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Ecological Risk Assessment for SPRFMO Deepwater Chondrichthyans

Australia

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Ecological risk assessment for SPRFMO deepwater chondrichthyans

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Purpose of this paper

This paper provides an update on the ecological risk assessment (ERA) for deepwater chondrichthyans in SPRFMO deepwater fisheries and includes a draft manuscript at Attachment A.

Introduction

Risks to deepwater chondrichthyans (sharks, rays and chimaeras) from fishing are poorly understood, particularly in areas beyond national jurisdiction. We adapted Productivity-Susceptibility Analysis (PSA) and Sustainability Assessment for Fishing Effects (SAFE) to assess the vulnerability of 174 deepwater chondrichthyans to various demersal fishing gears in the Southern Indian and South Pacific oceans. Several species were categorised as being at high or extreme vulnerability, including some in the Southern Indian Ocean that are reported to be commercially targeted by the Spanish longline fishery. There was good concurrence between PSA and SAFE results for species categorised as being at high or extreme vulnerability by the SAFE, but as expected there was an overall greater number assessed to be at higher vulnerability using PSA due to its precautionary nature. Our results indicate that running PSA and SAFE assessments concurrently provides more useful information than single assessments as it allows for better identification of potential false positives and false negatives. Our findings indicate that better catch, effort and biological information is needed to inform assessment and management of deepwater chondrichthyans.

Background

Australia presented preliminary results of the ERA for deepwater chondrichthyans to SPRFMO SC6 in 2018 (see SC6-DW08).

Following discussion of SC6-DW08, SC6 noted:

1. that there are a number of species assessed to be at high or extreme vulnerability to fishing using demersal trawl, midwater trawl and demersal longline gears
2. that the results are precautionary as they may include false positives (species assessed to be at a higher vulnerability than reality) from assuming that the degree of interaction with the fishing gear is higher than what actually occurs
3. the results may also include some false negatives (species assessed to be low vulnerability that are actually higher in reality) due to a lack of reporting species interactions with fishing gears or poor species identification
4. that the assessment has highlighted information gaps on the identification, productivity, distribution, stock structure and other life history attributes for many species
5. that the assessment has highlighted that additional work on post-capture mortality and gear selectivity of deepwater chondrichthyans would aid future analyses and inform potential future mitigation strategies that would minimise risk associated with susceptibility
6. that additional work would be attempted to refine the spatial resolution used in the analysis, and an update on this would be provided to SC7 in 2019.

These points and recommendations from SC6 were considered in the development of the final draft manuscript included at Attachment A. In relation to point 5, no additional information on post capture mortality or gear selectivity was available and, consequently, no changes were made to these attributes in the final draft manuscript. In relation to point 6, it was determined that additional work required to refine the spatial resolution used in the analysis was not commensurate with the benefits of doing so, and so this work was not attempted. The important point here is that while a refined spatial resolution might give a more accurate representation of absolute risk in the SAFE outputs, it would not necessarily change the relative vulnerability scores. Given that the analysis of catches indicates that fishing-related mortality of most species is relatively low and there are probably few sustainability concerns, this was not attempted. Given point 4 above, SC6 recommended to the SPRFMO Commission that identification protocols and biological data collection for deepwater chondrichthyans be strengthened for SPRFMO demersal fisheries. This was not addressed explicitly during the Commission meeting in January 2019 and the SC may wish to reiterate this recommendation during SC7.

Proposed recommendations for SC7

SC7 is invited to consider the following recommendations:

- **Note** that the ERA for deepwater chondrichthyans in the Southern Indian and South Pacific oceans has been finalised and the draft manuscript has been submitted for publication in a scientific journal;
- **Note** that other RFMO/As, such as SIOFA, have implemented measures prohibiting targeted fishing for deepwater chondrichthyans, which could be similarly implemented by SPRFMO to discourage such practices in the absence of scientifically based assessment and management;
- **Note** that a ban on the retention of deepwater chondrichthyans may provide an incentive for fishers to avoid them and mitigate potential risks;
- **Note** that information on deepwater chondrichthyan catches is often collected at a coarse resolution (for example, species identification is often at a genus level or coarser) and that improvements to this data collection would assist with future analyses;
- **Agree** that reductions in shark bycatch, particularly for species assessed to be at high or extreme vulnerability, would assist in mitigating any potential risk of overexploitation;
- **Agree** that improved assessments and estimates of sustainable yields would be useful in informing the level of reductions in shark bycatch required to mitigate any potential risk for overexploitation, particularly for species assessed to be at high and extreme risk that may be retained as byproduct;
- **Agree** that in the absence of this information, measures to reduce shark bycatch (if implemented) should be informed by the precautionary approach; and

- **Recommend** to the SPRFMO Commission that identification protocols and biological data collection for deepwater chondrichthyans be strengthened for SPRFMO demersal fisheries.

Attachment A – Draft manuscript (submitted September 2019)

Ecological risks of demersal fishing on deepwater chondrichthyan populations in the Southern Indian and South Pacific oceans

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Abstract

Risks to deepwater chondrichthyans (sharks, rays and chimaeras) from fishing are poorly understood, particularly in areas beyond national jurisdiction. We adapted Productivity-Susceptibility Analysis (PSA) and Sustainability Assessment for Fishing Effects (SAFE) to assess the vulnerability of 174 deepwater chondrichthyans to various demersal fishing gears in the Southern Indian and South Pacific oceans. Several species were categorised as being at high or extreme vulnerability, including some in the Southern Indian Ocean that are reported to be commercially targeted by the Spanish longline fishery. There was good concurrence between PSA and SAFE results for species categorised as being at high or extreme vulnerability by the SAFE, but as expected there was an overall greater number assessed to be at higher vulnerability using PSA due to its precautionary nature. Our results indicate that running PSA and SAFE assessments concurrently provides more useful information than single assessments as it allows for better identification of potential false positives and false negatives. Our findings indicate that better catch, effort and biological information is needed to inform assessment and management of deepwater chondrichthyans. If targeted fishing continues in the Southern Indian Ocean, improved assessments and estimates of sustainable yields are urgently required to mitigate risk of overexploitation.

Key words: elasmobranchs, ecosystem approach to fisheries, productivity susceptibility analysis, sustainability assessment for fishing effects, high seas fisheries, RFMOs

Introduction

A recent global assessment estimated that 25% of the world's chondrichthyans (sharks, rays and chimaeras) are threatened with extinction (Dulvy et al., 2014). Some of these species are caught in deep-sea demersal fisheries, such as those operating in the Southern Indian and South Pacific oceans. According to Dulvy et al. (2014), of the 479 deepwater chondrichthyans assessed by the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, approximately 5.2% are globally threatened (i.e. *Critically Endangered*, *Endangered* or *Vulnerable*), 9.4% are *Near Threatened*, 27.8% are *Least Concern* and 57.6% are *Data Deficient*. Deepwater chondrichthyans can be more vulnerable to overfishing in comparison to many teleost species due to their lower production potential (e.g. low fecundity, slow growth, late maturity and long life spans), which reduces their capacity to recover once populations are depleted (Simpfendorfer and Kyne, 2009; Rigby and Simpfendorfer, 2015). Fishing has resulted in a number of highly depleted and over-fished deepwater chondrichthyan stocks, including gulper sharks (*Centrophorus* spp.) (Graham et al., 2001; Williams et al., 2013), spiny dogfishes in the *Squalus mitsukurii* complex (Graham et al., 2001; Graham, 2005) and smalltooth sandtiger (*Odontaspis ferox*) (Fergusson et al., 2008), suggesting that management precaution is required.

As highlighted by the high proportion of *Data Deficient* deepwater chondrichthyans in the IUCN Red List of Threatened Species, deficiencies in existing catch, effort and biological (e.g. age, distribution and population structure) information for these species can make assessment of their vulnerability to fishing difficult (Veríssimo et al., 2012; McLean et al., 2015). This issue is made more problematic by existing taxonomic uncertainties that often do not allow for the collection of accurate species-specific catch data (Straube et al., 2011; Veríssimo et al., 2012). The difficulties in estimating biomass and fishing mortality through conventional stock assessments can necessitate the application of data limited assessment methods (e.g. Dowling et al., 2008; Dichmont and Brown, 2010; Marchal and Vermard, 2013) such as ecological risk assessment (ERA) to enable an evaluation of the vulnerability of species to potential fisheries interactions (Stobutzki et al., 2002). Vulnerability in this context is defined following Griffiths et al. (2017) as "the potential for the productivity of a stock to be diminished beyond expected natural fluctuations by direct and/or indirect fishing interactions."

Several ERA methods have been applied around the globe in situations where fishing mortality is unknown but information on the distribution of fishing effort and the basic biology of species may be available (e.g. Milton, 2001; Stobutzki et al., 2002; Zhou et al., 2007; Zhou and Griffiths, 2008; Arrizabalaga et al., 2011; Tuck, 2011; Zhou et al., 2012). Multiple methods, each with different assumptions and data requirements exist. Hobday et al. (2011) organised some of these methods under a hierarchical Ecological Risk Assessment for the Effects of Fishing (ERAEF) framework. This enables risk to be managed in a cost-effective way through the implementation of management actions at different stages of the hierarchy, from the largely qualitative analysis of risk based on expert opinion and stakeholder feedback (level 1), to a more focused and semi-quantitative approach (level 2), and finally to a highly focused and fully quantitative approach (level 3). The management response at each level may include additional assessment, identification of appropriate management or mitigation strategies, or scenarios in which no additional management actions are required. At the lower levels of the hierarchy, ERAEF is generally acknowledged to be more precautionary (i.e. missing information results in classifying species at higher risk), which can lead to a greater number of false positives (species assessed to be high risk that may be low risk) (Hobday et al., 2011). Although ERA methods only generate proxy estimates of fishing mortality ($F_{current}$), refinements made over the last decade (see, for example, Griffiths et al., 2018; Zhou et al., 2019) mean they are increasingly being used to inform management (Griffiths et al., 2018; Griffiths et al., in press). ERA tools (see below) are also being applied to categorise the vulnerability of species into risk categories to prioritise where the impacts of fishing may be sufficient to warrant further quantitative assessment or other management intervention.

A widely used ERA tool in fisheries is the semi-quantitative Productivity-Susceptibility Analysis (PSA) (Stobutzki et al., 2002), which considers risk to species as a function of their biological productivity and their susceptibility to fishing using various gears (Patrick et al., 2010; Hobday et al., 2011). PSA is considered useful for evaluating the vulnerability of many data-limited species by providing simple results that are easily interpreted by fisheries managers and policy makers (Griffiths et al., 2017; Williams et al., 2018).

Quantitative ERA tools such as Sustainability Assessment for Fishing Effects (SAFE) (Zhou et al., 2007; Zhou et al., 2012; Zhou et al., 2016; Zhou et al., 2019) and Ecological Assessment of Sustainable Impacts of Fisheries (EASI-Fish; (Griffiths et al., 2018) extend the PSA concept and derive a proxy for fishing mortality based on the susceptibility of species in relation to productivity. Both of these tools are also capable of quantifying cumulative impacts across multiple fisheries (Griffiths et al., 2018; Zhou et al., 2019). Both PSA and SAFE tools have been applied to teleosts and chondrichthyans in Australia (Zhou and Griffiths, 2008; Chin et al., 2010; Zhou et al., 2011; Zhou et al., 2019) and in high seas areas in the Atlantic Ocean (Cortés et al., 2010; Arrizabalaga et al., 2011), the Western and Central Pacific Ocean (Kirby, 2006), the Eastern Pacific Ocean (Griffiths et al., 2017) and the Indian Ocean (Murua et al., 2009; Murua et al., 2018). Zhou et al. (2016) demonstrated that estimates of F from SAFE were comparable to those derived from data-rich quantitative stock assessments in most cases, and that SAFE overestimated F (i.e. overestimated risk) in all other cases. An advantage of applying both PSA and SAFE analyses to the same fisheries and species is that it allows an assessment of the concurrence in vulnerability scores and improved evaluation of false positives and false negatives (Hobday et al., 2011).

We apply PSA and SAFE tools (after Zhou and Griffiths, 2008; Hobday et al., 2011) to evaluate the vulnerability of 174 deepwater chondrichthyans to demersal fisheries in the Southern Indian and South Pacific oceans under the regional management of the Southern Indian Ocean Fisheries Agreement (SIOFA) and the South Pacific Regional Fisheries Management Organisation (SPRFMO). Vulnerability is assessed for demersal trawl, midwater trawl, demersal longline and demersal gillnet[1] fishing gears. The PSA and SAFE are used to identify those species considered to be the most vulnerable (or at highest risk) to different types of fishing gear. We discuss the results in terms of species' vulnerability to certain gears and within the context of regional management of high seas fisheries.

Methods

Background to the fisheries operating in the Southern Indian and South Pacific oceans

Fisheries in the SIOFA area (Figure 1.1a) predominantly target demersal and bentho-pelagic species using either demersal trawl, midwater trawl and demersal longline gears. Midwater trawl vessels predominantly target alfonsino (*Beryx splendens*) and demersal trawl vessels predominantly orange roughy (*Hoplostethus atlanticus*). There is also a 'shallow' demersal trawl fishery for *Saurida* spp. and *Decapterus* spp. on the Saya de Malha bank (10° 2' 4.8" S, 60° 33' 45.6" E). Longline vessels target Patagonian toothfish (*Dissostichus eleginoides*), other demersal teleosts and deepwater sharks (predominantly Squalidae). Gillnet vessels

[1] The use of demersal gillnet gears was prohibited in the South Pacific Ocean in 2012 by the SPFRMO and this gear type is not assessed for this area.

targeting deepwater sharks operated in the SIOFA area until 2015. The SPRFMO Convention (Figure 1.1b) covers non-highly migratory species, which are caught using pelagic and demersal fishing gears. The main commercial fisheries managed by SPRFMO are Chilean jack mackerel (*Trachurus murphyi*) and jumbo flying squid (*Dosodicus gigas*). The SPRFMO also manages fisheries for lower volume demersal species such as orange roughy and alfonsino (caught using demersal trawl and midwater trawl gears) and a variety of species caught using demersal longline gears. Bottom fisheries in SIOFA and SPRFMO typically target demersal species in association with ridges, seamounts, plateaus and banks (Georgeson and Nicol, 2018).

Figure 1.1a: Southern Indian Ocean Fisheries Agreement Area

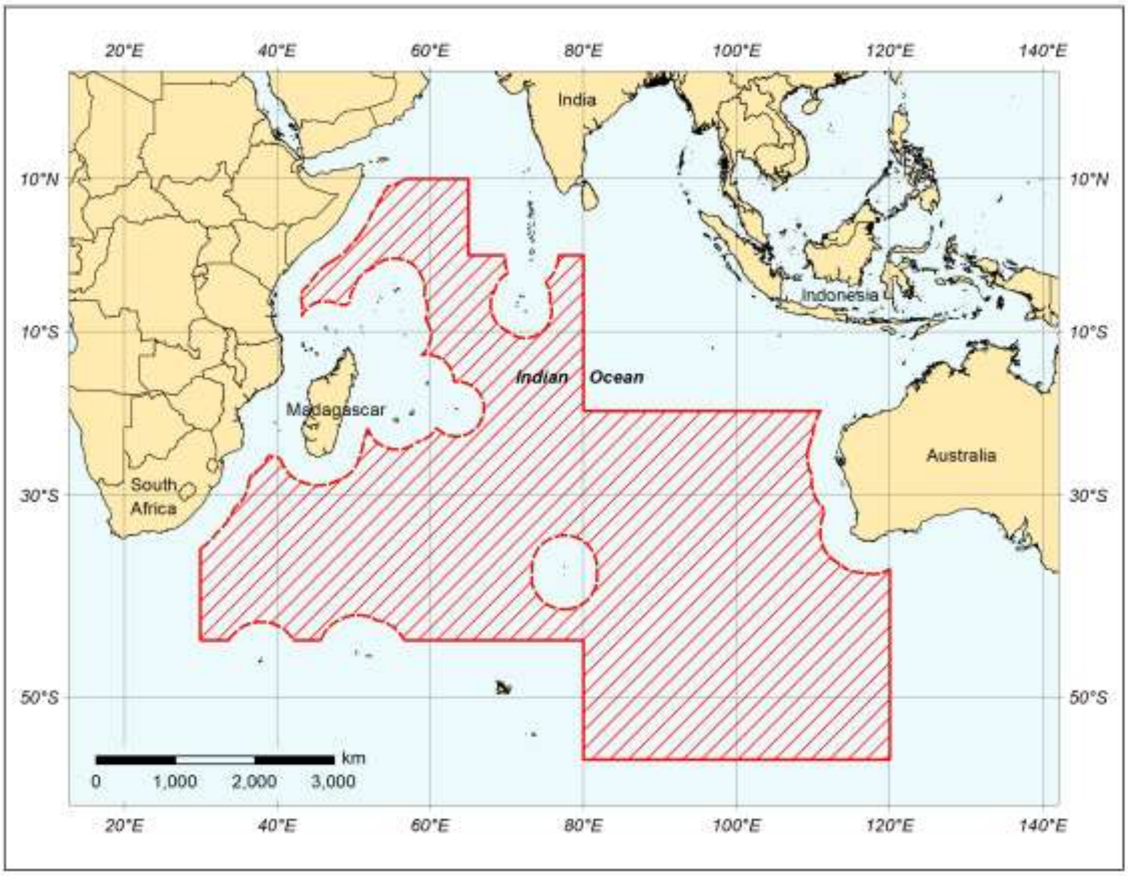
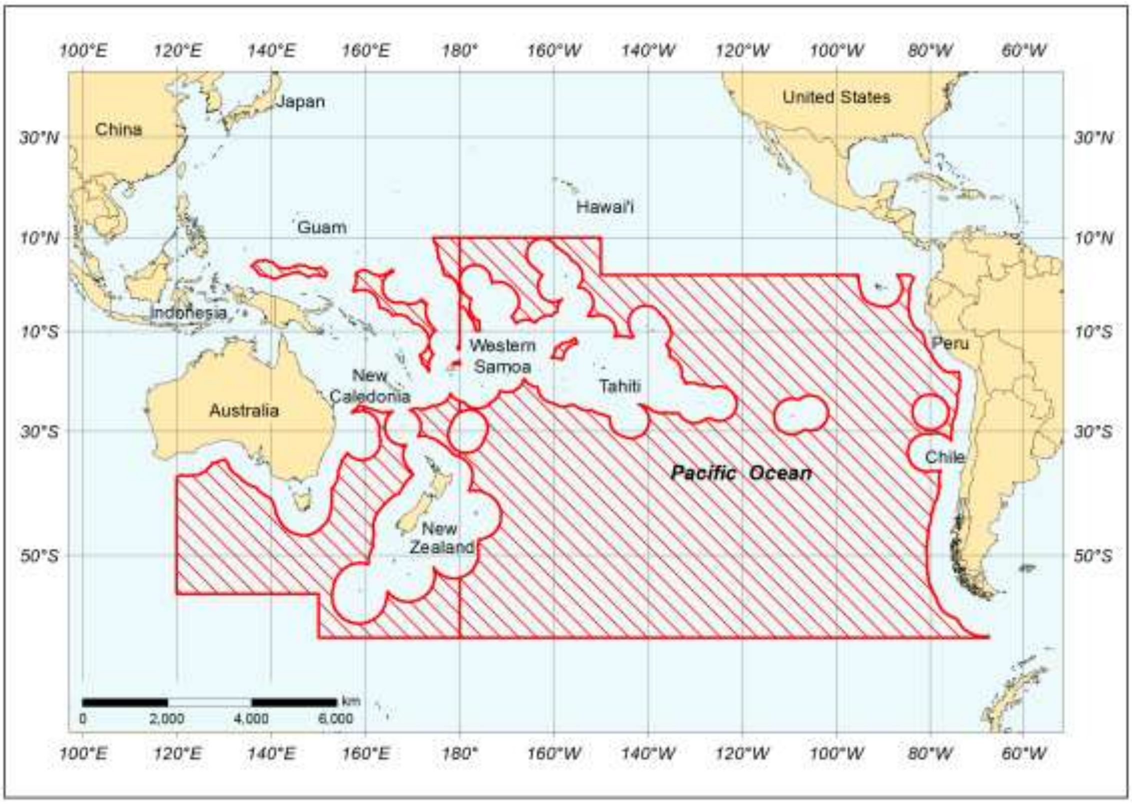


Figure 1.1b: South Pacific Regional Fisheries Management Organisation Convention area



Formulation of species list and data collection

To undertake the PSA and SAFE analyses, species lists for the Southern Indian and South Pacific oceans were formulated using available catch records and various sources in the published literature (e.g. Last and Stevens, 2009; Ebert, 2013; Ebert, 2014; Ford et al., 2015; Ebert, 2016; Last et al., 2016) and refined using input from chondrichthyan experts in Australia, New Zealand and the United States. This expert input was necessary for resolving numerous taxonomic uncertainties (for example, regarding species complexes) and some fishery data coding and species misidentification issues. Species were included in the list if they were thought to occur, and interact with gears, in each gear-type 'fishery'. The total number of species identified was 112 in the Southern Indian Ocean and 101 in the South Pacific Ocean, with 40 species included in both regions. These species lists are subsets of all chondrichthyan species present in the two areas and may also include species for which there are few or no records of fishery interaction. Some species known to be present in the two areas were excluded if they have a mainly coastal distribution and are not exposed to high seas fishing, or if they occur in habitat that is unsuitable for fishing. For the purposes of this study, 'deepwater' chondrichthyans were defined as those that spend most of their lifecycle below 200 m depth, as described by Kyne and Simpfendorfer (2007).

Life-history attributes for each deepwater chondrichthyan species were compiled from the relevant published literature. A paucity of biological information for many species resulted in the attribution of proxy biological characteristics from similar (e.g. congeneric or co-familiar) species, following protocols described in Hobday et al. (2011). This was done using expert input and was only applied in situations where it was deemed that the use of proxy attributes would represent a better option than simply assuming no data. Species distribution data were sourced from the FAO Catalogue of Species—Geonetwork database (http://www.fao.org/geonetwork/srv/en/main.search), the IUCN Red List (https://www.iucnredlist.org/) and various published sources. The FAO Catalogue of Species generally had the most recent distribution data, so was used if available. Fishing effort and catch data were requested from all relevant nations that have reported deep-sea bottom fishing in the Southern Indian and South Pacific oceans during the assessed period of 2012 to 2016. A complete fishing effort dataset was available for the South Pacific Ocean gear types but effort data for trawl and longline gears were incomplete for the Southern Indian Ocean.

Productivity-Susceptibility Analysis (PSA)

PSA (Stobutzki et al., 2002; Hobday et al., 2011) is based on scoring productivity and susceptibility attributes to estimate relative potential vulnerability. The productivity (P) attributes (Table 1) are assumed to influence the intrinsic rate of increase (r) and the susceptibility (S) attributes are assumed to influence catchability (q). While scoring and attribute variations have been developed around the world (See, e.g. Patrick et al., 2010), here the productivity score is calculated as the average of seven productivity attributes. The susceptibility (S) score is calculated as the product of four susceptibility attributes (Table 2). Attributes used in the PSA are typically scored a 1 (low vulnerability), 2 (medium vulnerability) or 3 (high vulnerability). In line with a precautionary approach, missing attributes are scored a 3. Data deficient species in the PSA are classified as those missing three or more P and/or S attributes. Low productivity species with high susceptibility scores are considered to be the most vulnerable, while high productivity species with low susceptibility scores are considered to be the least vulnerable. Species are assigned to an overall vulnerability category (high, medium or low) by dividing the 2-dimensional Euclidean distance ($\sqrt{P^2 + S^2}$) into equal thirds, such that scores <2.64 are low vulnerability, between 2.64 and 3.18 are medium vulnerability, and >3.18 are high vulnerability.

Productivity attributes

Productivity attributes were estimated from life history traits recommended in Hobday et al. (2011) and modified to be relevant to chondrichthyans, as outlined in Table 1. The correlation between these life history traits and productivity has been well established for chondrichthyans (Dulvy et al., 2008; Hutchings et al., 2012). For this study, *Fecundity* metrics were redefined from those used for teleosts in Hobday et al. (2011) to be relevant to deepwater chondrichthyans by using numbers of pups/egg cases (as opposed to eggs) that were typical of chondrichthyans with low, medium and high productivity. The Hobday et al. (2011) attribute values for *Average maximum size* and *Average size at maturity* were based on a large database of teleosts and chondrichthyans and described a strong negative relationship between size and productivity (i.e. larger species typically exhibit lower productivity and smaller species typically exhibit higher productivity). These attributes were rescaled based on an analysis of the size-productivity relationship using data from a global database for deepwater chondrichthyans (held by James Cook University). This analysis estimated the relationship to be weaker than that defined in Hobday et al. (2011). Deepwater shark productivity significantly declines with increasing depth yet there is no corresponding significant increase in size with increasing depth (Rigby and Simpfendorfer, 2015). However, the general negative relationship of size and productivity does hold for deepwater skates, as they generally increase in size with depth (Simpfendorfer and Kyne, 2009; Rigby and Simpfendorfer, 2015).

Table 1: Productivity attributes and risk categorisations (adapted from Hobday et al., 2011).

Attribute	Low productivity (high vulnerability, score = 3)	Medium productivity (medium vulnerability, score = 2)	High productivity (low vulnerability, score = 1)
P1. Average age at maturity	>15 years	5–15 years	<5 years
P2. Average maximum age	>25 years	10–25 years	<10 years
P3. Fecundity ***(redefined and rescaled for deepwater chondrichthyans)***	<10 pups/egg cases per year	10-20 pups/egg cases per year	>20 pups/egg cases per year
P4. Average maximum size ***(rescaled for deepwater chondrichthyans)***	>200 cm	70–200 cm	<70 cm
P5. Average size at maturity ***(rescaled for deepwater chondrichthyans)***	>150 cm	40–150 cm	<40 cm
P6. Reproductive strategy	Live bearer	Egg case layer	Broadcast spawner*
P7. Trophic level	>3.25	2.75–3.25	<2.75

*** This category was deemed irrelevant and was not used in this assessment due to the low productivity of deepwater chondrichthyans.**

<u>*Susceptibility attributes*</u>

Susceptibility was estimated based on traits recommended in Hobday et al. (2011), following Walker (2005) and outlined in Table 2. Specifically, *Availability* was calculated as the spatial overlap of species distribution within the SIOFA and SPRFMO areas (Figures 1a and 1b) and the spatial footprint of fishing effort for each gear (between 2012 and 2016) at a 20-minute resolution. For each gear the 'fished area' was defined as 20-minute grid cells with at least one fishing operation. *Encounterability* was calculated as the proportion of vertical overlap between fishing effort and species depth ranges (Table 3). The middle 90 percent (i.e. from the 5^{th} to 95^{th} percentiles) of fishing depth records for each gear was defined as the core depth range. Using this approach, outliers and zeros were discarded. *Selectivity* categorisations were informed by an analysis of available literature for gear selectivity (e.g. Kirkwood and Walker, 1986 for gillnet selectivity) and expert input (trawl and line gears). *Post capture mortality* (PCM) scores were formulated through a desktop analysis of the role of each species in each fishery (target, byproduct or bycatch species). Species that were assessed to be targeted or caught as byproduct (i.e. retained) were assigned high vulnerability and bycatch (i.e. discarded) species were assigned medium vulnerability. There were no species assigned low vulnerability for PCM.

1 **Table 2.** Susceptibility attributes and vulnerability categorisations (adapted from Hobday et al., 2011). Note that availability and encounterability attributes for the medium susceptibility/vulnerability category were scored on a continuous scale between 1 and 3 for the *Availability* and *Encounterability* attributes.

Attribute	Low susceptibility (low vulnerability, score = 1)	Medium susceptibility (medium vulnerability, score = >1 to <3 for S1 and S2; 2 for S3 and S4)	High susceptibility (high vulnerability, score = 3)
S1. Availability	<10% horizontal overlap	10-30% horizontal overlap	>30% horizontal overlap
S2. Encounterability *(modified using gear depth data)*	Low vertical overlap with fishing gear (<10%) based on middle 90% of the fishing depth range by gear type	Medium vertical overlap with fishing gear (10-30%) based on middle 90% of the fishing depth range by gear type	High vertical overlap with fishing gear (>30%) based on middle 90% of the fishing depth range by gear type
S3. Selectivity (scores vary by gear type)	Demersal and midwater trawl: 0-15 cm; > 500 cm max. length Line: 0-40 cm; >500 cm max. length Gillnet: 0-70 cm; >130 cm max length**^**	Demersal and midwater trawl: 15-30 cm; 400-500 cm max. length Line: 40-80 cm; 200-500 cm max. length Gillnet: 70-80 cm max. length**^**	Demersal and midwater trawl: 30-400 cm max. length Line: 80-200 cm max. length Gillnet: 80-130 cm max. length**^**
S4. Post-capture mortality (scores may vary by fishery and gear type)	Evidence of post capture release and survival	Bycatch species (discarded) or limited evidence of survival	Target or byproduct species (retained)

^ Only used in Southern Indian Ocean fisheries

Table 3: Core depth range (5th-95th percentiles) of gears used to inform *Encounterability* for the Southern Indian Ocean and South Pacific Ocean PSA assessments (calculated using available fishing effort data for 2012–2016)

Gear	South Pacific Ocean depth min. (m)	South Pacific Ocean depth max. (m)	Southern Indian Ocean depth min. (m)	Southern Indian Ocean depth max. (m)
Demersal trawl	520	1069	700	1235
Midwater trawl	327	548	430	970
Demersal longline	230	654	597	1716
Demersal gillnet	-	-	810	1390

Sustainability Assessment for the Effects of Fishing (SAFE)

The SAFE method (Zhou et al., 2007; Zhou and Griffiths, 2008; Zhou et al., 2009; Hobday et al., 2011; Zhou et al., 2016; Zhou et al., 2019) estimates the fishing mortality rate F (expressed as the estimated fraction of the population that has died because of fishing). We used three parameters: spatial overlap, catchability and post capture mortality as described by Zhou et al. (2011) to determine the current fishing mortality F_{curr} as:

$$F_{\mathrm{curr}} = \frac{\sum a_t}{A} q^h q^\lambda (1-s)(1-E)$$

where a_t and A represent the area fished and a species' distribution area (i.e. spatial overlap), respectively, q^h and q^λ are the habitat-dependent encounterability and size- and behaviour-dependent catch rate ('catchability'), E is the escapement rate (i.e. the amount of the population that does not get caught by fishing) and s is the post-capture survival rate.

Methods for estimating spatial overlap varied depending on the fishery characteristics, including the configuration of gears. Similarly, q^h, q^λ, E and s varied depending on the biology of the species. Zhou et al. (2011) describe the different methods used for estimating these parameters for trawl, longline and gillnet fisheries.

The SAFE method relates life history traits that inform natural mortality (M), growth rate and intrinsic rate of increase (r) to biological reference points using six formulae derived from Pauly (1980), Quinn and Deriso (1999), Hoenig (1983), Jensen (1996) and fishbase.org (see Zhou et al. (2012) for additional detail). The model uses the average of the six methods for defining the midpoint on the productivity axis. Where information is not available for estimating the parameters for one or more formulae, the model uses the average of the estimates of the remaining formulae from which parameters are able to be estimated. The result is that F_{curr} can be compared to F-based reference points F_{msm}, F_{lim} and F_{crash} (Box 1) and categorised into classes of vulnerability (Box 2). Data deficient species in the SAFE are classified as those for which F-based reference points could not be estimated due to missing productivity attribute data.

Box 1: Biological reference points used in SAFE assessment

F_{msm} – Fishing mortality rate corresponding to maximum sustainable fishing mortality (*MSM*) at B_{msm} (biomass that supports *MSM*, equivalent to *MSY*)

F_{lim} – Fishing mortality rate corresponding to limit biomass B_{lim}, where B_{lim} is defined as 50% biomass that supports the *MSM*

F_{crash} – minimum unsustainable fishing mortality rate that theoretically may lead to population extinction in the long term

Box 2: SAFE vulnerability categories

Low – $F < F_{msm}$
Medium – $F_{lim} > F \geq F_{msm}$
High – $F_{crash} > F \geq F_{lim}$

Extreme – $F \geq F_{crash}$

Sensitivity analysis of spatial overlap

Spatial distribution data varied significantly between data sources (e.g. FAO Geonetwork vs. IUCN Red List) for some species. As the selection of these data sources influences *Availability* scores, we evaluated the sensitivity of the overlap between fishing effort and species distribution in the PSA assessment by varying the *Availability* attribute overlap scores by ±10%, ±20% and ±30% increments. The *Availability* attribute was then scored as before, and the new susceptibility score recalculated. The number of species changing to a lower or higher risk category for each were then recorded for each of these six variations.

Comparing PSA and SAFE vulnerability scores

When assessing the level of concurrence between the PSA and SAFE results we made the assumption that the high and extreme vulnerability categories from the SAFE were comparable to the high vulnerability category from the PSA (following Zhou et al., 2016). This allowed us to plot the PSA 2D score against the SAFE F/F_{lim} score for each fishery in both the Southern Indian and South Pacific oceans and examine the difference between the PSA and SAFE results.

Results

Productivity-Susceptibility Analysis (PSA)

Supplementary online data (PSA) provide details of the PSA results for both the Southern Indian and South Pacific oceans. There was a total of 47, 51, 45 and 27 chondrichthyan species ranked as high vulnerability in the Southern Indian Ocean to demersal trawl, midwater trawl, demersal longline, and gillnet fisheries, respectively (Table 4). In the South Pacific Ocean, there were a total of 56, 31 and 39 species ranked as high vulnerability to demersal trawl, midwater trawl and demersal longline fisheries, respectively (Table 4).

Out of the 101 species assessed in the Southern Indian Ocean, the IUCN Red List of Threatened Species categorised around one third of them (35) as *Data Deficient,* similar to the South Pacific Ocean, where around a quarter (32) of the 112 species were *Data Deficient* (Figures 2a and Figure 2b). A total of two and four species were classified as *Endangered* in the Southern Indian and South Pacific oceans respectively, which was the highest IUCN Red List category among the species assessed in this study (Figures 2a and 2b).

Of the 101 species assessed in the Southern Indian Ocean, none were classified in this assessment as data deficient (i.e. missing three or more productivity or susceptibility attributes), while in the South Pacific Ocean, one (*Squalus fernandezianus*) of the 112 species assessed was classified as data deficient. Productivity attributes from congeneric or similar species were applied to 60 species in the Southern Indian Ocean and 76 species in the South Pacific Ocean.

Chondrichthyan species classified as high vulnerability across all fisheries in the Southern Indian Ocean included *Deania calcea, Chlamydoselachus anguineus, Etmopterus alphus, Scymnodon plunketi, Centroselachus crepidater, Chimaera willwatchi, Chimaera buccanigella, Dalatias licha* and *Centrophorus granulosus.* The two chimaera species are newly described (Clerkin et al., 2017) and had limited distribution data, resulting in these precautionary high vulnerability rankings. Chondrichthyan species classified as high vulnerability across all fisheries in the South Pacific Ocean included *Squalus fernandezianus*, *Deania calcea, Gollum attenuates, Squalus griffin, Centrophorus harrissoni, Oxynotus bruniensis, Mitsukurina owstoni* and *Echinorhinus cookei*.

The vulnerability scores by region (Southern Indian and South Pacific oceans) and fishery (i.e. gear type) are shown in Figures 3a and 3b. The vulnerability scores for most fisheries (midwater trawl in the South Pacific Ocean being a clear exception) cluster closely along the horizontal axis of the PSA plots (i.e. >2.0 productivity score) because the biological attributes and resulting productivity attribute rankings of many deepwater chondrichthyans are similar. In contrast, there was more variation in the vertical axis due to different susceptibilities between species. For example, in the Southern Indian Ocean, productivity scores for all high vulnerability species ranged from 1.86 to 2.86, while susceptibility scores ranged from 1.41 to 3.

Table 4. Count of data robust and data deficient species assessed to be at high vulnerability (PSA) and high and extreme vulnerability (SAFE) for each fishery in the Southern Indian Ocean and South Pacific Ocean. Data deficient species are classified as those missing three or more productivity and/or susceptibility attributes (PSA) and for which *F*-based reference points could not be estimated due to missing biological data (SAFE).

	Southern Indian Ocean								**South Pacific Ocean**					
	Demersal gillnet		**Demersal longline**		**Demersal trawl**		**Midwater trawl**		**Demersal longline**		**Demersal trawl**		**Midwater trawl**	
	PSA	*SAFE*	*PSA*	*SAFE*	*PSA*	*SAFE*	*PSA*	*SAFE*	*PSA*	*SAFE*	*PSA*	*SAFE*	*PSA*	*SAFE*
Data Robust	27	3	45	9	47	11	51	12	38	13	55	16	30	0
Data Deficient	0	1	0	0	0	0	0	0	1	4	1	4	1	4
Total	**27**	**4**	**45**	**9**	**47**	**11**	**51**	**12**	**39**	**17**	**56**	**20**	**31**	**4**

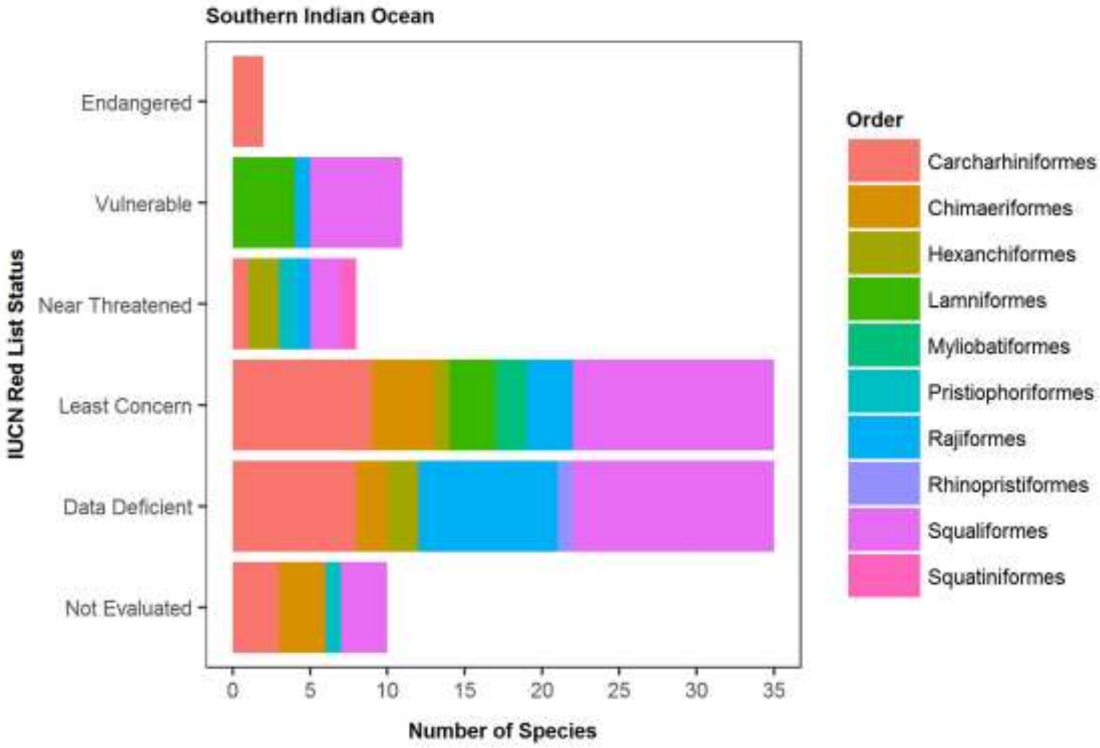


Figure 2a. Assessed chondrichthyan species (101) in the Southern Indian Ocean by IUCN Red List Category based on their taxonomic order.

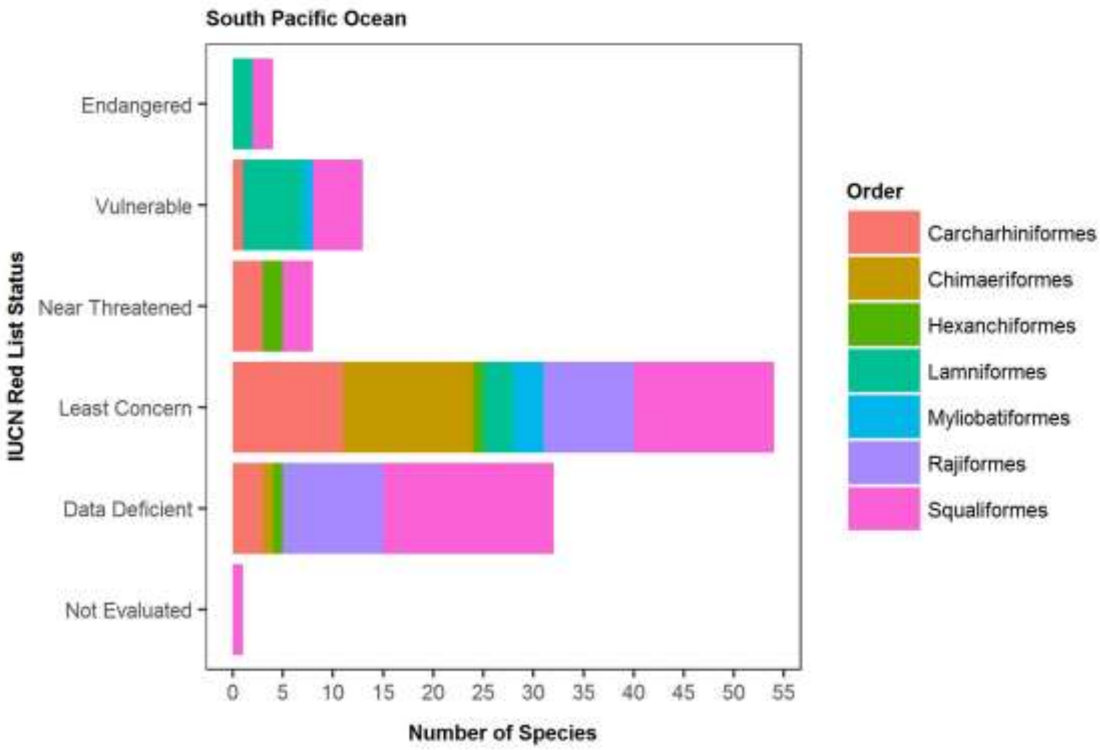


Figure 2b. Assessed chondrichthyan species (112) in the South Pacific Ocean by IUCN Red List Category based on their taxonomic order.

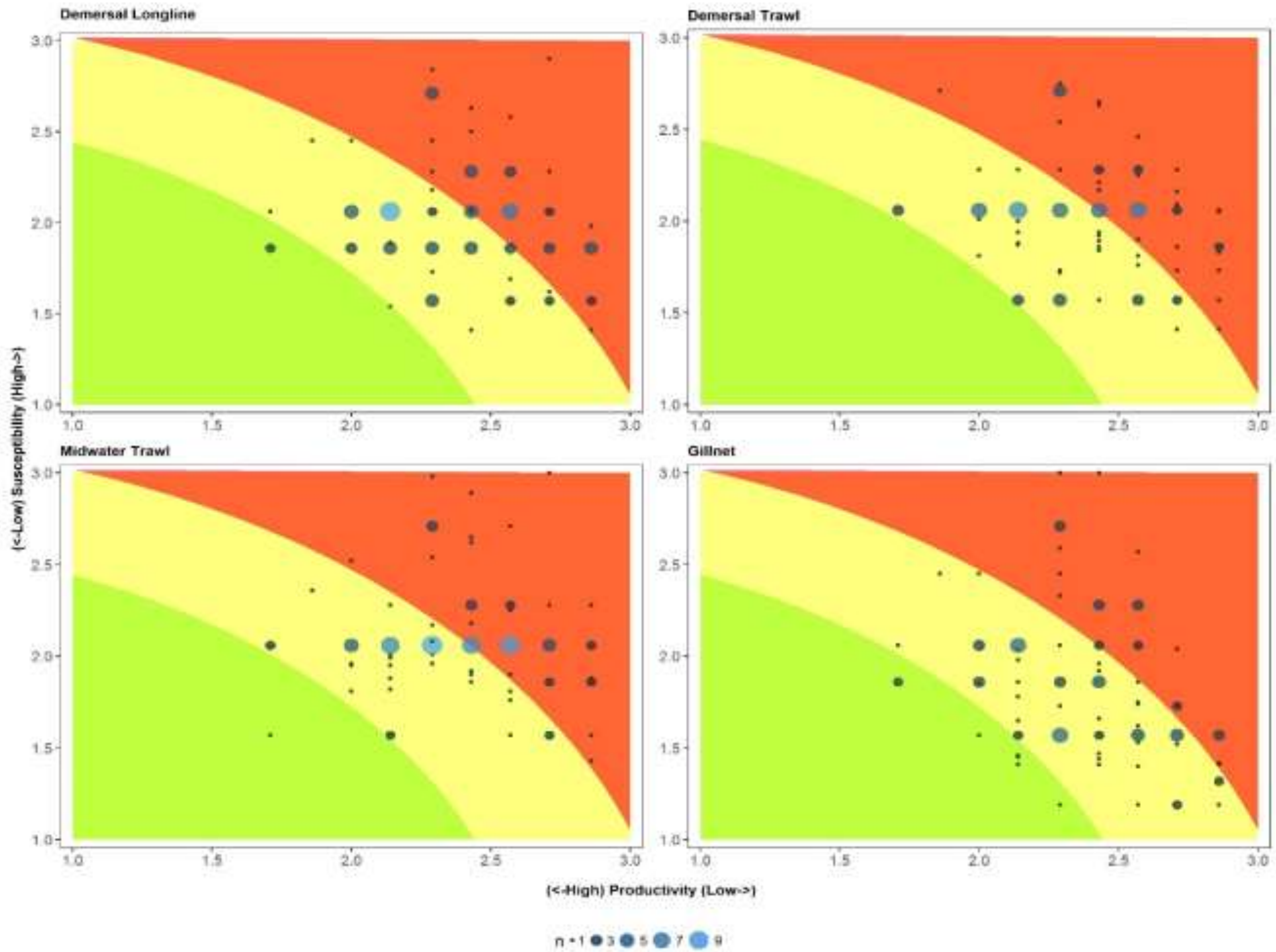


Figure 3a. PSA results for 101 chondrichthyan species with the potential to interact with longline, demersal and midwater trawl and demersal gillnet fisheries in the Southern Indian Ocean. Size of symbol represents number (n) of species with the same vulnerability score. The green, yellow and red shading indicates low, medium and high vulnerability rankings, respectively.

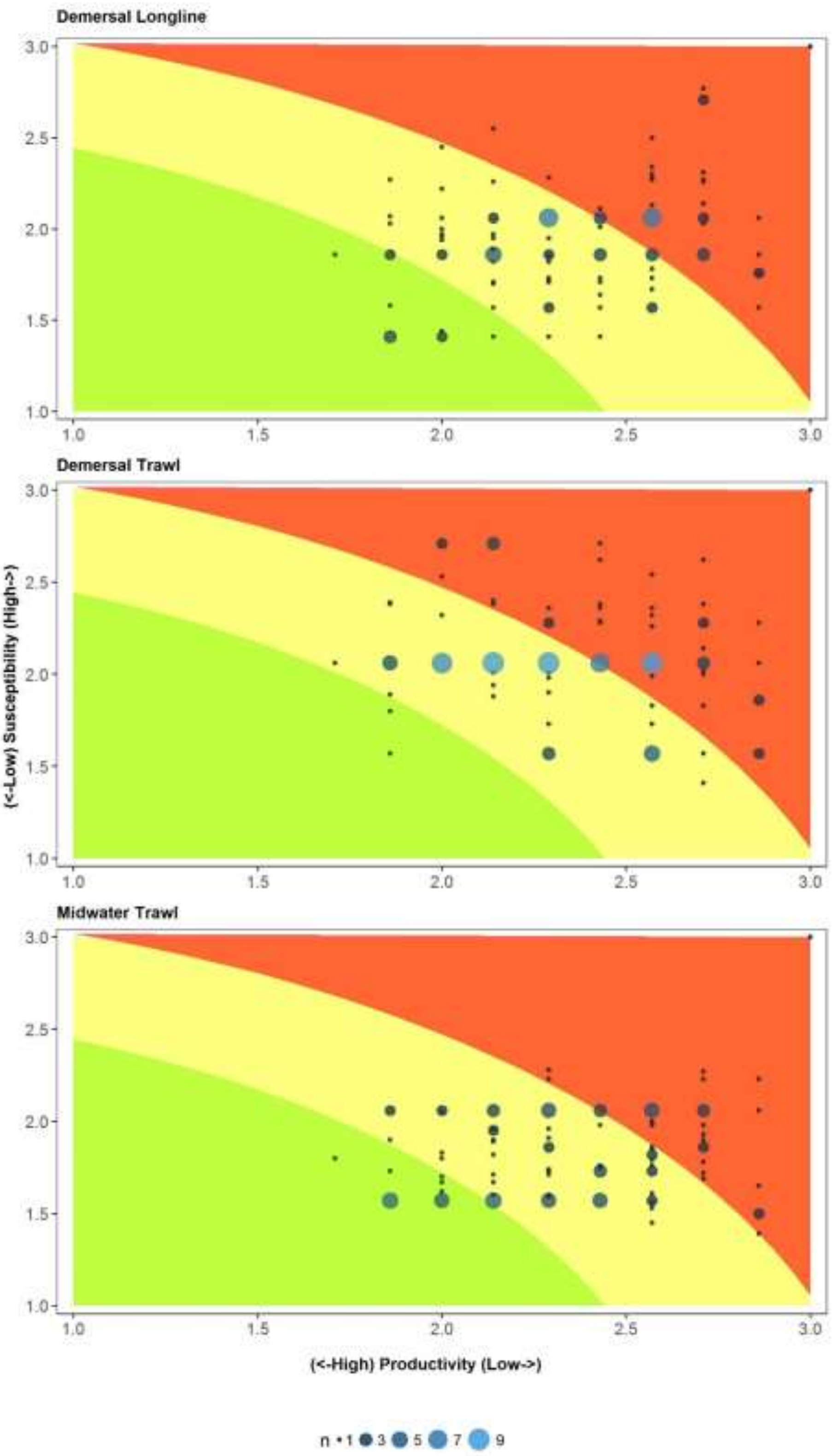


Figure 3b. PSA results for 112 chondrichthyan species with the potential to interact with longline, demersal trawl and midwater trawl fisheries in the South Pacific Ocean. Size of symbol represents number (n) of species with the same vulnerability score. The green, yellow and red shading indicates low, medium and high vulnerability rankings, respectively.

Sensitivity analysis of overlap

In the Southern Indian Ocean, one, three and one out of the 101 assessed species changed PSA vulnerability categories for demersal trawl, demersal longline and demersal gillnet gears, respectively, when overlap scores for the *Availability* attribute were varied by ±10–30%. In the South Pacific Ocean, six, one and four out of the 112 assessed species changed vulnerability categories for demersal trawl, midwater trawl and demersal longline gears, respectively. Across both the Southern Indian and South Pacific oceans, a total of six, 10 and 16 species changed vulnerability categories across the negative and positive 10%, 20% and 30% increments, respectively. More species changed vulnerability categories for the negative than positive increments.

Table 5. Sensitivity analysis for Southern Indian and South Pacific Oceans species that change vulnerability categories when overlap scores for the *Availability* attribute are varied by ±10–30%. Note that X denotes no change.

Fishery	Gear and *Species*	-30%	-20%	-10%	PSA vulnerability	+10%	+20%	+30%
Southern Indian Ocean	**Demersal trawl**							
	Etmopterus pusillus	Medium	Medium	X	High	X	X	X
	Midwater trawl							
	NA	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
	Demersal longline							
	Somniosus antarcticus	Medium	Medium	Medium	High	X	X	X
	Etmopterus pusillus	X	X	X	Medium	High	High	High
	Etmopterus granulosus	X	X	X	Medium	High	High	High
	Demersal gillnet							
	Etmopterus granulosus	Medium	Medium	X	High	X	X	X
South Pacific Ocean	**Demersal trawl**							
	Etmopterus lucifer	Medium	Medium	Medium	High	X	X	X
	Hydrolagus bemisi	Medium	Medium	Medium	High	X	X	X
	Zameus squamulosus	Medium	Medium	Medium	High	X	X	X
	Heptranchias perlo	Medium	X	X	High	X	X	X
	Apristurus ampliceps	X	X	X	Medium	X	X	High
	Echinorhinus brucus	Medium	X	X	High	X	X	X
	Midwater trawl							
	Deania quadrispinosa	X	X	X	Medium	X	X	High
	Demersal longline							
	Centrophorus squamosus	Medium	Medium	X	High	X	X	X
	Etmopterus lucifer	X	X	X	Medium	X	High	High
	Heptranchias perlo	X	X	X	Medium	X	X	High
	Hydrolagus bemisi	Medium	X	X	High	X	X	X

Sustainability Assessment for the Effects of Fishing (SAFE)

Supplementary online data (SAFE) provide details of the SAFE results for both Southern Indian and South Pacific oceans. The SAFE classified a total of 11, 12, 9 and 4 chondrichthyan species as high ($F>F_{lim}$) or extreme ($F>F_{crash}$) vulnerability in the Southern Indian Ocean area to demersal trawl, midwater trawl, demersal longline and gillnet fisheries, respectively (Table 4). In the South Pacific Ocean, there were a total of 20, 4 and 17 species classified as high ($F>F_{lim}$) or extreme ($F>F_{crash}$) vulnerability to demersal trawl, midwater trawl and demersal longline fisheries respectively. Out of the 101 species assessed in the Southern Indian Ocean, only two (*Mitsukurina owstoni* and *Benthobatis moresbyi*) were missing data needed to calculate F_{msm}, F_{lim} and F_{crash}, while in the South Pacific Ocean, four (*Echinorhinus cookei*, *Oxynotus bruniensis*, *Mitsukurina owstoni* and *Squalus fernandezianus*) of the 112 species assessed were missing these data.

Chondrichthyan species classified as high or extreme vulnerability across all fisheries (Table 6) in the Southern Indian Ocean included *Centrophorus granulosus*, *Centroselachus crepidater* and *Zameus squamulosus*. An additional four species were classified as high or extreme vulnerability across demersal trawl, midwater trawl and demersal longline fisheries in the Southern Indian Ocean including *Dalatias licha*, *Chimaera buccanigella*, *Chimaera didierae* and *Chimaera willwatchi*.

Chondrichthyan species classified as high or extreme risk across all fisheries (Table 7) in the South Pacific Ocean included *Echinorhinus cookei*, *Mitsukurina owstoni*, *Oxynotus bruniensis* and *Squalus fernandezianus*. An additional seven species were classified as high or extreme vulnerability across all fisheries with the exception of midwater trawl in the South Pacific Ocean including *Dalatias licha*, *Squalus acanthias*, *Deania calcea*, *Centrophorus harrissoni*, *Hydrolagus bemisi*, *Centrophorus squamosus* and *Chimaera carophila*.

The PSA and SAFE vulnerability scores for all species in the Southern Indian and South Pacific oceans are compared in Figures 4a and 4b. The results indicate good concurrence between the PSA and SAFE results for most species categorised as being at high or extreme vulnerability in the SAFE. There were three species (*Zameus squamulosus*, *Parmaturus macmillani* and *Chimaera carophila*) across both the Southern Indian and South Pacific oceans that were classified as medium vulnerability in the PSA but high or extreme vulnerability in the SAFE. Nonetheless, many species classified as high or medium vulnerability by the PSA in both the Southern Indian and South Pacific oceans were ranked as low vulnerability by the SAFE (Figures 4a and 4b).

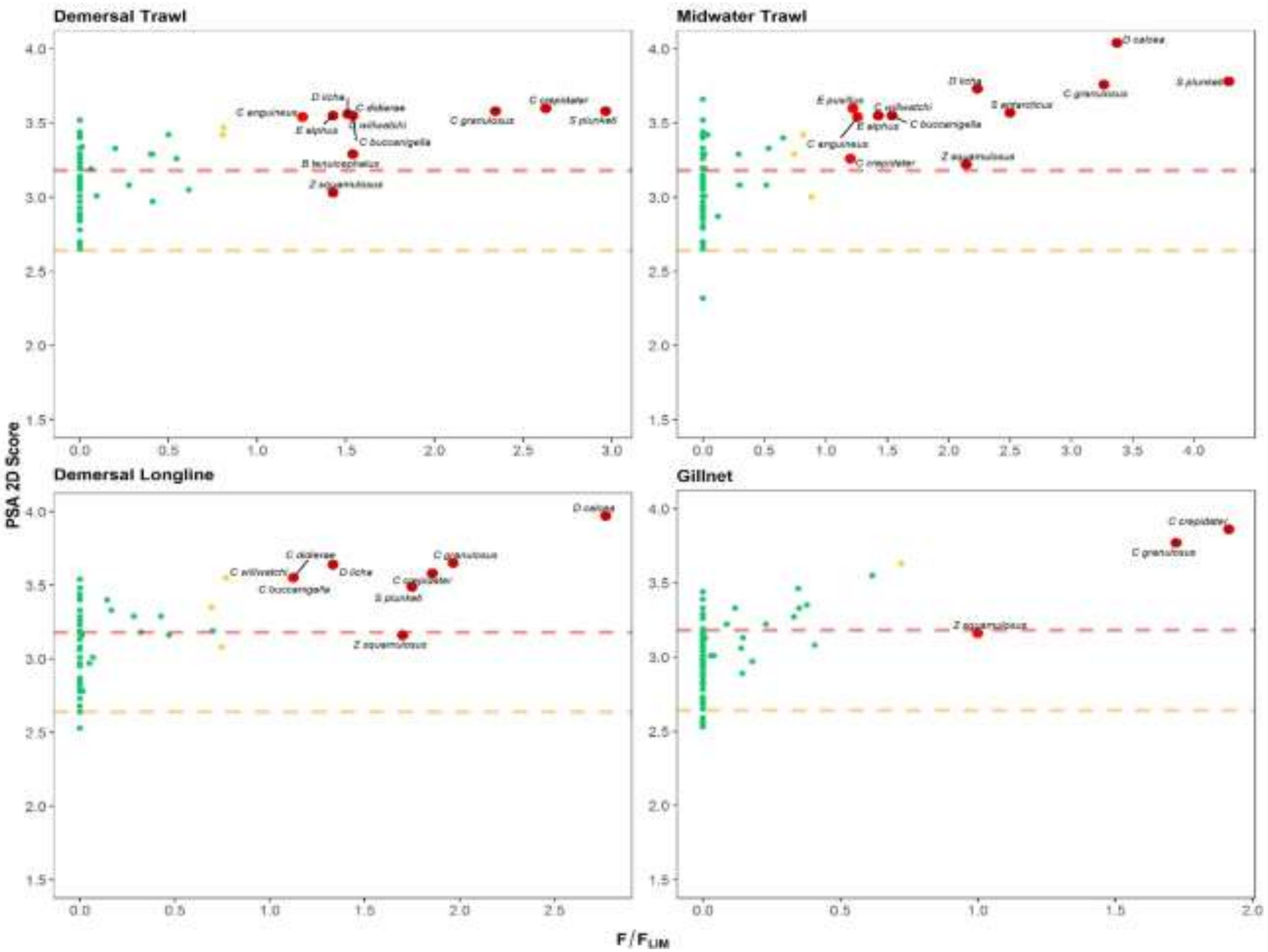


Figure 4a: Relationship between SAFE and PSA results for 101 chondrichthyan species with the potential to interact with demersal longline, demersal trawl, midwater trawl and demersal gillnet fisheries in the Southern Indian Ocean. Points are coloured dark red, light red, orange and green to signify species classified as extreme, high, medium and low vulnerability, respectively, in the SAFE. Dashed red and orange lines represent the high and medium vulnerability score boundaries from the PSA. Two species are not shown on the panels as their *F*-based reference points were unable to be calculated.

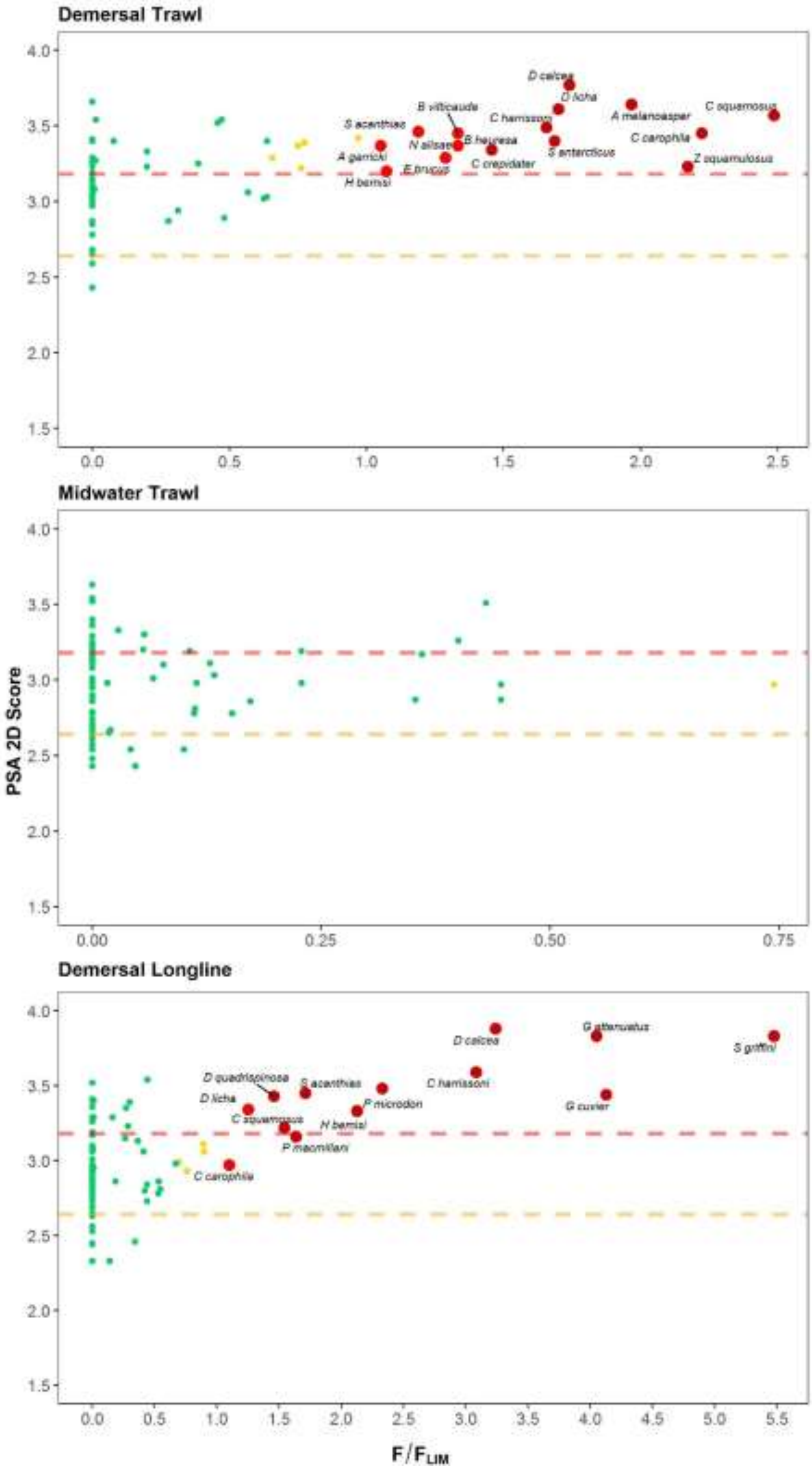


Figure 4b: Relationship between SAFE and PSA results for 112 chondrichthyan species with the potential to interact with demersal longline, demersal trawl and midwater trawl fisheries in the South Pacific Ocean. Points are coloured dark red, light red, orange and green to signify species classified as extreme, high, medium and low vulnerability, respectively, in the SAFE. Dashed red and orange lines represent PSA high and medium vulnerability score boundaries from the PSA. Four species are not shown on the panels as their *F*-based reference points were unable to be calculated.

Table 6. Matrix of high and extreme vulnerability species from the SAFE and their respective PSA score for each fishery in the Southern Indian Ocean.

Southern Indian Ocean	**Demersal longline**		**Demersal trawl**		**Midwater trawl**		**Gillnet**	
Species	**PSA**	**SAFE**	**PSA**	**SAFE**	**PSA**	**SAFE**	**PSA**	**SAFE**
Deania calcea	High	Extreme	High	Medium	High	Extreme	High	Low
Centrophorus granulosus	High	Extreme	High	Extreme	High	Extreme	High	Extreme
Dalatias licha	High	Extreme	High	Extreme	High	Extreme	High	Medium
Chimaera buccanigella	High	High	High	Extreme	High	Extreme	High	Low
Chimaera didierae	High	High	High	Extreme	Medium	Low	High	Low
Chimaera willwatchi	High	High	High	Extreme	High	Extreme	High	Low
Centroselachus crepidater	High	Extreme	High	Extreme	High	High	High	Extreme
Scymnodon plunketi	High	Extreme	High	Extreme	High	Extreme	High	Low
Zameus squamulosus	Medium	Extreme	Medium	Extreme	High	Extreme	Medium	High
Etmopterus alphus	High	Medium	High	Extreme	High	Extreme	High	Low
Bythaelurus tenuicephalus	Medium	Medium	High	Extreme	Medium	Medium	Medium	Low
Chlamydoselachus anguineus	High	Low	High	High	High	High	High	Low
Etmopterus pusillus	Medium	Low	High	Low	High	High	Medium	Low
Somniosus antarcticus	High	Low	Medium	Low	High	Extreme	Medium	Low
Mitsukurina owstoni	High	Low	High	Low	High	Low	Medium	Extreme

Table 7. Matrix of high (and extreme) vulnerability species from the SAFE and their respective PSA score for each fishery in the South Pacific Ocean.

South Pacific Ocean	Demersal longline		Demersal trawl		Midwater trawl	
Species	**PSA**	**SAFE**	**PSA**	**SAFE**	**PSA**	**SAFE**
Squalus fernandezianus	High	Extreme	High	Extreme	High	Extreme
Deania calcea	High	Extreme	High	Extreme	High	Low
Gollum attenuatus	High	Extreme	High	Low	High	Low
Squalus griffini	High	Extreme	High	Medium	High	Low
Centrophorus harrissoni	High	Extreme	High	Extreme	High	Low
Oxynotus bruniensis	High	Extreme	High	Extreme	High	Extreme
Mitsukurina owstoni	High	Extreme	High	Extreme	High	Extreme
Echinorhinus cookei	High	Extreme	High	Extreme	High	Extreme
Pseudotriakis microdon	High	Extreme	High	Medium	Medium	Low
Squalus acanthias	High	Extreme	High	Extreme	Medium	Low
Deania quadrispinosa	High	Extreme	High	Medium	Medium	Low
Galeocerdo cuvier	High	Extreme	Medium	Low	Medium	Low
Dalatias licha	High	High	High	Extreme	Medium	Low
Hydrolagus bemisi	High	Extreme	High	High	Medium	Low
Centrophorus squamosus	High	Extreme	High	Extreme	Medium	Low
Parmaturus macmillani	Medium	Extreme	Medium	Low	Medium	Low
Chimaera carophila	Medium	High	High	Extreme	Low	Medium
Apristurus melanoasper	High	Low	High	Extreme	Medium	Low
Brochiraja vitticauda	Medium	Low	High	High	Medium	Low
Notoraja alisae	Medium	Low	High	High	Medium	Low
Brochiraja heuresa	Medium	Low	High	High	Medium	Low
Apristurus garricki	Medium	Medium	High	High	Medium	Low
Somniosus antarcticus	Medium	Medium	High	Extreme	High	Low
Centroselachus crepidater	Medium	Low	High	Extreme	Medium	Low
Echinorhinus brucus	Medium	Low	High	High	Medium	Low
Zameus squamulosus	Low	Low	High	Extreme	Low	Low

Discussion

The results of our PSA and SAFE analyses highlight that some chondrichthyans in the Southern Indian and South Pacific oceans are likely to be vulnerable to fishing pressure due to their life-history traits (i.e. long-lived, slow growing and low fecundity), which compromises their ability to recover from fishing-induced depletion (Kyne and Simpfendorfer, 2007; Zhou and Griffiths, 2008; Simpfendorfer and Kyne, 2009; Irvine et al., 2012; Rigby and Simpfendorfer, 2015). SIOFA and SPRFMO and their member States have responsibilities under the United Nations (UN) Convention on the Law of the Sea (UNCLOS) (Article 64) and UN Fish Stocks Agreement (UNFSA) to assess the impacts of fishing interactions on fished stocks. There is a deficit of information on chondrichthyans globally, with over 50% of shark and ray species listed as data deficient on the IUCN Red List due to the taxonomic resolution of fishery catch data being too low to identify species-level trends in abundance (Cashion et al., 2019). Given the limited fisheries and biological data on deepwater chondrichthyans in the Southern Indian (e.g. Ebert, 2013; Ebert, 2014) and South Pacific (Duffy et al., 2017) oceans, data-poor methods such as ERA provides a useful tool for evaluating vulnerability of these species to fisheries interactions based on their biological productivity and susceptibility to the main fisheries operating across their geographic range (Zhou and Griffiths, 2008; Patrick et al., 2010; Hobday et al., 2011). This allows those species that are at highest vulnerability to be identified and the risk either mitigated or investigated further through data collection and research prioritisation (Griffiths et al., 2017).

A key challenge when considering the results of our ERA is the availability and quality of supplementary information that can be used to critically review results in the context of the fishery or fisheries that interact with species or groups of species. In particular, information on catch and effort over time and space can be valuable in making inferences about the likely true vulnerability of species to certain gears. Catch and effort information at a suitable species resolution were only available for a subset of the fisheries assessed in our analysis. This challenge is confounded by the nature of working within the RFMO/A context, where, even if the organisations hold good quality data, access to (often confidential) data can be problematic. Below we present information on catches where this information is publicly available, and explicitly note where information is unavailable or confidential.

A number of species taken in association with commercial deepwater chondrichthyan fisheries in the Southern Indian Ocean (as well as some species that are retained as byproduct in both the Southern Indian and South Pacific oceans) are assessed to be at high or extreme vulnerability to fishing using certain gears. In the Southern Indian Ocean, there has been historical targeted fishing of *Centroscymnus coelolepis* (Portuguese dogfish) by gillnet and longline vessels (SIOFA, 2019b). While this species was classified as low vulnerability in the SAFE due in part to its widespread distribution, it is caught in relatively high volumes and is thought to be caught in association with a number of other deepwater chondrichthyans, including *Centrophorus granulosus*, *Dalatias licha* and *Deania calcea*, that were classified as extreme vulnerability in our SAFE analysis. While targeted fishing of deepwater chondrichthyans in the gillnet fishery occurred during the period under assessment (2012–2016), there has been no recorded gillnet effort since 2015 (SIOFA, 2019a). Trawl effort has also declined in the Southern Indian Ocean since 2016 at the same time that longline effort has increased, and consequently the longline fishery is currently the main fishery affecting populations of deepwater chondrichthyans. While specific catch volume statistics are confidential, catches of *Centroscymnus coelolepis* reached approximately 1,300 tonnes in 2016, with overall catches of deepwater sharks taken totalling approximately 1,800 tonnes. In order of approximate catch volumes, the main species taken by the longline fishery in association with *Centroscymnus coelolepis* in 2016 were *Dalatias licha* (~270 tonnes), *Deania calcea* (~130 tonnes) and *Centrophorus granulosus* (~75 tonnes). Gillnet catches of *Centrophorus granulosus*, which is a particularly vulnerable species, reached around 128 t in 2013, 105 t in 2014 and 30 t in 2015, with an additional 102 t of this species being taken in 2015 using longline gears. Information on the recent and historical contribution of trawl gears to the fishing mortality of these key species is not available due to the coarse taxonomic resolution (generally genus level or higher) at which data have been collected. Trawl gears can and do interact with deepwater chondrichthyans in the Southern Indian Ocean and it is possible that historical trawl catches have contributed significantly to overall catches for a number of species.

In the South Pacific Ocean, deepwater chondrichthyans are caught mostly in demersal trawl fisheries targeting orange roughy and in demersal longline fisheries targeting species such as blue-eye trevalla (*Hyperoglyphe antarctica)*, hapuku (*Polyprion oxygeneios*) and bass groper (*Polyprion americanus*) (Duffy et al., 2017), but these catches are made in relatively low volumes. Recorded total chondrichthyan catches in the New Zealand demersal trawl fishery estimated from at-sea observer data ranged from 7.7 tonnes in 2014 to 228.1 tonnes in 2016 (Duffy et al., 2017), with two species (*Deania calcea* and *Dalatias licha*) classified at extreme vulnerability to demersal trawl in our SAFE analysis contributing to a total 47% of the catch between 2012 and 2016. Observers estimate the catch weight by species for almost 100% of New Zealand bottom trawl tows. However, they were able to identify to species level only 83–94% of chondrichthyans by weight (varying between years) leaving some scope for further species at high or extreme vulnerability to have been caught in these fisheries. Commercial fishers' logbook data from the same fishery had a much greater proportion of unspecified 'deepwater dogfish' recorded (67%) compared with just 9% for at-sea observers, meaning that the observer data are preferred (Duffy et al., 2017).

Deepwater chondrichthyans were also caught in New Zealand's line fisheries, including *Dalatias licha*, which made up 8% of the total chondrichthyan catch reported by at-sea observers between 2012 and 2016 (Duffy et al., 2017). Observers estimate the catch weight by species for only about 10–20% of New Zealand bottom line sets, necessitating more reliance on commercial fishers' logbooks. Other species including *Squalus acanthias* and *Deania calcea*, which were classified at extreme vulnerability in our SAFE analysis, have been recorded as caught in the longline fishery (SPRFMO, 2018). However, as identified by Duffy et al. (2017), some of these identifications (especially the commonly-reported *Squalus acanthias*) are probably errors and catches by species are therefore likely to be poorly estimated. This supposition is reinforced by 105 tonnes of unidentified deepwater sharks recorded as caught between 2012 and 2016 in the SPRFMO database. Similar to the Southern Indian Ocean, issues with species identification, reporting and the resolution at which historical data have been collected make it very difficult to make inferences about the historical contribution of fishing to overall catches of deepwater chondrichthyans species in the South Pacific Ocean.

It is important to note that because fishing effort (trawl and longline) data from the Southern Indian Ocean was not complete for all years assessed (i.e. 2012–2016), there may have been an underestimation of species vulnerability to fishing activity in our analysis. For longline gears in particular, a larger amount of missing effort data in the SAFE analysis may have resulted in the underestimation of risk to some species because the proportion of the overlap of species distributions with the available spatial distribution of fishing effort could be lower than if all effort data were available. This is because a species' core distribution range is divided by the area fished by the gear within the jurisdictional boundary of the fishery (Zhou et al., 2007).

Within-species comparison of PSA and SAFE results in our study demonstrated good concurrence between those listed at high or extreme vulnerability by the SAFE; however, the PSA estimated far more species to be at high or medium relative vulnerability than the SAFE, which classified them as low. A greater number of false positives in the PSA is to be expected (Hobday et al., 2011; Zhou et al., 2016) and in our assessment is largely driven by the PSA assuming a minimum score of 1 for the *Availability* attribute even if there is zero overlap between the species and the gears, while the SAFE gives a true zero for susceptibility (i.e. no overlap means no vulnerability and the susceptibility/*F*-estimate is zero). The number of possible false positives was less than it would have been if data on productivity attributes from congeneric species was not used to reduce the number of species classified as data deficient (i.e. those missing three or more attributes). While there will obviously be a bias in the vulnerability score if the imputed attributes from congeneric species are incorrect, given our limited knowledge of deepwater chondrichthyan species' biology and life history, we felt this approach was adequate and expert-informed substitution of missing data has been used previously (e.g. Zhou and Griffiths, 2008; Gallagher et al., 2012). Interestingly, three species were assessed to be at a high or extreme vulnerability by the SAFE that were ranked as medium relative vulnerability by the PSA. These discrepancies in vulnerability ranking, which are possibly false negatives, was unexpected and was likely driven by the inability of the PSA to be a reliable indicator of biological risk for species within these intermediate PSA vulnerability scores, which was highlighted by Hordyk and Carruthers (2018) when they mapped several interpretations of the PSA to conventional age-structured fisheries dynamics models and compared results. In other words, the vulnerability scores from our PSA are unlikely to be ordered correctly with respect to risk of overexploitation.

Between-species comparison of PSA and SAFE vulnerability classifications indicated that differentiation was driven more by susceptibility attributes than productivity attributes. This was similarly observed in a PSA of marine turtles in the Indian Ocean (Williams et al. (2018) and was expected given that many deepwater chondrichthyans exhibit low-productivity characteristics, resulting in similar scores with low variation on the productivity axis. Within the susceptibility attributes, the horizontal overlap of a species' distribution with fishing effort (*Availability*) was a key factor driving differentiation in species' relative vulnerability scores in both the PSA and SAFE. Species with limited spatial distributions and high susceptibility to encountering the fishing gears generally had higher relative vulnerability scores, while species that had low or zero overlap between fishing gears and their spatial distribution had lower vulnerability scores. Consequently, fisheries with broader effort distribution should result in more species being classified at higher vulnerability because they are more likely to overlap with a larger number of species' ranges.

The sensitivity analysis of spatial overlap of fishing effort and species distribution data revealed that the results were relatively robust to changes in overlap. The results were more sensitive to negative changes in the spatial overlap than positive changes, which may suggest that decreasing (or not increasing) the spatial fishing footprint—particularly where this overlaps with the ranges of key high vulnerability species—may be a suitable risk mitigation strategy. The sensitivity analysis of overlap also has implications for the selection of species distribution data (e.g. FAO Geonetwork vs. IUCN Red List) and indicates that unless there are large differences in the spatial distribution of species between different mapping sources, the results would be unlikely to change greatly from those presented herein. Unfortunately, missing effort data for a number of the Southern Indian Ocean fisheries is a key limitation reducing the ability to interpret overall results and the results of the sensitivity analysis. It is important to note that while a species may have a limited distribution and high susceptibility to encountering fishing gear and be classified at high or extreme vulnerability in our study, this same species may also have a large spatial distribution outside the Southern Indian or South Pacific oceans. Given it was not possible to assess the influence of fishing activities outside these areas, there remains an inherent uncertainty around final species' vulnerability scoring. Furthermore, we made no attempt to quantify the cumulative impact of multiple gears (i.e. fisheries) within the Southern Indian or South Pacific oceans. Recent refinement of the SAFE method (i.e. eSAFE) (Zhou et al., 2019) allows for an improved estimation of the cumulative impacts from fisheries through estimating a more realistic gear efficiency, as well as fish density distribution using shot by shot fishery or survey data. Cumulative fishing mortality (F_{cum}) is then derived from summing these individual fishing mortality rates across fisheries (Zhou et al., 2019). The recently developed EASI-Fish method (Griffiths et al., 2018) derives a proxy estimate for fishing mortality from the "volumetric overlap" of multiple fisheries on a species' three dimensional spatial distribution, which can be used in length-structured per-recruit models to evaluate overall vulnerability using conventional biological reference points (e.g. F/F_{msy}) (Griffiths et al., 2018).

The influence of the susceptibility attributes in our results highlights the limitation of the PSA in assuming a linear and additive relationship between the productivity and susceptibility scores in the calculation of relative vulnerability scores (Hordyk and Carruthers, 2018; Williams et al., 2018). Furthermore, the assumption that each individual productivity and susceptibility attribute contributes equally to each axis has been challenged by Hordyk and Carruthers (2018), with their study showing a complex non-linear relationship between individual attributes and over-parameterisation caused by irrelevant or correlated attributes. In a statistical exploration of productivity attributes Griffiths et al. (2017) showed a number of productivity attributes were redundant for species assessed in a purse seine fishery in the Eastern Pacific Ocean, with a clear correlation between attributes such as age at maturity and maximum age. They postulated that the use of these redundant attributes would create an implicit weighting and positive bias in productivity scores, leading to an overestimation of species productivity and underestimation of the effects of fishing. While re-weighting or re-scaling individual productivity attributes could be an appropriate solution as similarly undertaken in other PSAs (e.g. Nel et al., 2013) it was not attempted in our study, as it was not clear whether the additional effort required to do this would be commensurate with an improved representation of relative vulnerability. For example, Griffiths et al. (2017) found no evidence that weighing of attributes improved the differentiation between species for the purse seine fishery in the Eastern Pacific Ocean.

In both the South Pacific and Southern Indian Oceans there were a few deepwater chondrichthyans assessed to be at high or extreme vulnerability in the SAFE that were classified as medium vulnerability in the PSA. This evidence of possible false negatives in the PSA may highlight a potential limitation with the hierarchical implementation within level 2 of the ERAEF (Hobday et al., 2011), as species that were classified at medium vulnerability in the PSA may not typically be re-assessed using SAFE, as this is usually reserved for species classified at high vulnerability in PSA (for which residual risk could not be suitably managed). Our ability to concurrently compare PSA and SAFE results in this study indicated a failure of the PSA assessment to recognise a number of potentially vulnerable species, thereby presenting a risk to managers seeking to prioritise species for management and additional data collection and further research. Given that minimal additional effort is required to run a SAFE assessment in parallel with a PSA (apart from determining the actual gear swept area within each fishing grid) (see, Hobday et al., 2011; Zhou et al., 2016), and the SAFE provides an absolute measure of vulnerability (as opposed to relative vulnerability in a PSA), we recommend that PSA and SAFE are attempted concurrently to provide managers with additional confidence in identifying the most vulnerable species to fishing activity. This advice is reinforced by a recent validation study suggesting PSA vulnerability scores are unlikely to be accurate for all assessed species, particularly those with intermediate vulnerability scores (Hordyk and Carruthers, 2018).

Conclusion

Outcomes from ERA analyses need to reasonably accurate at defining vulnerability among species to enable managers to prioritise species for data collection, research and further analysis. While there were clear uncertainties in our ERA analysis (due in-part to missing effort data) and recognised limitations, this should not prevent a precautionary approach being taken by both SIOFA and SPRFMO to prioritise species at high or extreme vulnerability for further research, data collection and/or quantitative stock assessment to estimate sustainable yields. When coupled with information on the characteristics of fisheries (including, importantly, information on catches), such methods can be used to provide a semi-quantitative underpinning for these actions. It is clear that information on the identification, distribution, stock structure, biology and life history of deepwater chondrichthyans is lacking (Gallagher et al., 2012) and that at-sea identification protocols need to be improved in high seas fisheries to increase the accuracy of logbook and at-sea observer reporting (Duffy et al., 2017; Cashion et al., 2019; SIOFA, 2019b). Improved species-specific reporting of chondrichthyans in both the Southern Indian and South Pacific oceans would allow scientists to work with fine scale data to better estimate the extent of spatial overlap of fishing effort with the catch and distribution of assessed species, which is a key uncertainty in our ERA analysis. Research on post capture mortality and gear selectivity of deepwater chondrichthyans would be useful to inform mitigation strategies to minimise vulnerability associated with susceptibility. Quantitative assessment is urgently required for deepwater chondrichthyan species which are reported to be commercially targeted or retained in relatively high volumes in the Southern Indian Ocean to minimise the risk of overexploitation that has occurred in other fisheries globally. This was raised at the 4th meeting of the SIOFA Scientific Committee (SC) (SIOFA, 2019b), with a request that the SIOFA Meeting of the Parties (the SIOFA decision-making body) urgently consider measures to "mitigate the potential for overexploitation of 'key species of concern'"[2] as well as undertake further spatial analysis of catches (SIOFA, 2019b). This advice was considered by the SIOFA Meeting of the Parties in July 2019, where a decision was reached to prohibit targeted fishing for the 'key species of concern' identified by the SC. It is unclear whether this prohibition will result in a reduction in mortality, particularly if catches are simply redefined as 'byproduct'. If this does not eventuate, improved research and data collection programs should be prioritised to enable sustainable yields to be estimated. Lastly, a repeat of this analysis should be undertaken for all fisheries if there are significant changes in fishing activity in the Southern Indian and South Pacific oceans.

[2] According to SIOFA (2019b) "key species of concern" include *Centroscymnus coelolepis* (Portuguese dogfish – SAFE risk low), *Centrophorus granulosus* (Gulper shark - SAFE risk extreme), *Deania calcea* (Brier shark - SAFE risk extreme), *Dalatias licha* (Black shark – SAFE risk extreme), *Zameus squamulosus* (Velvet shark – SAFE risk extreme), *Scymnodon plunketi* (Plunket's dogfish – SAFE risk extreme), *Centroselachus crepidater* (Golden dogfish – SAFE risk extreme) and three newly described species of Chimaera (*Chimaera willwatchi*, *C. buccanigella* and *C. didierae*).

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