



Original research article

Australia's protected area network fails to adequately protect the world's most threatened marine fishes

Karen R. Devitt^{a,b}, Vanessa M. Adams^a, Peter M. Kyne^{a,*}^a Research Institute for the Environment and Livelihoods, Charles Darwin University, Darwin, Northern Territory 0909, Australia^b School for Resource and Environmental Management, Dalhousie University, Halifax, Nova Scotia, Canada

ARTICLE INFO

Article history:

Received 21 January 2015

Accepted 21 January 2015

Available online 23 January 2015

Keywords:

Sawfish

Pristidae

Protected areas

Marine reserves

National parks

ABSTRACT

In order to maintain ecosystems and biodiversity, Australia has long invested in the development of marine and terrestrial protected area networks. Within this land- and seascape, northern Australia represents a global population stronghold for four species of the world's most threatened marine fish family, the sawfishes (family Pristidae). The distribution of sawfishes across northern Australia has previously only been coarsely estimated, and the adequacy of their representation in protected areas has not been evaluated. The calculated range of each species was intersected with Australia's marine and terrestrial protected area datasets, and targets of 10% marine and 17% inland range protection were used to determine adequacy of sawfish range protection. Marine targets have been achieved for all species, but the inland range protection targets have not been met for any species. Results indicate that further protection of inland habitats is required in order to improve sawfish protection and habitat connectivity.

© 2015 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

The development of terrestrial and marine protected areas (MPAs) is essential in balancing the pressure of human development, the protection of biodiversity, and in aiding recovery of threatened species (Gaston et al., 2008). Globally, there has been a steady increase in protected areas with many countries investing in the development of protected area networks to reduce the loss of species and meet targets set forth in the Convention on Biological Diversity (CBD); however many ecoregions remain inadequately protected (Spalding et al., 2008; Jenkins and Joppa, 2009). While protected area planning must consider the conservation needs of various habitats and species, global and regional assessments of progress towards both the CBD Aichi Target 11 and 12 (protect 17% of the world's land surface by 2020, and prevent the further loss of known threatened species, respectively) show that many threatened species are not adequately protected and there are still significant shortfalls in meeting the targets (Shaw et al., 2014; Venter et al., 2014). Given that protected areas are an essential conservation tool for protecting threatened species and their critical habitat (Miller et al., 1990), due consideration is required to adequately incorporate threatened species into their design.

In Australia, both marine and terrestrial protected area networks have been developed through the use of the Comprehensive, Adequate, and Representative (CAR) system (NRMCC, 2005). This protected area planning system aims to protect adequate levels of ecosystems for each Australian bioregion to ensure viability and ecological integrity (ANZECC, 1999; Commonwealth of Australia, 2013). While the protected area system in Australia is extensive, there remain many ecoregions that are not adequately protected (Spalding et al., 2008; Jenkins and Joppa, 2009; Barr and Possingham, 2013).

* Corresponding author. Tel.: +61 8 8946 7616.

E-mail address: peter.kyne@cdu.edu.au (P.M. Kyne).

Though the ecoregional target shortfalls for the Australian protected area system and priority areas for further protection to meet targets have been explored (e.g. Watson et al., 2010 and Barr and Possingham, 2013), few studies have focused on investigating whether Australia's protected area systems are adequately protecting threatened species. Those that have been conducted focus on terrestrial birds, mammals and amphibians (Lemckert et al., 2009; Watson et al., 2010; Venter et al., 2014). No studies have been conducted to determine if aquatic, euryhaline, estuarine, or marine threatened species are effectively protected. A major barrier to conducting assessments on the adequacy of protection for these species is the lack of information required to accurately estimate species' ranges. Identifying a species' range is dependent upon spatial distribution information (Gaston and Fuller, 2009) and these data can be sparse for aquatic, euryhaline, estuarine, and marine species (for a more detailed review on the difficulties of assessing species distributions see Williams et al., 2002 and Cooke, 2008). Furthermore, given many of these species occupy or move between multiple realms, estimation of ranges should span relevant realms. Constructing these ranges is the first barrier to estimating the current adequacy of protection for these species.

The cartilaginous fishes (class Chondrichthyes) face a global conservation crisis, with an estimated one quarter of species threatened with extinction (Dulvy et al., 2014). The sawfishes (family Pristidae) are the most threatened chondrichthyan family, having undergone unprecedented declines in both range and abundance in the last few decades; indeed they are arguably the most threatened group of marine fishes (Faria et al., 2013; Dulvy et al., 2014). The world's five sawfish species face similar threats across their tropical ranges due to their shallow inshore coastal (and for some species, riverine) distributions in areas facing high exploitation and development pressures, and their toothed rostrums, which are highly vulnerable to entanglement in fishing gear and are often sought as curios (Harrison and Dulvy, 2014). Sawfishes generally conform to the limited life history characteristics displayed by long-lived and late-maturing elasmobranchs, which further increases their vulnerability (Peveler, 2005). Sawfishes also represent cross-realm management challenges as some species occupy different habitats (freshwater, estuarine, marine) at different stages of their life cycle.

Northern Australia holds some of the few remaining viable sawfish populations, providing globally important habitat for four of the five sawfish species: *Pristis pristis* Linnaeus, 1758 (Largetooth Sawfish), *P. clavata* Garman, 1906 (Dwarf Sawfish), *P. zijsron* Bleeker, 1851 (Green Sawfish) and *Anoxypristis cuspidata* (Latham, 1794) (Narrow Sawfish). Ranges for each species in Australian waters have been very coarsely mapped using limited records (for example, see the Atlas of Living Australia; www.ala.com.au). However, no studies have been conducted to define accurate range estimates. Defining a species' range can be accomplished by identifying the extent of occurrence (EOO) and area of occupancy (AOO), parameters which are also important when assessing the extinction risk of a species (IUCN, 2012). A species' EOO is defined as the minimum area that encompasses all known, projected, or inferred records of a species, excluding cases of vagrancy. The AOO refers to the area within the EOO that the species actually occurs in (IUCN, 2012). Both parameters have not been determined for sawfish species in northern Australia.

Given the current imperilled status of sawfishes globally, Australia's stated goals to reduce biodiversity loss, and the importance of northern Australia's marine, estuarine, and freshwater environments to these species, this study aims to identify, as accurately as possible with available species records, the Australian ranges of *P. pristis*, *P. clavata*, *P. zijsron* and *A. cuspidata* and determine if Australia's current marine and terrestrial protected area networks are effective at protecting sawfish species ranges. This is accomplished by addressing the following objectives: (1) accurately mapping each species' Australian range; (2) assessing the level of protection; and, (3) assessing connectivity between protected areas across terrestrial and marine realms.

2. Methods

2.1. Data collection

Australian sawfish species location records were obtained from Commonwealth and state/territory fisheries departments, museums, the literature, and expert consultation. Records were organized by species and records attributed to unspecified species (i.e. 'sawfish') were removed. Using these records, as well as available range and habitat preference information, and various datasets describing Australia's hydrological areas and marine bioregions, EOO and AOO were determined for each species in Australian waters (state/territory and Commonwealth waters to the 200 nm limit).

Australia's hydrological area data included catchments, estuaries, floodplains, rivers, and streams. Catchment data were obtained from the National Catchment Boundaries v.1.1.4, available through the Geoscience Australia website (<http://www.ga.gov.au>). This dataset describes the surface drainage pattern for Australia's hydrological areas. Estuary, floodplain, river, and stream data were obtained from the Australian Hydrological Geospatial Fabric (Geofabric) Product Suite V2.1: Geofabric Surface Cartography (AHGF HydroArea). The Geofabric Surface Cartography product provides 15 types of geometric representations of Australia's surface waters for use in ArcGIS. For the purpose of this project, estuaries, mapped streams, waterbodies, and hydrological area feature types were used.

Marine bioregion and jurisdiction information was obtained from the 2005 National Marine Bioregionalisation of Australia GIS Dataset available via Geoscience Australia. This data provided coarse information about average depths of each bioregion. The 2012 version of Australia's Network of Commonwealth Marine Reserves (CMR) and the Collaborative Australian Protected Area Database (CAPAD) 2010 were obtained through the Australian Government Department of the Environment (<http://www.environment.gov.au/metadataexplorer/explorer.jsp>). These datasets provide spatial data and in-

Table 1

The four (of five global) species of sawfish occurring in Australian waters and their broad global distribution, habitat, and conservation status (Harrison and Dulvy, 2014).

Species name	Common name	Distribution	Habitat	Global conservation status ^a
<i>Anoxypristis cuspidata</i>	Narrow Sawfish	Indo-West Pacific	Estuarine, Marine	Endangered
<i>Pristis clavata</i>	Dwarf Sawfish	Australia ^b	Estuarine, Marine, Riverine	Endangered
<i>Pristis pristis</i>	Large-tooth Sawfish	Indo-West Pacific, Eastern Pacific, Western Atlantic, Eastern Atlantic	Estuarine, Marine, Riverine	Critically Endangered
<i>Pristis zijsron</i>	Green Sawfish	Indo-West Pacific	Estuarine, Marine	Critically Endangered

^a IUCN Red List of Threatened Species (IUCN, 2014).

^b Historically more widely distributed in the Indo-West Pacific.

formation about the National Reserve System (NRS), which focuses on inland waters and terrestrial protected areas, and the National Representative System of Marine Protected Areas (NRSMPA), including status of the protected area and IUCN protected area category information (IUCN, 2012).

2.2. Data analysis

All analyses were performed using ESRI's ArcGIS 10.1 mapping and spatial analysis software. Location records were used to determine the spatial boundaries of the EOO and AOO for each species. Given that all sawfish species inhabit marine and inland waters, separate marine and inland ranges were determined for each species. The hydrological data used in this study includes estuaries and for the purpose of this study, estuaries are included within a species' inland range.

A convex polygon (a polygon that contains all records and does not include angles that are greater than 180°) was used to aid in identifying the most northern, eastern, and western extents of the marine ranges. The extents of the marine range for each species were clipped to include only the potential range within Australia's Exclusive Economic Zone. Though convex polygons are included as an appropriate method to measure EOO by the IUCN (IUCN, 2012), they are not encouraged for use in freshwater environments (Simaika and Samways, 2010). However, given the lack of specific habitat suitability data available for *P. pristis* and *P. clavata*, the use of a convex polygon is likely the best available technique. In order to ensure the range was biologically meaningful to each species, the convex polygon was restricted to only include appropriate water bodies. For *P. pristis* and *P. clavata*, the literature indicates that these species have been documented 400 km and 100 km inland from coastal waters, respectively (Thorburn et al., 2003; Last and Stevens, 2009). These parameters were used to define each species' inland range extent. Vagrants of *P. pristis* off southwestern Australia (Chidlow, 2007) and *P. zijsron* off southern Australia (Last and Stevens, 2009) were not included in the analyses. Records of *P. clavata* on the east coast of Queensland were also removed, as these records have not been substantiated (Kyne et al., 2013). Records for *A. cuspidata*, *P. clavata* and *P. pristis* are as recent as 2002 for the southeastern and southwestern extents of their ranges. However, in the case of *P. zijsron*, there are no recent records south of the Whitsunday Islands along the central coast of Queensland. As a result, records of *P. zijsron* south of this area were removed for the recent range estimates, as the species is extirpated from this area (Harry et al., 2011). These records were used to determine the species' historic range.

Omission errors and commission errors often occur when calculating range and overlaying ranges with protected area data (Rodrigues et al., 2004). Omission errors occur when a species is considered absent from a protected area when it is in fact present. Commission errors occur when a species is considered present in a protected area when it may actually be absent (Rodrigues et al., 2004). In order to identify each species' EOO and AOO, range was identified using two methods. Both methods involved the use of habitat preferences outlined in the literature. As such, omission errors have likely been avoided.

The first method involved including all available habitat based on habitat preferences outlined in the literature in an attempt to identify each species' EOO (Table 1). This method likely included many commission errors, resulting in an overestimated range. The second method aimed to identify each species' AOO by narrowing the selection process and only selecting marine and inland habitat in which records were found. This method aimed to reduce commission errors. Though both range calculation methods may be overestimating each species' range and protected area coverage, these range calculations are still a useful method for exploring conservation issues (e.g. Lemckert et al., 2009 and Cantú-Salazar et al., 2013).

The AOO estimates involved only including marine bioregions in the marine extent of each species' range that contained records. For *A. cuspidata* and *P. zijsron*, the AOO estimates also involved selecting for estuaries and hydrological areas where records were found and merging these areas with their marine extents. Given that *P. pristis* and *P. clavata* are considered euryhaline species, determining EOO and AOO for these species pose challenges given the fluctuations in northern Australia's inland waters between the wet and dry seasons. Seasonal fluctuations in water levels in northern Australian rivers and floodplains cause major changes in habitat availability (Winemiller, 1996; Douglas et al., 2005). In order to include these fluctuations, catchment data was used to identify potential range. The majority of the inland ranges for these species were determined by selecting for catchments that intersected major rivers and contained sawfish records. These catchments were used to identify the hydrological areas, mapped streams, estuaries and water bodies in which sawfish were found. The mapped streams feature type is constructed of line feature classes and was used to determine the ranges of *P. pristis* and *P. clavata*. In order to include streams in the range calculations, the streams were modified into polygons by buffering the

Table 2

Summary of area of occupancy (AOO) and extent of occurrence (EOO) estimates and the proportion of marine and inland range that is considered protected for each species.

Range type	<i>A. cuspidata</i>		<i>P. zijsron</i>			<i>P. clavata</i>		<i>P. pristis</i>	
	AOO	EOO	AOO	EOO	Historic EOO	AOO	EOO	AOO	EOO
Total range (km ²)	1,256,400	1,541,120	1,304,319	1,322,191	1,652,169	486,977	504,631	895,617	1,203,565
Inland range (km ²)	2669	3548	2812	20,684	25,962	18,898	36,552	80,103	295,565
Marine range (km ²)	1,253,731	1,517,829	1,301,507	1,301,507	1,626,207	468,079	468,079	815,515	908,000
% of records located in a PA ^a	9.52	11.93	15.07	15.07	13.76	21.56	21.56	4.68	4.68
% of inland range protected	8.59	15.23	1.55	16.74	13.34	13.28	15.46	15.15	13.34
17% target met?	No ^b	No ^b	No ^b	No	No	No	No	No	No
% of marine range protected	34.06	43.50	37.83	37.83	32.04	21.86	21.86	31.47	37.80
10% target met?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

^a Protected area.

^b Target of 1000 km² or 100% range protection not met.

streams by 200 m total. For records that were not connected to major rivers, the mapped stream and hydrological areas datasets were used to identify likely pathways the sawfish must have taken in order to reach the inland waterways.

Each range was intersected with Australia's network of CMR (2012) and CAPAD (2010) datasets to identify areas of the ranges and protected areas that overlapped. Across northern Australia there is a wide range of protected area sizes (from 0.01 to 491,202 km²); we therefore identified the largest protected areas within each species range to provide more qualitative details around the type of protection each species was receiving.

We considered whether Australia's protected area system provides adequate protection across sawfish life cycles by estimating the distance between marine and terrestrial protected areas. This was accomplished by converting all of Australia's protected area polygons into point data. The point data was then uploaded into Geospatial Modeling Environment software, a platform designed to aid in spatial analysis. This software calculates the distance between each point and identifies the nearest neighbour for each point (for a similar approach, see [Almany et al., 2009](#)). This analysis provides information on how far sawfishes must travel to reach other parts of their range under protection when moving between freshwater, estuarine and marine environments.

Targets were used to determine if species ranges were adequately protected. Target-based-conservation is a key component of many conservation decision support tools and has been incorporated into Australia's Strategy for the National Reserve System (NRS) ([Australian Government, 2009](#); [Barr and Possingham, 2013](#)). Ideally, targets are based on detailed population data ([Gaston et al., 2002](#)). This data is currently not available for sawfish. As a result we chose targets similar to those that have been previously used to assess the effectiveness of protected areas, for example in relation to representation of species ranges (e.g., [Watson et al., 2010](#)) and Antarctica's protected areas in a global context (e.g., [Shaw et al., 2014](#)). We adapted the targets used by [Watson et al. \(2010\)](#) such that for species with ranges < 10,000 km², the smaller value of 100% or 1000 km² range protection was set as the target. For species with ranges > 10,000 km², targets of 10% for marine range protection and 17% (as compared to a 10% target used by [Watson et al., 2010](#)) for inland range protections were used. We chose to use a 17% inland target to reflect the protection targets for marine, terrestrial and inland ecosystems set forth in Target 11 of the CBD Aichi Biodiversity Targets ([CBD, 2010](#)). Given that many countries are attempting to protect 17% and 10% of representative terrestrial and marine habitat, respectively, it is not unreasonable to assume that this should translate to 17% or 10% of a species' range. Australia is signatory to the CBD and has committed to meet these targets by adding 600,000 km² across terrestrial, aquatic, and marine environments to the protected area networks ([NRMCC, 2010](#)).

3. Results

3.1. Species ranges and protection levels

Of the records obtained, 2908 records of *A. cuspidata*, 741 records of *P. zijsron*, 247 records of *P. clavata*, and 470 of *P. pristis* were included in this study. Five hundred and twenty four of the records included were found within a protected area ([Table 2](#)).

AOO estimates indicate that *P. zijsron* has the largest range while *P. clavata* has the smallest range ([Fig. 1, Table 2](#)). The EOO estimates yielded similar results, however, the range of *A. cuspidata* is larger than *P. zijsron* using this method ([Fig. 2, Table 2](#)). The historic EOO estimate of *P. zijsron* extended as far south as Sydney and is over 300,000 km² larger than the current EOO estimate. Regardless of the way in which range was calculated (AOO or EOO), marine ranges for each species met the 10% target, with all species having >21% of their range protected ([Table 2](#)). AOO and EOO estimates for the inland range of *A. cuspidata* and AOO estimates for the inland range of *P. zijsron* are < 10,000 km² and did not meet the 1000 km² or 100% range protection targets. The amount of inland range protected by the NRS ranged from 1.55% to 15.15% for the AOO estimates, and 13.34% to 16.74% for the EOO estimates ([Table 2](#)); no species met the inland range protection target.

Based on the CAPAD (2010) and MPA (2012) datasets, the NRS has protected >900,000 km² of land and inland waters and the NRS marine protected areas have also protected >3,400,000 km² of marine habitat. According to IUCN categories of protected areas, most of Australia's marine and terrestrial protected areas are primarily considered protected areas with

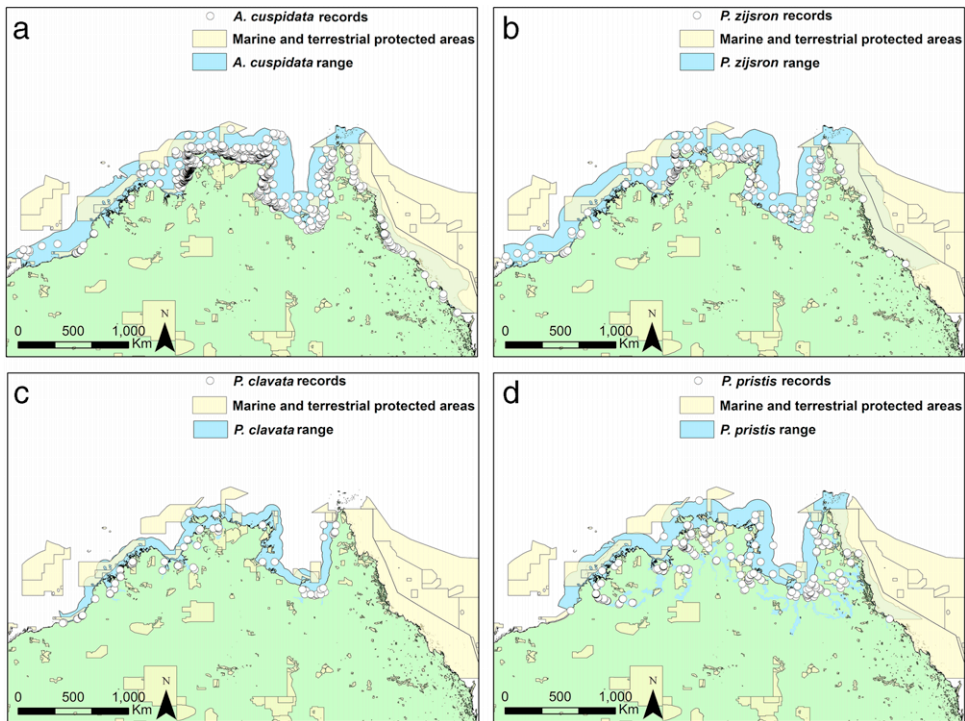


Fig. 1. Area of occupancy (AOO) estimates for (a) *A. cuspidata*, (b) *P. zisron*, (c) *P. clavata* and (d) *P. pristis*.

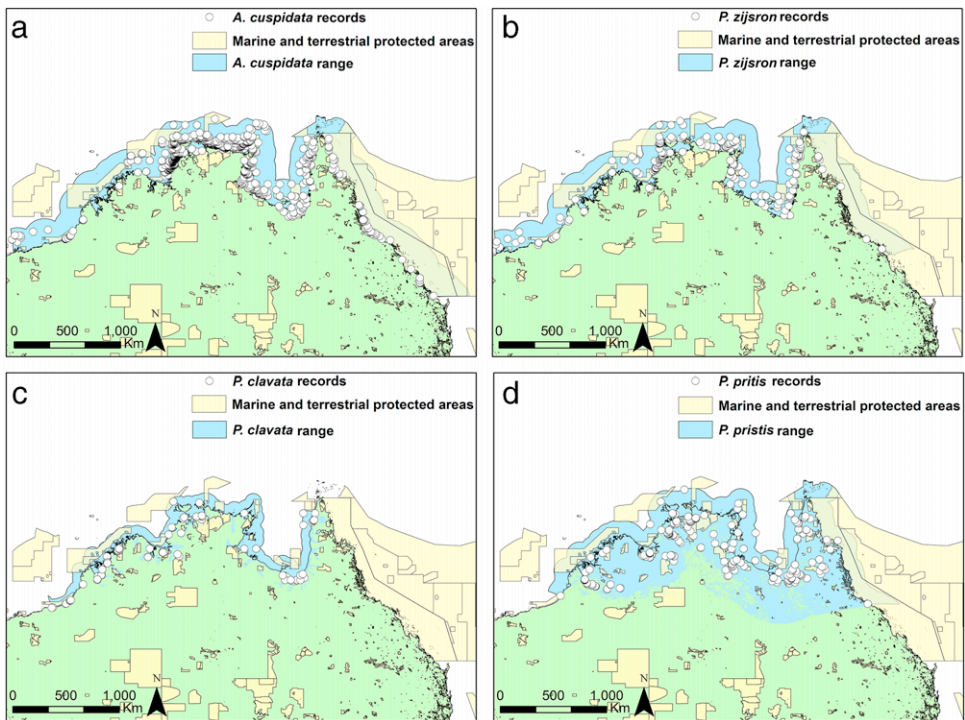


Fig. 2. Extent of occurrence (EOO) estimates for (a) *A. cuspidata*, (b) *P. zisron*, (c) *P. clavata* and (d) *P. pristis*.

sustainable development (IUCN category VI) (40.5%) and national parks (II) (31%) (Fig. 3). The results of the intersects indicate that the majority of protected areas that encompass sawfish ranges are protected areas with sustainable use (VI), regardless of how range was calculated. National parks (II) also encompass approximately 20% of the protected ranges of *A. cuspidata*

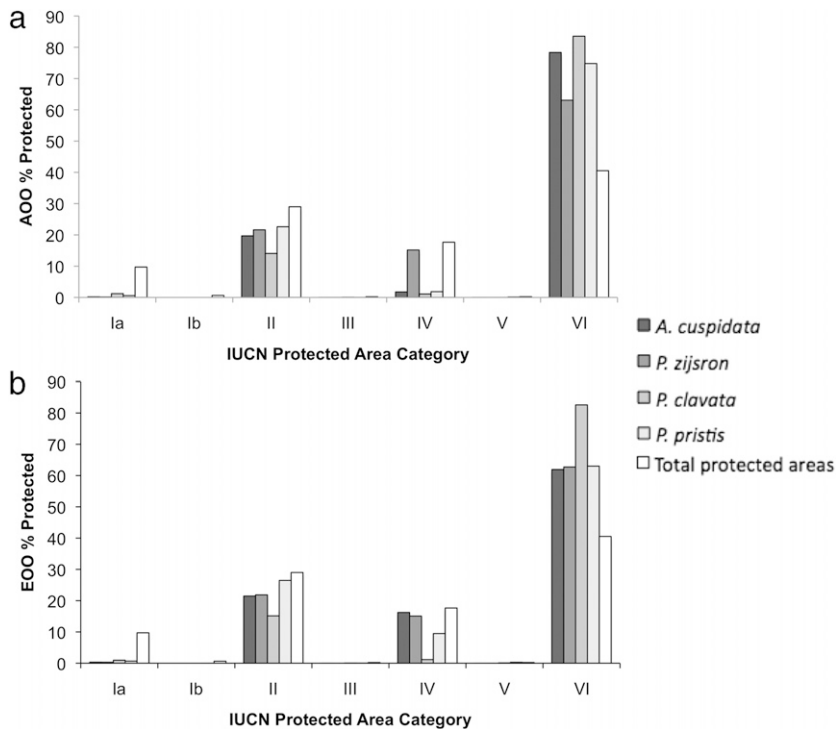


Fig. 3. Proportions of range protected for each species' (a) area of occupancy (AOO) and (b) extent of occurrence (EOO) that fall under each IUCN protected area category.

and *P. zijsron*, 22% of *P. pristis* and 14% of *P. clavata*. Very small amounts of the protected portions of each sawfish species' range fall under the other strict protected area categories (IUCN Ia, Ib, III) with the exception of IUCN IV. Habitat/species management areas (IV) cover approximately 15% of *P. zijsron* protected range as well as small amounts (1%) of other sawfish species' protected ranges. However, when the EOO estimates for *A. cuspidata* and *P. pristis* are considered, habitat/species management areas included in *A. cuspidata* and *P. pristis* range increases to approximately 16% and 9%, respectively.

There are some very large iconic protected areas that contribute to meeting the protection targets for the four species including two World Heritage Areas: the Great Barrier Reef and Kakadu National Park. The Great Barrier Reef marine protected area (GBR MPA) contributes the largest amount of marine protection for *A. cuspidata*, *P. zijsron*, and *P. pristis*. The Kimberley Commonwealth Marine Reserve (CMR) contributes the largest amount of marine protection for *P. clavata* (Fig. 4).

3.2. Nearest neighbour analysis

The distances a sawfish must travel between inland areas of protection and marine protected areas are large with all mean distances being >200 km for AOO estimates and >120 km for EOO estimates (Fig. 5). The largest protected areas (Kakadu National Park, GBR MPA and the Kimberley CMR) and their nearest cross realm parks (Arnhem MPA, Conway National Park and Monkhouse Timber Reserve, respectively) are shown in Fig. 4.

4. Discussion

This study provides a means for assessing the adequacy of protection for threatened species that need immediate conservation action but lack critical data. Furthermore, our assessment provides a method for considering adequacy of protection across multiple realms, which has not previously been incorporated. Our approach could be applied to other species that occupy or move across multiple realms. By considering not only the adequacy in terms of protection targets but also in terms of spacing, our approach provides insights into design issues for future expansion of the protected area system.

Given the global importance of northern Australia for threatened sawfishes, our study has direct implications for the global conservation of these threatened species. Prior to our study, sawfish ranges had been very coarsely mapped and were strictly based upon a limited number of records (see Atlas of Living Australia; <http://www.ala.org.au>). Using species records, habitat preferences, and datasets describing Australia's land- and sea-scapes, this study provides more accurate range estimates for the four sawfish species occurring in Australian waters. The ranges indicate that protection of inland

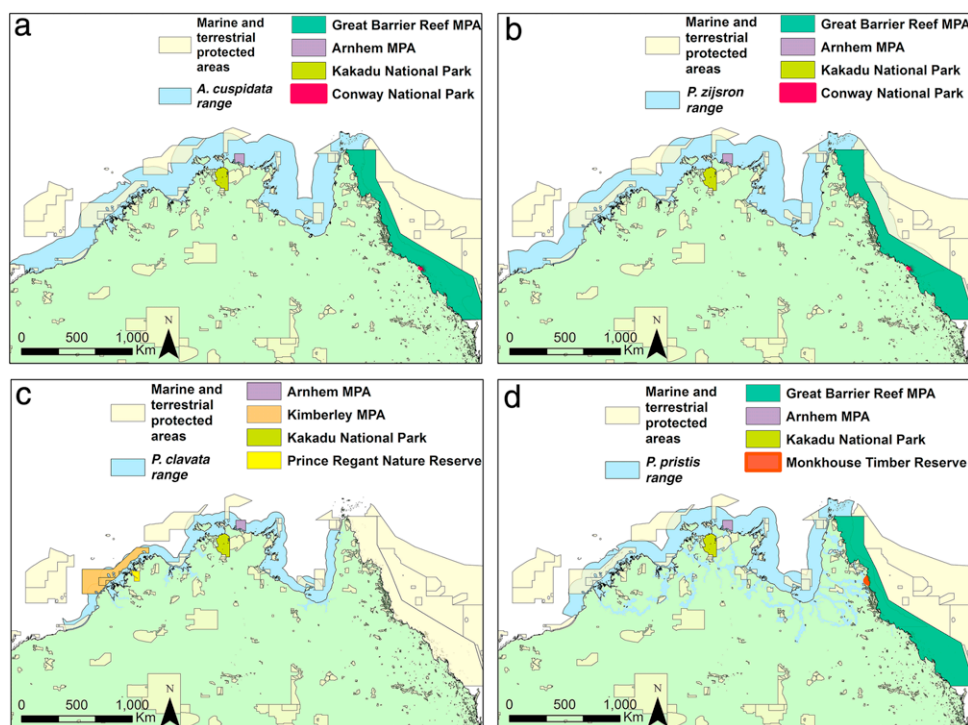


Fig. 4. Protected areas that provide the largest amount of protection for (a) *A. cuspidata*, (b) *P. zijron*, (c) *P. clavata* and (d) *P. pristis* as well as the closest cross realm park that provide protection within each species' range.

waters, including rivers and estuaries, as well as areas in-between inland and marine habitats require improvement in order to meet protection targets for sawfishes and promote connectivity between protected areas.

4.1. Mapping species ranges

The two methods used here to calculate range have provided EOO and AOO estimates. EOO and AOO help define a species' geographic range and are two parameters that are considered when determining a species' status for the IUCN Red List of Threatened Species (IUCN, 2012). The IUCN Red List 'geographic range' criteria require that EOO and AOO meet various thresholds in order to be classified in a threatened category (EOO, <20,000 km²; AOO, <2000 km²) (IUCN, 2012). Based on the results of this analysis, none of the species' Australian AOOs and EOOs meet the Red List 'geographic range' criteria. Historical records for *P. zijron* allowed for the calculation of this species' historical range, indicating a decline of 19% in the Australian EOO. Though the IUCN 'geographic range' criteria is intended for species with restricted, fragmented, declining, or fluctuating ranges, declining ranges are also used as a criteria by the IUCN when accessing population declines if abundance data are not available (IUCN, 2012). As such, the results of this study could act as a baseline for Australian sawfish ranges.

4.2. Assessing the level of protection

The results of this analysis indicate that within their globally significant northern Australian range, all species of threatened sawfish met the protection adequacy targets in their marine range but no sawfish met the targets in their inland range. Though all species met the 10% protected marine range target, it is important to note that the Commonwealth Marine Reserve (CMR) network was only proclaimed in 2012 and the future status of these reserves is unclear. Management plans and regulations for the CMR network were due to come into force in these areas in July of 2014 (Director of National Parks, 2013a,b). However, the new Australian Government (elected in 2013) suspended these plans (Hunt and Colbeck, 2013) and the zoning of the network faces uncertainty. As a result, it is unclear what level of conservation impact these areas will have on each species of sawfish. In addition, the protected area categories that offer the greatest levels of protection (Ia, Ib, and II) contribute very small amounts of protection for each species' range.

There are differences in the proportion of sawfish ranges protected in each IUCN category compared to the national average (Fig. 3); proportions of sawfish ranges protected in IUCN VI are greater than the national average and proportions protected in IUCN Ia, Ib, and II are less than the national average. The small proportion of ranges under strict protection (IUCN I–IV) is concerning when considering the effectiveness of different categories to contribute to species protection; for example Taylor et al. (2011) found that of four measures of conservation effort (protection across strictly protected areas (IUCN I–IV)

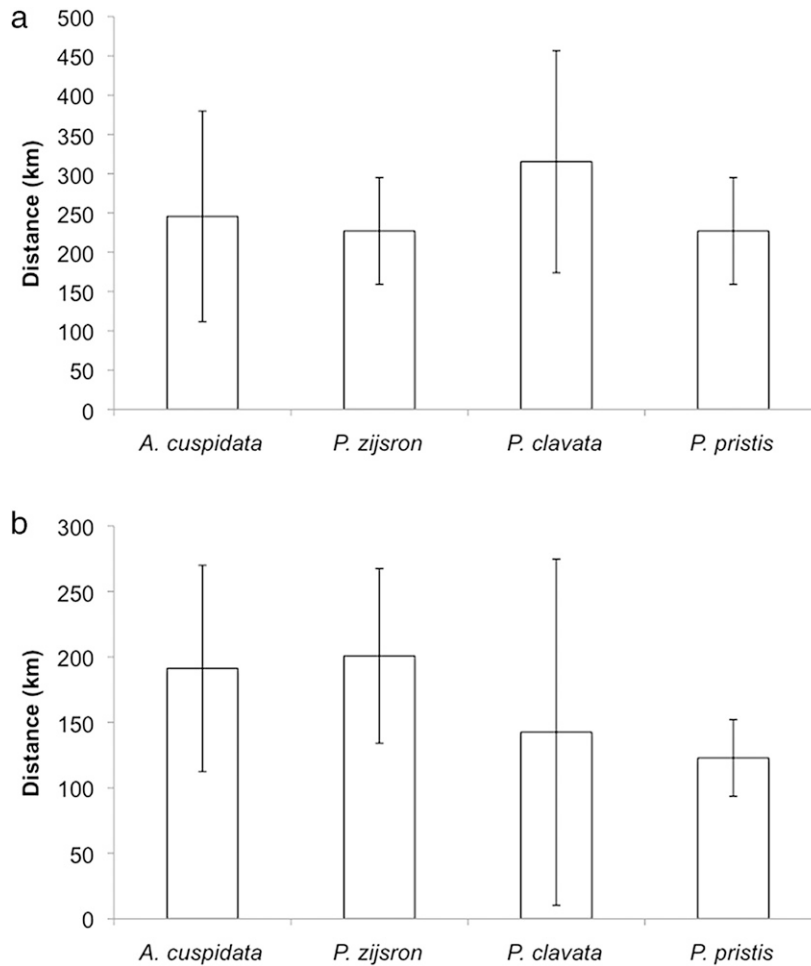


Fig. 5. Results of the nearest neighbour analysis. Mean distances between inland and marine protected areas for the (a) area of occupancy (AOO) estimates and (b) extent of occurrence (EOO) estimates for each species.

and other protected areas (IUCN V–VI), species recovery activities and other natural resource conservation activities), only strictly protected areas (IUCN I–IV) showed positive associations with stable or increasing population trends. The majority of the ranges that are considered protected fall under protected areas that allow for the sustainable use of resources (VI). In many of these areas, restricted forms of commercial and recreational fishing, mining operations, aquaculture, and tourism are still permitted (Director of National Parks, 2013a,b). Set mesh nets, pelagic gillnets, demersal longline, and bottom trawls are prohibited, however, commercial cast, scoop, barrier, drag, and skimmer nets are not prohibited (Director of National Parks, 2013a,b). Subsequently, all threatening processes have not been eliminated.

4.3. Protected areas of significance

The GBR MPA in northeastern Australia provides the largest area of protection for *A. cuspidata*, *P. zijsron*, and *P. pristis* and provides protection of multiple habitats including coastal mudflats, mangroves, and offshore areas (Great Barrier Reef Marine Park Authority, 2009). Though the design of the GBR MPA zones does not extend to include formal protection on adjacent coastal areas, the impacts of terrestrial runoff on the park are recognized and managed through other mechanisms such as the 2003 Reef Plan and 2007 Reef Rescue Package (Brodie et al., 2012). The results also indicate that Kakadu National Park in the Northern Territory plays a large role in protecting inland ranges of *P. clavata* and *P. pristis*. Improving protection of coastal and marine areas in close proximity to Kakadu would also improve connectivity between inland and marine protected areas.

The Kimberley CMR provides the largest area of protection for *P. clavata* and contributes towards the protection of the other three sawfish species' ranges. The Kimberley region has been identified as a global hotspot for sawfish (Thorburn et al., 2007, 2008; Morgan et al., 2011) and increasing the number of protected areas surrounding the Kimberley could promote connectivity between other protected areas and increase range protection for all sawfish. Further protection of

the Kimberley region is of particular importance due to the increasing pressure to further develop natural gas reserves in the area (Australian Government, 2014). Though no studies to our knowledge have directly studied the impact of natural gas extraction and infrastructure development on sawfish species, increasing infrastructure will likely lead to habitat destruction.

4.4. Assessing connectivity

In addition to identifying targets for marine and terrestrial protection, Target 11 of the CBD Aichi Biodiversity Targets also states that protected areas must be effectively and equitably managed, ecologically representative, and well connected (CBD, 2010). The analysis by Barr and Possingham (2013) demonstrates that the reserve network in the North and Northwest bioregions are not ecologically representative and given the uncertain implementation status of the new marine reserves, management is not yet underway.

The results of the nearest neighbour analysis have implications for management and planners when considering connectivity among protected areas. Our analysis indicates that all sawfish species must travel large distances (>200 km) between marine and inland protected areas. This is of particular importance for *P. clavata* and *P. pristis*, as female sawfish are thought to pup in estuaries (an inland area) and juveniles occupy riverine and freshwater habitats (represented by terrestrial protected areas) before moving into marine (coastal and offshore) environments (represented by MPAs) (Peverell, 2005; Thorburn et al., 2007, 2008). Additionally, tracking studies of *P. clavata* and *P. zijsron* in Western Australia indicate that these species inhabit shallow coastal mudflats as well as inundated mangrove forests (Stevens et al., 2008). While considering these multiple habitats in the design of protected areas is clearly important to ensuring adequate protection of the species, bioregional planning often considers each realm of the environment separately (terrestrial/freshwater or marine) (Stoms et al., 2005; Beger et al., 2010). As a result, important connections that are essential for many species between these environments are often not considered or protected (Stoms et al., 2005; Beger et al., 2010). Few attempts to integrate different realms have been made by protecting estuary and mangrove environments, and connectivity between these types of habitats and the surrounding environments is rarely considered (for comprehensive reviews of existing planning studies that have considered multiple realms see Álvarez-Romero et al., 2011 and Adams et al., 2014).

Ideally, the nearest neighbour analysis results could also be used to further assess the adequacy of protection for each species of sawfish by identifying specific areas for future protection. This can be done in conjunction with movement data for each species, as demonstrated by Pendoley et al. (2014), who used long-term tracking studies to identify a coastal corridor that promotes connectivity between multiple MPAs and improves the protection of multiple species in northern Australia. Telemetry studies have only investigated movement patterns for *P. clavata* and *P. zijsron* at a small-scale over a period of a few days (Peverell and Pillans, 2004; Stevens et al., 2008). Genetic studies of *P. pristis* indicate female philopatry, but the extent of movement away from natal rivers during non-breeding periods is unknown (Phillips et al., 2011). Conventional tagging has documented *P. pristis* travelling 220 km between river drainages in the Gulf of Carpentaria and migrating upstream and downstream in rivers (Peverell, 2008). No movement data is currently available for *A. cuspidata*. Overall, these data are insufficient to determine the migratory corridors used by sawfishes, and to address the adequacy of protection in the context of the nearest neighbour analysis. Moving forward, long-term sawfish movement studies are required to assist in identifying specific areas for future protection that promote connectivity.

Connectivity between realms is of particular importance given the proposed development of new dams for hydroelectricity and water storage for many areas in northern Australia (Australian Government, 2014). Barriers, such as dams, are likely to impact the distribution of migratory freshwater fish species such as *P. pristis* (Thorburn et al., 2007). The potential development in northern Australia, the sawfish tracking studies that are currently available (Stevens et al., 2008), the nearest neighbour analysis results and the spatial comparison of sawfish ranges with Australia's protected area networks conducted in this study demonstrate the need to promote connectivity and integrate different environments through the protection of estuaries and surrounding coastal habitats, in addition to inland waters and marine areas.

5. Conclusions

The establishment of protected areas that are 'comprehensive, adequate and representative', is a cornerstone for conservation of biodiversity, and while Australia has made important advances in meeting protected area targets, there are still significant shortfalls in protection, in particular for threatened species. Our findings of under-protection and lack of protected area connectivity are consistent with previous global and national studies (Watson et al., 2010; Venter et al., 2014). Furthermore, there is a real risk of the downgrading of Australia's reserves and environmental management in general, and uncertainty surrounds the persistence of the network (Ritchie, 2013).

Acknowledgements

We thank the numerous individuals and agencies which contributed sawfish records to this study: Richard Pillans, Kate Buckley, Andrew Storey, Jeff Whitty, Alastair Graham, John Garvey, Susan Theiss, Mark McGrouther, Blanche D'Anastasi, Rory McAuley, Nichole Phillips, CSIRO, Territory Wildlife Park, Australian Fisheries Management Authority, Northern

Territory Fisheries, Western Australia Fisheries, Queensland Fisheries, Museums and Art Galleries of the Northern Territory, Queensland Museum and Science Centre, Australian Museum, Museum Victoria, and the International Sawfish Encounter Database. Thanks to John Carlson for initial discussions on the study concept, and to Nic Bax for comments on the manuscript.

Role of Funding Sources

This project was supported by the Marine Biodiversity and Northern Australia Hubs, collaborative partnerships supported through funding from the Australian Government's National Environmental Research Program (NERP). NERP did not contribute towards the study design; collection, analysis and interpretation of data; writing of the report; and had no role in the decision to submit the article for publication.

References

- Adams, V.M., Álvarez-Romeo, J.G., Carwardine, J., et al., 2014. Planning across freshwater and terrestrial realms: cobenefits and tradeoffs between conservation actions. *Conserv. Lett.* <http://dx.doi.org/10.1111/conl.12080>.
- Almany, G.R., Connolly, S.R., Heath, D.D., et al., 2009. Connectivity, biodiversity conservation and the design of marine reserve networks for coral reefs. *Coral Reefs* 28, 339–351.
- Álvarez-Romero, J.G., Pressey, R.L., Ban, N.C., et al., 2011. Integrated land–sea conservation planning: the missing links. *Annu. Rev. Ecol. Evol. Syst.* 42, 381–409.
- ANZECC, 1999. Australian and New Zealand Environment and Conservation Council Task Force on Marine Protected Areas Strategic Plan of Action for the National Representative System of Marine Protected Areas: A Guide for Action by Australian Governments. Available from <http://www.environment.gov.au/system/files/resources/3a269c60-4fc0-4bc4-aa8b-3fd7bbf3e145/files/nrsmmpa-strategy.pdf> (Accessed 1 December 2013).
- Australian Government, 2009. Australia's strategy for the national reserve system 2009–2030. Available from <http://www.environment.gov.au/node/21198> (Accessed on 1 December 2013).
- Australian Government, 2014. Green paper on developing northern Australia. Available from <https://northernaustralia.dpmc.gov.au/media/2014-06-10/call-public-comment-green-paper-developing-northern> (Accessed 15 July 2014).
- Barr, L.M., Possingham, H.P., 2013. Are outcomes matching policy commitments in Australian marine conservation planning? *Mar. Policy* 42, 39–48.
- Beger, M., Grantham, H.S., Pressey, R.L., et al., 2010. Conservation planning for connectivity across marine, freshwater, and terrestrial realms. *Biol. Cons.* 143, 565–575.
- Brodie, J.E., Kroon, F.J., Schaffelke, B., et al., 2012. Terrestrial pollutant runoff to the Great Barrier Reef: an update of issues, priorities and management responses. *Mar. Pollut. Bull.* 65, 81–100.
- Cantú-Salazar, L., Orme, C.D.L., Rasmussen, P.C., Blackburn, T.M., Gatson, K.J., 2013. The performance of the global protected area system in capturing vertebrate geographic ranges. *Biodivers. Conserv.* 22, 1033–1047.
- CBD, 2010. Decision adopted by the conference of the parties to the convention biological diversity at its tenth meeting: the strategic plan for biodiversity 2011–2020 and the Aichi biodiversity targets. Available from <https://www.cbd.int/sp/> (Accessed on 1 December 2013).
- Chidlow, J.A., 2007. First record of the freshwater sawfish, *Pristis microdon*, from southwestern Australian waters. *Rec. West. Aust. Mus.* 23, 307–308.
- Commonwealth of Australia, 2013. Scientific framework. Available from <http://www.environment.gov.au/topics/land/nrs/science-maps-and-data/scientific-framework> (Accessed 1 December 2013).
- Cooke, S.J., 2008. Biotelemetry and biologging in endangered species research and animal conservation: relevance to regional, national, and IUCN Red List threat assessments. *Endanger. Species Res.* 4, 165–185.
- Director of National Parks, 2013a. North Commonwealth Marine Reserve Network Management Plan 2014–24. Available from <http://www.comlaw.gov.au/Details/F2013L00426> (Accessed on 28 November 2013).
- Director of National Parks, 2013b. North-West Commonwealth Marine Reserve Network Management plan 2014–24. Available from <http://www.comlaw.gov.au/Details/F2013L00428> (Accessed on 28 November 2013).
- Douglas, M.M., Bunn, S.E., Davies, P.M., 2005. River and wetland food webs in Australia's wet-dry tropics: general principles and implications for management. *Mar. Freshw. Res.* 56, 329–342.
- Dulvy, N.K., Fowler, S.L., Musick, J.A., et al., 2014. Extinction risk and conservation of the world's sharks and rays. *eLife* 3, e00590.
- Faria, V.V., McDavitt, M.T., Charvet, P., Wiley, T.R., Simpfendorfer, C.A., Naylor, G.J.P., 2013. Species delineation and global population structure of Critically Endangered sawfishes (Pristidae). *Zool. J. Linn. Soc.* 167, 136–164.
- Gaston, K.J., Fuller, R.A., 2009. The sizes of species' geographic ranges. *J. Appl. Ecol.* 46, 1–9.
- Gaston, K.J., Jackson, S.F., Cantú-Salazar, L., Cruz-Piñón, G., 2008. The ecological performance of protected areas. *Annu. Rev. Ecol. Evol.* 39, 93–113.
- Gaston, K.J., Pressey, R.L., Margules, C.R., 2002. Persistence and vulnerability: retaining biodiversity in the landscape and in protected areas. *J. Biosci.* 27, 361–384.
- Great Barrier Reef Marine Park Authority, 2009. Great Barrier Reef outlook report. Available from <http://elibrary.gbrmpa.gov.au/jspui/handle/11017/199> (Accessed on 15 July 2014).
- Harrison, L.R., Dulvy, N.K. (Eds.), 2014. Sawfish: A Global Strategy for Conservation. IUCN Species Survival Commission's Shark Specialist Group, Vancouver.
- Harry, A.V., Tobin, A.J., Simpfendorfer, C.A., et al., 2011. Evaluating catch and mitigating risk in a multispecies, tropical, inshore shark fishery within the Great Barrier Reef World Heritage Area. *Mar. Freshw. Res.* 62, 710–721.
- Hunt, G., Colbeck, R., 2013. Supporting recreational fishing while protecting our marine parks. Joint media release. Available at <http://www.environment.gov.au/minister/hunt/2013/mr20131214.html> (Accessed on 16 July 2014).
- IUCN, 2012. IUCN Red List Categories and Criteria: Version 3.1, second ed. In: IUCN Species Survival Commission, IUCN, Gland, Switzerland and Cambridge, UK. Available at http://www.iucnredlist.org/static/categories_criteria_3_1 (Accessed on 30 January 2014).
- IUCN, 2014. IUCN Red List of Threatened Species. Available at <http://www.iucnredlist.org> (Accessed on 30 January 2014).
- Jenkins, C.N., Joppa, L., 2009. Expansion of the global terrestrial protected area system. *Biol. Cons.* 142, 2166–2174.
- Kyne, P., Rigby, C., Simpfendorfer, C., 2013. *Pristis clavata*. In IUCN 2013. IUCN Red List of Threatened Species. Available from <http://www.iucnredlist.org/details/39390/0> (Accessed 7 December 2013).
- Last, P.R., Stevens, J.D., 2009. *Sharks and Rays of Australia*, second ed. CSIRO Publishing, Collingwood.
- Lemckert, F., Rosauer, D., Slatyer, C., 2009. A comparison of Australia's anuran records against the reserve system. *Biodivers. Conserv.* 18, 1233–1246.
- Miller, K.R., Reid, W.V., Mittermeier, R.A., Wernert, T.B., 1990. Approaches to conserving biodiversity. In: *Conserving the World's Biological Diversity*. IUCN, Gland, pp. 55–68.
- Morgan, D.L., Whitty, J.M., Phillips, N.M., Thorburn, D.C., Chaplin, J.A., McAuley, R., 2011. North-western Australia as a hotspot for endangered elasmobranchs with particular reference to sawfishes and the northern river shark. *J. R. Soc. West. Aust.* 94, 345–358.
- NRMMC, 2005. Directions for the National Reserve System—a partnership approach. Available from <http://www.environment.gov.au/node/21187> (Accessed 10 December 2013).
- NRMMC, 2010. Australia's biodiversity and conservation strategy 2010–2030. Available from <http://www.environment.gov.au/system/files/resources/58321950-f8b6-4ef3-bb68-6f892420d601/files/biodiversity-strategy-2010.pdf> (Accessed 10 December 2013).
- Pendoley, K.L., Schofield, G., Whittock, P.A., Ierodiakonou, D., Hays, G.C., 2014. Protected species use of coastal marine migratory corridor connecting marine protected areas. *Mar. Biol.* 161, 1455–1466.

- Peverell, S.C., 2008. Sawfish (*Pristidae*) of the Gulf of Carpentaria, Queensland Australia. (Masters Thesis) James Cook University.
- Peverell, S.C., 2005. Distribution of sawfishes (*Pristidae*) in the Queensland Gulf of Carpentaria, Australia, with notes on sawfish ecology. *Environ. Biol. Fishes* 73, 391–402.
- Peverell, S.C., Pillans, R., 2004. Determining feasibility of acoustic tag attachment and documenting short-term movements in *Pristis zijsron* Bleeker, 1851. The State of Queensland, Department of Primary Industries, Brisbane. Available from <http://www.environment.gov.au/system/files/resources/e9d254a4-19ff-4c46-a79f-b51abf476927/files/sawfish-tracking.pdf> (Accessed 15 January 2015).
- Phillips, N.M., Chaplin, J.A., Morgan, D.L., Peverell, S.C., 2011. Population genetic structure and genetic diversity of three critically endangered *Pristis* sawfishes in Australian waters. *Mar. Biol.* 158, 903–915.
- Ritchie, E.G., 2013. Conservation: relaxed laws imperil Australian wildlife. *Nature* 498, 434.
- Rodrigues, A.S.L., Akçakaya, H.R., Andelman, S.J., et al., 2004. Global gap analysis: priority regions for expanding the global protected-area network. *BioScience* 54, 1092–1100.
- Shaw, J.D., Terauds, A., Riddle, M.J., Possingham, H.P., Chown, S.L., 2014. Antarctica's protected areas are inadequate, unrepresentative, and at risk. *PLoS Biol.* 12, e1001888.
- Simaika, J.P., Samways, M.J., 2010. Large-scale estimators of threatened freshwater catchment species relative to practical conservation management. *Biol. Cons.* 143, 311–320.
- Spalding, M.D., Fish, L., Wood, L.J., 2008. Toward representative protection of the world's coasts and oceans—progress, gaps, and opportunities. *Conserv. Lett.* 1, 217–226.
- Stevens, J.D., McAuley, R.B., Simpfendorfer, C.A., Pillans, R.D., 2008. Spatial distribution and habitat utilisation of sawfish (*Pristis* spp) in relation to fishing in northern Australia. A Report to Department of the Environment, Water, Heritage and the Arts. Available from <http://www.environment.gov.au/resource/spatial-distribution-and-habitat-utilisation-sawfish-pristis-spp-relation-fishing-northern> (Accessed 1 December 2013).
- Stoms, D.M., Davis, F.W., Andelman, S.J., et al., 2005. Integrated coastal reserve planning: making the land–sea connection. *Front. Ecol. Environ.* 3, 429–436.
- Taylor, M.J., Sattler, P., Evans, M., Fuller, R.A., Watson, J.E., Possingham, H.P., 2011. What works for threatened species recovery? An empirical evaluation for Australia. *Biodivers. Conserv.* 20, 767–777.
- Thorburn, D.C., Morgan, D.L., Rowland, A.J., Gill, H.S., 2007. Freshwater sawfish *Pristis microdon* Latham, 1794 (Chondrichthyes: Pristidae) in the Kimberley region of Western Australia. *Zootaxa* 1471, 27–41.
- Thorburn, D., Morgan, D., Rowland, A., Gill, H., Paling, E., 2008. Life history notes of the critically endangered dwarf sawfish, *Pristis clavata*, Garman 1906 from the Kimberley region of Western Australia. *Environ. Biol. Fishes* 83, 139–145.
- Thorburn, D.C., Peverell, S., Stevens, J.D., Last, P.R., Rowland, A.J., 2003. Status of freshwater and estuarine elasmobranchs in northern Australia. Final Report to Natural Heritage Trust. Available from <http://www.environment.gov.au/resource/status-freshwater-and-estuarine-elasmobranchs-northern-australia> (Accessed 1 December 2013).
- Venter, O., Fuller, R.A., Segan, D.B., et al., 2014. Targeting global protected area expansion for imperiled biodiversity. *PLoS Biol.* 12, e1001891.
- Watson, J.E., Evans, M.C., Carwardine, J., et al., 2010. The capacity of Australia's protected-area system to represent threatened species. *Conserv. Biol.* 25, 324–332.
- Williams, B.K., Nichols, J.D., Conroy, M.J., 2002. Analysis and Management of Animal Populations. Academic Press, Oxford.
- Winemiller, K.O., 1996. Dynamic diversity: fish communities of tropical rivers. In: Cody, M.L., Smallwood, J.A. (Eds.), Long-Term Studies of Vertebrate Communities. Academic Press, Orlando, pp. 99–134.