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ASSESSING THE VULNERABILITY OF ELASMOBRANCHS TO WESTERN AND CENTRAL PACIFIC TUNA FISHERIES USING AN IMPROVED ECOLOGICAL RISK ASSESSMENT METHOD

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Executive Summary

This paper describes improvements to the Ecological Assessment of the Sustainable Impacts of Fisheries (EASI-Fish) framework. EASI-Fish is a quantitative and length-based approach for ecological risk assessment. The improved framework was then applied to 33 species of WCPFC shark and ray bycatch to determine their vulnerability to WCPFC fisheries. This analysis provides first or updated estimates of vulnerability for a number of these species. The work includes transcribing the EASI-Fish framework into R-code which is freely available from the repository link provided in the information paper. The satisfactory performance of EASI-Fish encourages its potential application to other species and applications within WCPFC work programme (such as the efficacy of various conservation and management measures (CMMs) on bycatch vulnerability via simulation). Moreover, EASI-Fish will likely be a tool for evaluation of WCPFC CMMs performance under the impacts of climate change given its use of species distribution models which are amendable for projecting future climate conditions and integrates animal and fishery dynamics.

Recommendations

SC22 is advised of the following:

- The EASI-Fish framework has been improved to more robustly estimate fisheries overlap with assessed species and the overlaps subsequent interpretation as a surrogate for fishing mortality.
- A full description of the improvements are published in volume 299 of Fisheries Research. A copy of that publication is provided as this information paper.
- That this is the most comprehensive ecological risk assessment to date for WCPFC fisheries, providing first or updated estimates of vulnerability for 33 shark and ray species that WCPFC fisheries interact with.
- The performance of the improved framework was satisfactory indicating that future WCPFC bycatch work could involve applying EASI-Fish to other species groups (e.g. teleost bycatch), and testing the efficacy of various conservation and management measures (CMMs) on bycatch vulnerability via simulation.
- R-code for the improved framework is available at github.com/nhill917/EASI-FishR.

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Assessing the vulnerability of elasmobranchs to western and central Pacific tuna fisheries using an improved ecological risk assessment method

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ABSTRACT

Tropical tuna fisheries are among the largest fisheries in the world and interact with a range of bycatch species. Understanding the impacts of these fisheries on bycatch species is important for fisheries management, however the vulnerability of many of these species remains largely unknown given available data. Here, a recent length-based ecological risk assessment method developed for data-limited settings, Ecological Assessment of the Sustainable Impacts of Fisheries (EASI-Fish), was applied to 33 elasmobranch species that interact with western and central Pacific Ocean (WCPO) tropical tuna fisheries. This quantitative, model-based ecological risk assessment provides estimates of vulnerability for these elasmobranchs. In summary, 13 of 33 species assessed were considered 'least vulnerable', 12 'most vulnerable', and eight 'data deficient'. Species considered 'most vulnerable' included several carcharhinids given their low productivity, as well as several *Sphyrna* species that are particularly susceptible to mortality when interacting with fishing gears. Deep-set longline gear was responsible for most fishing mortality for most species given its vast effort distribution throughout the WCPO and vertically in the water column. A thorough compilation of life history and fisheries information for bycatch species was also undertaken and its reliability qualitatively scored, which can be used to prioritise research. EASI-Fish methods were further developed, including an improved approach to estimating spatial overlap which decreased vulnerability scores. This assessment can assist fisheries administrations to revise their management, stock assessment and research priorities for these elasmobranch bycatch species and provides other practitioners with improved tools to undertake similar assessments going forward.

1. Introduction

Fisheries policy makers have historically focused on a single species approach to management (Juan-Jordá et al., 2018; Link et al., 2020; Pikitch et al., 2004). However, it has become apparent that fisheries can have unintended impacts on non-target species, habitats and associated ecosystems (Casey and Myers, 1998; Hall et al., 2000; Lewison et al., 2004). In response, there has been a determined shift towards an ecosystem approach to fisheries management (EAFM) that considers the impacts of fisheries on all species and the integrity of ecosystem more broadly (Garcia et al., 2003; Juan-Jordá et al., 2018).

Scientists have developed a range of tools to determine the ecological impacts of fisheries in recent decades (Fletcher, 2005; Griffiths et al., 2019; Hobday et al., 2011; Roux et al., 2015; Sharp, 2019; Stobutzki et al., 2001). One such approach is Ecological Risk Assessment (ERA), which aims to assess species vulnerability to the effects of fishing (and other anthropogenic stressors), identifying those species most at risk and prioritising them for management (Fletcher, 2015; Fulton et al., 2019). ERAs have been developed to be capable of assessing an array of taxonomic groups encountered in fisheries (e.g., elasmobranchs, sea turtles, sea birds), especially in data-limited settings (Griffiths et al., 2019; Hobday et al., 2011). Approaches to ERA range broadly in terms of their objectives, data requirements, methods used, and outputs (Fulton et al., 2019). They can vary from fully qualitative weight-of-evidence approaches that rely on expert opinion, to more quantitative approaches similar to conventional stock assessment methods (Fletcher, 2005; Griffiths et al., 2019; Hobday et al., 2011; Roux et al., 2015; Sharp, 2019)

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Ecological Assessment of the Sustainable Impacts of Fisheries (EASI-Fish) is a recently developed length-based, quantitative approach that extends the continuum of ERA methodologies for fisheries (Griffiths et al., 2019). EASI-Fish characterises both the susceptibility and productivity of a species to determine its vulnerability to fishing and other anthropogenic impacts. It determines a species susceptibility by estimating its three-dimensional 'volumetric' overlap with individual fisheries by using a species distribution model (SDM) as a basemap paired with information from fisheries such as spatially explicit fishing effort and operational characteristics like gear selectivity. Productivity is estimated using conventional life history parameters (e.g. L_{inf}, K, t_0) to characterise species population dynamics which are input into length-based per-recruit models (Chen and Gordon, 1997; Griffiths et al., 2019). EASI-Fish provides quantitative estimates of vulnerability for species from cumulative fisheries impacts in a way that is synonymous with fisheries management where quantitative fishing mortality and biomass related metrics can be represented relative to conventional management-based reference points. This methodology overcomes several limitations and assumptions made by other approaches that have shown to be limited in some instances (Grewelle et al., 2021; Hordyk and Carruthers, 2018), and has now been applied to a range of taxa (e.g., elasmobranchs, sea turtles, teleosts, seabirds, marine mammals) and fisheries (e.g., purse-seine, longline, gillnet, trawl) (Bell et al., 2025; Griffiths et al., 2022a, Griffiths et al., 2022b; Jiminez, 2024).

The Pacific Ocean's pelagic tuna fisheries are some of the world's largest fisheries in terms of catch volume, economic value, and footprint (FAO, 2024; ISSF, 2024). One group of species that are regularly encountered in these fisheries is elasmobranchs (i.e., sharks and rays, hereafter referred to as 'sharks' collectively), which are primarily considered bycatch, but for certain fleets can be targeted or incidental retained catch. A range of pelagic shark species occupy similar habitats to the target tuna and billfish species of these fisheries and are therefore susceptible to capture by the gears used such as longline and purse seine (Restrepo et al., 2024). Furthermore, many of these shark species have higher vulnerability to depletion given their life history characteristics of generally being slow-growing, long-lived and having low reproductive potential (Clarke et al., 2013; Dulvy et al., 2021; Pacoureau et al., 2021, 2023).

Like many fisheries administrations globally, the Conventions and policies of tuna regional fisheries management organisations (tRFMOs) are increasingly aligned with the aims of EAFM to better account for their broader ecological impacts. Within the Pacific Ocean, the Inter-American Tropical Tuna Commission (IATTC) and the Western and Central Pacific Fisheries Commission (WCPFC) are responsible for the management of tropical tuna and tuna-like species in the eastern Pacific Ocean (EPO) and the Western and Central Pacific Ocean (WCPO), respectively. Each of these RFMOs have implemented several initiatives to improve bycatch management which has included enhanced observer programs and coverage to expand data collection for bycatch species (WCPFC, 2018a), along with various conservation and management measures (CMMs) that aim to reduce bycatch interactions, such as banning the retention of some species (*Carcharhinus falciformis, C. longimanus, Rhincodon typus*) in some or all fisheries, the prohibition of shark finning, and minimising the use of wire traces (IATTC, 2011, 2016; WCPFC, 2012a, 2012b, 2013, 2014). For sharks, stock assessments or ERAs have also been undertaken for several species in attempts to determine their sustainability in respect to fishing (Clarke et al., 2013; Duffy et al., 2019; Griffiths et al., 2022a; Neubauer et al., 2018, 2021; Tremblay-Boyer et al., 2019).

Despite this progress, for many species there is still insufficient or unreliable data to build assessment models to determine stock status. In tuna fisheries, most information on bycatch species comes from onboard observers. Observer coverage is near 100% for purse seine fleets in the Pacific Ocean, however longline fleets that regularly encounter sharks have much lower coverage of approximately 5% or less (WCPFC, 2024, IATTC, 2025). Further, observers are often tasked with recording information related to compliance and target species, and so collection of information for bycatch is often a lower priority. Lastly, bycatch species are often released or discarded *in situ*, making species identification and animal disposition difficult to determine. Data is also collected by fishers in logbooks which can be used to inform unobserved sets, but these data are often incomplete for bycatch species and there are often issues with species identification, meaning that total catch is often unknown and must be estimated (Peatman et al., 2023, 2024; Peatman and Nicol, 2025). As a result, the total catches for most shark species in tuna fisheries are often highly uncertain and key life history data is also lacking or uncertain (Clarke et al., 2015). For species where stock assessments have been applied, these data limitations have often led to high uncertainty in stock status from which the implementation of management advice has been difficult (Clarke et al., 2018; Neubauer et al., 2021; Rice and Harley, 2013).

A recent EASI-Fish of sharks in the EPO assessed 20 of 32 species to be 'most vulnerable' (i.e., their fishing mortality exceeded reference points) to tuna fisheries, enabling the identification and prioritisation of several shark species for management (Griffiths et al., 2022a). A further assessment of silky and hammerhead sharks using EASI-Fish explored which management measures might be most effective in reducing fishing mortality and improving vulnerability status (Griffiths et al., 2023). However, many of these species have Pacific-wide distributions and so their overall vulnerability to tuna fisheries in the Pacific Ocean is currently not fully understood. Western Pacific fisheries also encounter a different suite of species than do fisheries in the EPO.

The aim of this study was to apply EASI-Fish to elasmobranchs encountered in WCPFC tuna fisheries to provide a baseline assessment of their vulnerability. A secondary aim was to further develop the EASI-Fish methodology by testing several different modelling approaches and inputs, as well as creating reproducible code so that it can be more easily applied by practitioners. This assessment represents a comprehensive ERA for sharks in WCPO tuna fisheries and will provide managers with key information to identify and prioritise species for management action or further research. It will also add to recent assessments undertaken for sharks in the eastern Pacific Ocean and associated tuna fisheries to improve our understanding of the vulnerability of sharks to tuna fisheries in the Pacific Ocean.

2. Methods

This EASI-Fish applies to the boundaries of the WCPFC Convention Area in the western and central Pacific Ocean for the year 2022 (Fig. 1). The year 2022 was chosen as the assessment year as it is the most recent year for which complete effort data are available for all fisheries and is representative of fisheries and species post-Covid disruptions. The convention area of the WCPFC extends from 60°S–50°N and from the western land boundary of the Pacific Ocean to 150°W, with a shared area with the IATTC from 130°W–150°W and from 5°S–60°S which is included in this assessment. A total of 33 species were assessed which represent most elasmobranch species (i.e., sharks and rays, hereafter referred to as 'sharks' collectively), encountered by WCPFC fisheries across all gear types (Table 1). Species not included had too few interactions (e.g., $n < 50$) to inform the assessment (e.g., presence points to inform SDM, lengths for selectivity curve). All analyses were implemented in R and the code and documentation are available online (github.com/nhill917/EASI-FishR) (R Core Team, 2024).

2.1. Fisheries

EASI-Fish requires fisheries to be disaggregated where different gear configurations or strategies are employed resulting in differing underlying parameters in EASI-Fish such as depth and area fished, size selectivity, and temporal fishery closures (Fig. 1). For this assessment, longline gear was separated into two fisheries based on the number of hooks between floats, including deep set (>12 hooks, 0–300 m) and

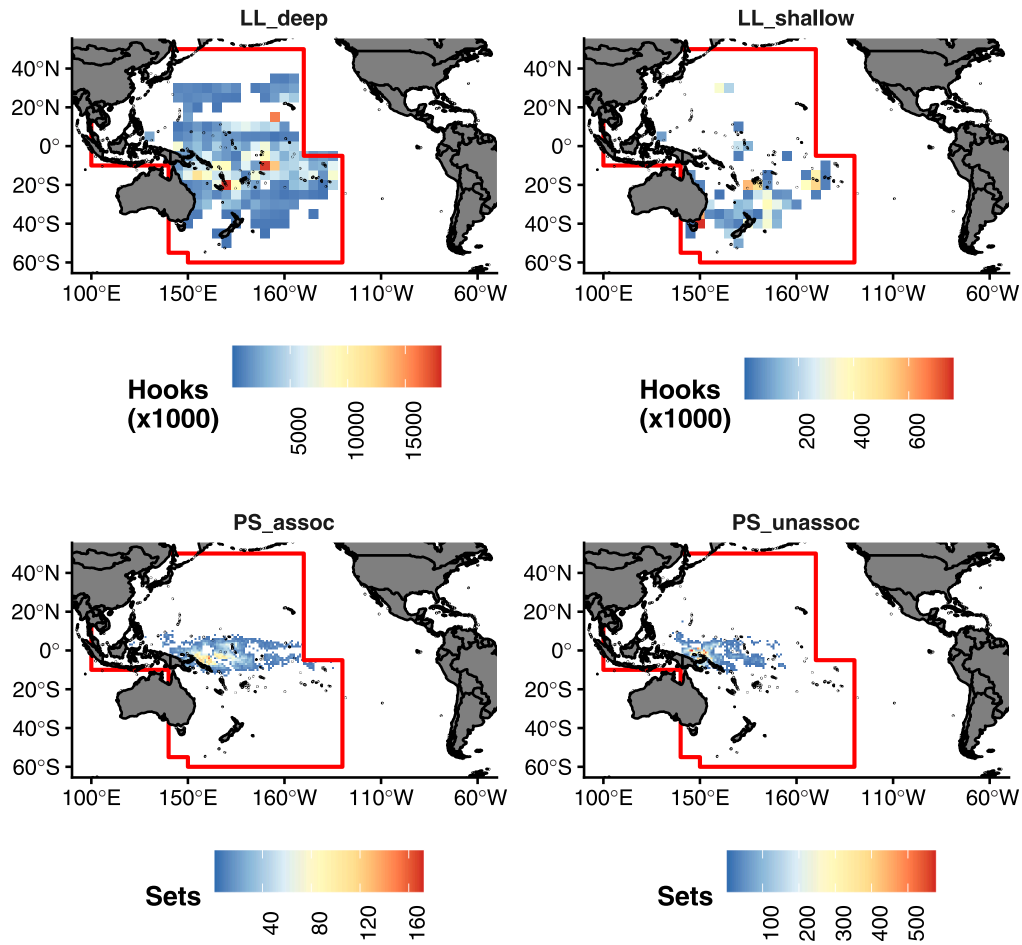

Fig. 1. Map of Western and Central Pacific Fisheries Commission convention area and effort of four fisheries for 2022. Grid cells with less than three vessels operating not shown. LL_deep = longline deep, LL_shallow = longline shallow, PS_assoc = purse seine associated, PS_unassoc = purse seine unassociated.

shallow set (<=12 hooks, 0–150 m). These longline gear configurations are used to target species in different parts of the water column and influence the encounterability parameter within EASI-Fish, that is, the extent of vertical overlap of the species with the fishing gear in the water column. Purse seine was also separated into two fisheries, based on whether the set was made in association with a floating object including artificial drifting or anchored fish aggregating device (FAD) and logs (i.e., associated), or on a free-swimming school of tunas not associated with a floating object (i.e., unassociated). This distinction was made as these set types have different shark bycatch composition, and because the seasonal FAD closure implemented by WCPFC influences the fishing season duration parameter within EASI-Fish.

2.2. Species

A total of 33 elasmobranch species were included for assessment using EASI-Fish (Table 1). Species were assumed to comprise a single stock within the study area. An exception was porbeagle shark (*Lamna nasus*), and salmon shark (*Lamna ditropis*), which were assumed to only occur in the southern and northern hemispheres respectively given their known distributions.

A literature review was undertaken to acquire best available life history parameters for each species (Table 1). Where multiple estimates were available for various life history parameters (e.g. growth), the study that was undertaken with the most scientific rigour (e.g., higher sample size, longer term sample collections) and based in the Pacific Ocean was preferred. EASI-Fish was applied for each species using four-centimetre length bins from 0 cm to species asymptotic length (L_{inf}) to maximise the number of bins which is consistent with previous EASI-Fish applications (Griffiths et al., 2022a). The length type used differed across species (e.g., total length (TL), fork length (UF)), but all parameter values for a given species are consistent. All lengths are presented in centimetres (cm) and weight in kilograms (kg).

2.3. Susceptibility

The original susceptibility equation of EASI-Fish estimates a proxy for instantaneous fishing mortality ($F_{yr\text{-}1}$) derived from the proportion of a population that is susceptible to mortality by fishery x for the assessment year (2022) as:

$$S_{xj} = \frac{G_x}{G}(D_x A_{xj} N_{xj} C_{xj} P_{xj}) \quad (1)$$

Where S is the susceptibility of a species to fishery x at length class j, G is the number of grid cells occupied by a species, G_x is the number of those cells occupied by at least one unit of fishing effort for fishery x, D_x is the fishing season duration which equates to the proportion of the year the fishery is open, A_{xj} is seasonal availability of length class j that is available to the fishery x to account for species migration, encounterability N_{xj} is the proportion of length class j that overlaps with the gear of fishery x vertically in the water column, contact selectivity C_{xj} is the proportion of length class j that is caught by the gear used by fishery x, and P_{xj} is post-capture mortality. Recently, post-capture mortality was disaggregated to (Griffiths et al. 2023):

Table 1
Species included in EASI-Fish and their life history parameters. All lengths are in centimetres (cm). T_{max} = maximum age, L_{inf} = species asymptotic length, K = growth curve parameter, L-Wa = length-weight a parameter, L-Wb = length-weight b parameter, M = natural mortality, L_m = length at first maturity, L_{50} = length at 50% maturity. TL = total length, UF = fork length, PC = pre-caudal length, DW = disc width. Depth = depth range (m) the species predominately occurs. Habitat column denotes if species was considered neritic (N) or pelagic (P) for species distribution models. See Supplementary Material (Table S5) for references.

Code	Scientific name	Length type	T_{max}	L_{inf}	K	L_0	L-W a	L-W b	M	L_m _L_{50}	Depth (m)	Habitat
ALS	*Carcharhinus albimarginatus*	TL	32	311	0.04	72.1	0.000003	3.24	0.13	_208.9	0–150	N
ALV	*Alopias vulpinus*	UF	22	245.8	0.14	81	0.000188	2.52	0.18	160_215	0–400	P
AML	*Carcharhinus amblyrhynchos*	TL	19	163.3	0.15	60	0.0000016	3.29	0.21	_136	0–150	N
BLR	*Carcharhinus melanopterus*	TL	25	158.5	0.25	61.7	0.0000003	3.65	0.16	_133.5	0–80	N
BRO	*Carcharhinus brachyurus*	TL	31	308	0.15	68	0.0000104	2.9	0.13	215_222.2	0–145	N
BSH	*Prionace glauca*	PC	24	284.9	0.12	36.2	0.0000054	3.1	0.17	141_160.9	0–400	P
BTH	*Alopias superciliosus*	PC	20	224.6	0.09	66.5	0.0000687	2.77	0.2	150_172.7	0–450	P
CCA	*Carcharhinus altimus*	TL	21	303.2	0.12	80	0.000001	3.46	0.19	_225	25–400	P
CCE	*Carcharhinus leucas*	TL	32	350.7	0.08	64	0.0000043	3.07	0.13	226_257	0–70	N
CCG	*Carcharhinus galapagensis*	TL	24	300	0.12	70	0.0000057	3.03	0.17	215_245	0–110	N
CCL	*Carcharhinus limbatus*	TL	24	263.6	0.14	72.8	0.0000044	3.06	0.17	_200.2	0–30	N
CCP	*Carcharhinus plumbeus*	TL	27	223	0.1	76	0.0000019	3.23	0.15	165_174.8	0–70	N
CYW	*Centroscymnus owstonii*	TL	12	120	0.22	30	0.0000028	3.17	0.35	_106	150–1200	P
DUS	*Carcharhinus obscurus*	TL	42	369.4	0.13	94	0.000002	3.22	0.11	_281	0–100	P
FAL	*Carcharhinus falciformis*	TL	28	268.3	0.05	75.5	0.0000029	3.15	0.14	_204	0–100	P
ISB	*Isistius brasiliensis*	TL	7	50.5	0.41	14	0.0000372	3.12	0.54	39_	0–1000	P
LMA	*Isurus paucus*	PC	31	279.6	0.11	60	0.0000462	2.77	0.14	_191.1	15–400	P
LMD	*Lamna ditropis*	PC	25	207.4	0.17	62.5	0.000044	2.88	0.16	_164.7	0–500	P
OCS	*Carcharhinus longimanus*	TL	25	309.4	0.09	64	0.0000166	2.89	0.16	190_193.4	0–120	P
PLS	*Pteroplatytrygon violacea*	DW	10	90	0.26	19	0.0000219	3.01	0.4	48_50	0–70	P
POR	*Lamna nasus*	UF	35	210.9	0.09	58	0.0000089	3.13	0.12	_175	0–500	P
PSK	*Pseudocarcharias kamoharai*	TL	14	118.4	0.15	45.5	0.000045	2.48	0.29	_91.2	0–590	P
PTH	*Alopias pelagicus*	TL	24	328.1	0.12	140	0.000159	2.61	0.17	_285.3	20–400	P
RHN	*Rhincodon typus*	TL	80	1582	0.02	64	0.0000121	2.86	0.08	_810	0–200	P
RMB	*Mobula birostris*	DW	45	707	0.1	122	0.0000187	2.88	0.1	_448	0–150	P
SCK	*Dalatias licha*	TL	11	162	0.2	35	0.0000008	3.41	0.36	_132.6	50–850	P
SMA	*Isurus oxyrinchus*	PC	31	279.6	0.11	60	0.0000462	2.77	0.14	_233	0–150	P
SPK	*Sphyrna mokarran*	TL	39	402.7	0.08	70	0.0000012	3.24	0.11	_227.9	0–60	P
SPL	*Sphyrna lewini*	TL	35	289.6	0.16	47	0.0000028	3.13	0.12	_219.4	0–100	P
SPZ	*Sphyrna zygaena*	TL	25	375.2	0.11	55	0.0000024	3.15	0.16	_259	0–60	P
SSQ	*Zameus squamulosus*	TL	54	96.1	0.07	24.5	0.000002	3.23	0.09	71.5_82	50–400	P
TIG	*Galeocerdo cuvier*	TL	33	418.3	0.07	78	0.0000001	3.67	0.13	_326	0–100	N
WSH	*Carcharodon carcharias*	UF	44	466.8	0.1	122	0.0000076	3.08	0.1	417_	0–100	N

$$P_{xj} = AVM_{xj} + \left[(1 - AVM_{xj})PRM_{xj}\right] \quad (2)$$

where at-vessel mortality (AVM_{xj}) is the proportion of length class j in fishery x that dies due to interaction with the fishing gear (e.g. retention, entangling), and PRM_{xj} is the proportion of individuals of size class j and fishery x released alive that soon after died because of interaction with the fishing gear.

2.3.1. *Updated susceptibility*

We updated the original susceptibility equation to maximise information from species distribution models (SDMs) and compared it against the original approach. Previously, spatial overlap (G_x/G) was estimated by converting the probability of occurrence predictions from SDMs and effort maps from fisheries to presence-absence layers and calculating a proportional overlap value from zero to one. This approach was developed to be able to estimate overlap for data-limited fisheries where only presence-absence effort data are available. However, this approach removes the continuous information present in SDM and effort layers where it is available spatially, and requires defining an arbitrary threshold value for the probability of occurrence (e.g., 0.5) where a species habitat becomes suitable enough to assume presence. These layers are also defined at a single annual timestep when both species and fisheries are often highly dynamic in time and space.

To utilise as much information as possible, two new approaches to estimating overlap, and thus susceptibility, were explored. Firstly, continuous prediction surfaces from SDMs which detail probability of occurrence (or habitat suitability) from zero to one are retained and each cell value is divided by the sum of all cell values of the layer so that its sum is equal to one (see details of SDM methods in Supplementary Material). Then the sum of all cell values that overlap with fishing effort is taken to estimate overlap. This allows the continuous nature of the SDM surface to be retained rather than converting it to a presence-absence layer (Figure S5).

This differs from the original approach which takes the count of cells, rather than the sum of their habitat suitability values. This removes the need to define an arbitrary threshold value to define cells where presence occurs (i.e. usually 0.5) and retains the continuous surface of the SDM. This can provide improved estimates of overlap where, for example, a fishery may have a spatial overlap with the core of a species distribution by 40% that likely represents more than 40% of its total abundance, and vice versa.

Secondly, this approach is applied at a monthly timestep as opposed to annually. SDMs, which are produced at a species level are projected onto monthly environmental surfaces for the assessment year (2022) and corresponding monthly effort layers also produced with overlap calculated each month. Each of these values is then divided by 12 (for each month) to calculate the mean overlap value. Applying a monthly timestep implicitly accounts for any seasonality (D_x) in fisheries (if a fishery is closed for a month, overlap would be zero for that month), and availability (A_{xj}) where a species may migrate into or out of fishing grounds. This approach combines the spatial overlap, fishing season duration and availability parameters in the original susceptibility equation into a single overlap term ($\overline{O_x}$).

$$\text{Updated susceptibility}: S_{xj} = \overline{O_x}N_{xj}C_{xj}P_{xj} \quad (3)$$

Estimates of susceptibility can then be converted to a proxy for instantaneous fishing mortality which was undertaken using the same equation as in previous EASI-Fish applications where effort and catchability are assumed to be one. This implies that all fish within a grid cell subject to at least one unit of effort are caught if all other susceptibility parameter values are fully realized. See Griffiths et al. (2019) for a more detailed description.

2.3.2. Susceptibility inputs

2.3.2.1. Spatial overlap (G). Species distribution models (SDMs) were developed for each species to inform estimation of overlap within the susceptibility equation (Fig. 2). A detailed description of the method is provided in the Supplementary Material and summarised here. For each species, presence records from the WCPFC and IATTC observer programs, and the Global Biodiversity Information Facility (GBIF; https://www.gbif.org/) collected between1993–2022 were used as inputs into SDMs (Table S1; Figure S1). Presence records were included from throughout the Pacific Ocean, rather than just the WCPFC convention area so that SDM outputs were estimated using greater environmental

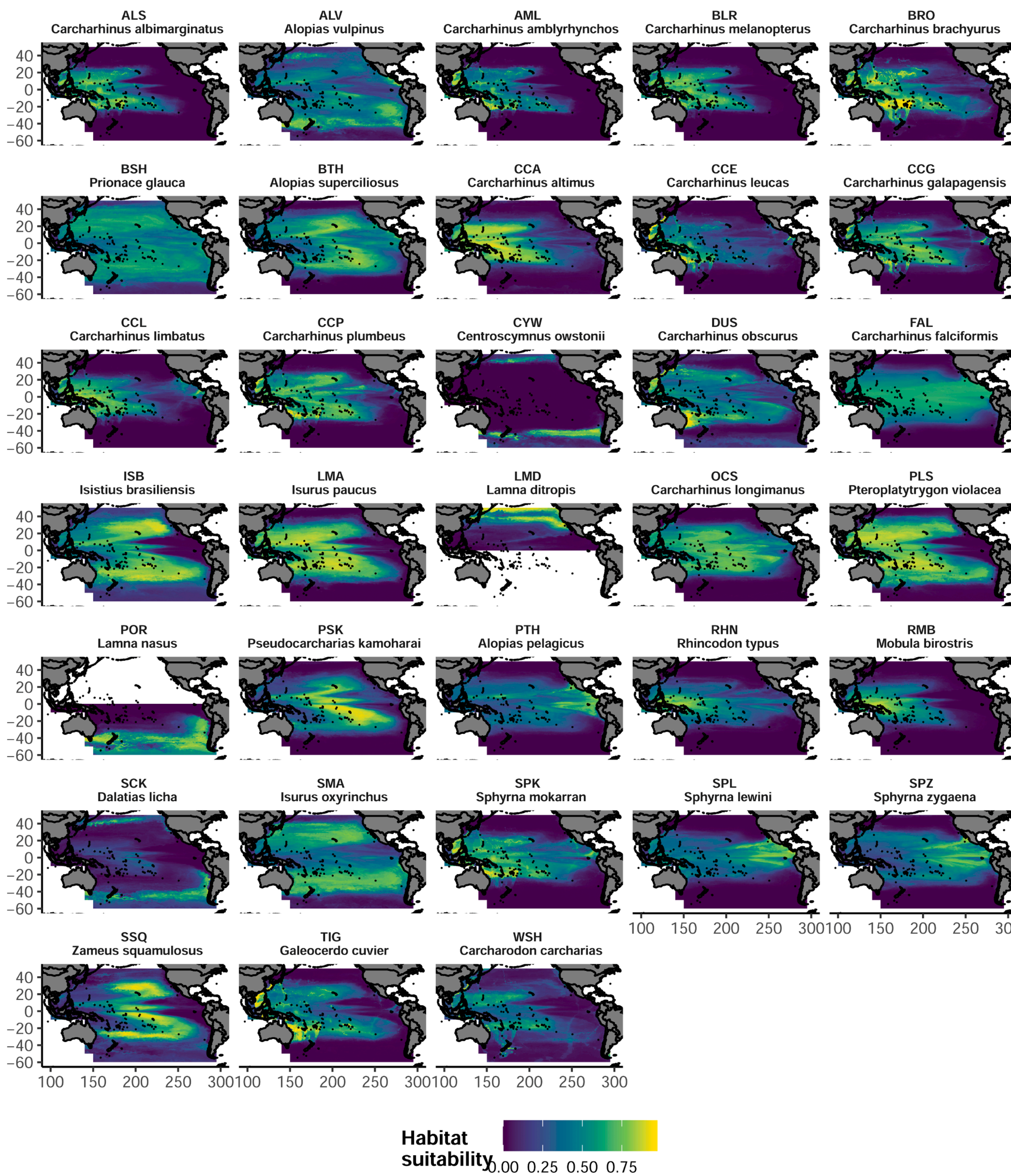

Fig. 2. Ensemble species distribution model outputs for species assessed in EASI-Fish projected onto 2022 environmental conditions.

gradients. SDM outputs were then cropped to the study area.

To evaluate the influence of non-independence of presence data, three different data sampling treatments were applied. These were geographic subsampling of presence points (geo) (Valavi et al., 2019), environmental subsampling of presence points (env) (Castellanos et al., 2019; Varela et al., 2014), and environmental subsampling of both presence and background points (env2) (Shipley et al., 2022). A total of 50000 background points were assigned throughout the study area using a biased sampling surface of presence records from all species created with the *spatSample* function from the *terra* package (Hijmans, 2023; Valavi et al., 2022). A total of seven environmental variables were extracted from 1993 to 2022 at monthly timesteps to capture the dynamic nature of the pelagic environment and species movements including (Brodie et al., 2021; Mannocci et al., 2017): temperature at surface and 100 m depth, mixed layer depth, sea surface height anomaly, dissolved oxygen at surface and 100 m, and chlorophyll (Table S2). Where a species was known to heavily associate with the coastline or other physical features (e.g., coral reefs), depth was added as an additional environmental variable and the species considered 'neritic' (Table 1).

Three different SDM methods were applied including weighted Boosted Regression Trees (BRT) (Ridgway, 2007), Maxnet (Phillips, 2021), and down-weighted Random Forest (RF) (Liaw and Wiener, 2002; Valavi et al., 2022). Each model was trained on a training data set (80% of presences) and evaluated using a testing dataset (the remaining 20% of presences) using AUC to inform model performance. To estimate spatial overlap, an AUC-weighted ensemble model was produced across the three methods using both the 'geo' and 'env2' data treatments. The 'env' data treatment was not incorporated as it provided very similar outputs to the 'geo' treatment.

2.3.2.2. Fishing effort (G_x). Effort data were extracted for each fishery for the year 2022 to estimate overlap (Fig. 1). For purse seine, sets at a 1° degree resolution were used, and for the longline fishery aggregated number of hooks at 5 ° resolution with hooks between floats information were used. Data were extracted at both annual and monthly time steps for use in the original and updated susceptibility approaches. Domestic purse seine fisheries from Indonesia, Philippines and Vietnam were not considered given data constraints and a latitudinal boundary of 20°N used to match stock assessment convention.

2.3.2.3. Fishing season duration (D_x). Fishing season duration was assigned a value of one (i.e., operating for 365 days) for all fisheries except for the associated purse seine fishery. In 2022, there was a 91-day closure of associated sets from 20°S-20°N from 1st July to 31st September (WCPFC, 2021). Therefore, season duration for the purse seine associated fishery was estimated as 1-(91/365). Where the updated susceptibility approach was applied, this parameter was implicitly accounted for.

2.3.2.4. Availability (A_{xj}). Availability was assumed to be one for all species (i.e., available year-round) when using the original estimation of susceptibility. In the updated approach, it is implicitly accounted for when calculating spatial overlap at monthly timesteps which should reflect shifts in species distribution relative to fishing effort when estimating susceptibility.

2.3.2.5. Encounterability (N_{xj}). Encounterability describes the extent of overlap between the fishing gear and species vertical distribution in the water column. This accounts for instances where a fishery and species may have a horizonal spatial overlap, but do not overlap in the water column (e.g., a bottom-dwelling species relative to surface fishing gear). Estimates of a species vertical distribution were extracted from the literature such as tagging studies and gear experiments using time-depth loggers (Table 1; Table S5). Species predominant depth (e.g., where they spend >50% of their time) was used where available as species likely only rarely dive to maximum depths and if used could lead to underestimation of encounterability. The effective fishing depth of the gear was defined for each fishery based on gear setting characteristics as:

- Longline shallow (<= 12 hooks between floats): 0–150 m
- Longline deep (>12 hooks between floats): 0–300 m
- Purse seine associated: 0–200 m
- Purse seine unassociated: 0–200 m

2.3.2.6. Selectivity (C_{xj}). Selectivity (C_x) describes the length frequency distribution of animals that can be caught and retained by the gear. To estimate selectivity, length data were extracted from WCPFC observer databases for each species and fishery where available to inform selectivity curves (Figure S6-S9). To make full use of the information available, length data from 2015 to 2022 inclusive were considered. A range of different length types (e.g., fork length, total length) were recorded throughout the database across time and different observer programs. Where available, length-length conversion equations were used to convert lengths to the length type required for each species (Table S3). Lengths that were not in the correct format and could not be converted were discarded. Selectivity was estimated as followed:

- Where more than 400 length samples were available at a species-fishery level (e.g., deep set longline), a generalised additive model (GAM) was used to fit to the length frequency data (i.e., dome-shaped curve) whereby AIC scores were used to determine the best fitting model based on the number of knots from 4 to 7 using the *mgcv* R package (Wood, 2017).
- Where less than 400 length samples were available at a species-fishery level (e.g., deep set longline), but more than 400 samples were available at a species-gear level (e.g., longline), a GAM was used to fit to the length frequency data (i.e., dome-shaped curve) at the species-gear level whereby AIC scores were used to determine the best fitting model based on the number of knots from 4 to 7 using the *mgcv* R package (Wood, 2017).
- Where 51–399 length samples were available at a species-gear level, a knife-edged 'box' selectivity curve was fit where selectivity rises from zero to one at the 10th length percentile, and one to zero at the 90th length percentile.
- Where 1–50 length samples were available at a species-gear level, a knife edge selectivity curve was applied at the 10th length percentile.
- Where zero length samples were available, the species was assumed to be fully selected for across its length range (i.e., selectivity = 1).

2.3.3. Post capture mortality (P_{xj})

Observer data from WCPFC fisheries from 2015 to 2022 were used to estimate at-vessel mortality (AVM) (Table S4). AVM reflects the proportion of individuals per species that die due to direct interactions with fishing gear, whether that be due to retention or other reasons (e.g., injuries suffered from hooking). For each species encountered, observers can record a range of fate and condition codes that describe whether a species is retained or released, and if released (or discarded) in what condition it was in (e.g., healthy, injured). Any fate code that suggested a mortality had occurred was recorded as an AVM (e.g., retained, discarded dead). Where a species was recorded as released, only individuals released in a healthy state were considered to have survived. In summary, AVM = (total individuals – released healthy individuals) / total individuals, where the proportion of a species that was not considered to be released healthy was an AVM. Where less than 200 records were available per species from the observer database for a species and fishery, the most appropriate value from the literature was used, if available, or the value of a related species was used.

A literature review was also undertaken to derive best available post-release mortality (PRM) estimates (Table S4). PRM reflects the proportion of individuals per species that die after release from the effects of a fishing event. If not available, a value from a related species was used or a value of one assumed (i.e., 100% PRM).

2.4. Productivity

To characterise the biological productivity of a species, EASI-Fish uses a length-based yield-per-recruit model (Chen and Gordon, 1997; Griffiths et al., 2019). Parameters used for each species are available in Table 1, and outputs of these parameters including growth curves, length-weight relationships and length at maturity can be found in the Supplementary Material (Figure S10-S12). References to the studies used to extract these parameters can be found in Table S5. For a detailed description of this and supporting equations, refer to Griffiths et al. (2019).

For growth, the best performing curve from the relevant study was used where possible for each species and so a range of different growth functions were fit across species (e.g., logistic, von Bertalanffy). Where growth had not been estimated for a species, the modified "L_0" version of the von Bertalanffy growth equation was fit as it accounts for the larger length at birth (L_0) of sharks (e.g., Smart et al., 2016). For weight, a length-weight relationship was used where $W = aL^b$ where W is weight (kg), L is length (cm), and a and b are estimated parameters. Length at maturity was estimated using the following hierarchy:

- Where length at 50% maturity (L_{50}) and an r (i.e., curvature) value were available, a logistic function was applied where maturity $m_j = 1 / (1 + e^{[-r(L_j - L_{50})]}$
- Where L_{50} was available but no value of r: knife edge maturity from L_{50}, and
- Where length at first maturity (L_m) was available but not L_{50} or r: knife edge maturity from L_m.

Natural mortality is notoriously hard to estimate, can be highly influential in stock assessments, and is often highly uncertain. In this study, a range of empirical equations that use key life history parameters (e.g., L_{inf}, K, t_{max}) were explored to produce a range of natural mortality estimates. After initial exploration, the mean natural mortality from three maximum-age based estimators were used based on their consistency in this initial exploration and performance from other studies (Cope and Hamel, 2022; Dureuil et al., 2021; Liu et al., 2020; Then et al., 2015; Zhou et al., 2021a) (Table 1). These estimators were:

- Hoenig 1983: $M = e^{(1.46 - 1.01\ln(T_{max}))}$
- Dureuil et al. (2021): $M = e^{(1.583 - 1.087\ln(T_{max}))}$
- Liu et al., 2020: M = Bayesian estimator function (K, L_{inf}, t_{max})

2.5. Data quality scoring

Input parameter values were subjectively scored from 0 to 10 based on their perceived quality, where zero reflects an absent or highly uncertain value, to ten which would be a highly accurate and precise value (Griffiths et al., 2019). Scores were assigned to inputs including maximum age (t_{max}), growth, length-weight, maturity, length at birth (L_0), natural mortality (M), depth range of the species, selectivity, species distribution model, and vessel mortality. Selectivity scores were averaged across the four fisheries, and AVM and PRM combined into a 'vessel mortality' score for longline and purse seine respectively. Where a species had three or more input parameter value scores below four, this species was considered data deficient within the assessment.

2.6. Application of EASI-Fish

This study explored alternative implementations of EASI-Fish. The first four scenarios explored the stepwise addition of the updated overlap approaches described above. From initial exploration of these scenarios, the updated EASI-Fish approach implemented at monthly timesteps (olap_cumsum_month) was considered most appropriate. An additional three scenarios were then implemented with this approach with different data inputs to explore various uncertainties and their impacts on species vulnerability scores. These included:

1. Olap_pa_annual: The original EASI-Fish approach as implemented by Griffiths et al. (2023) with overlap estimated using presence-absence at an annual timestep.
2. Olap_pa_month: The original EASI-Fish approach with overlap estimated using presence-absence at a monthly timestep.
3. Olap_cumsum_annual: The updated EASI-Fish approach using the cumulative sum to estimate overlap at an annual timestep and revised susceptibility equation.
4. Olap_cumsum_month: The updated EASI-Fish approach using the cumulative sum to estimate overlap at a monthly timestep and revised susceptibility equation.
5. Low M: Model 4 with M re-estimated using $1.2t_{max}$ to account for underestimation of maximum age.
6. AVM2_PRM2: Model 4 with an AVM and PRM estimate for all species rather than assuming a value of one for those without an estimate.
7. Combined: Model 4 with an AVM and PRM estimate for all species, and M re-estimated using $1.2t_{max}$.

Each scenario was run 1000 times to allow appropriate reflection of uncertainty in relevant parameters for each scenario. Uncertainty was incorporated into this assessment by varying several parameters. These included:

- Growth: The rate of growth parameter (K = von Bertalanffy, g = logistic, a = Schnute) within each relevant equation was varied using a lognormal distribution with a CV of 0.1 to vary growth and delta-T.
- Length-weight parameter a: lognormal distribution with a CV of 0.05 to vary weight at length.
- Natural mortality (M): uniform distribution of M $\pm$ 0.02.
- Maturity: Length at first maturity (L_m) and length at 50% maturity (L_{50}) were varied using a normal distribution with a SD of two.
- Overlap: A truncated normal distribution capped at 0–1 with a SD of 0.05 to incorporate uncertainty into SDM outputs.

In EASI-Fish, fishing mortality estimates are compared against various reference points derived from the yield-per-recruit and spawn-per-recruit analyses using estimated quantities from the susceptibility and productivity components, respectively. Productivity estimates are then cross-referenced from these estimates to a spawn-per-recruit curve to extract matching relative biomass estimates. Results are presented here showing only fishing mortality relative to various reference points (Zhou et al., 2021b). As in previous EASI-Fish applications involving sharks (Griffiths et al., 2022; 2023) and mobulid rays (Griffiths and Lezama-Ochoa, 2021), species are assessed relative to F_{40} as either 'least vulnerable' ($F < F_{40}$) or 'most vulnerable' ($F >= F_{40}$) where F_{40} is considered the level of fishing mortality that will keep a stock near 40% of its biomass in the absence of fishing. To provide a wider spectrum of reference points, we also present fishing mortality relative to a more precautionary F_{60} value which could be seen as a trigger reference point, and $F_{0.1}$ which is often used as a proxy for MSY and could be seen as a limit reference point (Braccini et al., 2015; Zhou et al., 2021b).

3. Results

EASI-Fish was applied to 33 elasmobranch species encountered in WCPFC tuna longline and purse seine fisheries, providing a first, or updated, estimate of their vulnerability status. Depending on the configuration of input data informing EASI-Fish, differing levels of certainty were achieved across species. In addition to identifying species vulnerabilities, the analyses show the data deficiencies that are required to be addressed to improve the reliability of future assessments of species with eight species considered data deficient (detailed below). Note that species considered data deficient are not included in below figures and summaries reporting EASI-Fish vulnerability scores (see Section 3.3 for details).

3.1. Overlap estimation

Estimating spatial overlap at a monthly resolution, and using a cumulative sum approach (olap_cumsum_month) with SDM outputs decreased overlap estimates and therefore estimates of vulnerability (i.e., fishing mortality) relative to the original EASI-Fish approach (olap_pa_annual) (Fig. 3). Using the cumulative sum of habitat suitability predictions per grid cell that overlap with fishing effort ('cumsum' scenarios) generally provided a slight reduction in overlap estimates relative to the original presence-absence approach. The estimation of overlap at monthly intervals ('month' scenarios) substantially reduced estimates of overlap, as it reduced the overall effort footprint of each fishery. This was particularly evident for the longline shallow-set fishery where estimates of overlap decreased by 50% or more depending on the species. This was because across a year, this fishery covers much of the WCPFC convention area, but in any one month its spatial coverage is quite variable and covers a much smaller area.

3.2. Vulnerability analyses

Overlap method and EASI-Fish input data configuration had a marked influence on species vulnerability estimates (Fig. 4). Vulnerability estimates based on annual overlap indicated that the fishing mortality for most species exceeded F_{40} and would therefore be considered 'most vulnerable'. For scenarios where monthly overlap estimates were used ('month' scenarios), fishing mortality was lower for most species. Counterintuitively, but consistent with yield-per-recruit analyses, the low natural mortality (low M) scenario resulted in higher estimates of fishing mortality and vulnerability. Lastly, the addition of AVM and PRM estimates (AVM2_PRM2) for species where they were otherwise assumed to be one reduced vulnerability. Considering these results, it was decided that the monthly cumulative sum overlap method with the inclusion of AVM and PRM data (AVM2_PRM2) was most appropriate for determining the vulnerability status of sharks in the WCPFC and all results hereafter were derived using this scenario. This was chosen because it uses the improved overlap approach, and uses best available information.

Overall, the estimated median fishing mortality exceeded F_{40} ($F/F_{40} > 1$) for 12 species, which were therefore classified as 'most vulnerable' (Fig. 5). These species included *Alopias pelagicus, A. vulpinus, Carcharhinus falciformis, C. leucas, C. limbatus, C. melanopterus, C. obscurus, C. plumbeus, Isurus oxyrinchus, Sphyrna lewini, S. mokarran, and S. zygaena*. Seven of these species also plausibly exceeded the $F_{0.1}$ reference threshold (Fig. 5). 13 species were considered 'least vulnerable' with a fishing mortality less than F_{40} including those having limited vertical overlap with WCPFC fisheries such as the deepwater *Pseudocarcharias kamoharai,* or limited horizontal overlap such as the temperate *Lamna nasus and L. ditropis* that are primarily distributed polewards of the main fishing grounds. The status of some of the most commonly encountered shark species in the WCPFC fisheries (e.g., *C. falciformis* and *I. oxyrinchus*) exceeded the $F_{0.1}$ fishing mortality threshold. The fishing mortality estimates for *P. glauca* was below ($<F_{60}$), whereas *C. longimanus* had fishing mortality estimates below F_{40} but above F_{60}. Fishing mortality by species and all scenarios, as well as additional results can be found in Supplementary Material (Figure S14-S17).

The fishery that contributed most to the total fishing mortality was the longline deep-set fishery given its widespread distribution throughout the WCPFC convention area and vertically through the water column (0–300 m) (Figure S12). The magnitude of impact by this fishery was exacerbated when shifting from an annual overlap method ('annual' scenarios) to a monthly timestep ('month' scenarios) as this reduced the spatial footprint of other fisheries, increasing the proportional contribution of the longline deep-set fishery to the overall fishing

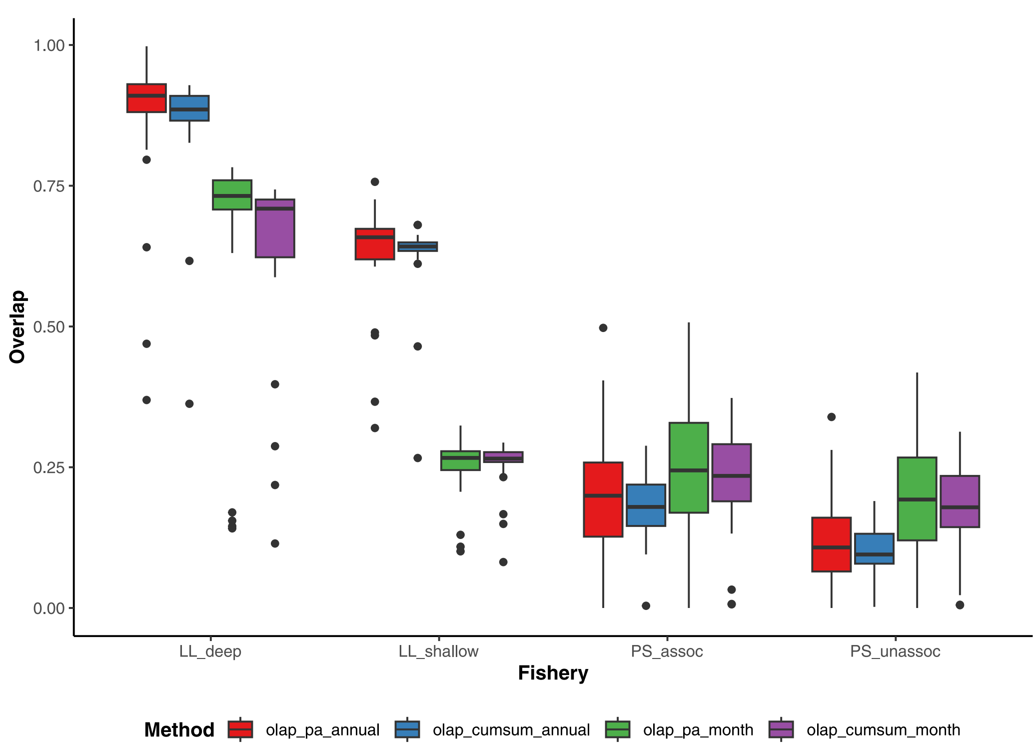

Fig. 3. Comparison of methods used to estimate overlap for input into EASI-Fish across species. LL_deep = longline deep, LL_shallow – longline shallow, PS_assoc = purse seine associated, PS_unassoc = purse seine unassociated.

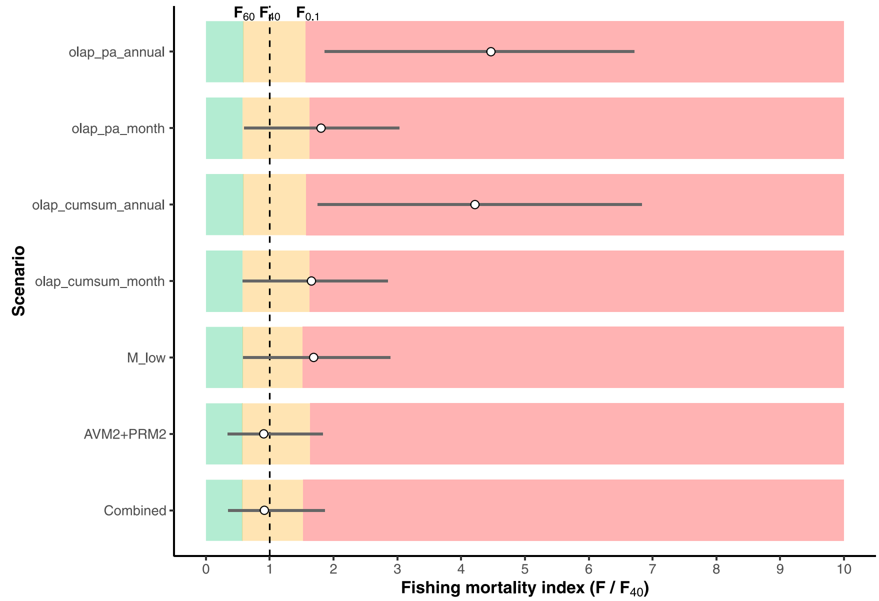

Fig. 4. Effect of different EASI-Fish input configurations on the vulnerability of 25 shark species in the WCPFC (data deficient species excluded). Green = 0-F_{60}, Yellow = F_{60}-$F_{0.1}$, Red = >$F_{0.1}$. Dashed line = F_{40}. Least vulnerable: $F/F_{40} < 1$. Most vulnerable: $F/F_{40} >= 1$. White dots = median, bars = 20th-80th percentile.

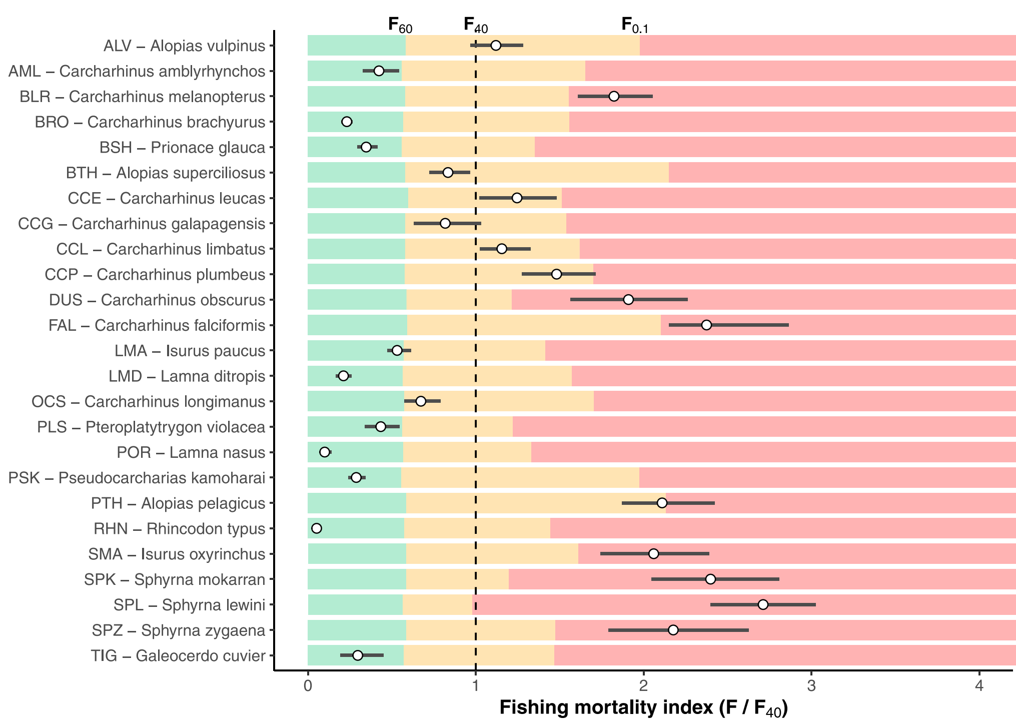

Fig. 5. EASI-Fish vulnerability scores for shark species in the WCPFC for the baseline scenario 'AVM2_PRM2'. Green = 0-F_{60}, Yellow = F_{60}-$F_{0.1}$, Red = >$F_{0.1}$. Dashed line = F_{40}. Least vulnerable: $F/F_{40} < 1$. Most vulnerable: $F/F_{40} >= 1$. White dots = median, bars = 20th-80th percentile.

mortality.

3.3. Data quality scoring

Data quality was variable across species and parameters (Fig. 6). In total, eight species were considered 'data deficient' where three or more input parameters had a score of less than four including: *C. albimarginatus, C. altimus, Centroscymnus ostonii, Isistius brasiliensis, Mobula birostris, Dalatias licha, Zameus squamulosus,* and *Carcharadon carcharias*. In terms of model parameters, AVM and PRM estimates for the purse seine fishery had the least reliable information across species, likely revealing that only some species interact with this fishery, or that these characteristics have not been well studied. The other parameters that were uncertain across most species were those based on ageing data including growth, maximum age, and natural mortality.

4. Discussion

This study represents a comprehensive ecological risk assessment of elasmobranchs in WCPO tuna fisheries and adds to a growing body of

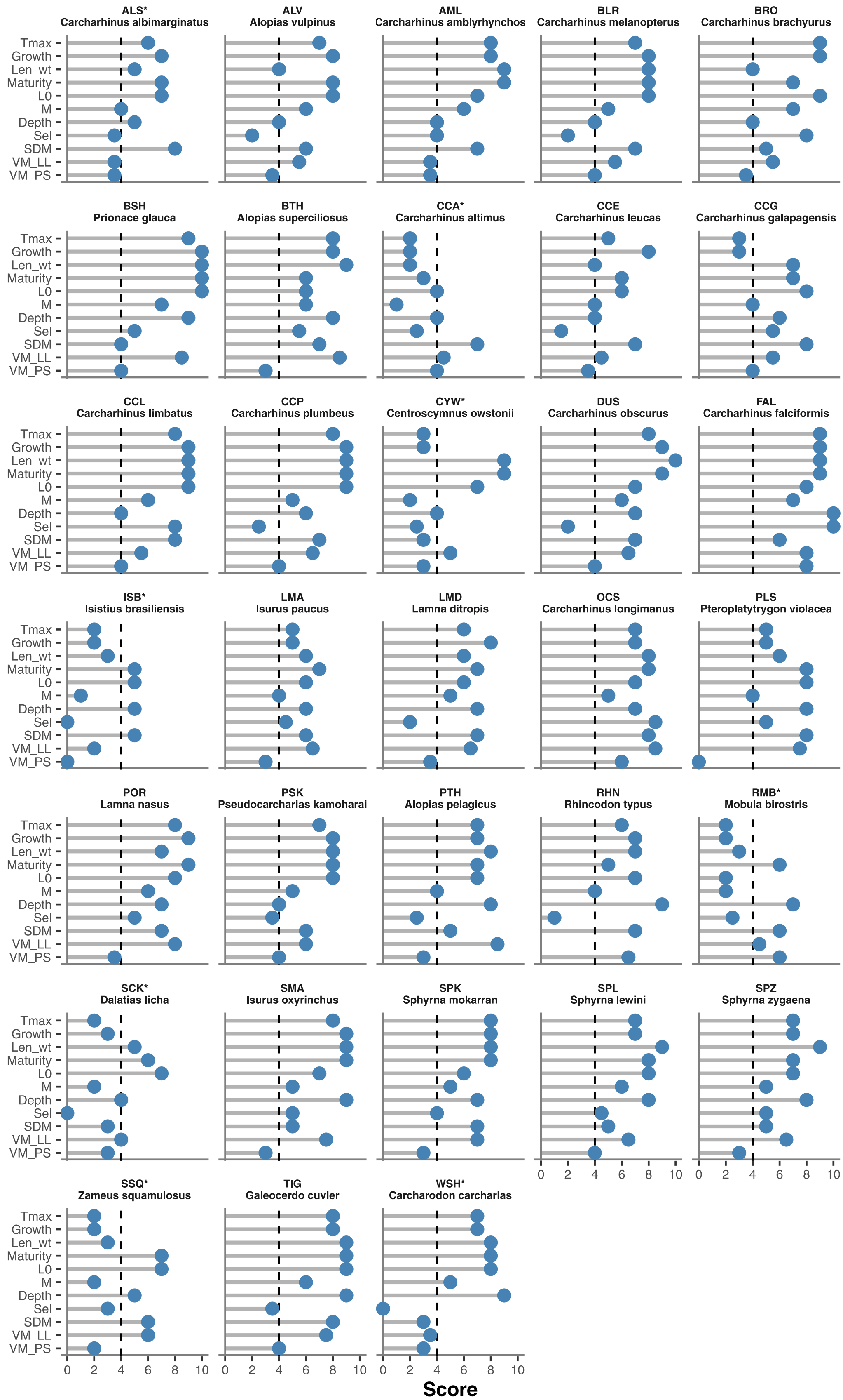

Fig. 6. EASI-Fish data quality scores for sharks in the WCPFC. Those species with * indicates those species considered data deficient with three or more input data sources with a score of less than four. t_{max} = maximum age, len_wt = length-weight, L_0 = length at birth, M = natural mortality, Sel = selectivity, SDM = species distribution model, VM_LL = longline vessel mortality (including at-vessel and post-release mortality), VM_PS = purse seine vessel mortality.

work that has focused on improving the understanding of the vulnerability of sharks to fisheries in the Pacific Ocean. In summary, 13 of 33 species assessed were considered 'least vulnerable', 12 were considered 'most vulnerable' and eight were considered 'data deficient'. This analysis also provides a first or updated compilation of key life history and fisheries information for several data-limited, bycatch species that can be used to identify gaps and prioritise future research. Several explorations and improvements of the EASI-Fish methodology (Griffiths et al., 2019) were also undertaken improving the robustness of this approach for future application.

Species assessed as 'most vulnerable' included several carcharhinids and alopiids that are known to have low productivity, and *Sphyrna* species that also have low productivity and are particularly susceptible to injury and mortality when interacting with fishing gears (Gallagher et al., 2014). Several commonly encountered species were considered 'most vulnerable' including *I. oxyrinchus* and *C. falciformis,* as well as several species that are not regularly recorded by observers in these fisheries such as *C. leucas* and *C. plumbeus* (Peatman and Nicol, 2025). Species with low productivity are unable to sustain high levels of fishing pressure, so in instances where there is high volumetric overlap of these species with fisheries, they are likely to be considered vulnerable by ERA techniques such as EASI-Fish (Griffiths et al., 2022a). *Sphyrna* species are highly susceptible to mortality when interacting with fishing gear and so have high rates of at-vessel and post-release mortality which increases their vulnerability. These results allow identification of species that management could now prioritise for further research or management action, identifying both species commonly encountered and actively managed, and several species not previously considered which may reflect the utility of EASI-Fish, or potential false positives. For example, after several species were assessed to be 'most vulnerable' to fishing in the eastern Pacific Ocean using EASI-Fish, additional research was undertaken to evaluate options for conservation and management measures for silky and hammerhead sharks (e.g., banning of wire traces), and the leatherback sea turtle (e.g., use of only large circle hooks) (Griffiths et al., 2022b; 2023).

Proxy estimates of fishing mortality derived from EASI-Fish for 2022 were broadly consistent with results from existing stock assessments. Although EASI-Fish should not be considered a stock assessment, a comparison of results is useful (Table S7). As part of WCPFC's bycatch management and broader research plan (Brouwer and Hamer, 2025; WCPFC, 2025), stock assessments have been applied to several species. The most recent stock assessments for *P. glauca* (Neubauer et al., 2021; ISC, 2022), *C. longimanus* (Neubauer and Large, 2025), *Rhincodon typus* (Neubauer et al., 2018), *A. superciliosus* (Fu et al., 2018), and *Lamna nasus* (Hoyle et al., 2017) indicate that it is unlikely these stocks were subject to overfishing. Our results similarly concluded that these species were considered 'least vulnerable' in 2022. For *C. longimanus*, EASI-Fish estimates of fishing mortality fell within the bounds of estimates from both stock assessment methods applied which were below or at F_{MSY} (Neubauer and Large, 2025). In contrast, EASI-Fish estimated that *C. falciformis* and *I. oxyrinchus* were 'most vulnerable' in 2022. The recent stock status assessments for *I. oxyrinchus* (Large et al., 2022, ISC, 2024) estimated lower levels of fishing mortality than EASI-Fish, however the model applied in the south Pacific was not considered sufficiently robust to conclude stocks were not subject to overfishing and so it is difficult to compare performance. The recent assessment for *C. falciformis* (Neubauer et al., 2024) however concluded that the stock has not been subject to overfishing since 2010 suggesting our result may be a false positive. Potential reasons for high fishing mortality estimates for *C. falciformis* in EASI-Fish include low productivity inputs, as well as high estimates of at-vessel mortality from purse seine gears (Hutchinson et al., 2015; 2025).

With changes in conservation and management measures that have reduced retention of some shark species, and therefore available input data in recent years, traditional stock assessments are becoming increasingly difficult to apply (Neubauer and Large, 2025). The above comparisons show that EASI-Fish produced similar fishing mortality estimates for most species with existing stock assessments. However, it is not yet clear if EASI-Fish, or other ERA approaches, represent a robust alternative to stock assessments. This would likely require development of a simulation framework where the true abundance and fishing mortality of various populations are known, and the performance of EASI-Fish and other potential approaches could be tested and compared. With an increasing focus on EAFM and the monitoring and assessment of byproduct and bycatch species, there is an increasing desire to develop and implement alternative stock assessment and monitoring approaches, such as ERAs and close-kin mark-recapture which are not as dependent on fishery dependent data. However, practitioners should be mindful that ERAs are primarily a tool for identifying and prioritising potential at-risk species, not necessarily providing quantitative estimates of abundance and resultant management advice that is the objective of more quantitative stock assessments.

Updating the approach of determining spatial overlap reduced overlap estimates, and therefore vulnerability (i.e., fishing mortality). Using the cumulative sum of species distribution model outputs where fishing effort occurs provides a more ecologically appropriate estimate of spatial overlap when compared to the original presence-absence approach, accounting for variability in the abundance of a species throughout its distribution and removing the need to define an arbitrary threshold value for where a species habitat becomes sufficiently suitable to assume presence (Liu et al., 2005). Further, estimating overlap at improved temporal resolutions (i.e. monthly) provides a more accurate representation of where species and fishing effort occur, both of which are highly dynamic in space and time (Brodie et al., 2021; Mannocci et al., 2017). A remaining area of exploration could be to also incorporate the continuous surface of effort into spatial overlap estimates. Currently, effort is still only considered as a presence-absence layer however, like species distribution, it is a heterogeneous surface that varies in space and time. In fisheries where spatially explicit fishing effort data are available, being able to consider effort density spatially could further improve overlap estimates. The updated spatial overlap approach developed also highlights the importance of input data resolution into EASI-Fish. Similar decreases in spatial overlap estimates would also likely occur with higher spatial resolution fishing effort data, particularly longline which is currently reported to WCPFC and IATTC at five-degree resolution (Griffiths and Lezama-Ochoa, 2021).

Understanding species life histories is fundamental to determining their vulnerability to fishing pressure and is a priority of fisheries management. In the process of applying EASI-Fish, information on species growth, natural mortality, maturity and so on were collated, providing an updated summary of information for these species (Clarke et al., 2015; Griffiths et al., 2022a). Uncertainty was present across input parameters for many species, which were often borrowed from other fisheries, ocean basins, or species. Parameters that were uncertain across species included at-vessel and post-release mortality estimates for purse-seine fisheries (Eddy et al., 2016; Gilman et al., 2022; Hutchinson et al., 2015; 2021), and age-based inputs such as growth and natural mortality given the resource intense nature of ageing sharks, and uncertainties with estimation (Harry, 2018; Natanson et al., 2018). Sourcing parameters from different origins can lead to incongruity whereby for example, length at maturity that has been estimated in one study is larger than $L_{\inf}$ estimated from an independent growth study. Another source of uncertainty is the robustness of SDMs given the input data used was largely derived from tropical tuna fisheries and are therefore environmentally biased (Anderson and Gonzalez, 2011; Brodie et al., 2021). As a result, habitats that may be suitable for some species may be underrepresented in the presence data and therefore the resulting SDMs (e.g., temperate species). These data deficiencies emphasise the need for improved biological sampling and monitoring programs for bycatch which will improve the robustness of future assessments.

Where data is absent or lacking, precautionary estimates are often used in their place for ERAs rather than necessarily the most likely value, increasing the likelihood of false positives. For example, a lack of length frequency data for many species meant that a precautionary 'knife-edge' or 'box-shaped' selectivity was required, rather than dome-shaped or logistic curves. This potentially contributed to inflated fishing mortality estimates for several species considered 'most vulnerable' but are rarely encountered by WCPFC fisheries and therefore, may represent false positives. This can also be seen by the reduction in vulnerability estimates from 'olap_cumsum_month' to 'AVM2_PRM2' scenarios whereby best estimates of at-vessel mortality and post-release mortality were used across species rather than assuming a precautionary value of one where no robust species-specific estimate was available. To account for uncertainty in the data, data quality scoring was used to determine that eight species were considered data deficient given large uncertainties in three or more parameters. Those species included several data-limited deepwater species where little information is known, and several large species that are difficult to sample. By excluding these species with large uncertainties, they cannot unduly influence outcomes of this analysis. However, we still do not have a good understanding of these species' vulnerability to tuna fisheries in the WCPO.

EASI-Fish represents an incremental improvement to previous ERA methodologies, addressing several limitations (Grewelle et al., 2021; Hordyk and Carruthers, 2018). EASI-Fish uses an improved quantitative length-based approach that is flexible in utilising a range of data inputs to rapidly and cost-effectively identify species across a range of life histories that are most vulnerable to fishing, which has been a previous challenge for data-limited settings. However, several further improvements could be explored. Firstly, the approach of estimating productivity (i.e. biomass), is not independent of susceptibility (i.e. fishing mortality). A species' vulnerability is determined by comparing its proxy for instantaneous fishing mortality, derived from the susceptibility component of EASI-Fish, against the various reference points derived from yield-per-recruit models. Productivity (i.e. biomass) is then estimated by cross-referencing those same fishing mortality estimates to a spawning biomass-per-recruit curve to extract corresponding biomass estimates. As a result, fishing mortality and biomass estimates are linked and when shown on a phase plot relative to reference points, can only fall in two of four of the grids. For this reason, only estimates of fishing mortality were presented in this analysis. It could be of utility to explore alternate approaches to estimating biomass.

Secondly, EASI-Fish (like other ERA approaches) operates at a coarse resolution which constrains the level of detail in the analysis. ERAs are generally designed to be applied in data-limited settings, and often to many species simultaneously. As a result, they do not incorporate higher resolution information often used in conventional stock assessments and may overlook key factors influencing a species vulnerability to fishing. For example, the approach to estimating susceptibility, and subsequently fishing mortality, is likely unable to consider some relevant parameters such as those related to catchability (e.g. day vs night fishing event, set type) unless they directly influence one of the defined susceptibility parameters (e.g., spatial extent, depth fished). EASI-Fish also only considers and assesses a single year of data. EASI-Fish can be applied repeatedly across years (e.g., Griffiths and Lezama-Ochoa, 2021), however the method itself does not consider time series information (e.g., catch-rate) in determining stock status. Further, the limited nature of the input data means that little would change year-to-year with most input parameters likely to be time invariant (e.g., growth, at-vessel mortality, post-release mortality). For example, given limited data, inputs such as selectivity were estimated by aggregating length data across years (and fisheries in some instances) to establish sample sizes for estimation, hence these values would not change. Similarly, given the coarse spatial scale of effort data (1 ° or 5 °), it is unlikely that this resolution would generate significant between year variability in overlap estimates.

Lastly, EASI-Fish seemed able to identify those species most susceptible to fishing, but not necessarily those species likely subject to the most fishing pressure. Currently, EASI-Fish uses volumetric overlap to inform susceptibility which is an intuitive approach, but a species' susceptibility to fishing gear can often be driven by various factors. For example, *C. falciformis* and *C. longimanus* likely have similar volumetric overlap estimates to many other species in this assessment for purse seine fishing gear, yet seem particularly susceptible to purse seine sets making up the overwhelming majority of shark bycatch, which could be due to differences in their behaviour or ecology (Hutchinson et al., 2019). Given the coarse data inputs and structure of EASI-Fish (and most other ERA methods), various factors that are important to a species susceptibility to fishing such as time of day (i.e., day vs. night) and set type (e.g., anchored vs drifting FAD) are difficult to explicitly consider like they can be in conventional stock assessment techniques. EASI-Fish as it has been applied so far has generally assumed effort and catchability terms in the susceptibility equation to be one given there have been insufficient information across fisheries to enable reasonable estimates to be made (Griffiths et al., 2022a). Incorporation of fisheries dependent information such as encounter rates or catches where available could help to address this issue and improve vulnerability estimates. For example, a proxy for catchability, or rather gear efficiency, could be quantified in data-limited fisheries by estimating the effective area fished by a gear (Griffiths et al., 2007).

This ecological risk assessment does not capture all sources of mortality for assessed species, nor all species encountered by WCPFC fisheries. There are a range of species encountered by WCPFC fisheries, both sharks and other taxa as bycatch. However, either due to the rarity of their interaction, species identification issues, a lack of observer coverage or other reason these species were unable to be considered herein. Of the species assessed, they are also likely subject to other sources of mortality such as artisanal fisheries throughout the Pacific with potentially high catches throughout the Indonesian and Papua New Guinea archipelago, as well as existing uncertain catch estimates from WCPFC fisheries (Peatman and Nicol, 2025; White et al., 2006; White et al., 2020). Many of these species also occur in the eastern Pacific Ocean and are susceptible to IATTC tuna fisheries. Of the species assessed using EASI-Fish across both the eastern and western Pacific (noting changes to methodology) (Griffiths et al., 2022a), nine species were considered 'most vulnerable' in both regions, five 'least vulnerable', and eight with a different status (Table S6). Incorporating cumulative risk and mortality into monitoring and management, by taking account of all sources of mortality, could be considered going forward as well as improving the resolution of data collected via tools such as improved species identification and sampling training, which is ongoing (Park et al., 2019).

From this ERA, several potential courses of management prioritisation are possible. For the carcharhinids considered 'most vulnerable', this is likely in large part due to their underlying high volumetric overlap with tropical tuna fisheries, and their inherent low productivity. Given that some carcharhinids are relatively resilient to interactions with fishing gear (i.e., high post release survival, Gilman et al., 2022), recent management interventions may be sufficient including restricting the use of wire trace and 'shark lines' (WCPFC, 2014), a ban on retention of some species (*C. falciformis, C. longimanus, R. typus*) (WCPFC, 2012a, 2012b, 2013), and best practice handling (WCPFC, 2018b), with recent trends of recovery apparent across some species with stock assessments (Neubauer and Large, 2025). However, recent analysis of the shark fin trade suggests fishing mortality of some species may still be high (Cardenosa et al., 2025). For *Sphyrna* species, they have both low productivity and are known to be susceptible to injury and mortality when interacting with fishing gear (Gallagher et al., 2014). If it is decided management intervention is required, then actions that reduce overlap and interactions with fishing gear would likely be most effective given their high post-release mortality, such as spatial or seasonal closures (Bowlby et al., 2024; Crespo et al., 2024; Griffiths et al., 2023). Some of the species considered most vulnerable in the present study may also represent false positives due to uncertain or precautionary data inputs, and so improved information on input data such as selectivity curves, and at-vessel and post-release mortality may revise current estimates of vulnerability.

This study represents a comprehensive ecological risk assessment of elasmobranchs in WCPO tuna fisheries. It has identified several species that are vulnerable to WCPFC fisheries, collated updated biological information, and helped prioritise species and different data inputs for future research and management attention. This assessment adds to the overall body of work undertaken by the WCPFC in applying an ecosystem approach to fisheries management, alongside periodic stock assessments for the more data-rich species and several recent management interventions that have been aimed at reducing shark bycatch interaction rates, and improving bycatch data collection. It also provides an incremental improvement to the EASI-Fish approach which is being increasingly adopted as an ERA tool across fisheries. Future actions from this assessment could include undertaking research to improve missing or uncertain input parameters, explore potential further management measures that would reduce vulnerability, or further application of this technique to other bycatch species such as teleosts, seabirds and sea turtles.

CRediT authorship contribution statement

Shane Griffiths: Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Simon Nicol:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Valerie Allain:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Nicholas James Hill:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Joanne Potts:** Writing – review & editing, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Cassandra L Rigby:** Writing – review & editing, Methodology, Data curation. **Naiten Bradley Phillip Jr:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2026.107759.

Data availability

The data that has been used is confidential.

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