Opportunities to reduce bycatch mortality of threatened species in a data-limited tuna longline fishery

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Abstract

Marine megafauna exposed to fisheries bycatch belong to some of the most threatened taxonomic groups and include apex and mesopredators that maintain ecosystem functions and stability. To identify evidence-informed bycatch management interventions for a data-limited albacore tuna longline fishery, this study analyzed a short time series of electronic monitoring data. The fishery requires the employment of additional seabird bycatch mitigation methods when fishing in the southwestern Pacific Ocean to bring it into compliance with regional management measures such as by adjusting the branchline weighting design or the time of day of setting. Based on fitting the data to a generalized linear mixed regression model, nighttime deep setting did not significantly affect the target species catch rate and had a >99% lower seabird catch rate compared to partial-daytime deep and shallow sets. This suggests that nighttime deep setting, which avoids diurnal-foraging seabirds as well as threatened epipelagic sharks and marine turtles, may be commercially viable for albacore tuna longline fisheries. The fishery has high compliance with regional management measures for sharks and rays. Findings identified approaches to reduce catch and mortality rates of marine turtles and elasmobranchs. This included modifications to gear designs such as having shallowest hooks fish below 100 m to reduce turtle catch risk, reducing retention of shark species with low at-vessel mortality rates, and improving handling practices for species such as the pelagic stingray for which at-vessel mortality rates were lower than release mortality rates. Tradeoffs from multispecies conflicts of fishing depth and using circle hooks are discussed. Findings support evidence-informed interventions to reduce the mortality of threatened bycatch species in data-limited pelagic longline fisheries.

Keywords: Albatross; Bycatch; Fisheries; Longline; Night setting

1. INTRODUCTION

Marine megafauna captured in fisheries belong to some of the most threatened taxonomic groups and include apex and mesopredators that have essential contributions towards maintaining ecosystem structure, functions and stability (Ferretti et al., 2010; Heithaus et al., 2014; Estes et al., 2016). Fisheries targeting relatively productive species such as tunas can have profound impacts on incidentally caught bycatch species that have lower reproductive potential due to long generation lengths, low fecundity and other life history traits (Musick, 1999; Wallace et al., 2013; Pardo et al., 2016; Avila et al., 2018; Dias et al. 2019; Dulvy et al., 2021).

Effective and commercially viable methods to avoid and minimize catch rates and the risk of fishing mortality of threatened bycatch species are now available for some gear types and some threatened taxa (Werner et al., 2006; Hall et al. 2017). However, there has been mixed progress in their uptake, in part, due to weak enabling environments of government management frameworks and market-based mechanisms (Gilman et al. 2014; Juan-Jorda et al., 2018; Crespo and Crawford, 2019).

Fisheries-dependent monitoring data are needed for robust assessment approaches that support evidence-informed bycatch policy (Moore et al., 2013; Geromont and Butterworth, 2015; Gilman et al., 2017). However, globally independent monitoring is lacking or at very low coverage rates for most marine capture fisheries. For instance, 47 of 68 fisheries that catch marine resources managed by regional fisheries management organizations have no observer coverage (Gilman et al. 2014). Fisheries electronic monitoring (EM) systems can augment conventional human onboard observer programs and establish at-sea monitoring where none previously existed (Emery et al., 2018; van Helmond et al., 2020). When properly designed, EM systems have several advantages over conventional human observer programs, including overcoming main sources of statistical sampling bias, enabling multiple areas of vessels to be monitored simultaneously and near-continuously and allowing questionable data to be audited (Gilman et al., 2019a). There have been about 100 fisheries EM pilot projects since the first in British Columbia, Canada in 1999 and there are now 12 fully implemented programs with 771 vessels (van Helmond et al., 2020), a modest contribution to filling the gap in at-sea monitoring of the 4.6 million fishing vessels in global marine capture fisheries (FAO, 2020).

To identify evidence-informed bycatch management interventions for a data-limited fishery, this study analyzed a short time series of data obtained from a fisheries EM system established in 2018, complemented with information collected from a dockside inventory. The objectives of analyses were to assess:

- Catch composition and nominal catch rates of sharks, rays, seabirds, marine turtles and marine mammals, to provide an indicator of relative risk;
- Compliance with regional fisheries management organizations' bycatch mitigation measures and opportunities to address any compliance deficits;
- The effect of the time of day of setting on seabird and target species catch rates;
- The relative depth and time of day of fishing, which are predictors of marine turtle and species-specific elasmobranch catch and at-vessel mortality rates;
- Informative operational predictors of marine turtle and elasmobranch catch and fishing mortality rates of bait and hook type, lightstick use and leader material;
- The fate (retained vs. discarded) of the catch of sharks, rays, seabirds, marine turtles and marine mammals;
- Differences in species-specific at-vessel mortality and retention rates, to identify opportunities to reduce total threatened bycatch fishing mortality; and
- Differences in species-specific at-vessel and release mortality rates for threatened bycatch that were not retained, to identify opportunities for improved handing-and-release methods.

Findings support evidence-informed interventions to reduce the mortality of threatened species in this tuna longline fishery through improved handling-and-release practices, reduced retention and employment of additional bycatch mitigation methods involving changes in gear designs and fishing methods.

2. METHODS

Monitoring data were collected through an EM system on four pelagic longline vessels that target albacore tuna (*Thunnus alalunga*). The vessels are 53 m in overall length and transship catch at sea. Vessels deploy about 3,300 hooks per set. The duration between the start of the set and end of the gear haulback is about 21 hours.

The proprietary EM equipment and reviewing software were produced by Satlink (Sea Tube system with central processing unit, digital video cameras and GPS antennae), with three video cameras with fields of view of the deck at the: (i) setting station at the stern, (ii) processing station in front of the wheelhouse looking towards the bow, and (iii) hauling station astern of the wheelhouse. During 16 trips made by the four vessels, 4.2 million hooks were deployed during 1,264 sets that were made between 28 May 2018 and 9 December 2020, in fishing grounds that ranged from 37.7 N to 39.0 S and from 148.8 E to 91.5 W.

The EM dataset was analyzed to determine the number of the catch of elasmobranchs and non-fish species, nominal catch rates (without standardizing effort by potentially informative predictors of catch risk other than number of hooks set), fate (retained vs. not retained), at-vessel condition (condition of the catch when retrieved before being handled by the crew), and condition upon release of non-retained catch. EM data were also analyzed to determine whether sets were made in an area where seabird bycatch mitigation methods are required by a regional fisheries management organization (RFMO) and whether setting occurred at night as defined in RFMO seabird conservation and management measures (IATTC, 2011a; WCPFC, 2018a). Based on the definitions of a night set adopted by the two Pacific tuna RFMOs (IATTC, 2011; WCPFC, 2018a), nautical dusk was used for all sets of the study sample (764 sets made in areas where Western and Central Pacific Fisheries Commission [WCPFC] or Inter-American Tropical Tuna Commission [IATTC] seabird measures apply), nautical dawn was applied for 706 sets made in the WCPFC convention area, including an overlap area with IATTC, and local dawn was applied for 58 sets made in the IATTC convention area excluding the overlap area. Of sets that were deployed in an area where seabird bycatch mitigation measures are required, EM data were reviewed to determine whether a bird-scaring *tori* line was deployed during gear setting.

The effect of the time of day of setting on seabird and albacore tuna catch rates was assessed for sets made in areas where RFMO seabird measures are required. Sets were categorized as either (1) Night, deep sets: sets that met RFMO definitions of night setting, with 20 to 22 hooks between float; (2) Not night, deep sets: sets not meeting the RFMO night setting definition, with 19 to 22 hooks between floats, and (3) Not night, shallow sets: sets not meeting the RFMO night setting definition with 10 to 12 hooks between floats. A Bayesian inference workflow (Gabry et al 2019, Gelman et al 2020) was used for this assessment based on fitting a generalized linear mixed regression model structure (Fahrmeir and Lang, 2001) with zero-inflated negative binomial likelihood (Yau et al., 2003, Fávero et al., 2021) for the albacore tuna catch rate model and Bernoulli likelihood for the catch model for combined albatross species and model for combined seabird species, following the approach described in Gilman et al. (2021b) and summarized in the Supplemental Material. A probability statement about the existence of an effect and its direction was determined using the probability of direction metric, also known as the maximum probability of an effect (Makowski et al., 2019).

A complementary dockside vessel inventory and interview of skippers and crew was conducted in July 2022 for two of the vessels. This enabled collecting information on gear characteristics that were not recorded by the EM program and that are potentially informative predictors of catch and at-vessel mortality rates of elasmobranchs and air-breathing species.

2. RESULTS

Table 1 summarizes the species-specific or otherwise higher taxonomic grouping catch levels, nominal catch rates, fate and at-vessel and release conditions for seabirds, marine turtles and elasmobranchs. No marine mammals were observed captured in the EM dataset.

Seabirds had a nominal catch rate of 0.384 per 1000 hooks, and 70% of captured seabirds were albatrosses, which the EM analyst was unable to identify to the species level. All but one of the captured seabirds were retrieved dead and all were discarded. The assessment of the effect of night setting from analyzing EM data from 656 sets that were in areas where RFMO seabird measures apply indicates that seabird interactions are rare events, with 148 seabirds of all species captured in only 33 of these sets. Eleven marine turtles were observed captured, with a nominal catch rate of 0.007 per 1000 hooks. Six turtles were observed to be dead at haulback, none were captured alive and then discarded dead, and none were retained. The EM analyst identified only three of the turtles to the species level, all of which were olive ridleys (*Lepidochelys olivacea*). Of 1,992 captured sharks, ≥79% were alive at capture, ≥77% of sharks retrieved alive were retained, and ≥4% of captured sharks that were retrieved alive were subsequently discarded dead. No shark finning (retention of fins and discarding of the remaining carcass) was observed. Sharks had a nominal catch rate of 1.252 per 1000 hooks, of which at least 64% were blue sharks (*Prionace glauca*). Of 2,148 captured rays, ≥99% were alive at capture, no rays were retained, and ≥17% of captured rays that were retrieved alive were discarded dead. All but one of the captured rays was a pelagic stingray (*Pteroplatytrygon violacea*). Rays had a nominal catch rate of 1.351 per 1000 hooks.

Table 2 summarizes the proportion of sets where night-setting and bird-scaring tori lines were employed when fishing in areas where seabird bycatch mitigation measures are required. Of the sets analyzed by EM analysts, 74% occurred in an area where WCPFC and IATTC require the employment of seabird bycatch mitigation measures (IATTC, 2011a; WCPFC, 2018). A tori line was deployed in 92% (35 of 38) of sets that were made in an area where seabird bycatch mitigation measures are required and that were reviewed by an EM analyst to determine if a tori line was deployed during setting. Gear setting occurred for a mean of 5.9 hours (95% CI: ±0.03 hours). Of the 764 sets made in areas where seabird bycatch mitigation measures are required, 13% met RFMO definitions of night setting. All but one of the sets that were in areas where seabird bycatch mitigation methods are required began after nautical dusk (i.e., all but 1 of the sets were in compliance with the night setting requirement for the time of the start of the set). These 764 sets began an average of 7.4 hours after nautical dusk. Thus, 664 of 665 did not meet the night setting definition due to the time of the end of the set being past nautical dawn (WCPFC, 2018a) or local sunrise (IATTC, 2011a). Of these sets, 23% exceeded nautical dawn or local sunrise by <1 hour, and 64% by <3 hours.

Fig. 1 presents the predicted marginal treatment effects of compliance with RFMO night setting definitions and hooks between floats for albacore tuna, combined albatrosses and combined seabird species, averaged over the sampling period. The albatross night-deep 95% HDI (0 to 0.0003) and seabird night-deep 95% HDI (0 to 0.0004) are concealed by the solid dot in Fig. 1. There was no significant difference in predicted median albacore tuna catch rates (expected catch per set) between the three set categories. The median albacore tuna catch rate in “day-shallow” sets was higher than for the other two set categories, but this effect was not significant, with only a 60% probability that there was an effect. The predicted median albatross catch rate (expected probability of catching at least 1 albatross per set) was significantly lower on “night-deep” sets compared to the other two set categories, with > 99% probability of an effect. We can only be > 85% sure that the albatross catch rate was higher in “day-shallow” sets compared to “day-deep” sets, and this effect was not significant. As with albatrosses, the predicted median catch rate for combined seabird species (expected probability of catching at least 1 seabird per set) was significantly lower in “night-deep” sets compared to the other two set categories, with > 99% probability of this effect. The night-deep predicted median albatross and seabird catch rates were >99% lower than both the day-deep and day-shallow rates (Fig.1). We can also be > 95% sure that the seabird catch rate was higher in “day-shallow” sets compared to “day-deep” sets. The day-deep median seabird catch rate was 83% lower than the day-shallow rate.

Small marine forage fish species such as Pacific saury (*Cololabis saira*) and sardines (Clupeidae) were used for bait. Branchlines and floatlines are a mean of 24.6 m (95% CI: ±0.3 m) and 26.8 m (95% CI: ±0.3 m) long, respectively. The distance between the point of attachment of the first branchline and the point of attachment of the floatline to the mainline is about 35 m. Lightsticks are not used. Vessels use 4.6 cm wide circle hooks with a 10 degree offset, use monofilament leaders, attach 60 g lead-centered swivels about midway on branchlines, about 12 m from the hook, and attach *ca*. 30 g unweighted swivels 1.2 m above the hook. Radio buoys are deployed in the gear when fishing to enable tracking position to reduce the risk of loss and recover sections of mainline that are temporarily lost.

3. DISCUSSION AND CONCLUSIONS

The estimated seabird bycatch rate and at-vessel life status in this fishery is a large concern given the threatened conservation status of albatrosses and petrels that are exposed to the fishery. Albatrosses and petrels are two of the three most threatened groups of seabirds (Dias et al., 2019). Of the 29 albatross and large petrel species listed under the Agreement on the Conservation of Albatrosses and Petrels, 19 are categorized as threatened (Phillips et al., 2016; IUCN, 2022). The seabird catch rate of 0.384 per 1000 hooks, with an albatross catch rate of 0.9 per set, is high relative to many other tuna longline fisheries (Anderson et al., 2011; Melvin et al., 2014; Huang, 2015; Jimenez et al., 2020). The EM analyst was unable to identify any seabird captures to the species level, preventing an assessment of species-specific risks.

All but 1 of the 611 observed captured seabirds was retrieved dead, suggesting that in this fishery seabirds are captured during the set and drown during the gear soak (Gilman et al., 2014). Thus, in this fishery, the largest seabird conservation gain can likely be achieved by reducing seabird capture risk during setting, and not during gear retrieval. Fishers did not retain any captured seabirds.

The vessels are in compliance with RFMO seabird bycatch measures in the area where measures are required in the north Pacific and in the IATTC Convention Area south of 30ºS by using a tori line, at least in ca. 92% of sets (assuming that the design meets the RFMO requirements), and using a mainline line shooter (IATTC, 2011a; WCPFC, 2018a). However, they do not currently meet requirements when fishing in a portion of the WCPFC convention area south of 30ºS (and west of 120ºW) (WCPFC, 2018a). The vessels could meet the RFMO branchline weighting design requirement through a minor adjustment to their contemporary gear design, such as by replacing unweighted swivels with a ≥ 45 g weighted swivel, and moving them from their current point of attachment of 1.2 m from the hook to within 1 m of the hook. Similarly, adjusting time of the end of sets earlier so that sets are completed prior to nautical dawn within the WCPFC convention area and prior to local dawn in the IATTC convention area would enable the vessels to meet the RFMOs' night setting definitions. This could be implemented in combination with initiating the set earlier, in order to avoid reducing the set duration, and still enable sets to meet the night setting definitions.

As is the case for several bycatch mitigation methods included in RFMO's measures, the inclusion of a mainline line shooter, used to set the mainline slack to get the gear to fish at a deeper depth, as a seabird bycatch mitigation option for pelagic longline vessels requires reconsideration. The sink rate of baited hooks will be unaffected by the sink rate of the mainline until the hook has settled to the full length of the branchline, which in most fisheries is below the depth where seabirds can dive and access baited hooks (WPRFMC, 2018). Thus, while the fishery's use of a mainline line shooter contributes to meeting RFMO seabird management requirements, this is unlikely to affect seabird catch risk. Other methods with a relatively larger effect size and higher strength of evidence of efficacy at mitigating seabird bycatch could be employed.

The significantly lower catch rates of albatrosses and combined seabird species in RFMO-defined night sets is consistent with an extensive body of studies finding lower seabird catch rates during night sets than daytime sets because the most seabirds that are susceptible to pelagic longline bycatch do not forage at night (ACAP, 2019; WPRFMC. 2019). However, night setting results in higher catch rates of crepuscular and nocturnal foraging seabird species in fisheries that overlap with these species (e.g., northern fulmars *Fulmarus glacialis*, Melvin et al., 2019).

The number of pelagic longline hooks that are attached between two floats is an approximate index for *relative* fishing depth. The more hooks that are deployed between two floats, the deeper the depth range of the hooks along a catenary curve will be if all other variables are constant. The number of hooks between floats is, however, a poor predictor of the actual fishing depth range of hooks. This is because variability in several other factors that affect fishing depth, including shoaling from ocean currents and wind, and variability in other gear designs (e.g., length of mainline between floats, mainline diameter, distance between floats, distance between the point of attachment to the mainline of the first branchline and the point of attachment of the nearest floatline, distance between branchlines, and length of branchlines and floatlines) affect the absolute depth range of the longline hooks (Ward and Myers, 2005; Rice et al., 2007). The sets with ca. 11 hooks between floats may have had a higher catch rate of non-albatross seabird species if a larger proportion of hooks are accessible to deep-diving seabird species, such as shearwaters and some petrel species, during setting, such as if hooks in shallower sets are more likely to be accessible to seabirds beyond the aerial coverage of *tori* lines. Only one of the four vessels made shallower sets. There may have been differences in additional predictors of seabird catchability between the sets made by the one shallower-setting and the three deeper-setting vessels. For example, the density of seabirds attending the vessels during setting (which may be explained differences in the spatial and seasonal distribution of effort and offal management practices), wind speed, and location where crew deploy baited hooks (e.g., into the prop wash, or outside of the area protected by the tori line streamers) (Zhou and Brothers, 2021) could have explained the observed differences in seabird catch rates between the 1 shallower vs. 3 deeper setting vessels, but these variables were not possible to explore with this limited EM dataset.

The lack of a significant difference in albacore tuna catch rates between the three set type categories suggests that it may be commercially viable for the fishery to conduct nighttime deep sets. However, more research is needed to determine the economic effects of fishing depth in combination with night setting from changes in catch rates of all principal market species in this and other longline fisheries that pose a hazard to seabirds. Having pelagic longline vessels switch from shallower daytime to deeper night setting would decrease the catch risk of seabirds, as well as of epipelagic species, including silky (*Carcharhinus falciformis*) and oceanic whitetip sharks (*C. longimanus*) and marine turtles, but would increase catch rates of threatened mesopelagic species, such as thresher sharks (Musy et al., 2011; Gilman et al., 2019b). Bycatch management strategy evaluation (Punt et al. 2016) could enable identifying and accounting for these conflicts so that unavoidable tradeoffs are intentional and best meet objectives for multispecies bycatch management. Shifting the time of day of setting to meet RFMO night setting definitions would eliminate some of the gear soak during the daytime. This might reduce the vertical overlap between the fishing gear and principal market species whose diel vertical migration cycles mirror movements of their prey. Additional assessment of effects of the time of day and depth of fishing on catch rates of albacore and other principal market species is a priority.

The turtle bycatch rate in this fishery is low relative to, for example, shallow-set longline fisheries with the majority of hooks fishing above 100 m and compared to fisheries that overlap relatively large turtle populations (Brouwer and Bertram, 2009; Gilman et al., 2016). However, effects of fishing mortality levels are population-specific and also depend on the reproductive value of the sex and age of fishery removals, where for some critically endangered populations, very small cumulative anthropogenic mortality levels can compromise population viability (Chaloupka, 2002; Curtis and Moore, 2013). Bycatch is a major threat to marine turtles (Lewison et al., 2004; Wallace et al., 2013). The Olive ridley has a global species-level conservation status of Vulnerable (IUCN, 2022). Several other marine turtle species that are exposed to this fishery are also threatened with extinction (leatherback turtle Pacific Ocean subpopulations are both Critically Endangered, the loggerhead south Pacific subpopulation is categorized as Critically Endangered, and green and hawksbill turtles are globally Endangered and Critically Endangered, respectively) (IUCN, 2022).

The WCPFC and IATTC marine turtle conservation and management measures require fishing vessels to employ methods that increase the probability of marine turtle post release survival, but do not require deep-set longline fisheries to employ methods to avoid or minimize turtle catch risk (WCPFC, 2018b; IATTC, 2019). Based on the lengths of sampled branchlines and floatlines and the distance between the point of attachment to the mainline of the first branchline and floatlines, the shallowest hooks may fish close to 100 m, which could be confirmed by using Time Depth Recorders. If necessary, the depth of shallowest hooks could be increased to get them below 100 m by using longer branchlines and/or by increasing the distance of the first branchline from floatlines. For comparison, regulations for the U.S. American Samoa albacore longline fishery require ≥ 30 m float lines, ≥ 10 m branchlines, ≥ 70 m between floatlines and first branchlines , and ≥ 15 hooks between floats in order to have all hooks fish deeper than 100 m (NMFS, 2011). Longer floatlines that exceed the length of branchlines are not recommended, as this reduces the probability that marine turtles and other air-breathing species will survive the gear soak. Fishing depth, in particular on shallowest hooks (closest to float lines) affects whether air-breathing species can reach the surface to breath during the gear soak. Thus, having hooks fish deeper reduces turtle catch rates but increases the at-vessel mortality rate. The fishery’s use of relatively wide circle hooks, small forage fish species for bait, and not using lightsticks contribute to reducing marine turtle catch and at-vessel mortality rates (Poisson et al., 2016; Hall et al., 2017). As no turtles were retained, and none of the turtles that were retrieved alive were discarded dead, changes to retention and handling practices do not present opportunities to reduce marine turtle fishing mortality.

The shark catch rate in this fishery is within the range reported for other tuna longline fisheries (Gilman et al., 2008; Oliver et al., 2015; Hall et al., 2017). The blue shark, categorized as Near Threatened by IUCN (2022), dominated the shark catch, which is typical of subtropical and temperate pelagic longline fisheries (Oliver et al., 2015; Hare et al., 2021). All but one of the captured rays were pelagic stingrays, categorized as Least Concern by IUCN (2022), and a common bycatch species in pelagic longline fisheries (Hall et al., 2017; Hare et al., 2021). Bycatch in pelagic longline fisheries is a global threat to the conservation of some elasmobranch species. Pelagic sharks underwent a 71% decline in global abundance over the past 50 years due to an 18-fold increase in fishing pressure (Pacoureau et al., 2021). Of 1,199 assessed species of sharks and rays, 33% were categorized as threatened (Critically Endangered, Endangered or Vulnerable) under the IUCN Red List due largely to fishing mortality from incidental catch (Dulvy et al., 2021).

The retention of Mobulid rays and oceanic whitetip sharks is prohibited by both IATTC and WCPFC (IATTC, 2011b, 2015; WCPFC, 2019a,b), WCPFC also prohibits silky shark retention (WCPFC, 2019a) while IATTC limits longline silky shark retention to 20% of the weight of the total catch per trip (IATTC, 2021). Fishers retained one silky shark which was captured within the WCPFC convention area, and no oceanic whitetip sharks or Mobulid rays were retained, suggesting that the retention of a prohibited elasmobranch species was an isolated event and not a systematic practice.

IATTC bans shark finning and the use of ‘shark lines’ (branchlines attached to floats or floatlines that fish shallow, baited with pieces of large incidental catch, used to target epipelagic sharks), and if silky sharks make up > 20% of the weight of the annual total catch by a shallow-set (majority of hooks fish shallower than 100 m) non-swordfish-targeting vessel, then wire leaders are prohibited for 3 consecutive months of the year (IATTC, 2005, 2016, 2021). WCPFC bans shark finning, and employs a menu approach where vessels select either a ban on using wire leaders or shark lines (WCPFC, 2019). No shark finning occurred. The dockside inventory found that only monofilament nylon is used for branchline leaders. Silky shark catch, which ranged from 0 to 16 individuals per trip, was far below the IATTC threshold of 20% of the weight of the total catch. The EM dataset did not include information on the use of shark lines.

The use of circle hooks by this fishery causes increased shark catch rates but lower at-vessel mortality rates relative to using J-shaped hooks (Gilman et al., 2016; Reinhardt et al., 2018). But almost all caught sharks are retained in this fishery, and therefore the use of circle hooks results in higher total shark fishing mortality than if a J-shaped hook were used. However, the use of wide circle hooks benefits marine turtles, and therefore, as with fishing depth, discussed above, bycatch management strategy evaluation could enable accounting for this conflict so that unavoidable tradeoffs best meet objectives for multispecies bycatch management. The use of small forage fish species, monofilament nylon leaders and not using lightsticks contributes to reducing shark catch rates, and the bait and no lightstick use also contribute to reduced turtle catch (Poisson et al., 2016; Hall et al., 2017; Gilman et al., 2020b).

Blue sharks and shortfin mako sharks (Endangered, IUCN, 2022) had high retention rates, and low at-vessel mortality rates (Table 1). Reducing or banning shark retention, combined with prescribed handling and release practices, would substantially reduce total fishing mortality. Some shark species had relatively high at-vessel mortality rates such as shortfin mako sharks with 36% of catch dead upon retrieval (Table 1). Managing operational fishing methods and gear designs such as reducing the soak duration, altering the fishing depth, increasing branchline length, and altering the spatial and seasonal distribution of effort could reduce at-vessel mortality rates (Gallagher et al., 2014; Ellis et al., 2017; Musyl and Gilman, 2019), which would reduce total fishing mortality rates if retention was reduced or eliminated. Improving pelagic stingray handling practices would contribute to reduced fishing mortality as currently 17% that were retrieved alive were discarded dead.

Several other bycatch mitigation methods may be effective in this fishery. This includes approaches appropriate across gear types. Output controls, such as retention bans and limits, bycatch quotas, shark finning prohibitions, and bans on international trade, can under certain enabling environments result in reduced retention, which would reduce the total fishing mortality of species with relatively low at-vessel, release and post-release mortality rates. These measures may also cause fishers to adjust their fishing methods and gear designs in order to increase selectivity to reduce the catch rates of species subject to the measures (Pascoe et al., 2010; Somers et al., 2019). Other cross-gear bycatch management approaches include input controls (Anderson et al., 2018), static and dynamic area-based management tools to avoid or reduce areal or temporal overlap for spatially and temporally predictable bycatch hotspots (Hillborn et al., 2021), and mitigating the production and adverse impacts, including ghost fishing, of abandoned, lost and discarded fishing gear (Gilman et al., 2022). Various longline-specific bycatch mitigation methods may also hold promise for the fishery, including, for example, managing gear designs such as hook size and shape and bait type (Ellis et al., 2017; Reinhardt et al., 2018; Gilman et al., 2019b). This also includes approaches to reduce depth overlap by adjusting the time of day of fishing and the fishing depth of the gear, while accounting for multispecies conflicts (Musyl et al., 2011; Gilman et al., 2019b). This includes, for example, banning shark lines. The fishery-specific efficacy of some of these approaches, such as area-based management tools, managing hook size and managing the seasonal distribution of effort, could be explored only once a longer and more robust time series of independent monitoring data becomes available (Maxwell et al., 2020).

The suitability of the EM sampling design used for this fishery could be evaluated to determine if sources of bias are adequately minimized. For example, to sample sets within a trip, designs with systematic sampling assignment (a form of probability-based sampling) and that are balanced may be preferrable to ‘simple randomization’ designs to account, for example, for variability in fishers’ retention practices in the final sets of a trip, when they may wish to fill the fish hold with less valuable species and sizes before offloading the catch, relative to earlier sets in the trip. Furthermore, to avoid statistical sampling bias, the necessary monitoring coverage rate depends on: (1) the objectives of analysis, including required levels of accuracy and precision of catch rates, and (2) aspects of each individual fishery – such as how many vessel classes exist, how many ports are used, the spatial and temporal distribution of effort, the frequency of occurrence of catch interactions for each species of interest, the amount of fishing effort, and the spatial and temporal distribution of catch (Hall 1999; Babcock et al. 2003; Wakefield et al. 2018). At lower coverage rates, catch estimates will likely have large uncertainties for species with low capture rates (Amande et al. 2012), and may result in high uncertainty even for species that are more commonly caught if a small sample size is observed per stratum (e.g., by port, vessel category, and season) (Bravington et al. 2003). When low coverage rates result in small sample sizes, it is very likely that rare species susceptible to capture will not be identified because species richness and other species-level biodiversity indices are extremely sensitive to sample size and species abundance distribution (evenness) (Heck et al. 1975; Lawton et al. 1998).

Consistent with findings from two previous assessments of the same EM system in tuna longline fisheries (Gilman et al., 2020, 2021a), simple modifications to the EM system would enable substantial improvements in data quality. EM analysts were unable to record a substantial proportion of the catch to the species level, and a substantial proportion or records were not identified to a higher taxonomic group (Table 1). Improving the species identification skills of the EM analysts in combination with adding additional cameras or adjusting camera fields of view to detect catch that crew release in the water, and having crew bring catch that they will release in the water within the camera field of view would produce a substantially richer EM dataset (Gilman et al., 2020). Marine mammal captures are relatively rare events in pelagic longline fisheries, however, they very likely occur in this fishery, where even small capture levels could cause substantial risks to populations exposed to the fishery (Nelms et al., 2021). These proposed improvements to the EM system would enable more robust monitoring of marine mammal captures, where the current EM camera fields of view might cause analysts to not detect captured marine mammals that crew release far from the hauling station.

Several priority data fields were unavailable in the EM dataset that are potentially informative predictors of catch and at-vessel mortality rates of threatened bycatch species some of which are regulatory requirements. Complimentary dockside audits, demonstrated here, can collect some of the data fields that EM systems currently lack the ability to collect (Gilman et al., 2019a). And, improvements to EM technology and protocols could enable collecting some of these fields. For example, vessel skippers and crew report that they do not use shark lines. This is not feasible to assess through a dockside audit, but is feasible to collect by conventional human observer and EM programs (Gilman et al., 2020).

To identify evidence-informed bycatch management interventions for a data-limited albacore tuna longline fishery, this study analyzed a short time series of electronic monitoring data. Findings enabled assessing compliance with RFMO bycatch measures and options to bring the fishery into compliance where deficits currently exist. Findings also support evidence-informed interventions to reduce the mortality of threatened species in this tuna longline fishery through improved handling-and-release practices, reduced retention and employment of additional bycatch mitigation methods involving changes in gear designs and fishing methods. Nighttime deep setting did not significantly affect the albacore tuna target species catch rate and had a >99% lower seabird catch rate compared to both partial-daytime deep and shallow sets. This finding that nighttime deep setting, which avoids seabirds as well as threatened epipelagic sharks and marine turtles, may be commercially viable has implications for global albacore tuna longline fisheries that pose a hazard to diurnal foraging species of seabirds.

ACKNOWLEDGMENTS

The study was possible through grant 0115.22.073680 from the National Fish and Wildlife Foundation and a grant from the Pew Fellows Program in Marine Conservation at The Pew Charitable Trusts. We thank Gonzalo Legorburu and Borja Martin Amezaga of Digital Observer Services for assistance with an electronic monitoring data request. Daniel Yang and Jimmy Zhong of Key Traceability kindly assisted with implementing dockside inventories of the fishing vessels.

SUPPLEMENTAL INFORMATION

This article includes Supplemental Information.

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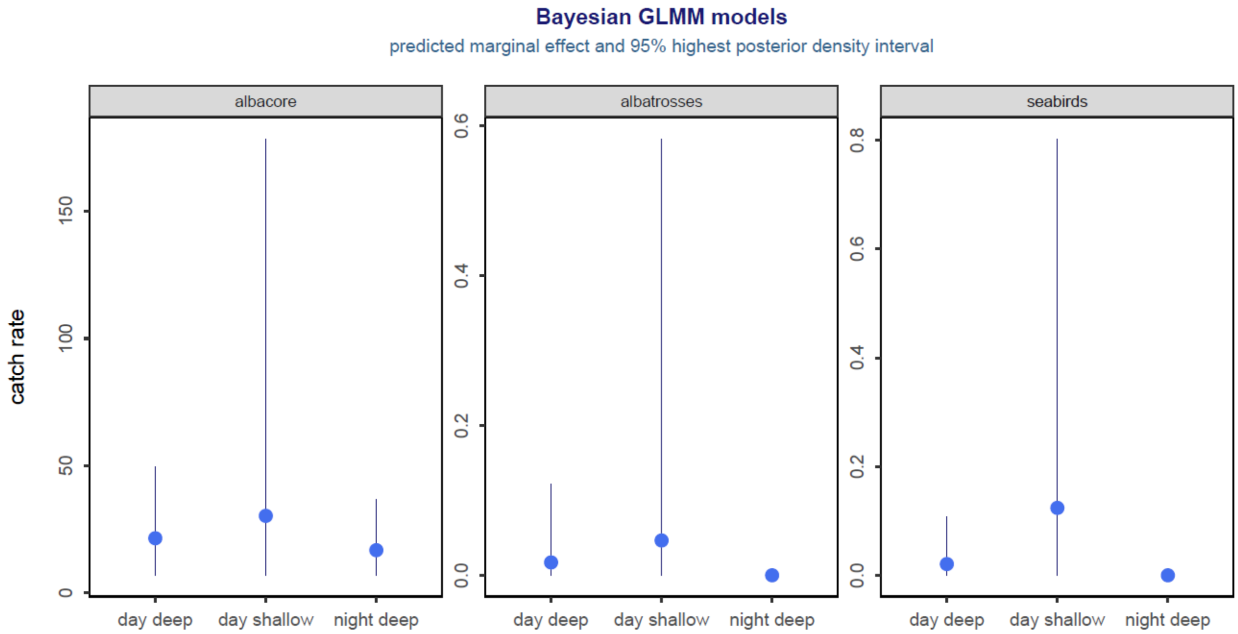

Fig. 1. Predicted 3-category set deployment treatment effect for albacore catch per set (left), probability of catching at least 1 albatross per set (middle), and probability of catching at least 1 seabird per set (right). Solid dot = median predicted marginal effect. Vertical bar = 95% highest posterior density interval.

TABLES

Table 1. Catch levels, nominal catch rates, fate, and at-vessel and release conditions of seabirds, marine turtles and elasmobranchs captured by a Pacific Ocean albacore tuna longline fishery from 479 sets made during 12 trips, 2018-2020.

				No. caught by fate and life status								
				Retained[1]			**Not-retained[2]**					
Species	**No. caught**	**CPUE (no. x 10^3 hooks)**	**% retained**	**A**	**D**	**unk**	**A-A**	**A-D**	**A-unk**	**D-D**	**unk-D**	**unk-unk**
Seabirds												
Albatrosses unknown species	426	0.268	0	0	0	0	0	0	1	425	0	0
Non-albatrosses, unknown species	185	0.116	0	0	0	0	0	0	0	185	0	0
Marine turtles												
Olive ridley	3	0.002	0	0	0	0	0	0	1	2	0	0
Unknown species	8	0.005	0	0	0	0	1	0	2	4	0	1
Sharks												
Bigeye thresher	1	0.001	0	0	0	0	0	0	0	1	0	0
Blue	1,272	0.800	95	1,009	198	0	42	7	5	11	0	0
Common thresher	1	0.001	0	0	0	0	1	0	0	0	0	0
Crocodile	4	0.003	0	0	0	0	1	1	0	2	0	0
Longfin mako	3	0.002	33	0	1	0	0	0	0	2	0	0
Oceanic whitetip	4	0.003	0	0	0	0	4	0	0	0	0	0
Scalloped hammerhead	1	0.001	0	0	0	0	1	0	0	0	0	0
Shortfin mako	141	0.089	76	72	35	0	7	10	1	16	0	0
Silky	30	0.019	3	0	1	0	13	6	0	10	0	0
Smooth hammerhead	1	0.001	0	0	0	0	0	0	0	1	0	0
Velvet dogfish	14	0.009	0	0	0	0	4	4	0	6	0	0
Unknown species	520	0.327	41	131	74	7	192	56	3	46	0	10
Rays												
Pelagic stingray	2,147	1.350	0	0	0	0	288	353	1,478	27	0	1

Unknown Mobula species	1	0.001	0	0	0	0	1	0	0	0	0	0
Unknown												
Unknown taxonomic group and species	1,058	0.665	16	19	96	50	19	6	53	326	60	429

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[1] At-vessel condition of either A=alive, D=dead, unk=unknown

[2] First digit is at-vessel condition, second digit is release condition of either A=alive, D=dead, unk=unknown.

Table 2. Proportion of sets employing night-setting and bird-scaring *tori* lines when fishing in areas where seabird bycatch mitigation measures are required, during 15 trips by a Pacific Ocean albacore tuna longline fishery, 2019-2020.

		Night set		**Tori line**	
No. sets	**No. hooks**	**No. sets RFMO seabird required measures**[1]	**No. night sets during seabird required sets**[2]	**No. tori sampled sets**[3]	**No. tori sets**[4]
101	298,255	3	0	0	NA
111	354,239	110	4	0	NA
27	82,684	27	4	3	3
4	13,538	0	NA	NA	NA
16	45,687	16	3	3	3
70	237,949	64	0	3	3
165	522,933	165	20	6	6
9	29,149	9	1	3	0
106	404,112	106	0	5	5
94	333,021	78	0	5	5
34	112,123	0	NA	NA	NA
79	262,563	4	0	0	NA
76	252,928	75	22	4	4
106	357,366	76	38	3	3
31	98,801	31	6	3	3

[1] Number of sets made in an area where WCPFC or IATTC require the employment of seabird bycatch mitigation measures.

[2] Number of sets made in an area where WCPFC or IATTC require the employment of seabird bycatch mitigation measures and meets the relevant RFMO definition of a night set.

[3] Number of sets made in an area where WCPFC or IATTC require the employment of seabird bycatch mitigation measures that the EM analyst reviewed to determine if a *tori* line was deployed during setting.

[4] Number of sets sampled for *tori* line use during which a *tori* line was observed being used.