SCIENTIFIC COMMITTEE

SEVENTEENTH REGULAR SESSION

Online

11 – 19 August 2021

UPDATED PURSE SEINE BYCATCH ESTIMATES IN THE WCPO

WCPFC-SC17-2021/ST-IP-06

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Executive Summary

The Western and Central Pacific Fisheries Commission (WCPFC) has a responsibility to assess the impact of fishing on non-target species. In this report, we estimate the bycatch of the large-scale purse seine fishery operating primarily in tropical waters of the WCPFC Convention Area east of 140°E. These large vessels, typically greater than 500 tonnes carrying capacity, have been responsible for approximately 85% of the purse seine catch of tropical tunas in recent years, a catch that has varied between 1.7 and 2.2 million tonnes annually since 2010. This report provides an update to the equivalent report prepared in 2018 and submitted to WCPFC SC14.

We summarise bycatches for 45 species and/or species groups that provide comprehensive coverage of finfish, billfish, shark and ray, sea turtle and marine mammals observed in purse seine catches. We do not report on seabird bycatch due to the low number of observed catch events.

Available observer coverage for 2020 represented 29% coverage of total sets, compared with annual coverage rates ranging from 62 - 78% for the period 2010-2019. This is partially due to incomplete loading of 2020 observer trips at the time of preparing the report, as well as difficulties in placing observers caused by the Covid-19 pandemic. As such, the bycatch estimates of 2020 should be considered preliminary.

The report concludes with recommendations to the Scientific Committee:

- The Scientific Committee note the estimates of bycatch of the large-scale equatorial purse seine fishery in the WCPFC Convention Area;
- The Scientific Committee note that the bycatch estimates should be interpreted as the bycatch that would have been recorded by observers with 100% coverage of fishing events;
- The Scientific Committee note that other studies suggest that shark bycatch estimates are likely to be underestimates, due to underestimation of captures by observers;
- The Scientific Committee consider whether the estimated effects from the fitted presence/absence models, in combination with time-series of bycatch rates, have utility in identifying species of potential concern that may warrant more detailed investigation;
- The Scientific Committee consider whether the estimates of purse seine bycatch should be made publicly available in electronic format to facilitate extraction and use of data by Commission Members, Cooperating Non-members and participating Territories (CCMs), and potentially other stakeholders.

1. Introduction

WCPFC has responsibilities to assess the impact of fishing and environmental factors on non-target species and species belonging to the same ecosystem or dependent upon or associated with the target stocks (article 5d), to minimize catch of non-target species (article 5e), to protect biodiversity (article 5f), and to adopt, when necessary, Conservation and Management Measures (CMMs) for non-target species to ensure the conservation of such species (article 6c).

Stock assessments have been undertaken for a range of species that are incidentally caught in WCPO purse seine fisheries, including silky (Common Oceans Tuna Project, 2018a) and oceanic whitetip sharks (Tremblay-Boyer et al., 2019), as well as assessments of the risk to whale sharks from purse seine fisheries (Common Oceans Tuna Project, 2018b). The WCPFC is also contributing to an open resource that focuses on bycatch mitigation and management in oceanic tuna and billfish fisheries: the Bycatch Management Information System (BMIS, https://www.bmis-bycatch.org/) (Fitzsimmons et al., 2015).

A number of Conservation and Management Measures (CMMs) have been implemented for non-target species, including:

- A resolution has been taken to encourage avoiding the capture of all non-target fish species and encourage prompt release to the water, unharmed (Resolution 2005-03); and
- CMMs have been implemented for billfishes (CMM 2010-01 for north Pacific striped marlin), and on species of special interest: sea turtles (CMM 2008-03, 2018-04), sharks (CMM 2010-07, CMM 2014-05, CMM 2019-04), oceanic whitetip shark (CMM 2011-04), whale sharks (CMM 2012-04), silky sharks (CMM 2013-08), cetaceans (CMM 2011-03), seabirds (CMM 2018-03) and mobulid rays (CMM 2019-05).

CMM 2008-01 introduced a requirement for 100% observer coverage for purse seine operations between 10°S and 10°N from 2010 onwards, with CMM 2007-01 requiring a minimum of 5% observer coverage for purse seine fishing elsewhere. The high rates of available observer coverage offer the possibility of robust estimates of bycatch rates and quantities for non-target species caught in WCPO purse seine fisheries.

This report provides comprehensive bycatch estimates for the large-scale equatorial purse seine fishery in the WCPFC Convention Area from 2003 to 2020, providing an update to Peatman et al. (2018). These estimates provide a complement to comprehensive bycatch estimates for WCPFC longline fisheries (Peatman & Nicol, 2020).

2. Data and methods

The observer and aggregate effort datasets used in this report were extracted from SPC data holdings on 25th May and 28th June 2021 respectively. The method used in this study was based on that from Peatman et al. (2018) and summarised here, with an emphasis on aspects that have been revised and improved. The overall approach was to estimate stratified catch rates using a combination of presence/absence models and bootstrap sampling for catch when present, and then to use these catch rates to estimate bycatch for unobserved sets. Recorded catches were used directly for observed sets, and assumed to be known without error.

The estimates of bycatch cover the large-scale equatorial purse seine fishery operating in the WCPFC-CA. Bycatch estimates were not generated for purse seine fleets for which SPC holds limited representative observer data, namely small-scale domestic fisheries of Indonesia, Vietnam and the Philippines, and, purse seiners operating in temperate waters. However, the estimates do cover the Philippines high-seas pocket fishery, which was previously excluded.

Bycatch estimates were generated in units of individuals for billfish, sharks and rays, marine mammals and sea turtles, with finfish bycatch estimated in units of metric tonnes. These units match those most commonly used by observers when recording catch volumes of the respective species groups and were considered to provide the most accurate dataset of observed catches in SPC's purse seine observer data holdings.

Following Peatman et al. (2018), the estimates of catch rates and bycatches were generated for 45 species, or groups of species, covering the full range of finfish, shark, marine mammal and sea turtle species observed in longline catches (Table 1). These are referred to throughout as estimation groups. Species were grouped together in cases for which robust species-level identification was considered to be problematic, e.g. frigate and bullet tuna, or for groups of rarely reported species codes.

Presence/absence models were fitted to observer data using Generalised Estimating Equations (GEEs) to account for correlation between observations within observer trips. Models were fitted using the R package 'geepack' (Højsgaard et al., 2006) in R version 4.0.3 (R Core Team, 2020), with a quasi-binomial error structure and a logit link function. An 'exchangeable' working correlation structure was used for all models, where residuals from observations from the same observer trip are correlated, with a shared correlation parameter for all observer trips. Explanatory variables included in the models were: cubic splines for year and sea-surface temperature (SST – Reynolds et al., 2002); and categorical variables for quarter and school association.

The specification of the presence/absence models was:

$$E[P_{ij}] = \gamma_{ij} \qquad\qquad Var[P_{ij}] = \phi\, \gamma_{ij}(1 - \gamma_{ij})$$

$$\ln\left(\frac{\gamma_{ij}}{1-\gamma_{ij}}\right) = \beta_0 + \beta_1 quarter_{ij} + \beta_2 association_{ij} + f_1(year_{ij}) + f_2(SST_{ij})$$

where P_{ij} denotes whether captures of the estimation group were observed, subscripts i and j refer to observer trip and set number respectively, f_n represent natural cubic splines and ϕ is a variance inflation parameter. All covariates were retained in the presence/absence models regardless of statistical significance. However, all covariates were statistically significant for the majority of the models, and so reduced predictive accuracy due to over-parameterisation was considered unlikely. We did not include, or test for, interactions between explanatory variables.

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 and school association. Uncertainty in the presence/absence of bycatch was generated by taking 1,000 random draws of parameters from the multivariate normal distribution defined by the vector of mean parameter values $\boldsymbol{\beta}$ and their covariance matrix $\boldsymbol{\Sigma}$, $N_k(\boldsymbol{\beta}, \boldsymbol{\Sigma})$ where k is the number of estimated parameters. The random draws of parameter values were then used to generate 1,000 estimates of the probability of presence for each strata. The volume of catch when present was estimated by bootstrap sampling from sets with observed captures, stratified by association type, again taking 1,000 random draws. 1,000 estimates of the overall bycatch 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. As such, the units of bycatch rate were numbers or metric tonnes per set. The estimated catch rates were then applied to the number of unobserved sets in each strata, to calculate unobserved bycatch. The estimates of unobserved bycatch were then combined with recorded bycatch from observed sets to give estimates of total bycatch.

It was not possible to fit a satisfactory presence/absence model for 'billfishes nei'. The probability of presence for 'billfishes nei' was estimated using bootstrap sampling.

Whale and whale-shark associated sets are recorded more frequently by observers than in vessel logbook data. As discussed in Peatman et al. (2018), this has likely led to under-estimation of whale shark and cetacean captures in earlier iterations of this work. To mitigate downwards bias in catch estimates, whale and whale-shark were treated as free school sets when estimating catch rates and bycatch of whale sharks and marine mammals, both in the observer and aggregate effort dataset.

3. Results

Reported sets by the large-scale equatorial purse seine fishery increased from 2003 through to 2010, remaining relatively constant at 50,000 - 60,000 annually from 2010 to 2020 (Table 2). The number of sets on logs and anchored FADs decreased from 2003 to 2020, with increases in the number of free school sets and sets on drifting FADs. The number of reported sets on schools associated with whales varied between 85 and 305 sets per year from 2010 to 2020, with between 1 and 52 reported sets 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 1). Observer coverage rates increased in 2010, with observer data available for an average of two-thirds of reported sets from 2010 through to 2020. Available observer data for 2020 as of May 2021 represented 29% of total reported sets. This decrease in 2020 reflects difficulties in deploying observers due to the Covid-19 pandemic, as well as incomplete loading of data for 2020 observer trips when datasets were extracted from SPC data holdings. Observer coverage has been spatially distributed relatively evenly, particularly from 2010 onwards (Figure 2 and Figure 3).

Annual estimates of bycatch are provided by species group in Table 3. Over the last five years, the majority of estimated finfish bycatch was accounted for by associated sets (Table 4), with low estimated bycatch rates on free school sets (Table 5). Estimated billfish bycatch over the last five years was distributed relatively evenly between free school and associated sets (Table 4), with lower bycatch rates on free school sets offset by greater numbers of free school sets (Table 1, Table 5). Approximately two-thirds of the estimated bycatch of sharks and rays over the last five years was accounted for by associated sets, though again the lower bycatch rate on free school sets was offset by higher effort (Table 1, Table 5). Approximately half of estimated marine mammal bycatch, and two-thirds of sea turtle bycatch, was accounted for by sets on free schools and schools associated with whales and whale sharks (Table 4). Annual estimated bycatches are provided by estimation group in Table 6 through to Table 9, with average annual bycatch and bycatch rates for the last five years provided by estimation group and school association in Table 10 and Table 11 respectively.

Appendix A provides plots of the fitted relationships between covariates and bycatch presence/absence for selected estimation groups. There are apparent declining trends in bycatch presence for a number of estimation groups, including oceanic triggerfish (Figure 6), frigate and bullet tuna (Figure 7), mahi mahi (Figure 8), wahoo (Figure 10), Indo-Pacific sailfish (Figure 14) and swordfish (Figure 15). Conversely, there are apparent increasing trends for oceanic whitetip presence since 2012 (Figure 17), and silky shark presence since 2014 (Figure 16).

4. Discussion

This report provides bycatch estimates for the large-scale equatorial purse seine fleet operating in the WCPFC Convention Area, covering finfish, billfish, sharks & rays, marine mammals and sea turtles. Bycatch of seabirds was not estimated due to limited observed capture rates, though estimates were generated through Project 68 (Peatman et al., 2019). Bycatch estimates for 2020 should be considered preliminary given that a reasonable proportion of 2020 observer trips had not been loaded in to SPC's observer database and so were not available for this analysis. Precision of estimates for 2020 will increase once the remaining trips have been loaded, though they are unlikely to be as precise as those for 2010 – 2019 if expected observer coverage rates materialise based on observer placement information, i.e. at best 45 to 50% of sets. Precision of bycatch estimates for 2021 are likely to be similarly impacted given ongoing difficulties in placing observers due to Covid-19.

The estimates of bycatch presented in this report should be interpreted as the catch that would have been observed and recorded if observer data were available for all fishing events. A recent study compared shark catches recorded by observers with a reference dataset collected by dedicated scientists; observers underestimated shark catches for the majority of sets across the three trips, resulting in underestimation of shark catch at a trip level of between 10 and 40% (Forget et al. ,2021). As such, it is reasonable to expect that the shark bycatch estimates presented here underestimate the actual number of sharks caught in the large-scale equatorial purse seine fishery. It remains a matter for speculation whether bycatch estimates for other taxa are likely to be similarly downwards-biased.

In earlier iterations of the work, bycatch of whales and whale sharks were likely under-estimated (see Peatman et al., 2018). This resulted from using school association-specific reported effort when raising observed catch rates to total bycatch estimates, in combination with the relatively low rates of reported whale and whale-shark associated sets in vessel logbooks compared with observer data. In this report, we mitigated this bias by combining whale and whale-shark associated sets with free school sets when estimating bycatch and bycatch rates of marine mammals and whale sharks. The estimates of marine mammal and whale shark bycatch reported here represent an increase of 150% and 90% respectively, relative to those in Peatman et al. (2018). Future work should consider estimating marine mammal bycatch at a finer taxonomic resolution, to allow more meaningful monitoring of bycatch and bycatch rates of marine mammal species.

In this iteration we fitted presence/absence models for all estimation groups, whereas in earlier iterations presence/absence models were fitted for twelve estimation groups. This should result in more accurate estimates of bycatch, and also allow more detailed monitoring of a wider range of species. Confidence intervals have also been included for all estimated quantities.

Fitted year effects from the presence/absence models, in combination with time-series of school association-specific bycatch rates, provide a means to identify apparent temporal changes that could reflect declines in abundance of bycatch species. For example, there are a number of finfish species with apparent declines in presence/absence through time (see Section 3 and Appendix A). This information could be used to focus additional targeted research at species of concern, e.g. standardised catch rate modelling.

Future work should also consider explicitly modelling spatial variation in models of bycatch presence/absence. This could improve the accuracy of bycatch and bycatch rate estimates pre-2010, when observer coverage was more limited and less balanced both between fleets and spatially. Explicitly modelling spatial variation may also improve the utility of year effects in identifying apparent declines in abundance of bycatch species, as the spatial effects would account for temporal variation in bycatch presence/absence due to shifts in the distribution of purse seine effort.

We invite the Scientific Committee to:

- Note the estimates of bycatch of the large-scale equatorial purse seine fishery in the WCPFC Convention Area;
- Note that the bycatch estimates should be interpreted as the bycatch that would have been recorded by observers with 100% coverage of fishing events;
- Note that other studies suggest that shark bycatch estimates are likely to be underestimates, due to underestimation of captures by observers;
- Consider whether the estimated effects from the fitted presence/absence models, in combination with time-series of bycatch rates, have utility in identifying species of potential concern that may warrant more detailed investigation;
- Consider whether the estimates of purse seine bycatch should be made publicly available in electronic format to facilitate extraction and use of data by Commission Members, Cooperating Non-members and participating Territories (CCMs), and potentially other stakeholders.

Acknowledgements

T. Peatman’s contribution was supported by the European Union’s “Pacific-European Union Marine Partnership Programme”. The authors would like to thank all those responsible for collecting and managing the data used in this report, as well as Aurélien Panizza, Emmanuel Schneiter and Peter Williams (SPC) for their assistance with data extracts.

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Tables

Table 1 Estimation groups used to estimate bycatch in the large-scale equatorial purse seine fishery, and their unit of bycatch.

Code	Common name	Scientific name	Bycatch unit
ALB	Albacore	Thunnus alalunga	Tonnes
FRZ	Frigate & bullet tunas	Auxis thazard & A. rochei	Tonnes
KAW	Kawakawa	Euthynnus affinis	Tonnes
TUN.nei	Scombrids nei	Scombridae nei	Tonnes
WAH	Wahoo	Acanthocybium solandri	Tonnes
AMX	Amberjacks	Seriola spp	Tonnes
BAR	Barracudas	Sphyraenidae	Tonnes
BAT	Batfishes	Platax spp	Tonnes
BRZ	Pomfrets	Bramidae	Tonnes
CGX.nei	Carangids nei	Carangidae nei	Tonnes
DOL	Mahi mahi	Coryphaena hippurus	Tonnes
FLF	Filefishes	Monacanthidae	Tonnes
GLT	Golden trevally	Gnathanodon speciosus	Tonnes
KYC	Sea chubs	Kyphosidae	Tonnes
LOB	Triple-tail	Lobotes surinamensis	Tonnes
MOP	Sunfish	Molidae	Tonnes
MSD	Mackerel scad	Decapturus macarellus	Tonnes
RRU	Rainbow runner	Elagatis bipinnulata	Tonnes
TEL.nei	Marine fishes nei	Teleosts nei	Tonnes
TRE	Trevallies	Caranx spp	Tonnes
TRI	Oceanic triggerfish	Balistidae	Tonnes
BIL.nei	Billfishes nei	Billfishes nei	Individuals
BLM	Black marlin	Makaira indica	Individuals
BUM	Blue marlin	Makaira nigricans	Individuals
MLS	Striped marlin	Tetrapturus audax	Individuals
SFA	Sailfish (indo-pacific)	Istiophorus platypterus	Individuals
SSP	Short-billed spearfish	Tetrapturus angustirostris	Individuals
SWO	Swordfish	Xiphias gladius	Individuals
BSH	Blue shark	Prionace glauca	Individuals
FAL	Silky shark	Carcharhinus falciformis	Individuals
MAK	Mako sharks	Isurus spp	Individuals
MAN	Mobulid rays	Mobulidae	Individuals
OCS	Oceanic whitetip shark	Carcharhinus longimanus	Individuals
RHN	Whale shark	Rhincodon typus	Individuals
SPN	Hammerhead sharks	Sphyrnidae	Individuals
THR	Thresher sharks	Alopiidae	Individuals
PLS	Pelagic stingray	Dasyatis violacea	Individuals
SHK.nei	Elasmobranchs nei	Elasmobranchii nei	Individuals
MAM	Marine mammal	Mammalia	Individuals
DKK	Leatherback turtle	Dermochelys coriacea	Individuals
LKV	Olive ridley turtle	Lepidochelys olivacea	Individuals
TTH	Hawksbill turtle	Eretmochelys imbricata	Individuals
TTL	Loggerhead turtle	Caretta caretta	Individuals
TTX	Marine turtles nei	Chelonioidea	Individuals
TUG	Green turtle	Chelonia mydas	Individuals

Table 2 Annual reported sets by school association for the large-scale equatorial purse seine fishery from 2003 to 2020.

Year	aFAD	dFAD	log	FS	whale	whale shark	Total
2003	3,877	3,578	8,076	17,624	29	33	33,217
2004	5,641	4,776	13,495	11,232	32	2	35,178
2005	5,902	3,982	10,100	19,548	39	4	39,575
2006	5,321	4,918	11,207	15,324	28	9	36,807
2007	5,727	5,539	9,115	19,714	76	11	40,182
2008	6,622	10,522	5,486	23,278	75	9	45,992
2009	5,670	11,703	7,171	23,302	88	10	47,944
2010	2,855	6,844	4,157	39,446	305	19	53,626
2011	3,286	15,232	3,727	30,778	166	1	53,190
2012	2,990	13,380	4,580	36,874	144	8	57,976
2013	3,775	12,236	4,084	40,326	105	5	60,531
2014	2,612	13,865	2,938	39,840	85	9	59,349
2015	3,134	10,341	2,189	34,015	133	7	49,819
2016	2,152	10,775	2,457	33,772	205	17	49,378
2017	1,305	14,173	1,850	35,476	255	52	53,111
2018	1,749	15,566	2,203	34,345	216	13	54,092
2019	2,682	13,088	1,091	37,907	269	35	55,072
2020	2,199	13,841	694	33,875	158	27	50,794

Table 3 Estimated annual bycatch for the large-scale equatorial purse seine fishery from 2003 to 2020 by species group. 95% CIs are provided in parentheses. Estimates for 2020 are preliminary.

Year	Finfish (mt)	Billfish (individuals)	Sharks & rays (individuals)	Marine mammals (individuals)	Turtles (individuals)
2003	6,275 (5,868-6,720)	6,583 (6,176-7,042)	65,146 (60,445-70,728)	1,623 (1,378-1,939)	290 (232-378)
2004	10,197 (9,761-10,664)	7,007 (6,741-7,288)	80,606 (76,838-85,374)	1,700 (1,511-1,934)	225 (191-272)
2005	8,241 (7,851-8,632)	6,547 (6,292-6,805)	68,000 (65,006-71,208)	1,322 (1,171-1,502)	209 (182-242)
2006	8,812 (8,469-9,191)	6,177 (5,967-6,424)	66,587 (63,657-69,490)	1,648 (1,465-1,872)	224 (196-260)
2007	8,380 (7,940-8,863)	6,614 (6,402-6,828)	59,777 (56,916-62,917)	2,052 (1,805-2,339)	304 (267-345)
2008	7,083 (6,628-7,575)	7,479 (7,201-7,750)	57,395 (54,428-60,531)	1,925 (1,703-2,184)	304 (264-351)
2009	7,555 (7,197-7,896)	6,970 (6,801-7,126)	63,285 (60,891-65,896)	2,263 (2,112-2,430)	338 (311-371)
2010	5,324 (5,245-5,402)	6,020 (5,937-6,115)	43,827 (43,167-44,579)	1,252 (1,206-1,305)	282 (270-295)
2011	4,654 (4,581-4,728)	6,478 (6,402-6,559)	58,386 (57,555-59,233)	2,120 (2,060-2,176)	421 (408-435)
2012	4,684 (4,613-4,750)	8,720 (8,636-8,809)	50,833 (50,100-51,611)	3,197 (3,116-3,285)	425 (411-440)
2013	5,739 (5,639-5,852)	8,946 (8,879-9,014)	53,875 (53,306-54,473)	3,861 (3,789-3,945)	483 (471-496)
2014	5,644 (5,541-5,759)	8,269 (8,186-8,350)	58,931 (58,298-59,565)	2,952 (2,884-3,026)	319 (306-334)
2015	6,168 (6,089-6,244)	7,337 (7,289-7,388)	49,086 (48,662-49,567)	1,891 (1,846-1,941)	273 (266-280)
2016	6,459 (6,405-6,518)	6,152 (6,089-6,213)	70,883 (70,287-71,514)	1,982 (1,922-2,042)	223 (214-234)
2017	3,756 (3,693-3,827)	6,623 (6,551-6,695)	81,637 (80,887-82,472)	2,214 (2,127-2,300)	223 (211-235)
2018	3,512 (3,441-3,578)	6,112 (6,056-6,174)	79,897 (79,193-80,638)	1,710 (1,645-1,781)	291 (282-301)
2019	2,612 (2,564-2,667)	5,626 (5,583-5,672)	98,777 (98,177-99,423)	1,912 (1,848-1,980)	201 (193-211)
2020	3,255 (3,009-3,653)	4,913 (4,710-5,154)	93,402 (88,181-100,040)	2,298 (2,062-2,569)	136 (115-163)

Table 4 Average annual bycatch from 2016 to 2020 by species group and school association for the large-scale equatorial purse seine fishery. Bycatch units are metric tonnes for finfish, and individuals for billfish, sharks & rays, marine mammals and turtles. 95% CIs are provided in parentheses. Marine mammal bycatch for free school sets also includes whale and whale shark sets (see Section 2).

Species group	aFAD	dFAD	log	FS	whale	whale shark
Finfish	821 (798-844)	1,902 (1,856-1,978)	952 (939-969)	238 (232-246)	3 (2-6)	1 (0-3)
Billfish	85 (79-92)	2,440 (2,403-2,482)	362 (356-367)	2,959 (2,918-3,004)	35 (29-43)	4 (2-6)
Sharks & rays	2,245 (2,175-2,331)	42,262 (41,351-43,523)	8,080 (7,939-8,253)	31,378 (30,819-31,988)	867 (744-982)	64 (44-91)
Marine mammals	126 (105-150)	669 (634-712)	178 (170-188)	1,050 (1,004-1,105)	-	-
Turtles	9 (7-11)	50 (47-53)	15 (15-16)	138 (132-146)	1 (1-3)	0 (0-1)

Table 5 Average bycatch rate from 2016 to 2020 by species group and school association type for the large-scale equatorial purse seine fishery. Bycatch rate units are metric tonnes per set for finfish, and individuals per set for billfish, sharks & rays, marine mammals and turtles. 95% CIs are provided in parentheses. Marine mammal bycatch rates for free school sets also includes whale and whale shark sets (see Section 2)

Species group	aFAD	dFAD	log	FS	whale	whale shark
Finfish	0.407 (0.396-0.418)	0.141 (0.138-0.147)	0.574 (0.566-0.584)	0.007 (0.007-0.007)	0.015 (0.008-0.026)	0.022 (0.003-0.114)
Billfish	0.042 (0.039-0.045)	0.181 (0.178-0.184)	0.218 (0.215-0.221)	0.084 (0.083-0.086)	0.160 (0.133-0.193)	0.139 (0.083-0.208)
Sharks & rays	1.113 (1.078-1.155)	3.133 (3.066-3.227)	4.871 (4.785-4.975)	0.895 (0.879-0.912)	3.932 (3.372-4.452)	2.229 (1.535-3.167)
Marine mammals	0.062 (0.052-0.074)	0.050 (0.047-0.053)	0.107 (0.102-0.113)	0.030 (0.029-0.032)	-	-
Turtles	0.005 (0.004-0.006)	0.004 (0.004-0.004)	0.009 (0.009-0.010)	0.004 (0.004-0.004)	0.006 (0.003-0.012)	0.014 (0.000-0.035)

Table 6 Estimated annual finfish bycatch (mt) by estimation group for the large-scale equatorial purse seine fishery from 2003 to 2020. 95% CIs are provided in parentheses. 'Others' includes estimated bycatch of amberjacks, barracudas, batfishes, pomfrets, carangids, filefishes, golden trevally, sea chubs, triple-tail, sunfish, trevallies, other scombrids, and other marine fishes. Estimates for 2020 are preliminary.

Year	Rainbow runner	Mackerel scad	Oceanic triggerfish	Frigate & bullet tunas	Mahi mahi	Kawakawa	Wahoo	Albacore	Others
2003	2,689 (2,362-3,045)	881 (738-1,063)	649 (553-762)	893 (787-1,016)	396 (349-454)	157 (124-205)	94 (79-115)	142 (100-207)	358 (314-423)
2004	4,696 (4,331-5,067)	1,734 (1,544-1,946)	1,293 (1,173-1,417)	951 (860-1,059)	615 (565-665)	128 (107-155)	137 (125-153)	119 (96-151)	519 (484-563)
2005	3,708 (3,400-4,042)	1,591 (1,428-1,785)	978 (882-1,087)	779 (700-871)	460 (419-511)	93 (79-112)	102 (90-116)	152 (126-186)	362 (336-392)
2006	4,073 (3,801-4,394)	1,727 (1,577-1,903)	1,058 (961-1,156)	746 (671-829)	517 (480-561)	86 (72-103)	109 (97-122)	133 (111-163)	351 (327-375)
2007	3,747 (3,392-4,126)	1,632 (1,443-1,831)	905 (800-1,019)	929 (831-1,034)	467 (423-521)	130 (108-155)	121 (108-140)	143 (117-173)	296 (274-320)
2008	3,131 (2,779-3,559)	1,260 (1,092-1,469)	610 (520-722)	865 (752-1,009)	485 (432-551)	151 (120-189)	177 (155-206)	154 (125-194)	226 (209-247)
2009	3,503 (3,225-3,789)	1,480 (1,345-1,623)	781 (709-865)	529 (477-594)	541 (501-579)	164 (143-188)	150 (136-168)	79 (67-93)	322 (304-342)
2010	2,623 (2,557-2,684)	916 (882-952)	696 (678-713)	201 (189-217)	362 (353-371)	85 (78-94)	100 (97-103)	59 (53-66)	282 (276-289)
2011	2,260 (2,198-2,328)	598 (572-628)	472 (458-489)	269 (259-279)	332 (323-341)	211 (204-219)	161 (157-165)	156 (150-163)	195 (190-200)
2012	2,076 (2,018-2,134)	715 (684-747)	441 (426-459)	349 (337-362)	355 (346-364)	171 (163-180)	162 (159-166)	199 (189-219)	212 (208-217)
2013	2,141 (2,085-2,208)	1,320 (1,266-1,373)	549 (533-564)	586 (549-625)	479 (469-491)	226 (217-237)	143 (140-146)	118 (82-190)	178 (173-183)
2014	1,868 (1,824-1,920)	1,246 (1,197-1,299)	404 (393-416)	1,138 (1,071-1,219)	358 (348-369)	257 (223-306)	167 (164-170)	46 (41-52)	154 (150-160)
2015	2,405 (2,365-2,447)	1,547 (1,507-1,593)	425 (415-436)	924 (881-970)	419 (412-427)	117 (112-123)	80 (77-82)	50 (46-53)	199 (196-203)
2016	3,193 (3,156-3,232)	1,747 (1,713-1,784)	623 (615-633)	266 (255-279)	176 (172-180)	109 (101-120)	83 (81-85)	75 (69-82)	186 (183-189)
2017	1,737 (1,691-1,783)	983 (943-1,025)	322 (313-333)	87 (80-97)	205 (200-211)	94 (87-103)	106 (103-109)	129 (122-139)	92 (89-95)
2018	1,558 (1,516-1,602)	1,050 (998-1,101)	245 (239-253)	104 (91-123)	198 (191-206)	110 (99-133)	121 (118-124)	54 (49-58)	69 (67-72)
2019	1,236 (1,211-1,259)	677 (646-713)	197 (194-200)	161 (132-190)	153 (145-162)	44 (35-60)	48 (47-49)	42 (38-46)	55 (54-57)
2020	1,259 (1,061-1,624)	1,288 (1,192-1,427)	172 (147-222)	190 (165-222)	91 (75-122)	53 (42-73)	40 (31-65)	35 (22-62)	110 (99-125)

Table 7 Estimated annual billfish bycatch (individuals) by estimation group for the large-scale equatorial purse seine fishery from 2003 to 2020. 95% CIs are provided in parentheses. Estimates for 2020 are preliminary.

Year	Blue marlin	Black marlin	Striped marlin	Sailfish (indo-pacific)	Swordfish	Short-billed spearfish	Billfishes nei
2003	2,488 (2,234-2,798)	2,536 (2,267-2,873)	594 (488-722)	665 (560-792)	117 (88-157)	163 (120-237)	0 (0-0)
2004	2,983 (2,803-3,190)	2,306 (2,133-2,475)	641 (566-717)	797 (720-887)	182 (154-214)	101 (81-126)	0 (0-0)
2005	3,094 (2,931-3,276)	1,799 (1,668-1,941)	622 (555-701)	771 (682-868)	180 (155-212)	80 (62-104)	0 (0-0)
2006	3,148 (2,998-3,326)	1,543 (1,436-1,657)	587 (525-658)	610 (551-680)	211 (183-243)	67 (54-85)	0 (0-1)
2007	3,707 (3,534-3,899)	1,517 (1,419-1,623)	602 (540-670)	477 (424-538)	214 (186-246)	91 (75-114)	0 (0-0)
2008	4,186 (3,963-4,423)	1,860 (1,722-2,005)	700 (630-787)	405 (356-457)	214 (181-249)	102 (78-135)	0 (0-0)
2009	3,484 (3,358-3,605)	1,711 (1,626-1,798)	838 (780-905)	607 (562-654)	200 (178-226)	111 (94-129)	13 (3-36)
2010	2,757 (2,697-2,823)	1,610 (1,565-1,656)	803 (775-839)	558 (533-584)	137 (129-148)	151 (142-163)	0 (0-0)
2011	3,028 (2,975-3,089)	1,759 (1,714-1,804)	909 (878-940)	532 (511-555)	153 (144-165)	97 (88-107)	0 (0-0)
2012	4,359 (4,305-4,425)	2,337 (2,291-2,386)	1,239 (1,205-1,272)	437 (420-457)	173 (165-184)	172 (161-186)	0 (0-0)
2013	4,500 (4,451-4,547)	2,501 (2,467-2,535)	1,221 (1,198-1,247)	445 (430-462)	119 (113-126)	160 (152-168)	0 (0-0)
2014	4,643 (4,585-4,707)	1,932 (1,895-1,968)	1,043 (1,014-1,075)	419 (399-442)	100 (95-107)	127 (116-140)	0 (0-0)
2015	4,457 (4,421-4,495)	1,478 (1,457-1,503)	948 (931-967)	270 (262-281)	69 (65-74)	113 (108-119)	0 (0-0)
2016	3,775 (3,722-3,822)	1,235 (1,209-1,264)	755 (733-778)	247 (234-262)	79 (74-84)	61 (55-68)	0 (0-0)
2017	4,174 (4,116-4,230)	1,387 (1,356-1,419)	691 (669-717)	248 (237-263)	59 (53-65)	62 (54-73)	0 (0-0)
2018	3,982 (3,934-4,030)	1,234 (1,208-1,262)	535 (520-553)	242 (233-254)	42 (39-45)	78 (72-84)	0 (0-0)
2019	3,552 (3,518-3,588)	1,220 (1,202-1,239)	504 (492-516)	237 (227-251)	44 (41-48)	63 (60-67)	6 (4-9)
2020	3,152 (2,973-3,351)	1,043 (953-1,148)	486 (426-552)	123 (100-156)	31 (23-47)	41 (28-63)	22 (1-106)

Table 8 Estimated annual shark and ray bycatch (individuals) by estimation group for the large-scale equatorial purse seine fishery from 2003 to 2020. 95% CIs are provided in parentheses. Estimates for 2020 are preliminary.

Year	Silky shark	Mobulid rays	Oceanic whitetip shark	Whale shark	Pelagic stingray	Mako sharks	Thresher sharks	Blue shark	Hammerhead sharks	Elasmobranchs nei
2003	47,997 (43,697-52,201)	2,575 (2,297-2,915)	2,093 (1,569-3,052)	255 (177-363)	93 (62-147)	1,040 (570-2,519)	308 (189-550)	23 (10-70)	65 (44-98)	10,559 (8,392-14,230)
2004	70,082 (66,447-74,173)	2,400 (2,252-2,583)	1,885 (1,535-2,417)	191 (163-221)	108 (87-138)	482 (297-863)	197 (138-300)	62 (35-112)	43 (33-59)	5,055 (3,995-6,445)
2005	61,623 (58,659-64,975)	2,267 (2,106-2,442)	1,188 (997-1,457)	307 (262-371)	135 (111-167)	188 (117-327)	103 (73-146)	202 (132-420)	22 (15-35)	1,892 (1,410-2,529)
2006	61,629 (58,713-64,570)	2,119 (1,987-2,265)	785 (662-961)	325 (286-375)	169 (142-204)	161 (110-252)	78 (59-106)	91 (51-181)	19 (14-26)	1,201 (936-1,557)
2007	54,713 (51,786-57,803)	2,421 (2,248-2,618)	702 (598-828)	384 (332-447)	330 (297-372)	159 (102-281)	64 (47-90)	55 (34-94)	19 (13-28)	896 (685-1,201)
2008	51,453 (48,472-54,611)	2,597 (2,403-2,827)	829 (700-985)	436 (376-509)	552 (491-630)	160 (96-327)	78 (58-111)	39 (19-85)	28 (18-45)	1,183 (896-1,589)
2009	57,870 (55,431-60,510)	2,589 (2,454-2,720)	564 (492-648)	306 (280-335)	512 (470-555)	130 (85-219)	77 (61-101)	38 (24-63)	18 (13-24)	1,182 (971-1,428)
2010	38,725 (38,042-39,442)	2,591 (2,521-2,664)	583 (561-608)	382 (364-401)	445 (423-470)	80 (69-96)	52 (47-59)	28 (21-40)	24 (21-27)	919 (841-1,004)
2011	52,853 (52,059-53,715)	2,986 (2,922-3,054)	562 (542-586)	375 (362-390)	344 (323-374)	83 (65-107)	56 (50-64)	51 (44-63)	38 (34-42)	1,026 (943-1,131)
2012	43,069 (42,361-43,838)	4,847 (4,765-4,940)	465 (450-483)	645 (623-668)	556 (537-577)	323 (306-355)	47 (43-52)	28 (22-37)	60 (56-66)	789 (722-886)
2013	47,218 (46,657-47,799)	4,100 (4,037-4,167)	417 (404-433)	618 (603-634)	515 (498-531)	43 (35-53)	34 (31-39)	36 (31-44)	52 (48-57)	835 (798-872)
2014	52,443 (51,846-53,050)	3,614 (3,553-3,684)	494 (480-510)	628 (608-651)	516 (496-540)	42 (36-50)	39 (35-45)	40 (30-55)	52 (48-56)	1,034 (949-1,219)
2015	42,634 (42,215-43,114)	2,977 (2,935-3,020)	486 (450-546)	520 (510-531)	339 (329-349)	63 (58-68)	36 (33-40)	28 (24-34)	55 (52-58)	1,939 (1,880-2,017)
2016	63,987 (63,382-64,616)	4,049 (3,974-4,129)	473 (459-490)	325 (311-340)	272 (261-285)	37 (30-45)	36 (31-43)	38 (33-47)	53 (50-57)	1,603 (1,510-1,733)
2017	74,973 (74,202-75,776)	3,536 (3,457-3,614)	626 (605-650)	445 (429-464)	228 (217-240)	64 (56-75)	38 (32-45)	29 (20-45)	52 (48-58)	1,648 (1,560-1,751)
2018	73,389 (72,671-74,105)	3,991 (3,932-4,052)	1,042 (1,017-1,071)	496 (482-512)	229 (220-238)	30 (25-39)	25 (21-30)	89 (77-119)	59 (55-65)	548 (501-605)
2019	92,165 (91,579-92,801)	3,887 (3,816-3,964)	1,084 (1,068-1,101)	676 (662-691)	145 (139-153)	26 (23-30)	28 (26-32)	71 (46-125)	61 (58-64)	628 (596-666)
2020	88,071 (82,875-94,847)	2,654 (2,452-2,886)	989 (885-1,132)	506 (443-576)	80 (65-98)	30 (17-53)	24 (15-46)	27 (10-82)	65 (50-86)	901 (690-1,224)

Table 9 Estimated annual marine mammal and turtle bycatch (individuals) by estimation group for the large-scale equatorial purse seine fishery from 2003 to 2020. 95% CIs are provided in parentheses. Estimates for 2020 are preliminary.

Year	Marine mammal	Green turtle	Olive ridley turtle	Loggerhead turtle	Hawksbill turtle	Leatherback turtle	Marine turtles nei
2003	1,623 (1,378-1,939)	19 (8-68)	16 (7-44)	1 (0-7)	31 (16-67)	4 (1-19)	208 (162-273)
2004	1,700 (1,511-1,934)	22 (12-43)	23 (15-38)	4 (2-13)	25 (17-38)	9 (5-19)	137 (108-179)
2005	1,322 (1,171-1,502)	40 (31-56)	33 (24-44)	19 (13-32)	25 (17-38)	10 (5-19)	78 (62-103)
2006	1,648 (1,465-1,872)	59 (45-79)	61 (48-79)	40 (28-59)	29 (21-41)	8 (5-15)	24 (18-35)
2007	2,052 (1,805-2,339)	90 (71-119)	77 (60-100)	80 (63-102)	36 (26-52)	6 (4-13)	11 (7-18)
2008	1,925 (1,703-2,184)	76 (56-103)	58 (45-75)	107 (83-142)	44 (32-59)	8 (4-18)	6 (3-12)
2009	2,263 (2,112-2,430)	74 (62-92)	84 (73-99)	108 (91-128)	57 (45-71)	5 (4-9)	7 (5-10)
2010	1,252 (1,206-1,305)	62 (57-68)	63 (58-69)	78 (71-86)	57 (52-64)	9 (7-11)	12 (10-14)
2011	2,120 (2,060-2,176)	87 (82-93)	130 (123-138)	94 (88-103)	81 (75-88)	12 (10-14)	17 (15-20)
2012	3,197 (3,116-3,285)	110 (104-118)	121 (114-129)	89 (83-98)	75 (69-83)	10 (8-13)	19 (17-23)
2013	3,861 (3,789-3,945)	140 (133-148)	110 (104-116)	97 (92-103)	107 (101-113)	11 (10-13)	17 (16-20)
2014	2,952 (2,884-3,026)	92 (85-101)	77 (71-85)	56 (51-62)	72 (66-80)	10 (9-13)	11 (9-13)
2015	1,891 (1,846-1,941)	92 (89-95)	69 (65-74)	56 (54-59)	35 (33-38)	9 (8-11)	11 (10-12)
2016	1,982 (1,922-2,042)	54 (50-60)	75 (70-82)	46 (42-51)	24 (22-28)	13 (12-16)	9 (7-11)
2017	2,214 (2,127-2,300)	67 (62-73)	71 (65-78)	42 (38-48)	26 (23-31)	8 (6-10)	8 (7-10)
2018	1,710 (1,645-1,781)	94 (89-101)	64 (60-68)	70 (66-76)	46 (43-50)	9 (8-12)	7 (6-8)
2019	1,912 (1,848-1,980)	58 (55-62)	48 (43-53)	52 (48-57)	34 (31-40)	5 (4-6)	4 (4-5)
2020	2,298 (2,062-2,569)	30 (23-43)	41 (31-55)	32 (22-46)	13 (8-22)	10 (6-25)	6 (4-15)

Table 10 Average annual bycatch from 2016 to 2020 by estimation group and school association for the large-scale equatorial purse seine fishery. Bycatch units are metric tonnes for finfish estimation groups, and individuals for billfish, shark & ray, marine mammal and turtle estimation groups. 95% CIs are provided in parentheses. Marine mammal and whale shark bycatch estimates from free school sets also includes whale and whale shark sets (see Section 2).

a) Finfish estimation groups

Species group	aFAD	dFAD	log	FS	whale	whale shark
Rainbow runner	204 (193-215)	1,041 (1,000-1,113)	486 (475-499)	64 (62-67)	1 (0-3)	0 (0-0)
Mackerel scad	457 (437-475)	386 (372-412)	288 (281-297)	17 (16-19)	0 (0-1)	0 (0-3)
Oceanic triggerfish	12 (11-13)	189 (184-199)	102 (99-105)	10 (9-10)	0 (0-0)	0 (0-0)
Frigate & bullet tunas	96 (89-104)	20 (18-26)	11 (10-13)	33 (31-36)	0 (0-1)	0 (0-0)
Mahi mahi	28 (25-30)	104 (100-110)	26 (25-26)	8 (7-8)	0 (0-0)	0 (0-0)
Kawakawa	13 (9-19)	10 (8-12)	8 (8-8)	50 (48-54)	1 (0-2)	0 (0-0)
Wahoo	1 (1-2)	72 (70-77)	4 (4-4)	2 (2-2)	0 (0-0)	0 (0-0)
Albacore	1 (0-1)	16 (14-20)	6 (6-6)	44 (40-49)	0 (0-1)	0 (0-0)
Barracudas	2 (2-2)	11 (11-12)	3 (3-3)	3 (2-3)	0 (0-0)	0 (0-0)
Sea chubs	1 (1-1)	13 (13-14)	7 (7-7)	1 (0-1)	0 (0-0)	0 (0-0)
Amberjacks	0 (0-0)	13 (12-16)	3 (2-5)	1 (1-2)	0 (0-0)	0 (0-0)
Pomfrets	0 (0-0)	3 (2-3)	1 (1-1)	1 (0-1)	0 (0-0)	0 (0-0)
Scombrids nei	0 (0-0)	1 (1-1)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)
Trevallies	0 (0-0)	4 (4-5)	1 (1-1)	0 (0-0)	0 (0-0)	0 (0-0)
Filefishes	0 (0-0)	2 (2-2)	0 (0-1)	0 (0-0)	0 (0-0)	0 (0-0)
Sunfish	0 (0-0)	3 (3-3)	1 (1-1)	2 (2-3)	0 (0-0)	0 (0-0)
Batfishes	0 (0-0)	2 (2-2)	1 (1-1)	0 (0-0)	0 (0-0)	0 (0-0)
Carangids nei	0 (0-1)	5 (4-5)	1 (1-1)	0 (0-1)	0 (0-0)	0 (0-0)
Triple-tail	0 (0-0)	1 (0-1)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)
Golden trevally	5 (5-6)	2 (2-2)	1 (1-1)	0 (0-0)	0 (0-0)	0 (0-0)
Marine fishes nei	0 (0-0)	2 (2-2)	2 (2-2)	1 (1-1)	0 (0-0)	0 (0-0)

b) Billfish estimation groups

Species group	aFAD	dFAD	log	FS	whale	whale shark
Blue marlin	45 (41-51)	1,536 (1,507-1,575)	224 (219-228)	1,896 (1,864-1,932)	22 (17-28)	2 (1-4)
Black marlin	17 (15-20)	554 (538-573)	74 (71-76)	574 (557-595)	5 (3-7)	1 (0-2)
Striped marlin	14 (12-15)	253 (242-265)	44 (43-46)	279 (267-293)	4 (2-5)	0 (0-1)
Sailfish (indo-pacific)	4 (3-6)	58 (55-61)	13 (12-13)	141 (134-150)	4 (2-7)	0 (0-1)
Swordfish	2 (2-4)	21 (19-24)	6 (5-6)	21 (19-24)	0 (0-0)	0 (0-1)
Short-billed spearfish	2 (1-3)	17 (15-19)	2 (1-2)	39 (36-45)	1 (0-3)	0 (0-1)
Billfishes nei	0 (0-0)	0 (0-0)	0 (0-0)	6 (1-22)	0 (0-0)	0 (0-0)

c) Shark & ray estimation groups

Species group	aFAD	dFAD	log	FS	whale	whale shark
Silky shark	2,127 (2,054-2,215)	40,377 (39,458-41,634)	7,746 (7,603-7,917)	27,382 (26,806-27,991)	813 (691-925)	59 (40-86)
Mobulid rays	71 (62-83)	795 (776-819)	128 (124-133)	2,592 (2,533-2,649)	34 (24-45)	4 (1-8)
Oceanic whitetip shar	6 (4-9)	517 (495-545)	49 (44-54)	268 (255-282)	4 (2-6)	0 (0-1)
Whale shark	2 (1-3)	37 (35-39)	5 (5-6)	447 (430-464)	-	-
Pelagic stingray	4 (3-6)	69 (66-73)	7 (7-8)	110 (105-116)	0 (0-1)	0 (0-1)
Mako sharks	1 (0-3)	20 (16-27)	2 (1-3)	15 (12-18)	0 (0-0)	0 (0-0)
Thresher sharks	2 (1-3)	16 (13-22)	2 (2-3)	10 (8-12)	0 (0-0)	0 (0-0)
Blue shark	2 (2-3)	22 (18-31)	0 (0-1)	23 (17-34)	4 (0-14)	0 (0-0)
Hammerhead sharks	2 (2-3)	26 (23-30)	2 (2-2)	27 (25-31)	0 (0-1)	0 (0-0)
Elasmobranchs nei	27 (21-34)	382 (342-442)	140 (127-154)	506 (469-555)	10 (1-29)	0 (0-0)

d) Marine mammal and turtle estimation groups

Species group	aFAD	dFAD	log	FS	whale	whale shark
Marine mammal	126 (105-150)	669 (634-712)	178 (170-188)	1,050 (1,004-1,105)	-	-
Green turtle	2 (1-3)	13 (12-15)	4 (4-5)	41 (38-45)	0 (0-1)	0 (0-0)
Olive ridley turtle	5 (3-6)	14 (12-15)	6 (5-6)	35 (33-39)	0 (0-1)	0 (0-1)
Loggerhead turtle	1 (1-2)	13 (12-14)	3 (3-3)	31 (28-35)	1 (0-1)	0 (0-1)
Hawksbill turtle	1 (0-2)	6 (5-7)	2 (2-2)	20 (18-22)	0 (0-1)	0 (0-0)
Marine turtles nei	0 (0-1)	2 (2-3)	0 (0-0)	5 (4-7)	0 (0-0)	0 (0-0)
Leatherback turtle	0 (0-0)	2 (2-4)	0 (0-0)	7 (5-9)	0 (0-0)	0 (0-0)

Table 11 Average bycatch rates from 2016 to 2020 by estimation group and school association for the large-scale equatorial purse seine fishery. Bycatch rate units are metric tonnes per set for finfish estimation groups, and individuals per set for billfish, shark & ray, marine mammal and turtle estimation groups. 95% CIs are provided in parentheses. Marine mammal and whale shark bycatch rate estimates for free school sets also includes whale and whale shark sets (see Section 2).

a) Finfish estimation groups

Species group	aFAD	dFAD	log	FS	whale	whale shark
Rainbow runner	0.101 (0.096-0.107)	0.077 (0.074-0.083)	0.293 (0.286-0.301)	0.002 (0.002-0.002)	0.006 (0.002-0.014)	0.001 (0.000-0.004)
Mackerel scad	0.226 (0.217-0.235)	0.029 (0.028-0.031)	0.173 (0.169-0.179)	0.000 (0.000-0.001)	0.001 (0.000-0.003)	0.002 (0.000-0.093)
Oceanic triggerfish	0.006 (0.005-0.006)	0.014 (0.014-0.015)	0.061 (0.060-0.063)	0.000 (0.000-0.000)	0.000 (0.000-0.001)	0.000 (0.000-0.001)
Frigate & bullet tunas	0.048 (0.044-0.051)	0.001 (0.001-0.002)	0.007 (0.006-0.008)	0.001 (0.001-0.001)	0.002 (0.001-0.005)	0.002 (0.000-0.009)
Mahi mahi	0.014 (0.013-0.015)	0.008 (0.007-0.008)	0.015 (0.015-0.016)	0.000 (0.000-0.000)	0.000 (0.000-0.001)	0.000 (0.000-0.000)
Kawakawa	0.006 (0.005-0.010)	0.001 (0.001-0.001)	0.005 (0.005-0.005)	0.001 (0.001-0.002)	0.003 (0.001-0.009)	0.000 (0.000-0.002)
Wahoo	0.001 (0.001-0.001)	0.005 (0.005-0.006)	0.002 (0.002-0.002)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.014)
Albacore	0.000 (0.000-0.001)	0.001 (0.001-0.001)	0.004 (0.004-0.004)	0.001 (0.001-0.001)	0.001 (0.000-0.004)	0.000 (0.000-0.014)
Barracudas	0.001 (0.001-0.001)	0.001 (0.001-0.001)	0.002 (0.002-0.002)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.005)
Sea chubs	0.000 (0.000-0.001)	0.001 (0.001-0.001)	0.004 (0.004-0.004)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)
Amberjacks	0.000 (0.000-0.000)	0.001 (0.001-0.001)	0.002 (0.001-0.003)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)
Pomfrets	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)
Scombrids nei	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)
Trevallies	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.001 (0.001-0.001)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)
Filefishes	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)
Sunfish	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)
Batfishes	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.001 (0.001-0.001)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)
Carangids nei	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.001 (0.000-0.001)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)
Triple-tail	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)
Golden trevally	0.003 (0.002-0.003)	0.000 (0.000-0.000)	0.001 (0.001-0.001)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)
Marine fishes nei	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.001 (0.001-0.001)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)

b) Billfish estimation groups

Species group	aFAD	dFAD	log	FS	whale	whale shark
Blue marlin	0.022 (0.020-0.025)	0.114 (0.112-0.117)	0.135 (0.132-0.138)	0.054 (0.053-0.055)	0.100 (0.078-0.126)	0.083 (0.042-0.139)
Black marlin	0.009 (0.007-0.010)	0.041 (0.040-0.043)	0.044 (0.043-0.046)	0.016 (0.016-0.017)	0.021 (0.012-0.030)	0.028 (0.000-0.056)
Striped marlin	0.007 (0.006-0.008)	0.019 (0.018-0.020)	0.027 (0.026-0.028)	0.008 (0.008-0.008)	0.016 (0.008-0.025)	0.014 (0.000-0.035)
Sailfish (indo-pacific)	0.002 (0.001-0.003)	0.004 (0.004-0.005)	0.008 (0.007-0.008)	0.004 (0.004-0.004)	0.017 (0.007-0.031)	0.000 (0.000-0.035)
Swordfish	0.001 (0.001-0.002)	0.002 (0.001-0.002)	0.003 (0.003-0.004)	0.001 (0.001-0.001)	0.000 (0.000-0.001)	0.000 (0.000-0.028)
Short-billed spearfish	0.001 (0.001-0.001)	0.001 (0.001-0.001)	0.001 (0.001-0.001)	0.001 (0.001-0.001)	0.005 (0.000-0.013)	0.000 (0.000-0.021)
Billfishes nei	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.001)	0.000 (0.000-0.000)	0.000 (0.000-0.000)

c) Shark & ray estimation groups

Species group	aFAD	dFAD	log	FS	whale	whale shark
Silky shark	1.054 (1.018-1.098)	2.993 (2.925-3.087)	4.669 (4.583-4.772)	0.781 (0.764-0.798)	3.684 (3.133-4.192)	2.062 (1.382-2.987)
Mobulid rays	0.035 (0.031-0.041)	0.059 (0.058-0.061)	0.077 (0.075-0.080)	0.074 (0.072-0.076)	0.154 (0.111-0.203)	0.139 (0.042-0.285)
Oceanic whitetip shar	0.003 (0.002-0.004)	0.038 (0.037-0.040)	0.029 (0.027-0.033)	0.008 (0.007-0.008)	0.016 (0.008-0.026)	0.007 (0.000-0.035)
Whale shark	0.001 (0.000-0.001)	0.003 (0.003-0.003)	0.003 (0.003-0.003)	0.013 (0.012-0.013)	-	-
Pelagic stingray	0.002 (0.001-0.003)	0.005 (0.005-0.005)	0.004 (0.004-0.005)	0.003 (0.003-0.003)	0.002 (0.000-0.005)	0.000 (0.000-0.021)
Mako sharks	0.000 (0.000-0.001)	0.002 (0.001-0.002)	0.001 (0.001-0.002)	0.000 (0.000-0.001)	0.000 (0.000-0.002)	0.000 (0.000-0.000)
Thresher sharks	0.001 (0.000-0.001)	0.001 (0.001-0.002)	0.001 (0.001-0.002)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)
Blue shark	0.001 (0.001-0.001)	0.002 (0.001-0.002)	0.000 (0.000-0.000)	0.001 (0.000-0.001)	0.018 (0.000-0.065)	0.000 (0.000-0.000)
Hammerhead sharks	0.001 (0.001-0.001)	0.002 (0.002-0.002)	0.001 (0.001-0.001)	0.001 (0.001-0.001)	0.002 (0.000-0.005)	0.000 (0.000-0.007)
Elasmobranchs nei	0.013 (0.011-0.017)	0.028 (0.025-0.033)	0.084 (0.076-0.093)	0.014 (0.013-0.016)	0.045 (0.004-0.133)	0.000 (0.000-0.014)

d) Marine mammal and turtle estimation groups

Species group	aFAD	dFAD	log	FS	whale	whale shark
Marine mammal	0.062 (0.052-0.074)	0.050 (0.047-0.053)	0.107 (0.102-0.113)	0.030 (0.029-0.032)	-	-
Green turtle	0.001 (0.001-0.001)	0.001 (0.001-0.001)	0.003 (0.002-0.003)	0.001 (0.001-0.001)	0.002 (0.000-0.005)	0.000 (0.000-0.000)
Olive ridley turtle	0.002 (0.002-0.003)	0.001 (0.001-0.001)	0.003 (0.003-0.004)	0.001 (0.001-0.001)	0.001 (0.000-0.003)	0.007 (0.000-0.021)
Loggerhead turtle	0.001 (0.000-0.001)	0.001 (0.001-0.001)	0.002 (0.002-0.002)	0.001 (0.001-0.001)	0.003 (0.001-0.005)	0.007 (0.000-0.021)
Hawksbill turtle	0.000 (0.000-0.001)	0.000 (0.000-0.001)	0.001 (0.001-0.001)	0.001 (0.001-0.001)	0.000 (0.000-0.003)	0.000 (0.000-0.014)
Marine turtles nei	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)
Leatherback turtle	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)	0.000 (0.000-0.000)

Figures

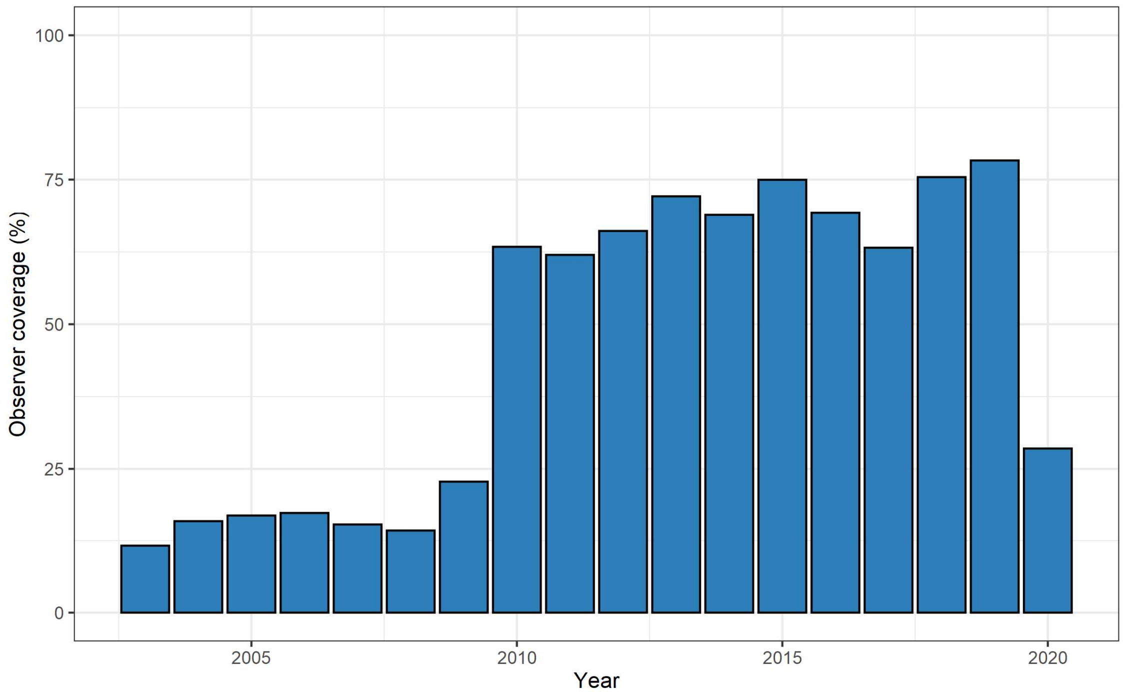

Figure 1 Annual observer coverage in the large-scale equatorial purse seine fishery, 2003 to 2020, where observer coverage is defined as the percentage of sets for which observer data are available in SPC data holdings.

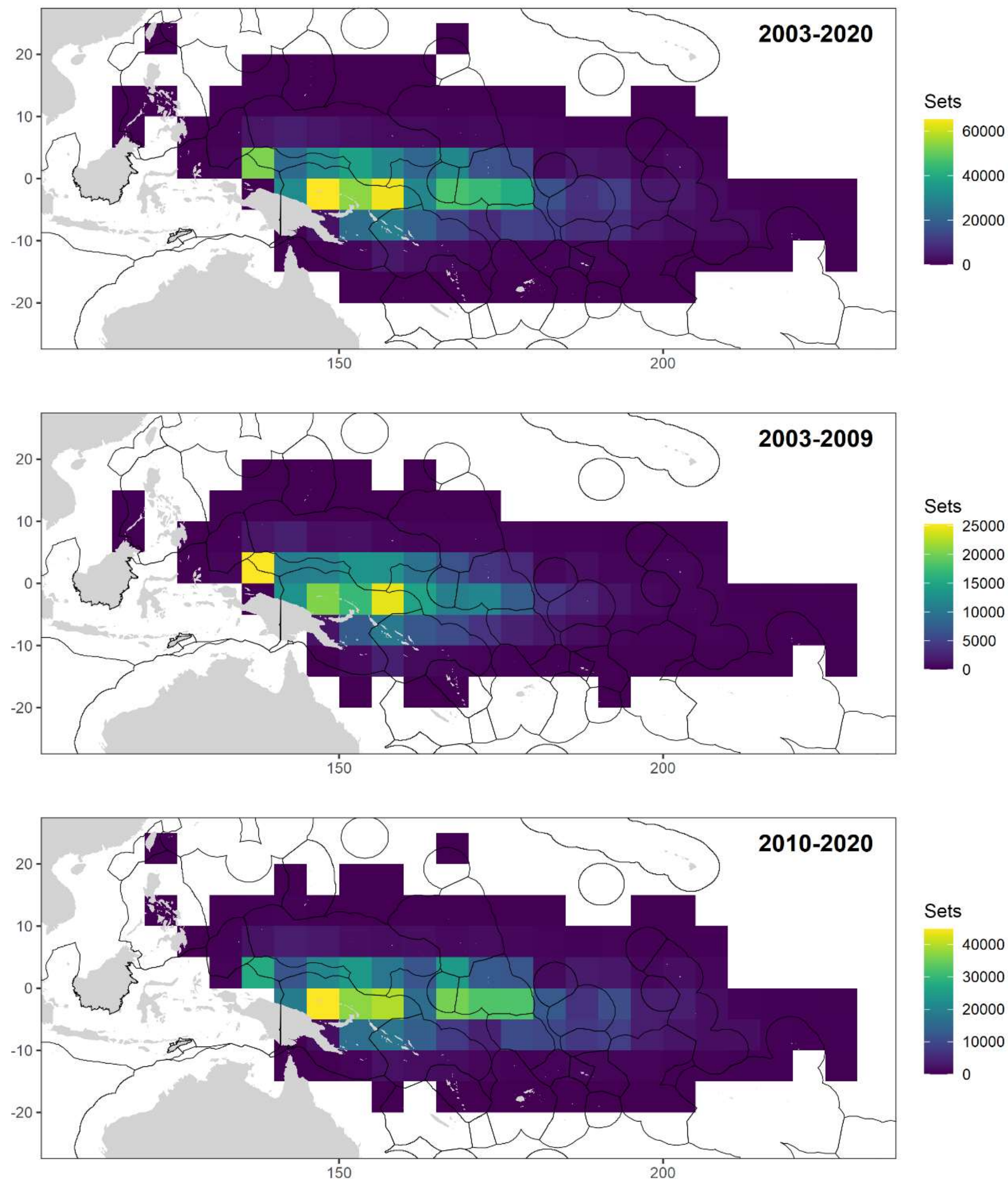

Figure 2 Reported sets of the large-scale equatorial purse seine fishery by 5° cell for 2003 to 2020 (top), 2003 to 2009 (middle) and 2010 to 2020 (bottom).

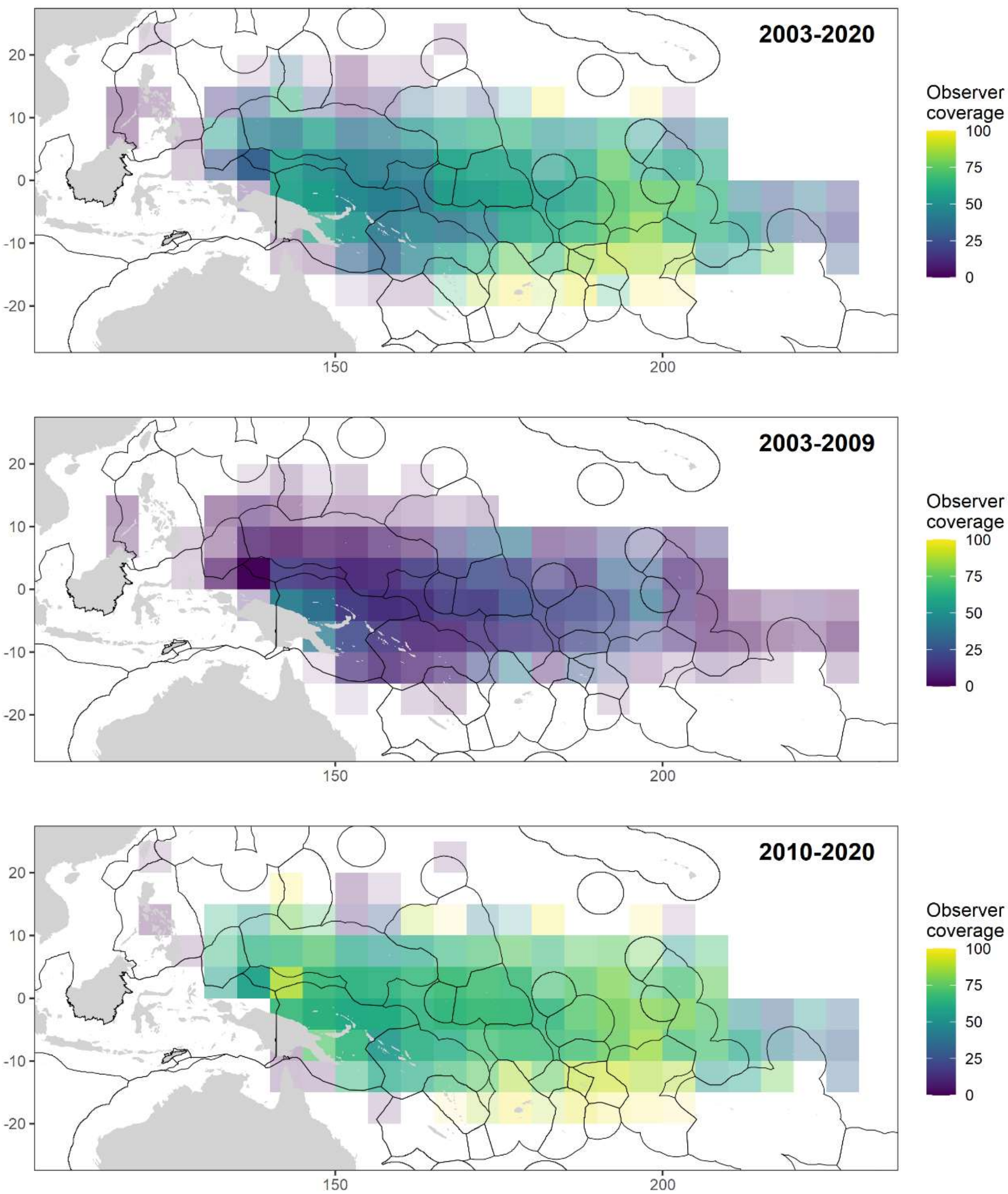

Figure 3 Observer coverage of the large-scale equatorial purse seine fishery by 5° cell for 2003 to 2020 (top), 2003 to 2009 (middle) and 2010 to 2020 (bottom). Observer coverage was defined as the percentage of sets for which observer data are available in SPC data holdings. The transparency of each 5° cell is a function of reported effort, such that cells with less reported effort are more transparent.

Appendix A

Estimated effects of covariates on bycatch presence/absence

Selected finfish estimation groups

Rainbow runner

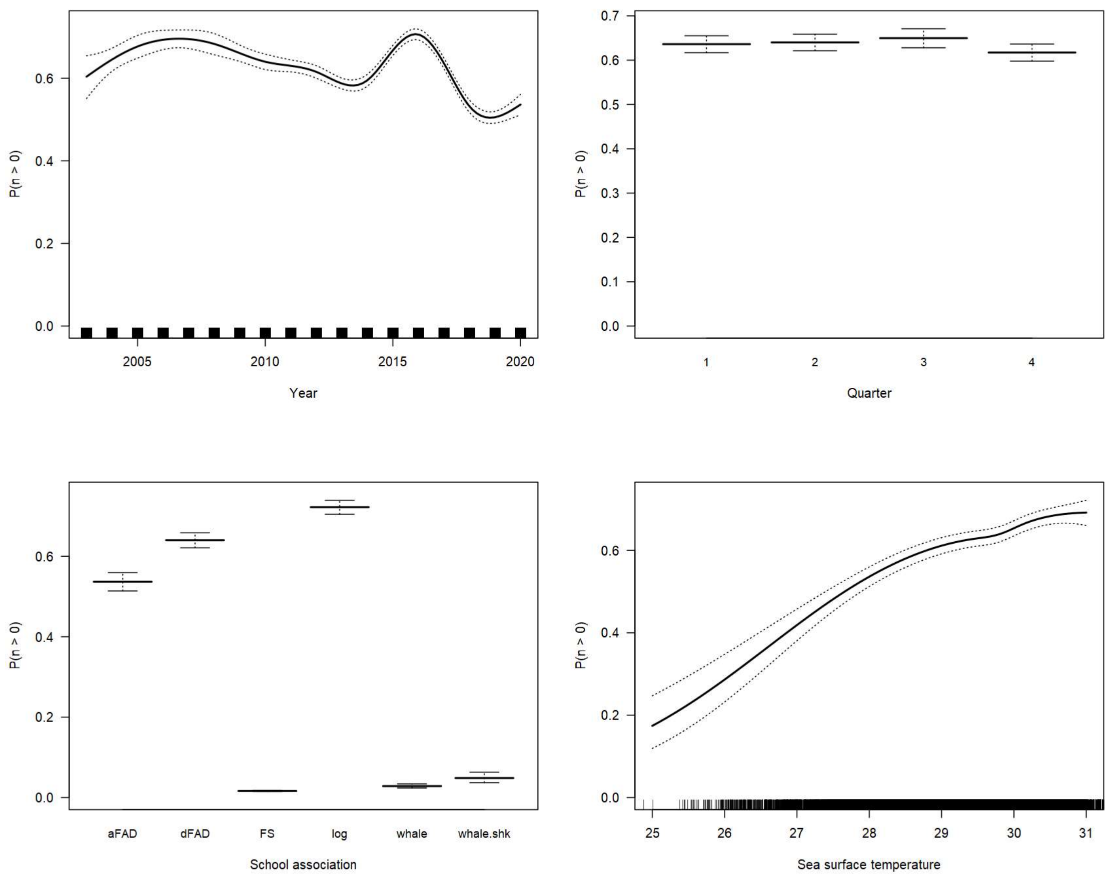

Figure 4 Predicted probability of presence (mean ± 2 s.e.) for rainbow runner against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C.

Mackerel scad

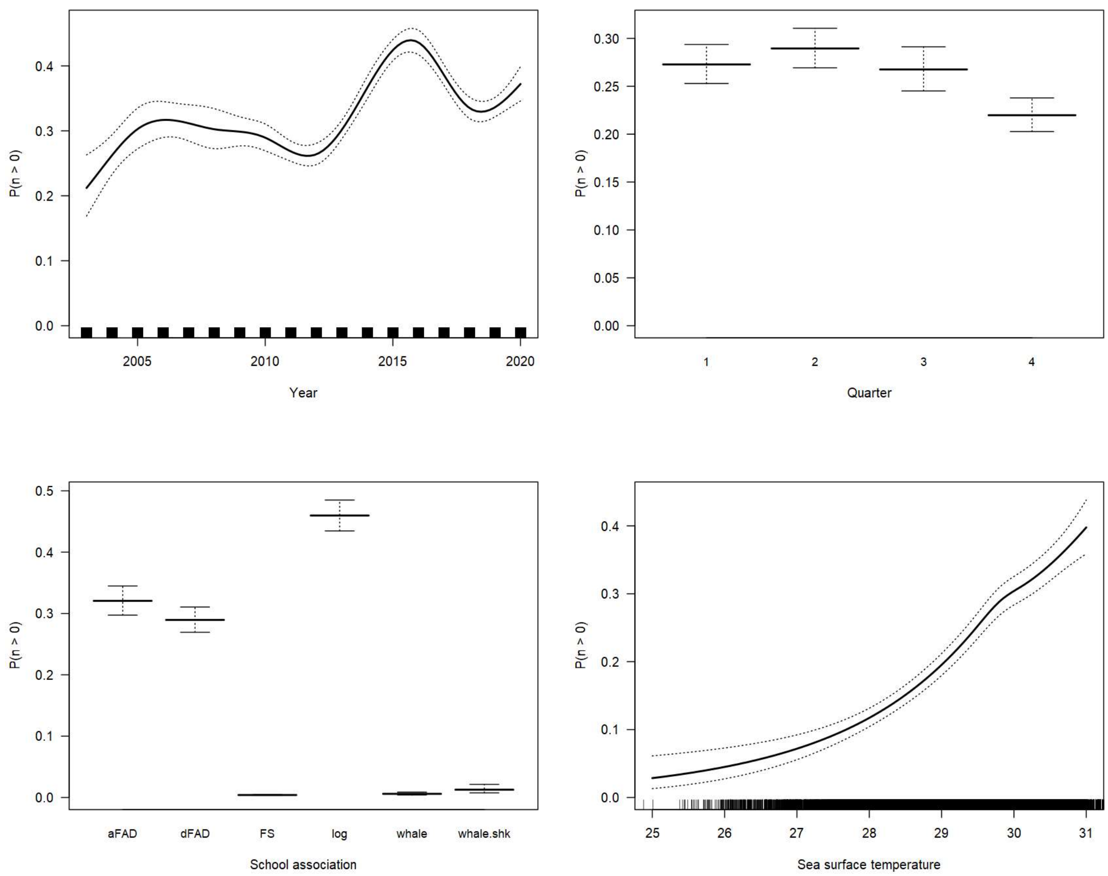

Figure 5 Predicted probability of presence (mean ± 2 s.e.) for mackerel scad against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C.

Oceanic triggerfish

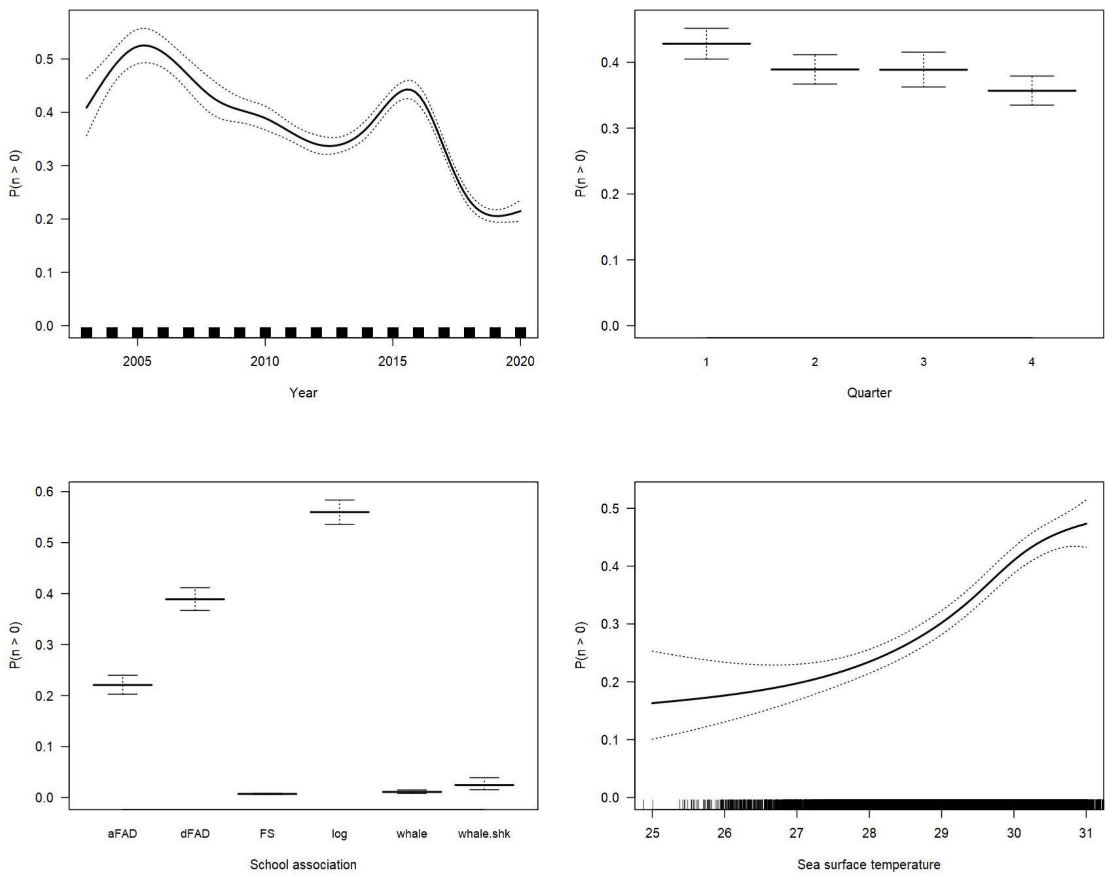

Figure 6 Predicted probability of presence (mean ± 2 s.e.) for oceanic triggerfish against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C.

Frigate & bullet tuna

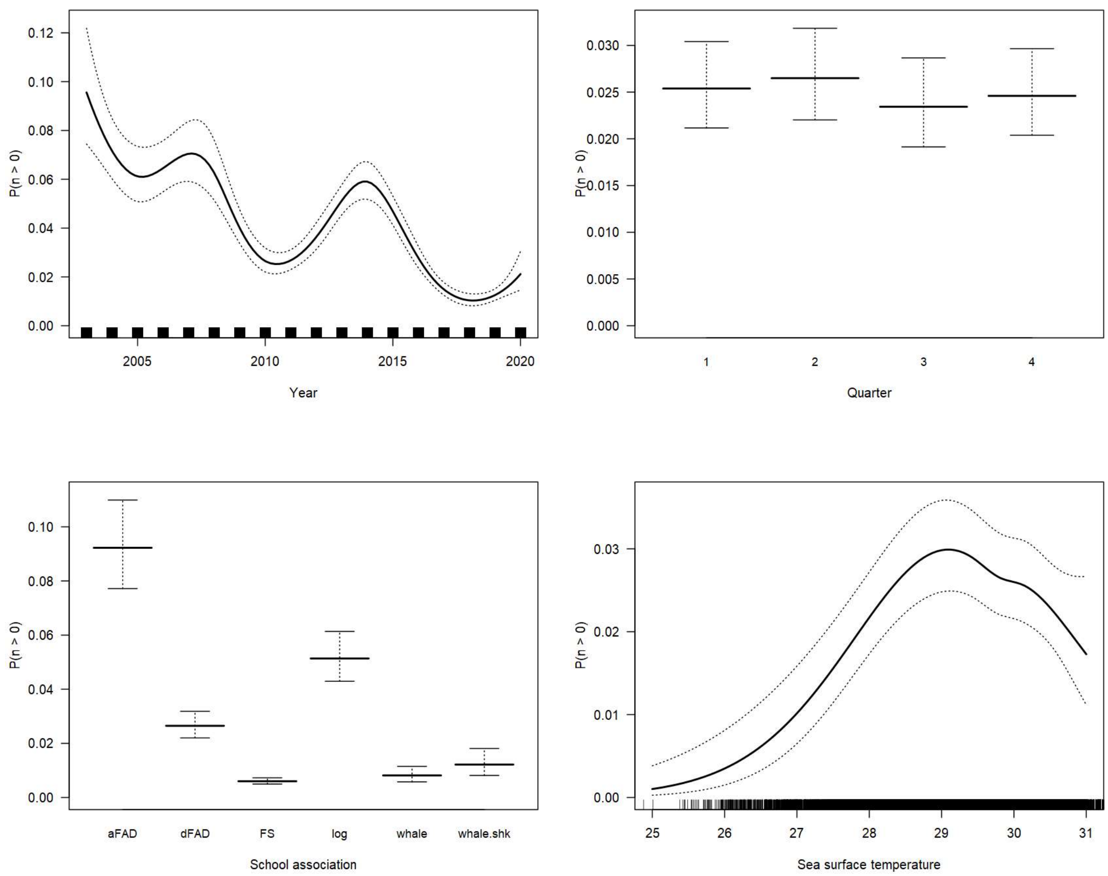

Figure 7 Predicted probability of presence (mean ± 2 s.e.) for frigate & bullet tuna against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C.

Mahi mahi (common dolphinfish)

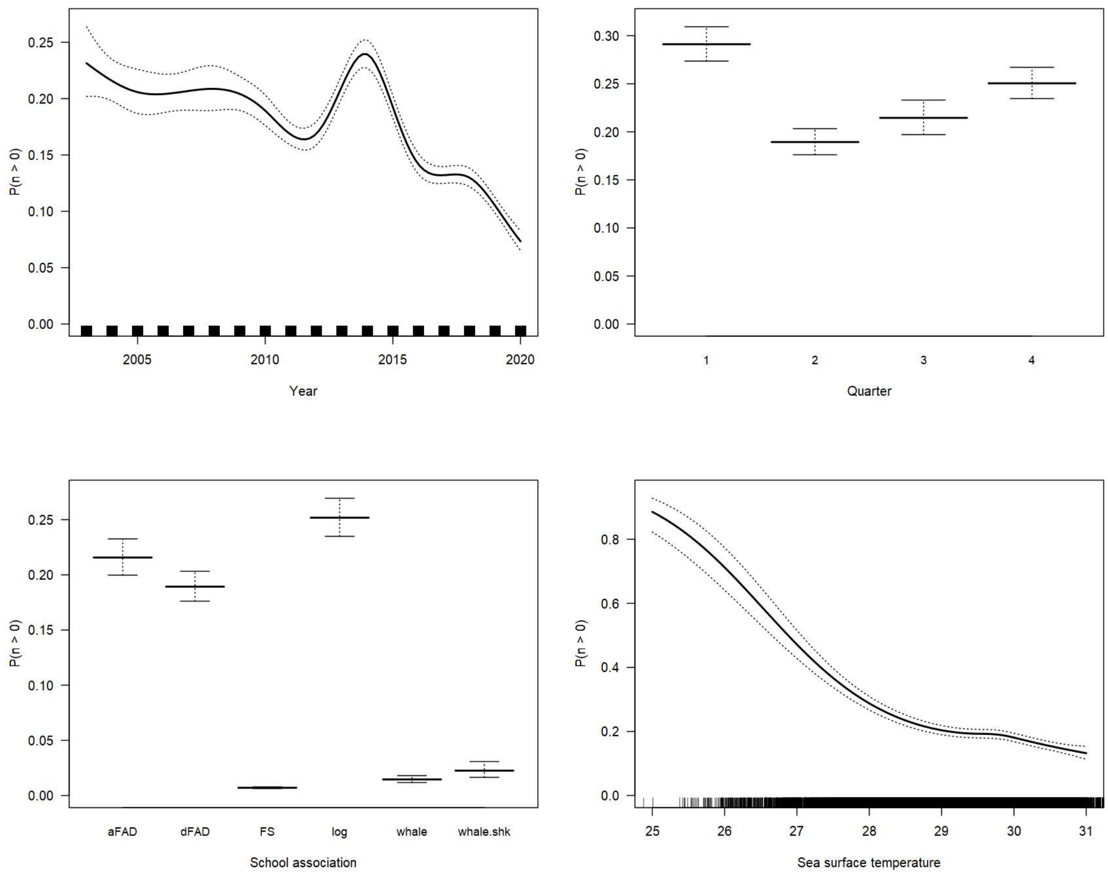

Figure 8 Predicted probability of presence (mean ± 2 s.e.) for mahi mahi against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C.

Kawakawa

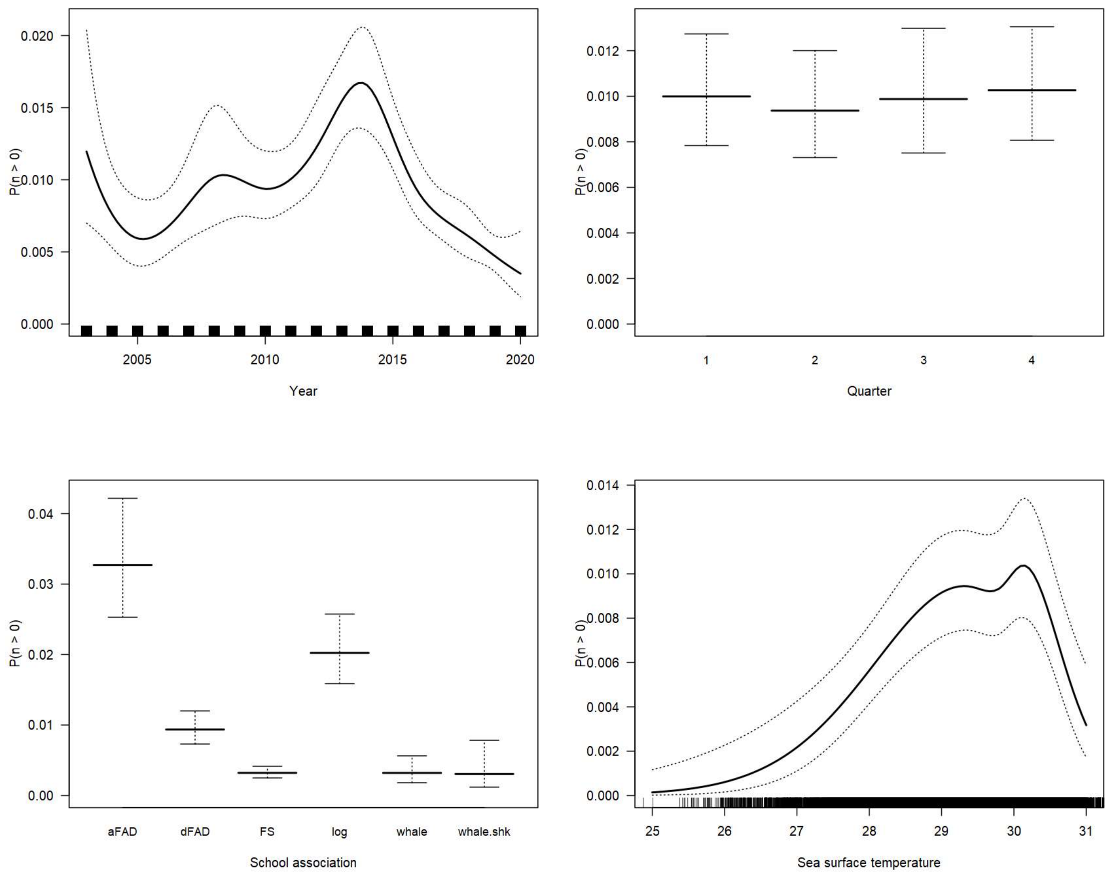

Figure 9 Predicted probability of presence (mean ± 2 s.e.) for kawakawa against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C.

Wahoo

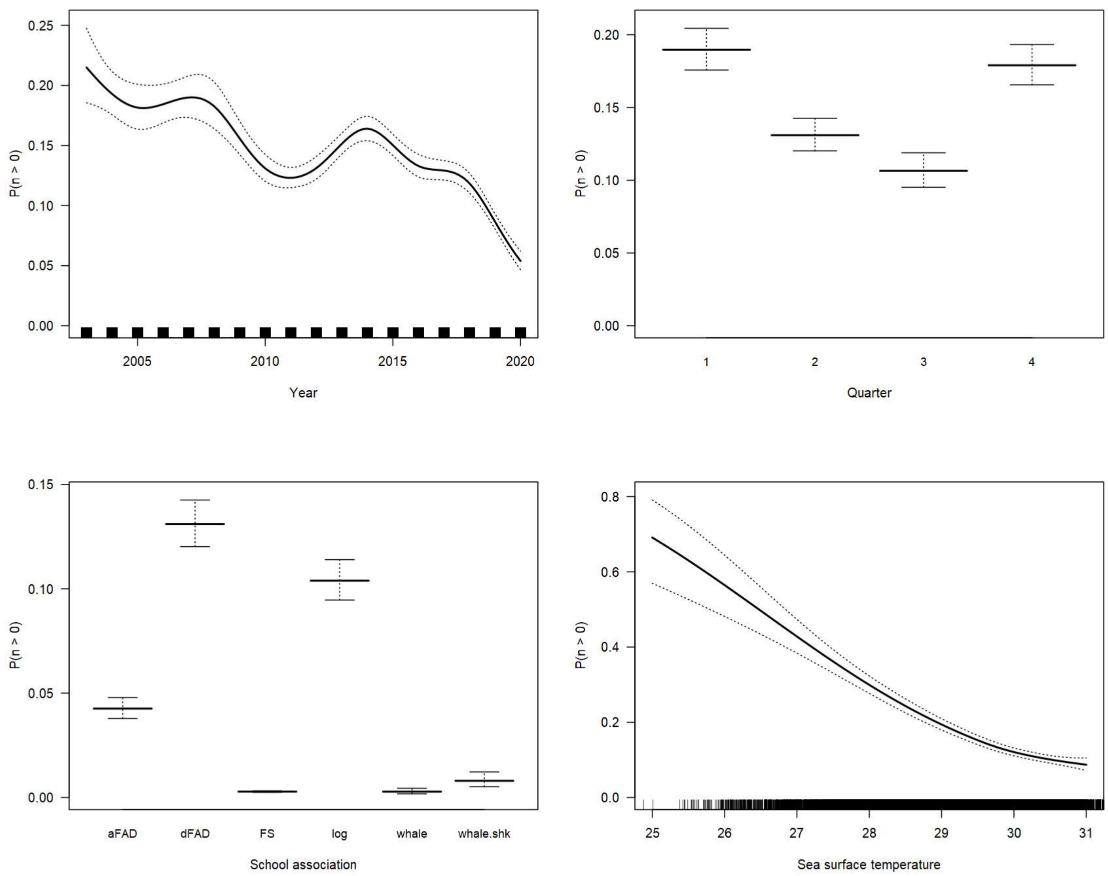

Figure 10 Predicted probability of presence (mean ± 2 s.e.) for wahoo against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C.

Selected billfish estimation groups

Blue marlin

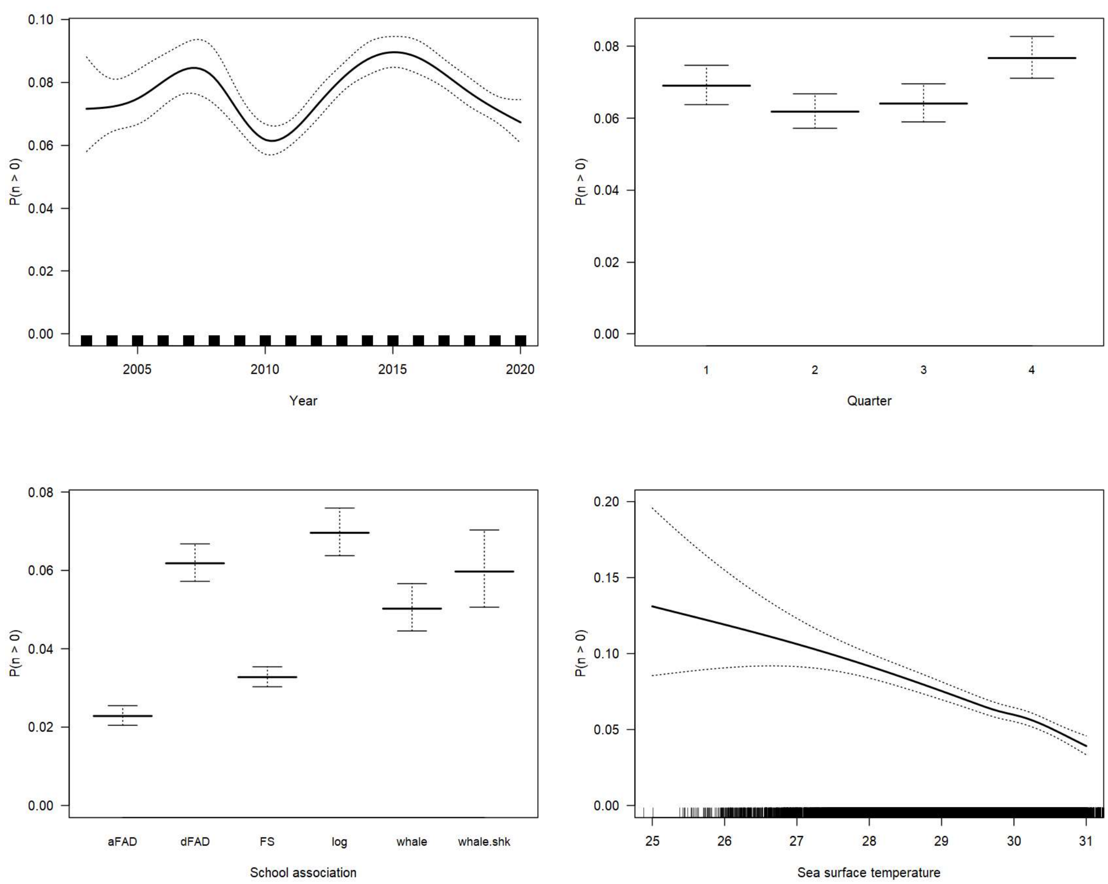

Figure 11 Predicted probability of presence (mean ± 2 s.e.) for blue marlin against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C.

Black marlin

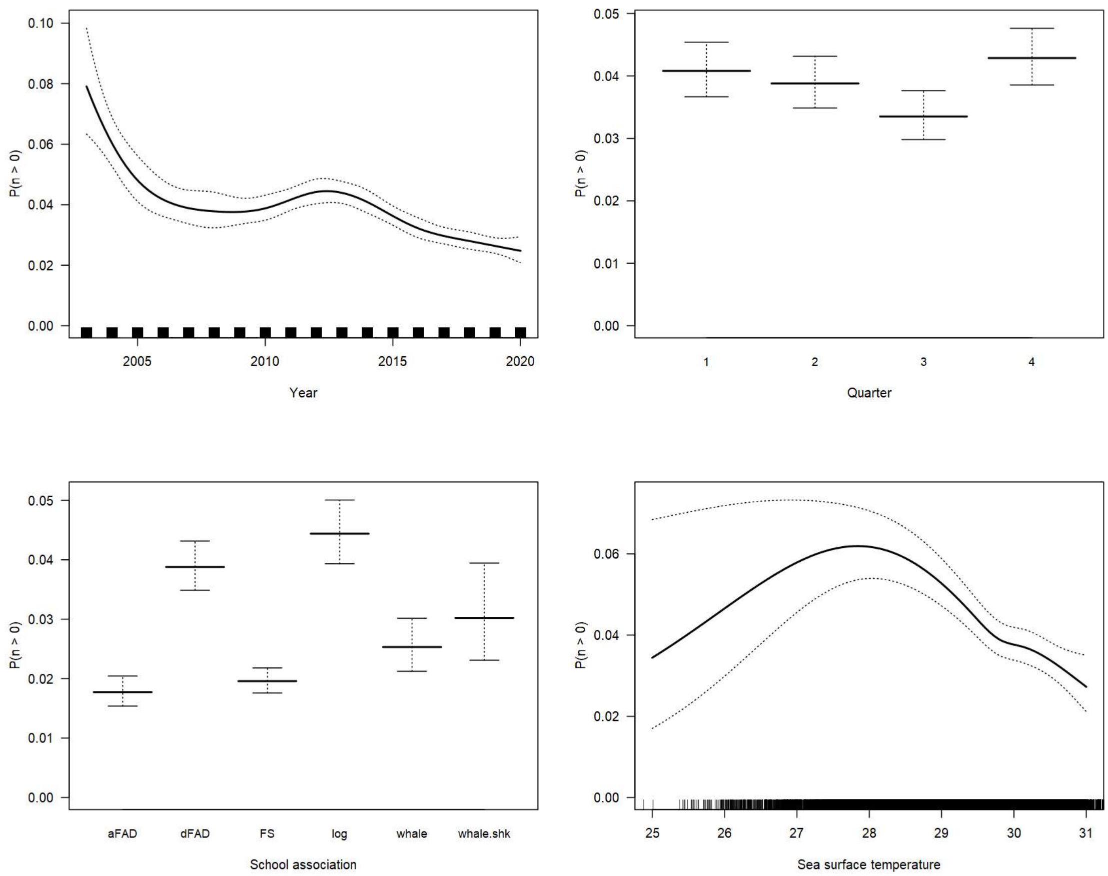

Figure 12 Predicted probability of presence (mean ± 2 s.e.) for black marlin against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C.

Striped marlin

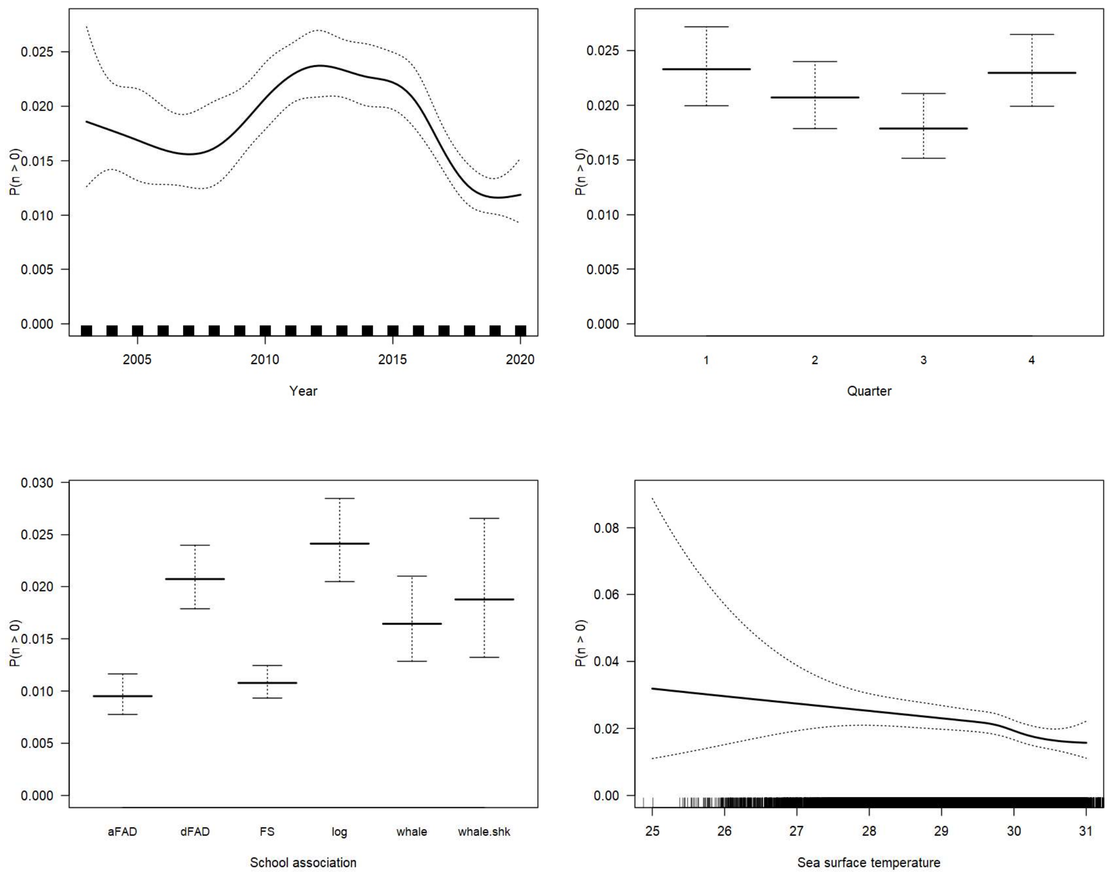

Figure 13 Predicted probability of presence (mean ± 2 s.e.) for striped marlin against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C.

Indo-Pacific sailfish

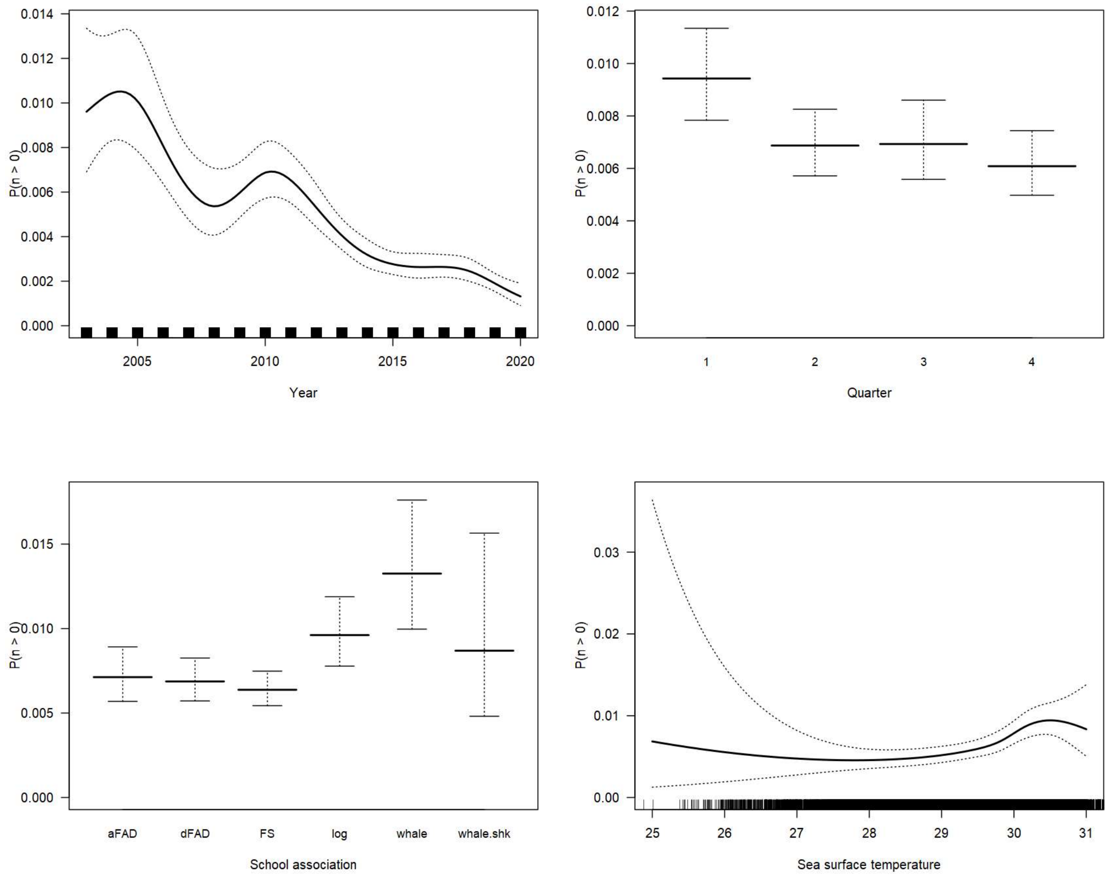

Figure 14 Predicted probability of presence (mean ± 2 s.e.) for Indo-Pacific sailfish against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C.

Swordfish

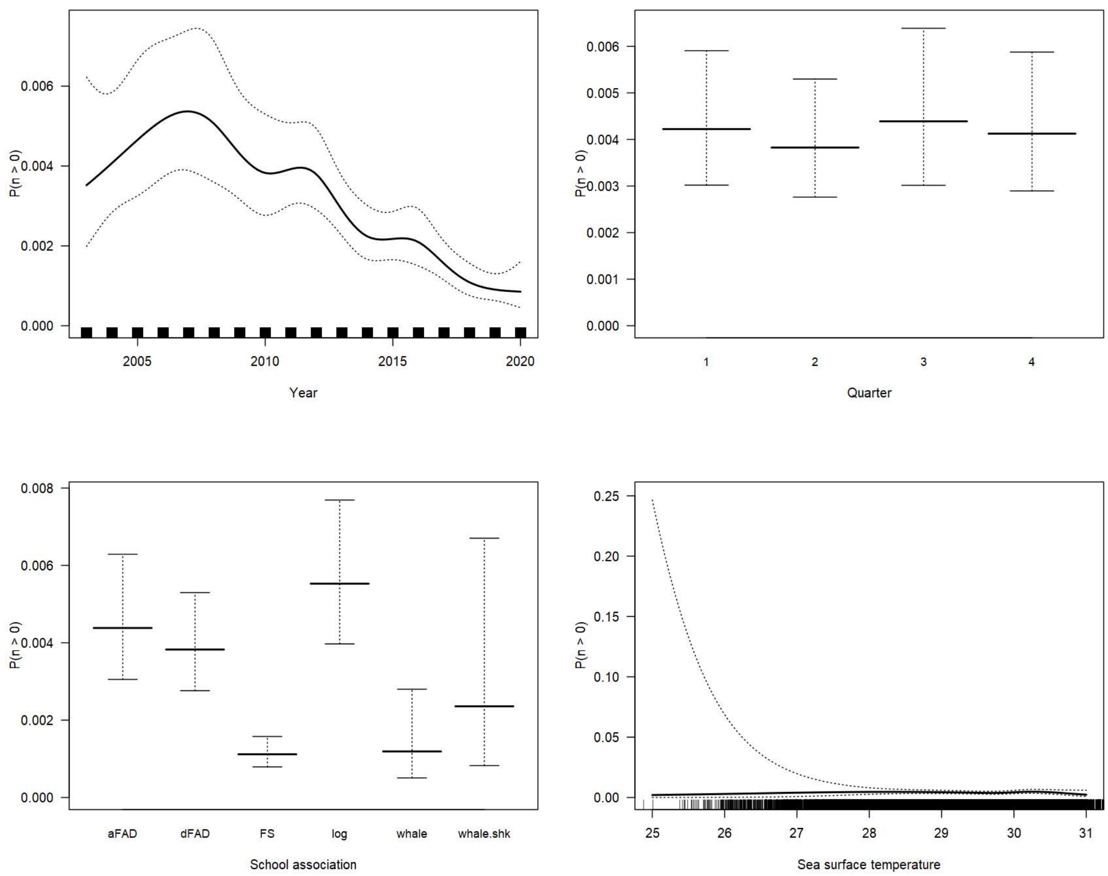

Figure 15 Predicted probability of presence (mean ± 2 s.e.) for swordfish against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C.

Selected shark & ray estimation groups

Silky shark

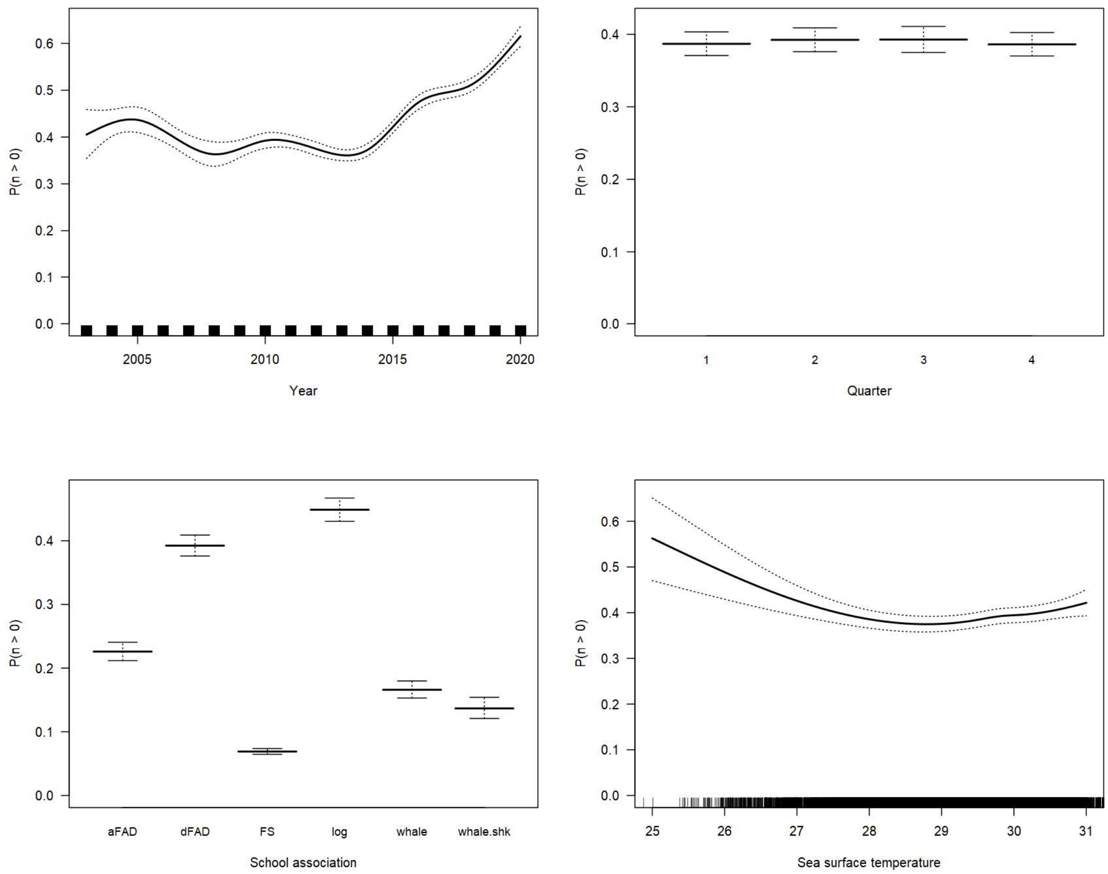

Figure 16 Predicted probability of presence (mean ± 2 s.e.) for silky shark against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C.

Oceanic whitetip

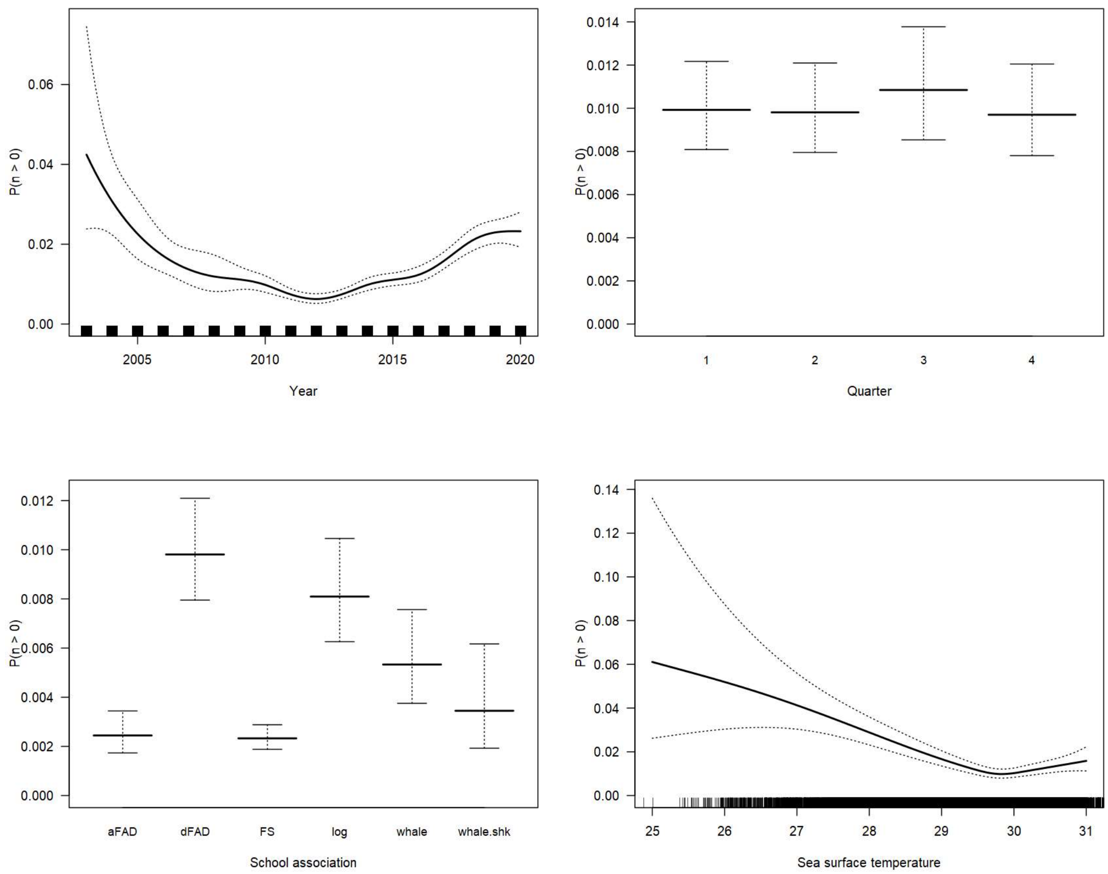

Figure 17 Predicted probability of presence (mean ± 2 s.e.) for oceanic whitetip against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C.

Mobulid rays

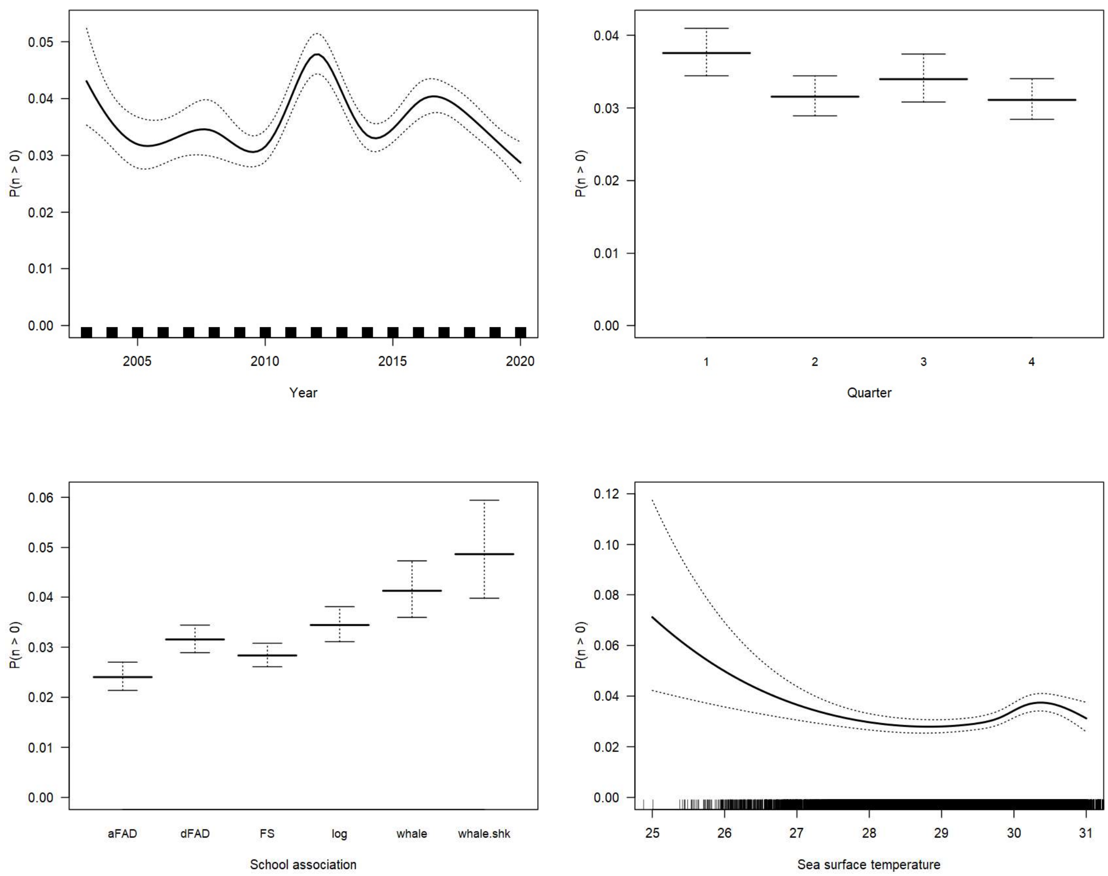

Figure 18 Predicted probability of presence (mean ± 2 s.e.) for mobulid rays against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C.

Whale shark

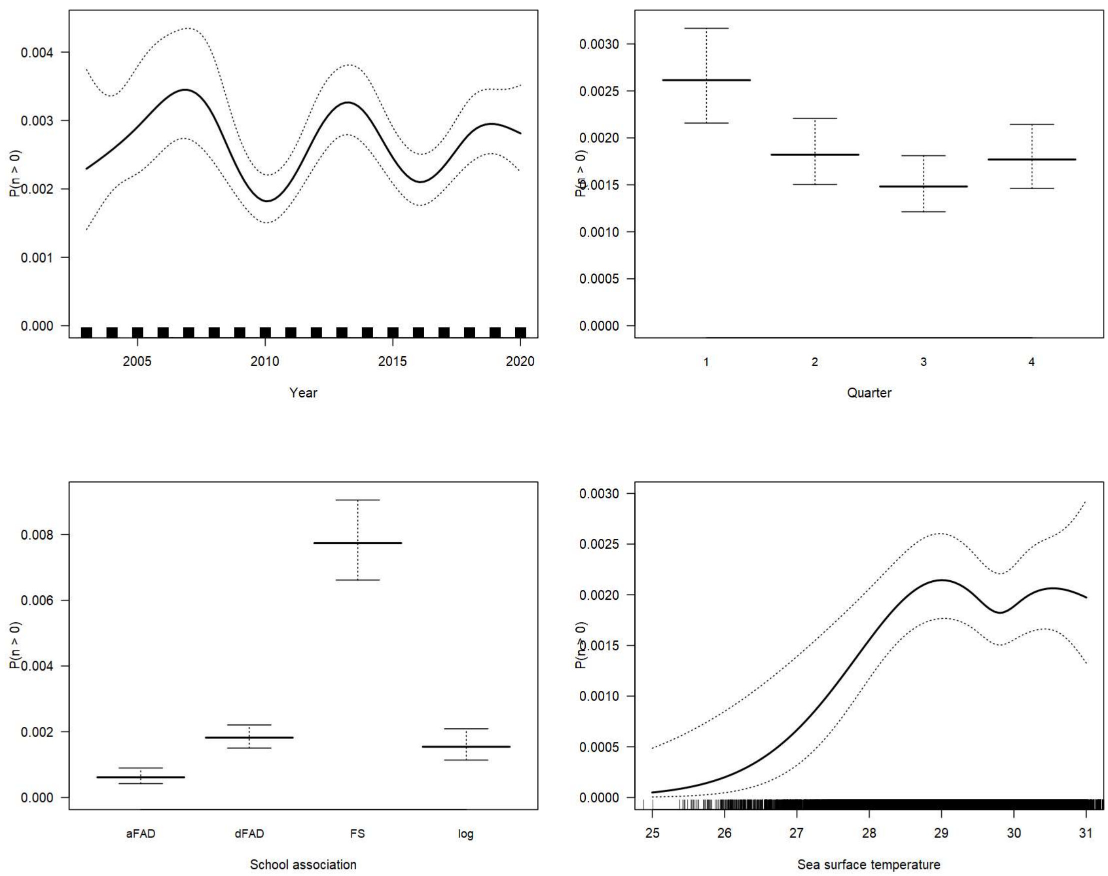

Figure 19 Predicted probability of presence (mean ± 2 s.e.) for whale shark against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C. Whale and whale-shark sets were treated as free school sets when fitting the presence-absence model for whale shark (see Section 2).

Selected marine mammal and sea turtle estimation groups

Marine mammals

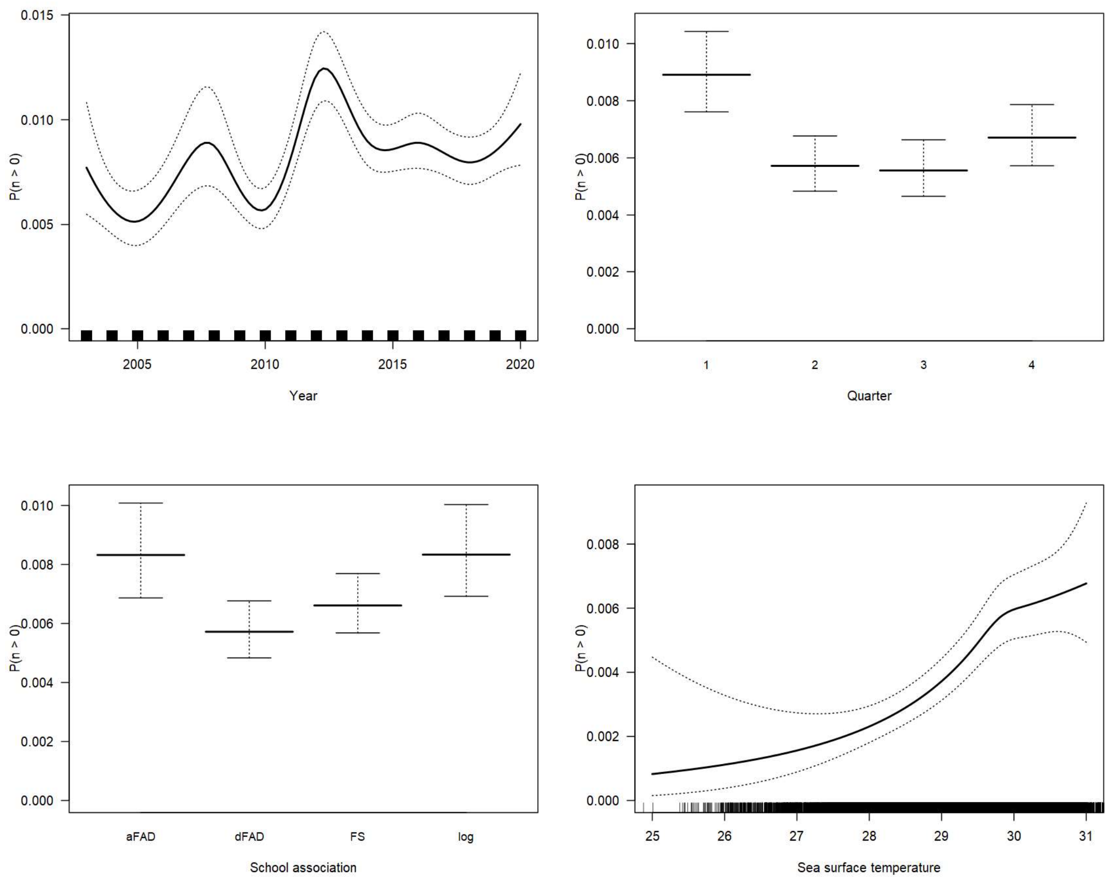

Figure 20 Predicted probability of presence (mean ± 2 s.e.) for marine mammals against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C. Whale and whale-shark sets were treated as free school sets when fitting the presence-absence model for whale shark (see Section 2).

Green turtle

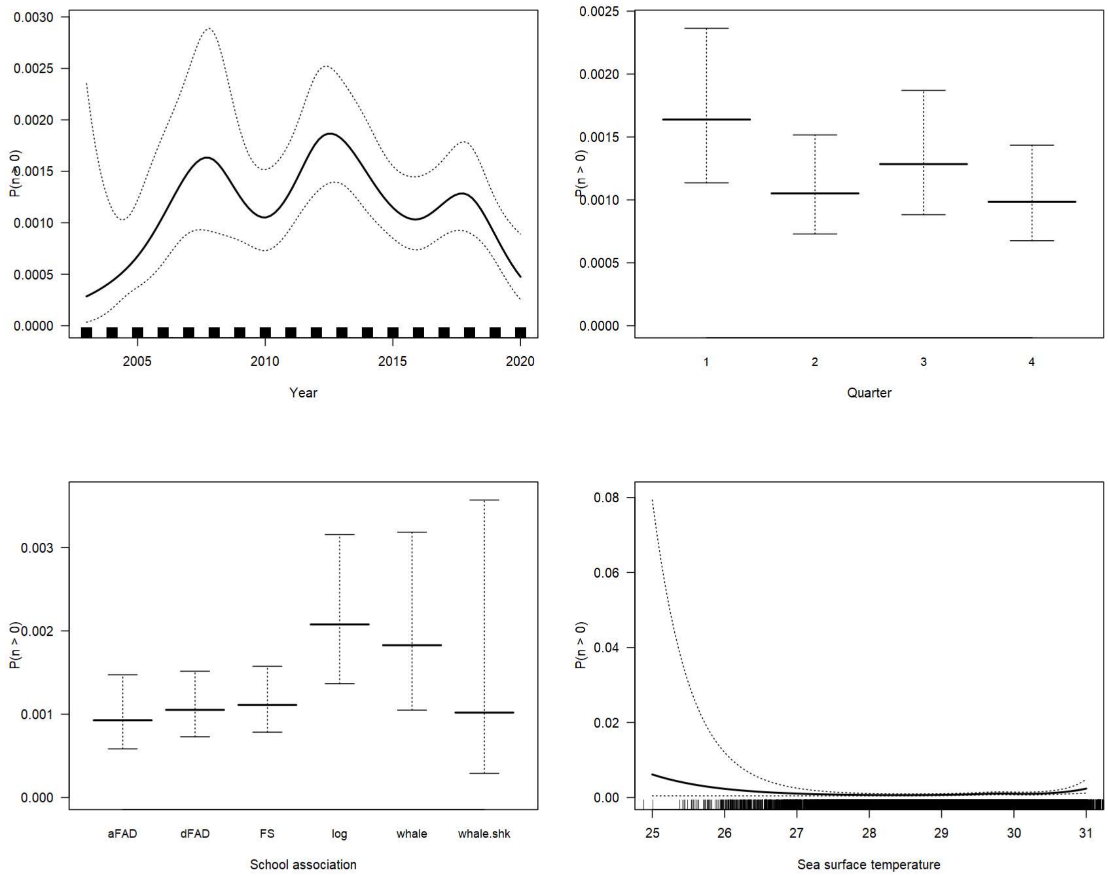

Figure 21 Predicted probability of presence (mean ± 2 s.e.) for green turtle against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C.

Olive ridley turtle

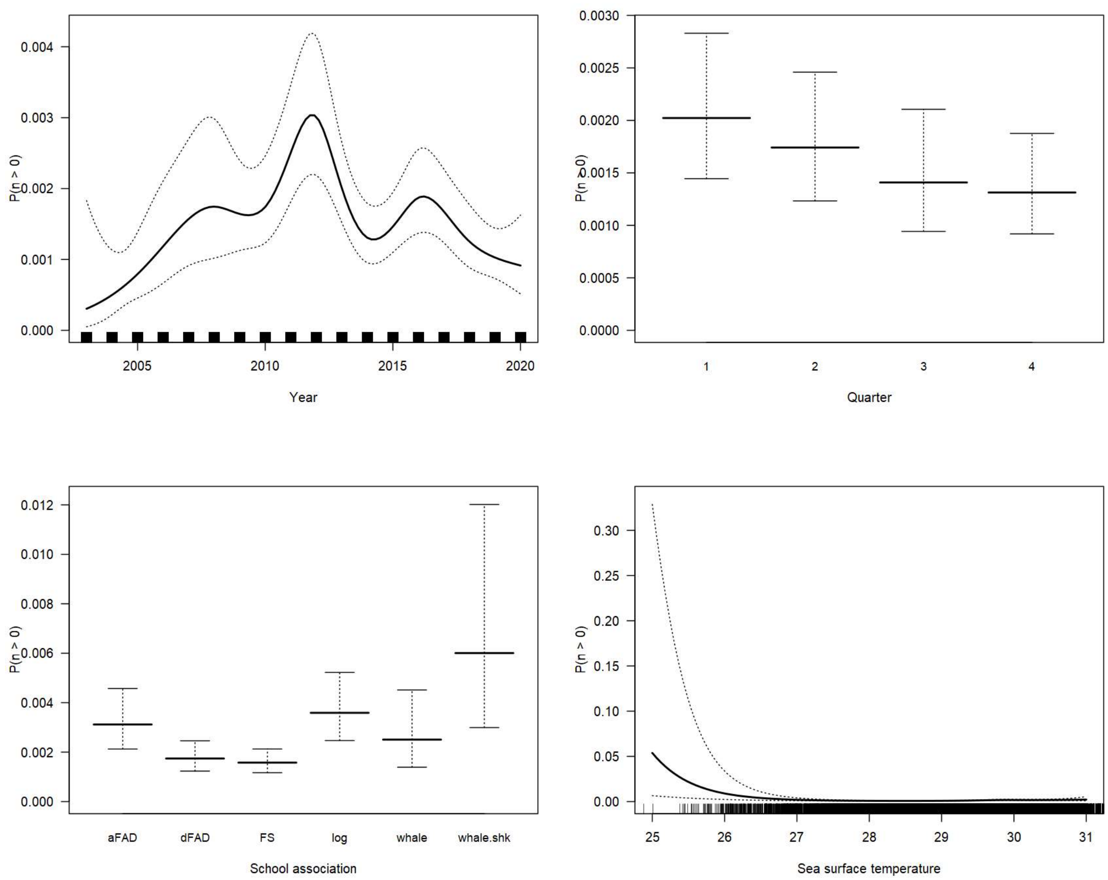

Figure 22 Predicted probability of presence (mean ± 2 s.e.) for olive ridley turtle against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C.

Loggerhead turtle

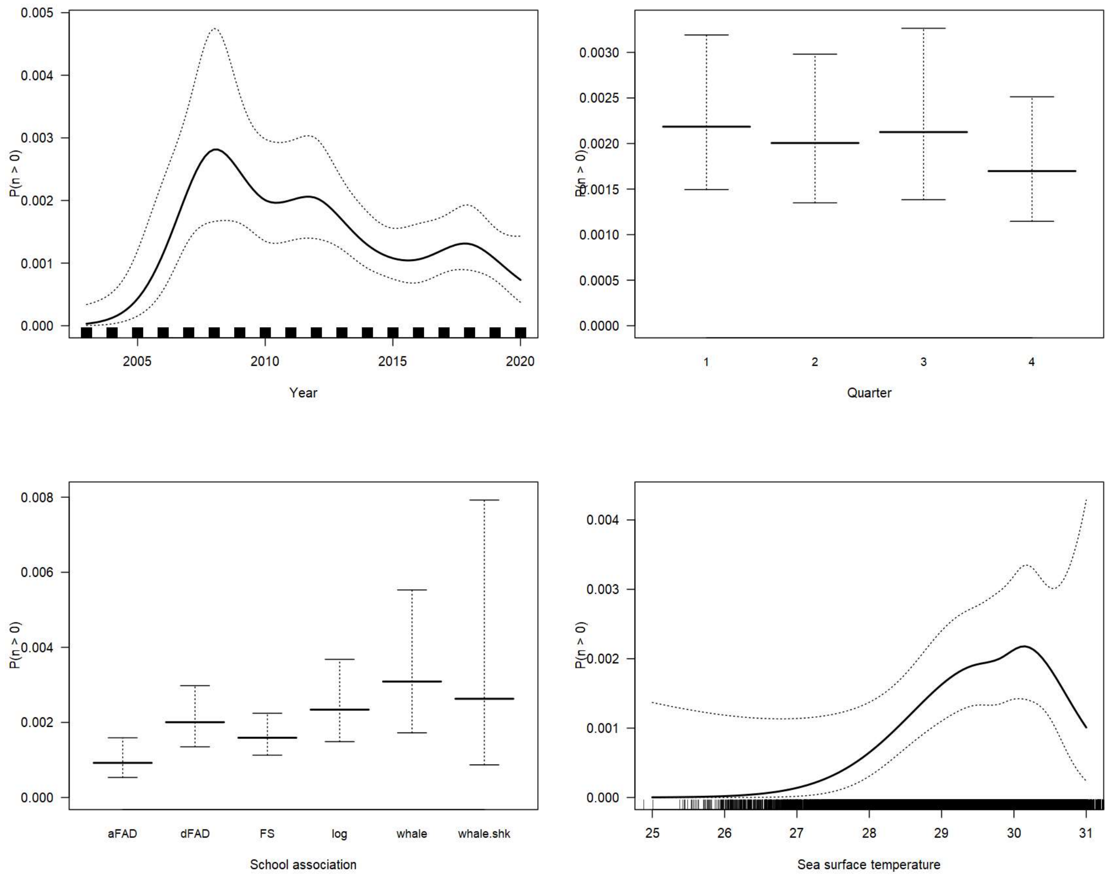

Figure 23 Predicted probability of presence (mean ± 2 s.e.) for loggerhead turtle against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C.

Leatherback turtle

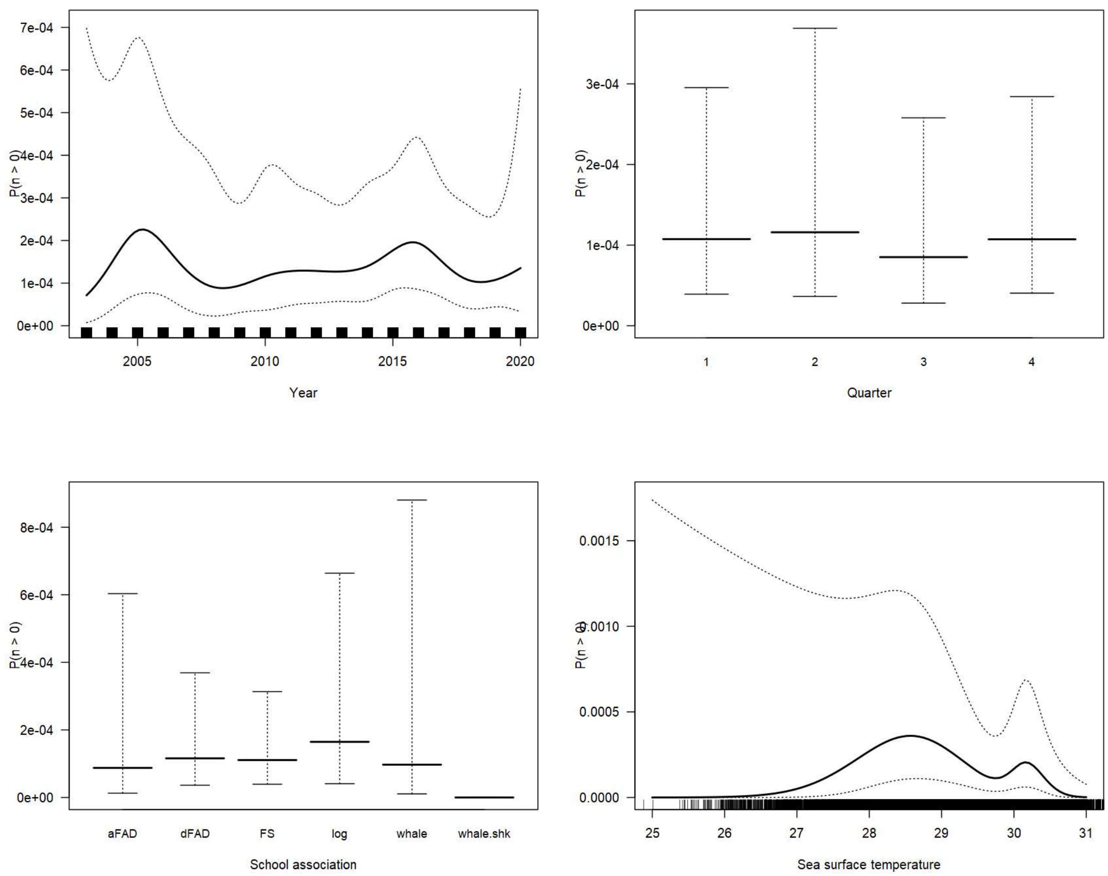

Figure 24 Predicted probability of presence (mean ± 2 s.e.) for leatherback turtle against year (top left), quarter (top right), school association (bottom left), and sea surface temperature (bottom right). When predicting for a given covariate, the remaining model terms were set at the following reference levels: year = 2010; quarter = 2; association = dFAD, SST = 29.8°C.