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Successful fisher-driven reduction of megafauna bycatch in a tuna gillnet fishery

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Abstract

Bycatch in gillnet fisheries is a major source of marine megafauna mortality but effective mitigation options remain limited, especially in low-income countries. Technical solutions developed for industrial fleets are often too costly or impractical for these fisheries, while regulatory measures demand substantial monitoring and enforcement capacity. Collaborative solutions that harness fisher innovation and social networks remain underexplored and underfinanced. Controlling for key factors affecting bycatch risk, we analysed over 5,500 gillnet sets using Generalized Additive Models to quantify the performance of 13 captains participating in a crew-based observer program in Pakistan from 2012–2016. A co-developed subsurface net setting strategy, combined with bycatch awareness training and peer-learning, coincided with substantial reductions in dolphin and sea turtle bycatch. Although gillnets are widely viewed as simple, unselective, and universally high-risk gears, we found significant variation among individual captains' bycatch rates, even as the group improved remarkably over time through iterative changes in fishing practices and accumulated fisher experience. This variation suggests that, beyond known factors such as fishing location, season, and gear configuration, individual fishers employ nuanced and adaptive tactics that strongly influence bycatch outcomes. Encouragingly, reductions in bycatch did not come at the expense of target catch, suggesting that improved selectivity and profitability can be aligned. These findings highlight the need for fisher-led bycatch interventions that acknowledge individual variation and actively leverage fishers' capacity to adapt their practices to fish more selectively.

Keywords: Marine megafauna conservation; Small-scale fisheries; Bycatch mitigation; Fisher engagement, Sustainable blue foods; Gillnets

Introduction

Incidental capture of non-target species in fisheries ("bycatch") remains a primary conservation threat for marine megafauna, including many mammal and sea turtle species (Lewison *et al.* 2014; Huang *et al.* 2024). Mitigation efforts typically target a single species or taxonic group using technical measures such as bycatch reduction devices (Squires *et al.* 2021). Many fisheries are now grappling with more complex problems, such as species that are difficult to avoid, gears that are hard to modify, or fisheries that interact with a wide variety of species of conservation concern (Pons *et al.* 2022; Huang *et al.* 2024). Thus, fishers face the increasingly difficult task of reducing bycatch of multiple species while maintaining profitable target catches.

Bycatch mitigation has been particularly challenging in small-scale fisheries, which use many different methods to target a wide variety of species and contribute at least 40% of global catch volumes (FAO 2023). The definition of "small-scale" has never been fully resolved, especially as these fleets can have hundreds or thousands of vessels fishing far offshore or even beyond the 200 nautical mile Exclusive Economic Zone (EEZ) (Alfaro-Shigueto *et al.* 2010; Haas and Shahid 2026). This ambiguity is not only definitional but also has practical repercussions for fisheries management, as fleets classified as small-scale are often subject to less monitoring and management than those classified as industrial (Haas and Shahid 2026). Many low-income countries have large small-scale fleets operating with minimal oversight, and these fisheries can have disproportionate impacts on megafauna species (Pita *et al.* 2019; Temple *et al.* 2021). For instance, bycatch in small-scale fisheries was a leading cause of the extinction of the baiji (*Lipotes vexillifer*) and remains the primary threat to many other small cetaceans, most notably the vaquita porpoise in the gulf of California, where gillnet fisheries have caused catastrophic population declines (Brownell *et al.* 2019). Consequently, effective bycatch mitigation in these contexts requires approaches that are adapted to dispersed fleets, limited monitoring capacity, and diverse fishing practices, rather than relying on management approaches developed for industrial fisheries (Pita *et al.* 2019).

Gillnets are widely used in low-income countries and tend to generate high bycatch mortality, especially for air-breathing species such as small cetaceans and sea turtles (Gray and Kennelly 2018). These nets require little specialized equipment to deploy and can be anchored or drifting and deployed near the seabed, in the water column, or at the surface. Despite substantial efforts, there has been limited success developing modifications for gillnets that are economically viable in fisheries supplying lower-value markets—where incentives and profit margins for change are limited—while also remaining practical for real-world operations and effective over time (Northridge *et al.* 2017; Martin and Shahid 2021; Huang *et al.* 2024).

Gillnets are a particular concern in the Indian Ocean, a global megafauna biodiversity hotspot harboring numerous threatened and endemic marine species (Wafar *et al.* 2011; Roberson *et al.* 2021, 2022). Since the early 2000s, gillnet fisheries targeting tunas and other species have expanded, but are subject to much less oversight than industrial purse seine and longline fleets in the region (Roberson *et al.* 2019; Haas and Shahid 2026). Unlike other regions, gillnets are the dominant gear in the Indian Ocean, accounting for approximately 30% of tuna catches, of which 85% comes from Iran, India, Indonesia, Pakistan, and Sri Lanka (Elliott *et al.* 2024). There are substantial data gaps in this region, but gillnets are known to pose a serious threat to Indian Ocean megafauna, with estimates of 30,000 sea turtles and up to 100,000 cetaceans captured annually (Nel *et al.* 2013; Moazzam and Nawaz 2014; Shahid *et al.* 2018; Anderson *et al.* 2020).

Pakistan has a fleet of approximately 700 vessels fishing for tuna with multifilament nylon gillnets (Kiszka *et al.* 2021). In 2012, World Wildlife Fund–Pakistan (WWF–Pakistan) implemented a monitoring program in partnership with gillnet fishers, where they trained captains to collect data, and practice safe handling and release (Moazzam 2021). As part of this initiative, fishers proposed setting pelagic drift gillnets below the surface to reduce megafauna bycatch. They tested the approach and experimented with different net depths before ultimately adopting a configuration of approximately 2 m subsurface (Kiszka *et al.* 2021). A preliminary study of the first five participants found this tactic

was effective in reducing dolphin bycatch overall, but bycatch rates varied among vessels (Kiszka *et al.* 2021). This suggests captains employed other strategies beyond net depth that affected bycatch outcomes. Here, we extend that earlier work using a larger dataset collected over the expansion and evolution of the crew-based observer program, allowing us to quantify captain-level heterogeneity in both dolphin and sea turtle bycatch and evaluate whether these patterns are consistent across taxa.

Understanding whether some captains consistently produce lower bycatch rates can help identify pathways for scaling mitigation through peer learning and targeted engagement. While gear based mitigation trials often focus on technical efficacy, far less attention has been paid to the role of individual fisher behaviour and heterogeneity in bycatch outcomes (Eayrs and Pol 2019). Here we examine a larger group of captains from the Pakistani fleet, quantify the variation in bycatch rates among individuals, and assess their potential to reduce bycatch of multiple taxa simultaneously. If this relatively low-cost approach—engaging directly with fishers to identify bycatch solutions—is effective across multiple taxa, it could offer a promising pathway to mitigate bycatch in fleets with limited technical or regulatory solutions and substantial bycatch problems, particularly in low-income gillnet fisheries.

Methods

We analysed fisher level variability in sea turtle and dolphin bycatch among 13 Pakistani captains using records from more than 5,500 gillnet sets collected through a crew-based observer program between 2012 and 2016 (see Panel S1 for more details about the data collection). The program evolved from an initial port-based monitoring effort into a structured at-sea reporting program, with participation expanding progressively from a small group of trained captains to approximately 75 participants by the end of 2017. Data collection procedures were refined through regular engagement, training, feedback, and the development of species identification guides, with skipper reports validated using photographs, interviews, and independent observer activities.

Our objective was to isolate the effect of individual captains and evaluate the factors driving variation in catches, as opposed to predicting bycatch. We fit generalised additive models (GAMs) with Tweedie distributions and the default log link function using the mgcv package in R (Wood 2015). Candidate models were evaluated using Akaike's Information Criterion (AIC) alongside diagnostic assessment of residual patterns, dispersion, and fitted-versus-observed relationships to balance model fit, explanatory power, and biological interpretability. After comparing negative binomial and Tweedie distributions, we retained the latter because they provided substantially better fit (see Panel S2 for more details about the statistical approach).

Total net area (net panel width * panel length * number of panels) was included as an effort offset to account for differences in fishing effort among sets and allow comparisons on a per-unit-effort basis. Net dimensions were consistently recorded, whereas soak time was not, precluding its inclusion as an effort metric. Discussions with researchers involved in the logbook program indicated that soak times are generally similar among vessels because nets are typically set in the late afternoon and hauled the following morning, whereas net dimensions varies substantially among sets. As a result, total net area was considered the most reliable measure of relative fishing effort.

Models included bycatch count per set as the response variable and a suite of environmental and operational variables as predictors. Because the objective was to explain variation in bycatch interaction rates rather than mortality outcomes, the response variable included all entanglements irrespective of whether the animal was alive or dead at haulback. Based on exploration of the raw data, retained tuna and tuna-like catch volume, retained catch of other species, chronological month of the fishing season, set start time, number of crew, and fishing location were included as smooth terms, with latitude and longitude as a 2D spatial smooth. Year was included as a linear continuous effect and fishing method was a fixed effect with two levels (bottom or surface-set gillnets). Based off model diagnostics and the AIC, we explored different covariate parameterizations.

Captain identity was initially fitted as a random effect to account for unequal sample sizes among the 13 captains as the observer program expanded. The random effect tests whether variation among captains contributes to variation in bycatch rates, without estimating effects for individual captains. After identifying the best supported model structure for each species, equivalent models were refitted with captain identity as a fixed effect, which quantifies the effect of individual captains on bycatch rates. This allowed direct estimation and comparison of captain-specific effects. Instead of the default treatment contrasts setting in R, we used deviation coding (also called sum contrast coding), which estimates captain effects relative to the grand mean rather than a reference captain. Because five captains recorded zero dolphins, we applied a penalty to the captain term using the paraPen framework in *mgcv*, which stabilizes coefficient estimates in the case of separation and prevents estimates for zero-bycatch captains from tending toward negative infinity (Wood 2015). The random effect model for dolphins was marginally better supported than the fixed effect model (ΔAIC = 2), whereas the unpenalized fixed effect model was best supported for sea turtles.

The fixed effect models for both taxa (with the penalization on the captain term for dolphins) were used for post hoc analyses comparing captains, which required explicit estimates of individual effects. However, because several captains entered the program during later years and adoption of subsurface net configurations occurred gradually over the same period, the dataset does not allow robust separation of longitudinal changes in individual captain performance from broader temporal changes in fishing practices. To examine the contribution of captain identity in explaining variation in bycatch rates, we compared the final model for each taxon with an otherwise identical model excluding the captain effect.

To assess whether captains differed meaningfully in their bycatch rates, we used two complementary approaches. First, we interpreted the captain regression coefficients from the best supported models as representing residual differences among captains after accounting for measured operational and environmental covariates. Second, we calculated Estimated Marginal Means (EMMs) using the R package *emmeans* (Lenth and Piaskowski 2025), which estimates each captain's expected bycatch rate under standardized operating conditions with covariates held at their mean values. Pairwise differences among captains were evaluated using Wald tests with Tukey-adjusted p-values.

We used both metrics to test correlations between dolphin and sea turtle bycatch. Correlations between captain regression coefficients indicate whether residual captain effects were consistent across taxa. Pearson's correlation coefficients were calculated between the raw dolphin and sea turtle captain coefficients from the GAMs, and parameter uncertainty was then propagated using a multivariate normal bootstrap. For each species, 1,000 draws were generated from a multivariate normal distribution defined by the estimated coefficient vector and associated variance-covariance matrix. Pearson's correlation coefficient was calculated for each bootstrap iteration, and the resulting distribution was used to estimate the mean correlation and 95% confidence interval. We also evaluated correlations between dolphin and sea turtle EMMs, which indicate whether captains under standardized operating conditions are expected to have high bycatch of both taxa.

Results

The captains were similar in several general aspects of their fishing operations but showed significant variability in their bycatch rates. The fleet uses open air wooden vessels with 12–22 crewmembers (median=17). Fishing effort was concentrated within 200 km (~100 nm) of Karachi, although many trips venture farther (Figure 1). Nets were usually set in the late afternoon (typically between 15:00–17:00). Net configuration varied; the panel drop (hanging) height was between 8–14 m, but each panel ranged from 50–90 m long and captains used between 70–190 panels per set. Total net area varied by an order of magnitude, ranging from 39,200–212,800 m^2, with an average of 116,612 m^2.

From 2012 to 2016, the 13 captains recorded 173 dolphins in 156 nonzero sets and 614 turtles in 534 nonzero sets. Bycatch declined markedly over the five year period, from 7.8 to 0.4 dolphins per 100

sets and 25.5 to 2.7 turtles per 100 sets, reductions of 95% and 90%, respectively (Figure 2). Most sea turtles (94.7%) were recorded alive at haulback, compared to only 13.9% of dolphins. The status of these captured individuals does not include any potential post-release mortality. Captains' bycatch rates were variable, with no evidence of correlation with target catch or observed fishing effort (Figure 2). All captains recorded at least one turtle whereas five (38%) recorded zero dolphin captures. These five captains all joined in 2015 or 2016, when many fishers had partially or fully shifted to subsurface sets (Moazzam 2021).

Captain identity was a significant predictor of bycatch for both taxa and, together with year, was the most consistently retained and strongly supported variable across all candidate models (Table 1). The final dolphin model included captain, year, retained tuna catch, and location, whereas the final turtle model additionally included season and crew size. Although the spatial smooth was not statistically significant in either model, its inclusion improved model fit substantially (>6 ΔAIC) and was therefore retained. This suggests the presence of broad-scale spatial structure in bycatch risk that was not fully explained by the other covariates. The weak statistical support for the smooth term may reflect the fact that bycatch hotspots are associated with specific habitat features or bathymetric characteristics rather than geographic position alone. This interpretation is consistent with information from fisher interviews, which identified particular high-risk areas that are not adequately represented by latitude and longitude.

Model diagnostics supported the adequacy of both final Tweedie GAMs for describing drivers and variations in bycatch. Basis-dimension checks indicated that smoothing complexity was appropriate, concurvity among predictors was low, and simulation-based residual diagnostics showed no evidence of overdispersion, zero inflation, or excess outliers (Figure S1). Although residual plots exhibited the banding patterns and mild skewness expected for Tweedie models fitted to sparse, zero-dominated bycatch data, no systematic departures from model assumptions were evident.

Turtle bycatch risk was highest during the nesting period (October–February; months 3–7 of the fishing season) and lowest in the northeastern portion of the fishing grounds near Karachi, although the spatial effect was weak. Turtle bycatch decreased nonlinearly with very large tuna catches, with increasing uncertainty at very high tuna catches, and showed a nonlinear relationship with crew size, with wider confidence intervals at small and large crew sizes because of fewer observations at the extremes. Dolphin bycatch was also significantly related to tuna catch volume, but the estimated effect of tuna catch was small and uncertainty increased markedly at the highest tuna catches because of limited observations in this portion of the distribution (Figure S2).

Surprisingly, the fishing method factor was not retained in the final models for either taxon. This suggests that the broad gear classifications recorded in the logbooks did not adequately capture biologically meaningful variation in gear configuration. Interviews with fishers and observations by program staff indicated substantial variation in gillnet configuration and deployment practices, including differences in net depth, construction, material, and nuanced deployment tactics that were not recorded in the logbooks. Consequently, the effects of net configuration are likely confounded with captain identity, season, and location, as fishers adapt gear configurations to specific fishing grounds, environmental conditions, and target species throughout the year.

Table 1: Summary of the best Generalized Additive Models for dolphin and sea turtle bycatch rates. Significant (p<0.05) variables denoted with * in bold. Season-month is the chronological month of the fishing season (August=1, May=10). Fishing location was included as a 2D spatial smooth. All models included total gillnet area (number of panels * panel length * panel drop) as an effort offset. R^2 Adj=approximate adjusted R^2 based on the reduction in deviance. AIC=best model's AIC score, AIC (null)=best model minus the captain factor. ΔDeviance=increase in deviance explained by adding the captain factor to the null model. No obs= number of observations (sets) included in the model dataset; nonzero obs=number of sets with at least one dolphin or sea turtle (not total bycatch counts).

DOLPHINS

Parametric coefficient	*Estimate*	*Std. Error*	*t value*	*Pr(>|t|)*	*Deviance explained:*	20.4%
(Intercept)	1258.8	191.4	6.5783	< 0.001		
***Year**	**-0.6328**	**0.0950**	**-6.6628**	**< 0.001**	*ΔDev.*	4.2%
Smoothed terms	*Est. df*	*Ref df*	*F*	*P-value*	*R^2 (Adj):*	0.0714
***s(Tunas & tuna-likes weight)**	**3.5481**	**4.4628**	**4.8945**	**< 0.001**	*AIC:*	869.72
s(Latitude, Longitude)	2.0027	2.0053	1.6151	0.2	*AIC null:*	892.0
Fixed effects	***Captain** (n=13; 5 significant) with paraPen()				*No. obs:*	5442
Effort offset:	log(total net area m2)				*No. non-zero obs:*	158
Excluded variables:	Season-month, Fishing method, Time of day gear set, Other retained species weight, Number of crew					

SEA TURTLES

Parametric coefficient	*Estimate*	*Std. Error*	*t value*	*Pr(>|t|)*	*Deviance explained:*	24.2%
(Intercept)	740.92	99.94	7.4133	< 0.001		
***Year**	**-0.3746**	**0.0496**	**-7.5461**	**< 0.001**	*ΔDev.*	6.1%
Smoothed terms	*Est. df*	*Ref df*	*F*	*P-value*	*R^2 (Adj):*	0.2
***s(Tunas & tuna-likes weight)**	**2.7281**	**9**	**2.5134**	**< 0.001**	*AIC (fe):*	1856.1
***s(Season-month)**	**0.8694**	**2**	**3.2801**	**0.005**	*AIC null:*	2030.2
***s(Number of crew)**	**3.5543**	**9**	**1.6039**	**0.002**	*No. obs:*	5442
s(Latitude, Longitude)	1.2025	29	0.1122	0.066	*No. non-zero obs:*	536
Fixed effects	***Captain** (n=13; 9 significant)					
Effort offset:	log(total net area m2)					
Excluded variables:	Fishing method, Time of day gear set, Other retained species weight					

Regression coefficients and EMMs revealed a similar performance gradient across captains, indicating strong agreement between residual captain effects and expected performance (Figure 3). Using deviation coding, regression coefficients represent deviations from the fleet mean after accounting for the environmental and operational covariates retained in each model. For dolphins, the five most positive captain coefficients (high bycatch) differed significantly from the fleet average. However, there was substantial uncertainty around some captain-specific estimates, particularly at the low-bycatch end of the performance gradient because five captains recorded no dolphin captures during the study period. There was also substantial uncertainty around the EMM estimate for the thirteenth captain, who entered the fishery most recently, had the fewest observations, and recorded no dolphin captures. No pairwise differences among captains remained significant after adjustment for multiple testing. Consequently, estimates for individual low-bycatch captains should be interpreted with caution. Nevertheless, captain identity substantially improved model fit, explained a large proportion of the deviance, and revealed clear differences in adjusted dolphin bycatch performance among captains.

Variation among captains was more pronounced for sea turtles. Nine of the 13 captain coefficients differed significantly from the fleet average, including captains at both the low and high ends of the performance gradient, indicating substantial heterogeneity in turtle bycatch rates after accounting for year, season, location, retained tuna catch, crew size, and fishing effort. The distribution of EMMs closely mirrored the regression coefficients, and pairwise comparisons identified significant differences among numerous captain pairs, demonstrating that some captains consistently exhibited higher or lower expected turtle bycatch rates than others under comparable operating conditions. Together, these results demonstrate substantial captain-specific variation in both residual bycatch risk and expected turtle bycatch rates that was not explained by the measured environmental and operational covariates.

Correlation tests revealed a strong positive relationship between dolphin and turtle bycatch across captains. Residual captain effects, represented by the regression coefficients, were strongly correlated between taxa (Pearson's $r = 0.71$, $p = 0.007$; 95% CI: 0.26-0.91). Captains with above-average turtle bycatch rates therefore tended to have above-average dolphin bycatch rates after accounting for environmental and operational covariates. When parameter uncertainty was propagated using a multivariate normal bootstrap, the positive relationship remained strong (mean $r = 0.74$, SD = 0.12; 95% CI: 0.50-0.94), demonstrating robustness to uncertainty in the coefficient estimates. Expected captain performance, represented by covariate-adjusted EMMs, showed an even stronger correlation between taxa (Pearson's $r = 0.86$, $p < 0.001$; 95% CI: 0.59-0.96). The consistency of these relationships across both residual captain effects and expected bycatch rates indicates that captains with relatively high turtle bycatch rates also tended to have relatively high dolphin bycatch rates. This pattern persisted despite the dolphin and turtle models retaining different environmental and operational predictors, suggesting that some captains consistently achieve lower bycatch rates of both taxa through behaviours or fishing practices not captured by the measured covariates.

Discussion

Gillnets are commonly used in many low-income countries and are associated with high megafauna bycatch and few feasible mitigation options (Northridge *et al.* 2017). Using logbook data from 13 tuna drift gillnet fishers in Pakistan, we examined individual and cumulative bycatches during the first five years of a crewbased observer program implemented as part of broader, evolving fisher engagement initiative. Fishers co-developed a subsurface net setting strategy, in tandem with bycatch awareness and safe release training. Encouragingly, there was a dramatic reduction in bycatch of both sea turtles and dolphins.

The results for dolphins corroborate findings from a preliminary study, which used a similar modelling approach to compare dolphin bycatch in surface and subsurface sets for the first five captains that entered the program (Kiszka et al. 2021). The logbook data subsets differ slightly

between the two studies due to data filtering for records with complete covariate information. In this earlier work, the strongest predictor of dolphin bycatch was subsurface setting, although logistical constraints precluded a direct paired comparison with surface sets. Season and distance from the coast were not significant, although both were included in the best model. Consistent with these preliminary results, we found no significant spatial or seasonal effects for dolphins (although the variables were coded differently), but location improved model performance, indicating spatial variability contributes to differences in dolphin catch rates. Seasonal patterns may not have been fully captured by our seasonal variable (e.g., a monsoon versus dry-season effect). However, if strong seasonal effects were present, the smoothed term for chronological month within the fishing season would likely have detected at least part of that signal. Captain was a significant random effect in the previous study, indicating that individual behavior explained some variability in dolphin bycatch that was not explained by subsurface sets.

Here we focused on how individual captains contributed to fleetwide bycatch improvement. We found that captain identity and year were the strongest predictors of dolphin and sea turtle bycatch rates. Although the logbooks were self reported, we are confident that identification to broad taxonomic levels is reliable because bycatch was not penalized, logbooks were validated with photos and interviews, and captains received extensive training and stipends for completing the logbooks. Reporting quality likely improved rather than declined over the study period due to ongoing training, feedback, and engagement with captains, particularly for taxonomic identification. This improvement was one reason for analysing broad taxonomic groups, as many early records were reported only as "dolphins" or "sea turtles". Some portion of the observed captain effect could reflect differences in recording practices among captains and crewmembers, but repeated trainings and validation of bycatch records with photographs and interviews likely minimized this source of variation. Improved trust and participation over time could have influenced reporting rates, but these dynamics would be expected to increase, rather than decrease, reported bycatch and therefore do not provide an obvious explanation for the observed decline. The consistency of the reporting program and multiple validation measures provide sufficient confidence that the observed patterns reflect real changes in bycatch rather than artefacts of reporting. Thus, we draw six encouraging conclusions for bycatch management in low-income fisheries.

First, simple modifications to gear configuration or deployment strategies can reduce megafauna entanglements in gillnets when developed and implemented in genuine collaboration with fishers. Adjusting net depth is easier, less expensive, and more likely to be adopted than expensive technical solutions like pingers or lights, or spatio-temporal restrictions on fishing opportunities (Senko *et al.* 2014; Hamilton and Baker 2019; Huang *et al.* 2024). The shift to subsurface setting was the most visible and well-documented change that emerged from the engagement program, but interviews with fishers and observations during the trials indicate it is only one aspect of a broad and nuanced suite of fishing tactics. More important than the effect of this specific tactic is the demonstration that pelagic gillnets can be modified to fish more selectively without expensive technological interventions. This is particularly important because gillnets are trypically considered to be hard to modify, and mitigation efforts often focus on post-capture measures, such as safe release practices or retention bans, rather than preventing entanglements in the first place (Hamilton and Baker 2019; Zollett and Swimmer 2019). Reducing intiital entanglement is especially important for air breathing species captured in gillnets with long soak times, because many animals are likely to drown before gear retrieval (Northridge *et al.* 2017).

Second, our findings are doubly encouraging for sea turtles because the initial catch rates were reduced and the rate of live release was unexpectedly high. Turtles survived entanglement longer than anticipated given that nets soak overnight. Crewmembers observed that turtles entangled closer to the boat (meaning they were retrieved sooner) were more likely to be alive upon haulback. Although we focused on initial entanglements as opposed to mortalities, this finding merits further investigation as alive-at-haulback rates in comparable gillnet fisheries are much lower (Gilman *et al.* 2010). Similar patterns have been reported in other fisheries, where turtles are found alive more often than expected based on recorded breath-holding limits and gear soak times (Dodge *et al.* 2022; James *et al.* 2024).

Although post-release mortality could not be assessed in this study, available evidence suggests most turtles released alive likely survive. Telemetry data from a similar gillnet fishery in Peru detected no short-term mortality following release, with cumulative mortality increasing to 18.7% only after a month or more, and some deaths likely attributable to subsequent entanglement events rather than the original capture (Mangel *et al.* 2024). Although available estimates cannot be directly extrapolated to Pakistan's fleet, they suggest short-term survival is likely quite high (Cardona *et al.* 2025). The effect of the safe-release trainings on post-release mortality remain uncertain, but the training likely improved fishers' awareness of protected species and promoted handling and release practices intended to maximise survival, suggesting this intervention was a worthwhile investment (Zollett and Swimmer 2019).

Third, these captains likely innovated additional tactics beyond subsurface setting. While reporting incongruities precluded isolation of the captain effect from the subsurface net effect, significant variation among captains persisted even as the group adopted the practice. Moreover, captains differed in both their residual bycatch effects (holding other variables constant) and their expected bycatch rates under comparable fishing conditions. This suggests captains employ additional practices that reduce bycatch, some likely relating to other variables in our models (e.g., season, fishing location) and others that were not recorded. Captains may have nuanced strategies to manage net tautness or orientation (Hamilton and Baker 2019), or fine-scale knowledge of habitats and bycatch species, including patterns in lunar phases, prey species, rainfall, frontal systems, or sea surface temperature (Seidu *et al.* 2022). The fishers use a wide variety of gillnet configurations and likely adjusted their tactics according to season and environmental conditions. The nonlinear effect of crew size on sea turtle bycatch may also reflect differences in fishing practices. Larger vessels usually carried larger crews, and because nets are hauled by hand, crew size may influence hauling speed, gear handling, or other operational practices that affect bycatch risk.

Fourth, our findings suggest the fisher engagement program effectively spread bycatch mitigation strategies through the group relatively quickly. Anecdotal evidence indicates the vast majority of the 700-vessel fleet adpoted subsurface gear configurations in roughly five years (Moazzam and Khan 2019; Moazzam 2021). Our results show that early entrants to the program showed substantial reductions in bycatch over the five-year period, while later entrants generally began with much lower bycatch rates than the initial group. This pattern is consistent with the possibility that some fishers had already modified their practices before formally joining the program, either through direct exposure to program activities or through interactions with participating captains. However, we cannot exclude the possibility that later entrants had inherently lower bycatch rates irrespective of the program. The year effect likely reflects a combination of changing fishery and environmental conditions, including unrecorded changes in gear configurations and fishing tactics, as well as shifts in species distributions and abundance. Nevertheless, the engagement program, which included the development and promotion of subsurface net setting, was the only major bycatch mitigation intervention implemented during the study period (Moazzam and Khan 2019; Kiszka *et al.* 2021). Given the relatively short timeframe, the magnitude of the observed declines, and the lack of evidence for major declines in dolphin or sea turtle populations, we suspect the program drove changes in fishing practices that contributed to the observed year effect.

In comparison, voluntary uptake of bycatch mitigation practices at a global level has been unexpectedly slow (Eayrs and Pol 2019). This engagement program invested substantial time in training sessions, capacity building, and repeated onboard interviews and data review meetings. One plausible mechanism is that these activities reinforced socially acceptable tactics for responsible fishing and facilitated knowledge exchange of successful mitigation strategies among captains (Jenkins *et al.* 2017). Strategic public acknowledgement at various forums may also have encouraged healthy competition to reduce entanglements and increase safe releases. However, these mechanisms were not explicitly measured, and the study cannot determine the relative importance of peer learning, behavioural change, or other factors in driving the observed reductions in bycatch. Nevertheless, the encouraging results highlight the potential value of peer learning and targeted capacity building for promoting bycatch mitigation within gillnet fleets.

Pakistan is representative of the management challenges facing many under-resourced coastal states, with extensive fleets deploying large gillnets and few effective management levers available. Gillnet regulations in the Indian Ocean are limited and poorly enforced; moreover, Pakistan objected to IOTC Resolution 17/07 prohibiting driftnets longer than 2.5 km in its EEZ (Elliott *et al.* 2024). Most Pakistani gillnet vessels are 15-20 m in length, below the 24 m length threshold used by the IOTC to define industrial vessels, for which more management measures apply (Kiszka *et al.* 2021). In the absence of effective regulation or availability of practical bycatch reduction devices, fisher-stewarded solutions may be one of the most practical pathways for reducing bycatch (Squires *et al.* 2021; Suuronen 2022).

Fifth, the positive correlation between dolphin and sea turtle bycatch taxa indicates that some fishers are able to reduce bycatch of multiple taxa simultaneously. Fishers initially expressed strong interest in preventing turtle and cetacean bycatch, especially larger species, because of the effort required to disentangle and the damage to nets (Kiszka *et al.* 2021). Interviews with fishers and observations by the program staff suggested that, over time, releasing dolphins and turtles became an increasingly important ethical commitment for participants. Attitudes appeared to shift from viewing these species as nuisance bycatch to recognising them as animals worthy of protection.

Finally, our results corroborate earlier evidence that average target catch volumes were not reduced during the study period (Shahid *et al.* 2018; Kiszka *et al.* 2021; Moazzam 2021) In fact, our results suggest bycatch rates were potentially lower when target catch was above average. Previous studies found that target catch increased (Moazzam and Khan 2019). While the composition of tuna and tuna like species changed, there were no noticeable changes in overall profits because increases in some high value tuna species (e.g., yellowfin) compensated for loss of other high value species (e.g., billfishes) (Shahid *et al.* 2018; Moazzam 2021). This result is encouraging because fishers will not accept mitigation measures that reduce their real or perceived profits (Suuronen 2022). More broadly, it reinforces the idea that avoiding bycatch and catching target species could be complementary aspects of fishing skill (Roberson and Wilcox 2025).

Addressing fisheries bycatch requires solutions tailored to individual fisheries—and often individual people—a daunting challenge in low-income fisheries given the sheer number of participants, diversity of gears and impacted species, and limited resources (Eayrs and Pol 2019; Pita *et al.* 2019). Our findings indicate that a crew-based observer and fisher engagement program influenced bycatch mitigation practices, including the fisher-led development of a simple, low-cost operational modification that likely contributed to dramatic reductions in dolphin and sea turtle bycatch over a short period of time. However, the transferability of these outcomes beyond this fishery is uncertain. The persistence of these gains in Pakistan is also unclear due to interruptions to the program during COVID-19. Furthermore, the subsurface gear configuration developed through this program may not be as effective for other species, areas, or fisheries. In some regions, the value of sea turtles and small cetaceans for bait or consumption presents additional obstacles for bycatch mitigation (FAO 2023; De La Hoz Schilling *et al.* 2023).

Even so, several aspects of the program are likely to be broadly transferable. Early engagement of fishers in identifying problems, testing potential solutions, and evaluating outcomes can generate context-specific innovations that are both practical and acceptable to industry (Suuronen 2022). This differs fundamentally from engagement focused primarily on increasing adoption of externally developed mitigation measures (Jenkins 2023). The value of collaborative, fisher-centric approaches has been demonstrated across small-scale to industrial fisheries (Eayrs and Pol 2019; Squires *et al.* 2021; Suuronen 2022; Cronin *et al.* 2026). In addition, the relatively low initial bycatch rates observed among later program entrants suggests that social networks and peer-to-peer learning may have played an important role in spreading mitigation practices (Jenkins *et al.* 2017). Supporting respected fishers as local champions could therefore be an effective mechanism for accelerating adoption in other fisheries (Hall *et al.* 2007; Suuronen 2022). Sustained fisher engagement promotes behavior change and can enable the documentation, support, and scaling of fisher-led solutions to

overcome persistent sustainability barriers in wild-capture fisheries (Eayrs and Pol 2019). Encouragingly, this example suggests that opportunities for innovation exist even in under-resourced fisheries and globally high-risk gear types such as gillnets.

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Ethics & Animal Welfare

This study used the data of the fishery-independent observations recorded by trained crew-observers during routine tuna-gillnet operations in Pakistan's EEZ (2012–2019). No experimental manipulation was undertaken, and controlled access was provided by the data custodian (WWF–Pakistan). Vessel identifiers and personal information were anonymised before analysis. No animals were captured for research purposes. Handling and release practices followed IOTC Resolution 12/04 on marine turtle conservation and handling, and WWF–Pakistan's standard operating procedures.

CRediT authorship contribution statement

Leslie Roberson: Conceptualization, Methodology, Formal analysis, Validation, Visualization, Writing – original draft; funding acquisition (digitisation of crew-based observer data). **Shoaib Abdul Razzaque**: Data curation, Investigation, Resources, Project administration, Writing – review & editing. **Brianna Elliot:** Writing – review & editing; funding acquisition (digitisation of crew-based observer data). **Rab Nawaz:** Funding acquisition (ABNJ Tuna Project), Writing – review & editing. **Altaaf Sheikh:** Project administration, Writing – review & editing. **Andrew Read:** Writing – review & editing, funding acquisition (digitisation of crew-based observer data). **Umair Shahid:** Writing – review & editing, Conceptualization, Investigation, Resources, Project administration.
All authors reviewed and approved the final manuscript.

Data Statement

The data supporting the findings of this study were collected through a crew-based observer program implemented by WWF–Pakistan in collaboration with fishing communities and relevant government authorities. Due to confidentiality with participating fishers and regulatory restrictions associated with fisheries management and conservation, the datasets are not publicly available. Access to anonymised

or aggregated data should be directed to WWF–Pakistan (info@wwf.org.pk). Any data access is subject to review and approval by WWF–Pakistan and relevant program authorities and would require the execution of formal data sharing agreements. Access may be restricted where confidentiality, legal, regulatory, or conservation obligations cannot be adequately protected.
The full code and the data to replicate the analysis and reproduce the figures cannot be made publicly available because they contain confidential fisheries information, including fishing locations. An anonymised version of the stepwise model selection procedure used in this analysis is available as a .Rmd file in a public GitHub repository (https://github.com/lroberson/pakistan_gillnet_bycatch_pub), along with the summarized and fully anonymised data needed to recreate Figure 2.

Declaration of generative AI and AI-assisted technologies:

During the preparation of the final manuscript, the authors used Microsoft Copilot (Microsoft Teams Version 26246.1709.5146.8945) for copy editing to improve the grammar and readability. The authors reviewed and edited the output as needed and take full responsibility for the content of the published article.

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Figure captions

Figure 1: (a) A participating crewmember with an entangled spinner dolphin (*Stenella longirostris),* (C/O WWF–Pakistan); **(b)** A typical Pakistani gillnet fishing boat, which are smaller than the 24m overall length threshold classifying "industrial" vessels in the Indian Ocean (C/O Muhammad Moazzam); **(c)** Fishing effort is concentrated in the northeast section of Pakistan's EEZ near Karachi (blue dashed line=EEZ boundary).

Figure 2: Dolphin and sea turtle bycatch reported by 13 gillnet captains from 2012-2016. Captain ID is chronological (eg Captains 1 joined first and Captain 13 joined most recently). **(a)** Combined bycatch per gillnet set improved over time, with notable variability among captains especially in the first three years (black dashed line shows group average). **(b)** There is no obvious correlation between average target catch (tuna and tuna-likes) and bycatch for the individual captains over the five-year period (lines=standard errors, larger circles=captains with more recorded sets). (c) Average tuna catch increased slightly, while catches of other retained species were consistent or decreased slightly.

Figure 3: Comparison of estimated marginal mean (EMM) response values **(a)**, regression coefficient estimates **(b),** and average bycatch rates of dolphins and sea turtles for the 13 captains. Yellows=lower average bycatch per set and reds=higher observed bycatch rates. EMMs represent the expected bycatch rate after accounting for other covariates in the model; lower EMM values indicate better expected bycatch performance. Regression coefficients represent the residual captain effect after controlling for measured environmental and operational covariates; more negative values=lower bycatch risk, more positive values=higher bycatch risk. Captain 1 was the reference level and this coefficient was calculated as the negative sum of the remaining captain coefficients under the sum-to-zero constraint. Standard errors, test statistics, and p-values are not available for this derived estimate. Triangles=significant coefficient estimates, X=non-significant estimates. Error bars=standard error of the estimated values.

Figures

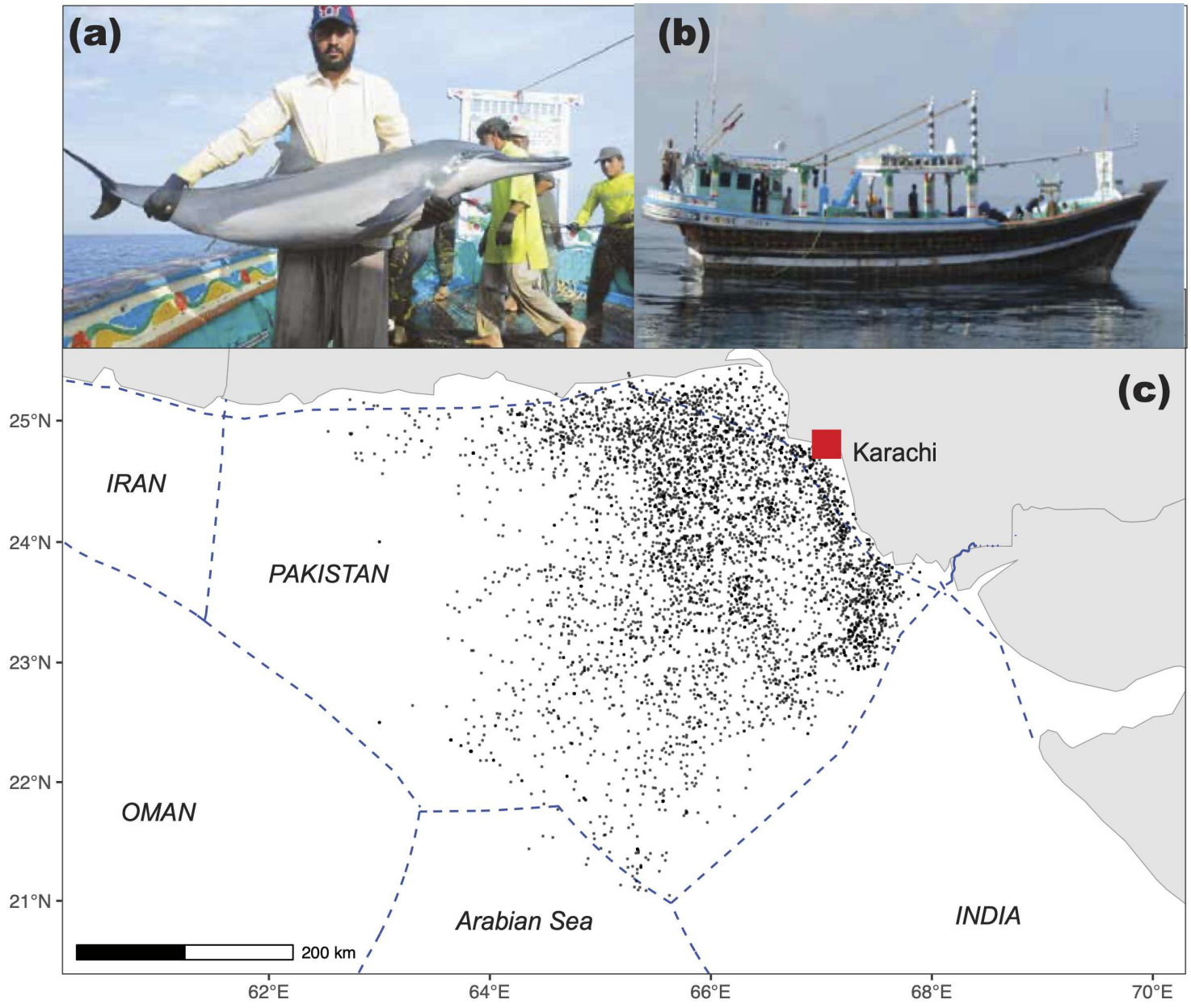


Figure 1

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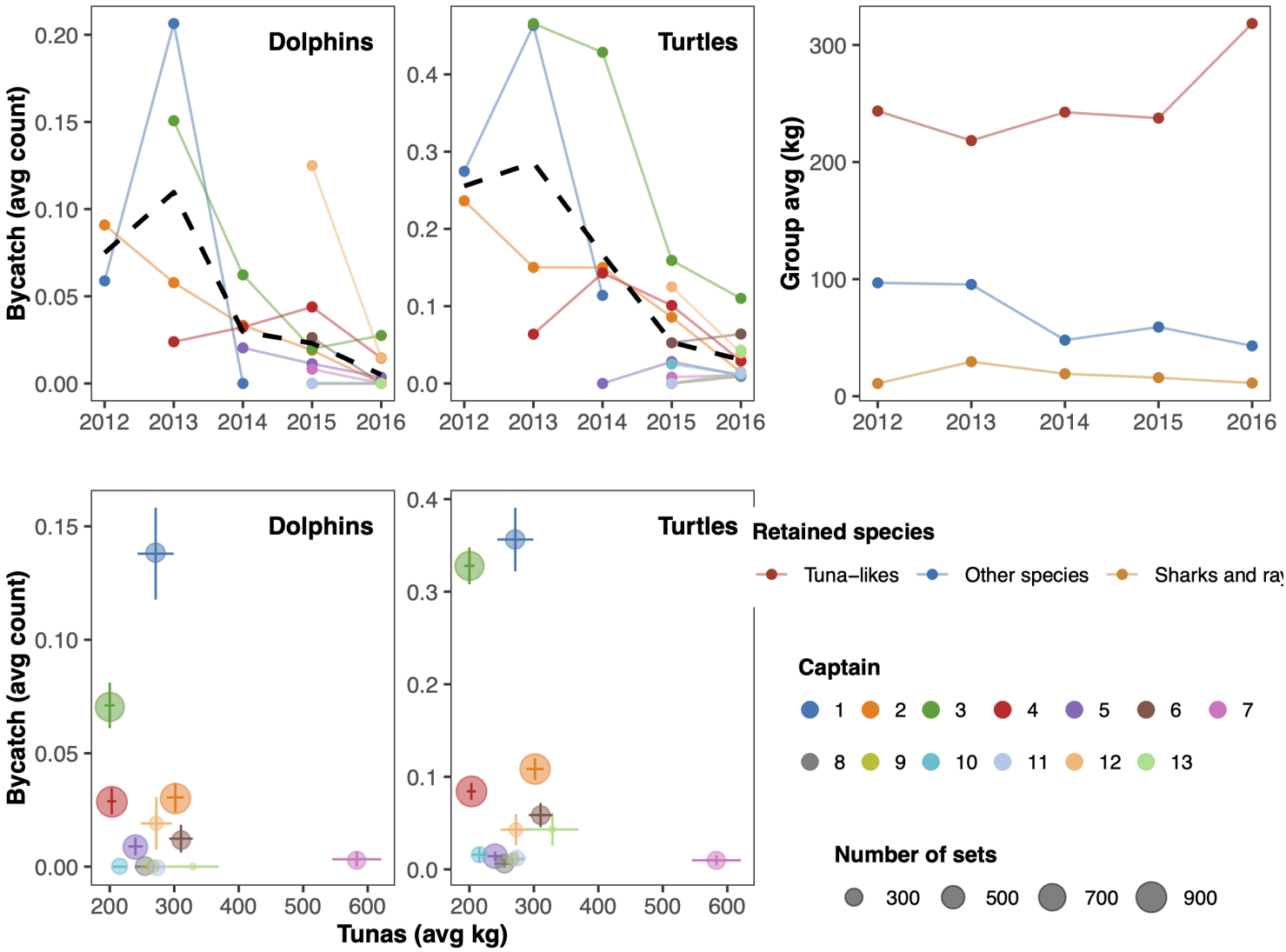


Figure 2

Dolphin and sea turtle bycatch reported by 13 gillnet captains from 2012-2016. Captain ID is chronological (eg Captains 1 joined first and Captain 13 joined most recently). **(a)** Combined bycatch per gillnet set improved over time, with notable variability among captains especially in the first three years (black dashed line shows group average). **(b)** There is no obvious correlation between average target catch (tuna and tuna-likes) and bycatch for the individual captains over the five-year period (lines=standard errors, larger circles=captains with more recorded sets). (c) Average tuna catch increased slightly, while catches of other retained species were consistent or decreased slightly.

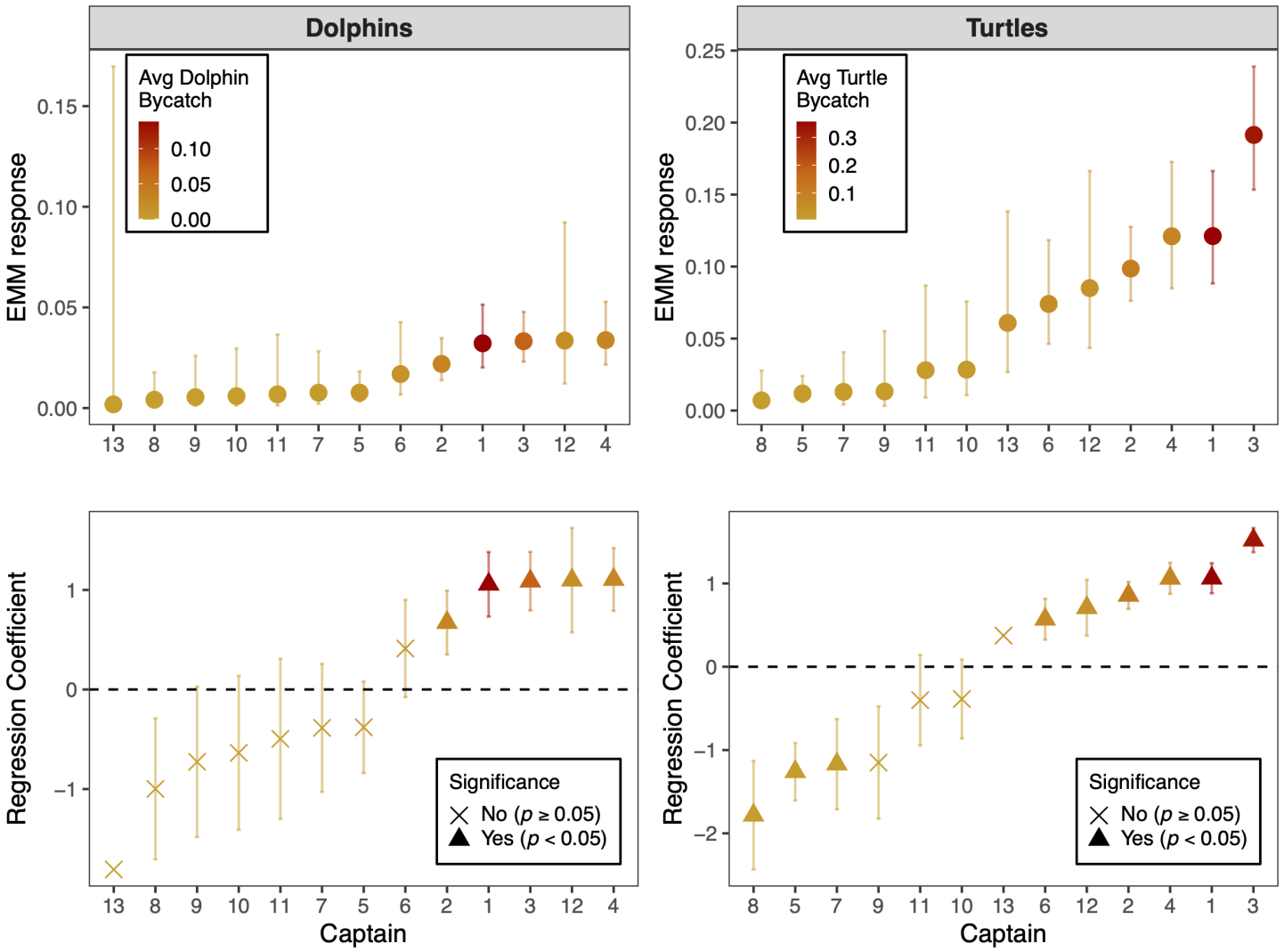


Figure 3

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