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Original Article

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

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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 173 deepwater chondrichthyans to various demersal fishing gears in the Southern Indian and South Pacific Oceans. Several species were categorized as being at high or extreme vulnerability, including some deepwater shark species in the Southern Indian Ocean that are reported to be commercially targeted. There was good concurrence between PSA and SAFE results for species categorized as being at high or extreme vulnerability by the SAFE, but as expected there was an overall greater number assessed to be as higher vulnerability using PSA due to its precautionary nature. Our results indicate probable misclassifications in the PSA relative vulnerability rankings, highlighting the value of applying more quantitative tools, such as SAFE, when adequate data are available. Our findings indicate that better catch, effort, and biological information are needed to inform the assessment and management of deepwater chondrichthyans. If targeted fishing of deepwater shark species continues in the Southern Indian Ocean, improved assessments and estimates of sustainable yields are urgently required to mitigate the risk of overexploitation.

Keywords: chondrichthyans, ecosystem approach to fisheries, high seas fisheries, productivity–susceptibility analysis, regional fisheries management organisations, sustainability assessment for fishing effects

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, ~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.*, 2007), 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 the 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 exist, each with different assumptions and data requirements. Hobday *et al.* (2011) organized 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 species assessed to be high risk that may be low risk in reality (i.e. potential false positives) (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 that they are increasingly being used to inform management (Griffiths *et al.*, 2018; Griffiths *et al.*, 2019). ERA tools (see below) are also being applied to categorize the vulnerability of species into risk categories to prioritize 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; Griffiths *et al.*, 2019) 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 an improved evaluation of potential 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 173 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 fishing gears (note: 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). 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 1a) predominantly target demersal and bentho-pelagic species using either demersal trawl, midwater trawl, and demersal longline gears. Midwater trawl

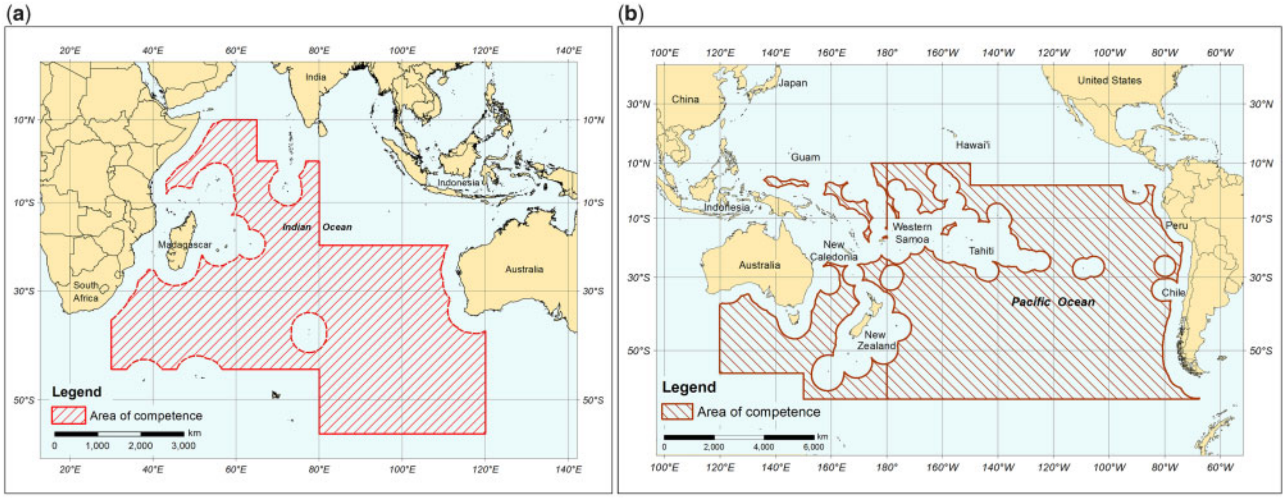

Figure 1. (a) Southern Indian Ocean Fisheries Agreement area. (b) South Pacific Regional Fisheries Management Organisation Convention area.

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 targeting deepwater sharks operated in the SIOFA area until 2015. The SPRFMO Convention (Figure 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).

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 101 in the Southern Indian Ocean and 112 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 <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 Food and Agriculture Organization (FAO) Catalogue of Species—Geonetwork database (http://www.fao.org/geonetwork/srv/en/main.search), the International Union for Conservation of Nature (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 2012–2016. 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 (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) with a calculation applied to rescale the range of scores back to the 1–3 interval.

Table 1. Productivity attributes and risk categorizations for individual species (adapted from Hobday *et al.*, 2011).

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

[a] This category was not used in this assessment due to the low productivity of deepwater chondrichthyans and only scores of 2 or 3 were given for this attribute.

Table 2. Susceptibility attributes and vulnerability categorizations for individual species (adapted from Hobday *et al.*, 2011).

Attributes	**Low susceptibility (low vulnerability, score = 1)**	**Medium susceptibility (medium vulnerability, score = >1 to <3 for S1 and S2 and 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 or >500 cm maximum length Line: 0–40 cm or >500 cm maximum length Gillnet: 0–70 cm or >130 cm maximum length[a]	Demersal and midwater trawl: 15–30 cm or 400–500 cm maximum length Line: 40–80 cm or 200–500 cm maximum length Gillnet: 70–80 cm maximum length[a]	Demersal and midwater trawl: 30–400 cm maximum length Line: 80–200 cm maximum length Gillnet: 80–130 cm maximum length[a]
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)

[a] Only used in Southern Indian Ocean fisheries.

Attributes used in the PSA are typically scored as 1 (low vulnerability), 2 (medium vulnerability), or 3 (high vulnerability). In line with a precautionary approach, missing attributes are scored as 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 two-dimensional Euclidean distance ($\sqrt{P^2 + S^2}$) into three cohorts, such that scores <2.64 are low vulnerability, scores between 2.64 and 3.18 are medium vulnerability, and scores >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 or 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).

Susceptibility attributes

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

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 minimum (m)	South Pacific Ocean depth maximum (m)	Southern Indian Ocean depth minimum (m)	Southern Indian Ocean depth maximum (m)
Demersal trawl	520	1 069	700	1 235
Midwater trawl	327	548	430	970
Demersal longline	230	654	597	1 716
Demersal gillnet	–	–	810	1 390

overlap of species distribution within the SIOFA and SPRFMO areas (Figure 1a and b) and the spatial footprint of fishing effort for each gear (between 2012 and 2016) at a 20-min resolution. For each gear, the "fished area" was defined as 20-min grid cells with at least one fishing operation. *Encounterability* was calculated as the proportion of vertical overlap between fishing effort and species depth ranges [Species depth ranges were obtained from a desktop review of life-history attributes that drew on a global database of deepwater chondrichthyans (CLR, unpublished data) and published literature.] (Table 3). The middle 90% (i.e. from the 5th to 95th percentiles) of fishing depth records for each gear was defined as the core depth range. Using this approach, outliers and zeros were discarded. *Selectivity* categorizations 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.

Sustainability assessment for the effects of fishing

The SAFE tool (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 PCM 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 tool 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 www.fishbase.org [see Zhou *et al.* (2012) for additional detail on these methods]. 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 with F-based reference points F_{msm}, F_{lim}, and F_{crash} (Box 1) and categorized 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% of the 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—$F < F_{\mathrm{msm}}$

Medium—$F_{\mathrm{lim}} > F \geq F_{\mathrm{msm}}$

High—$F_{\mathrm{crash}} > F \geq F_{\mathrm{lim}}$

Extreme—$F \geq F_{\mathrm{crash}}$

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 was 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

Table 4. Count of data-robust and data-deficient species assessed to be as high vulnerability (PSA) and high or extreme vulnerability (SAFE) for each fishery in the Southern Indian Ocean and South Pacific Ocean.

	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

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).

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 two-dimensional 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

Details of the PSA results for both the Southern Indian and South Pacific Oceans are provided in the Supplementary Data. 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 categorized 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* (Figure 2a and b). A total of two (*Holohalaelurus favus* and *Holohalaelurus punctatus*) and four (*Centrophorus harrissoni*, *Isurus paucus*, *Isurus oxyrinchus*, and *Squalus cholorculus*) 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 (Figure 2a and b).

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 *S. fernandezianus*, *D. calcea*, *Gollum attenuates*, *Squalus griffin*, *C. 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 Figure 3a and b. 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 along 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.

Sensitivity analysis of overlap

Table 5 contains the results of the sensitivity analysis of overlap between fishing effort and species distribution. 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 6, 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.

Sustainability assessment for the effects of fishing

Details of the SAFE results for both Southern Indian and South Pacific Oceans are provided in the Supplementary Data. The SAFE classified a total of 11, 12, 9, and 4 chondrichthyan species as high ($F > F_{\mathrm{lim}}$) or extreme ($F > F_{\mathrm{crash}}$) 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 ($F > F_{\mathrm{lim}}$) or extreme ($F > F_{\mathrm{crash}}$) vulnerability to demersal trawl, midwater trawl, and demersal longline fisheries, respectively. Out of the 101 species assessed in the Southern Indian Ocean, only two (*M. owstoni* and *Benthobatis moresbyi*) were missing data needed to calculate F_{msm}, F_{lim}, and F_{crash}, while

Table 5. Sensitivity analysis for species in the Southern Indian and South Pacific Oceans that change relative vulnerability categories when overlap scores for the *Availability* attribute are varied by ±10–30%.

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

in the South Pacific Ocean four (*Echinorhinus cookei*, *O. bruniensis*, *M. owstoni*, and *S. fernandezianus*) of the 112 species assessed were missing these data.

Chondrichthyan species classified by the SAFE as high or extreme vulnerability across all fisheries (Table 6) in the Southern Indian Ocean were *C. granulosus*, *C. 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, namely *D. licha*, *C. buccanigella*, *Chimaera didierae*, and *C. willwatchi*.

Chondrichthyan species classified by the SAFE as high or extreme risk across all fisheries (Table 7) in the South Pacific Ocean were *Echinorhinus cookei*, *M. owstoni*, *O. bruniensis*, and *S. 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, namely *D. licha*, *Squalus acanthias*, *D. calcea*, *C. harrissoni*, *Hydrolagus bemisi*, *Centrophorus squamosus*, and *Chimaera carophila*.

Comparison of PSA and SAFE scores

The PSA and SAFE vulnerability scores for all species in the Southern Indian and South Pacific Oceans are compared in Figure 4a and b. The results indicate good concurrence between the PSA and SAFE results for most species categorized as being at high or extreme vulnerability in the SAFE. There were three species (*Z. squamulosus*, *Parmaturus macmillani*, and *C. 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 (Figure 4a and b).

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 recent fishing pressure due to their life-history traits (i.e. long lived, slow growing, and low fecundity), which compromise 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 (Article 64) and UN Fish Stocks Agreement 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 Ocean (e.g. Ebert, 2013, 2014) and South Pacific Ocean (Duffy *et al.*, 2017), data-poor methods such as ERA provide a useful way to evaluate the 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 likely to be at highest vulnerability to be identified and the

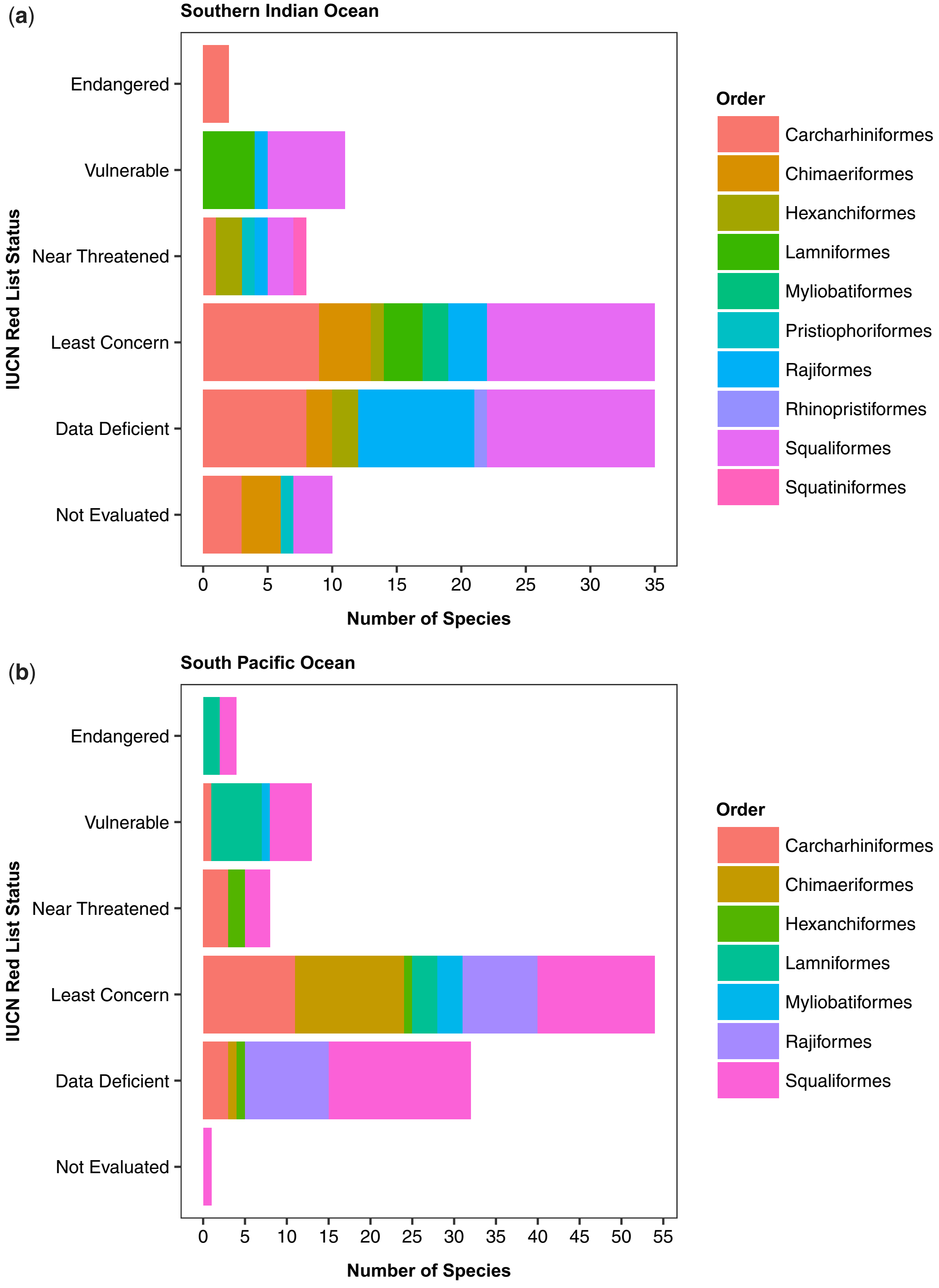

Figure 2. (a) Assessed chondrichthyan species (101) in the Southern Indian Ocean by IUCN Red List category based on their taxonomic order. (b) Assessed chondrichthyan species (112) in the South Pacific Ocean by IUCN Red List category based on their taxonomic order.

risk either mitigated or investigated further through data collection and research prioritization (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

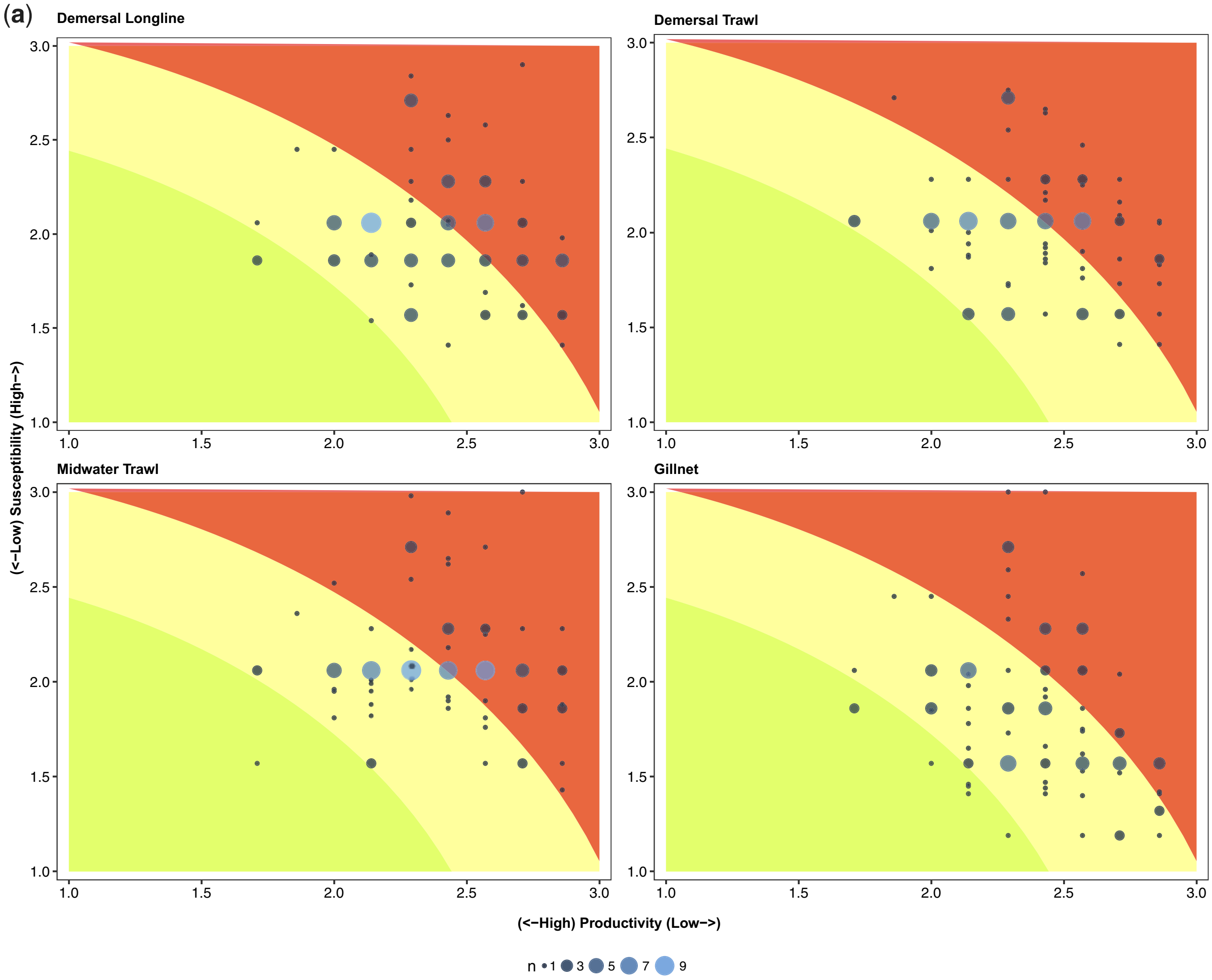

Figure 3. (a) PSA results for 101 chondrichthyan species with the potential to interact with longline, demersal, and midwater trawl and demersal gillnet fisheries in the Southern Indian Ocean. Size of symbol represents number (*n*) of species with the same vulnerability score. The green, yellow, and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

certain gears. Catch and effort information at a 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 organizations hold good quality catch and effort data, access to (sometimes confidential) data can be problematic. Below we present information on catches where this information is publicly available.

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 as 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 *C. granulosus*, *D. licha*, and *D. 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. Catches of *C. coelolepis* reached ∼1 300 000 kg in 2016, with overall catches of deepwater sharks taken totalling ∼1 800 000 kg. In order of approximate catch volumes, the main species taken by the longline fishery in association with *C. coelolepis* in 2016 were *D. licha* (∼270 000 kg), *D. calcea* (∼130 000 kg), and *C. granulosus* (∼75 000 kg). Gillnet catches of *C. granulosus*, which is a particularly vulnerable species, were ∼128 000 kg in 2013, 105 000 kg in 2014, and 30 000 kg in 2015, with an additional 102 000 kg 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

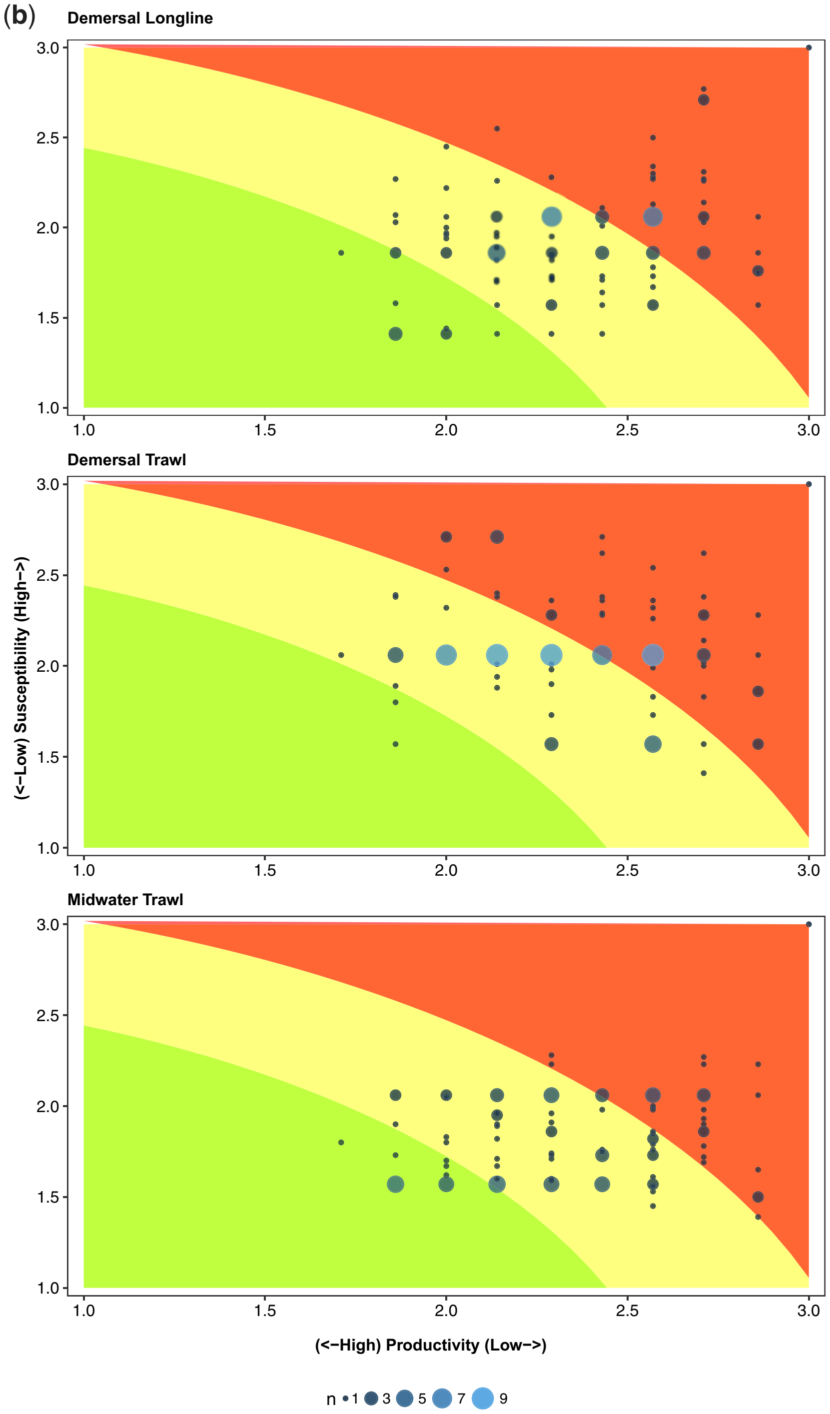

Figure 3. Continued (b) PSA results for 112 chondrichthyan species with the potential to interact with longline, demersal trawl, and midwater trawl fisheries in the South Pacific Ocean. Size of symbol represents number (n) of species with the same vulnerability score. The green, yellow, and red shadings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

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). Recorded total chondrichthyan catches in the New Zealand demersal trawl fishery estimated from at-sea observer data ranged from 7700 kg in 2014 to 228 100 kg in 2016 (Duffy *et al.*, 2017), with two species (*D. calcea* and *D. licha*) classified as extreme vulnerability to demersal trawl in our SAFE analysis and

Table 6. High and extreme vulnerability species from the SAFE and their respective relative vulnerability 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. High and extreme vulnerability species from the SAFE and their respective relative vulnerability 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

contributing to a total of 47% of the catch between 2012 and 2016. Observers estimate the catch weight by species for ~100% of New Zealand bottom trawl tows. However, they were able to identify 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 *D. licha*, which made up 8% of the total chondrichthyan catch reported by at-sea observers

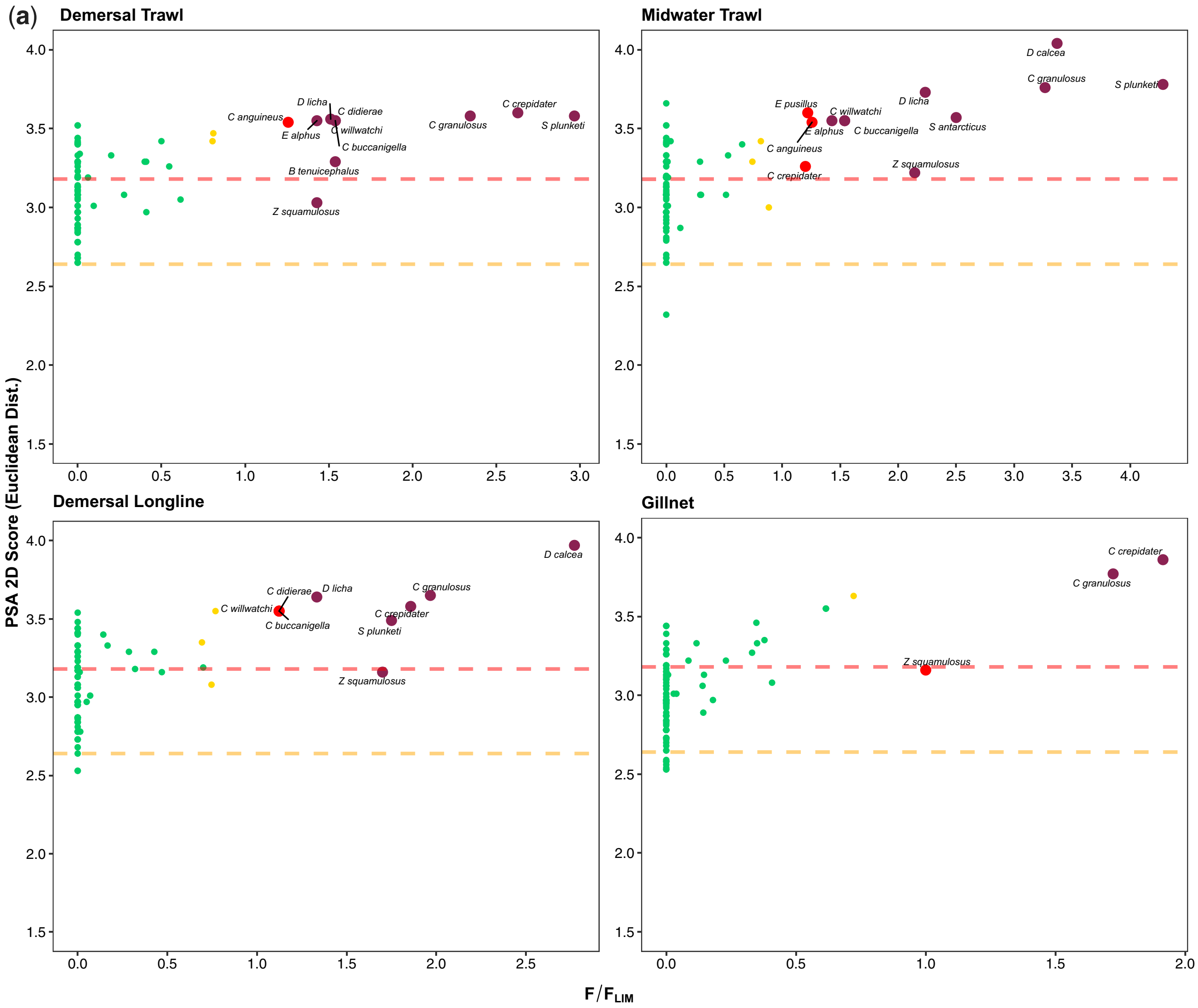

Figure 4. (a) Relationship between SAFE (F/F_{LIM}) and PSA (two-dimensional score) results for 101 chondrichthyan species with the potential to interact with demersal longline, demersal trawl, midwater trawl, and demersal gillnet fisheries in the Southern Indian Ocean. Points are coloured dark purple, red, orange, and green to signify species classified as extreme, high, medium, and low vulnerabilities, 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.

between 2012 and 2016 (Duffy *et al.*, 2017). Observers estimate the catch weight by species for only ∼10–20% of New Zealand bottom line sets, necessitating more reliance on commercial fishers' logbooks. Other species including *S. acanthias* and *D. calcea*, which were classified as 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 *S. acanthias*) are probably errors and catches by species are, therefore, likely to be poorly estimated. This supposition is reinforced by 105 000 kg 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 were 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.

Within-species comparison of PSA and SAFE results in our study demonstrated good concurrence between those listed as high or extreme vulnerability by the SAFE with those listed as high vulnerability by the PSA; however, the PSA estimated far more species to be at high or medium relative vulnerability than the SAFE, which classified these species as low vulnerability. A greater number of species classified to be at higher relative

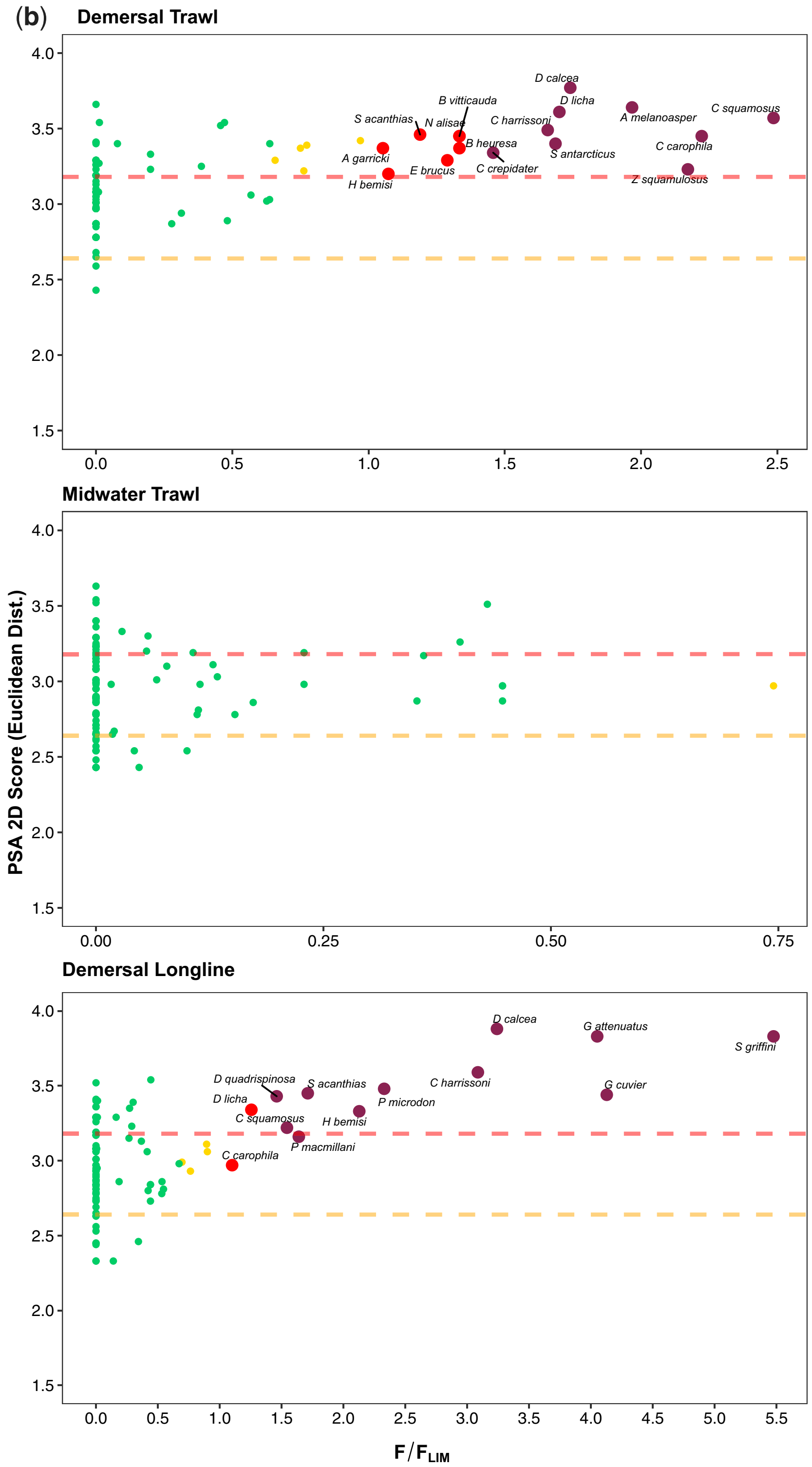

Figure 4. Continued (b) Relationship between SAFE (F/F_{LIM}) and PSA (two-dimensional score) results for 112 chondrichthyan species with the potential to interact with demersal longline, demersal trawl, and midwater trawl fisheries in the South Pacific Ocean. Points are coloured dark purple, red, orange, and green to signify species classified as extreme, high, medium, and low vulnerabilities, 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.

vulnerability in the PSA (i.e. potential false positives) than in the SAFE are to be expected (Hobday *et al.*, 2011; Zhou *et al.*, 2016) and, in our assessment, are 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 species classified as higher relative vulnerability in the PSA was less than it would have been if data on productivity attributes from congeneric species were 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 an error 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 that 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 as 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 species classified to be as lower relative vulnerability that are actually at risk (i.e. false negatives), were unexpected and were 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.

Between-species comparison of both PSA and SAFE vulnerability classifications indicated that differentiation between species 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 between 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 as 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 revealed that PSA results were more sensitive to decreases in the spatial overlap than increases, 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 are 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 as 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 tool (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 tool (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 various productivity scores, and between the various 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-parameterization caused by irrelevant or correlated attributes. In a statistical exploration of productivity attributes, Griffiths *et al.* (2017) showed that 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 as high or extreme vulnerability in the SAFE that were classified as medium vulnerability in the PSA. These discrepancies in vulnerability ranking (i.e. potential false negatives) highlight a potential limitation with the hierarchical implementation within level 2 of the ERAEF (Hobday *et al.*, 2011), as species that were classified as medium vulnerability in the PSA may not typically be re-assessed using SAFE, as this is usually reserved for species classified as 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 tool to recognize a number of potentially vulnerable species, thereby presenting a risk to managers seeking to use the ERAEF to prioritize species for management and additional data collection and further research. Given these findings, we recommend that caution is used in the implementation of the ERAEF and contend that the PSA should never be used as an alternative to more quantitative ERA tools such as SAFE if appropriate data are available. This advice is reinforced by a recent validation study suggesting that 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 be reasonably accurate at defining vulnerability among species to enable managers to prioritize 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 recognized limitations, this should not prevent a precautionary approach being taken by both SIOFA and SPRFMO to prioritize 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 PCM and gear selectivity of deepwater chondrichthyans would be useful to inform mitigation strategies to minimize vulnerability associated with susceptibility. Quantitative assessments are 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 minimize the risk of overexploitation that has occurred in other fisheries globally [This was raised at the fourth 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'" 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 redefined as "byproduct". According to SIOFA (2019b) "key species of concern" include *C. coelolepis* (Portuguese dogfish—SAFE risk low), *C. granulosus* (Gulper shark—SAFE risk extreme), *D. calcea* (Brier shark—SAFE risk extreme), *D. licha* (Black shark—SAFE risk extreme), *Z. squamulosus* (Velvet shark—SAFE risk extreme), *S. plunketi* (Plunket's dogfish—SAFE risk extreme), *C. crepidater* (Golden dogfish—SAFE risk extreme), and three newly described species of Chimaera (*C. willwatchi*, *C. buccanigella*, and *C. didierae*).]. 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.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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