

Post-release survival of silky sharks in tropical tuna purse seine fishery under best handling practices: insights from tagging and predictive modelling

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Purpose, expectation and action intended (select one or more and include corresponding text)

The aim of this study is to update the group on recent advances in the assessment of post-release survival of silky sharks in tropical tuna purse seine fishery where best practices are applied and bycatch release devices are being implemented on-board. Specifically, the study investigated the biological, environmental and operational factors influencing post-release survival and estimated survival probabilities at the scale of commercial fishing operations using satellite-tagging data and predictive modelling

Discussions (for information and open discussion):

This study provides the most comprehensive assessment to date of post-release survival of silky sharks in tropical tuna purse seine fisheries under current best handling and release practices. Combining data from 3,086 observed sharks and 195 tagged individuals with known fates, the results showed an overall post-release survival rate of 70.3% for those tagged and release with signs of life. It identified vitality at release as the primary predictor of survival. Sharks released in better condition exhibited markedly higher survival probabilities, highlighting the importance of minimizing capture and handling stress. In addition, catch size emerged as a key operational driver, with survival declining steadily as catches increased, likely reflecting longer retention times and greater physiological stress. Shark length also influenced survival, with intermediate-sized individuals showing the highest survival probabilities. The final GAM, which incorporated vitality, catch size, and body length, explained 41.7% of the deviance and demonstrated strong predictive performance, enabling survival estimates to be extrapolated to commercial fishing operations. Application of the model to all the observations in the trip revealed substantial variability among trips, with mean predicted survival probabilities by trip ranging from 0.184 to 0.538, suggesting that operational conditions strongly influence post-release outcomes. Although no clear effect of release devices was detected, all trips were conducted under BHRPs, and the results should not be interpreted as evidence that BHRPs or BRDs are ineffective. Rather, they indicate that factors such as large catches and prolonged retention times may mask their benefits, while reinforcing the importance of maintaining these measures to maximize the likelihood that sharks surviving capture also survive following release. Overall, the study highlights vitality assessment as a practical tool for large-scale survival estimation and emphasizes the need to better understand the relative contributions of at-vessel and post-release mortality to support more effective bycatch mitigation and shark conservation strategies.

Feedback (to collect input and suggestions)

The authors would welcome feedback from the group to further improve the analysis and to identify aspects of particular interest that should be considered in the manuscript.

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Conclusion (to record a concluded position or summary)

This study demonstrates that post-release survival of silky sharks in tropical tuna purse seine fisheries is primarily driven by shark condition at release, with vitality emerging as the strongest predictor of survival. Survival probability decreased with increasing catch size and varied with shark body length, highlighting the importance of both biological and operational factors. The predictive modelling approach provided robust estimates of survival at the scale of commercial fishing operations and revealed substantial variability among fishing trips, suggesting that operational conditions strongly influence outcomes. The effectiveness of the best handling practices is variable and highly depends on operational aspects other than the application of best practices itself. Although the specific effects of BHRPs and BRDs could not be directly isolated, all trips were conducted under these mitigation measures, and the results support their continued implementation as essential tools for maximizing survival and reducing fishing-related mortality. Future research should focus on distinguishing at-vessel and post-release mortality, improving the collection of vitality and retention-time data, and further evaluating the effectiveness of mitigation measures to support evidence-based shark conservation and fisheries management.

Recommendation (to ask the meeting to endorse a recommendation)

Overall, this study supports the continued implementation of Best Handling and Release Practices (BHRPs) and Bycatch Reduction Devices (BRDs) as key measures to reduce silky shark mortality in tropical tuna purse seine fisheries. The results also highlight the need for future research and innovation aimed at developing and evaluating alternative practices and technologies that further reduce retention time, handling stress, and overall capture-related impacts, thereby maximizing post-release survival.

Decisions (to request formal approval of actions)

[The paper is to seek approval on..., as set out in Section X]

Abstract

Silky sharks (*Carcharhinus falciformis*) are the most common shark bycatch species in tropical tuna purse seine fisheries. Although purse seine fisheries account for a small proportion of total silky shark catches, reliable post-release survival estimates are essential to evaluate mitigation measures and quantify fishery impacts on the species. This study aimed to identify the main factors influencing post-release survival and to estimate survivorship at the scale of commercial fishing operations. Between 2020 and 2026, 3,086 released silky sharks were monitored aboard purse seiners operating in the Atlantic, Indian, and Pacific Oceans. Of these, 220 individuals were equipped with satellite tags to determine post-release fate. Using sharks with known fate, binomial Generalized Additive Models (GAMs) were developed to evaluate the influence of biological, environmental, physiological, and operational variables on post-release survival probability. The best-performing model included vitality condition at release, total tuna catch in the set, and shark length, explaining 41.7% of the observed deviance and showing good predictive performance (AUC = 0.87; TSS = 0.66). Survival probability increased markedly with vitality condition, approaching 100% for sharks released in excellent condition, whereas increasing fishing set catch size was associated with reduced survival. Shark length showed a non-linear relationship with survival, with intermediate-sized individuals exhibiting the highest probabilities of survival. Application of the model to the entire population of sharks observed during these fishing trips, regardless of whether they were tagged, revealed substantial variation in mean predicted survival among fishing trips. Estimated mean survival rates by trip ranged from 0.184 to 0.538 in trips where best release handling practices were applied. Exploratory trip-level analyses further indicated that larger target catches and longer retention times in the sack were associated with lower survival probabilities. These findings highlight the importance of shark condition at release and suggest that differences in trip-level survival are largely driven by the proportion of sharks brought aboard in poor vitality condition, which in turn depends on fishing operations and catch handling practices that influence retention time and duration of the fishing set. The widespread implementation of best handling and release practices therefore remains essential to increase the survival rates. Further improvements in post-release survival are likely to depend primarily on minimizing the time sharks are exposed to stressful conditions (i.e., during sacking-up and on deck), thereby reducing the risk of injury.

Post-release survival of silky sharks in tropical tuna purse seine fishery under best handling and release practices: insights from tagging and predictive modelling

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survival rates. Further improvements in post-release survival are likely to depend primarily on minimizing the time sharks are exposed to stressful conditions (i.e., during sacking-up and on deck), thereby reducing the risk of injury.

Keywords: silky shark, bycatch, post-release survival, tuna purse seine, satellite-tagging, Best Handling and Release Practices (BHRPs), Bycatch Release Devices (BRDs).

1. Introduction

Silky sharks (*Carcharhinus falciformis*) are the most common shark bycatch species in tropical tuna fisheries (Acevedo-Iglesias et al., 2025; Murua et al., 2021). They are targeted by artisanal small-scale fisheries and taken as a bycatch in industrial fisheries worldwide (Garcia and Herrera, 2018; IATTC, 2023; IOTC, 2026; Lopetegui-Eguren et al., 2026). The species has slow growth and low fecundity, making it vulnerable to high fishing pressure. In 2016, the species was included in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), reflecting growing concerns regarding its conservation status. The current global conservation status of the species on the IUCN Red List is Vulnerable. In the western Pacific Ocean, the most recent stock assessment concluded that the status of silky shark remains uncertain, although there is high confidence that current fishing mortality is below the level that would prevent stock rebuilding (Neubauer et al., 2024). In the Atlantic Ocean, an Ecological Risk Assessment (ERAs) has quantified the cumulative impacts of multiple fisheries on species vulnerability, identifying silky sharks as highly vulnerable to fishing pressure, although their vulnerability status remains uncertain (Lopetegui-Eguren et al., 2026). In the Indian Ocean, ERAs have consistently ranked silky sharks among the species most vulnerable to fishing pressure from both longline and purse seine fisheries (Murua et al., 2018). However, no quantitative stock assessment or basic fishery indicators are currently available for silky sharks in the Indian Ocean, and therefore their stock status remains unknown.

In the Indian Ocean the average reported catch has remained at around 2,800 t, with 70% and 30% coming both from artisanal and industrial fisheries, respectively. However, catch estimates may be underestimated (IOTC, 2026). The industrial fisheries component is mostly made up of offshore gillnet catches (53%), followed by deep-frozen longline (24%) and fresh longline (7%) (IOTC, 2026). The purse seine fishery is responsible for 1.3% of the total catch (Garcia and Herrera, 2018). Tropical tuna purse seine fisheries are generally characterized by lower bycatch rates than many other industrial fishing gears (Kelleher, 2005; Murua et al., 2021). Nevertheless, incidental captures of Endangered, Threatened and Protected (ETP) species still occur and remain an important conservation concern, particularly for silky sharks, which represent the most common shark bycatch species in these fisheries (Acevedo-Iglesias et al., 2025; Gilman et al., 2024; Ortuño-Crespo et al., 2024; Torres-Irineo et al., 2014). The species' tendency to remain in the upper layers of the water column, where purse seine operations are conducted, together with its strong association with floating objects and its co-occurrence with tropical tuna species targeted by FAD fisheries, increases the likelihood of interactions with these fisheries (Filmatler et al., 2015).

Recognizing the need to reduce fisheries-related mortality of sharks and other ETP species, tuna Regional Fisheries Management Organizations (RFMOs) have progressively adopted conservation and management measures aimed at minimizing bycatch mortality (i.e. including retention bans, no finning, non-entangling FADs, the implementation of best handling and release practices aimed at increasing post-release survival, and enhanced requirements for data collection and reporting). In parallel, industry-led initiatives have played a major role in developing and implementing mitigation measures. In 2012, the European tropical tuna purse seine fleet adopted a Code of Best Practices promoting safe handling and release for incidentally captured marine fauna. More recently, collaborative initiatives involving scientists, fishers and industry stakeholders have led to the co-development of specialized release devices, including hoppers, release ramps, conveyor systems and other shark release tools designed to improve release efficiency, reduce handling time and increase post-release survival (Murua et al., 2025a, 2025b; Poisson et al., 2014a). These efforts have been complemented by crew training programs and observer-based monitoring schemes that support the implementation of Best Handling and Release Practices (BHRPs) across fleets (Grande et al., 2019; Murua et al., 2025a; 2025b; Wain et al., 2025).

Assessing the effectiveness of these mitigation measures requires reliable estimates of post-release survival. Previous studies in purse seiners have demonstrated that silky shark survival varies among fishing trips (Grande et al., 2022; Grande et al., 2025; Hutchinson et al., 2015; Murua et al., 2024; Onandia et al., 2021; Poisson et al., 2014b). These studies have provided valuable insights into the effects of physiological stress, handling practices, and operational procedures on survival probability. However, results have been explored at trip level with small sample sizes that limit their applicability for estimating the influence of different factors in survival and mortality across the broader population of sharks encountered in commercial fisheries. Consequently, there is a need to understand factors affecting survivorship and developing predictive approaches capable of extrapolating information from tagged individuals to larger datasets collected by observers aboard commercial fishing vessels. Such approaches can improve estimates of fisheries-related mortality while providing a scientific basis for evaluating current mitigation measures and identifying opportunities for further reducing impacts on vulnerable species. Better understanding of silky shark behavior, habitat use, vertical and horizontal movements, and post-release fate is also essential for identifying spatial and operational measures that could further reduce fishing mortality.

Using data collected aboard purse seine vessels operating in the Pacific, Atlantic, and Indian Oceans between 2020 and 2026, including satellite-tagged silky sharks with known post-release fates, this study aims to identify the environmental, physiological, and operational factors influencing post-release survival and to estimate survival probabilities at the scale of commercial fishing operations. By combining tagging data, observer information, and predictive modeling techniques, this study not only contributes to improving estimates of post-survival in silky sharks but it provides scientific evidence supporting the effectiveness of current handling and release practices in reducing the impacts of purse seine fisheries on the species, while facilitating the development of future conservation and management measures.

2. Material and Methods

2.1. Field sampling

Twelve scientific research trips were conducted on board purse seiners during commercial fishing operations between 2020 and 2026 in the Pacific, Atlantic, and Indian Oceans (Figure 1 and Table 1). Best handling guidelines were applied on board to ensure the immediate release of all bycaught sharks (Murua et al., 2025a). To facilitate and expedite shark release, some vessels were equipped with bycatch release devices, including hoppers with ramps, upper-deck ramps, gutters and bycatch release conveyor belts installed on the lower deck. During 351 fishing operations monitored, 3,086 silky sharks were observed on board and immediately released following best handling guidelines (Table 1).

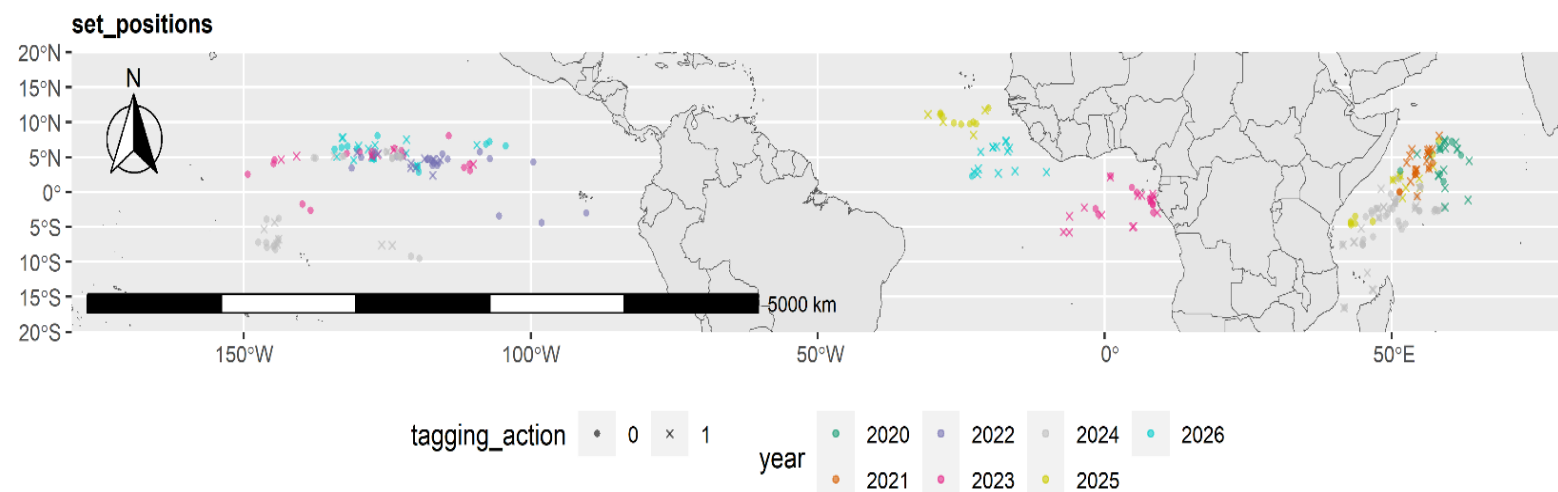


Figure 1. Fishing locations with presence of silky sharks (o) and where sharks were tagged (x) from 2020 to 2026.

Table 1. Scientific research trips characteristics.

Ocean	Year	Releasing devices	n silky sharks caught	n tags deployed	n blood samples
Indian	2020	Bycatch conveyor belt	282	28	45
Indian	2021	Bycatch conveyor belt	247	32	78
Pacific	2022	Hopper with ramp	304	16	0
Pacific	2023	Hopper with ramp	316	8	0
Atlantic	2023	None	247	23	90
Indian	2024	Gutter	151	19	38

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Pacific	2024	Hopper with ramp	312	15	52
Indian	2024	Gutter and Hopper with ramp	420	13	36
Atlantic	2025	Ramp	43	7	0
Indian	2025	None	84	15	32
Atlantic	2026	Velcros	94	28	49
Pacific	2026	Hopper with ramp	586	17	39
Total			3,086	220	459

On board, scientific observers collected data according to the EU Data Collection Protocol for Tuna Purse seiners (Sabarros et al., 2025) and Best Practices Program guidelines, as well as additional information to support the analysis of shark post-release survival. For each interaction, the following information was recorded through direct observations and GoPro camera footage:

- sex (i.e., female, male, indeterminate or unknown),
- total length in cm (TL),
- release phase: If the animal was entangled in the net, or if it was brailled on board, the number of the brail in which the specimen was brought on board (entangled, 1st, 2nd, 3rd brail and subsequent),
- strapping time, time when the shark was brailled on board and time when it was released. From this information time in the sack and time on deck was obtained,
- mode of release: after disentanglement; brailer; stretcher, tarpaulin, 'sarria', cargo net; shark velcro; gaff, hook or other pointed tools; rope; ramp; hopper with ramp; hopper; lower deck conveyor belt and gutter.
- Release place: Place from which the animal has been released (i.e. net, upper deck, lower deck)
- vitality state (i.e., state of the animal at release based on the states proposed by Heuter and Manire (1994)):
 - (i) excellent (i.e., very active and energetic, strong signs of life on deck and when returned to water);
 - (ii) good (i.e., active and energetic, moderate signs of life on deck and when returned to water);
 - (iii) correct (i.e., tired and sluggish, limited signs of life, moderate revival time required when returned to water, slow or atypical swimming away);
 - (iv) poor (i.e., exhausted, no signs of life, bleeding from gills, jaw or cloaca, long revival time required when returned to water, limited or no swimming observed upon release);
 - (v) Moribund or dead (i.e., moribund, no signs of life, excess bleeding from gills, jaw, or cloaca, unable to revive upon return to water, no swimming movement, sinks).

220 of the 3,086 observed individuals were tagged (Table 1). Sharks were selected for tagging to ensure adequate representation across all vitality categories, while prioritizing individuals that

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exhibited signs of life. The tags were mainly attached with a 10 cm long monofilament tether protected by a silicone tube to prevent abrasion. In those, large Domeier or small titanium dart anchors were used. To facilitate the entry of the anchor, a small cut of two centimeters was previously made with a scalpel at the base of the dorsal fin (i.e., tether, anchor and scalpel were smeared with Betadine Antiseptic Cream 5% povidone iodine to prevent infections). Alternatively, some of the tags were attached to the dorsal fin using a loop. The steps followed in the tagging action are illustrated in Figure 2.



Figure 2. Silky shark tagging guidelines.

SPAT tags were programmed to be released after 60 days of deployment and set by default to record maximum and minimum daily depths and temperatures, and ten-minute interval depth data for the end of the deployment (i.e., last 4 days). MiniPATs tags were programmed for 180 day release. Daily data recorded with MiniPATs correspond to the temperature and depth, and change in light-level for each UTC day light intensity data every 600 seconds. If depth exceeded 1,400-1,700 meters or remained at a constant depth for more than 3 days, both being signs of mortality, the pop-up tags were programmed to automatically release.

To evaluate physiological stress through lactate levels, in some of the trips (Table 1) blood samples were taken from the caudal peduncle of silky sharks and measured “in situ” using a lactate meter (Lactate plus).

2.2. Fate of tagged sharks and physiological indicators

For each of the tagged sharks, a fate was determined (i.e., dead or alive) based on the depth records transmitted by the tags and the time elapsed from tagging to tag detachment. Sharks were considered to have survived the fishing operation if their tags indicated normal daily depth and horizontal migration behavior for more than 10 days. This time frame was used following standard protocols employed in prior silky shark post-release survival studies in purse seiners (Hutchinson et al., 2015), which are taken as a sign that sharks remained alive after the purse seiner fishing event. If a premature tag release occurred before the 10-day threshold and there was no evidence of mortality (i.e. absence of excessive depths and normal vertical movements), or if the tag failed to transmit data, the individual was excluded from the analysis.

In tagged specimens, physiological indicators were analysed to better understand their relationship with post-release survival. Differences in survival rates among vitality index categories were assessed using a chi-square test. For silky sharks tagged with blood sampled, a Wilcoxon rank sum test was used to evaluate differences in lactate levels between survivors and dead sharks. A logistic regression model was done to relate survivorship (based on tagging) and lactate concentration estimated from blood samples (Hutchinson et al., 2015).

2.3. Modelling silky shark survival

Given the binary nature of the response variable (alive = 1; dead = 0) and the potential non-linear relationships between the predictor variables (Table 2) and the response, data were modeled using a binomial Generalized Additive Models (GAMs) fitted with the *mgcv* package and a binomial error distribution with logit link (Wood, 2014).

To investigate the factors influencing the post-release survival of silky sharks, a set of biological, environmental, operational, and physiological variables was considered (Table 2). Biological variables included shark sex and length, which may influence individual resilience to capture and handling stress. Environmental conditions at the capture location, specifically dissolved oxygen concentration and sea surface temperature (SST), were obtained from the Copernicus Marine Environment Monitoring Service (CMEMS), as these factors can affect shark physiology and the severity of capture stress. Operational variables describing the fishing event, including catch size, set type, retention time in the sack and on deck, release mode (e.g., release ramps), release location (i.e., upper deck or lower deck), and release phase (i.e., entangled, 1st brail, 2nd brail or 3rd brail and subsequent), were selected because they are directly related to the intensity and duration of handling, and, therefore, influence post-release survival (Hutchinson et al., 2015). Indicators of physiological condition, namely lactate concentration and vitality state at release, were included as proxies of stress and overall health status and were expected to be closely associated with survival probability (Hutchinson et al., 2015). Finally, vessel identity and ocean basin were incorporated to account for potential differences in operational practices, environmental

conditions, and regional characteristics not captured by other predictors. Most biological, operational, and physiological data were obtained from the observer dataset, whereas environmental variables were extracted from CMEMS products (Table 2).

Because GAMs are sensitive to multicollinearity of predictor variables, relationships among continuous predictors were assessed using Pearson correlation coefficients and visualized using correlation matrices. Pairwise correlations were generally weak to moderate, with the strong association observed only between dissolved oxygen and sea surface temperature ($r = -0.86$). Dissolved oxygen was retained in the models instead of sea surface temperature because it was considered a more direct physiological predictor. To further assess multicollinearity among continuous variables, Variance Inflation Factors (VIFs) were calculated using the *usdm* package. No variable exceeded the commonly used threshold of $VIF = 5$, indicating that multicollinearity was not considered problematic.

Associations among categorical variables were evaluated using chi-square tests and quantified using Cramér's V . Several operational variables exhibited moderate to strong associations, particularly release mode, release place, vessel, and ocean basin. The strongest association was observed between vessel and ocean basin (Cramér's $V = 1.00$), indicating that some vessels operated exclusively within a single ocean basin. Strong associations were also found between release mode and release place (Cramér's $V = 0.75$), release mode and ocean basin (Cramér's $V = 0.74$), and release mode and vessel (Cramér's $V = 0.66$).

Relationships between continuous and categorical predictors were explored using Kruskal-Wallis tests. Shark sex and length, environmental conditions (i.e., dissolved oxygen), and operational variables (i.e., catch size, time on deck, and set type) differed among release mode, release phase, release place, vitality, lactate, time in the sack, vessel, and ocean basin.

Table 2. Variables explored in the analysis.

Type	Variable	Acronym	Unit	Justification	Source
Biological	Sex	Sex	<i>4 categories</i>	Survival differences on sex.	Observer dataset
	Length	Length	<i>cm</i>	Size may affect survival.	
Environmental	Oxygen	O2	<i>mmol.m-3</i>	Low oxygen concentrations can produce anoxia on capture, decreasing the survival of silky sharks.	CMEMS – 001_029
	SST	SST	<i>°C</i>	Sea surface temperature, negatively correlated with oxygen.	CMEMS – 001_030
Fishing operation	Catch of the set	Catch	<i>Tonnes</i>	All these fishing operational variables may affect the survival of released individuals.	Observer dataset
	Set type	Type_set	<i>FOB or FSC</i>		
	Time in the sack	Time_sack	<i>minutes</i>		
	Time on deck	Time_deck	<i>minutes</i>		
	Release mode	Rel_mode	<i>9 categories</i>		
	Release place	Rel_place	<i>2 categories</i>		
	Release phase	Rel_phase	<i>4 categories</i>		
Indicators	Lactate concentration	Lactate	<i>mmol.L-1</i>	Lactate concentration may explain the probability of survival.	Observer dataset
	Vitality state	Vitality	<i>5 categories</i>	Vitality state may explain the probability of survival.	Observer dataset
Others	Vessel	Vessel	<i>11 categories</i>	Differences between vessels.	Observer dataset
	Ocean	Ocean	<i>3 categories</i>	Differences between oceans.	Observer dataset

Considering the observed correlations among continuous predictors, as well as the associations and potential collinearity among categorical variables, different combinations of predictors were evaluated to identify the most parsimonious final model (Table 3). Highly associated variables were not included simultaneously in the same candidate model, and alternative model formulations were compared to identifying the most parsimonious model.

Table 3. Combinations of variables to build up models based on correlations, collinearity, and associations between variables.

Combination of variables		
1. Release phase	Sex,	Vessel or Ocean
2. Release place	Length,	Vessel or Ocean
3. Release mode + vitality	Oxygen, Catch,	-
4. Release mode + lactate	Time in the deck,	-
5. Time in the sack	Set type	Vessel or Ocean

For model selection, we applied a forward stepwise variable selection procedure, starting with a null model. Covariates were then added sequentially to check their contribution based on significance ($p < 0.05$) and Akaike Information Criterion (AIC) improvement ($\Delta AIC > 2$) (Venables & Ripley, 2002). The degrees of freedom of the smooth functions for each predictor variable in the models were restricted to $k = 3$ to avoid overfitting and to simplify interpretation of the results (Lezama-Ochoa et al., 2019; Lopez et al., 2020). Each GAM was fitted using thin plate regression splines for non-linear covariates. The final model was selected based on the lowest AIC value and the highest explained deviance (Akaike, 1974).

2.4. Model validation

The selected model was assessed using diagnostic procedures implemented in *mgcv* package in R. Adequacy of smooth basis dimensions was evaluated using *gam.check*. Values of the k-index close to 1 and non-significant p-values were interpreted as evidence that the selected basis dimensions were sufficient. Concurvity among model terms was assessed using the package *concurvity*. Concurvity values below 0.2 for smooth terms were interpreted as evidence of low redundancy among predictors.

Final model was also validated using a 4-fold cross-validation (Elith & Leathwick, 2009), with 75% training and 25% testing subsets, using the *kfold* function from the *dismo* package version 1.3-9 in R software (Hijmans et al., 2020). The performance scores' obtained in the 4-fold cross-validation were averaged over the different random sets to evaluate the predictive performance of the distribution model (Pearson et al., 2006).

We evaluated model performance using several metrics: Area Under the receiver operating Curve (AUC), the mean True Skill Statistic (TSS), and Miller's Calibration Slope (MCS) (Pearson, 2010) using the R package *modEvA* version 3.9.3 (Barbosa et al., 2020). The AUC is a threshold-independent discrimination index that ranges from 0 to 1, and measures the ability of the model to correctly predict species presence or absence (Elith et al., 2006). An AUC value of 0.5 indicates

that the prediction is as good as random, whereas 1 indicates perfect prediction (Fielding & Bell, 1997). The TSS index, which is calculated as sensitivity plus specificity minus 1, ranges from -1 to +1, where +1 indicates perfect agreement, and values of zero or less indicate a performance no better than random (Brodie et al., 2015). The TSS index is threshold dependent and thus, the thresholds were determined using the Maximized Sum Threshold (MST), suitable for low-prevalence data (Jiménez-Valverde & Lobo, 2007; Liu et al., 2005). The MST method gives the most accurate predictions with low prevalence data while avoiding omission (false negative) errors, even if TSS is not independent of the prevalence (Somodi et al., 2017). Miller's Calibration Slope (MCS) assesses model reliability, i.e., the overall deviation of predicted probabilities from observed occurrence frequencies. If predictions are perfectly calibrated, the slope will equal 1 (or close) and the intercept will equal 0, so the model's calibration line will perfectly overlap with the reference diagonal (Miller et al., 1991; Pearce & Ferrier, 2000; Wintle et al., 2005).

2.5. Predicting observed individuals' fate

The final model was subsequently used to estimate survival probabilities for observed but untagged silky sharks. Predictions were obtained using the *predict.gam* function implemented in the *mgcv* package (Wood, 2014). For individuals lacking information on variables included in the final model (e.g., length), missing values were imputed using the mean for the corresponding set.

Expected survival was then estimated at trip levels. For each individual shark, the GAM provided a predicted probability of survival, and the expected number of survivors was calculated by summing these probabilities within each trip. Mean survival probability was calculated as the average of individual predicted survival probabilities within each trip level.

Uncertainty in the estimated number of survivors was quantified using a parametric bootstrap with 10,000 iterations. In each iteration, a new vector of GAM coefficients was randomly drawn from a multivariate normal distribution defined by the estimated model coefficients and their variance-covariance matrix. These simulated coefficients were then used to recalculate survival probabilities for all individuals. Survival probabilities were aggregated within trips to obtain bootstrap estimates of both the expected number of survivors (sum of individual survival probabilities) and the mean survival probability. This procedure generated a distribution of 10,000 estimates for each metric and trip. The lower and upper 95% confidence limits were calculated as the 2.5th and 97.5th percentiles of the bootstrap distributions, respectively. The resulting estimates therefore represent the expected number of survivors and the mean survival probability for each trip, together with the uncertainty arising from estimation of the GAM parameters.

To further investigate factors associated with variability in post-release survival among fishing trips, exploratory trip-level analyses were conducted using the predicted survival probabilities. Mean survival probability was calculated for each trip and compared against trip-level operational and biological characteristics, including mean catch size, mean sack time and mean shark length. Associations between mean survival probability and continuous variables were assessed using Spearman's rank correlation coefficient. In addition, trips were grouped according to their dominant release mode, defined as the release method most frequently used during the trip, and differences in mean survival probability among release-mode categories were evaluated using a



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Kruskal-Wallis rank-sum test. These analyses were intended to identify broad patterns in survival among fishing operations and to assess whether trip-level characteristics were associated with variation in predicted survivorship. Given the limited number of trips represented in some release-mode categories, results from these comparisons were interpreted with caution.

3. Results

3.1. Silky sharks bycaught and released

A total of 3,086 elasmobranchs were incidentally captured during the twelve trips that were conducted between 2020 and 2026 worldwide. The total length of silky sharks ranged from 40 cm to 270 cm (mean $\pm$ SD, 130.4 $\pm$ 33.9 cm) corresponding mainly to juveniles (Figure 3), considering the size at maturity (L50) in the Indian Ocean is estimated at from 207-212 for males and 210-220 cm for females (Hall et al., 2012; Joung et al., 2008). Significant differences in total length (TL) were observed among ocean basins, with sharks captured in the Atlantic being significantly larger (141.0 $\pm$ 35.8 cm) than those captured in the Indian (127.0 $\pm$ 34.7 cm) and Pacific oceans (130.0 $\pm$ 32.4 cm).

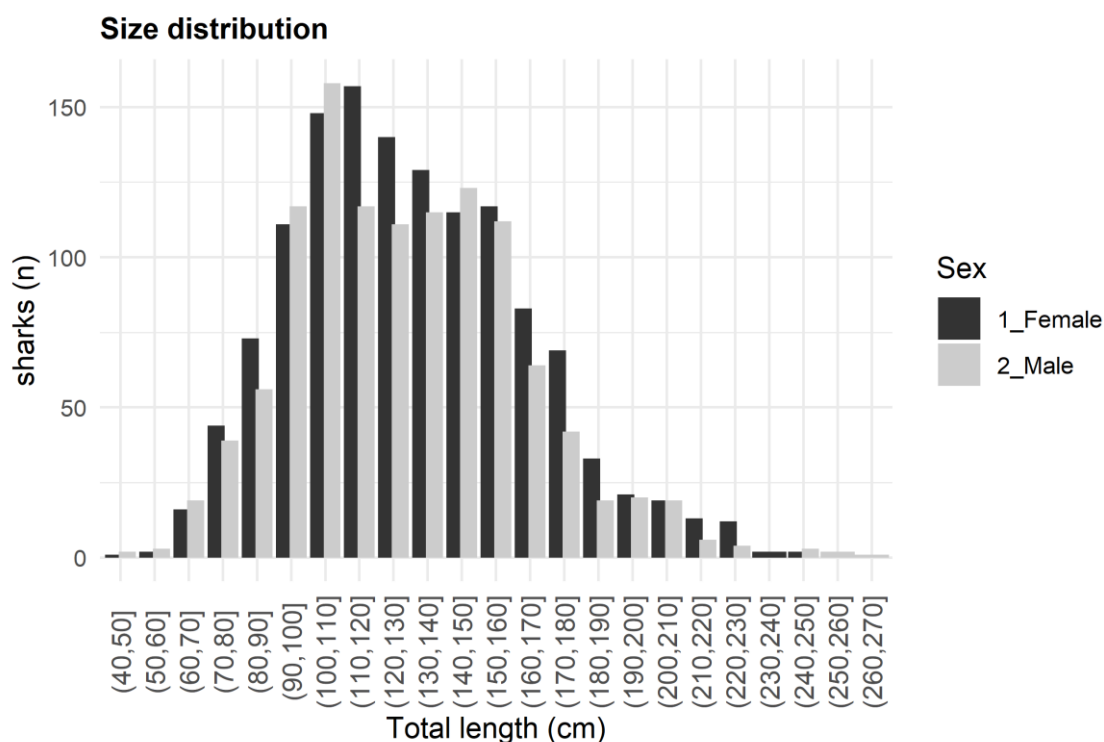


Figure 3. Size distribution of shark caught in fishing operations in purse seiners.

Considering all the fishing trips 68.9% of the sharks were released at moribund or poor state and 31.1% in correct, good or excellent state (Table 4). There was considerable variability among trips in the distribution of shark vitality, with the proportion of individuals classified as being in very poor or poor condition ranging from 38.5% to 84.3%.

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Table 4. Number of sharks caught and released by releasing phase and vitality state.

Release stage	Vitality Status					Total
	Moribund	Poor	Correct	Good	Excellent	
Entangled	24	10	40	56	35	165
1st brail	154	143	186	89	12	584
2nd brail	215	127	164	47	3	556
3er brail or later	1230	223	273	53	2	1,781
TOTAL	1,623	503	663	245	52	3,086

The sharks were released using any method included under the BHRPs, primarily by hand (21.2%), using a hopper with a ramp (41.6%), or gutters (14.5%). Other release methods included the use of ramps, stretchers, or Velcro slings, among others. The availability of some devices, particularly the larger units requiring specialized installation, was vessel specific. Consequently, the observed proportions of release methods were influenced by both the equipment available on each vessel and the number of shark interactions recorded during each trip.

3.2. Survivorship and physiological indicators of tagged sharks

After removal of tagged records with unknown survival status, 195 individuals were available for analysis. The overall survival rate of tagged sharks was 70.3% (137 individuals) whereas 29.7% (58 individuals) were recorded as mortality (Figure 4).

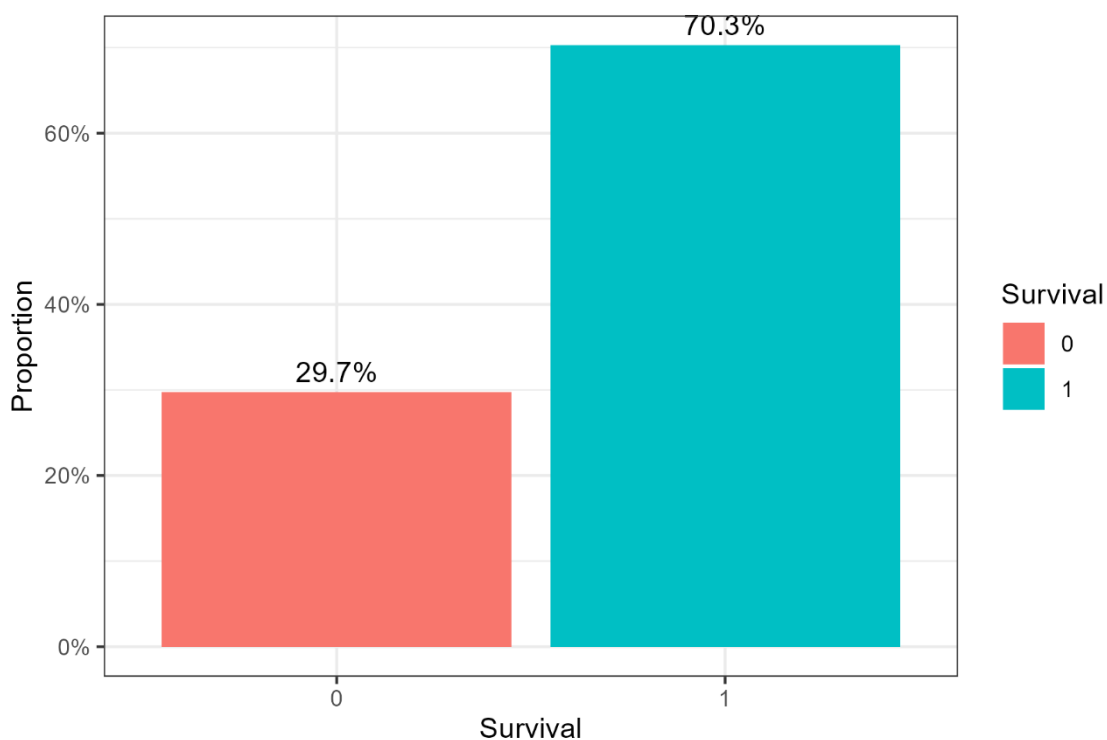


Figure 4. Proportion of tagged silky sharks classified as surviving (1) or dead (0) following release.

For tagged sharks, significant differences were detected in survivorship among vitality index categories (p -value < 0.01). The percentage of tagged sharks that survived according to the vitality index was 100% for those released in excellent condition, 95.7% for those in good condition, 73.2% for those in correct condition, 31.6% for sharks in poor condition and 11.1% for very poor or moribund condition (Figure 5).

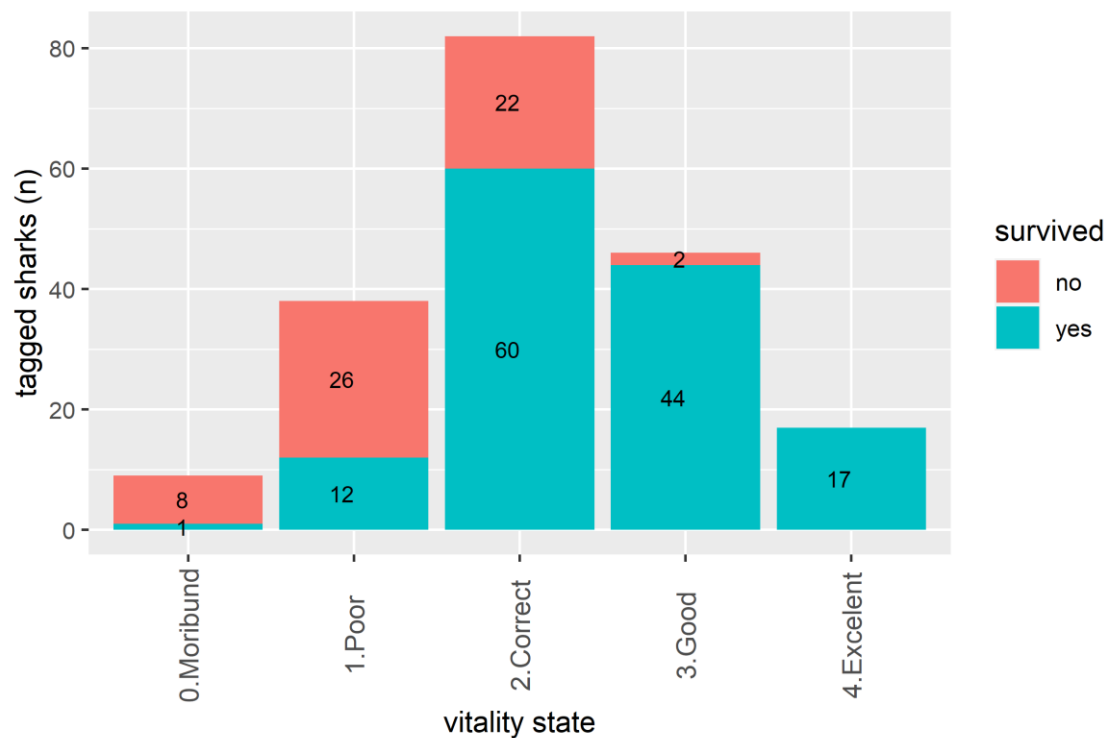


Figure 5. Number of tagged sharks by vitality and fate.

Significant differences in lactate concentrations were found (Wilcoxon rank sum, $n = 150$, p -value < 0.05) between tagged and blood sampled sharks that survived the fishing operation ($n=101$) and dead sharks ($n=49$). There were also significant differences in lactate levels among vitality states of tagged individuals (Figure 6), with lactate concentrations decreasing as vitality condition improved.

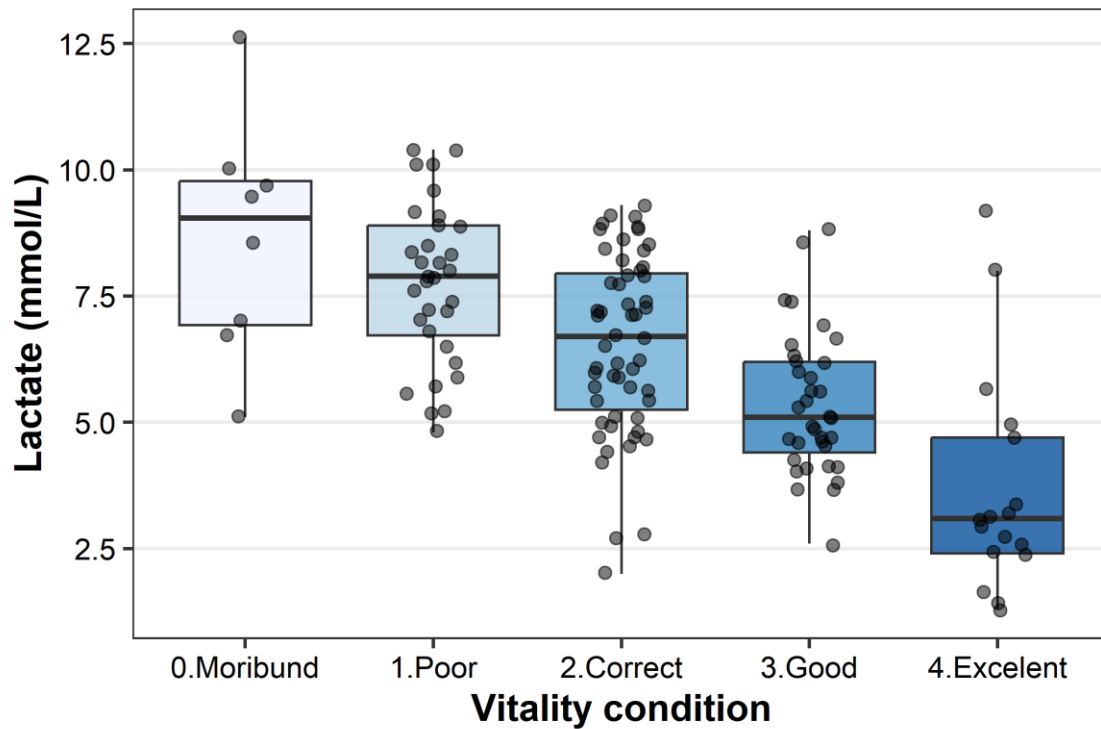


Figure 6. Lactate levels by vitality state of tagged individuals.

Using survival rates estimated across lactate concentration intervals from tagged individuals, we derived the survivorship curve shown in Figure 7. The analysis identified a lactate threshold of 8.03 mmol L⁻¹, corresponding to a survival probability of $p = 0.5$. Based on this threshold, individuals with lactate concentrations below 8.03 mmol L⁻¹ could be classified as potential survivors, whereas those with concentrations above this value could be classified as potential non-survivors.

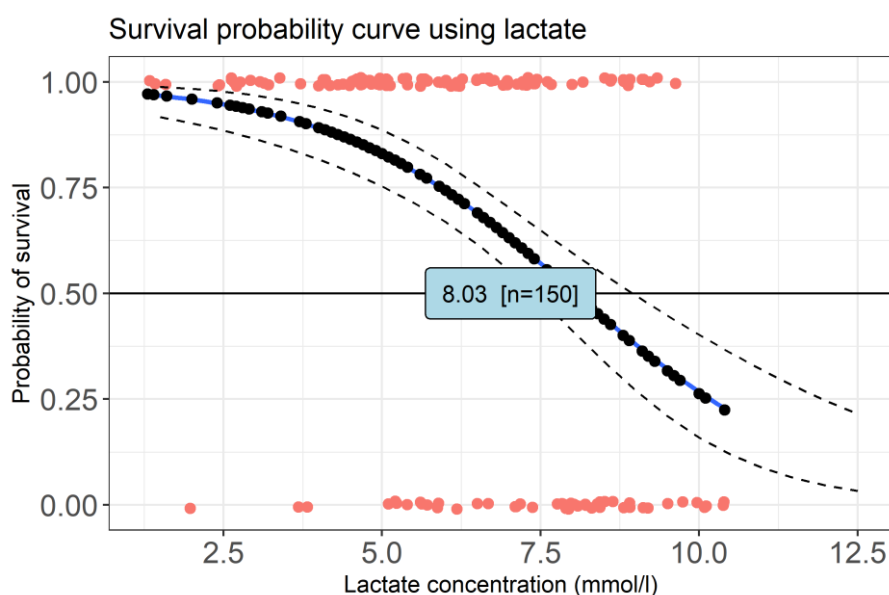


Figure 7. Logistic regression model for the estimated proportion of survival *C. falciformis* at lactate concentration (LC) intervals. Red points are the observations of shark with blood samples that were released and survived or died. Black points represent the predicted proportion of survival sharks. The solid blue line is the logistic regression curve.

3.3. Modelling silky shark survival

Model performance varied substantially among the alternative predictor combinations evaluated (Table 5). Models including physiological condition variables outperformed those based solely on operational release variables. The model including vitality state, fishing set catch size, and shark length showed the highest explanatory power, explaining 41.7% of the deviance (AIC = 152.88, $n = 192$). The model including lactate concentration, catch size, and shark length also performed well, explaining 26% of the deviance and yielding a low AIC (155.9; $n = 154$). The model including time in the sack, catch size, and shark length explained 19.1% of the deviance (AIC = 193; $n = 184$).

In contrast, models based on release-related variables showed lower explanatory power. The release phase model (catch size + release phase) explained 15.5% of the deviance, whereas the release place model (catch size + release place) explained 10.7%. Overall, catch size was consistently retained in all candidate models, while models incorporating physiological indicators of shark condition provided the best fit to the data.

Table 5. Selected variables in the GAMs in the different variables' combinations and their metrics of performance (Explained deviance and Akaike's information criterion – AIC).

Model		Final model variables	Expl. dev.	AIC	n
1	Releasing phase	Catch + releasing phase	15.5 %	212.08	195
2	Releasing place	Catch + releasing place	10.7 %	212.72	189
3	Releasing mode + vitality	Vitality + catch + length	41.7 %	152.88	192
4	Releasing mode + lactate	Lactate + catch + length	26 %	155.9	154
5	Time in the sack	Time in the sack + catch + length	19.1 %	193	184

Among models fitted with all available observations, the model including **vitality, catch, and body length** provided the strongest overall performance:

This model explained 41.7% of deviance, had an adjusted R^2 of 0.42, and produced an AIC of 152.88 (Table 6).

Table 6. Summary results for the parametric coefficients and smooth terms of the final GAM selected to model the probability of silky shark survival. Estimated degrees of freedom (e.d.f.).

Family	Binomial
Link function	Logit
Adjusted r^2	0.42
Deviance explained	41.7 %

Parametric coefficients

	Estimate	Std. Error	z value	Pr(> z)
Intercept - Vitality (Moribund)	-2.156	1.123	-1.920	< 0.05
Vitality (Poor)	1.300	1.180	1.102	< 1
Vitality (Correct)	3.325	1.164	2.856	< 0.001
Vitality (Good)	5.510	1.388	3.970	< 0.001
Vitality (Excelent)	46.92	1.628e+07	0	1

Smooth terms

	e.d.f	Ref. df	Chi.sq	p-value
Catch	1.000	1.000	15.86	< 0.001
Length	1.868	1.983	6.42	< 0.05

The probability of post-release survival increased progressively with vitality condition (Table 6; Figure 8). Compared with moribund sharks, individuals classified as having correct or good vitality showed significantly higher survival probabilities (both $p < 0.001$), while the effect of the poor vitality category was not significant. Predicted survival increased from approximately 15% in moribund individuals to nearly 100% in sharks classified as excellent condition. However, the

estimate for the excellent category was associated with substantial uncertainty due to the small number of observations and the absence of observed mortalities within this group (which could be the evidence of high survival rate attributed to this state); consequently, the wide confidence interval reflects the limited sample size (Figure 8).

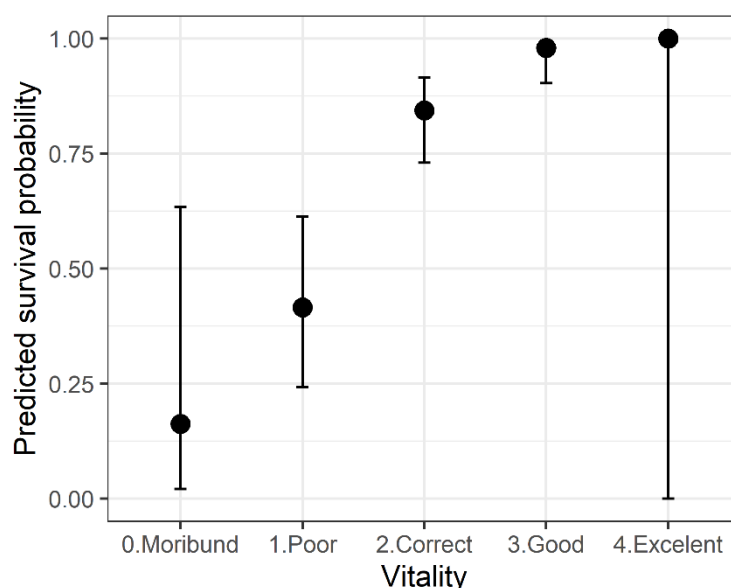


Figure 8. Predicted post-release survival probability (mean $\pm$ 95% confidence interval) of silky sharks across vitality categories estimated from the final GAM.

Beyond vitality status, both catch size and body length significantly influenced survival probability. Among both predictors, catch size was the stronger predictor ($\chi^2 = 15.86$, e.d.f. = 1.00, $p < 0.001$), while body length also had a significant, albeit weaker, effect ($\chi^2 = 6.42$, e.d.f. = 1.86, $p = 0.032$).

Partial effect plots from the final GAM revealed significant relationships between survival probability and both catch size and shark body length (Figure 9). Catch size exhibited a strong negative effect on survival probability, with predicted survival declining steadily as catch size increased (Figure 9a). The smooth term had an estimated degree of freedom close to 1 (edf = 1.000), indicating that this relationship was essentially linear. Survival probability was highest at low catch sizes and approached very low values at larger catches (i.e., 50 tons), although uncertainty increased at the extremes of the observed range, as reflected by the wider confidence intervals due to limited number of observations (Figure 9a).

In contrast, the effect of body length was moderately non-linear (edf = 1.862) and displayed a hump-shaped pattern (Figure 9b). Predicted survival increased with shark size up to approximately 160-170 cm total length, where survival probability was highest, and then declined for larger individuals (Figure 9b). Confidence intervals widened at both the lower and upper ends of the size distribution, indicating greater uncertainty in these sizes due to the relatively small number of observations for the smallest and largest sharks.

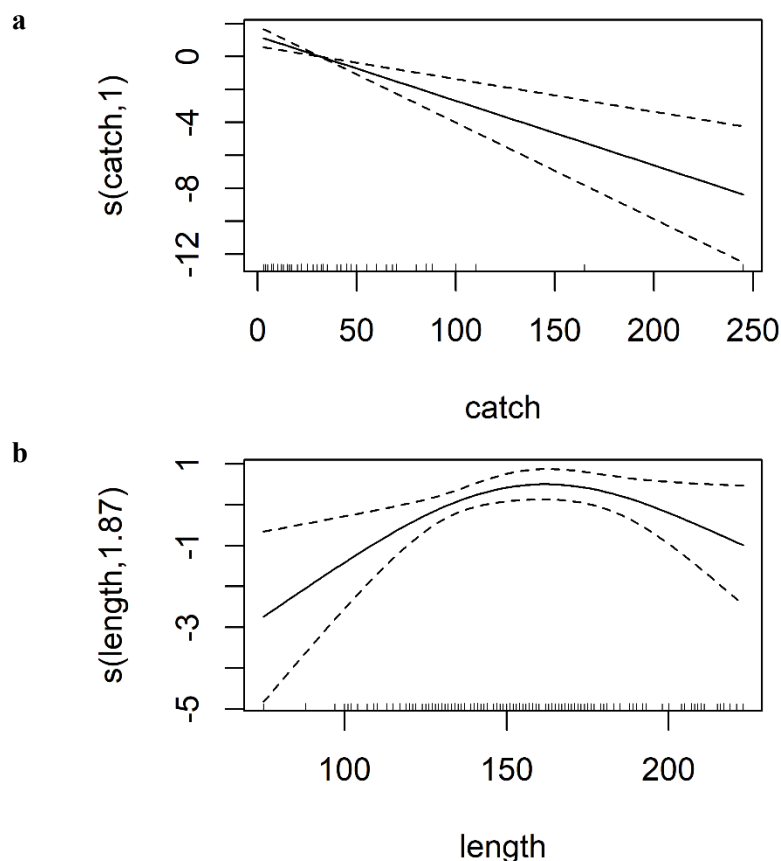


Figure 9. Partial effect plots of (a) target tuna catch and (b) length selected variables.

To account for potential clustering among observations sampled from the same fishing vessel, vessel identity was also evaluated as a random in the final model. Model performance was compared using AIC, adjusted R^2 , deviance explained, and statistical significance of model terms. However, when vessel was included together with vitality, catch size, and body length, the random effect was penalized to zero ($\text{edf} = 0.0001$; $p = 0.625$) and model fit remained unchanged ($\text{AIC} = 152.88$).

These results indicate that apparent vessel-level differences were largely explained by variation in vitality, catch size, and body size among vessels, and that vessel identity did not contribute additional explanatory power once these variables were included. Consequently, vessel was not retained in the final model.

3.4. Model validation

Model diagnostics supported the adequacy of the final GAM. The model converged successfully after five iterations, and basis-dimension checks indicated that the chosen smoothness parameters were sufficient ($s(\text{catch})$: $k\text{-index} = 0.92$, $p = 0.20$; $s(\text{length})$: $k\text{-index} = 0.92$, $p = 0.12$). Concurrency between smooth terms was low (worst concurrency < 0.09), suggesting minimal redundancy

between catch size and body length. These diagnostics indicate that the model was well specified and showed no evidence of overfitting.

Cross-validation results indicated that the final model had good predictive performance and was robust across training and testing subsets (Table 7). AUC values ranged from 0.85 to 0.91 across the four folds, with a mean value of 0.87, indicating a high ability to discriminate between surviving and non-surviving individuals. The True Skill Statistic (TSS) ranged from 0.58 to 0.71, with a mean of 0.66, demonstrating good agreement between observed and predicted outcomes. Miller's Calibration Slope (MCS) varied between 0.66 and 1.53, with an average value of 0.98, indicating that predicted survival probabilities were generally well calibrated with observed survival outcomes. Overall, the consistently high AUC values, positive TSS values, and mean MCS close to the ideal value of 1 suggest that the final model provided reliable and accurate predictions of post-release survival probability.

Table 7. Metrics of performance (Area Under the receiver operating Curve – AUC, True Skill Statistic – TSS, Miller's calibration slope – MCS) of the cross-validation (k=4).

Cross-validation	AUC	TSS	MCS
1	0.86	0.71	0.92
2	0.85	0.58	0.79
3	0.91	0.71	1.53
4	0.87	0.61	0.66
Mean	0.87	0.66	0.98

3.5. Predicting observed individuals' fate

Predicted post-release survival varied markedly among fishing trips (Table 8; Figure 10). Mean survival probabilities ranged from 0.184 (95% CI: 0.146-0.324) for Trip 1 to 0.538 (95% CI: 0.420-0.666) for Trip 12. Trip 11 (0.534; 95% CI: 0.434-0.657), Trip 10 (0.499; 95% CI: 0.365-0.689), and Trip 9 (0.440; 95% CI: 0.324-0.560) also exhibited relatively high predicted survival probabilities. In contrast, Trip 2 (0.218; 95% CI: 0.171-0.388), Trip 3 (0.224; 95% CI: 0.164-0.442), and Trip 4 (0.242; 95% CI: 0.189-0.348) showed comparatively lower survival probabilities.

Table 8. Predicted number of surviving sharks by fishing trip derived from the generalized additive model (GAM). Expected survivors were calculated as the sum of individual predicted survival probabilities within each trip. Mean survival corresponds to the average predicted probability of survival for sharks within a trip. Values in parentheses represent the 95% bootstrap confidence interval, calculated as the 2.5th and 97.5th percentiles of the bootstrap distribution obtained from 10,000 parametric bootstrap iterations.

Trip ID	Ocean	n individuals	Expected survivors	Mean probability of survival
Trip 1	Pacific	586	108 (85.3 – 190)	0.184 (0.146 – 0.324)
Trip 2	Pacific	312	68.1 (53.5 – 121)	0.218 (0.171 – 0.388)
Trip 3	Indian	420	94 (69 – 186)	0.224 (0.164 – 0.442)
Trip 4	Indian	247	59.7 (46.7 – 86)	0.242 (0.189 – 0.348)
Trip 5	Atlantic	247	68.2 (51 – 99.2)	0.276 (0.207 – 0.402)
Trip 6	Pacific	316	121 (96.7 – 179)	0.383 (0.306 – 0.565)
Trip 7	Indian	84	32.4 (20.4 – 39.3)	0.39 (0.246 – 0.474)
Trip 8	Indian	151	59.4 (43.7 – 95.4)	0.394 (0.29 – 0.632)
Trip 9	Indian	282	124 (91.3 – 158)	0.44 (0.324 – 0.56)
Trip 10	Atlantic	94	46.9 (34.3 – 64.8)	0.499 (0.365 – 0.689)
Trip 11	Pacific	304	162 (132 – 200)	0.534 (0.434 – 0.657)
Trip 12	Atlantic	43	23.2 (18.1 – 28.6)	0.538 (0.42 – 0.666)

**Trip IDs were anonymized and assigned according to increasing mean predicted survival probability (Trip 1 = lowest mean survival; Trip 12 = highest mean survival).*

The estimated number of survivors reflected both survival probability and the number of sharks observed in each trip. The highest numbers of expected survivors were estimated for Trip 11 (162.0; 95% CI: 132.0-200.0), Trip 9 (124.0; 95% CI: 91.3-158.0), Trip 6 (121.0; 95% CI: 96.7-179.0), and Trip 1 (108.0; 95% CI: 85.3-190.0) (Table 8). In contrast, Trip 12 and Trip 10 had among the highest mean survival probabilities but relatively low numbers of expected survivors (23.2 and 46.9, respectively), largely because fewer sharks were observed during those trips.

The forest plot (Figure 10) highlights substantial variability in mean survival probability among trips and the uncertainty associated with each estimate. Survival probabilities for Trips 9-12 were consistently above the overall average survival probability (0.36; red dashed line), whereas Trip 1 showed substantially lower survival than all other trips. Although confidence intervals overlapped for several trips, the contrast between Trip 1 and the highest-survival trips suggests meaningful differences in predicted post-release survival among fishing operations. Overall,

mean predicted survival varied approximately three-fold across trips, emphasizing considerable heterogeneity in post-release survival conditions among observed fishing events.

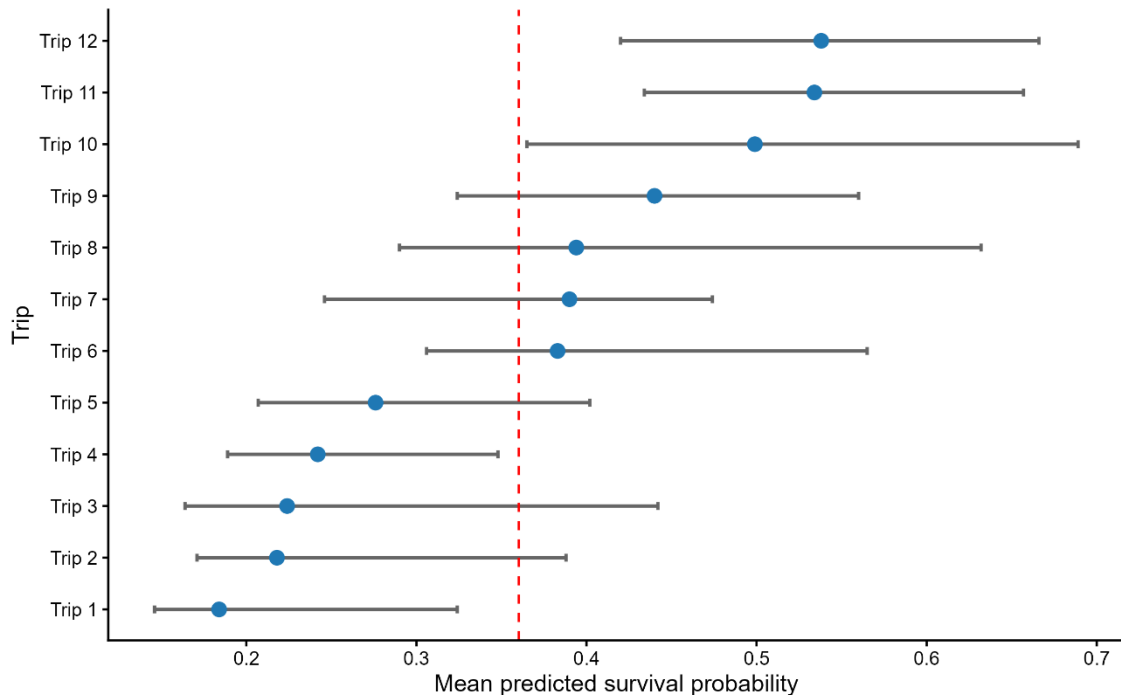


Figure 10. Mean predicted post-release survival probability by fishing trip estimated from the generalized additive model (GAM). Points represent trip-specific mean survival probabilities and horizontal error bars indicate 95% bootstrap confidence intervals derived from 10,000 parametric bootstrap iterations. The red dashed vertical line represents the overall mean survival probability across all trips (0.36) and serves as a reference for comparing trip-specific estimates to the average predicted survival. Trips located to the right of the line exhibited higher-than-average predicted survival, whereas trips to the left exhibited lower-than-average predicted survival.

Exploratory analyses of trip-level characteristics (Table S1) revealed significant negative associations between mean predicted survival probability and both mean catch per trip (Spearman's $\rho = -0.71$, $p = 0.012$) and mean sack time ($\rho = -0.82$, $p = 0.011$). These results suggest that trips with larger catches and longer average sack times tended to exhibit lower predicted survival probabilities. Time in the sack may also be influenced by other operational factors, such as the absence of a port roller and differences in net size or configuration. No significant relationship was detected between mean survival probability and mean shark length ($\rho = 0.08$, $p = 0.817$). Differences in mean survival among trips grouped by dominant release mode were not statistically significant (Kruskal-Wallis $\chi^2 = 3.02$, $df = 3$, $p = 0.388$). However, because releasing devices are vessel-specific and are only installed on some vessels and the use of some of them is still limited, the power to detect among-group differences was limited and these results should be interpreted cautiously.

4. Discussion and Conclusion

Our results suggest that post-release survival is strongly influenced by both shark condition at release and capture-related factors. Sharks released in better vitality condition were more likely to survive, with predicted survival increasing markedly from moribund to excellent vitality categories as observed in previous studies (Hutchinson et al., 2015; Grande et al., 2022, 2025; Murua et al., 2024; Murua et al., 2026; Onandia et al., 2021). This highlights the importance of minimizing capture and handling stressors that may compromise shark condition prior to release. We consider vitality assessment to be a valuable and practical predictor of silky shark survival proxy. Vitality can be readily recorded by trained onboard observers. In fleets equipped with Electronic Monitoring Systems (EMS), vitality at release cannot currently be accurately identified given the cameras positioning. However, cameras could be repositioned to document the release of ETP species and facilitate retrospective vitality assessments. Although all tuna RFMOs have adopted minimum standards for EMS, none explicitly recommend that purse-seine vessels include a camera oriented towards the sea on the starboard side of the vessel, where sharks are typically released with a view that would facilitate the assessment of shark vitality at release. Expanding the collection of vitality data would provide a cost-effective approach for estimating post-release survival across fleets, particularly when compared with large-scale satellite-tagging programs. Within this study, we estimated a higher survival probability for sharks classified as moribund than reported in previous studies (Grande et al., 2022; 2025; Murua et al., 2024; Onandia et al., 2021), in which all individuals in this condition were generally assumed to die. The potential misclassification between adjacent vitality states that may exhibit similar behavioural responses (e.g., poor and very poor), could explain these differences. Such classification uncertainty may hinder the distinction between AVM and PRM and affect overall survival estimates at the trip level. An alternative physiological indicator is blood lactate concentration, which is closely related to vitality and has been used as predictor of shark mortality (Hutchinson et al., 2015, 2026). However, within this study vitality was more informative and selected in the final model selection. In addition, its application requires specialized training in blood sampling, limiting its integration into routine observer programs, and reducing the achievable sample size. Therefore, vitality assessments provide an operationally feasible approach for estimating post-release survival in fishing operations.

Survival probability was also related to body length, with intermediate-sized individuals showing the highest predicted survival, whereas both smaller and larger sharks appeared to be more vulnerable following capture and release. Although larger individuals appear to better tolerate capture-related stress (Eddy et al., 2016; Hutchinson et al., 2026), the lower survival probabilities observed in larger sharks in this study may be explained by the greater difficulty of handling and releasing these individuals quickly due to their size.

In addition, catch size showed a strong negative effect on survival probability, with survival declining steadily as catch volume increased. Sharks captured in larger fishing sets exhibited lower post-release survival probabilities, likely reflecting longer retention times and increased physiological stress while confined in the sack during high-catch events. Consistent with this finding, post-release survival experiments in purse seine fisheries have shown that blood lactate

concentrations increase and physical condition declines with the time sharks remain confined in the sack, indicating greater levels of physiological stress (Eddy et al., 2016; Hutchinson et al., 2026). The absence of internal or external injuries in necropsied individuals reported in previous studies suggests that impaired swimming ability and the resulting reduction in ram ventilation while confined in the sack may be major drivers of physiological deterioration and reduced post-release survival (Eddy et al., 2016). Consistent with this interpretation, exploratory trip-level analyses showed lower mean survival probabilities on trips characterized by larger catches and longer average sack times. Thus, these analyses further suggest that retention duration within the sack may be an important operational factor influencing survival outcomes (Eddy et al., 2016; Hutchinson et al., 2026). However, time in the sack was less informative than vitality in our analyses and was unavailable for all observed individuals, preventing its inclusion in the final predictive model. Furthermore, this variable may be more closely associated with at-vessel mortality (AVM) than post-release mortality (PRM), emphasizing the importance of distinguishing between these mortality components in future analyses.

Our results revealed substantial trip-to-trip variability in predicted survival, indicating that the conditions experienced during different fishing operations can strongly influence outcomes. Mean predicted survival probabilities varied approximately threefold, ranging from 0.184 in Trip 1 to 0.538 in Trip 12, with Trips 9-12 consistently exceeding the overall average. This variability suggests that operational and physiological factors may play a significant role in determining AVM and PRM. Although confidence intervals overlapped among several trips, the contrast between Trip 1 and the highest-survival trips points to biologically meaningful differences in survival conditions. Trips in which releasing devices were implemented did not necessarily result in higher predicted survival rates, likely reflecting the high influence of other factors such as catch size, shark size and vitality at release, which is impacted by time in the sack, and may have masked the benefits of the implementation of the Best Release Devices (BRD).

In vessels where Best Handling and Release Practices (BHRPs) and dedicated release devices are already implemented, variability in shark survival among trips appears to be driven largely by fishing operational characteristics, which are difficult to address through best practices alone. Consequently, further improvements in post-release survival are likely to depend on tailoring release devices and handling procedures to vessel-specific configurations, as well as reducing stress and injury prior to release. In particular, additional reductions in mortality may be achieved by minimizing retention time and limiting the adverse conditions experienced by sharks while confined in the sack. However, achieving such improvements will require further research, as no proven technologies or operational measures have yet been identified to effectively mitigate these impacts.

Even in fisheries where post-release survival probabilities remain low because of severe capture-related stressors, the continued use of BRDs and BHRPs remains essential for maximizing survival. These measures expedite shark release and minimize handling-related injuries and stress, thereby increasing the likelihood that individuals surviving the at-vessel mortality (AVM) phase also survive the subsequent post-release mortality (PRM) period. As such, their implementation should remain a central component of best-practice bycatch mitigation strategies,

helping to ensure that survival gains achieved during capture and release are retained beyond the point of release.

Future research should focus on increasing sample sizes and improving the collection of key explanatory variables, particularly vitality scores and individual time-in-the-sack measurements. Expanding human observer and EMS-based monitoring programmes to routinely record vitality at release would provide a practical and cost-effective means of improving survival estimates, identifying mitigation measures that maximize post-release survival, and quantifying silky shark mortality associated with purse seine fisheries. A particular priority should be the disentanglement of AVM and PRM processes, as these influence trip-level survival estimates and are likely driven by different mechanisms and predictors. Variables such as time in the sack and oxygen availability may primarily affect AVM, whereas deck time, release techniques, and handling procedures may exert stronger effects on PRM. Further research should therefore investigate strategies to reduce stress during the sacking phase, when sharks may experience prolonged confinement and adverse environmental conditions. Additional analyses should also examine the influence of shark abundance in catches and further evaluate the effectiveness of BHRPs and BRDs under a wider range of operational conditions.

In conclusion, this study demonstrates that post-release survival of silky sharks is strongly influenced by their condition at release. Although survival outcomes varied substantially among trips, our results provide encouraging evidence that the implementation of BHRPs and dedicated BRDs can increase trip-level survival probabilities to as high as 0.54 under favourable operational conditions. However, this level of survival should not be considered a universal expectation across fleets, as vessel-specific characteristics, catch dynamics, and capture conditions impose important constraints on survival outcomes. Nevertheless, the consistent positive association between release vitality and survival highlights the importance of minimizing capture-related stress while promoting the widespread implementation of BHRPs and BRDs. Together, these measures represent practical and effective tools for maximizing survival opportunities and reducing the ecological impacts of tuna purse seine fisheries on shark populations.

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Supplementary information

Table S1. Operational characteristics of each trip.

Trip ID	Ocean	n individuals	Main releasing mode	Mean catch (tons)	Mean length (cm)	Mean time in the sack (minutes)
Trip 1	Pacific	586	Hopper with ramp	60.9	137	42
Trip 2	Pacific	312	Hopper with ramp	49.3	130	41
Trip 3	Indian	420	Hopper with ramp and gutter	31.7	128	37
Trip 4	Indian	247	Manual and bycatch conveyor belt	64	126	NA*
Trip 5	Atlantic	247	Manual	46.4	143	26
Trip 6	Pacific	316	Hopper with ramp	30.3	122	31
Trip 7	Indian	84	Manual	52.3	113	NA*
Trip 8	Indian	151	Manual and gutter	18.3	129	8
Trip 9	Indian	282	Bycatch conveyor belt	36.1	137	NA*
Trip 10	Atlantic	94	Manual	12.2	137	11
Trip 11	Pacific	304	Hopper with ramp	20.7	123	22
Trip 12	Atlantic	43	Manual and ramp	25.2	140	17

**Time in the sack only collected for tagged sharks.*