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Estimating trends and magnitudes of bycatch in the tuna fisheries of the Western and Central Pacific Ocean

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Abstract

Minimising the unintended capture of fish, marine mammals, reptiles, seabirds and other marine organisms is an important component of responsible fisheries management and for stabilising declines and rebuilding populations of threatened species. The analyses presented were designed to establish the first quantitative baseline of historical catches, catch rates and species composition for the dominant tuna fisheries operating in the western and central Pacific, the world's largest in terms of tuna catch. Using records from 612,148 fishing events collected by independent 'at sea' observers, estimates for finfish, billfish, elasmobranchs, marine mammals and sea turtles show that the composition and magnitude of catches varied considerably by fishery type and practice for the period 2003–2019. Simulations indicated that precision in longline estimates would be improved by monitoring a proportion of fishing sets from all fishing trips rather than full coverage from a proportion of all fishing trips. While attributing reasons for temporal trends in estimated bycatch was difficult due to the confounding impacts of changing abundances and fishing practices, the trends identified the nature of potential relationships for species that are not accurately quantified, or not covered, by fishing vessel logbooks. The trends in catch estimates, and the catch rate models, have utility in identifying species which may require targeted additional analyses and management interventions, including species of conservation interest (either due to their threatened status or vulnerability to fishing) such as elasmobranchs and sea turtles. Moreover, the estimates should support future evaluations of the impact of these industrial-scale fisheries on bycatch species.

KEYWORDS
elasmobranch, finfish, observer coverage, sharks, threatened species, turtles

1 | INTRODUCTION

Minimising the unintended capture of fish, marine mammals, reptiles, seabirds and other marine organisms by fishing gear (defined by the term bycatch; Davies et al., 2009) is an important component of responsible fisheries management (FAO, 1995, 2011) and for stabilising declines and rebuilding populations of threatened species (Jennings & Kaiser, 1998). After capture, animals deemed bycatch are typically discarded due to regulatory constraints or for economic reasons; those discarded animals may be either dead or alive (Brooke et al., 2012; Crowder & Murawski, 1998). The ecological impacts of this mortality on the population dynamics of bycatch species are of increasing concern (Kelleher, 2005; Pérez Roda et al., 2019; Sala & Knowlton, 2006), with negative impacts demonstrated at the species, population and ecosystem levels (Hall et al., 2000; Kelleher, 2005; Lewison, Crowder, et al., 2004; Lewison, Freeman, & Crowder, 2004; Read et al., 2006). Unintended capture and mortality has been implicated as a threat to approximately half of global marine mammal and seabird species, the majority of elasmobranch species (Žydelis et al., 2009) and all seven sea turtle species (Wallace et al., 2010). Furthermore, overfishing has been identified as a threat for all elasmobranch species listed as threatened in the International Union for the Conservation of Nature Red List of Threatened Species (hereafter IUCN Red List; Dulvy et al., 2021), and captures of sharks in tuna fisheries has been linked to large declines in oceanic elasmobranch populations (Juan-Jordá et al., 2022; Pacoureau et al., 2021).

Quantifying the magnitude of bycatch is an important first step for prioritising policy making to minimise bycatch (Alverson et al., 1994; Lewison et al., 2005; Pauly et al., 2002). Once an understanding is obtained on the magnitude by taxa, fishery, gear type and region, strategies to monitor and mitigate risks can be developed and implemented (Gilman, 2011; Gilman et al., 2019; Wilcox & Donlon, 2007). However, estimating levels of commercial fisheries bycatch can be challenging due to a lack of observer coverage (Kennelly, 2020; Lewison et al., 2014; Lewison, Freeman, & Crowder, 2004). While reporting by the vessel on the quantity of retained catch of commercially important species is a requirement for many fisheries (FAO, 2020) the requirement to report on discarded (or minor retained) species is often a duty of independent observers (Gilman et al., 2014). Observer coverage rates, however, are typically low and often not representative of the fishery effort (Nicol et al., 2013). Despite such challenges global estimates of bycatch and discarding have been attempted (Gilman et al., 2020; Pérez Roda et al., 2019; Zeller et al., 2018). Comparing across fishery types and regions, these analyses indicate that discarding rates for fisheries targeting tunas and pelagic fish are lower than for other fisheries (Gilman et al., 2020) and that discard rates in the western and central Pacific Ocean are lower in comparison to neighbouring regions and other ocean basins (Zeller et al., 2018).

The global tuna catch in 2020 has been provisionally estimated at just over 4.4 million tonnes, with the fisheries of the western and central Pacific Ocean accounting for 56% of this catch (Williams & Ruaia, 2022). Longline and purse seine fisheries account for 80% of the catch in the western and central Pacific Ocean (Williams & Ruaia, 2022). The stocks of the western and central Pacific Ocean are typically wide ranging and transboundary and are consequently managed by international agreement under the auspices of the Western and Central Pacific Fisheries Commission (WCPFC), which has 26 members, 7 participating territories and 9 co-operating non-members. The longline and purse seine fisheries of these fishing nations that operate in the WCPFC Convention Area (Figure 1) are known to interact with 7 species of sea turtles (Chelonioidea), 35 species of seabird (Procellariiformes, Suliformes, Phaethontiformes, *Stercorariidae*, *Laridae*, *Sternidae*, *Alcidae*), 38 species of marine mammal (Cetacea and Pinnipeds), 61 species of sharks and rays (elasmobranch) and numerous species of non-target finfish (teleosts; Pacific Community Data Holdings). However, the magnitude and temporal trend of these interactions is largely unknown or not accurately quantified.

The Western and Central Pacific Fisheries Commission has required all Purse seine fishing activity undertaken within the area bounded by 20°N and 20°S (excluding trips with fishing activity within the national jurisdiction of a single coastal state) to be independently observed and reported upon since 2010 (WCPFC CMM 2008-01). It has also required that at least 5% of longline fishing activity on vessels >24 m in length is observed since 2012. In practise, coverage rates of available observer data for longline and purse seine fisheries in the WCPFC Convention Area have often been lower than the mandated minimum rates, and in the case of longline fisheries have varied markedly between fleets (Panizza et al., 2022). The observer data were used to estimate catch rates, which were then applied to reported effort data from vessel logbooks to obtain catch estimates for the period 2003 to 2019. Estimates for 2020 and 2021 were not included due to the reduced levels of observer coverage caused by the COVID-19 pandemic. The derived estimates

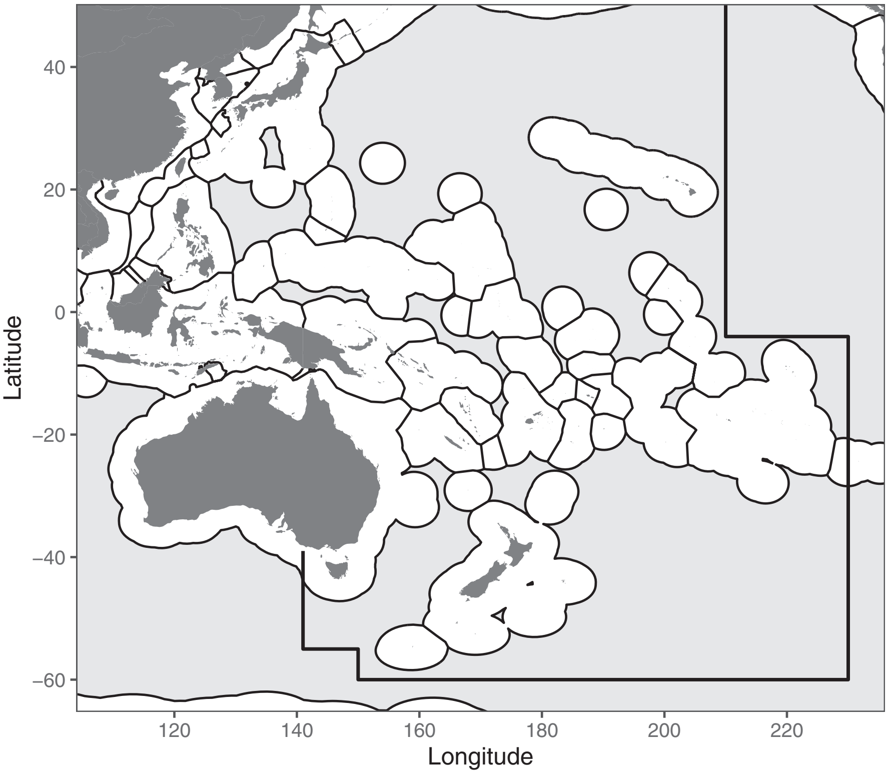


FIGURE 1 The western and central Pacific Ocean. Indicative exclusive economic zone boundaries are provided (white polygons with thin black boundaries), along with the boundary of the WCPFC Convention Area (thick black line).

provide the first whole of jurisdiction analyses on the magnitude and catch trends of bycatch associated with the industrial tuna fisheries operating in the WCPFC Convention Area.

2 | METHODS

2.1 | Data—longline fisheries

The analysed longline observer data set included data from the WCPFC Regional Observer Programme, as well as additional data held by the Pacific Community (SPC). The data set included 184,655 fishing events from 2003 through to 2019, from 10,991 observer trips. Sea surface temperature (SST) was combined with the longline data sets, in order to allow SST to indirectly account for spatial variation in catch rates. SST was taken from the National Oceanic and Atmospheric Administration's Optimum Interpolation Sea Surface Temperature data set (version 2; Reynolds et al., 2002).

The Western and Central Pacific Fisheries Commission's aggregated catch and effort data set provided total hooks deployed, and the numbers of individuals caught for selected tuna and billfish species, for longline fisheries in the WCPFC Convention Area. The aggregated catch and effort data have a resolution of year, month, flag-fleet and 5° grid. The aggregated catch and effort data are based on vessel logbooks, raised to account for incomplete coverage of available logbook data. We refer to this data hereafter as reported catch and effort data. K-means clustering was applied to reported longline catch data, to group longline effort with similar reported species compositions. The clustering analysis was applied to proportions (by number) of albacore (*Thunnus alalunga*, Scombridae), bigeye (*T. obesus*, Scombridae), yellowfin (*T. albacares*, Scombridae), swordfish (*Xiphias gladius*, Xiphiidae) and sharks, with the number of clusters determined by identifying the point of inflection in variance explained as the number of cluster increases. The assigned cluster was used as an explanatory variable in longline catch rate models, allowing apparent targeting behaviour to inform estimated species compositions.

Hooks between floats (HBF) provides a proxy for the fishing depth of a longline set, which is available for both the observer and reported effort data sets, though fishing depths are influenced by a range of other variables (Bigelow et al., 2006). Reported HBF-specific aggregated catch and effort data are available for longline fisheries in the WCPFC Convention Area, with coverage rates of 28% of total effort (hooks) from 2003 to 2006, increasing to 85% for the period 2014 to 2019. We used random forest classification models fitted using the R package 'randomForest' (Liaw & Wiener, 2002) to predict HBF for reported effort data with no HBF information, trained on reported HBF-specific catch and effort (following Ducharme-Barth & Vincent, 2020; Tremblay-Boyer & Neubauer, 2019; Supporting Information). Set depth was inferred from HBF, with a HBF ≤ 10 defined as shallow set and a HBF > 10 defined as deep set, to allow for separation of estimated longline catch estimates by set depth.

2.2 | Data—purse seine fisheries

The analysed purse seine observer data set included data from the WCPFC Regional Observer Programme, as well as additional data held by the Pacific Community. The modelled data set included 427,493 fishing events covering 2003 to 2020, from 17,836 observer trips. Sea surface temperature was combined with the purse seine data sets, in order to allow for SST to indirectly account for spatial variation in catch rates.

The Western and Central Pacific Fisheries Commission's aggregated catch and effort data set provided total sets and catches of selected tuna species for purse seine fisheries operating in the WCPFC Convention Area, which are held at a resolution of year, month, flag-fleet, set type and 1° grid. The aggregated catch and effort data are based on reported data from vessel logbooks, raised to account for incomplete coverage of available logbook data. We refer to this data hereafter as reported catch and effort data. Set types include sets on free schools, and schools associated with anchored fish aggregating devices (FADs), drifting FADs, logs and other natural floating objects, whale sharks (*Rhincodon typus*, Rhincodontidae) and whales (Cetacea). Set type has been demonstrated to have a strong effect on catch rates and compositions in purse seine fisheries (Amandè et al., 2010; Pilling et al., 2015). Intentional setting on schools associated with whales and whale sharks has been prohibited since 2013 (WCPFC CMM 2011-03).

2.3 | Catch estimation groups

Catch estimates were generated for species, or groups of species, referred to as estimation groups. The estimation groups covered all finfish, elasmobranch, marine mammal and sea turtle species with observed captures. Seabird bycatch was not included but separate estimates of captures and mortalities are available (Peatman et al., 2019). Estimation groups were defined separately for longline and purse seine, with consideration of the frequency of observed captures and the likely robustness of species-level identification. Species-specific estimation groups were used where appropriate for species of conservation interest: WCPFC 'key shark species' (WCPFC CMM 2019-04)—blue shark (*Prionace glauca*, Carcharhinidae), silky shark (*Carcharhinus falciformis*, Carcharhinidae), oceanic whitetip shark (*Carcharhinus longimanus*, Carcharhinidae), longfin and shortfin mako shark (*Isurus paucus* and *I. oxyrinchus*, respectively, Lamnidae), thresher sharks (*Alopias* species, Alopiidae), porbeagle shark (*Lamna nasus*, Lamnidae), selected hammerhead sharks (winghead—*Eusphyra blochii*, scalloped—*Sphyrna lewini*, great—*S. mokarran* and smooth—*S. zygaena*, Sphyrnidae) and whale shark; sea turtles; marine mammals. Estimation groups were not mutually exclusive, with for example, species-specific estimation groups for some sea turtles, as well as an estimation group covering other species as well as unspecified sea turtles (sea turtles—Chelonioidea). Observed catches were mapped to estimation groups using the most detailed available taxonomic classification.

2.4 | Longline catch rate and catch estimation

Reported catches from vessel logbooks were used for albacore, bigeye, yellowfin and skipjack tuna (*Katsuwonus pelamis*, Scombridae), and for billfish species, and were assumed to be known without error. For the remaining 34 estimation groups, Generalised Estimating Equations were fitted to observer data and used to model longline catch rates (Table 1). Models were fitted using the R package 'geepack' (Højsgaard et al., 2006) in R v4.1.1 (R Core Team, 2021). Poisson-like error structures were used where possible, with a two-stage delta-lognormal modelling approach implemented where necessary to account for zero-inflation (see Table 1). An 'exchangeable' working correlation structure was assumed, where residuals from observations from the same observer trip are correlated, with a shared correlation parameter for all observer trips. It was not possible to fit models with exchangeable correlation structures for all estimation groups, in which case independence between residuals within trips was assumed (Table 1).

The specification of the Poisson-like models was

$$E\left[Y_{ij}\right] = \mu_{ij} \quad \mathrm{Var}\left[Y_{ij}\right] = \phi\mu_{ij}$$

$$\begin{aligned}\ln\ \mu_{ij} = {} & \ln\left(\mathrm{thooks}_{ij}\right) + \beta_0 + \beta_1\mathrm{cluster}_{ij} + \beta_2\mathrm{flag}_{ij} \\ & + f_1\left(\mathrm{year}_{ij}\right) + f_2\left(\mathrm{HBF}_{ij}\right) + f_3\left(\mathrm{SST}_{ij}\right)\end{aligned}$$

where subscripts *i* and *j* refer to observer trip and set number, respectively, Y_{ij} denotes observed catch rate (individuals per thousand hooks), f_n represent natural cubic splines and ϕ is a variance inflation parameter. Explanatory variables included: categorical variables for flag (flag_{ij}), and the species composition cluster from reported catch data ($\mathrm{cluster}_{ij}$); year (year_{ij}), included as a cubic spline to prevent overfitting to temporal variation, and, sea surface temperature (SST_{ij}; Reynolds et al., 2002) and hooks between floats (HBF_{ij}), included as cubic splines to account for potentially non-linear relationships with catch rates.

For the delta-lognormal modelling approach, the specification of the presence–absence model was

$$E\left[P_{ij}\right] = \gamma_{ij} \quad \mathrm{Var}\left[P_{ij}\right] = \phi\gamma_{ij}\left(1 - \gamma_{ij}\right)$$

$$\ln\left(\frac{\gamma_{ij}}{1 - \gamma_{ij}}\right) = \beta_0 + \beta_1\mathrm{cluster}_{ij} + \beta_2\mathrm{flag}_{ij} + f_1\left(\mathrm{year}_{ij}\right) + f_2\left(\mathrm{HBF}_{ij}\right) + f_3\left(\mathrm{SST}_{ij}\right)$$

where P_{ij} denotes whether individuals of the estimation group were present/absent in observed catches from observer trip *i* and set *j*. The catch-when-present component of the delta-lognormal modelling approach was specified as

$$E\left[N_{ij}\right] = \eta_{ij} \quad \mathrm{Var}\left[N_{ij}\right] = \phi\sigma^2$$

$$\ln\left(\eta_{ij}\right) = \beta_0 + \beta_1\mathrm{cluster}_{ij} + \beta_2\mathrm{flag}_{ij} + f_1\left(\mathrm{year}_{ij}\right) + f_2\left(\mathrm{HBF}_{ij}\right) + f_3\left(\mathrm{SST}_{ij}\right)$$

where N_{ij} denotes the observed catch rate (numbers per '000 hooks). The estimated mean catch rate for the delta-lognormal models, ζ_{ij}, is then $\zeta_{ij} = \gamma_{ij}\,\eta_{ij}$.

Estimates of catch were generated at a resolution of year, SST, HBF, catch composition cluster, flag and region, where region was defined as 'north' (≥10°N), 'tropical' (≥10°S and <10°N) and 'south' (<10°S). SSTs were mean monthly values per 5° grid (Reynolds

TABLE 1 Estimation groups for longline catches and their corresponding species type, estimation approach and assumed correlation structures (ind. = indendence, exch. = exchangeable).

Common name	Scientific name	Species type	Estimation approach	Correlation structure
Skipjack	*Katsuwonus pelamis*	Tropical tuna & albacore	Reported catches	–
Albacore	*Thunnus alalunga*	Tropical tuna & albacore	Reported catches	–
Yellowfin	*Thunnus albacares*	Tropical tuna & albacore	Reported catches	–
Bigeye	*Thunnus obesus*	Tropical tuna & albacore	Reported catches	–
Wahoo	*Acanthocybium solandri*	Other finfish	Delta-lognormal	ind.—exch.
Lancetfishes	*Alepisauridae*	Other finfish	Poisson	exch.
Longsnouted lancetfish	*Alepisaurus ferox*	Other finfish	Delta-lognormal	exch.—exch.
Pomfrets	*Bramidae*	Other finfish	Delta-lognormal	exch.—exch.
Mahi mahi	*Coryphaena hippurus*	Other finfish	Delta-lognormal	exch.—ind.
Escolars	*Gempylidae*	Other finfish	Delta-lognormal	exch.—exch.
Lampriformes nei	Lampriformes	Other finfish	Poisson	exch.
Opah	*Lampris guttatus*	Other finfish	Delta-lognormal	exch.—exch.
Sunfish	*Molidae*	Other finfish	Poisson	exch.
Slender sunfish	*Ranzania laevis*	Other finfish	Delta-lognormal	exch.—ind.
Scombrids	*Scombridae*	Other finfish	Delta-lognormal	exch.—exch.
Great barracuda	*Sphyraena barracuda*	Other finfish	Delta-lognormal	ind.—exch.
Barracudas	*Sphyraenidae*	Other finfish	Poisson	exch.
Marine fishes	*Teleosts*	Other finfish	Delta-lognormal	exch.—ind.
Indo-Pacific sailfish	*Istiophorus platypterus*	Billfish	Reported catches	–
Black marlin	*Makaira indica*	Billfish	Reported catches	–
Blue marlin	*Makaira nigricans*	Billfish	Reported catches	–
Shortbill spearfish	*Tetrapturus angustirostris*	Billfish	Reported catches	–
Striped marlin	*Tetrapturus audax*	Billfish	Reported catches	–
Swordfish	*Xiphias gladius*	Billfish	Reported catches	–
Bigeye thresher	*Alopias superciliosus*	Elasmobranchs	Delta-lognormal	ind.—exch.
Thresher sharks	*Alopiidae*	Elasmobranchs	Delta-lognormal	exch.—ind.
Silky shark	*Carcharhinus falciformis*	Elasmobranchs	Delta-lognormal	exch.—ind.
Oceanic whitetip shark	*Carcharhinus longimanus*	Elasmobranchs	Delta-lognormal	exch.—ind.
Elasmobranchs	Elasmobranchii	Elasmobranchs	Delta-lognormal	exch.—exch.
Shortfin mako	*Isurus oxyrhinchus*	Elasmobranchs	Poisson	exch.
Longfin mako	*Isurus paucus*	Elasmobranchs	Poisson	exch.
Mako sharks	*Isurus* spp	Elasmobranchs	Poisson	exch.
Porbeagle shark	*Lamna nasus*	Elasmobranchs	Delta-lognormal	ind.—ind.
Mobulid rays	*Mobulidae*	Elasmobranchs	Poisson	exch.
Blue shark	*Prionace glauca*	Elasmobranchs	Delta-lognormal	ind.—exch.
Pelagic stingray	*Pteroplatytrygon violacea*	Elasmobranchs	Delta-lognormal	exch.—exch.
Hammerhead sharks	*Sphyrnidae*	Elasmobranchs	Delta-lognormal	exch.—exch.
Marine mammals	Cetacea & pinnipeds	Marine mammals	Poisson	exch.
Loggerhead turtle	*Caretta caretta*	Sea turtles	Poisson	exch.
Green turtle	*Chelonia mydas*	Sea turtles	Poisson	exch.
Sea turtles	*Chelonioidea*	Sea turtles	Poisson	ind.
Leatherback turtle	*Dermochelys coriacea*	Sea turtles	Poisson	exch.
Hawksbill turtle	*Eretmochelys imbricata*	Sea turtles	Poisson	exch.
Olive ridley turtle	*Lepidochelys olivacea*	Sea turtles	Poisson	exch.

Note: Correlation structures for delta-lognormal models are provided for the delta component, then the lognormal component. Rows are ordered by species type and then alphabetically by scientific name.

et al., 2002), rounded to the nearest ⅓°C to reduce the number of strata. For each catch rate model, 1000 random draws of parameters were taken from the multivariate normal distribution defined by the vector of mean parameter values $\boldsymbol{\beta}$ and their covariance matrix $\boldsymbol{\Sigma}$, $N_k(\boldsymbol{\beta}, \boldsymbol{\Sigma})$, where k is the number of estimated parameters. The random draws of parameter values were then used to generate 1000 estimated catch rates for each record of effort. Estimated catches were then obtained by taking the product of the catch rates and the effort. Porbeagle shark catch rates and catches were estimated using data south of 20°S as the species is likely absent north of this latitude in the Pacific Ocean (Francis et al., 2008). The unit of estimated longline catch was individuals for all estimation groups, that is the unit used by observers when recording the catch.

2.5 | Purse seine catch rate and catch estimation

Reported catches from vessel logbooks were used for skipjack, yellowfin and bigeye tuna. For the remaining 45 estimation groups (Table 2), observer data were used to estimate catch rates for unobserved sets. Presence/absence models were fitted to observer data using Generalised Estimating Equations using the R package ‘geepack’ (Højsgaard et al., 2006) in R v4.1.1 (R Core Team, 2021). A quasi-binomial error structure was assumed, with a logit link function. An ‘exchangeable’ working correlation structure was used for all models. Explanatory variables included in the models were: cubic splines for year (year_{ij}) and sea surface temperature (SST_{ij}—Reynolds et al., 2002); a categorical variable for quarter (quarter_{ij}—Jan to Mar, Apr to Jun, Jul to Sep and Oct to Dec); a categorical variable for set type (type_{ij}—free school, log, whale, whale shark, anchored FAD and drifting FAD), and, a categorical variable for vessel flag (flag_{ij}).

The specification of the presence/absence models was:

$$E\left[P_{ij}\right] = \gamma_{ij} \quad \text{Var}\left[P_{ij}\right] = \phi\gamma_{ij}\left(1-\gamma_{ij}\right)$$

$$\ln\left(\frac{\gamma_{ij}}{1-\gamma_{ij}}\right) = \beta_0 + \beta_1\text{quarter}_{ij} + \beta_2\text{type}_{ij} + \beta_3\text{flag}_{ij} + f_1\left(\text{year}_{ij}\right) + f_2\left(\text{SST}_{ij}\right)$$

where subscripts i and j refer to observer trip and set number, respectively, P_{ij} denotes whether captures of the estimation group were observed, f_n represent natural cubic splines and ϕ is a variance inflation parameter.

The fitted presence/absence models were used to estimate the probability of presence for a given estimation group and strata, with strata defined as combinations of year, quarter, flag and set type. Sea surface temperature was set at the catch-weighted mean for each strata. Uncertainty in the presence/absence of catch was generated by taking 1000 random draws of parameters from the multivariate normal distribution defined by the vector of mean parameter values $\boldsymbol{\beta}$ and their covariance matrix $\boldsymbol{\Sigma}$, $N_k(\boldsymbol{\beta}, \boldsymbol{\Sigma})$. The random draws of parameter values were then used to generate 1000 estimates of the probability of presence for each strata.

Attempts to model catch when present were unsuccessful, with covariates explaining minimal variation in catch volumes and clear violation of model assumptions. Instead, the volume of catch when present was estimated by taking 1000 bootstrap samples from sets with observed captures, stratified by set type. 1000 estimates of the overall catch rate were then obtained for each estimation group and strata by taking the product of the probability of presence and the volume of catch when present. The estimated catch rates were then applied to the number of unobserved sets in each strata, to calculate unobserved catch. The estimates of unobserved catch were then combined with recorded catch from observed sets to give estimates of total catch.

The unit of estimated purse seine catch varied between estimation groups (Table 2), with individuals used for billfish, elasmobranchs, marine mammals and sea turtles, and metric tonnes used for finfish. These catch units were most commonly used by observers when recording purse seine catch volumes of the respective species and were considered to provide the most accurate data set of observed catch volumes.

For strata where observed sets exceeded those reported in logbook data, we drew random samples without replacement from the observer data set such that the effective number of observed sets matched the number of reported sets. Whale and whale shark-associated sets are recorded more frequently by observers than in vessel logbook data (Neubauer et al., 2018). To mitigate downwards bias in catch estimates, whale and whale shark sets were treated as free school sets when estimating catch rates and catches of whale sharks and marine mammals, both in the observer and reported effort data set.

2.6 | Coverage of catch estimates

The catch estimates cover longline and purse seine fishing in the WCPFC Convention Area (Figure 1), including the region overlapping the Inter-American Tropical Tuna Commission Convention Area. The estimates do not cover domestic longline and purse seine fisheries of the Philippines, Vietnam and Indonesia, and purse seiners operating in temperate waters off Japan and New Zealand, due to limited representative observer data in Pacific Community data holdings. Additionally, former shark-targeted longline fisheries in the exclusive economic zones of Papua New Guinea and the Solomon Islands were not included, as these fisheries are also not contained within the reported effort data held by the Pacific Community. Purse seine fisheries covered by our analysis contributed 86% of total reported purse seine catch of skipjack, yellowfin and bigeye in the WCPFC Convention Area for the period 2003–2019. Longline fisheries covered by our analysis accounted for 88% of total reported longline catch of albacore, yellowfin and bigeye in the WCPFC Convention Area over the same period.

2.7 | Post-processing of catch estimates

Estimated catches were summed across relevant strata to obtain estimates at more aggregated resolutions, for example, annual totals. Estimates of total catch were generated for different ‘species types’

TABLE 2 Estimation groups for purse seine catches and their corresponding species type and catch unit (ordered by species type and then alphabetically by scientific name).

Common name	Scientific name	Species type	Catch unit
Skipjack	*Katsuwonus pelamis*	Tropical tuna	Tonnes
Yellowfin	*Thunnus albacares*	Tropical tuna	Tonnes
Bigeye	*Thunnus obesus*	Tropical tuna	Tonnes
Wahoo	*Acanthocybium solandri*	Other finfish	Tonnes
Frigate & bullet tunas	*Auxis thazard & A. rochei*	Other finfish	Tonnes
Oceanic triggerfish	*Balistidae*	Other finfish	Tonnes
Pomfrets	*Bramidae*	Other finfish	Tonnes
Carangids	*Carangidae*	Other finfish	Tonnes
Trevallies	*Caranx* spp	Other finfish	Tonnes
Mahi mahi	*Coryphaena hippurus*	Other finfish	Tonnes
Mackerel scad	*Decapturus macarellus*	Other finfish	Tonnes
Rainbow runner	*Elagatis bipinnulata*	Other finfish	Tonnes
Kawakawa	*Euthynnus affinis*	Other finfish	Tonnes
Golden trevally	*Gnathanodon speciosus*	Other finfish	Tonnes
Sea chubs	*Kyphosidae*	Other finfish	Tonnes
Triple-tail	*Lobotes surinamensis*	Other finfish	Tonnes
Sunfish	*Molidae*	Other finfish	Tonnes
Filefishes	*Monacanthidae*	Other finfish	Tonnes
Batfishes	*Platax* spp.	Other finfish	Tonnes
Scombrids	*Scombridae*	Other finfish	Tonnes
Amberjacks	*Seriola* spp.	Other finfish	Tonnes
Barracudas	*Sphyraenidae*	Other finfish	Tonnes
Marine fishes	*Teleosts*	Other finfish	Tonnes
Albacore	*Thunnus alalunga*	Other finfish	Tonnes
Billfishes	*Istiophoridae & Xiphiidae*	Billfish	Individuals
Indo-Pacific sailfish	*Istiophorus platypterus*	Billfish	Individuals
Black marlin	*Makaira indica*	Billfish	Individuals
Blue marlin	*Makaira nigricans*	Billfish	Individuals
Short-billed spearfish	*Tetrapturus angustirostris*	Billfish	Individuals
Striped marlin	*Tetrapturus audax*	Billfish	Individuals
Swordfish	*Xiphias gladius*	Billfish	Individuals
Thresher sharks	*Alopiidae*	Elasmobranchs	Individuals
Silky shark	*Carcharhinus falciformis*	Elasmobranchs	Individuals
Oceanic whitetip shark	*Carcharhinus longimanus*	Elasmobranchs	Individuals
Elasmobranchs	Elasmobranchii	Elasmobranchs	Individuals
Mako sharks	*Isurus* spp.	Elasmobranchs	Individuals
Mobulid rays	*Mobulidae*	Elasmobranchs	Individuals
Blue shark	*Prionace glauca*	Elasmobranchs	Individuals
Pelagic stingray	*Pteroplatytrygon violacea*	Elasmobranchs	Individuals
Whale shark	*Rhincodon typus*	Elasmobranchs	Individuals
Hammerhead sharks	*Sphyrnidae*	Elasmobranchs	Individuals
Marine mammals	Cetacea & pinnipeds	Marine mammals	Individuals
Loggerhead turtle	*Caretta caretta*	Sea turtles	Individuals
Green turtle	*Chelonia mydas*	Sea turtles	Individuals
Sea turtles nei	*Chelonioidea*	Sea turtles	Individuals
Leatherback turtle	*Dermochelys coriacea*	Sea turtles	Individuals
Hawksbill turtle	*Eretmochelys imbricata*	Sea turtles	Individuals
Olive ridley turtle	*Lepidochelys olivacea*	Sea turtles	Individuals

to facilitate comparisons of catch compositions and catch rates, that is tropical tuna (skipjack, bigeye and yellowfin), billfish, other finfish species, elasmobranchs, marine mammals and sea turtles (Tables 1 and 2). Estimates were combined across estimation groups by assuming that estimation group catch estimates were independent. Summary statistics were then computed, using the 2.5 and 97.5 percentiles to generate 95% confidence intervals.

2.8 | Precision of estimated longline catch rates at differing levels of monitoring coverage

Simulations were used to explore the precision of estimated longline catch rates at differing levels of fisheries observer coverage, using a stratified sub-sampling approach similar to Lawson (2004; Supporting Information). There are a range of options available for allocating electronic and/or observer monitoring coverage within a longline fleet. Two approaches were used: a target coverage rate of 5%, 10% or 20% of trips, with full coverage of sets within a trip, and, partial coverage of all trips, with a target coverage rate of 10%, 20% or 50% of sets for each trip.

Simulations were undertaken separately for two broad regions within the WCPFC Convention Area: the area from 10°S to 30°S, primarily vessels targeting albacore tuna, and the area from 10°S to 20°N, primarily vessels targeting yellowfin and/or bigeye tuna. Eleven species were selected for each region, covering a range of species including target species, bycatch species and species of conservation interest.

3 | RESULTS

3.1 | Estimation of hooks between float (HBF) for reported longline effort data

The accuracy of the predictive model of HBF was considered adequate. HBF was estimated with a classification accuracy of 66% for the testing data set and predictions accurate to ± one HBF class for 91% of records in the testing data set (Table S1). Uncertainty in the overall proportions of inferred shallow set and deep set effort was lower for 2007 onwards, when HBF information was more widely available in reported longline effort data.

3.2 | Patterns in reported effort and observer data coverage

Total reported longline effort in the WCPFC Convention Area averaged 800 million hooks per year from 2003 to 2006, increasing to 1010 million hooks in 2012, before returning to an average of 840 million hooks per year from 2013 to 2019 (Table S2). The estimated temporal trend in deep set effort (>10 HBF) from 2003 to 2012 was similar to that for total effort, though with deep set effort levels from 2016 onwards demonstrating an increasing trend. Shallow set (≤10 HBF) effort levels averaged 160 million hooks per year from 2003 to 2006, increasing to 240 million hooks per year from 2007 to 2012. Shallow set effort levels then decreased to an average of 110 million hooks per year from 2013 onwards, with a weak declining trend in effort levels over this time period.

Longline observer coverage over the whole Convention Area was relatively consistent at approximately 1% from 2003 to 2010 (Figure S1), with coverage rates defined as the proportion of hooks from sets with available observer data. Observer coverage increased from 2011 onwards, exceeding 5% in 2018 and 2019. Longline fishing effort was deployed widely throughout the WCPFC Convention Area from 2003 to 2019 (Figure S2). However, observer coverage was not distributed evenly across the WCPFC Convention Area over the same period, for example with higher coverage rates in the region around Hawaii, and generally lower rates in the north-west Pacific (Figure S3). Observer coverage was more widespread from 2015 to 2019 (Figure S3).

Reported sets by the large-scale equatorial purse seine fishery in the WCPFC Convention Area increased from 2003 (33,200 sets) through to 2010 (53,600 sets), before stabilising at 50,000–60,000 sets per year from 2010 to 2019 (Table S2). The number of sets on logs and anchored FADs decreased from 2003 to 2019 by 86 and 30%, respectively, with increases in the number of free school sets (115%) and sets on drifting FADs (265%) over the same period. The number of reported sets on schools associated with whales varied between 85 and 305 sets per year from 2010 to 2019. Between 1 and 52 sets were reported on schools associated with whale sharks over the same period.

Annual rates of observer coverage of the large-scale equatorial purse seine fishery averaged 17% from 2003 to 2009, with coverage rates defined as the proportion of reported sets with available observer data (Figure S1). Observer coverage rates increased in 2010, with observer data available for an average of two-thirds of reported sets from 2010 through to 2019. Observer coverage has been spatially distributed relatively evenly, particularly from 2010 onwards (Figures S4 and S5). Observer coverage pre-2010 was relatively low for free school sets compared to coverage rates of associated sets (Figure S6).

3.3 | Longline catch, catch rates and composition

The estimated catch composition of modelled longline fisheries in the WCPFC Convention Area from 2003 to 2019 was dominated by tropical tunas and albacore, representing 67% of the catch by numbers (Figure 2). Elasmobranchs and billfish accounted for 11% and 5% of the total catch by number. Other finfish (teleost) species accounted for 17% of the total catch by numbers. Total catches of sea turtles and marine mammals represented c. 0.1% and 0.01% of total catch by numbers, respectively.

Estimation group specific catches are provided in Supporting Information (Figures S7–S10). Excluding tropical tunas, albacore and billfish, the finfish estimation groups with the highest estimated catch were mahi mahi (*Coryphaena hippurus*, Coryphaenidae; 27% of finfish catch excluding tropical tunas, albacore and billfish),

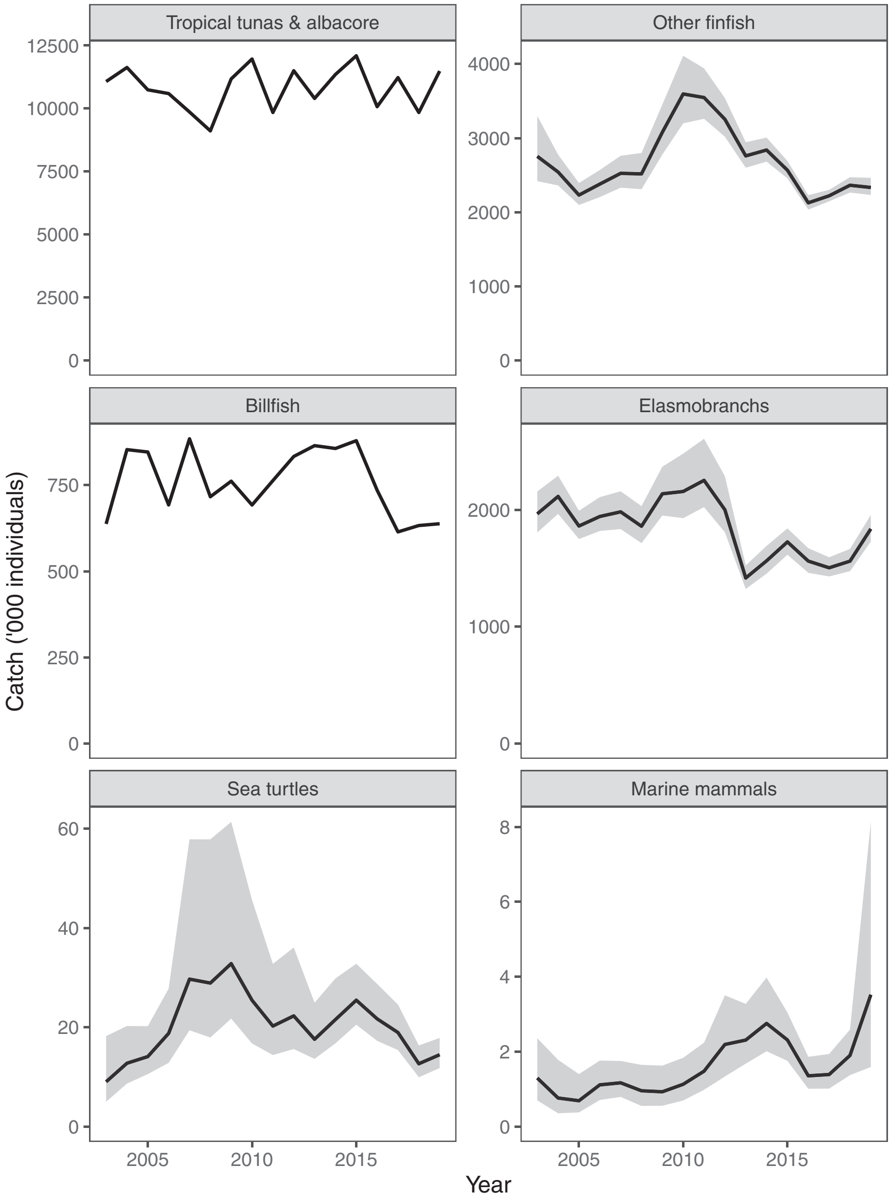


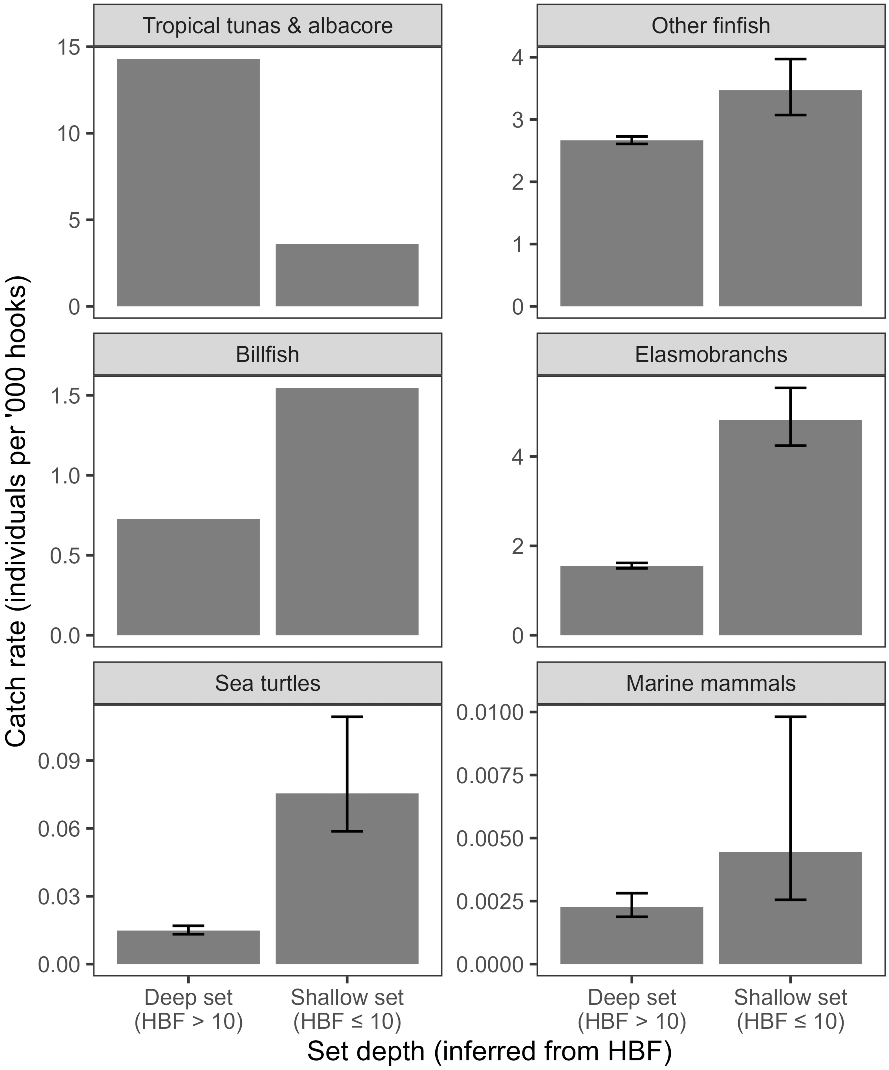
FIGURE 2 Total estimated annual catch ('000 individuals; grey region provides 95% CIs) of longline fisheries in the WCPFC Convention Area by species type (see Table 1). Estimated catches do not cover domestic fisheries of the Philippines, Vietnam and Indonesia and former shark-targeted fisheries in the exclusive economic zones of Papua New Guinea and the Solomon Islands. Reported catches were used where available, covering tropical tuna, albacore and billfish and were assumed to be known without error.

escolars (Gempylidae; 17%), longsnouted lancetfish (*Alepisaurus ferox*, Alepisauridae; 13%) and lancetfishes (Alepisauridae; 9%), wahoo (*Acanthocybium solandri*, Scombridae; 11%) and pomfrets (Bramidae, 6%). Billfish catch from 2003 to 2019 was dominated by swordfish (41% of total billfish catch), blue marlin (*Makaira nigricans*, Istiophoridae; 37%) and striped marlin (*Tetrapturus audax*, Istiophoridae; 10%). The five elasmobranch species with the highest estimated catches were blue shark (55% of total elasmobranch catch), pelagic stingray (*Pteroplatytrygon violacea*, Dasyatidae; 13%), silky shark (12%), shortfin mako shark (6%) and oceanic whitetip shark (3%). Estimated sea turtle catch was predominantly accounted for by olive ridley (*Lepidochelys olivacea*, Cheloniidae; 52% of sea turtle catch), loggerhead (*Caretta caretta*, Cheloniidae; 15%) and green turtles (*Chelonia mydas*, Cheloniidae; 13%), with lower proportions of leatherback (*Dermochelys coriacea*, Dermochelyidae; 6%) and hawksbill turtles (*Eretmochelys imbricata*, Cheloniidae; 5%). Proportions of sea turtle catches accounted for by species-level estimation groups were highest from 2007 to 2013, and lowest at the beginning and the end of the time series.

Estimated longline catch compositions and catch rates varied by set depth as inferred from HBF (Figure 3). Catch rates of tropical tunas and albacore were higher for deep sets than shallow sets, whereas catch rates of billfish, other finfish species, elasmobranchs, marine mammals and sea turtles were highest for shallow sets.

The estimated annual longline catch of finfish, excluding tropical tunas and albacore, decreased from 2003 through to 2005, then increased to a peak of 3.6 million individuals in 2010, before declining again through to 2016 (Figure 2). The temporal trends in estimated catches varied between finfish taxa (Figure S7), with the trend generally driven both by the year effects of the catch rate models, as well as the combination of the HBF effects and the volumes of hooks-between-float specific effort. For example, the temporal trends for estimated mahi mahi were more influenced by shallow

FIGURE 3 Estimated average catch rates (individuals per '000 hooks with 95% CIs) for longline fisheries in the WCPFC Convention Area from 2015 to 2019 for deep and shallow sets (based on hooks between floats, HBF), by species type (see Table 1). Estimated catch rates do not cover domestic fisheries of the Philippines, Vietnam and Indonesia and former shark-targeted fisheries in the exclusive economic zones of Papua New Guinea and the Solomon Islands. Reported catch and effort from hook-between-floats specific aggregated data were used to calculate catch rates for tropical tuna, albacore and billfish.



set effort levels, along with the year effects of the delta-lognormal models, whereas estimated catches for pomfrets were more influenced by the deep set effort levels. Longline catches of billfish were variable from 2003 to 2010, then increased through to 2015 before decreasing (Figure 2). Estimated longline catches of elasmobranchs averaged 1.95 million individuals from 2003 to 2008, increasing to 2.15 million individuals from 2009 to 2012 driven by silky shark and pelagic stingray, before decreasing to an average of 1.6 million individuals from 2013 onwards (Figure 2 and Figure S9). The temporal trend in blue shark displayed a decreasing trend reflecting the year effect of the presence–absence model (Figure S9). Estimated catches of oceanic whitetip shark displayed a stronger declining trend through time, with an increase from 2018 to 2019, driven by the year effects in the presence–absence model (Figure S9). Estimated catches of shortfin mako shark were relatively stable until 2014, before declining sharply from 2014 to 2016 again driven by year effects (Figure S9). Estimated longline catches of sea turtles increased from 2003 (9000 individuals) to 2009 (33,000 individuals), before displaying a generally declining trend from 2009 through to 2019 (Figure 2), largely driven by olive ridley catch (Figure S10). However, estimated catches of loggerhead, green and leatherback turtles did display increasing trends in the early 2010s driven by their respective year effects, though confidence intervals of estimates were broad. Marine mammal catches were imprecise making identification of trends difficult, though catches were elevated from 2012 to 2015 (Figure 2).

3.4 | Purse seine catch, catch rates and composition

The estimated catch composition of modelled purse seine fisheries in the WCPFC Convention Area from 2003 to 2019 was dominated by tropical tunas (Figure 4), though direct comparison of catches is complicated by the differing units of catches between species types (Table 2). Estimation group specific catches are provided in Supporting Information (Figures S11–S14). Excluding tropical tunas and billfish, estimated finfish catch was dominated by rainbow runner (*Elagatis bipinnulata*, Carangidae; 44% of total finfish catch excluding tropical tunas and billfish), mackerel scad (*Decapturus macarellus*, Carangidae; 20%), oceanic triggerfish (Balistidae; 10%) and mahi mahi (6%). Estimated catches of billfish were predominantly

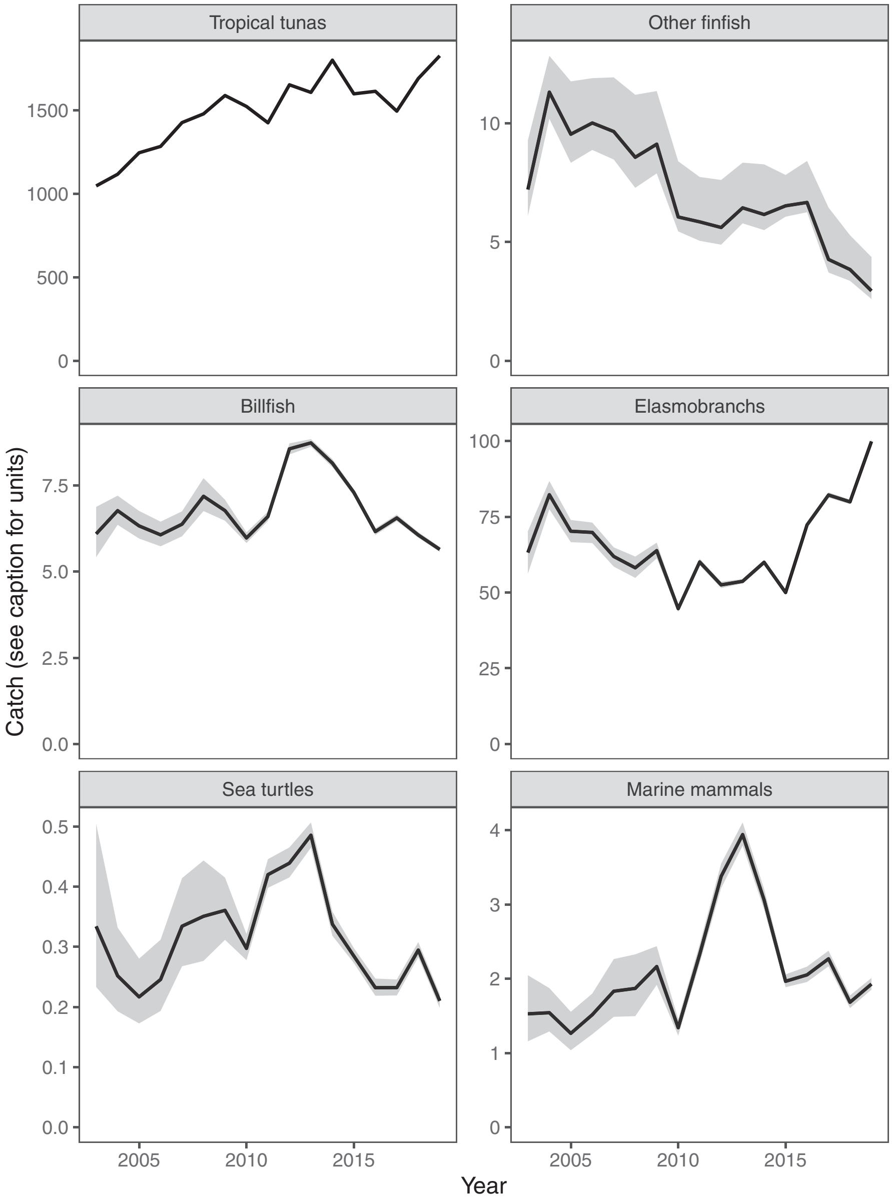


FIGURE 4 Total estimated annual catch (grey region provides 95% CIs) of the large-scale equatorial purse seine fishery in the WCPFC Convention Area by species type (see Table 2). Catch units are '000 tonnes for tropical tuna and other finfish, and '000 individuals for elasmobranchs, sea turtles and marine mammals. Estimated catches do not cover domestic fisheries of the Philippines, Vietnam and Indonesia and purse seiners operating in temperate waters off Japan and New Zealand. Reported catches were used for tropical tuna and assumed to be known without error.

accounted for by blue marlin (53% of total billfish catch), black marlin (*Makaira indica*, Istiophoridae; 25%), striped marlin (11%) and Indo-Pacific sailfish (*Istiophorus platypterus*, Istiophoridae; 7%). Estimated catches of elasmobranchs were dominated by silky shark (89% of total elasmobranch catch) with a range of estimation groups providing lower catch proportions, including mobulid rays (Mobulidae; 5%), oceanic whitetip shark (1.3%) and whale shark (0.66%). Estimated catches of sea turtles were relatively low, with green (25% of total sea turtle catch), olive ridley (24%), loggerhead (21%) and hawksbill turtles (16%) dominating. Catches of sea turtles (unspecified) were relatively common at the beginning of the time series.

Estimated purse seine catch compositions, and catch rates, varied between association types with the highest catch rates of tropical tunas on drifting FADs (Figure 5). Relative to the other school association types, anchored FAD sets had high catch rates of 'other finfish' (i.e. not tropical tunas), and relatively low catch rates of billfish and elasmobranchs. Drifting FAD sets had relatively high catch rates of elasmobranchs and billfish, and low catch rates of 'other finfish'. Log sets had the highest catch rates of elasmobranchs, billfish, 'other finfish' and marine mammals. Free school sets had the lowest catch rates of 'other finfish', billfish, elasmobranchs, marine mammals and low catch rates of turtles. Sets on schools associated with whales and whale sharks both had low catch rates of 'other finfish' and relatively high catch rates of billfish and elasmobranchs. Sets on schools associated with whale sharks had the highest catch rates of turtles.

The estimated annual purse seine catch of finfish, excluding tropical tunas and billfish, displayed a generally decreasing trend from 2003 to 2019 (Figure 4). There were declining trends in estimated catches for a number of finfish estimation groups, including rainbow runner, oceanic triggerfish and mahi mahi, driven both by declining trends in year effects as well as increases in the proportions of free school sets. The year effects of finfish presence–absence displayed a declining trend for wahoo for 2003–2019, though this was

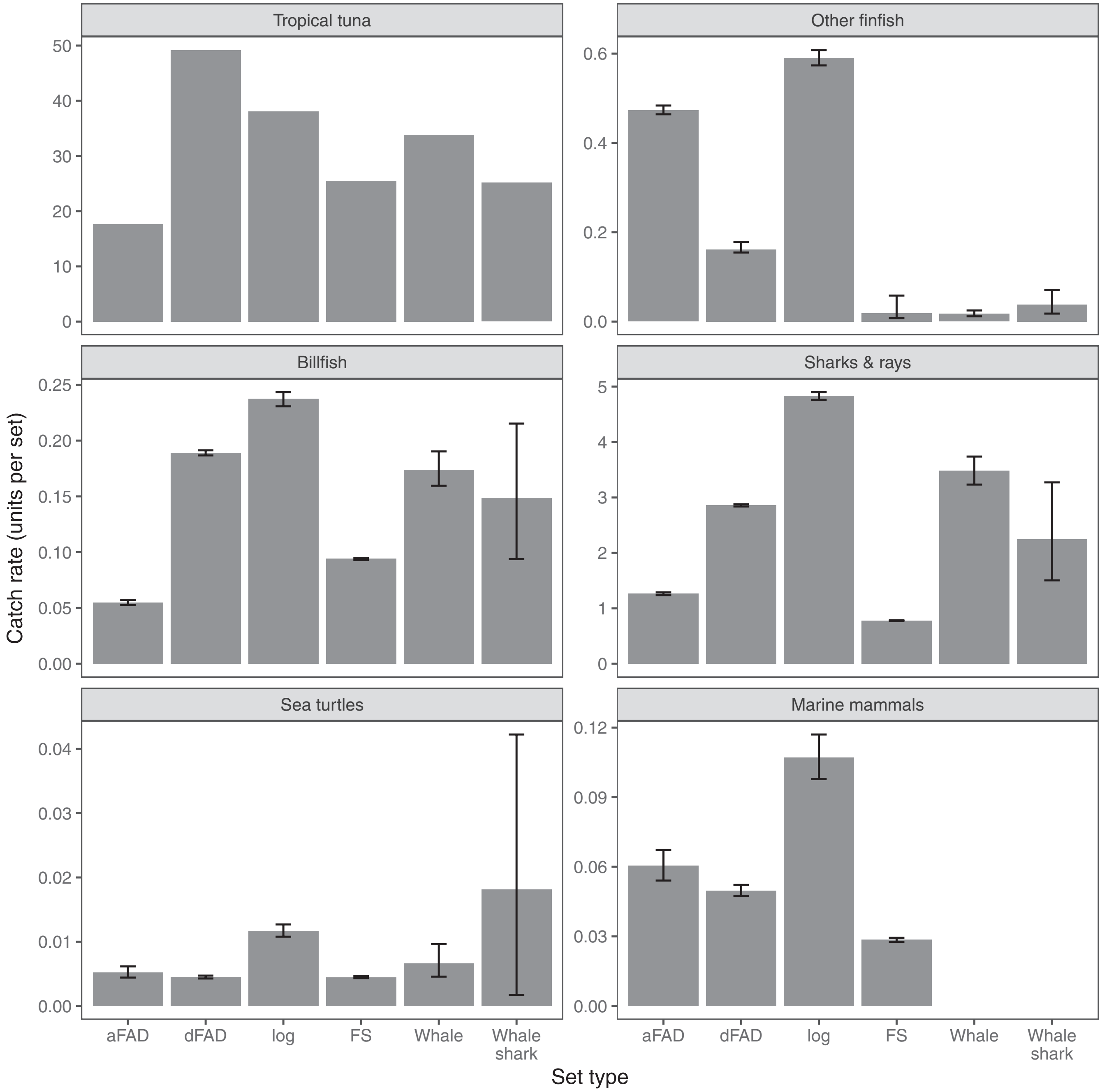


FIGURE 5 Estimated average catch rates with 95% CIs for the large-scale equatorial purse seine fishery in the WCPFC Convention Area from 2015 to 2019, by species type (see Table 1) and set type. Catch rate units are tonnes per set for tropical tuna and other finfish, and otherwise individuals per set (for billfish, sharks & rays, marine mammals and turtles). Reported catches were used to calculate catch rates for tropical tuna. Catch rates do not cover domestic fisheries of the Philippines, Vietnam and Indonesia and purse seiners operating in temperate waters off Japan and New Zealand. Purse seine sets are defined as: schools associated with anchored fish aggregating devices (aFAD), schools associated with drifting fish aggregating devices (dFAD), schools associated with drifting natural logs (Log), free schools (FS), schools associated with whales (Whale), schools associated with whale sharks (Whale shark).

not reflected in the catch estimates (Figure S11). Estimates of purse seine billfish catch remained relatively constant from 2003 to 2019 (Figure 4). Catches of billfish estimation groups were largely driven by year effects of the presence–absence models, as well as the temporal trends in effort by association type. Blue marlin displayed a variable and generally increasing trend. Black marlin, Indo-Pacific sailfish and swordfish displayed decreasing trends (Figure S12).

Purse seine catches of elasmobranchs displayed a decreasing trend from 2004 to 2010 and remained constant through to 2015 before increasing again (Figure 4), largely driven by silky shark (Figure S13). Decreasing silky shark from 2003 to 2010 was largely driven by reduced levels of drifting FAD and log sets, which have high school association effects; the increase in silky shark from 2013 onwards was largely driven by the year effect. Estimated catches of mobulid rays were relatively constant from 2003 to 2010, before displaying a generally increasing trend through to 2019 with a pronounced peak in 2012 (Figure S13). Estimated catches of oceanic whitetip shark decreased sharply from 2003 to 2007, remained relatively stable from 2008 through to 2016 and then increased (Figure S13), largely reflecting the year effects of the presence–absence model. Estimated catches of whale shark displayed a relatively weak increasing trend throughout the time series, with elevated catches from 2012 to 2015, reflecting the trend in free school sets through time (Figure S13). Estimated purse seine catch of marine mammals was relatively stable, with elevated catches from 2012 to 2014 reflecting the year effect of the presence–absence model coupled with the high levels of effort in those years (Figure 4). Estimated purse seine catches of sea turtles demonstrated an increasing trend from 2003 to 2013, before decreasing through to 2017 (Figure 4), though catches were limited compared to those in the longline fishery.

3.5 | Precision of estimated longline catch rates at differing levels of monitoring coverage

Coefficients of variation (CVs) were generally higher in years with lower numbers of observed sets and for species that were more rarely caught (Tables S5–S8). CVs demonstrated strong between species variation for a given target coverage rate. CVs at a departure year bin resolution for a target coverage rate of 10% of sets (and partial coverage of all trips) were generally lower or equivalent to those for a target coverage rate of 20% of trips (with full coverage of an observed trip). Exceptions to this were leatherback and green turtle, the rarest observed species considered, for which CVs for a target coverage rate of 10% of sets (and partial coverage of all trips) were more consistent with those for a target coverage rate of 10% of trips. CVs at a resolution of departure year bin and flag were higher, and more variable, than at a resolution of departure year bin.

4 | DISCUSSION

Assessing the impact of global fisheries has become increasingly important as responsible authorities seek to demonstrate that they are employing ecologically sustainable fishing practices. Demonstrating this sustainability includes the requirement to monitor bycatch levels and trends, as well as the impacts of bycatch on other ecosystem properties. Our work represents the first quantitative evaluation of the magnitude of bycatch in the industrial Purse seine and longline fisheries operating in the WCPFC Convention Area, which are the world's largest in terms of tuna catch. The study was designed to establish a baseline of historical catches, catch rates and species composition for the dominant tuna fisheries operating in the western and central Pacific to support future evaluations of the ecological performance and sustainability of these fisheries. Our analyses include estimates of bycatch for finfish, billfish, elasmobranchs, marine mammals and sea turtles and shows that the composition and magnitude of the catch varies considerably by fishery type and practice. These results, which are broadly consistent with empirical studies of the impacts of tuna fisheries in other ocean basins (Amandè et al., 2010; Gilman et al., 2020), are not surprising. The configurations of fishing gears and strategies deployed are common to all industrial tuna fisheries and not unique to the western and central Pacific region.

Historically, estimates and analyses of bycatch have been hampered by inadequate temporal and spatial observation across fishery fleets and gears (Lewison et al., 2014; Mace et al., 2014). Our estimates were similarly influenced by the inadequacies of sufficient observation. This uncertainty is present both due to the level of coverage by observers across fleets and gears and by their capacity to monitor all catch related activities. In particular, our estimates of bycatch for the longline fisheries were complicated by the coverage of available observer data, and for some years, the coverage of aggregated effort data specific to hooks between floats. As such, the catch estimates presented here must be viewed in the context of the limitations of the data set, and the methodology used to obtain the estimates.

A recent study has also highlighted the uncertainty that is generated by the limited capacity to observe across all activities during a catch event on purse seiners (Forget et al., 2021). Across three trips, observations by fisheries observers underestimated shark catches for the majority of sets, resulting in underestimation of shark catch at a trip level of between 10% and 40%. As such, it is reasonable to expect that the estimates presented here underestimate the actual number of individuals caught in the large-scale equatorial purse seine fishery even when fisheries observer coverage rates are 100%. Additionally, there may be inaccuracies in species identifications by observers (Williams et al., 2018). In this context our bycatch estimates should be interpreted as the bycatch that would have been recorded by observers with 100% coverage of fishing events, rather than estimates of the total bycatch encountered.

These observational inadequacies are compensated to some degree by the approach used to generate uncertainty in catch estimates. However, residual diagnostics indicated a lack of fit for a number of the lognormal longline model components, and spatial patterns in residuals for most longline and purse seine catch rate models, particularly for longline models for commonly observed estimation groups. This appears to reflect the inability of the longline catch rate models to adequately capture both targeting behaviour and spatial variation in catch rates more generally. Recent increases in the spatial coverage of longline observer data should support explicit inclusion of spatial effects in catch rate models in the future. There may also be value in considering other approaches to account for targeting in future analyses of longline catches, for example, by fitting separate catch rate models to appropriate subsets of available observer data informed by variables such as catch compositions or the spatial distribution of fishing effort. Further refinements to the modelling approach should also be considered in future work, for example, separate estimation of catch rate and catches for marine mammals at more detailed taxonomic groupings.

More recently, observer coverage rates of longline and purse seine fisheries in the WCPFC Convention Area have been impacted by COVID-19. Overall coverage rates have been lower since mid-2020 and the spatial coverage of available observer data has been less representative of overall fishing effort (Panizza et al., 2022). It is reasonable to assume that future estimates of bycatch and bycatch rates will be less precise for the period with reduced observer coverage rates. Additionally, the reduction in the representativeness of observer data may introduce bias in catch estimates. In combination, the impacts of COVID-19 are likely to compromise the ability to detect temporal trends in bycatch in recent years.

To evaluate the efficacy of the methodology applied we compared the reported catches from longline vessel logbooks to the estimates generated from the observer data using our modelling approach for the target albacore, bigeye, yellowfin, skipjack and billfish species (Figure S7). The accuracy of the catch estimates varied between species when compared with logbook records, though catches tended to be overestimated for billfish species and underestimated for tuna species. However, for most species, the trends in estimated annual catches were comparable to the trends in reported catches. This suggests that, more generally, for this study the trends in predicted catches through time may be more reliable than the magnitude of those predicted catches.

Observer coverage in the longline fishery has been increasing in recent years, with an increase in spatial coverage. Our simulations to better understand how precision in catch rate estimates changes with varying observer coverage levels indicated that for most species, more precise estimates of catch rates are obtained by covering a proportion of sets from all trips, rather than having full coverage of the same proportion of trips. For example, precision would be improved by having 10% coverage of sets from all trips, rather than covering all sets from 10% of trips. Moreover, for frequently caught species, coverage of 10% of sets from all trips obtained more precise estimates than full coverage of 20% of trips. The personnel required to achieve 10% coverage of all trips is likely to be substantially higher than that required to observe all sets from 10% of trips. Electronic monitoring (Emery et al., 2018) may be a way to supplement fisheries monitoring by observers to achieve a greater observation rate of trips. Electronic monitoring may also be a means to supplement the monitoring undertaken by observers within a capture event. It should be noted that the simulations assumed that observed longline effort is representative of all effort in the regions considered. This assumption may not hold given the relatively low coverage rates of WCPFC longline effort.

Indicators are important tools for measuring the benefits derived from fisheries conservation and management measures. Once established, performance thresholds can be defined that represent the desirable conditions of each indicator (de Bie et al., 2018). If well formulated and clearly defined, thresholds provide an objective means of defining acceptable conditions and demonstrating whether those conditions has been achieved. Our analyses are an important first step towards defining performance thresholds for bycatch. Despite the limitations identified, the fitted year effects from the catch rate models, in combination with time-series of bycatch rates, provide a means to identify apparent temporal changes in catches and catch rates of bycatch species. While attributing reasons for temporal trends in the bycatch estimates is difficult due to the confounding impacts of changing abundances and fishing practices, these trends identify the nature of potential relationships (particularly where there is a priori knowledge). For example, the decreasing trend in the catch of finfish in the purse seine fishery coincides with the decreasing proportional contribution of anchored FAD and log sets through the time-series, whereas the increasing trend in the latter half of the time series for elasmobranchs coincides with an increasing proportion of drifting FAD sets and increasing catches of silky shark. Furthermore, these trends may also flag where additional analyses are warranted. For example, the observed decrease in the catches of elasmobranchs in the longline fisheries highlights the need to understand whether this reduction is reflective of changing population abundances or fisher behaviour or management intervention, given non-retention requirements for some species.

Our baseline of estimates of bycatch are important reference points for future conservation status assessments, ecolabelling and construction of trophic and ecosystem models. The conservation status of elasmobranchs, sea turtles and mammals has become an issue of global significance (Dulvy et al., 2021; Rhodin et al., 2018). Over fifty species of the bycatch considered in this study are listed as threatened (Critically Endangered, Endangered or Vulnerable) or Near Threatened on the IUCN Red List (IUCN, 2022), including 35 elasmobranch species, 6 sea turtle species, 7 species of marine mammals and several billfishes and teleosts. While the conservation status for a selection of bycatch species that most commonly interact with the tuna fisheries have been assessed through formal population dynamics models (Clarke et al., 2013; Young & Carlson, 2020), all have been assessed using the IUCN Red List criteria (IUCN, 2022). Our estimates provide important information for calculating population sizes, trends and mortalities that inform extinction risk assessments (e.g. IUCN Red List) and vulnerability assessments (Walker et al., 2021). Sustainability certifications and international trade requirements (e.g. the Convention on the International Trade of Endangered Species of Wild Flora and Fauna, CITES) are increasingly requiring quantification of the magnitude and trends in bycatch. For example, determining and restricting marine mammal bycatch to be within or below potential biological removals is a requirement for import of seafood into the United States (Félix et al., 2021). Parameterisation and tuning of ecosystem models constructed to evaluate the ecosystem effects of differing fishing activities are also dependent on a baseline of information on the magnitude and trends in bycatch species (Griffiths et al., 2019). We did not estimate seabird bycatch due to insufficient observer coverage for a number of longline fleets pre-2015 operating in high latitude areas where fisheries pose the greatest risk to seabirds (Waugh et al., 2012). However, at least nine threatened seabirds interact with WCPFC fisheries (IUCN, 2022). With improved observer coverage the methods applied here for other taxa could be adapted for application to seabird observations to generate time series of bycatch estimates.

Annual catches of tuna in the WCPFC Convention Area have varied between 2.5 and 2.9 million mt since 2012 (OFP, 2021) of which approximately 57% is harvested annually from the exclusive economic zones of the Pacific Island Countries and Territories (Bell et al., 2021). Food security is increasingly becoming an issue of concern for Pacific Island Countries and Territories and the leaders of the Pacific Islands have committed to increase the availability of fish from tuna fisheries for local consumption by 40,000 tonnes per year to meet the food security needs of their populations (FFA and SPC, 2015). Developing opportunities to access fish from tuna fisheries through offloading of bycatch (e.g. non-threatened teleost species) from the industrial fisheries is considered an important component to this supply chain (James et al., 2018). Our baseline estimates for bycatch magnitude and trends provide a necessary first step for evaluating the feasibility of this option to meet all or some of the identified food security gap.

Our study has established a baseline of catches and catch compositions for the industrial purse seine and longline fisheries operating in the western and central Pacific Ocean. This baseline should allow for future monitoring of trends in estimated catches of species, which are not accurately quantified, or not covered, by vessel logbook data. The trends in catch estimates, and the fitted catch rate models, have utility in identifying species, which may require targeted additional analyses and management interventions.

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DATA AVAILABILITY STATEMENT

The analysed observer and aggregated catch and effort data sets are not in the public domain. Access to these data sets can be requested (see https://www.wcpfc.int/doc/data-02/rules-and-procedures-protection-access-and-dissemination-data-compiled-commission).

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