Assessment of the vulnerability of sea turtles to IOTC tuna fisheries

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Abstract

Mortality from interactions with fishing gear poses a significant threat to sea turtle populations globally. Within the Indian Ocean Tuna Commission (IOTC) area of competence, semi-quantitative risk assessments in 2012 and 2013 identified specific sub-populations of olive ridley, loggerhead, leatherback and hawksbill turtles to be highly vulnerable to the impacts of fishing. Here, we present an update to these previous risk assessments using a Productivity-Susceptibility Analysis (PSA) within the Ecological Risk Assessment for the Effects of Fishing (ERAEF) framework developed by Hobday et al. (2011). Results revealed that no sea turtle sub-populations were classified as low vulnerability to longline, purse seine or gillnet fisheries – all were classified as either medium or high vulnerability. Sea turtles were found to be more vulnerable to gillnet and longline fisheries than purse seine fishing, due mostly to the large spatial area and depth distribution of longline fishing, and the assumed high post-capture mortality of sea turtles in gillnet fisheries. Within these fisheries, the species identified to be most vulnerable to fishing were green turtles, loggerhead turtles and hawksbill turtles, particularly in the Arabian Sea and Bay of Bengal. Our results were generally consistent with previous assessments, which suggests that there would be minimal gain in repeating a PSA for sea turtles in the short to medium term, unless there is a significant change in the data available for the assessment. It is important to note that the results from the PSA provide only relative measures of vulnerability. Results are also limited by a lack of information and the underlying assumptions of the PSA. Most notable is the lack of effort data for gillnet fisheries, and information on gear selectivity and post-capture mortality of sea turtles from all gear types. Notwithstanding these limitations, management efforts would benefit from prioritising the implementation and enforcement of mitigation measures, particularly for gillnet and longline fisheries. Priority should also be given to improving reporting of sea turtle interactions in all fisheries, and collating and analysing existing data on sea turtle interactions from IOTC member countries to identify factors that contribute to higher interaction and mortality rates. This information is essential to underpin the development and implementation of effective mitigation strategies for sea turtle.

Introduction

Six of the world's seven species of sea turtle are considered to be threatened with extinction according to International Union for the Conservation of Nature (IUCN) Red List criteria (IUCN 2017). Interactions with fishing gear is considered to be one of the major threats to populations of sea turtles, with fisheries bycatch precipitating declines in some populations (Lewison et al. 2004, Wallace et al. 2011, 2013). In response, the United Nations Food and Agriculture Organisation (FAO) developed guidelines to reduce sea turtle bycatch in fishing operations (FAO 2010) and some tuna Regional Fisheries Management Organisations (tRFMOs) have adopted conservation and management measures that require member states to implement mitigation methods and safe handling guidelines to reduce the impacts of fishing operations on sea turtles.

In recognition of the potential impact of fisheries on sea turtle populations in the Indian Ocean, the Indian Ocean Tuna Commission (IOTC) adopted Resolution 12/04 *On the conservation of sea turtles* (http://www.iotc.org/cmm/resolution-1204-conservation-sea-turtles). This resolution encourages member countries to implement the FAO guidelines for reducing sea turtle bycatch, provide data on all fishing related interactions with sea turtles, and to implement safe handling protocols to maximise survival of released turtles. Compliance with this (voluntary) resolution has been inconsistent among member countries, with few member countries reporting data on sea turtle bycatch. The lack of data has limited the ability to evaluate the population impacts of fishing on sea turtles and the implementation of effective strategies to mitigate against fishing induced mortality.

In the absence of reliable data to undertake quantitative assessments, ecological risk assessments (ERAs) provide a useful alternative for assessing the relative vulnerability of species to fisheries interactions (Stobutzki et al. 2002, Fletcher 2005, Zhou & Griffiths 2008, Hobday et al. 2011). Hobday et al. (2011) developed the Ecological Risk Assessment for the Effects of Fishing (ERAEF) framework which has applicability in a wide range of fisheries, and facilitates repeatability and comparison between studies. As a result, the ERAEF framework is the risk assessment approach adopted by the Marine Stewardship Council to evaluate fisheries for certification. The ERAEF framework includes a Productivity-Susceptibility Analysis (PSA) which is a common tool used in fishery-related ERAs, representing a semi-quantitative rapid prioritisation option (Hobday et al. 2011). PSAs are considered particularly useful to evaluate the vulnerability of bycatch species, as typically there is insufficient information available to allow for a more quantitative assessment. For example, in the Indian Ocean, PSAs have been used to assess the vulnerability of bycatch species in the IOTC purse seine and longline fisheries (Murua et al. 2009, Lucena-Frédou et al. 2017) and artisanal gillnet fisheries (Kiszka 2012). Nel et al. (2013) used a PSA to assess specifically the vulnerability of sea turtles in the IOTC longline, purse seine and gillnet fisheries. Since originally conceived, there has been a divergence in the development and application of PSAs in fisheries, which has limited the ability to directly compare results between studies, and to replicate previous PSAs (e.g. Hordyk and Carruthers 2018), but the base method remains transparent and repeatable. The outcome of a PSA is a relative ranking of vulnerability to each of the species considered. It is important to note the PSA provides a measure of relative and not absolute vulnerability.

An update to the PSA for sea turtles conducted by Nel et al. (2013) was requested by the IOTC Working Party on Ecosystems and Bycatch (WPEB) in 2017 (IOTC 2017b). Here, we use the ERAEF PSA to evaluate the relative vulnerability of sea turtles to longline, purse seine and gillnet fisheries operating in the IOTC area of competence. An online tool is available to facilitate transparency in the application of this PSA, and to allow different users to evaluate alternative scoring for the productivity and susceptibility attributes within the PSA (http://www.marine.csiro.au/apex/f?p=127). Results from the

PSA can be used to prioritise management action for those populations of sea turtle that are considered to have the highest relative vulnerability, and explore the effect of new data or interventions on assessment results.

Methods

Regional Management Units

Six species of sea turtles occur in the Indian Ocean, including loggerhead (*Caretta caretta*), green (*Chelonia mydas*), leatherback (*Dermochelys coriacea*), hawksbill (*Eretmochelys imbricata*), olive ridley (*Lepidochelys olivacea*) and flatback (*Natator depressus*) turtles. Wallace et al. (2010) identified 20 individual subpopulations, or regional management units (RMUs), for these species in the Indian Ocean (Appendix A). This PSA focusses on assessing the relative vulnerability of each of these 20 sea turtle RMUs to longline, purse seine and gillnet fisheries operating in the IOTC area of competence.

Productivity-Susceptibility Analysis

A PSA evaluates the relative vulnerability of each species or stock based on the assumption that vulnerability to fishing is a function of i) productivity: the life history characteristics which determine the intrinsic rate of population increase, and ii) susceptibility: the impact of the fishery on the stock determined by the interactions between the species and the fishery. Attributes of productivity and susceptibility are combined for each species or stock to determine an overall vulnerability score. 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.

In the ERAEF PSA approach used here, each attribute of productivity (P) and susceptibility (S) was scored on a three point scale that indicates low (1), medium (2) or high (3) vulnerability. A precautionary approach was taken for missing attributes, which were assigned a default score of 3 (high vulnerability). Since Hobday et al. (2011), the PSA method has been refined to allow continuous scoring for some attributes, such as availability. Some productivity and susceptibility attributes (P1 to P5, S1 and S2) have a decimal score (between 1 and 3) based on the attribute value relative to the minimum and maximum cut-off values for each attribute, allowing for better differentiation of vulnerability among RMUs. An overall vulnerability score was then calculated as the 2-dimensional Euclidean distance from the origin (Hobday et al. 2011). Species were then assigned to an overall vulnerability category (high, medium and low) by arbitrarily dividing the 2-dimensional Euclidean distance ($\sqrt{P^2 + S^2}$) into equal thirds, such that scores <2.64 are considered low vulnerability, between 2.64 and 3.18 are medium vulnerability, and >3.18 are high vulnerability (Figure 1). The online tool for the ERAEF PSA developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) was used to run the PSA.

Productivity attributes

Productivity attributes influence the intrinsic rate of increase (*r*) of the population, and determine the resilience of the population to the assessed level of fishing pressure (Hobday et al. 2011). Seven attributes were used to evaluate the productivity for each species (assumed to be the same for each RMU within a species), based on those of Hobday et al. (2011) (Table 1). The cut-off scores for productivity attributes 1-5 were rescaled to be more applicable to the range of these attributes for sea turtles. This provided some separation in productivity and overall vulnerability scores among species, and increases the resolution for species without changing their relative ranking. Biological data for the productivity attributes were sourced from the literature (Appendix B), and are available through the CSIRO online tool. The total productivity score (P) was calculated for each species as the average score across all seven productivity attributes.

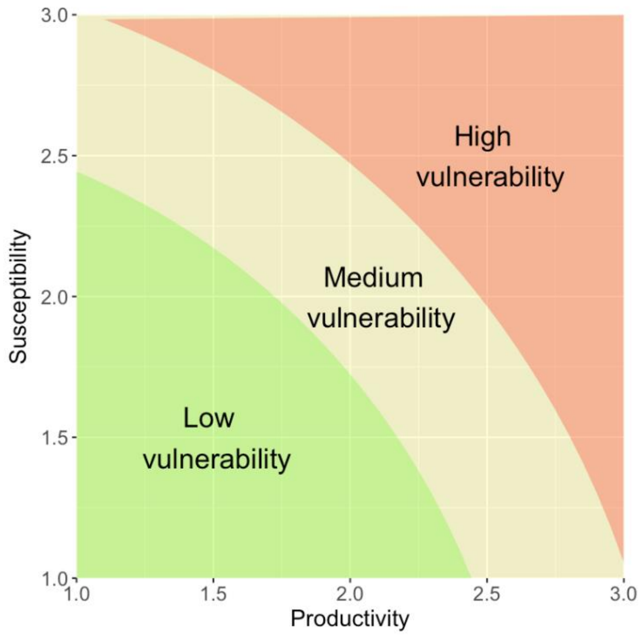

Figure 1. Productivity-Susceptibility Analysis (PSA) plot showing the relationship between productivity, susceptibility and overall vulnerability. The combination of susceptibility (high = 3) and productivity (low = 3) determines the overall relative vulnerability. The coloured areas divide the PSA plot into thirds, representing low, medium and high vulnerability.

Table 1. Productivity attributes and vulnerability categorisations (based on Hobday et al. 2011), modified for sea turtles to improve resolution of results. Note that productivity attributes 1-5 were scored on a decimal scale between 1 and 3.

Attribute	**Low productivity (high vulnerability) Score 3**	**Medium productivity (medium vulnerability) Score 2**	**High productivity (low vulnerability) Score 1**
P1. Average age at maturity	>20 years	10–20 years	<10 years
P2. Average maximum age	>70 years	30–70 years	<30 years
P3. Fecundity	<50 eggs per year	50–100 eggs per year	>100 eggs per year
P4. Average maximum size	>150 cm	100–150 cm	<100 cm
P5. Average size at maturity	>150 cm	100–150 cm	<100 cm
P6. Reproductive strategy	Live bearer, birds and turtles	Demersal egg layer	Broadcast spawner
P7. Trophic level	>3.25	2.75–3.25	<2.75

Susceptibility attributes

Four attributes were used to evaluate the susceptibility of each RMU to each of the three gear types (longline, purse seine and gillnet), based on the attributes and cut-off scores described by Hobday et al. (2011) (Table 2). The total susceptibility score (S) was then calculated for each RMU for each gear type as the product of the scores across all four susceptibility attributes. Hobday et al. (2011) considered a multiplicative approach was more appropriate for susceptibility because a low vulnerability score for any one susceptibility attribute will act to reduce overall vulnerability.

Table 2. Susceptibility attributes and vulnerability categorisations (based on Hobday et al. 2011), and modified for the gear types and their interaction with sea turtles. Note that susceptibility attributes 1 and 2 were scored on a decimal scale between 1 and 3.

Attribute	**Low susceptibility (low vulnerability) Score 1**	**Medium susceptibility (medium vulnerability) Score 2**	**High susceptibility (high vulnerability) Score 3**
S1. Availability	<10% horizontal overlap with fishing effort	10-30% horizontal overlap with fishing effort	>30% horizontal overlap with fishing effort
S2. Encounterability	<10% vertical overlap with fishing gear	10-30% vertical overlap with fishing gear	>30% vertical overlap with fishing gear
S3. Selectivity	Longline: <20 cm Purse seine: <20 cm Gillnet: <15 cm	Longline: 20-40 cm, >120 cm Purse seine: 20-40 cm Gillnet: 15-30 cm	Longline: 40-120 cm Purse seine: >40 cm Gillnet: >30 cm
S4. Post-capture mortality	Evidence of post-capture release and survival (Purse seine)	Released alive (Longline)	Retained species, or majority dead when released (Gillnet)

Availability was calculated as the percentage horizontal overlap of fishing effort for each fishing gear type with each sea turtle RMU within the IOTC area. Fishing effort was sourced from the catch-and-effort database available on the IOTC website (http://www.iotc.org/data-and-statistics). Longline fisheries included those identified in the IOTC database as longline, longline fresh, longline targeting swordfish, longline targeting sharks and exploratory longline. Purse seine fisheries included those identified as purse seine, small purse seine, ring net or ring net (offshore). Gillnet fisheries included those identified as gillnet, offshore gillnet, gillnet and handline, and gillnet and longline combination. Effort data for each gear type were pooled across the five year period 2012-2016 and mapped against the 20 sea turtle RMUs (Appendix A). The spatial resolution of reported effort varied among gear types, with most longline effort reported at 5°, purse seine at 1°, and gillnet at both 1° and 5° grid areas. The gillnet effort reported to the IOTC is recognised to be grossly underestimated (IOTC 2017). Therefore, we combined the reported gillnet effort and the area of the Exclusive Economic Zones (EEZs) of the main gillnet countries (Iran, Oman, Pakistan, Yemen, India, Sri Lanka, and Indonesia) to obtain an estimated footprint of the gillnet fisheries in the IOTC. This approach assumed that gillnet fishing occurred throughout the entire EEZ of each of these countries. However, it is likely that this estimated footprint is still an underestimate of the true spatial extent of gillnet fishing in the IOTC, as it does not consider underreported gillnet fishing effort in the high seas (e.g. in the northwest Indian Ocean), or gillnet fishing effort in the EEZs of other countries that is not reported (e.g. artisanal fisheries along the east African coast).

Encounterability was calculated as the percentage vertical overlap of the fishing gear for each gear type and the reported depth range for each sea turtle species. The depth at which each gear type operates varies among vessels. To obtain a single depth profile for each gear type, we assumed the depth range for longline was 0-300 m, purse seine 0-200 m, and gillnet 0-25 m. The depth range for each sea turtle species is given in Appendix B. An important assumption in using the percentage vertical overlap to estimate encounterability is that individuals occupy all depths equally within the species depth range. This assumption is unlikely to hold for air-breathing taxa, which likely spend proportionally more time nearer to the surface. Therefore, estimates of encounterability may be underestimated for shallow gear types and overestimated for deeper gear types.

Selectivity of different gear types has not been estimated for sea turtles. Therefore, *Selectivity* categories were informed by expert input. For purse seine and gillnet fisheries, an average mesh size of 20 cm for purse seine and 15 cm for gillnet were used as a guide to determine selectivity, with low selectivity for individuals with a curved carapace length (CCL) smaller than the mesh size, and high selectivity for individuals more than twice the mesh size. For longline, the selectivity of individuals between 40 and 120 cm CCL was considered high, while selectivity of individuals smaller than 20 cm was considered low. Selectivity categories were determined by comparing the average length at maturity for each species (Appendix B) relative to the selectivity cut off values for each category.

Post-capture mortality is not well defined for any species of sea turtle. There are many estimates of post-capture mortality from longline (e.g. Swimmer & Gilman 2012, Swimmer et al. 2017), purse seine (e.g. Bourjea et al. 2014), and gillnet (e.g. Echwikhi et al. 2010) fisheries, but results have been highly variable, often based on small sample sizes, and few have included estimates of post-release mortality of turtles captured alive. However, a general pattern observed from these studies is that post-capture mortality appears to be higher in gillnet than longline fisheries (Casale 2011, Wallace et al. 2013), and lower than both these gear types in purse seine fisheries (Bourjea et al. 2014). Therefore, for this analysis, post-capture mortality was considered low for purse seine, medium for longline, and high for gillnet fisheries.

Sensitivity to these assumptions and scoring can be explored in the online tool (see Appendix C for screen shots).

Results

The overall vulnerability scores for each RMU and fishery are shown in Table 3 and Figures 2 and 3. All RMUs were classified as either medium or high vulnerability due to the relatively high vulnerability scores on the productivity axis (range 2.30 – 2.60, Appendix B) indicating relatively low productivity. We focus here on the relative ranking across the RMUs. Because the biological attributes are common to RMUs in the same species, the vulnerability scores for the RMUs for each species cluster closely along the horizontal dimension of the PSA plots. There is more resolution in the vertical axis, due to different susceptibilities between RMUs.

Overall, the most vulnerable turtle RMUs to fishing across all fisheries include all green turtle RMUs, and hawksbill and loggerhead RMUs in the northwest and northeast Indian Ocean (Figure 3). More RMUs were classified as high vulnerability to longline than gillnet, while for purse seine, all RMUs were classified as medium vulnerability (Table 3). This result was driven mostly by the large spatial overlap (high availability) and wide depth range (high encounterability) for longline fishing compared to the other gears and the relatively low post-capture mortality of all turtle species for purse seine fisheries (Appendix B).

Green turtle RMUs were assessed as the most vulnerable to longline, followed by flatback and loggerhead turtle RMUs. All hawksbill and olive ridley RMUs were also classified as high vulnerability to longline fishing. For leatherback turtles, all RMUs were classified as medium vulnerability to longline fishing, due to their wider depth range (lower encounterability) and larger size (lower selectivity to longline) compared to other species (Appendix B).

While all RMUs were classified as medium vulnerability to purse seine, three green turtle RMUs (IO-NW, IO-SW and IO-NE) were classified as the highest vulnerability within the medium vulnerability category, followed by two loggerhead RMUs (IO-NE and IO-SW). This was due mostly to the large spatial overlap of purse seine fishing and these RMUs.

Three hawksbill turtle RMUs (IO-NE, IO-NW and PO-W) were classified as the highest vulnerability to gillnet fisheries due to the large spatial overlap and relatively shallow depth range for this species. Three green turtle RMUs (IO-NE, IO-NW and IO-SE) and two loggerhead RMUs (IO-NE and IO-NW) were also classified as high vulnerability to gillnet fishing.

Table 3. Overall PSA scores and vulnerability categories for each sea turtle regional management unit (RMU) for each fishery, ranked by PSA score for longline fishing. PSA scores are shaded from highest (dark) to lowest (light) across all fisheries.

		Longline		Purse seine		Gillnet	
Species	**RMU**	**PSA Score**	**Vulnerability**	**PSA Score**	**Vulnerability**	**PSA Score**	**Vulnerability**
Green turtle	IO-NE	3.49	High	2.97	Medium	3.35	High
Green turtle	IO-NW	3.49	High	3.08	Medium	3.35	High
Green turtle	IO-SE	3.49	High	2.87	Medium	3.35	High
Green turtle	IO-SW	3.49	High	3.08	Medium	2.93	Medium
Flatback turtle	IO-SE	3.36	High	2.71	Medium	2.94	Medium
Loggerhead turtle	IO-NE	3.36	High	2.93	Medium	3.21	High
Loggerhead turtle	IO-NW	3.36	High	2.85	Medium	3.21	High
Loggerhead turtle	IO-SE	3.36	High	2.70	Medium	2.80	Medium
Loggerhead turtle	IO-SW	3.36	High	2.93	Medium	2.77	Medium
Hawksbill turtle	IO-NE	3.33	High	2.90	Medium	3.58	High
Hawksbill turtle	IO-NW	3.33	High	2.90	Medium	3.58	High
Hawksbill turtle	PO-W	3.33	High	2.67	Medium	3.58	High
Hawksbill turtle	IO-SE	3.33	High	2.71	Medium	2.84	Medium
Hawksbill turtle	IO-SW	3.33	High	2.90	Medium	2.84	Medium
Olive ridley turtle	IO-NE	3.27	High	2.83	Medium	2.93	Medium
Olive ridley turtle	PO-W	3.27	High	2.82	Medium	2.93	Medium
Olive ridley turtle	IO-W	3.27	High	2.83	Medium	2.86	Medium
Leatherback turtle	IO-NE	3.10	Medium	2.91	Medium	3.06	Medium
Leatherback turtle	PO-W	3.10	Medium	2.80	Medium	3.06	Medium

Leatherback turtle	IO-SW	3.10	Medium	2.91	Medium	2.84	Medium

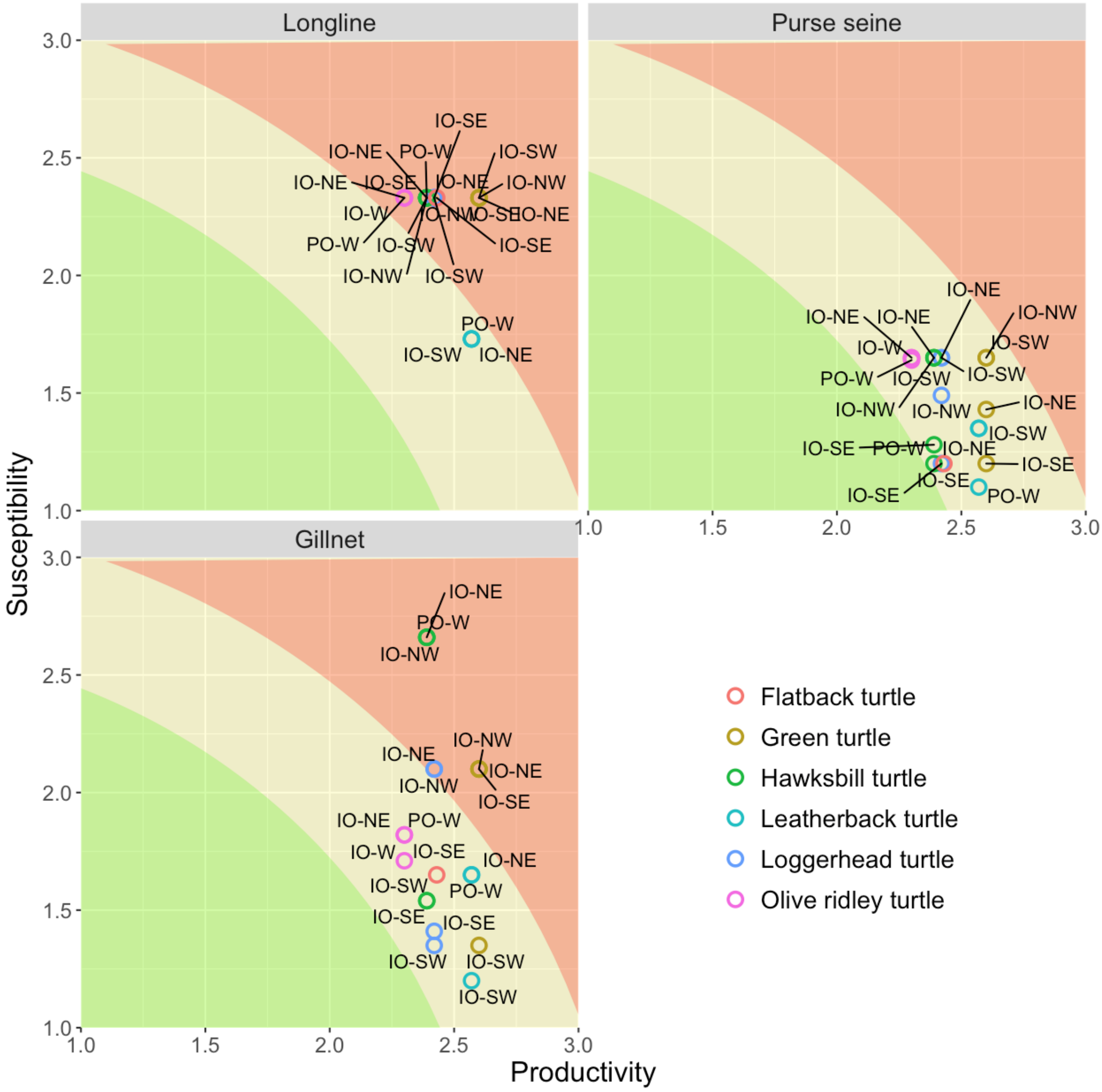

Figure 2. PSA results by fishery for 20 sea turtle regional management units (RMUs) interacting with longline, purse seine and gillnet fisheries in the Indian Ocean. Data labels represent RMUs for each species (see Appendix A for details).

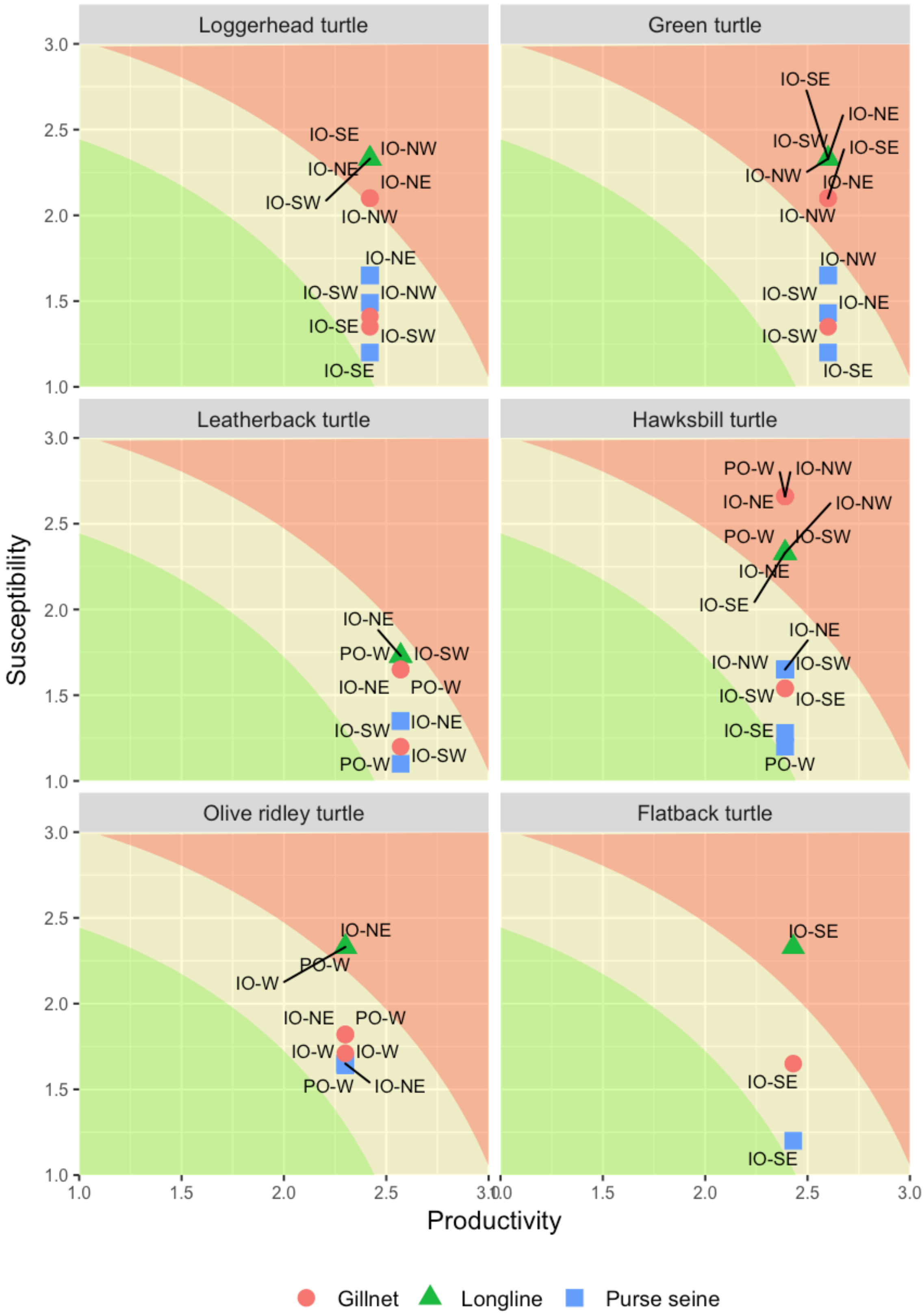

Figure 3. PSA results by species for 20 sea turtle regional management units (RMUs) interacting with longline, purse seine and gillnet fisheries in the Indian Ocean. Data labels represent RMUs for each species (see Appendix A for details).

Discussion

The application of the ERAEF PSA approach to sea turtles in the IOTC area of competence revealed that no RMUs were classified as low vulnerability to longline, purse seine or gillnet fisheries – all were classified as either medium or high vulnerability. This highlights a priority for developing and implementing management measures to minimise the impacts of fishing activities on sea turtles in the Indian Ocean. Our results indicate that sea turtles may be more vulnerable to gillnet and longline fisheries than purse seine fishing, due mostly to the large spatial area and depth distribution of longline fishing, and the high post-capture mortality of sea turtles in gillnet fisheries. Accordingly, management efforts would benefit from prioritising mitigation measures for gillnet and longline fisheries. Within these two fisheries, the species identified to be most vulnerable to fishing were green turtles, loggerhead turtles and hawksbill turtles, particularly in the Arabian Sea and Bay of Bengal.

The results from our PSA were generally comparable with those reported by Nel et al. (2013), even though we classified many more RMUs as high and medium vulnerability to fishing activities. RMUs classified as highly vulnerable by Nel et al. (2013) were generally the same as those classified as highly vulnerable in our PSA (Table 4). For example, Nel et al. (2013) classified 17 interactions between IOTC fisheries and RMUs as either high or medium vulnerability, of which 11 were consistent with our results. The greater number of RMUs classified as high and medium vulnerability in our PSA is most likely a result of different productivity and susceptibility attributes used in the PSAs, the different approaches for scoring and weighting productivity and susceptibility attributes, and different approaches for classifying overall vulnerability. This highlights the problems associated with comparing results between PSA studies, and the need to apply consistent methodologies to enable valid comparisons and monitoring of changes to vulnerability through time.

Table 4. Comparison of vulnerability outcomes from the PSA conducted by Nel et al. (2013) and the PSA in this report (2018) for those interactions between fisheries and RMUs that were scored as high or medium by Nel et al. (2013).

Species	RMU	Fishery	Nel et al. (2013)	2018
Loggerhead turtle	IO-NE	Longline	High	High
Hawksbill turtle	PO-W	Longline	High	High
Loggerhead turtle	IO-NE	Gillnet	High	High
Hawksbill turtle	PO-W	Gillnet	High	High
Leatherback turtle	PO-W	Longline	High	Medium
Loggerhead turtle	IO-NE	Purse seine	High	Medium
Hawksbill turtle	PO-W	Purse seine	High	Medium
Leatherback turtle	PO-W	Gillnet	High	Medium
Hawksbill turtle	IO-NE	Longline	Medium	High
Hawksbill turtle	IO-NE	Gillnet	Medium	High
Leatherback turtle	IO-SW	Longline	Medium	Medium
Hawksbill turtle	IO-NE	Purse seine	Medium	Medium
Leatherback turtle	PO-W	Purse seine	Medium	Medium
Loggerhead turtle	IO-SW	Gillnet	Medium	Medium
Olive ridley turtle	PO-W	Gillnet	Medium	Medium
Olive ridley turtle	IO-W	Gillnet	Medium	Medium
Leatherback turtle	IO-SW	Gillnet	Medium	Medium

The ERAEF PSA was developed for fisheries that capture or interact with teleosts, chondrichthyans, birds, mammals and sea turtles. However, the productivity attributes in the PSA are probably more relevant to the productivity of teleosts, and may not represent well the productivity of other taxa such as sea turtles. Other productivity attributes, such as the number of nesting females and number of clutches per individual (as used by Nel et al. 2013) may be more representative of the productivity of sea turtles, while also providing information on which to separate the productivity of individual RMUs within a species. RMU-specific productivity attributes were not implemented in the ERAEF PSA, as they are not known for all RMUs, and so the missing data score (3) is used, which precautionarily inflates the vulnerability ranking. The result was that productivity scores for all RMUs were identical within each species, and overall vulnerability of individual RMUs was separated solely on the basis of horizontal overlap of the fisheries with each RMU. Similarly, differentiation in overall vulnerability scores among species was driven mostly by the horizontal (availability) and vertical (encounterability) overlap of the fisheries with each RMU, rather than by any differences in productivity attributes among species. This sensitivity to the susceptibility axis is to be expected given the low productivity of all sea turtle species, resulting in high scores and low variation on the productivity axis.

A limitation of the PSA is that it assumes an equal contribution of the productivity and susceptibility scores to the overall vulnerability score, and also assumes an equal contribution from each individual attribute within the productivity and susceptibility axes. Hordyk and Carruthers (2018) challenged this assumption and demonstrated that it does not hold in many circumstances. Rescaling or reweighting the relationship between productivity and susceptibility, or weighting individual productivity and/or susceptibility attributes within each axis (e.g. Nel et al. 2013) may be more appropriate in some cases, but not all. For example, Duffy & Griffiths (2017) found no evidence that weighting productivity and susceptibility attributes improved the differentiation among species in a PSA for the purse seine fishery in the eastern Pacific Ocean. Therefore, the application of weightings to the attributes within a PSA should be evaluated carefully to ensure that any modifications provide an improved representation of vulnerability.

Given the greater influence of the susceptibility attributes to the overall relative vulnerability scores (Hordyk and Carruthers 2018), it is important to understand the limitations of the effort data and depth information used in the PSA. For example, the coarse spatial resolution of longline data (5° grid squares) may have overestimated the true availability of sea turtles to the longline fishery and resulted in inflated vulnerability scores and an overestimate of the number of RMUs classified as high vulnerability to the longline fishery. Conversely, the substantial underreporting of gillnet fishing effort data to the IOTC may have resulted in an underestimate of the true availability of sea turtles to the gillnet fishery, despite our assumption that gillnet fishing occurred throughout the entire EEZs of each of the main gillnet fishing countries. Furthermore, the assumption that individual sea turtles occupy all depths equally within the species depth range when estimating encounterability is unlikely to hold for air-breathing taxa like sea turtles, which are likely to spend most of the time closer to the surface. Therefore, estimates of encounterability may be underestimated for shallow gear types such as gillnets, and overestimated for deeper gear types like longline and purse seine. Therefore, the true vulnerability of sea turtles in the IOTC area of competence may be higher for gillnet fisheries than longline fisheries, particularly in the northwest and northeast Indian Ocean.

Selectivity and post-capture mortality of sea turtles in any IOTC fishery are not well known, and assumptions were necessary in scoring these susceptibility attributes in the PSA. Selectivity was scored as high (3) for all gear types and all RMUs, so it had no influence on the overall relative vulnerability scores. Post-capture mortality, however, was scored differently for each gear type, and it was assumed that post-capture mortality is highest in gillnets, lowest in purse seine and intermediate for longline.

Different gear configurations (e.g. length of longline/nets, mesh sizes and hook type/size) and setting behaviours (e.g. depth of sets, time of day) are likely to influence both of the attributes. Available evidence suggests the scores for post-capture mortality are accurate on a relative scale (Wallace et al. 2013), but more information on selectivity and post-capture mortality of sea turtles in IOTC fisheries is needed to validate the assumptions for these attributes.

While PSAs provide a useful tool to rapidly assess the relative vulnerability of species in data-poor fisheries, the threshold scores used for categorising overall vulnerability in a PSA are not related to biological thresholds. Therefore, it is not appropriate to assess the cumulative impacts from multiple fisheries within a PSA because the vulnerability scores cannot be summed across fisheries. Two approaches are in development to allow improved assessment of cumulative impact – the Sustainability Assessment for Fishing Effects (SAFE) (Zhou & Griffiths 2008; Zhou et al. in review) and the Ecological Assessment of Sustainable Impacts of Fisheries (EASI-Fish) (Griffiths et al. 2018). To date, both methods have been developed and applied to teleosts and elasmobranchs, but could be refined for taxa such as turtles in future.

For example, EASI-Fish is an alternative approach to the PSA that quantifies the cumulative impacts of multiple fisheries and uses fewer input parameters than a PSA. EASI-Fish derives a proxy estimate for fishing mortality (*F*) which is used in a per-recruit analysis to evaluate overall vulnerability of each species using conventional biological reference points (e.g. F/F_{MSY} and SB/SB_{MSY}). The results from EASI-Fish can then been plotted on a phase plot (e.g. Figure 4), which facilitates communication of results to managers and provides a useful framework for monitoring shifts in relative vulnerability over time. The parameters required to implement the EASI-Fish model are mostly available for sea turtle RMUs. Therefore, the application of EASI-Fish to turtles, and other bycatch species in IOTC fisheries, would provide managers with additional confidence to identify the most vulnerable species and populations to fishing impacts, to which resources can be directed to implement mitigation measures or prioritise data collection and further research.

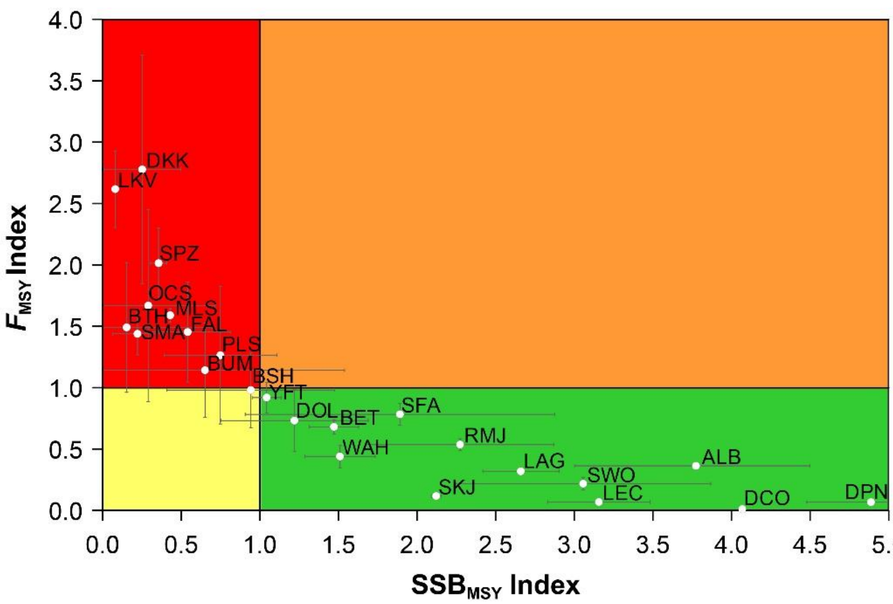

Figure 4. Example phase plot from Griffiths et al. (In Review) showing the results from an EASI-Fish assessment of 24 species, including leatherback (DKK) and olive ridley turtles (LKV), caught in the eastern Pacific Ocean tuna fisheries, relative to the reference points F/F_{MSY} and SB/SB_{MSY}.

As noted previously, it is important to emphasise that PSAs provide only a relative measure of vulnerability to fishing by ranking populations from most to least vulnerable. This information is useful for prioritising those species ranked as most vulnerable for additional data collection, assessments, or mitigation measures, and by simulating changes to the attribute scores can provide insight to managers on how to reduce the overall vulnerability of these species to the impacts of fishing. However, the population benefit of these measures cannot be estimated with the PSA. Given the high vulnerability of sea turtles to fishing activities in the IOTC area of competence, particularly to gillnet and longline fishing, and the lack of compliance with Resolution 12/04, priority should be given to implementing and enforcing effective mitigation strategies in the Indian Ocean. Several studies have identified factors (e.g. use of circle as opposed to 'J' hooks and finfish as opposed to squid baits) that contribute to significantly lower probabilities of turtle interactions and subsequent mortality in longline fisheries in the Pacific (e.g. Swimmer et al. 2017, Common Oceans (ABNJ) Tuna Project 2017) and Atlantic (e.g. Huang et al. 2016, Swimmer et al. 2017) oceans. However, similar studies have not been conducted in the Indian Ocean, and it is unclear whether the results from other oceans are directly transferable to the Indian Ocean. Therefore, priority should be given to collating existing data on turtle interactions from IOTC member countries to undertake an analysis to identify factors that contribute to higher interaction and mortality rates. Ideally, this should include data from both longline and gillnet fisheries (interaction rates and post-capture mortality are relatively low for purse seine fisheries). The joint analysis by the Common Oceans (ABNJ) Tuna Project (2017) provides a useful model for approaching such an analysis, including holding workshops to collate datasets and bring together all stakeholders with an interest in improving turtle conservation. Such a workshop was recommended by the Working Party on Ecosystems and Bycatch in 2017 (IOTC 2017b), but no funding has yet been allocated to this work.

Recommendations

Data

- There is an urgent need to improve the reporting of sea turtle interactions from all fisheries, but particularly gillnet fisheries for which there is currently no information. This will require a commitment from member countries to comply with their data collection and reporting requirements for sea turtles, including ensuring that observers record the details of all sea turtle interactions.
- Difficulties placing at-sea observers on vessels is often the reason given for not providing data on sea turtle interactions. Electronic monitoring with cameras may be an alternative and effective method for obtaining information on sea turtle interactions (and interactions with other species), particularly for gillnet fisheries where placement of observers is most difficult.
- Fishing effort data is important for scaling up observer data on sea turtle interactions to the whole fishery. The coverage of reported fishing effort for IOTC fisheries is incomplete, especially for gillnet fisheries where there are large data gaps. There is an urgent need to improve the reporting of fishing effort data which requires a commitment from all member countries to comply with their data reporting obligations.
- Estimates of post-capture mortality of sea turtles vary widely among studies, which can have a significant influence on estimates of fishing mortality and subsequent assessment outcomes. Further research is needed to provide more reliable estimates of post-capture mortality for all sea turtle species and all gear types.

Assessments

- The results from this PSA are broadly similar to those from Nel et al. (2013) and are unlikely to change significantly with further PSAs unless new information, other than additional years of effort data, becomes available. Therefore, there is likely to be minimal gain in repeating a PSA for sea turtles in the short to medium term, unless there is a significant improvement in reporting of fishing effort data from gillnet fisheries, a significant change in fishing effort, or if more information becomes available on the vulnerability of specific turtle RMUs.
- Research efforts would be best spent developing improved assessments that quantify the cumulative impacts of multiple fisheries to estimate total fishing mortality to provide better estimates of absolute vulnerability (e.g. Griffiths et al. 2018). Such methods would allow the reporting of the vulnerability status of sea turtles against recognised biological reference points, facilitate communication of results to managers, and provide a useful framework for monitoring shifts in relative vulnerability over time.
- Priority should be given to collating existing data on turtle interactions from IOTC member countries to undertake an analysis to identify factors that contribute to higher interaction and mortality rates. Ideally, this should include data from both longline and gillnet fisheries (interaction rates and post-capture mortality are relatively low for purse seine fisheries). The joint analysis by the Common Oceans (ABNJ) Tuna Project (2017) provides a useful model for approaching such an analysis, which should include, *inter alia*:
  - Collating all observer data, and all other relevant information, either held by the IOTC Secretariat or by member countries. The Secretariat would be best placed to collate and manage these data.
  - Convening joint analysis workshops to bring together IOTC scientists and other interested stakeholders to analyse the collated data. Maintaining confidentiality of these data will be critically important and will need to be managed during the workshops.
  - Analysing the collated data using an approach similar to that used by the ABNJ Tuna Project (2017), including estimating the effects of different operational variables on interaction rates and turtle mortality at capture.
  - Simulation-testing the results of the analyses to test the degree to which additional mitigation would reduce sea turtle interactions and mortalities compared to the status quo.

Management

- Priority should be given to implementing and enforcing effective mitigation strategies for sea turtles in the Indian Ocean. Factors that contribute to significantly lower probabilities of turtle interactions and mortality have been identified in other oceans and should be used as a starting point for developing mitigation measures in the Indian Ocean.
- Effective measures should be implemented to ensure member countries are compliant with their data collection and reporting obligations for sea turtles (and other species), including Resolution 12/04.

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Appendix A. Sea turtle Regional Management Units (RMUs) in the Indian Ocean Tuna Commission area of competence

Table A1. Description of sea turtle regional management units in the Indian Ocean Tuna Commission area of competence (adapted from Wallace et al. 2010). *Note that Wallace et al. (2010) identified two RMUs for the olive ridley turtle in the northeast Indian Ocean with identical spatial boundaries. Both of these RMUs are treated as a single RMU in this PSA analysis.

Species	Common name	Ocean	Region	RMU abbreviation
Caretta caretta	Loggerhead turtle	Indian	Northeast	IO-NE
Caretta caretta	Loggerhead turtle	Indian	Northwest	IO-NW
Caretta caretta	Loggerhead turtle	Indian	Southeast	IO-SE
Caretta caretta	Loggerhead turtle	Indian	Southwest	IO-SW
Chelonia mydas	Green turtle	Indian	Northeast	IO-NE
Chelonia mydas	Green turtle	Indian	Northwest	IO-NW
Chelonia mydas	Green turtle	Indian	Southeast	IO-SE
Chelonia mydas	Green turtle	Indian	Southwest	IO-SW
Dermochelys coriacea	Leatherback turtle	Indian	Northeast	IO-NE
Dermochelys coriacea	Leatherback turtle	Indian	Southwest	IO-SW
Dermochelys coriacea	Leatherback turtle	Pacific	West	PO-W
Eretmochelys imbricata	Hawksbill turtle	Indian	Northeast	IO-NE
Eretmochelys imbricata	Hawksbill turtle	Indian	Northwest	IO-NW
Eretmochelys imbricata	Hawksbill turtle	Indian	Southeast	IO-SE
Eretmochelys imbricata	Hawksbill turtle	Indian	Southwest	IO-SW
Eretmochelys imbricata	Hawksbill turtle	Pacific	West	PO-W
Lepidochelys olivacea	Olive ridley turtle	Indian	Northeast	IO-NE*
Lepidochelys olivacea	Olive ridley turtle	Indian	West	IO-W
Lepidochelys olivacea	Olive ridley turtle	Pacific	West	PO-W
Natator depressus	Flatback turtle	Indian	Southwest	IO-SE

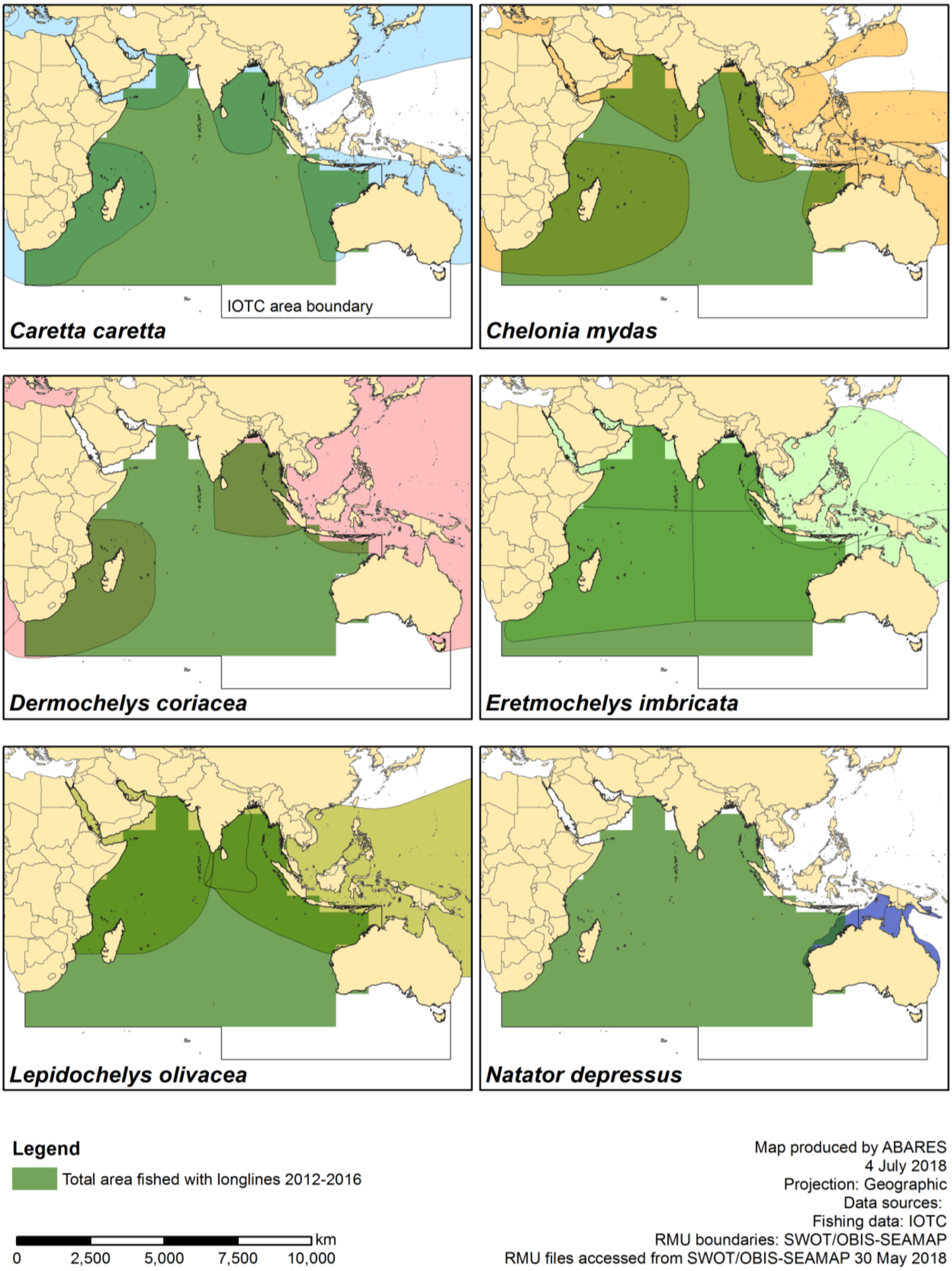


Figure A1. Distribution of reported longline fishing effort in the IOTC for the years 2012-2016 overlaid on the regional management unit (RMU) boundaries for each species of sea turtle.

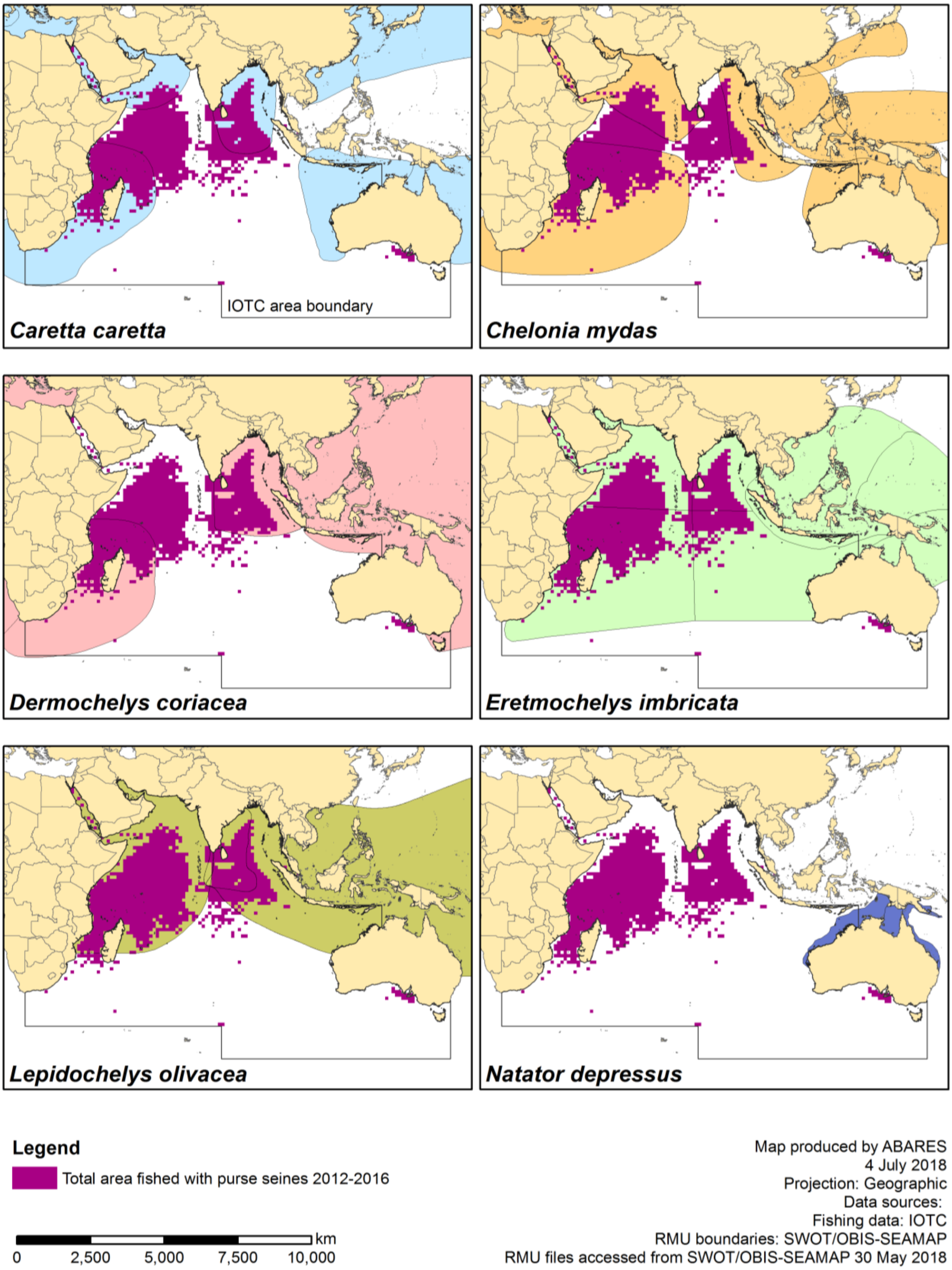


Figure A2. Distribution of reported purse seine fishing effort in the IOTC for the years 2012-2016 overlaid on the regional management unit (RMU) boundaries for each species of sea turtle.

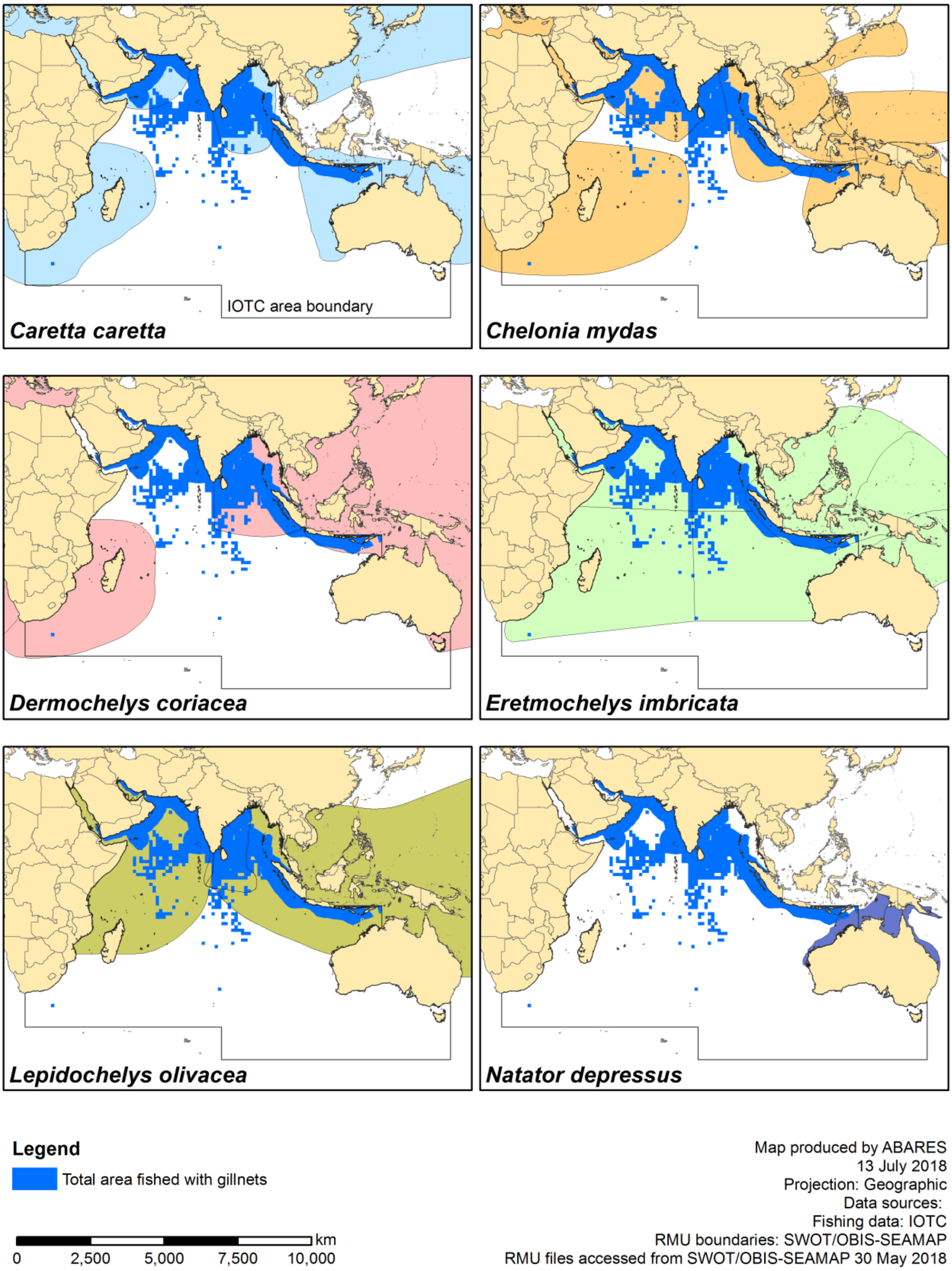


Figure A3. Distribution of gillnet fishing effort in the IOTC for the years 2012-2016 overlaid on the regional management unit (RMU) boundaries for each species of sea turtle. Note that reported gillnet fishing is grossly underestimated in the IOTC, and in these maps, and this assessment, gillnet fishing was assumed to occur within the entire Exclusive Economic Zones (EEZs) of the main gillnet countries (Iran, Oman, Pakistan, Yemen, India, Sri Lanka, and Indonesia).

Appendix B. Productivity and susceptibility attributes for sea turtles in the Indian Ocean

Table B1. Productivity attribute values used for the Productivity-Susceptibility Analysis for sea turtles in the Indian Ocean

Species	Common name	Average age at maturity (years)	Average maximum age (years)	Fecundity (No. of eggs per year)	Average maximum size (cm)	Average size at maturity (cm)	Reproductive strategy	Trophic level	Maximum depth (m)
Caretta caretta	Loggerhead turtle	16	69	119	113	65	Marine reptile	-	150
Chelonia mydas	Green turtle	23	75	125	111	78	Marine reptile	-	150
Dermochelys coriacea	Leatherback turtle	18	30	108	175	155	Marine reptile	-	1200
Eretmochelys imbricata	Hawksbill turtle	17	75	134	94	70	Marine reptile	-	100
Lepidochelys olivacea	Olive ridley turtle	15	75	99	78	49	Marine reptile	-	200
Natator depressus	Flatback turtle	10	?	44	99	84	Marine reptile	-	25

Table B2. Scores for individual productivity attributes and overall productivity score for each sea turtle RMU.

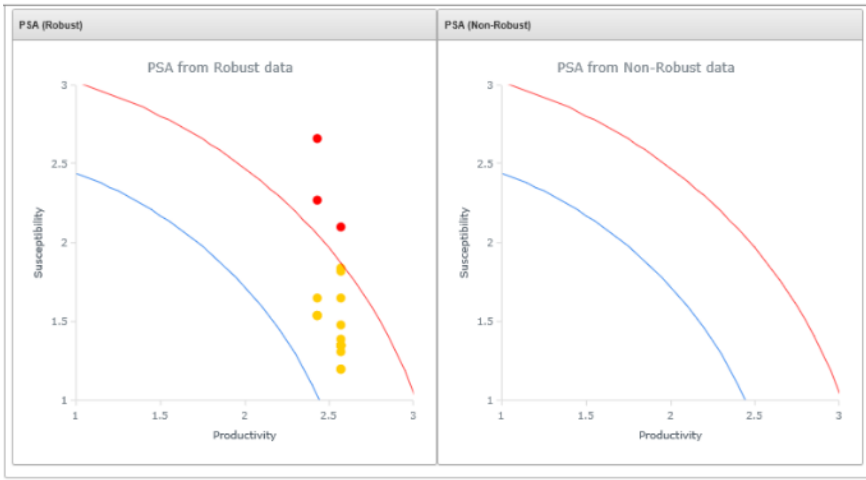
Species	RMU	Average age at maturity	Average max age	Fecundity	Average max size	Average size at maturity	Reproductive strategy	Trophic level	Productivity Score
Caretta caretta	IO-NE	2.20	2.90	2.25	2.01	1.60	3	3	2.42
Caretta caretta	IO-NW	2.20	2.90	2.25	2.01	1.60	3	3	2.42
Caretta caretta	IO-SE	2.20	2.90	2.25	2.01	1.60	3	3	2.42
Caretta caretta	IO-SW	2.20	2.90	2.25	2.01	1.60	3	3	2.42
Chelonia mydas	IO-NE	3.00	3.00	2.15	1.96	2.12	3	3	2.60
Chelonia mydas	IO-NW	3.00	3.00	2.15	1.96	2.12	3	3	2.60
Chelonia mydas	IO-SE	3.00	3.00	2.15	1.96	2.12	3	3	2.60
Chelonia mydas	IO-SW	3.00	3.00	2.15	1.96	2.12	3	3	2.60
Dermochelys coriacea	IO-NE	2.60	1.00	2.42	3.00	3.00	3	3	2.57
Dermochelys coriacea	IO-SW	2.60	1.00	2.42	3.00	3.00	3	3	2.57
Dermochelys coriacea	PO-W	2.60	1.00	2.42	3.00	3.00	3	3	2.57
Eretmochelys imbricata	IO-NE	2.40	3.00	2.02	1.51	1.80	3	3	2.39
Eretmochelys imbricata	IO-NW	2.40	3.00	2.02	1.51	1.80	3	3	2.39
Eretmochelys imbricata	IO-SE	2.40	3.00	2.02	1.51	1.80	3	3	2.39
Eretmochelys imbricata	IO-SW	2.40	3.00	2.02	1.51	1.80	3	3	2.39
Eretmochelys imbricata	PO-W	2.40	3.00	2.02	1.51	1.80	3	3	2.39
Lepidochelys olivacea	IO-NE	2.00	3.00	3.00	1.08	1.00	3	3	2.30
Lepidochelys olivacea	IO-W	2.00	3.00	3.00	1.08	1.00	3	3	2.30
Lepidochelys olivacea	PO-W	2.00	3.00	3.00	1.08	1.00	3	3	2.30
Natator depressus	IO-SE	1.00	3.00	3.00	1.64	2.36	3	3	2.43

Table B3. Scores for individual susceptibility attributes and overall susceptibility scores for each sea turtle RMU and each fishery

	Fishery	Longline					Purse seine					Gillnet				
Species	**RMU**	**Availability**	**Encounter-ability**	**Selectivity**	**Post-capture mortality**	**Susceptibility Score**	**Availability**	**Encounter-ability**	**Selectivity**	**Post-capture mortality**	**Susceptibility Score**	**Availability**	**Encounter-ability**	**Selectivity**	**Post-capture mortality**	**Susceptibility Score**
Caretta caretta	IO-NE	3.00	3.00	3	2	2.33	3.00	3.00	3	1	1.65	3.00	1.67	3	3	2.10
Caretta caretta	IO-NW	3.00	3.00	3	2	2.33	2.30	3.00	3	1	1.49	3.00	1.67	3	3	2.10
Caretta caretta	IO-SE	3.00	3.00	3	2	2.33	1.00	3.00	3	1	1.20	1.16	1.67	3	3	1.41
Caretta caretta	IO-SW	3.00	3.00	3	2	2.33	3.00	3.00	3	1	1.65	1.00	1.67	3	3	1.35
Chelonia mydas	IO-NE	3.00	3.00	3	2	2.33	2.03	3.00	3	1	1.43	3.00	1.67	3	3	2.10
Chelonia mydas	IO-NW	3.00	3.00	3	2	2.33	3.00	3.00	3	1	1.65	3.00	1.67	3	3	2.10
Chelonia mydas	IO-SE	3.00	3.00	3	2	2.33	1.00	3.00	3	1	1.20	3.00	1.67	3	3	2.10
Chelonia mydas	IO-SW	3.00	3.00	3	2	2.33	3.00	3.00	3	1	1.65	1.00	1.67	3	3	1.35
Dermochelys coriacea	IO-NE	3.00	2.50	2	2	1.73	3.00	1.67	3	1	1.35	3.00	1.00	3	3	1.65
Dermochelys coriacea	IO-SW	3.00	2.50	2	2	1.73	3.00	1.67	3	1	1.35	1.00	1.00	3	3	1.20
Dermochelys coriacea	PO-W	3.00	2.50	2	2	1.73	1.00	1.67	3	1	1.10	3.00	1.00	3	3	1.65
Eretmochelys imbricata	IO-NE	3.00	3.00	3	2	2.33	3.00	3.00	3	1	1.65	3.00	2.50	3	3	2.66
Eretmochelys imbricata	IO-NW	3.00	3.00	3	2	2.33	3.00	3.00	3	1	1.65	3.00	2.50	3	3	2.66
Eretmochelys imbricata	IO-SE	3.00	3.00	3	2	2.33	1.34	3.00	3	1	1.28	1.00	2.50	3	3	1.54
Eretmochelys imbricata	IO-SW	3.00	3.00	3	2	2.33	3.00	3.00	3	1	1.65	1.00	2.50	3	3	1.54
Eretmochelys imbricata	PO-W	3.00	3.00	3	2	2.33	1.00	3.00	3	1	1.20	3.00	2.50	3	3	2.66
Lepidochelys olivacea	IO-NE	3.00	3.00	3	2	2.33	3.00	3.00	3	1	1.65	3.00	1.25	3	3	1.82
Lepidochelys olivacea	IO-W	3.00	3.00	3	2	2.33	3.00	3.00	3	1	1.65	2.60	1.25	3	3	1.71
Lepidochelys olivacea	PO-W	3.00	3.00	3	2	2.33	2.96	3.00	3	1	1.64	3.00	1.25	3	3	1.82

Natator depressus	IO-SE	3.00	3.00	3	2	2.33	1.00	3.00	3	1	1.20	1.00	3.00	3	3	1.65

Appendix C. Productivity-Susceptibility Analysis online tool



Robust PSA Summary	
Low	0
Medium	17
High	3

Data Deficient PSA Summary	
Low	0
Medium	0
High	0

Go Actions

Caab code	Scientific name	Common name	P1	P2	P3	P4	P5	P6	P7	S1	S2	S3	S4	Prod score	Susc score	Missing attributes	PSA 2D	Risk Category
	Eretmochelys imbricata : Indian Ocean Northeast	Eretmochelys imbricata : Indian Ocean Northeast	3	3	2	1	2	3	3	3	2.5	3	3	2.43	2.66	1	3.6	High
	Eretmochelys imbricata : Indian Ocean Northwest	Eretmochelys imbricata : Indian Ocean Northwest	3	3	2	1	2	3	3	2.3	2.5	3	3	2.43	2.27	1	3.33	High
	Caretta caretta : Indian Ocean Northeast	Caretta caretta : Indian Ocean Northeast	3	3	2	2	2	3	3	3	1.667	3	3	2.57	2.1	1	3.32	High
	Chelonia mydas : Indian Ocean Northwest	Chelonia mydas : Indian Ocean Northwest	3	3	2	2	2	3	3	2.3	1.667	3	3	2.57	1.84	1	3.16	Medium
	Lepidochelys olivacea : Indian Ocean Northeast	Lepidochelys olivacea : Indian Ocean Northeast	3	3	3	1	2	3	3	3	1.25	3	3	2.57	1.82	1	3.15	Medium
	Dermochelys coriacea : Indian Ocean Northeast	Dermochelys coriacea : Indian Ocean Northeast	3	3	2	2	2	3	3	3	1	3	3	2.57	1.65	1	3.05	Medium
	Lepidochelys olivacea : Pacific Ocean West	Lepidochelys olivacea : Pacific Ocean West	3	3	3	1	2	3	3	1.8	1.25	3	3	2.57	1.48	1	2.97	Medium
	Natator depressus : Indian Ocean Southeast	Natator depressus : Indian Ocean Southeast	2	3	3	1	2	3	3	1	3	3	3	2.43	1.65	2	2.94	Medium
	Caretta caretta : Indian Ocean Northwest	Caretta caretta : Indian Ocean Northwest	3	3	2	2	2	3	3	1.1	1.667	3	3	2.57	1.39	1	2.92	Medium
	Chelonia mydas : Indian Ocean Northeast	Chelonia mydas : Indian Ocean Northeast	3	3	2	2	2	3	3	1	1.667	3	3	2.57	1.35	1	2.9	Medium
	Caretta caretta : Indian Ocean Southwest	Caretta caretta : Indian Ocean Southwest	3	3	2	2	2	3	3	1	1.667	3	3	2.57	1.35	1	2.9	Medium
	Chelonia mydas : Indian Ocean Southeast	Chelonia mydas : Indian Ocean Southeast	3	3	2	2	2	3	3	1	1.667	3	3	2.57	1.35	1	2.9	Medium

Figure C1. Screen shot from the PSA online tool (http://www.marine.csiro.au/apex/f?p=127) showing results for the gillnet fishery.

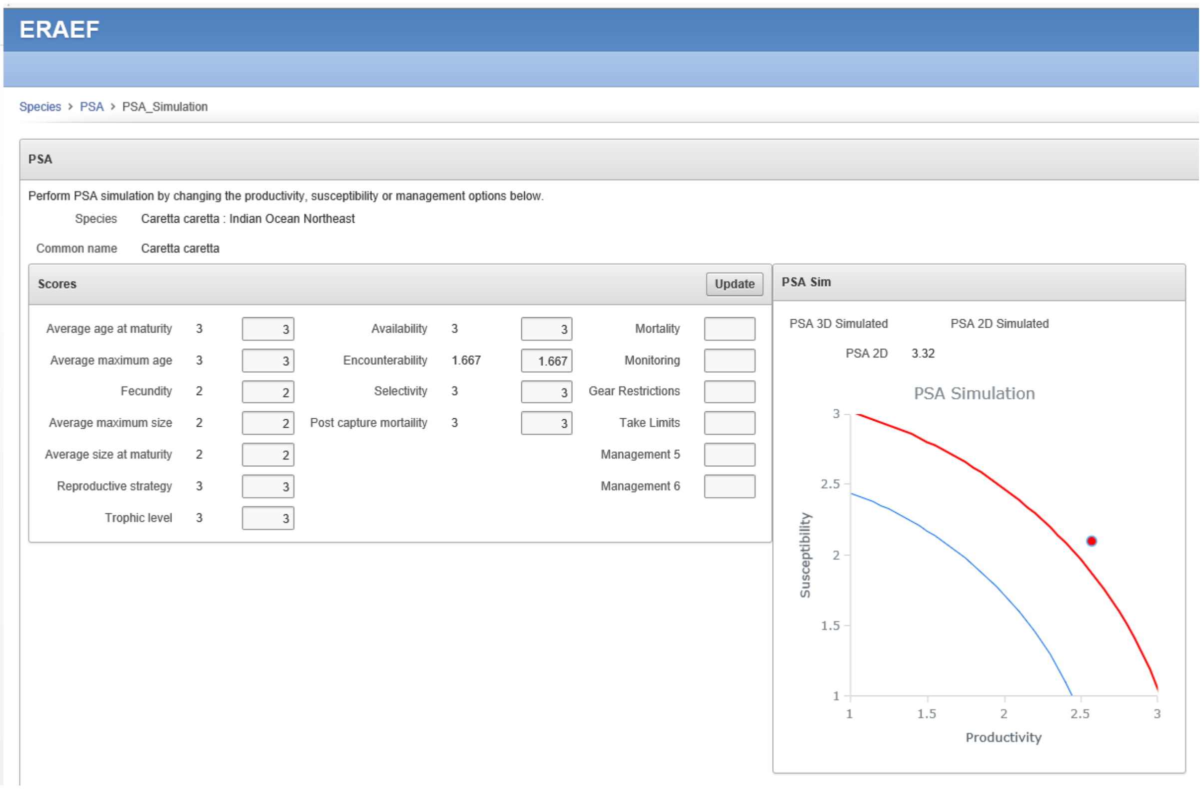


Figure C2. Screen shot from the PSA online tool (http://www.marine.csiro.au/apex/f?p=127) showing individual results for the northeast Indian Ocean regional management unit (RMU) of loggerhead turtle (*Caretta caretta*) and the gillnet fishery. Changes to individual productivity and susceptibility scores can be simulated here to provide insight to managers on how to reduce the overall vulnerability of species RMUs to the impacts of fishing.