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RESEARCH ARTICLE

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Setting the net lower: A potential low-cost mitigation method to reduce cetacean bycatch in drift gillnet fisheries

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Abstract

1. Bycatch is the most significant threat to marine megafauna (sea turtles, marine mammals, elasmobranchs, seabirds) worldwide, and the leading cause of the decline of several cetacean species. The bycatch issue in the Indian Ocean is poorly understood, but high bycatch levels in gillnet fisheries have been documented for the past two decades, in both small-scale and semi-industrial fisheries. Unfortunately, methods to reduce bycatch are often unavailable, financially non-viable or socially unacceptable to fishermen.
2. Using a network of trained boat captains in the tuna drift gillnet fishery in the Arabian Sea, targeted catch and bycatch data were collected from 2013 to 2017 off the coast of Pakistan (northern Indian Ocean). Two fishing methods using multifilament gillnets were used: surface deployment and subsurface deployment (i.e. headline of net set below 2 m depth).
3. Predicted catch rates for targeted species did not differ significantly between the two fishing practices, although a drop in tuna (6.2%) and tuna-like (10.9%) species captures was recorded in subsurface sets. The probability of cetacean bycatch, however, was 78.5% lower in subsurface than in surface sets.
4. Cetacean bycatch in tuna drift gillnet fisheries has the potential to be significantly reduced at a relatively low cost for fishers. However, further research with an appropriate sampling design and a large sample size is required to confirm the efficacy of the proposed mitigation method. The acceptability and adoption of subsurface setting by fishers also needs to be further investigated. Despite some limitations, this preliminary study also highlights the importance of crew-based observer data as an alternative source of data when observers cannot be deployed on fishing vessels.

KEYWORDS
CPUE, fisheries, incidental capture, mitigation, small cetaceans, tuna

1 | INTRODUCTION

The incidental capture (commonly known as bycatch) of marine megafauna, including marine mammals, sea turtles, seabirds and elasmobranchs, is the most significant threat to these long-lived organisms worldwide (Lewison et al., 2004; Read, Drinker & Northridge, 2006; Wallace et al., 2010; Molina & Cooke, 2012). Despite decades of bycatch assessments across the globe, particularly

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in commercial fisheries but now increasingly also in small-scale fisheries, there are still few estimates of the magnitude of marine mammal bycatch, and little awareness of the seriousness of its impact on species survival (Dawson et al., 2001; Read, Drinker & Northridge, 2006; Robertson & Chilvers, 2011; Reeves, McClellan & Werner, 2013; Brownell et al., 2019). The first human-caused extinction of a cetacean, the baiji (*Lipotes vexillifer*) from the Yangtze River, was due to bycatch (Turvey et al., 2007). Another cetacean species, the vaquita (*Phocoena sinus*), will also probably go extinct owing to unsustainable bycatch levels in the northern Gulf of California (Rojas-Bracho & Reeves, 2013; Taylor et al., 2017; Rogan, Read & Berggren, 2021). Today, 13 species, subspecies or subpopulations of coastal and freshwater cetaceans are currently assessed as Critically Endangered on the IUCN Red List, including 11 for which bycatch is the leading cause of their decline (Brownell et al., 2019).

Bycatch in gillnets is of greatest concern in terms of impacts on cetacean populations (Lewison et al., 2004; Read, Drinker & Northridge, 2006; Reeves, McClellan & Werner, 2013). Gillnets are relatively inexpensive to operate and maintain, and can result in high catch rates of various taxa, including tuna and other large pelagic fishes, but they are also notorious for their poor selectivity and high bycatch rates of marine megafauna (Lewison et al., 2004; Reeves, McClellan & Werner, 2013). Although some mitigation methods or devices such as acoustic and visual deterrents have been shown to reduce bycatch rates (e.g. Mangel et al., 2013; Bielli et al., 2020; Omeyer et al., 2020), most of them seem to work for some species and not others, which can be an issue when bycatch can affect multiple taxa at the same place and time. Moreover, the cost of the available mitigation devices is usually high and this limits their use, particularly in developing countries where bycatch is increasingly recognized to be a major problem (Brownell et al., 2019; Anderson et al., 2020). In most cases, mitigation devices are time-consuming and logistically challenging to use, and fishers are often resistant to implementing them.

In the Indian Ocean, there are growing concerns about the magnitude of marine mammal bycatch in both coastal (Kiszka et al., 2009; Temple et al., 2018) and offshore gillnet fisheries (Anderson et al., 2020), whereas cetacean bycatch rates in open ocean purse-seine (Romanov, 2002; Escalle et al., 2015) and pelagic longline (Huang & Liu, 2010) fisheries seem to be low. Tuna fisheries, including industrial, semi-industrial and artisanal, are of major economic and social importance throughout the Indian Ocean. The number of gillnet fishing boats has been increasing for several years, probably owing to the low operating cost of gillnets compared with other gear types (Roberson, Kiszka & Watson, 2018). Recently, preliminary bycatch estimates based on relatively small bycatch monitoring programmes in portions of the Indian Ocean suggest that as many as 100,000 cetaceans per year were taken between 2004 and 2006 (Anderson et al., 2020). Although this estimate is based on limited data collected over a long time period, it is clear that the magnitude of bycatch in Indian Ocean tuna gillnet fisheries is significant. Nine out of the 22 countries with currently the largest gillnet catches of tuna and tuna-like species account for almost 96% of the estimated cetacean bycatch across the Indian Ocean (Anderson et al., 2020).

It is therefore critical to better understand the magnitude of cetacean bycatch in Indian Ocean tuna gillnet fisheries at a regional level in order to inform evidence-based fisheries management. In that context, late in 2012, World Wildlife Fund – Pakistan (WWF-Pakistan) implemented a monitoring programme on tuna drift gillnet boats operating in the Arabian Sea based on a strong partnership with drift gillnet fishers. Since employing independent observers on gillnet fishing boats is very challenging in Pakistan, particularly owing to the difficult living conditions and lack of space on board, an alternative approach using captains as data recorders was adopted. Five boat captains working on four different boats were trained during multiple workshops to collect data and to test a method to reduce cetacean bycatch. Subsurface setting of gillnets (i.e. lowering the net in the water column) had already been trialed successfully in other regions around the globe, including the west coast of the USA (Moore et al., 2009) and Australia (Hembree & Harwood, 1987). Following discussions with the boat captains involved in the monitoring programme, subsurface settings were first tested at 2 m below the surface, starting in 2015.

This preliminary study, using crew-based observer data, quantified the magnitude of bycatch of cetaceans in tuna drift gillnet fisheries off Pakistan, and evaluated subsurface setting as a potential low-cost method to reduce cetacean bycatch in tuna drift gillnet fisheries in the Arabian Sea.

2 | METHODS

2.1 | Tuna drift gillnet fishery in Pakistan

Off Pakistan, tunas are caught mainly using pelagic drift gillnets made from multifilament nylon. Approximately 700 fishing boats are exclusively engaged in tuna fishing. Most of these vessels operate from Karachi harbour; others operate on the west coast from Gwadar. This study used data collected from four 15–20 m wooden vessels (five captains) operating out of Karachi harbour. Net lengths on the sampled vessels ranged from 7,700 to 14,400 m. Such nets are normally placed at the surface, have a height ranging from 10 to 14 m, and have a stretched mesh size of 13–17 cm (Figure 1). The nets are set in late afternoon and hauling begins after 12 h of soak time, with 2–5 h needed on average to complete the process. Fishing effort was distributed throughout the Pakistan Exclusive Economic Zone, particularly on the continental shelf off the Indus canyon (Figure 2).

2.2 | Data collection

Data were collected by five captains, who had all been trained by WWF-Pakistan. Captains were recruited following informal meetings with WWF-Pakistan in 2012. A small number expressed some interest

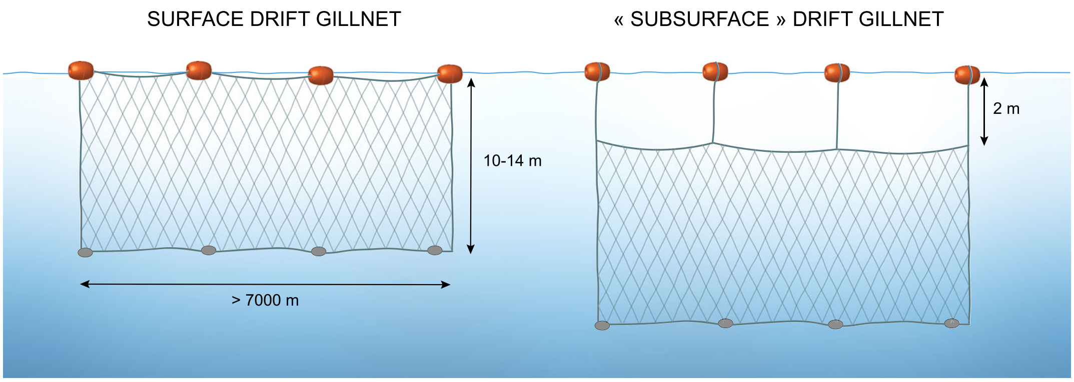

FIGURE 1 Setting of surface (left) and subsurface (right) drift gillnets in Pakistan

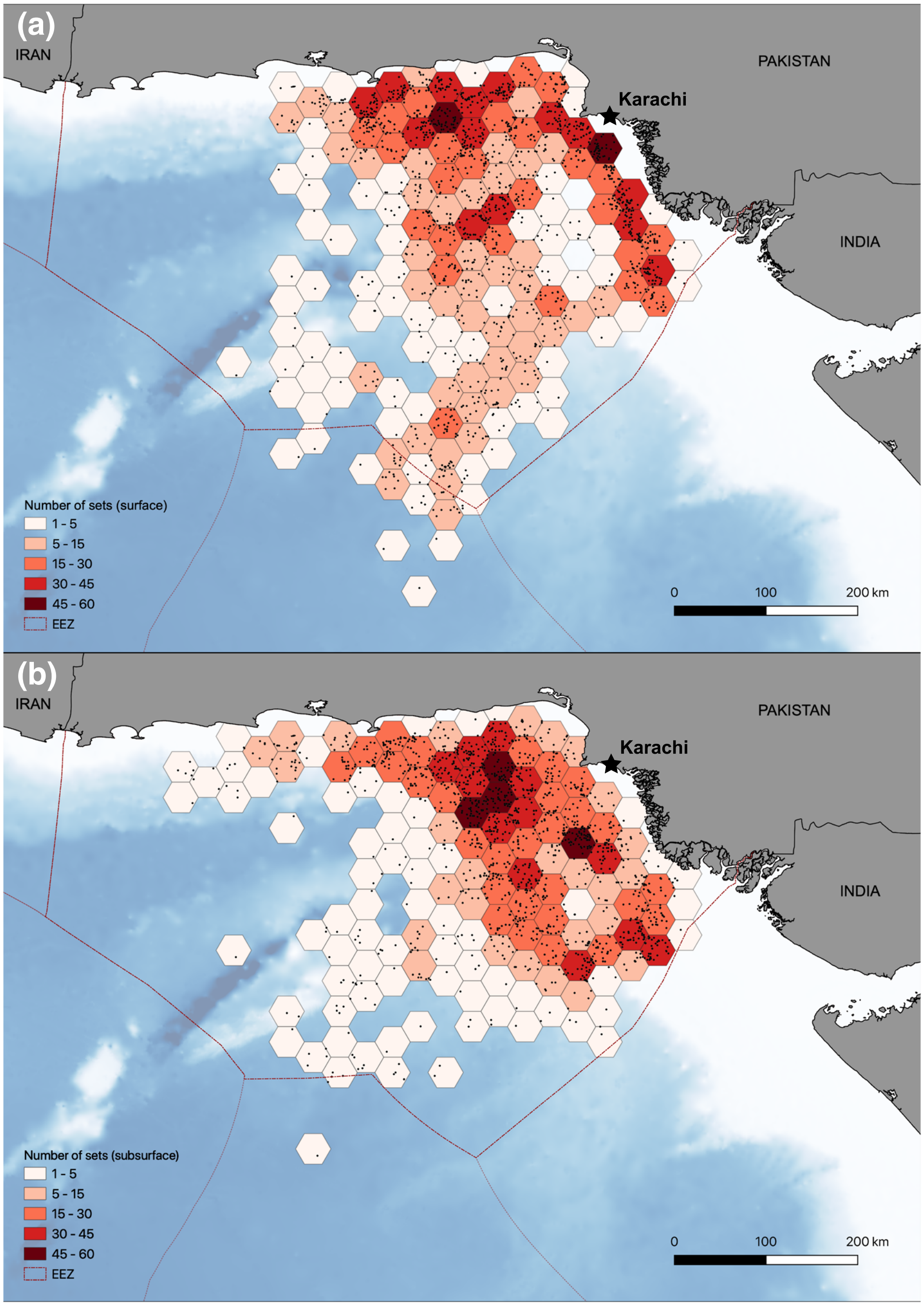

FIGURE 2 Tuna drift gillnet fishing sets off Pakistan from 2013 to 2017. (a) Surface drift gillnets. (b) Subsurface drift gillnets

and willingness to collect data. The five captains who were recruited received a monthly stipend for collecting data over the 5-year data collection programme. Captains trained crew members to take pictures of catches. Data were collected between January 2013 and December 2017. However, surface and subsurface net settings were not used simultaneously (or over a short period of time), and therefore no proper experimental design could be implemented for several reasons (e.g. willingness to participate but without changing their fishing methods, trust of the research team). Thus, fishers agreed to collect data using their main original method (surface setting) from January 2013 to September 2015, and then shifted to subsurface setting from March 2015 to December 2017. Species-identification guides from the Indian Ocean Tuna Commission (IOTC) were prepared in the local language (Urdu), and captains were trained to document any capture: targeted species (tuna and tuna-like species), non-targeted species including fishes (billfish, dolphinfish, other teleosts), marine reptiles (sea turtles and sea snakes), cetaceans and invertebrates. During each trip, captains recorded fishing hours, the position of gillnet sets and the length of net deployed. They were provided with digital cameras to confirm the identification of captured species and data-recording templates from the IOTC. Workshops and focused group discussions were held regularly with captains to make sure that data were properly recorded, and to address potential issues (mostly logistical). Such activities involved 'triangulation' of information received from fishers based on interviews, from the submitted data sheets and from the digital records of each trip. The same procedure and format for data collection were used for all trips, and the captain recorded in separate columns on the raw data sheets the fishing and gear-setting method used for each set. The relevant notations were later confirmed during post-trip interviews. In addition, the fishing locations were recorded for all sets by reference to a GPS installed on each vessel.

2.3 | Data analysis

Generalized linear mixed-effects models (GLMMs) were used to examine differences in both targeted-species catch and cetacean bycatch between surface and subsurface drift gillnet sets. Such models are preferred for analysing non-normal data incorporating random effects (Bolker et al., 2009). Statistical analyses were conducted using R (R Core Team, 2019). Given the zero-inflated nature of the data, the *glmer* function from the *lme4* package (Bates et al., 2014) was used with a binomial distribution and a logit link function to model the probability of catching at least one cetacean in the set. Predictor variables included fishing method (surface or subsurface drift gillnet setting), log-transformed distance to the coast, season and net length as fixed effects, whereas captain was used as a random effect. Season was defined as follows: winter, December–February; spring, March–May; summer/monsoon, June–August; and autumn, September–November.

The *glmer.nb* function from the same package was used to fit GLMMs with a negative binomial distribution to account for overdispersion in catch data, for both count of tuna per set and count of tuna-like individuals per set. Predictor variables were the same as for cetacean bycatch except that net length was included as an offset. Indeed, log(net length) was used as an offset term to account for the differences in total net length between fishing boats and consequent variation in catch counts. Model selection was realized independently for the three models based on Akaike's information criterion (AIC; Akaike, 1998). All combinations of fixed effects were tested and models with the lowest AIC and highest AIC weight were selected. Conditional and marginal Nakagawa's R^2 were calculated to explore the amount of variance explained by both fixed and random effects in the selected GLMMs (Nakagawa & Schielzeth, 2013). To explore the differences between surface and subsurface nets in regard to cetacean bycatch probability and target species catch per unit effort (CPUE), the *predict* function (*stats* package) was used on the best models to obtain predicted values accounting for other fixed and random effects.

Annual cetacean bycatch numbers (B) corresponding to two different fishing methods (either the whole fleet using surface or subsurface gears) were estimated at the scale of the entire Pakistan tuna drift gillnet fishery by multiplying the mean predicted probability of capture (P) per set (one set per vessel being deployed per day) by the average number of days at sea per vessel between 2013 and 2017 (D), the average number of individuals caught if at least one was captured (C) and n, the total number of vessels participating in the fishery (see Equation 1). The standard error of the estimated bycatch was calculated with the delta method taking into account variability of P, C and D (*deltamethod* function of the *msm* package; Jackson, 2007):

$$B = P\,C\,D\,n \tag{1}$$

3 | RESULTS

3.1 | Effort and bycatch composition

From January 2013 to December 2017, a total of 3,429 drift gillnet sets were monitored, including 1,754 surface settings (Figure 2a) and 1,675 subsurface settings (Figure 2b). Sets were distributed throughout the Pakistan Exclusive Economic Zone and international waters. Over the course of the monitoring, cetacean species identification was based on photographs collected by boat captains (Figure 3). A total of 203 cetaceans were captured, and of these, 45 individuals were identified at the species level based on photographs. Identified species were, in order of occurrence, spinner dolphin (*Stenella longirostris*, $n = 30$, 67%), common bottlenose dolphin (*Tursiops truncatus*, $n = 5$, 11%), Indo-Pacific common dolphin (*Delphinus delphis tropicalis*, $n = 4$, 8%), Risso's dolphin (*Grampus griseus*, $n = 2$, 5%), pantropical spotted dolphin (*Stenella attenuata*, $n = 1$, 3%), dwarf sperm whale (*Kogia sima*, $n = 1$, 3%) and Omura's whale (*Balaenoptera omurai*, $n = 1$, 3%). Another species, the striped dolphin (*Stenella coeruleoalba*), was also identified based on anecdotal

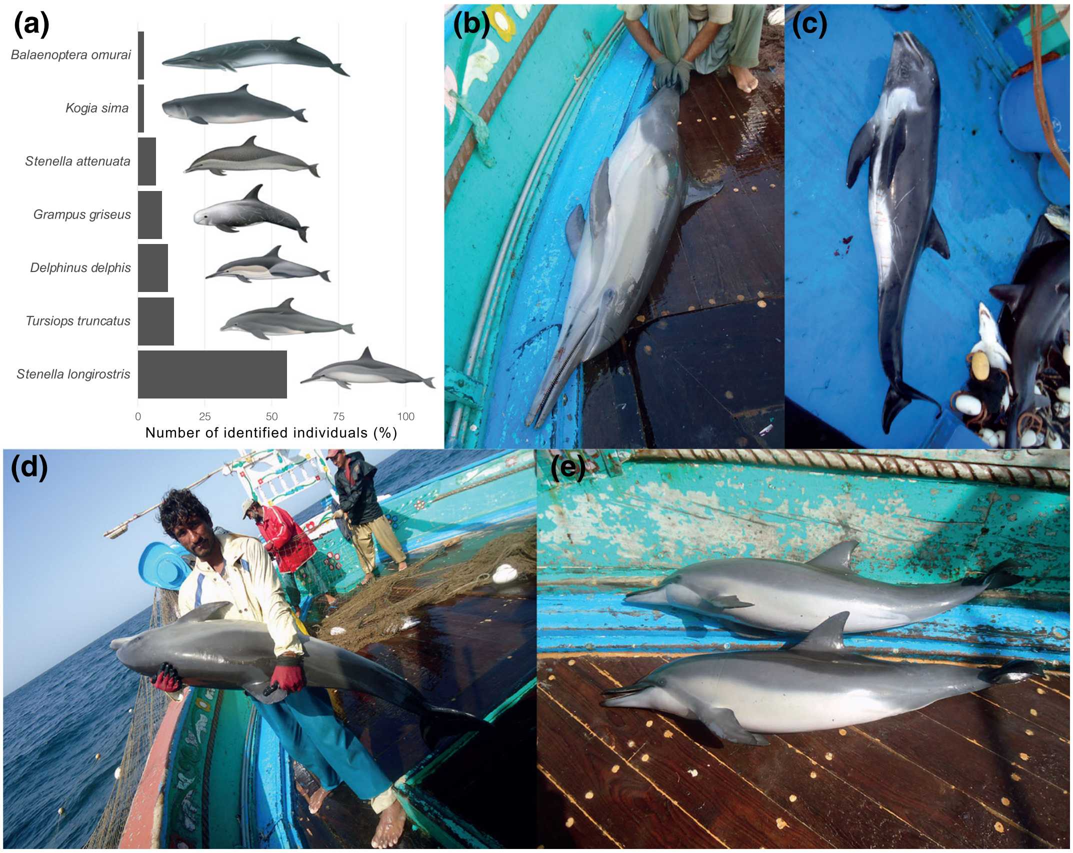

FIGURE 3 Bycaught cetacean species photographed by boat captains: (a) proportion of individuals belonging to each species ($n = 45$). (b) Indo-Pacific common dolphin (*Delphinus delphis tropicalis*); (c) Risso's dolphin (*Grampus griseus*); (d) common bottlenose dolphin (*Tursiops truncatus*); (e) spinner dolphins (*Stenella longirostris*)

reports but no data were collected on the species. No information on the status of caught animals was collected (caught dead or alive, or post release status).

3.2 | Factors affecting catch and bycatch rates

The negative binomial models revealed that all of the variables explained only 19.8% of tuna CPUE variance (Table 1), driven mainly by season, with fewer catches in winter (Table 2). A similar pattern was observed for tuna-like CPUEs, with 49.9% of variance explained, season and distance to the coast being the main explanatory factors (Table 2). Fishing method was also found to be linked to tuna and tuna-like CPUE variation, but to a lesser extent. Additionally, the second- or third-best model fits did not include fishing method as a predictor. Therefore, the difference between surface and subsurface setting accounted for a negligible amount of variance in tuna and tuna-like CPUEs. Predictions with the best-fit model showed similar CPUEs with surface and subsurface setting (Figure 4a,b).

In contrast, binomial GLMMs revealed that cetacean bycatch probability is driven mainly by fishing method (Table 1, Table 2). Predicted values using the best-fit model showed a large difference in bycatch probability when using subsurface nets compared with surface nets. Indeed, the likelihood of catching at least one cetacean per set dropped from 4.0% to 0.8%, i.e. subsurface sets were 78.5% less likely to catch at least one cetacean than were surface sets (Figure 4c). Therefore, annual overall bycatch estimates for the two fishing methods (surface and subsurface settings) differed significantly, from 8,411 individuals per year (SE = 1,057) in surface to 1,584 (SE = 429) in subsurface sets.

4 | DISCUSSION

This study provides the first assessment of cetacean bycatch in the tuna drift gillnet fishery in the Arabian Sea off the coast of Pakistan. Previous studies suggest that the magnitude of cetacean bycatch in the Indian Ocean tuna drift gillnet fisheries is high and possibly unsustainable (Anderson et al., 2020). This paper also describes the first mitigation trial undertaken in drift gillnet fisheries in the Indian Ocean. Individuals from a variety of cetacean species were caught incidentally during the trials, including small delphinids, other toothed cetaceans (*K. sima*) and one species of baleen whale (*B. omurai*). The results suggest that the magnitude of bycatch is significantly higher for small oceanic delphinids, particularly spinner, common and common bottlenose dolphins. These are among the most common

TABLE 1 Best generalized linear mixed-effects models (GLMMs) for bycaught cetaceans, tuna and tuna-like species off Pakistan. Response variables for cetaceans are bycatch probability per set and catch per unit effort (CPUE) for tuna and tuna-like species, as net length was included as an offset term

Cetaceans (binomial)	AIC	ΔAIC	Weight	R^2_m	R^2_c
***P* (bycatch) ≈ Fishing method + log(Distance to coast) + Season + (1| Captain)**	**899.81**	**0**	**0.36**	**0.203**	**0.249**
P (bycatch) ≈ Fishing method + Season + (1| Captain)	899.92	0.105	0.35	0.196	0.239
P (bycatch) ≈ Fishing method + log(Distance to coast) + Season + Net length + (1| Captain)	901.59	1.78	0.15	0.207	0.258
P (bycatch) ≈ Fishing method + Season + Net length + (1|Captain)	901.70	1.89	0.14	0.199	0.248
Tuna (negative binomial)					
Catch ≈ Fishing method + log(Distance to coast) + Season + (1|Captain) + offset (log(Net length))	**35,315**	**0**	**0.997**	**0.136**	**0.198**
Catch ≈ Fishing method + Season + (1|Captain) + offset (log(Net length))	35,327	12	0.002	0.126	0.190
Catch ≈ log(Distance to coast) + Season + (1|Captain) + offset (log(Net length))	35,328	14	0.001	0.134	0.208
Tuna-like (negative binomial)					
Catch ≈ Fishing method + log(Distance to coast) + Season + (1|Captain) + offset (log(Net length))	**25,898**	**0**	**>0.999**	**0.435**	**0.499**
Catch ≈ log(Distance to coast) + Season + (1|Captain) + offset (log(Net length))	25,922	24	<0.001	0.428	0.503

Abbreviation: AIC, Akaike's information criterion.

TABLE 2 Summary of the best GLMM for bycaught cetaceans, tuna and tuna-like species, with parameter estimates, standard errors (SE), *Z*-values and *P*-values

Fixed effects	Estimate	SE	*Z*-Value	Pr(>|*Z*|)
Cetaceans				
(Intercept)	−5.3524	0.6648	−8.052	<0.001
Fishing method: surface	1.5864	0.3107	5.106	<0.001
log(Distance to coast)	0.1985	0.1370	1.449	0.1473
Season: spring	0.3821	0.2424	1.576	0.1150
Season: summer	−0.7479	0.6146	−1.217	0.2236
Season: winter	−0.8549	−0.8549	−0.8549	0.0131
Tuna				
(Intercept)	2.45894	0.15277	16.096	<0.001
Fishing method: surface	0.16208	0.04083	3.970	<0.001
log(Distance to coast)	−0.09735	0.02567	−3.793	<0.001
Season: spring	0.09166	0.04753	1.928	0.0538
Season: summer	0.18972	0.08176	2.321	0.0203
Season: winter	−0.58249	0.05078	−11.470	<0.001
Tuna-like				
(Intercept)	3.32439	0.19552	17.003	<0.001
Fishing method: surface	0.23587	0.04616	5.110	<0.001
log(Distance to coast)	−0.44336	0.03001	−14.775	<0.001
Season: spring	−1.62596	0.05032	−32.313	<0.001
Season: summer	−0.88057	0.08814	−9.991	<0.001
Season: winter	−1.33069	0.05647	−23.564	<0.001

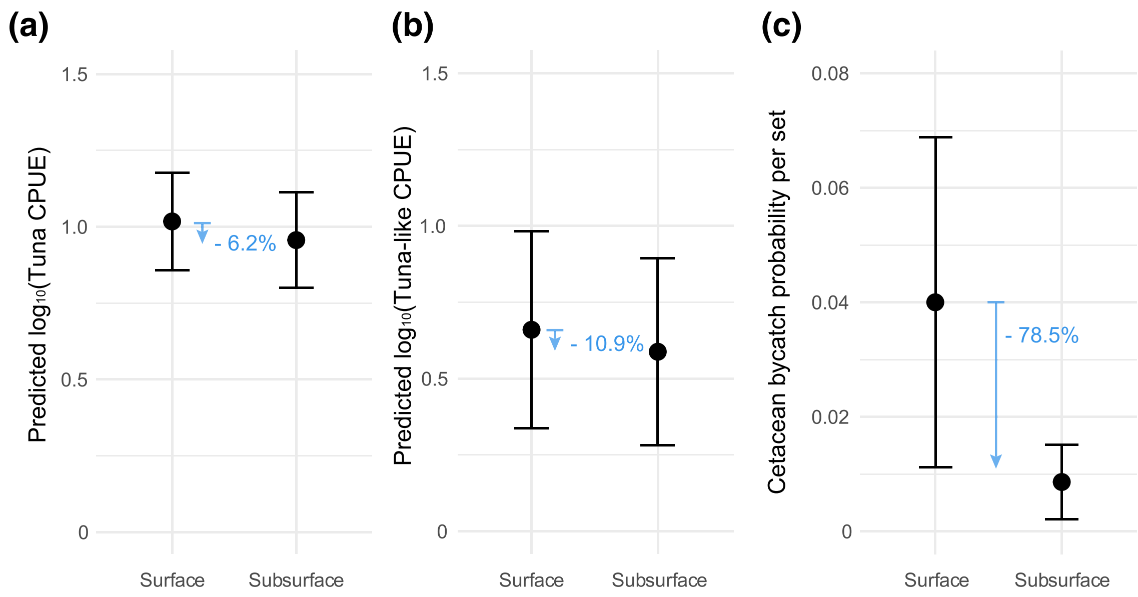

FIGURE 4 Difference between surface and subsurface drift gillnet setting for targeted and bycaught species. Predicted mean $\log_{10}$-transformed CPUE (number of individuals per km of net) for (a) tuna and (b) tuna-like species. (c) Predicted mean bycatch probability per set for cetaceans. Error bars represent standard deviations

cetaceans in continental and oceanic waters off Pakistan (Gore et al., 2012). Two more coastal small cetaceans, Indian Ocean humpback dolphins *Sousa plumbea* and Indo-Pacific finless porpoises *Neophocaena phocaenoides*, both listed as Endangered on the IUCN Red List and extremely vulnerable to bycatch in gillnets (Brownell et al., 2019), inhabit the inshore and near-shore waters of Pakistan (Gore et al., 2012). The lack of these two species in the documented bycatch during the drift gillnet trials highlights the limited level of spatial overlap between them and tuna gillnet fisheries in this region. Assessment of their interactions with more coastal, small-scale, bottom-set gillnet fisheries, however, should be carried out.

A few issues related to data collection and the experimental design need to be acknowledged. Firstly, data were collected by captains, and not scientific observers. Therefore, although data collection was carefully monitored, there is a risk that errors could have been introduced. Self-reporting of fisheries data by captains and crew members is an inexpensive means of collecting information, but the accuracy of data collected is questionable and challenging to measure (Starr & Vignaux, 1997; Sampson, 2011), including for bycatch assessments (e.g. Walsh, Kleiber & McCracken, 2002). Some studies suggest congruence between logbook data and electronic monitoring, but reporting is higher for retained than discarded catches (Emery et al., 2019). Interestingly, communication between fisheries managers and fishers can have a positive impact on protected species catch reporting (Emery et al., 2019). Although we believe that the captains involved in the crew-based observer programme in Pakistan have been rigorous, it is critical to remain cautious and the data collected may be incomplete or contain errors. This study is also opportunistic and preliminary in nature and is based upon a partnership between fishers and WWF-Pakistan. No proper experimental design has been implemented, particularly to test the influence of fishing method (i.e. surface vs. subsurface sets) on catch and bycatch rates, in both space and time. Thus, subsurface settings were implemented in March 2015, 2 years after all surface setting data were collected. Unfortunately, owing to logistical constraints, the two fishing methods could not be tested simultaneously (or very partially). It is therefore important to remain cautious about the interpretation of the data collected. To obtain reliable species-specific bycatch rates in tuna gillnets off Pakistan, improved species identification and reporting are also required. Finally, extrapolation of bycatch estimates to the entire drift gillnet fishery in Pakistan needs to be considered with caution, as the five captains and their fishing practices might not constitute an adequate sample reflecting the whole fishery.

Nevertheless, this preliminary study based on a 5-year trial period (2013–2017) of the crew-based observer programme provides a useful preliminary assessment of the magnitude of cetacean bycatch and shows the potential usefulness of subsurface settings in reducing cetacean bycatch in drift gillnets in this region. The programme has also provided empirical evidence related to an alternative data collection method for small-scale and semi-industrial vessels when independent observer coverage is not feasible because of limited space for accommodation and poor living conditions onboard. The crew-based observer programme is recognized by the IOTC as an alternative data-collection method which can be combined with electronic monitoring systems in an attempt to further validate the data. However, the reliability of crew-based observer data still needs to be assessed, particularly if future investigations will combine electronic monitoring and self-reporting data.

The magnitude of bycatch, in both surface and subsurface sets, reveals slight differences from previously published estimates of 10,150–12,000 individuals per year in the Pakistani offshore drift gillnet fishery for tuna (Anderson et al., 2020). Between 2013 and 2017, annual captures were estimated at 8,411 cetaceans in surface sets and 1,584 in subsurface sets. However, these estimates are based on limited sampling, since the five vessel captains might not be representative of a fleet of about 700 vessels at the country level. This study highlights the importance of bycatch in drift gillnet fisheries and represents the most in-depth assessment conducted in recent years (see Anderson et al. (2020) for a review of studies conducted in the Indian Ocean). Without information on the abundance of cetaceans in the waters of Pakistan, no assessment of the population-level impacts of gillnet bycatch is possible. However, the significant difference in cetacean bycatch rates between the two setting methods, considered alongside the relatively small impacts on catch rates of tuna (6.2% less in subsurface than in surface sets) and tuna-like species (10.9% less in subsurface than in surface sets), indicates the potential for slight changes in fishing practices to reduce the cetacean bycatch without having a significant effect on catch rates of targeted species or increasing the cost of fishing operations.

The underlying factors that would explain the lower catch rates of certain species, particularly cetaceans, are poorly understood and should be investigated. Fishers in Pakistan reported that the time and effort involved in disentangling cetaceans (especially large species) were not trivial. It can be an exhausting process; sometimes a portion of the net has to be cut off and discarded and the entangled animal can cause damage to crew members as well as to the vessel. Therefore, the fishers expressed a strong interest in testing ways of preventing cetacean bycatch in gillnets. Several Pakistani fishers (including several not involved in the crew-based observer programme) have generally accepted the idea of shifting to subsurface setting as an acceptable method for reducing cetacean entanglement in the tuna gillnet fishery. However, a more in-depth investigation of the acceptability of this potential mitigation method should be carried out in the future.

A deep-sea fishing policy that would regulate gillnetting, restrict the length of individual gillnets to 2.5 km and require fishers to follow best practices (such as subsurface gear setting) is under development in Pakistan. Similarly, the IOTC has adopted the use of subsurface gears in gillnet fisheries under resolution 19/01 as part of an interim plan for rebuilding the Indian Ocean yellowfin tuna stocks. Using electronic monitoring should improve species identification and data quality more generally. Dedicated surveys to obtain estimates of cetacean abundance should be carried out, which will be crucial to understanding population-level impacts of bycatch on cetaceans in the region.

ROLE OF FUNDING SOURCE AND DECLARATION OF CONFLICTS OF INTEREST

The funders played no part in the study, analysis, interpretation of data, writing of the paper or decision to submit for publication.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest that would inappropriately influence any aspect of the work.

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