult. Only through shared and standard data is it possible to support the decision making process to manage animal collections as metapopulations across the global aquarium community (Conde et al., 2013). Despite our focus on the Species360 member's data, it is essential to stress the conservation importance of other aquariums that collect high-quality data but are not currently sharing it. Consequently, the number of species reported here is an underestimation of the real number of ex situ managed species.

5. Conclusion

The main goal of species conservation is to protect wild ecosystems, but when we fail to preserve viable genetically diverse populations against threats such as habitat loss, disease, overharvesting, predation and pollution, complementary ex situ programs can make the critical difference for species survival. For such conservation breeding programs to be viable, it is crucial to quantify aquariums' species holdings as these institutions have a great potential for contributing to the conservation of wild populations at risk. Here we overcame the uncertainty of the figure of species by assessing the number of described fish and corals in aquariums in the Species360 global network. Furthermore, we provided a list of targeted species based on prioritization schemes that conservation practitioners can access to further inform their collection planning and conservation program development. We showed the great value of sharing real-time standardized data among aquariums and urge that more institutions realize their data's full potential when shared in a standard way. Concerted efforts to utilize standardized and shared animal record databases, address species identification gaps and taxonomic issues would greatly improve the conservation chances for many aquatic species and we urge that this challenge is met with the urgency it requires.

Acknowledgements

We would like to give special thanks to record keepers and to the more than one thousand institutions part of Species360 for providing data. We would like to thank the financial support from members of the Species360 Conservation Science Alliance for making this work possible. Authors would also like to thank Andrew Mooney, Maria Baden, Jim Guenter and Johanna Staerk for comments on this manuscript.

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