On-deck condition and mortality of Indo-Pacific Sailfish (*Istiophorus platypterus*) in Indian Ocean tuna longline fisheries

Na Zhang[1], Wei Tang[1], Jie Cao[2], Yanan Li[1], Huihui Shen[1], Jiangfeng Zhu[1],

Jiaqii Wang[1], Xuefang Wang[1]

E-mail: 18473271095@163.com; xfwang@shou.edu.cn

SUMMARY

The Indo-Pacific sailfish (Istiophorus platypterus), an oceanic pelagic migratory fish species, has been increasingly at risk of overfishing in recent years due to rising fishing pressure. In the Indian Ocean, mandatory release for billfish below specific body lengths has become one of the key conservation management strategies. Nevertheless, current research paradigms largely overlook the physiological condition of individuals upon deck retrieval—a critical factor influencing post-release survival. This study analyzes observer data from the Chinese tuna longline fishery collected between 2012 and 2019. A total of 516 Indo-Pacific sailfish captured in the Indian Ocean were assessed for on-deck condition (A1: healthy; A2: lightly injured; A3: severely injured; D: dead), alongside associated environmental factors and operational parameters. Statistical modeling was applied to identify key drivers of individual condition and mortality. The results showed that the lower-jaw fork length of sampled individuals ranged from 93 to 239 cm, of which 10.66% were classified as A1, only 0.97% as A2, while a striking 73.06% were recorded as D. Bait type, capture latitude, chlorophyll a concentration, and hook type significantly influenced condition and mortality (p < 0.05), with the bait type and latitude exerting the most prominent effects. Specifically, the use of sardines as bait significantly increased the proportion of A1and A2 individuals. Optimal individual condition was observed near 20° S, whereas mortality approached 90% in the area near the equator. These findings suggest that release operations for Indo-Pacific sailfish should be spatially differentiated. Priority should be given to release operations in mid- to high-latitude areas. In low-latitude (high-risk areas), efforts should focus on optimizing operational technical parameters such as bait type and hook type to improve on-deck condition and post-release survival, thereby enhance the effectiveness of management.

---

[1] College of Marine Living Resources and Management, Shanghai Ocean University, Shanghai 201306, China.

[2] Department of Applied Ecology, Center for Marine Sciences and Technology, North Carolina State University, Morehead City, North Carolina, USA.

KEYWORDS

Indo-Pacific sailfish (Istiophorus platypterus); on-deck condition; on-deck mortality; safe release strategy; tuna longline fishery; Indian Ocean.

1. Introduction

The Indo-Pacific sailfish (*Istiophorus platypterus*) is a fast-swimming, oceanic pelagic migratory species of the family *Istiophoridae* and the genus *Istiophorus*. It is widely distributed across the tropical and subtropical waters of the Indian, Atlantic, and Pacific Oceans (Nakamura, 1983). In the Indian Ocean, it is mainly caught by gillnets, tackle (handlines) and longline fisheries (IOTC, 2024). According to statistics and assessments by the Indian Ocean Tuna Commission (IOTC), catches of this species have consistently exceeded the maximum sustainable yield (MSY = 25 905 t) since 2013. For three consecutive years (2020–2022), catches have exceeded the limit of 25 000t set by Resolution 18/05 (Parker et al., 2022). To address the overexploitation of billfish stocks in the Indian Ocean, particularly those in poor stock status, the resolution mandates the release of individuals with a lower-jaw fork length (LJFL) of less than 60 cm. It also recommends that Contracting Parties and Cooperating Non-Contracting Parties strengthen relevant research, including guidelines for post-release survival and safe release, improvement of fishing methods and gear selectivity, and report to the scientific committee (IOTC, 2018).

Persistent catch overages over a long period of time may place stocks at risk of future overfishing. Enhancement of fisheries' eco-friendliness, particularly with respect to non-target and immature individuals, has become a critical issue for sustainable fisheries management (Melvin et al., 2014). In this context, the concept of safe release has emerged as a core element of international fisheries regulations, centred on improving the design and operation of fishing gear to minimize physiological stress and physical injury during the capture, handling and release of fish in order to increase the likelihood of post-release survival (Gilman et al., 2011). Although the principles of safe release have been widely promoted at the policy level, much of the related scientific research has concentrated on the assessment of post-release mortality. Less attention has been given to the actual physiological state of the individuals prior to being brought on deck.

On-deck mortality (OM) in longline fisheries refers to the proportion of captured individuals that are confirmed to have died physiologically by the time they are retrieved and placed on the vessel's deck. Such mortality typically results from stress, asphyxiation, mechanical injury, or physiological exhaustion incurred during the fishing operations (Marshall et al., 2015). As a direct indicator of whether a fish has died upon being caught and hauled on deck, OM serves an important piece of reference information for evaluating the potential effectiveness of release strategies. However, OM reflects only the survival status of individuals at the completion of the fishing effort and does not account for those that, while not immediately deceased, are in a severely weakened or near-death condition. Implementing a graded assessment of on-deck condition (e.g., healthy, injured, dying, dead) would provide more nuanced understanding of individual's potential viability (Campana et al., 2015).

In this context, conducting a systematic study of the on-deck condition of billfish offers more comprehensive and fine-grained informational support than focusing solely on on-deck mortality (Coelho et al., 2012). In particular, identifying the environmental, biological and operational factors that influence on-deck condition and mortality levels can provide a scientific foundation for optimizing fishing gear operations to enhance safe release outcomes. While such studies have been extensively conducted for species such as seabirds, elasmobranchs, marine mammals and sea turtles (Bowlby, 2020; Moore et al., 2024), research on the impacts of fishing operations on incidentally caught, threatened species like billfish in the Indian Ocean remains relatively limited.

In addition, Meta-analysis has been applied in studies assessing the effectiveness of bycatch mitigation techniques in tuna fisheries, offering a robust approach for synthesizing results from multiple independent studies and improving statistical efficacy (Reinhardt et al., 2016). However, the effectiveness of Meta-analyses highly depends on the quantity and quality of underlying case studies (Gurevitch, 2018). While a high number of Meta-analysis studies have been conducted on bycatch species such as sharks and turtles in longline fisheries (Musyl et al., 2019; Yan et al., 2024), there are still relatively few case studies for species such as swordfish (Musyl, 2015).

In response to the current critical information gap on the on-deck condition and mortality of Indo-Pacific sailfish in the Indian Ocean, this study used multinomial logistic regression models as well as Generalized Additivity Models (GAMs) to analyze observer recorded fishery data from the Chinese Tuna Longline Fishery Observer Program, alongside publicly available marine environmental datasets. The analysis examined the potential effects of biological characteristics, spatial-temporal and environmental factors, gear and operational factors on on-deck condition and mortality of Indo-Pacific sailfish in this area. Trends in individual condition were predicted at different factor levels. The results of the study offer a valuable case with detailed data and standardized methodology to support future Meta-analyses, and provide a reference basis for the development of more scientific safe release strategies and conservation management measures.

2. Materials and methods

2.1 Gear configuration

The target species of the Chinese tuna longline fishery fleet operating in the Indian Ocean are mainly bigeye tuna (*Thunnus obesus*) and albacore tuna (*Thunnus alalunga*). During the study period, the mainline used by fishing vessels consisted mainly of braided nylon ropes or glass monofilaments, with total lengths ranging from about 70 000 to 249 570 m. The mainline between the two floats were 726–1 102 m in length, while the floating lines were 20–40 m in length. The branch lines measured 18–52 m, with spacing between them ranging from 30 to 57 m. Hook types included Japanese hooks (52.44%), circle hooks (29.12%) and other hook types (18.44%). Sardines were the most commonly used bait (56.63%), followed by mackerel (38.11%) and a few other bait types (5.26%). The spatial distribution of hook and bait types at captured locations is shown in Appendix Figures A1 and A2, respectively.

2.2 Observer data

The fishery data used in this study were obtained from the records and measurements of Chinese tuna longline fishery observers. During the period from 2012 to 2019, a total of 21 trained observers were deployed in 21 longline fishing trips**,** during which data were recorded from 2 439 sets conducted mainly within the region spanning 10°N–31°S and 40°E–78°E. The spatial distribution of observation sites is shown in Figure 1. Observers were responsible for recording essential information for each set, such as date, time, operation location (latitude and longitude), hook type, and bait type. For each captured individual, the lower-jaw fork length (LJFL) was measured, and on-deck condition was assessed. On-deck condition refers to the state of the catch when retrieved onto the vessel deck, and was categorized into four classes: alive and healthy (A1), slightly injured (A2), seriously injured to near death (A3), and dead (D). A total of 561 Indo-Pacific sailfish (*Istiophorus platypterus*) were recorded as incidental catch during these sets, approximately accounting for 0.67% of the total catch. Of these, 45 individuals were excluded from analysis due to missing biological data (e.g., LJFL), resulting in 516 valid records used for statistical analysis of on-deck condition and mortality.

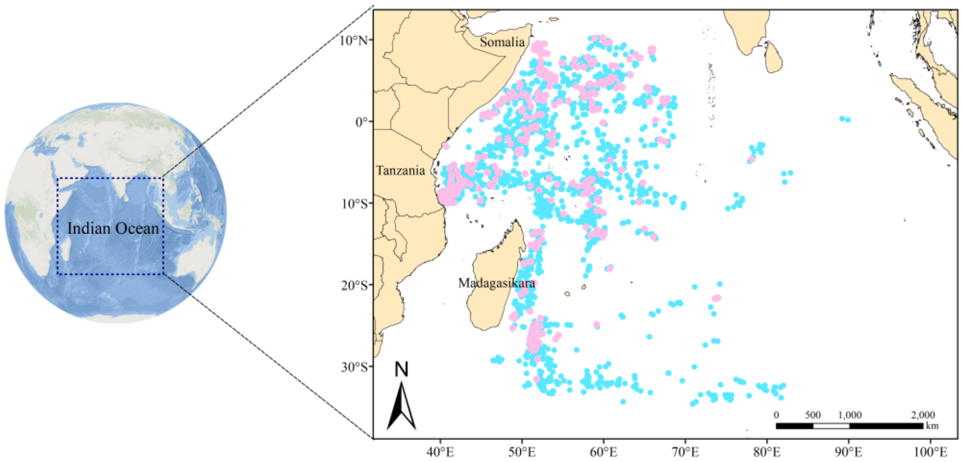

Figure 1. Distribution of tuna longline fishery sites recorded by fisheries observers during 2012–2019. Sites where no Indo-Pacific sailfish (*Istiophorus platypterus*) were captured are indicated by "●", while sites where Indo-Pacific sailfish were captured are indicated by "●".

2.3 Environmental and spatial data

Studies on the on-deck mortality of billfish in other oceanic regions have shown that hooking-related mortality of billfish can be affected by various marine environmental factors, such as Sea Surface Temperature (SST), Sea Surface Salinity (SSS), mass concentration of chlorophyll a (CHL) and Dissolved Oxygen (DO) (Epperly et al., 2012; Sippel et al., 2007; Plumb et al., 1988). Therefore, these four factors were selected in this study as key environmental parameters potentially affecting the on-deck condition of Indo-Pacific sailfish. Environmental data were obtained from the Copernicus Marine Service (CMEMS, https://marine.copernicus.eu/). Raw data on SST, SSS, CHL and DO featured a monthly temporal resolution and a spatial resolution of 0.25° × 0.25°. Environmental variables were coupled with fishing locations through the "Extract Values to Points" function in the ArcMap (10.8) toolbox.

As it is not feasible to account for all possible environmental factors affecting billfish survival, this study also incorporated the capture geographic location (longitude and latitude) and season as spatial–temporal proxies in the model to indirectly reflect potential environmental heterogeneity.

2.4 Initial variable screening

The names, types, and value ranges of all initial variables used in this study are detailed in Table 1. When there is a high degree of correlation between the variables, it affects the stability of the model and the accuracy of the coefficient estimates, so the initial variables need to be screened to mitigate this issue (Dormann, 2013). The Pearson's correlation coefficient (*r*) was used to examine pairwise correlations among SST, SSS, CHL, DO, LJFL, capture longitude (Lon), and capture latitude (Lat), with one of the two variables excluded if the $|r| \geq 0.7$ between the two variables, and the filtered variables used to construct the model.

Table 1. Scope and classification of each continuous explanatory variable

Explanatory variable	**Name**	**Type**	**Scope/classification**
Biological characteristics	Lower jaw-fork length/cm	Continuous	93-239
Environmental factors	Sea surface temperature/°C	Continuous	17.95-30.62
	Sea surface salinity	Continuous	34.28-36.20
	Chlorophyll a/ mg/m³	Continuous	0.05-0.62
	Dissolved oxygen/ mmol/m³	Continuous	196.08-241.03
Gear and operation	Hook type	Categorical	Japanese tuna hook/circle hook/other
	Bait type	Categorical	Mackerel/sardine/others
Spatial–temporal elements	Longitude	Continuous	40°E-78°E
	Latitude	Continuous	10°N-31°S
	Quarter	Categorical	1 (Jan, Feb, Mar)/2 (Apr, May, Jun)/3 (Jul, Aug, Sept)/4 (Oct, Nov, Dec)

2.5 Prediction of on-deck condition

The study assessed the factors influencing the on-deck condition of Indo-Pacific sailfish and their probability of occurrence through Multinomial Logistic Regression (MLR) modelling. The MLR establishes probabilistic associations between predictor variables and a multicategory response variable via a logit link function (Hosmer et al., 2013). Optimal predictor variables were identified based on the Akaike information criterion (AIC; Akaike, 1998). The model is expressed as follows:

$$log\left(\frac{P(Y=k)}{P(Y=K)}\right) = \alpha + \beta_1 \cdot Hooktype + \beta_2 \cdot Baittype + \beta_3 \cdot Quarter + \beta_4 \cdot LJFL + \beta_5 \cdot Lat + \beta_6 \cdot Lon + \beta_7 \cdot SST + \beta_8 \cdot SSS + \beta_9 \cdot Chl + \beta_{10} \cdot \mathrm{DO} + \varepsilon, \quad (1)$$

where: k is Indo-Pacific sailfish on-deck condition (A1,A2,A3), K is the reference category (D); α is the intercept of the model; β is the regression coefficient of the predictor variables; $Hooktype$ is the hook type, $Baittype$ is the bait type, $Quarter$ is the quarter of the catch, $LJFL$

is the lower-jaw fork length of the individual, Lat is the latitude of the catch site, Lon is the catch site longitude, SST is the sea surface temperature at the capture site, SSS is the sea surface salinity at the capture site, Chl is the mass concentration of chlorophyll a at the capture site, DO is the dissolved oxygen at the capture site; ε is the random error of the model.

2.6 Prediction of on-deck mortality

A Generalized Additive Model (GAM) utilizes a spline smoothing function to describe the complex relationship between the response variable and the explanatory variables (Hastie, 1986). In this study, a GAM with response variables obeying a binomial distribution was applied to assess the factors influencing the on-deck mortality and its probability of occurrence in Indo-Pacific sailfish. The link function used was the logit function and the model expression was:

$$g(Y) = \alpha + Hooktype + Baittype + Quarter + s(LJFL) + s(Lat) + s(Lon) + s(SST) + s(SSS) + s(Chl) + \mathrm{s(DO)} + \varepsilon, \quad (2)$$

where Y is the Indo-Pacific sailfish on-deck mortality (0-1); α is the intercept of the model; $Hooktype$ is the hook type, $Baittype$ is the bait type, $Quarter$ is the quarter of capture, $LJFL$ is lower-jaw fork length, Lat is the latitude of the capture site, Lon is the latitude of the capture site, SST is the sea surface temperature of the capture site, SSS is the sea surface salinity of the capture site, Chl is the mass concentration of chlorophyll a at the capture site, DO is dissolved oxygen at the capture site and ε is the random error of the model.

2.7 Model goodness-of-fit validation

For model fit validation, MLR's goodness-of-fit was assessed using the Kappa coefficient; the GAM was assessed using R^2. For model prediction accuracy, the Area Under the Receiver Operating Characteristic Curve (AUC) was used as a measure of model pre-evaluation. To reduce model stochasticity, models were constructed using 80% of the data as the training set and the remaining 20% as the validation set (Fushiki, 2011). The cross-validation process was repeated 100 times, each time randomly dividing 20% of the data as the validation dataset, and finally calculating the AUC values as well as the 95% confidence interval of the model, the AUC range between 0 and 1. As the AUC gets closer to 1, the higher the model predictive ability, and vice versa, the lower the model predictive ability (Bradley, 1997).

2.8 Statistical tools

All statistical analyses were performed using R (version 4.4.3). The results of Pearson's correlation analyses were presented using the package “GGally”; the relationships between explanatory and response variables were presented using the packages “nnet”, “mgcv” and “ggplog2”; and the package ’cvAUC" was used for cross-validation.

3. Results and analysis

3.1 Analysis of sample character

The LJFL distribution of 516 samples ranged from 93 to 239 cm, with the dominant group (86.05%) falling within the range of 150–210 cm (Fig. 2). Among these, 50 samples were classified as A1, accounting for 9.69%; 5 samples were A2, comprising only 0.97%; 84 samples were A3, representing 16.28%; and 377 samples were recorded as D, accounting for the largest proportion (73.06%). On-deck condition varied significantly across different levels of latitude, longitude, SST, LJFL, Quarter, and bait type. Specifically, mortality rates increased markedly in the equatorial region (0–10ºN, Fig. 3E) and at higher sea temperatures (25–35°C, Fig. 3G). Quarter 1 and 2 showed a higher proportion of mortalities compared to Quarter 3 and 4 (Fig. 3C). In addition, a significantly higher survival rate was observed when sardines were used as bait (Fig. 3A), in individuals with large body sizes (240 cm > LJFL > 210 cm, Fig. 3D), under high DO conditions (DO > 215 mmol/m^3, Fig. 3H), at low CHL concentrations (CHL < 0.4 mg/m^3, Fig. 3I), and in the eastern part of the fishery area (Fig. 3F).

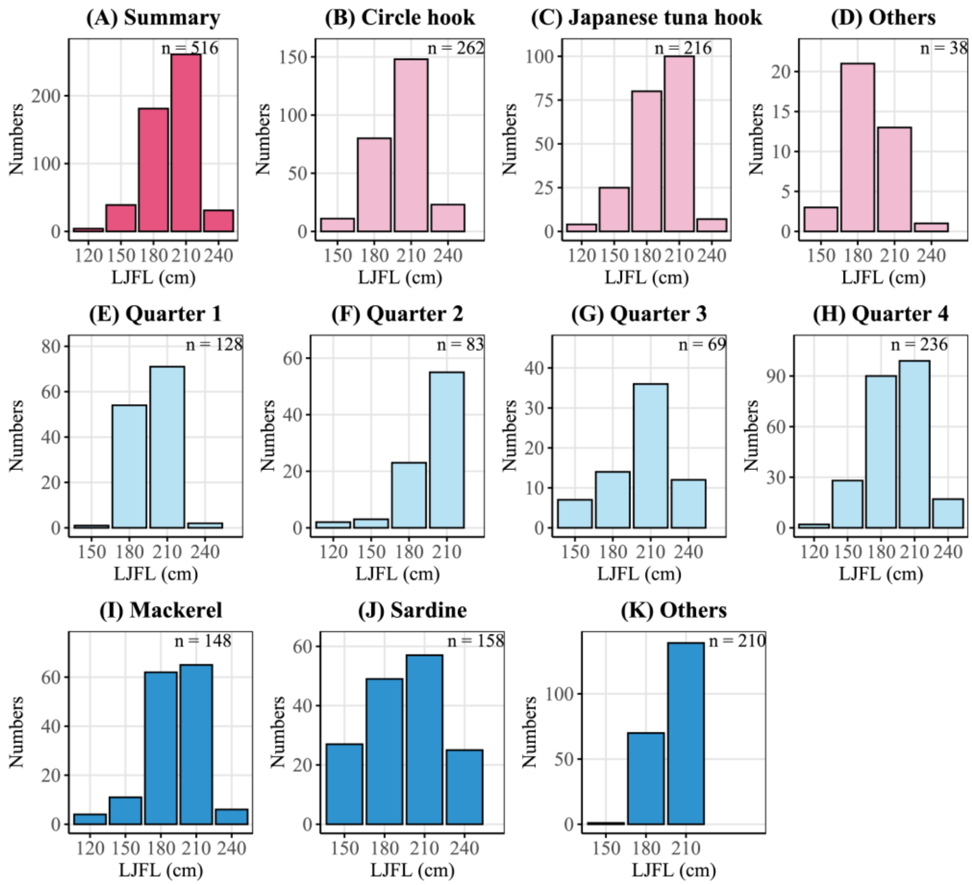

Figure 2. Distribution of lower jaw-fork length of Indo-Pacific sailfish in the Western Indian Ocean from 2012 to 2019. (A: Overall distribution; B-D: Comparison of different hook types; E-H: Comparison of different Quarter; I-K: Comparison of different bait types.)

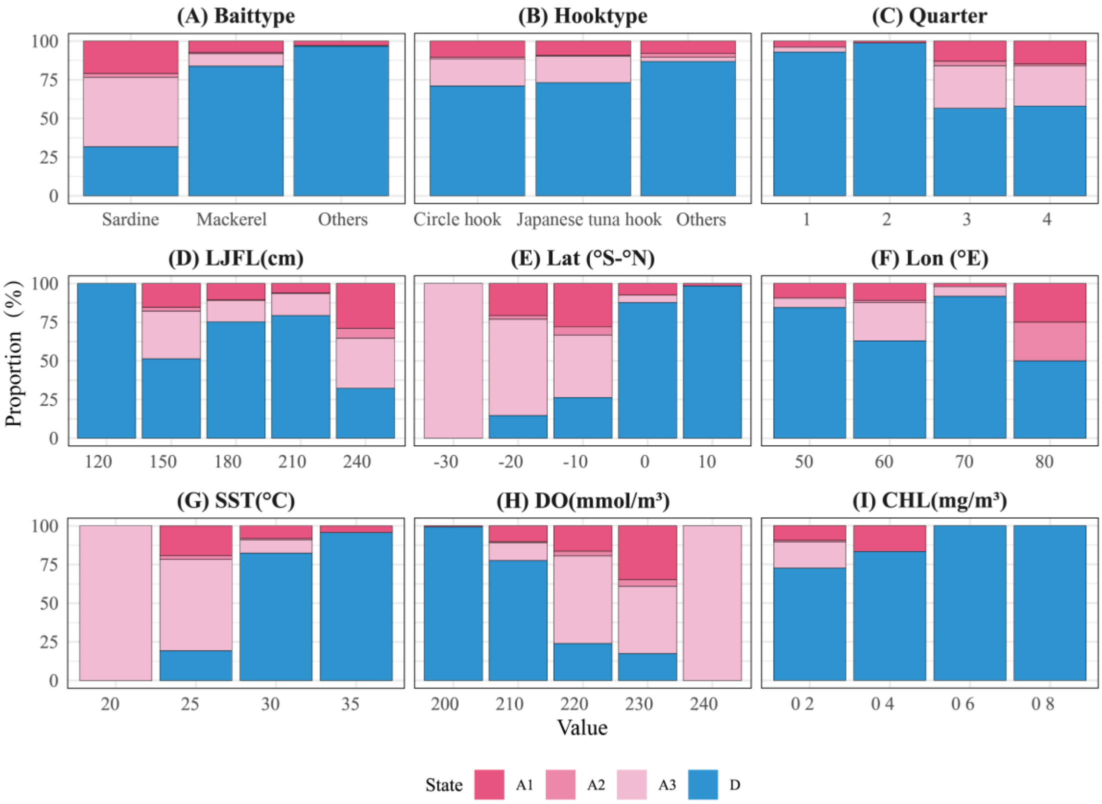

Figure 3 Proportion of Indo-Pacific sailfish with on-deck condition (A1, A2, A3, D) for different explanatory variables (LJFL indicates lower jaw-fork length; Lon indicates the longitude of the capture site; Lat indicates the latitude of the capture site; SST is sea surface temperature at the capture site; DO is dissolved oxygen at the capture site; CHL is the mass concentration of chlorophyll a at the capture site.)

Further analysis of the cumulative frequencies and ranges of the various variables associated with different on-deck conditions revealed significant latitudinal and temperature-related differences between dead and live samples. Specifically, few dead individuals were observed at south of 15°S (Fig. 4B), in waters with temperatures below 26°C (Fig. 4D), and with dissolved oxygen concentrations exceeding 215 mmol/m^3 (Fig. 4E).

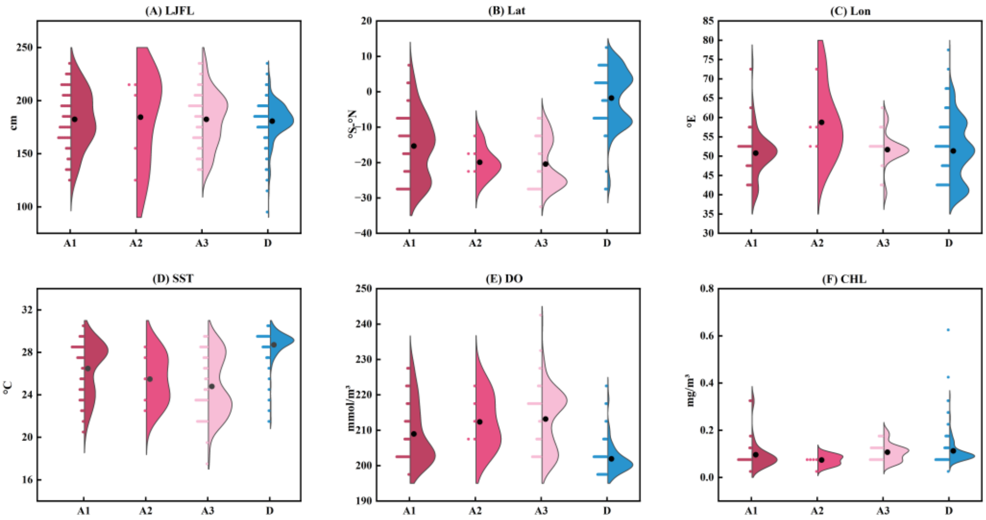

Figure 4 Range of values and distribution density of explanatory variables for different on-deck condition (A1, A2, A3, D). (LJFL indicates lower jaw-fork length; Lon indicates the longitude of the capture site; Lat indicates the latitude of the capture site; SST is sea surface temperature at the capture site; DO is dissolved oxygen at the capture site; CHL is the mass concentration of chlorophyll a at the capture site. "●" indicates the mean value of the variable.)

3.2 Selection of explanatory variables

Pearson analysis revealed high correlations between latitude and SST (r = 0.87), and between DO and SST (r = -0.95) (Fig. 5). Therefore, SST was excluded from the analysis, and the preliminary model ultimately retained the continuous variables such as LJFL, Lon, Lat, SSS, DO, and CHL, as well as the categorical variables such as hook type, bait type, and Quarter of capture.

Figure 5 Pearson correlation analysis. (LJFL indicates lower jaw-fork length; Lon indicates the longitude of the capture site; Lat indicates the latitude of the capture site; SST is sea surface temperature at the capture site; SSS is sea surface salinity at the capture site; DO is dissolved oxygen at the capture site; CHL is the mass concentration of chlorophyll a at the capture site.)

3.3 Prediction of the probabilities of on-deck condition

After stepwise variable screening of the preliminary model based on the AIC, variables such as Quarter, LJFL, and SSS were removed. The final optimal model retained only five variables: bait type, Lat, CHL, hook type, and Lon. The explanation of the deviation of each explanatory variable pair is shown in Table 2.

Table 2 Analysis of deviance in the model for the on-deck condition of Indo-Pacific sailfish

	Df	Deviance explained, %	Cumulative Deviance explained, %	Residual. Deviance	$Pr(>\lvert z\rvert)$
NULL				821.3954	<0.05
Baittype	6	26.97	26.97	599.8934	<0.05
Lat	3	7.89	34.85	535.0247	<0.05
CHL	3	1.96	36.29	523.1956	<0.05
Hooktype	6	1.44	38.25	512.3862	<0.05
Lon	3	0.68	38.93	501.6320	<0.05
Total deviance explained		38.93%			

Note: “Df” is the degrees of freedom. “Deviance explained” is the interpretation deviation. “Residual. Deviance” is the residual deviance. “Pr (> Chisq)” is the p-value, indicating whether the factor is significant or not. “Lat” is latitude. “CHL” is the mass concentration of chlorophyll a. “Lon” is, longitude.

The results of model validation showed that the model had good goodness-of-fit, with no evidence of overfitting or overdispersion. The Kappa coefficient was 0.569 (95% CI: 0.558–0.580), suggesting a medium-strength consistency; and the overall prediction accuracy was 83.33% (95% CI: 79.83%–86.45%). The mean value of the AUC metric obtained through 100-fold cross-validation was 0.735 (range: 0.628–0.863), and its 95% confidence interval was 0.646–0.826, further confirming the robustness of the model.

The MLR predictions showed that the probability of individuals being in condition A1 or A2 was highest near 20ºS latitude. As proximity to the equator increased, the probability of survival (A1/A2/A3) decreased, while the probability of mortality (D) increased (Fig. 6A). Survival probability decreased rapidly as the CHL increased to 0.2 mg/m^3, with the mortality showing the opposite trend (Fig. 6B). In terms of longitude, the sensitivity to spatial variation varied slightly between sub-models (Fig. 6C). Bait type significantly affected the on-deck condition of Indo-Pacific sailfish. The death probability was notably higher when mackerel and other bait types were used, compared to sardines (Fig. 7A), but differences in on-deck condition across hook types were not statistically significant (Fig. 7B).

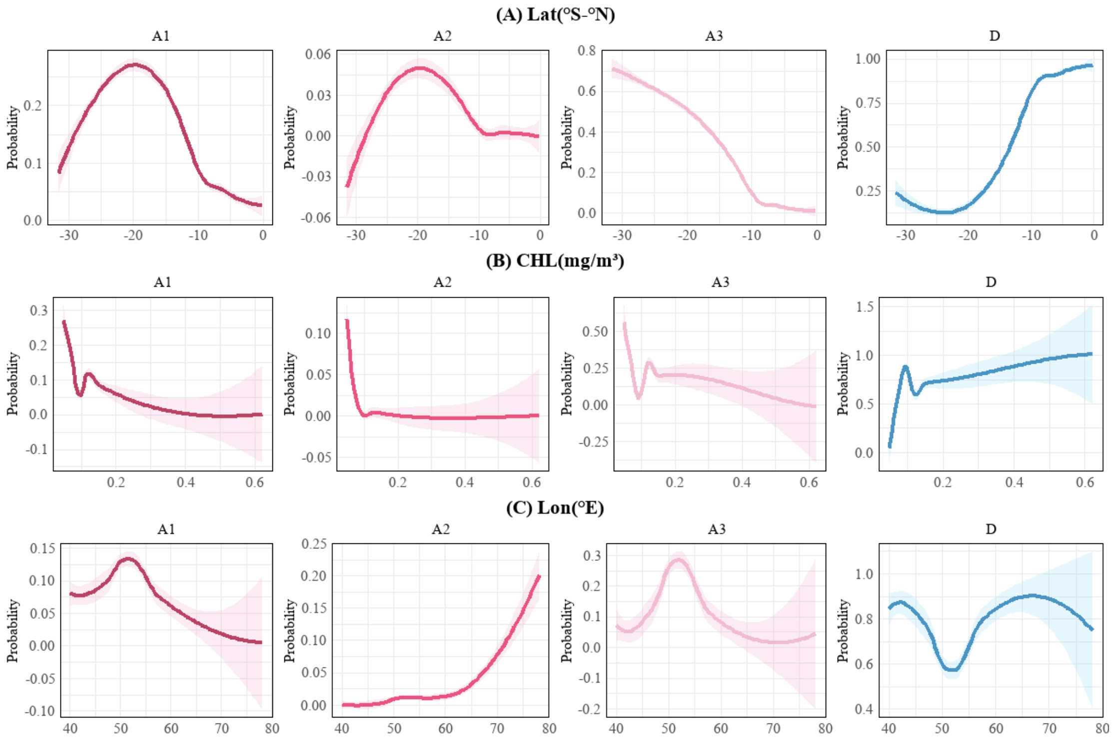

Figure 6 Effects of different continuous variables on predictions of expected condition (A1, A2, A3, D) of Indo-Pacific sailfish in the Western Indian Ocean. (The solid line indicates the change in predicted condition with each explanatory variable; the shaded area indicates the 95% confidence interval of the variable. Lon is longitude; Lat is latitude; CHL is the mass concentration of chlorophyll a.)

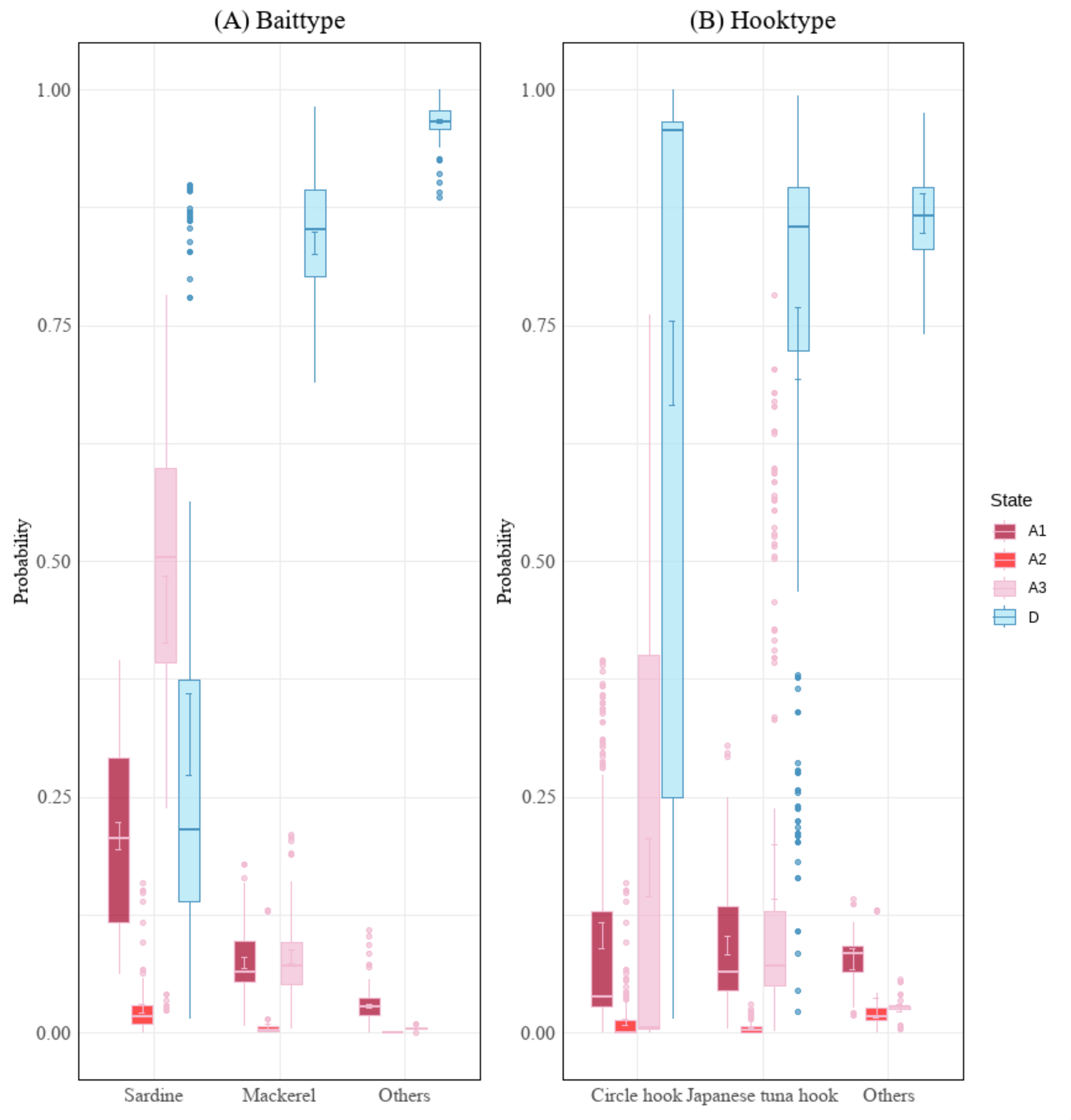

Figure 7 Effects of different categorical variables on predictions of expected condition (A1, A2, A3, D) of Indo-Pacific sailfish in the Western Indian Ocean. (The solid lines indicate the changes in predicted condition with each explanatory variable, the shaded area indicates the 95% confidence interval of the variable; the "I" in the box plot indicates the upper and lower limits of the data, with the upper limit being the smaller value between the maximum observed value and the maximum value, and the lower limit being the larger value between the minimum observed value and the true minimum value.)

3.4 Prediction of the probabilities of on-deck mortality

The deviance explained by each explanatory variable in the model is shown in Table 3. Of the variables used to explain Indo-Pacific sailfish on-deck mortality, the largest contributor to the explanation of model deviance was bait type (35.17%), followed in order by Lat (10.02%), CHL (1.25%), and hook type (1.23%).

Table 3 Analysis of deviance in the model for the on-deck mortality of Indo-Pacific sailfish

	Df	Deviance explained, %	Cumulative Deviance explained, %	Residual. Deviance	Pr(>|z|)
NULL				601.29	
Baittype	2	35.17	35.17	389.8166	<0.05
Lat	1	10.02	45.19	329.5501	<0.05
CHL	1	1.25	46.44	322.0484	<0.05
Hooktype	2	1.23	47.67	314.6555	<0.05
Lon	1	0.51	48.18	311.5670	0.07
Total deviance explained		48.18%			

Note: "Df" is the degrees of freedom. "Deviance explained" is the interpretation deviation. "Residual. Deviance" is the residual deviance. "Pr (> Chisq)" is the p-value, indicating whether the factor is significant or not. "Lat" is latitude. "CHL" is the mass concentration of chlorophyll a. "Lon" is, longitude.

The results of the model validation demonstrated good goodness of fit, with no signs of overfitting or overdispersion. The R^2 of the model was 0.5567; the mean value of the AUC metric obtained through 100 cross-validations was 0.910 (range: 0.849–0.969), and its 95% confidence interval was 0.861–0.955, further confirming the robustness of the model.

Model results indicated that bait type, Lat, CHL, and hook type all had significant effects on on-deck mortality. The effect of bait type on mortality was particularly significant, with the lowest individual mortality observed when sardines were used as bait, followed by mackerel, and the significantly highest mortality associated with other bait types (Fig. 8A). Mortality of individuals also varied by hook type, with individuals caught on circle hooks having a slightly lower mortality rate than those caught on Japanese tuna hooks and other hook types (Fig. 8B). On-deck mortality increased closer to the equator, approaching 90% in the equatorial region (Fig. 8C). In addition, mortality rose significantly as CHL increased until it approached 100% above 0.25 mg/m^3 (Fig. 8D). Mortality of Indo-Pacific sailfish also tended to increase as the operational area moved eastward (Fig. 8E), but the effect was not statistically significant (Table 3).

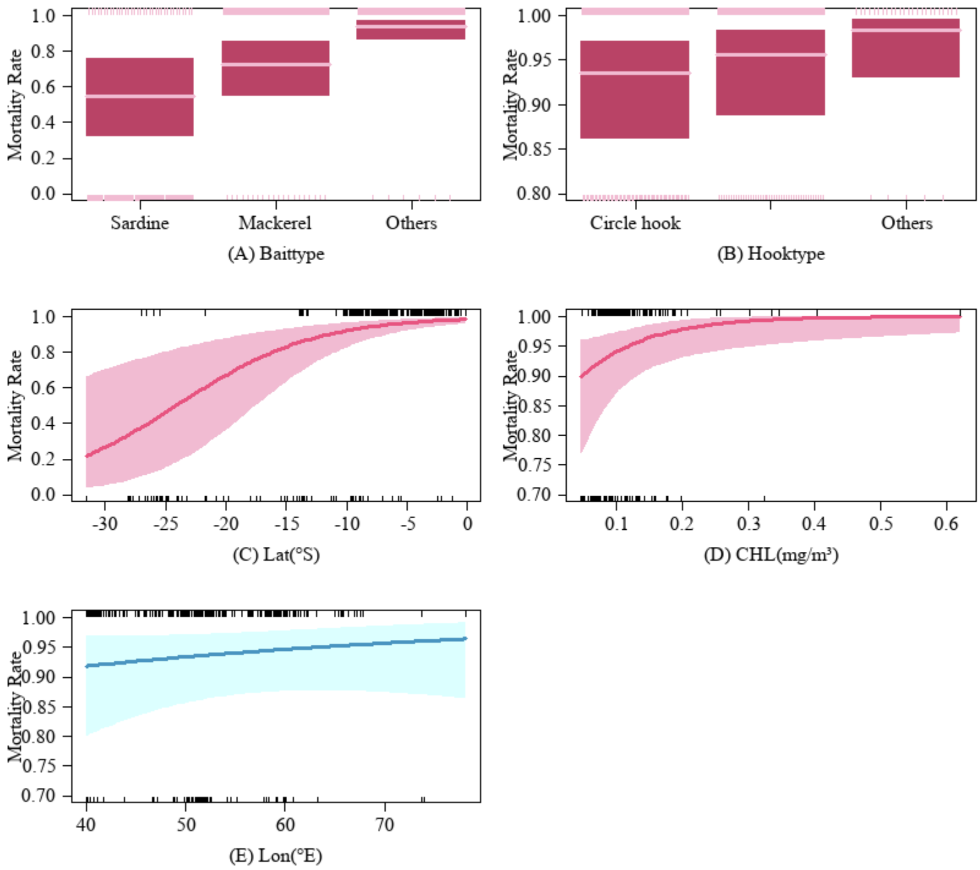

Figure 8 Effects of different explanatory variables on on-deck mortality of Indo-Pacific sailfish in the Western Indian Ocean.(The solid line indicates the change in predicted condition with each explanatory variable, the shaded area indicates the 95% confidence interval of the variable; The short lines at the top and bottom of the figure indicate the numbers of fish that died and survived under that explanatory variable; Lon is longitude; Lat is latitude; CHL is the mass concentration of chlorophyll a.)

4. Discussion

Although there have been a large number of studies on catch on-deck mortality in tuna longline fisheries, systematic research on billfish, particularly regarding their on-deck condition, remains scarce. Such information is essential for scientifically understanding safe release practices for non-target species. It contributes to enhancing the effectiveness of release strategies and informs the development of more precise management measures. Therefore, by not only evaluating the on-deck mortality of Indo-Pacific Sailfish, but also quantitatively analyzing individual on-deck conditions and their contributing factors, this study addresses fundamental knowledge gaps in this field.

4.1 Factors affecting the on-deck condition of Indo-Pacific sailfish

In this study, bait type was identified as the most critical factor influencing the on-deck condition of Indo-Pacific sailfish in the Indian Ocean. Results showed that individuals caught using sardines as bait had significantly better condition compared to those caught with mackerel or other bait types (Fig. 7A). This difference may be attributed to the smaller size and softer texture of sardines, which likely facilitate gentler biting behavior by Indo-Pacific sailfish during feeding, resulting in outer hook location and lower struggle intensity (Moore et al., 2024; Santos et al., 2024). A comparable effect has been observed in studies of sea turtles, where the use of finfish as bait proved more effective at reducing bycatch than squid (Gilman and Huang, 2017).

Latitude of capture was identified as a secondary influential factor. The closer to the equator, the smaller the proportion of Indo-Pacific sailfish in good condition and the greater the proportion and probability of mortality (Fig. 4B and 6A). This pattern may reflect the strong correlation between latitude and water temperature ($r = 0.87$, Fig. 5), with temperatures rising closer to the equator. Water temperature may be directly related to physiological constraints on fish (Muoneke et al., 1994). As warmer waters hold less dissolved oxygen, thereby increasing respiratory demand for fish, the lack of dissolved oxygen availability limits metabolic activity (Bartholomew and Bohnsack, 2005; Rubalcaba et al., 2020) and reduces the ability of captured individuals to recover (Guida et al., 2016). Also, injured individuals are more vulnerable to infections in warm waters (Muoneke, 1992).

In this study, CHL was found to be positively correlated with the on-deck mortality of Indo-Pacific sailfish (Fig. 6B), a result consistent with findings by Li et al. (2024) regarding the mortality of striped marlin (*Tetrapturus audax*) in the Western Indian Ocean. As typical visual predators, billfish forage less efficiently in environments with higher CHL and more turbid waters (Sippel et al., 2007). As a result, their feeding in such conditions may not sufficiently meet their higher metabolic demands (Hyde et al., 2006), which in turn affects individual condition, leading to poor on-deck condition and an increased mortality risk (Li et al., 2024). Given that Indo-Pacific sailfish inhabit shallower waters compared to striped marlin (Domeier et al., 2003; Mourato et al., 2014), the influence of changes in surface CHL may be more pronounced, elevating the relative importance of this environmental factor.

In terms of hook type, Indo-Pacific sailfish caught with circle hooks were in significantly better condition than those captured using Japanese tuna hooks (Fig. 7B). For billfish, the use of circle hooks generally improves survival rates during capture (Serafy et al., 2009), a pattern demonstrated in both recreational fisheries (Prince et al., 2002; Horodysky and Graves., 2005) and commercial longline fisheries (Guo et al., 2022; Li et al., 2024). This result may be attributed to the desire of the circle hook that its tip curves inwards perpendicular to the shank and usually hooks into the mouth or jaw of the catch (Ward et al., 2009), reducing the likelihood of fatal injuries. In contrast, Japanese tuna hooks with tips aligned parallel to the shank, are more prone to snag deeper (e.g. in the stomach and throat), leading to severe hemorrhaging (Cooke and Suski, 2004; Kerstetter and Graves, 2006), internal organ damage and consequently poorer condition of the catch.

4.2 Comparison of factors affecting the condition of Indo-Pacific sailfish and mortality

The effects of biotic and abiotic factors on marine species are complex, with overlapping influences on both individual condition and mortality (Santos et al., 2024). In this study, bait type, hook type, CHL and latitude were found to significantly affect the deck condition and mortality of Indo-Pacific sailfish, while longitude had a significant effect only on on-deck condition. Given that on-deck condition and mortality were driven by similar factors in this study, it is plausible that the influencing factors identified in studies focusing solely on-deck mortality may also affect an individual's on-deck condition.

Individual on-deck condition reflects not only the immediate physiological response to fishing stress, but also largely determines their likelihood of survival after release. It serves as a key reference point for assessing the feasibility of releases practices, for how to assess and optimize release conditions (Butcher et al., 2015). In the study, bait type, hook type, and CHL showed trend-consistent effects on on-deck condition and mortality. However, mortality only reflects the life-and-death state of an individual at the completion of fishing operations, whereas on-deck condition provides information on the intermediate stages of physiological changes experienced by an individual during the course of a capture stress (Skomal et al., 2010). In terms of bait type, for example, using sardines as bait significantly reduced mortality and increased the proportion of individuals classified as A1 and A2, suggesting that sardines may help mitigate physiological damage and stress during capture. Hook type also showed a consistent trend, with circle hooks significantly increasing the proportion of healthy individuals. These results suggest that condition rating offer a more informative indicator for post-release survival potential than a mortality indicator alone, thereby providing a key basis for improving gear setups, optimizing release strategies and enhancing release effectiveness.

4.3 Implications for management practice

Currently, management measures for Indian Ocean billfish include a minimum conservation size requirement, whereby fishing vessels are required to immediately release individuals with a LJFL of less than 60 cm (IOTC, 2018). However, there is a lack of a dynamic assessment mechanism for physiological condition of individuals, operational conditions, or spatial variability, leading to a high degree of uncertainty regarding the effectiveness of such release practices (Patterson et al., 2014). Therefore, developing region-specific, differentiated, and practically implementable release guidelines is essential to advance precision fisheries management.

To enhance the scientific validity and effectiveness of billfish release strategies, future management measures can be optimized in two key directions. First, in tropical low-latitude regions, particularly near the equator, the mortality rate of Indo-Pacific sailfish exhibits significantly elevated mortality rates, with individuals predominantly in condition A3 or D. Under such circumstances, release operations are unlikely to yield substantial survival outcomes. Thus, efforts should be concentrated on waters where individuals are more likely to be in good condition (e.g., high proportions of A1 and A2) in order to improve overall release survival. For operational areas with higher mortality risks, technical operational improvements should be promoted, such as the use of smaller baits (e.g. sardines) and circle hooks, to reduce individual stress and hook-related injuries. These strategies can increase the proportion of individuals captured in healthier states (A1 or A2), thereby enhancing the effectiveness of releases from the source.

4.4 Future work

This study evaluated multiple critical factors influencing the on-deck condition and mortality of Indo-Pacific sailfish. Compared to mortality-only assessments, implementing a multilevel assessment of on-deck condition provides more comprehensive insights into the physiological stress responses of individuals during capture operations. This approach offers a scientifically actionable foundations for developing ecologically sustainable fishing practices and safe release strategies for billfish. Nevertheless, translating these research findings into effective management measures presents several challenges. First, current classification of on-deck condition primarily relies on observers' subjective assessments, which may introduce human bias. It is therefore recommended that future efforts develop a more standardized classification incorporating objective assessment metrics, such as abdominal distension, visceral hooking, gill hemorrhage, mobility (Tracey et al., 2023); Secondly, as a highly migratory species, billfish condition is influenced by a complex interplay of biotic and abiotic factors, and tolerance to external stresses may vary among different life-history stages. Future research should comprehensively incorporate biological characteristics (e.g., sex and sexual maturity status) to refine assessments of their effects on on-deck condition and mortality risk (Hollowed et al., 2013). Furthermore, it is recommended to prioritize investigation of two critical operational parameters: gear soak time and hook deployment depth. Extended gear soak time prolongs individuals' submersion duration, intensifying asphyxiation and physical exertion, which may significantly deteriorate an individual's on-deck condition. Concurrently, hook deployment depth determines species-specific exposure to environmental stressors, where thermocline-associated variations in temperature, dissolved oxygen concentration, and photoperiodic stimuli critically modulate fish stress responses.

Therefore, such spatiotemporally factors should be systematically integrated into future assessment frameworks to enhance the predictive capacity for evaluating fish condition and to provide a scientific basis for fishing gear refinement and release effectiveness optimization.

References

Akaike, H. (1998). Information theory and an extension of the maximum likelihood principle. In *Selected papers of hirotugu akaike* (pp. 199-213). New York, NY: Springer New York.

Bartholomew, A., & Bohnsack, J. A. (2005). A review of catch-and-release angling mortality with implications for no-take reserves. *Reviews in Fish Biology and Fisheries*, *15*, 129-154.

Bowlby, H., Joyce, W., Benoit, H., & Sulikowski, J. (2020). Evaluation of post-release mortality for porbeagle and shortfin mako sharks from the Canadian pelagic longline fishery. *Collect. Vol. Sci. Pap. ICCAT*, *76*(10), 365-373.

Bradley, A. P. (1997). The use of the area under the ROC curve in the evaluation of machine learning algorithms. *Pattern recognition*, *30*(7), 1145-1159.

Butcher, P. A., Peddemors, V. M., Mandelman, J. W., McGrath, S. P., & Cullis, B. R. (2015). At-vessel mortality and blood biochemical status of elasmobranchs caught in an Australian commercial longline fishery. *Global Ecology and Conservation*, *3*, 878-889.

Campana, S. E., Joyce, W., Fowler, M., & Showell, M. (2016). Discards, hooking, and post-release mortality of porbeagle (*Lamna nasus*), shortfin mako (*Isurus oxyrinchus*), and blue shark (*Prionace glauca*) in the Canadian pelagic longline fishery. *ICES Journal of Marine Science*, *73*(2), 520-528.

Coelho, R., Fernandez-Carvalho, J., Lino, P. G., & Santos, M. N. (2012). An overview of the hooking mortality of elasmobranchs caught ina swordfish pelagic longline fishery in the Atlantic Ocean. *Aquatic Living Resources*, *25*(4), 311-319.

Cooke, S. J., & Suski, C. D. (2004). Are circle hooks an effective tool for conserving marine and freshwater recreational catch-and-release fisheries? *Aquatic Conservation: Marine and Freshwater Ecosystems*, *14*(3), 299-326.

Domeier, M. L., Dewar, H., & Nasby-Lucas, N. (2003). Mortality rate of striped marlin (*Tetrapturus audax*) caught with recreational tackle. *Marine and Freshwater Research*, *54*(4), 435-445.

Dormann, C. F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carré, G., ... & Lautenbach, S. (2013). Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. *Ecography*, *36*(1), 27-46.

Epperly, S. P., Watson, J. W., Foster, D. G., & Shah, A. K. (2012). Anatomical hooking location and condition of animals captured with pelagic longlines: the grand banks experiments 2002–2003. *Bulletin of Marine Science*, *88*(3), 513-527.

Fushiki, T. (2011). Estimation of prediction error by using K-fold cross-validation. *Statistics and Computing*, *21*, 137-146.

Gilman, E. L. (2011). Bycatch governance and best practice mitigation technology in global tuna fisheries. *Marine Policy*, *35*(5), 590-609.

Gilman, E., & Huang, H. W. (2017). Review of effects of pelagic longline hook and bait type on sea turtle catch rate, anatomical hooking position and at-vessel mortality rate. *Reviews in Fish Biology and Fisheries*, *27*, 43-52.

Guida, L., Walker, T. I., & Reina, R. D. (2016). Temperature insensitivity and behavioural reduction of the physiological stress response to longline capture by the gummy shark, *Mustelus antarcticus*. *PLoS One*, *11*(2), e0148829.

Guo, Y., Wang, X., Li, X., Wu, F., & Zhu, J. (2022). Analysis of at-haulback mortality and influencing factors of Indian Ocean swordfish (*Xiphias gladius*). *Fishes*, *7*(5), 256.

Gurevitch, J., Koricheva, J., Nakagawa, S., & Stewart, G. (2018). Meta-analysis and the science of research synthesis. *Nature*, *555*(7695), 175-182.

Hammond, T. R., & Trenkel, V. M. (2005). Censored catch data in fisheries stock assessment. *ICES Journal of Marine Science*, *62*(6), 1118-1130.

Hastie, T., & Tibshirani, R. (1986). Generalized additive models. *Statistical science*, *1*(3), 297-310.

Hollowed, A. B., Barange, M., Beamish, R. J., Brander, K., Cochrane, K., Drinkwater, K., ... & Yamanaka, Y. (2013). Projected impacts of climate change on marine fish and fisheries. *ICES Journal of Marine Science*, *70*(5), 1023-1037.

Hyde, J. R., Humphreys, R., Musyl, M., Lynn, E., & Vetter, R. (2006). A central North Pacific spawning ground for striped marlin, *Tetrapturus audax*. *Bulletin of Marine Science*, *79*(3), 683-690.

IOTC Secretariat. (2024). Review of the statistical data available for Indian Ocean Indo-Pacific sailfish (1950-2022). IOTC-2024-WPB22-INF08-SFA[e].

IOTC. (2018). Resolution 18/05 on management measures for the conservation of the billfishes: striped marlin, black marlin, blue marlin and Indo-Pacific sailfish.

Kerstetter, D. W., & Graves, J. E. (2006). Effects of circle versus J-style hooks on target and non-target species in a pelagic longline fishery. *Fisheries research*, *80*(2-3), 239-250.

Li, X., Wang, X., Guo, Y., Wu, F., & Zhu, J. (2024). Factors influencing the at-haulback mortality of striped marlin *Tetrapturus audax* caught by tuna longline fishery in the Western Indian Ocean. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *34*(4), e4135.

Marshall, H., Skomal, G., Ross, P. G., & Bernal, D. (2015). At-vessel and post-release mortality of the dusky (*Carcharhinus obscurus*) and sandbar (*C. plumbeus*) sharks after longline capture. *Fisheries Research*, *172*, 373-384.

Melvin, E. F., Guy, T. J., & Read, L. B. (2014). Best practice seabird bycatch mitigation for pelagic longline fisheries targeting tuna and related species. *Fisheries Research*, *149*, 5-18.

Moore, B.R.; Finucci, B. (2024). Estimation of release survival of pelagic sharks and fish in New Zealand commercial fisheries. New Zealand Fisheries Assessment Report 2024/07. 129 p.

Mourato, B. L., Carvalho, F., Musyl, M., Amorim, A., Pacheco, J. C., Hazin, H., & Hazin, F. (2014). Short-term movements and habitat preferences of sailfish, *Istiophorus platypterus* (*Istiophoridae*), along the southeast coast of Brazil. *Neotropical Ichthyology*, *12*, 861-870.

Muoneke, M. I. (1992). Seasonal hooking mortality of bluegills caught on natural baits. *North American Journal of Fisheries Management*, *12*(3), 645-649.

Muoneke, M. I., & Childress, W. M. (1994). Hooking mortality: a review for recreational fisheries. *Reviews in Fisheries Science*, *2*(2), 123-156.

Musyl, M. K., & Gilman, E. L. (2019). Meta-analysis of post-release fishing mortality in apex predatory pelagic sharks and white marlin. *Fish and Fisheries*, *20*(3), 466-500.

Musyl, M. K., Moyes, C. D., Brill, R. W., Mourato, B. L., West, A., McNaughton, L. M., ... & Sun, C. L. (2015). Postrelease mortality in *istiophorid* billfish. *Canadian Journal of Fisheries and Aquatic Sciences*, *72*(4), 538-556.

Nakamura, I. (1983). Systematics of the billfishes (*Xiphiidae* and *Istiophoridae*). *Publications of the Seto Marine Biological Laboratory*, *28*(5-6), 255-396.

Parker, D., Espittia, J. (2022). Alternative methods to assess the data-limited Indo-Pacific sailfish (*Istiophorus platypterus*) stock. IOTC-2022-WPB20-15.

Patterson, H., Hansen, S., & Larcombe, J. (2014). A review of shark bycatch mitigation in tuna longline fisheries. *WCPFC Scientific Committee tenth regular session*.

Plumb, J. A., Grizzle, J. M., & Rogers, W. A. (1988). Survival of caught and released largemouth bass after containment in live wells. *North American Journal of Fisheries Management*, *8*(3), 325-328.

Prince ED, Ortiz M, Venizelos A. (2002). A comparison of circle hook and “J” hook performance in recreational catch-and-release fisheries for billfish. AFS Symposium 30, Bethesda, Maryland. p. 66–79.

Reinhardt, J. F., Weaver, J., Latham, P. J., Dell'Apa, A., Serafy, J. E., Browder, J. A., ... & Blankinship, D. R. (2018). Catch rate and at-vessel mortality of circle hooks versus J-hooks in pelagic longline fisheries: A global meta-analysis. *Fish and Fisheries*, *19*(3), 413-430.

Rubalcaba, J. G., Verberk, W. C., Hendriks, A. J., Saris, B., & Woods, H. A. (2020). Oxygen limitation may affect the temperature and size dependence of metabolism in aquatic ectotherms. *Proceedings of the National Academy of Sciences*, *117*(50), 31963-31968.

Santos, C. C., Santos, M. N., Rosa, D., & Coelho, R. (2024). Leader material and bait effects on target and bycatch species caught in an Atlantic Ocean pelagic longline fishery. *Fisheries Research*, *278*, 107093.

Serafy, J. E., Kerstetter, D. W., & Rice, P. H. (2009). Can circle hook use benefit billfishes? *Fish and Fisheries*, *10*(2), 132-142.

Sippel, T. J., Davie, P. S., Holdsworth, J. C., & Block, B. A. (2007). Striped marlin (*Tetrapturus audax*) movements and habitat utilization during a summer and autumn in the Southwest Pacific Ocean. *Fisheries Oceanography*, *16*(5), 459-472.

Skomal, G., & Bernal, D. (2010). Physiological responses to stress in sharks. In *Sharks and their relatives II* (pp. 475-506). CRC Press.

Tracey, S. R., Wolfe, B. W., Hartmann, K., Pepperell, J., & Williams, S. M. (2023). Movement behavior of swordfish provisions connectivity between the temperate and tropical southwest Pacific Ocean. *Scientific Reports*, *13*(1), 11812.

Ward, P., Epe, S., Kreutz, D., Lawrence, E., Robins, C., & Sands, A. (2009). The effects of circle hooks on bycatch and target catches in Australia's pelagic longline fishery. *Fisheries Research*, *97*(3), 253-262.

Yan, H., Zhou, C., Gilman, E., Cao, J., Wan, R., Zhang, F., ... & Tian, S. (2025). A Meta-analysis of bycatch mitigation methods for sea turtles vulnerable to swordfish and tuna longline fisheries. *Fish and Fisheries*, *26*(1), 45-64.