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# IDENTIFYING RISK FACTORS IN LEATHERBACK BYCATCH IN HAWAII'S DEEP-SET LONGLINE FISHERY

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# Executive Summary

Sea turtle bycatch mitigation regulations were established in 2004 for Hawaiʻi's longline fisheries with a focus on shallow-setting gear, requiring the use of finfish bait (vs. squid) and 18/0 circle hooks (offset ≤ 10°), among other measures, to decrease interactions with leatherback (*Dermochelys coriacea*) and loggerhead (*Caretta caretta*) turtles. Shallow-set gear targeting swordfish (*Xiphias gladius*) had a significantly higher bycatch per unit of effort compared to deep-set tuna-targeting gear and thus management efforts requiring mitigation measures were initially limited to the shallow-set sector. Analyses of the efficacy of these measures have indicated these mitigation measures significantly reduced sea turtle interactions. However, the proportion of shallow-set effort relative to total longline effort in the Pacific (including Hawaii) is currently relatively low (< 3%), and mitigation measures applied to the deep-set longline have never been evaluated.

An analysis of measures' efficacy in deep-set longline gear is warranted as leatherback interactions within this fishery are three times more likely to be fatal and the total interactions are estimated to be 6.5 times higher than those in shallow-set operations. Entanglement in the deep-set gear at deeper depths increases the risk of asphyxiation and is likely the cause of the higher mortality rate. Deep-setting vessels fish with a mean of 25 hooks between floats and generally between 100-400 m depth. Since 2004, Hawaii deep-setting vessels have used a combination of circle and tuna hooks. In 2012, hooks were restricted to weak (wire diameter < 4.5 mm), offset (≤ 10°) circle hooks 16/0 or smaller to minimize false killer whale (*Pseudorca crassidens*) injuries. Since 2022, the fishery banned wire leaders and switched entirely to monofilament leaders to reduce oceanic whitetip shark *(Carcharhinus longimanus)* retention. Bait types have varied among sardine, mackerel, milkfish, saury, and squid and bait choice is often determined by availability and price. Predominant bait types have been primarily milkfish (*Chanos chanos*) in the last five years. While some existing mitigation measures (e.g., circle hooks) are expected to reduce bycatch of protected species (e.g., false killer whales, oceanic whitetip sharks, and hard-shell sea turtles), the effectiveness of the suite of mitigation measures for reducing leatherback bycatch in the deep-set fishery has not been investigated.

Our analysis uses human observer data collected by the Pacific Island Regional Observer Program for the period 2005-2024, when the fishery was mandated to have observer coverage for ~20% of Hawaii deep-set longline trips. Herein we provide summary statistics demonstrating the nature of leatherback interactions, specifically the variables (eg., SST, hook depth) associated with interactions as well as types of interaction (eg., hooked or entangled). As these events are statistically rare, we applied ensemble random forest models to identify oceanographic and operational covariates that are associated with increases or decreases in bycatch risk for leatherback sea turtles in the Hawaiʻi deep-set longline fishery. We then assess the change in risk associated with changes in gear requirements over time (circle hooks and monofilament leader).

During the Informal Intersessional Working Group to Review the Conservation and Management Measure (2018-04) for sea turtles (CMM 2018-04 Review Report), participants supported a U.S. request for access to WCPFC Regional Observer Programme (ROP) data to undertake an analysis of WCPFC sea turtle interaction data. In an effort to provide more comprehensive coverage and analyses of leatherback bycatch interactions we extended this work to include additional data from the WCPFC convention area. The preliminary analysis presented here lays the foundation for expanding the work to incorporate ROP data in future analyses, thereby enabling the identification of oceanographic and operational factors associated with leatherback turtle bycatch across the WCPFC convention area using combined observer datasets.

# Contents

# 1. Introduction

Pacific sea turtle populations are vulnerable to extinction, and bycatch in longline fisheries in the Western and Central Pacific Ocean (WCPO) is identified as one of the main threats (Wallace et al. 2013; Pilcher 2026). West Pacific Leatherback sea turtles (*Demorchelys coriacea)* are assessed as Critically Endangered by IUCN (Tiwari et al. 2013). In the WCPO, mitigation is currently mandated only for shallow-set longline gear, despite deep-set longline effort contributing to ~85% of total longline fishing effort (Peatman and Nicol 2026).

There is a strong need to clarify effective bycatch mitigation measures for leatherbacks, as their primary interaction mechanism differs from that of other sea turtles: entanglement or external hooking rather than mouth hooking (Watson et al. 2005; Coelho et al. 2015; Okamoto et al. 2026). This analysis uses U.S. observer data from the Hawaii deep-set longline (DSLL) from 2005 to 2024 to assess potential drivers of leatherback bycatch. The first objective is to predict bycatch hotspots based on the oceanographic conditions. The second objective is to predict bycatch risk in a more comprehensive framework by incorporating gear covariates, current and eddy dynamics, habitat features, and particular operational characteristics that could influence the interaction (e.g., hook type/size, bait type, and leader material).

This type of analysis could be applied to the broader leatherback bycatch in the WCPO region, provided certain data fields are completed. It also highlights the data fields needed for such an analysis. A joint analysis of WCPFC Regional Observer Programme sea turtle interaction data could strengthen CMM 2018-04.

## 2.1 Fishery

The DSLL fleet is primarily based out of Honolulu, Hawaii, U.S.A. and targets bigeye and yellowfin tuna (*Thunnus obesus* and *T. albacares*). To ensure that hooks are not set shallow, the deepest point between any two float lines is required to be at least 100 m with ≥ 15 branchlines deployed between any two floats, and all float lines ≥ 20 m long (66 FR 31561). It operates year-round to depths of up to 400 m. The DSLL accounts for 97.5% of total longline effort in HI (per number of hooks set) (WPRFMC, 2023).

### 2.1.1 Sea turtle regulations

Beginning in 2001, sea turtle handling and resuscitation measures were mandated, and all vessel operators must attend annual protected species workshops conducted by NMFS (66 FR 31561). Effective Dec 15 2005, operators of DSLL vessels were required to carry and use specific mitigation gear to aid the release of sea turtles accidentally hooked or entangled (70 FR 69282).

Several gear modifications with potential bycatch implications were introduced over the following years. Effective Nov 29 2012, DSLL vessels were required to use “weak” circle hooks sized ≤ 16/0, ≤ 4.5 mm wire diameter and offset ≤ 10° to minimize post-release mortality of false killer whales (50 CFR § 229.37). Effective May 31 2022, the use of wire leaders was prohibited in the DSLL fishery to improve post-hooking survival rates of oceanic whitetip sharks (87 FR 25153); the fleet subsequently used monofilament leaders.

## 2.2 Observer data

NOAA Fisheries Pacific Islands Fisheries Regional Office maintains the Pacific Islands Regional Observer Program (PIROP), which oversees data on target catch and bycatch collected from observers on fishing vessels. Analysis was limited to Hawaii-permitted pelagic longline vessels from 2005-2024, during which annual observer coverage was ~20% but declined to 17.4% in 2023 and 13.4% in 2024 for DSLL (NMFS, 2025).

In addition to a suite of data reporting requirements, observers record longline gear configuration. If a turtle becomes hooked or entangled in longline gear, observers record the species; the hook number on the line (relative to the float); the location of entanglement or hooking (e.g., flipper, carapace, ingested); the hook type/size when possible; gear remaining on the turtle prior to release; and the turtle’s disposition outcome (e.g., released alive with an injury or dead at-vessel). If possible, the approximate straight carapace length (SCL) was also estimated.

### 2.2.1 Summary statistics

#### *2.2.1.1. Catenary hook depth*

Hook depth was estimated for each observed interaction following Bigelow et al (2006; Eq. 3). The depth of catenary hook $j$ ($D_j$) was calculated as:

$$D_j = h_a + h_b + 0.5L \times \left\{ \left(1 + cot^2\varphi\right)^{1/2} - \left[\left(1 - \frac{2j}{N}\right)^2 + cot^2\varphi\right]^{1/2} \right\}$$

where $D_j$ is the depth of catenary hook $j$, $h_a$ is the length of the branchline, $h_b$ is the length of the floatline, $j$ is the number of the catenary hook midway between floats, and $N$ is the number of hooks between floats plus one (HBF + 1). The stretched mainline length between consecutive floats ($L$) was derived by dividing the total mainline length by the number of float intervals (number of floats − 1).

Branchline length, floatline length, number of floats, hook number, and hooks per float were obtained directly from observer records for each set. Total mainline length and catenary angle ($\varphi$) were not recorded in the observer data and were therefore assigned fleet-specific mean values from Bigelow et al. (2006): mainline length of 64.4 km and catenary angle of 62.0°.

## 2.3 Oceanographic data

Twenty-three oceanographic variables were extracted for each fishing set from the observer data (Table 1), encompassing the temporally dynamic conditions (lunar phase), spatiotemporally dynamic attributes (e.g., sea surface temperature (SST), sea surface height (SSH), ocean currents and winds, chlorophyll-a concentrations) and static features (distance to seamount).

**Table 1**. Environmental covariates included in the (1) oceanographic-only ERF model and (2) Principal Component Analyses for the operational ERF model.

| Covariate category | Covariate | Definition | Spatial resolution | Temporal resolution | Citation |
|---|---|---|---|---|---|
| Temporal | Moon phase | continuous, circular lunar phase bounded between 0 and 2pi radians provided by the lunar package in R | 0.04 ° | 1 day | Lazaridis 2014 |
| SST Attributes | SST | sea surface temperature | 4 km | 8 days | OceanWatch-ERDDAP |
| | SST anomaly | sea surface temperature anomaly | 4 km | 8 days | OceanWatch-ERDDAP |
| | SST front | strength of the SST front | | | Derived |
| | SST distance to front (S.E.S.) | S.E.S. distance to the nearest SST front | | | Derived |
| Chlorophyll Attributes | Chla | chlorophyll-a concentration | 4 km | 8 days | ESA OC OCCI |
| Ocean Current Attributes | Current speed (zonal) | zonal current speed (W-E) | 0.33 ° | 5 days | PO.DAAC-JPL |
| | Current speed (meridional) | meridional current speed (N-S) | 0.33 ° | 5 days | PO.DAAC-JPL |
| | Current front | strength of the current front | 0.33 ° | 5 days | Derived |
| | Current divergence | current divergence | 0.33 ° | 5 days | Derived |
| | Distance to current front (S.E.S.) | S.E.S. distance to nearest current front | 0.33 ° | 5 days | Derived |
| | Current vorticity | current vorticity | 0.33 ° | 5 days | Derived |
| Sea Surface Height Attributes | SLA | sea level anomaly | 0.17 ° | 5 days | PO.DAAC-JPL |
| | Okubo Weiss | Okubo Weiss value | 0.17 ° | 5 days | Derived |
| | EKE | eddy kinetic energy | 0.17 ° | 5 days | Derived |
| Sea Wind Attributes | Mean wind (zonal) | mean zonal wind speed across 6 h intervals of set soak (W-E) | 0.25 ° | 1 day | NOAA NCEI |
| | Mean wind (meridional) | mean meridional wind speed across 6 h intervals of set soak (N-S) | 0.25 ° | 1 day | NOAA NCEI |

| | | | | | |
|---|---|---|---|---|---|
| | Mean wind front | mean wind front across 6 h intervals of set soak | 0.25 ° | 1 day | NOAA NCEI |
| | Mean wind divergence | mean wind divergence across 6 h intervals of set soak | 0.25 ° | 1 day | Derived |
| | Mean wind vorticity | mean vorticity across 6 h intervals of set soak | 0.25 ° | 1 day | Derived |
| | Mean Ekman pumping velocity | mean Ekman pumping velocity across 6 h intervals of set soak | 0.25 ° | 1 day | Derived |
| Static Attributes | Bathymetry | depth of seafloor below set | 0.0083 ° | - | GEBCO |
| | Distance to seamount (S.E.S.) | the S.E.S of the shortest distance to the top of the nearest seamount from a given set | 0.0083 ° | - | Yesson et al. 2011 |

Lazaridis E (2022). lunar: Lunar Phase & Distance, Seasons and Other Environmental Factors. (Version 0.2-01).
European Space Agency Ocean Colour Climate Change Initiative dataset, Version 5.0, European Space Agency, available online at http://www.esa-oceancolour-cci.org/
ESR. 2009. OSCAR third deg. Ver. 1. PO.DAAC, CA, USA. Dataset accessed 2021-10-12 at https://doi.org/10.5067/OSCAR-03D01
https://podaac.jpl.nasa.gov/dataset/SEA_SURFACE_HEIGHT_ALT_GRIDS_L4_2SATS_5DAY_6THDEG_V_JPL1609
https://www.ncei.noaa.gov/thredds/catalog/uv/daily/2000s/catalog.html
https://www.gebco.net/data_and_products/gridded_bathymetry_data/
Yesson C, Clark MR, Taylor ML, Rogers AD (2011) The global distribution of seamounts based on 30 arc seconds bathymetry data. Deep Sea Research Part I: Oceanographic Research Papers 58:442–453.

## 2.4 Oceanographic-only ensemble random forest model

We used ensemble random forests (ERFs) to model leatherback bycatch risk. Ensemble random forests are a machine learning approach that are an extension of random forest (RF) decision trees (Siders et al. 2020). Each RF receives mutually exclusive random subsets of the data: one to grow the decision trees (training set) and a second to conduct internal validation (test set). These datasets are created by stratified random draws with replacement from the total dataset to generate training and test datasets with class proportions close to those of the total dataset. Each RF grows a decision tree on a subset of its training set and holds out some data to internally measure its prediction error. When growing decision trees, each RF uses a balanced weighting scheme (i.e., equal class proportions) to reduce bias introduced by class imbalance. Each RF then predicts on the test dataset to generate individual RF performance metrics, and on the full dataset. The predictions of each RF on the full dataset are then averaged to form the ERF predictions. This down-sampling makes ERFs particularly adept at learning and predicting rare events, such as protected species bycatch.

We first modeled the probability of interaction for leatherback sea turtles using an ERF model with only oceanographic covariates (Table 1). This model serves as the baseline predictive model for leatherback bycatch, excluding gear or operational characteristics (e.g., number of hooks, leader material, hook type, bait type). We fit the ERF model using 200 random forests, each with 1000 decision trees, trying 5 covariates at each node. To evaluate model performance, we calculated threshold-independent metrics for training and test datasets, including area under the curve (AUC), root mean squared error (RMSE), and true skill statistic (TSS) (Long et al. 2024). AUC refers to the receiver operating curve plotting 1 - specificity against sensitivity at thresholds ranging from 0 to 1. AUC values range from 0 to 1, with values above 0.5 indicating a model performs better than random. Second, we used root mean square error (RMSE), calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(y_i - \hat{y}_i\right)^2}{N}}$$

Where $\hat{y}_i$ is the model prediction for a set, $y_i$ is the true value, and $N$ is the total number of sets. Finally, we used the True Skill Statistic, the maximum of the sum of the true positive rate (TPR) and true negative rate (TNR) minus 1:

$$TSS = max(TPR + TNR - 1)$$

We also calculated the variable of importance using mean decrease in accuracy and accumulated local effects, which measure the change in the model's predicted probability of a return state for a given covariate.

## 2.5 Operational ensemble random forest model

### 2.5.1 Gear PCoA

Longline gear configuration varies across sets. Recorded longline gear configuration includes the number of hooks and floats, drop weight size, and the lengths of the float line, branchline, and leader. We summarized gear configurations using Principal Coordinates Analysis (PCoA). Because PCoA requires a dissimilarity matrix, and computing this matrix at the scale of our dataset was computationally expensive, we first grouped sets into discrete gear-configuration clusters. We tested the number of clusters ranging from 20 to 1000 and found that the ratio of between-cluster sum of squares to the total sum of squares reached an asymptote around 500 clusters. Cluster-level gear characteristics were then used to compute a Gower dissimilarity matrix for PCoA. We retained the first two PCos out of 123 which accounted for more than 50% of the total variance in the gear configuration cluster means. We then assigned each set the PCo scores of its corresponding cluster, yielding a reduced set of orthogonal gear covariates for inclusion in the ERF model. Hook type/size, leader material, and bait type are also recorded but were excluded from the PCoA to isolate their effects.

### 2.5.2 Oceanographic PCA's

To isolate the effects of lunar phase and operational characteristics, we decomposed the two sets of environmental covariates by conducting Principal Component Analyses (PCA) 1) current and eddy dynamics (i.e., east current speed, north current speed, current front, eddy kinetic energy, current divergence and vorticity, distance to current front, sea level anomaly, and Okubo-Weiss) and 2) habitat environmental features (i.e., SST, SST anomaly, SST front, distance to SST front S.E.S., chlorophyll-a, bathymetry, and distance to seamount S.E.S.). For both, we included their principal component (PC) scores (PC1-PC3) in the operational ERF model. Prior to each PCA, all environmental variables were transformed using bestNormalize (Peterson, 2021).

### 2.5.3 Operational ensemble random forest and output

We again modeled the probability of interaction for leatherback sea turtles using an ERF but to focus on operational characteristics, covariates were reduced to gear PCo1-2, current and eddy dynamic PC1-3, and habitat environmental feature PC1-3. Other covariates included leader material (monofilament or wire), hook type (offset circle hook 14/0, 15/0, 16/0, or 18/0; offset tuna hook 3.6 mm or 3.8 mm; or other), bait type (saury, sardine, milkfish, mackerel, herring, mixed bait, or other), and lunar phase. We fit the ERF model using 200 random forests, each with 1000 decision trees, trying 5 covariates at each node. Performance was evaluated as described above (2.4). Raw accumulated local effects for the categorical predictors (hook type/size, bait type, and leader material) were extracted from the fitted random forest model and weighted by proportional representation in the data.

### 2.5.4 Thresholds

Predicted interaction probabilities from the ERF model were converted to binary classifications (interaction vs. no interaction) using a threshold selected using the maximum sensitivity plus specificity (MSS) criterion. This approach is commonly used in species distribution modeling to convert continuous habitat suitability or occurrence probabilities into binary presence/absence classifications (Liu et al. 2013, 2016; Long et al. 2024).

# 3. Results

## 3.1 Fishery operations

The DSLL fishery shifted from primarily using tuna hooks to circle hooks gradually from 2006 and fully transitioned in 2012 (Fig. 1). Since 2013, offset 15/0 circle hooks were the dominant hook type, followed by 14/0 and 16/0 (Fig. 1). Leader material was predominantly wire until 2021 (Fig. 2). Bait type was primarily saury/sanma 2004-2020, with occasional use of sardine in the earlier years (Fig. 3). In 2021, milkfish or mixed bait became the dominant bait types used. Mixed bait can include any finfish and/or squid (Fig. 3).

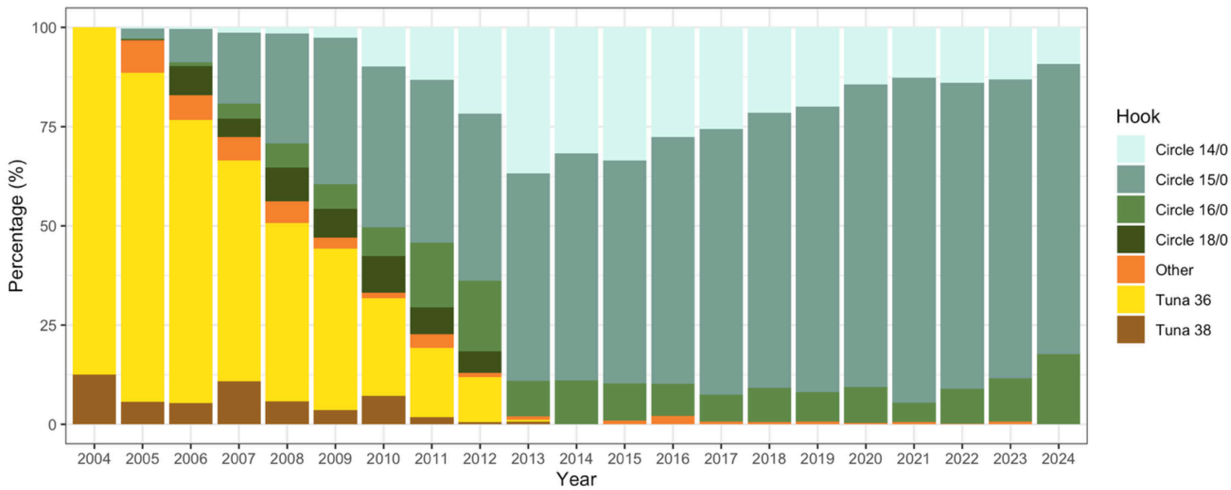



**Figure 1.** Percent hook type/size used in Hawaii DSLL sets from 2004-2024. Circle hooks are offset ≤10°.

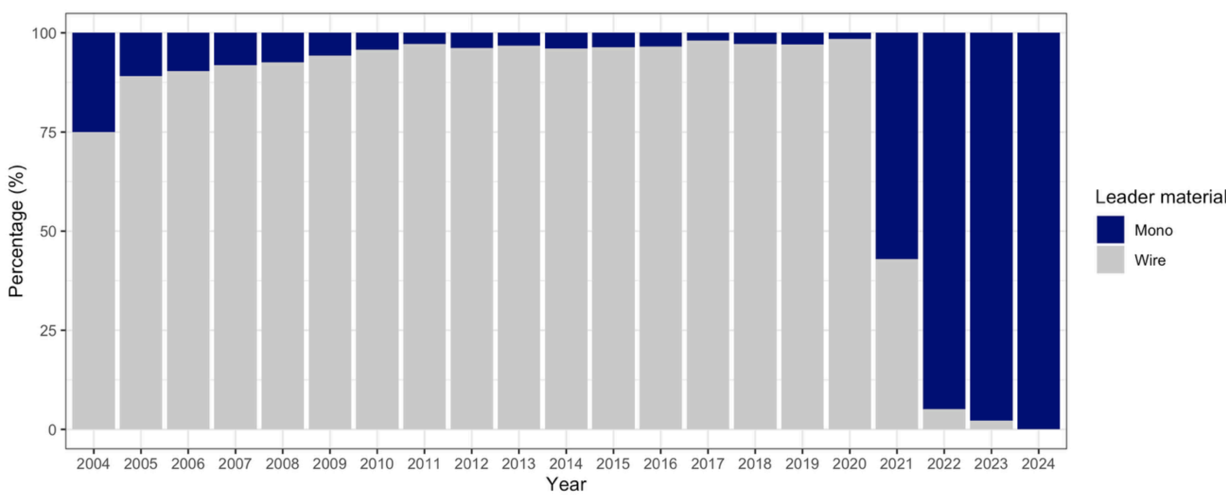



**Figure 2.** Percent leader material used in Hawaii DSLL sets from 2004-2024.


**Figure 3.** Percent bait used in Hawaii DSLL sets from 2004-2024. Mixed bait can include any finfish and/or squid.

## 3.2 Leatherback bycatch

Out of 76,155 DSLL sets from 2005-2024, vessels interacted with 57 leatherback turtles. With regards to disposition of animals upon retrieval, 13 (23%) were dead at-vessel and 44 were released alive (Table 2). Interactions predominantly occurred from external hooking and/or entanglement (82%, n = 40; Fig. 4). Only 12% of turtles were hooked in the mouth, and no turtles ingested hooks (Fig. 4). Interactions occurred across the hook positions, including at the shallowest (~50 m) and deepest (~250 m) hooks (Fig. 5). Interactions were slightly more frequent in the hooks with longer soak times (deployed earlier, retrieved later; Fig. 5). Observed mortalities were independent of hook depth (Fig. 5).

**Table 2.** Disposition of leatherback sea turtles in the Hawaii DSLL by number of individuals from 2005 to 2024.

| **Observed disposition** | **Number leatherbacks** |
|---|---|
| Released | 44 |
| At-vessel mortality | 13 |
| Total | 57 |

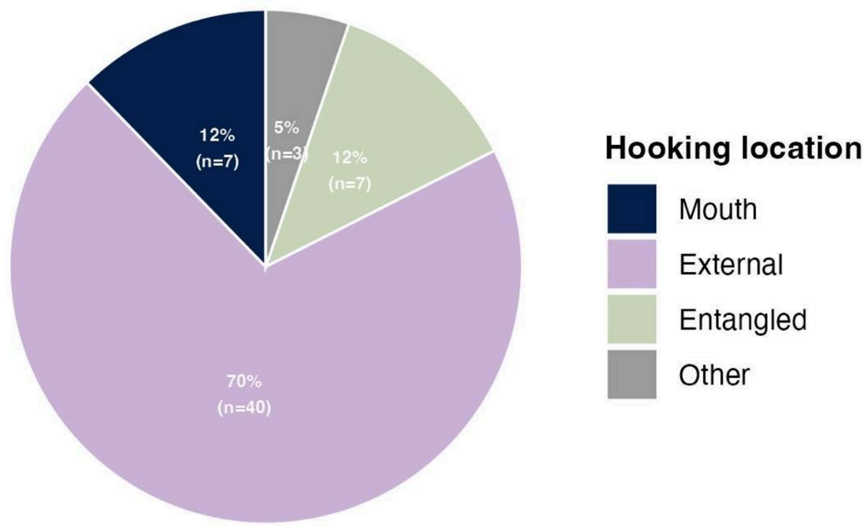



**Figure 4.** Hooking location of leatherback sea turtles in the DSLL by percent and number of individuals. External hooks include hooking by the flipper or carapace. Entangled category represents entanglements only (no hooking). Out of the 57 interactions, no hooks were ingested.

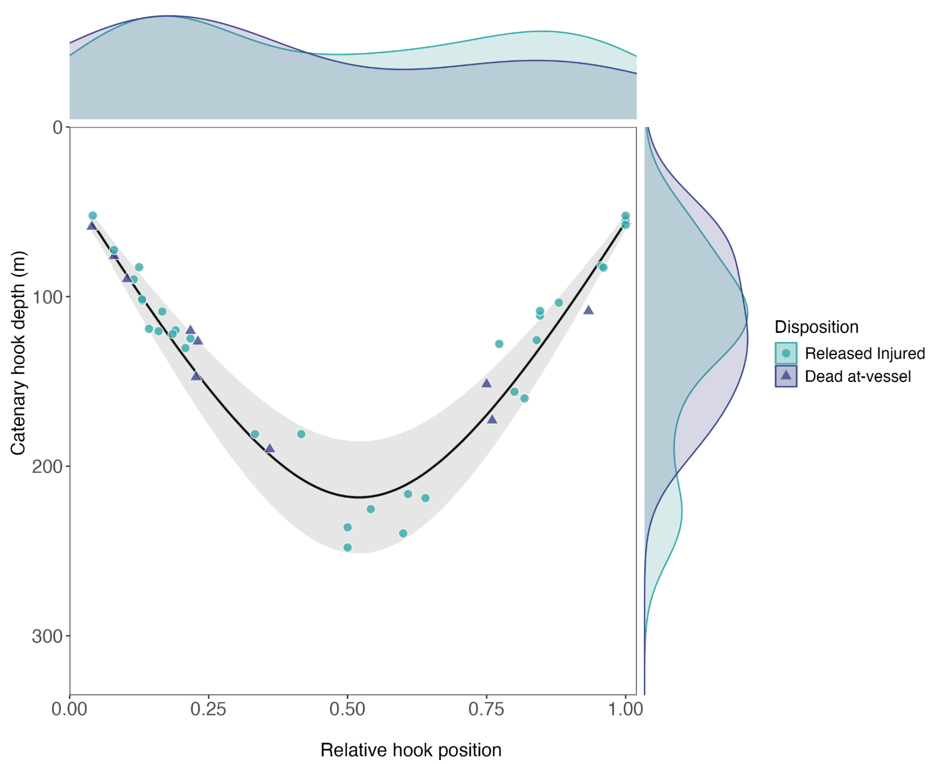



**Figure 5.** Catenary hook depth of turtle interaction for injured (turquoise circle) and dead at-vessel (purple triangle) leatherback individuals. Each point represents a single interaction, positioned by its relative hook position on the mainline between floats (x-axis) and estimated catenary depth at capture (y-axis). The solid black line and shaded region show the mean and SD catenary depth profile across all sets with sea turtle interactions. Marginal density plots show the distribution of hook positions (top) and depths (right) by disposition.

## 3.3 Oceanographic-only ERF Model

The oceanographic-only ERF performed moderately, with an AUC of 0.658 (Table 3). Of the 23 oceanographic covariates, 14 had median variable importance greater than that of the random covariate (Fig. 6). The most important predictor for leatherback interaction is SST, with the greatest risk at SST between 26 and 27°C (Fig. 6, 7). The next important variable was chlorophyll-a, with increased leatherback interaction probability at lower chlorophyll-a levels (Fig. 6, 7). While no clear hotspot exists in the Hawaii region, leatherback interactions with longline vessels are most probable in the southwest regions (Fig. 8).

**Table 3.** Ensemble random forest model performance (oceanographic-only ERF) measured by three threshold-independent metrics: AUC, RMSE, and TSS for training and test datasets.

| Threshold-independent metric | Train | Test |
|---|---|---|
| AUC | 0.998 | 0.658 |
| RMSE | 0.388 | 0.390 |
| TSS | 0.987 | 0.399 |

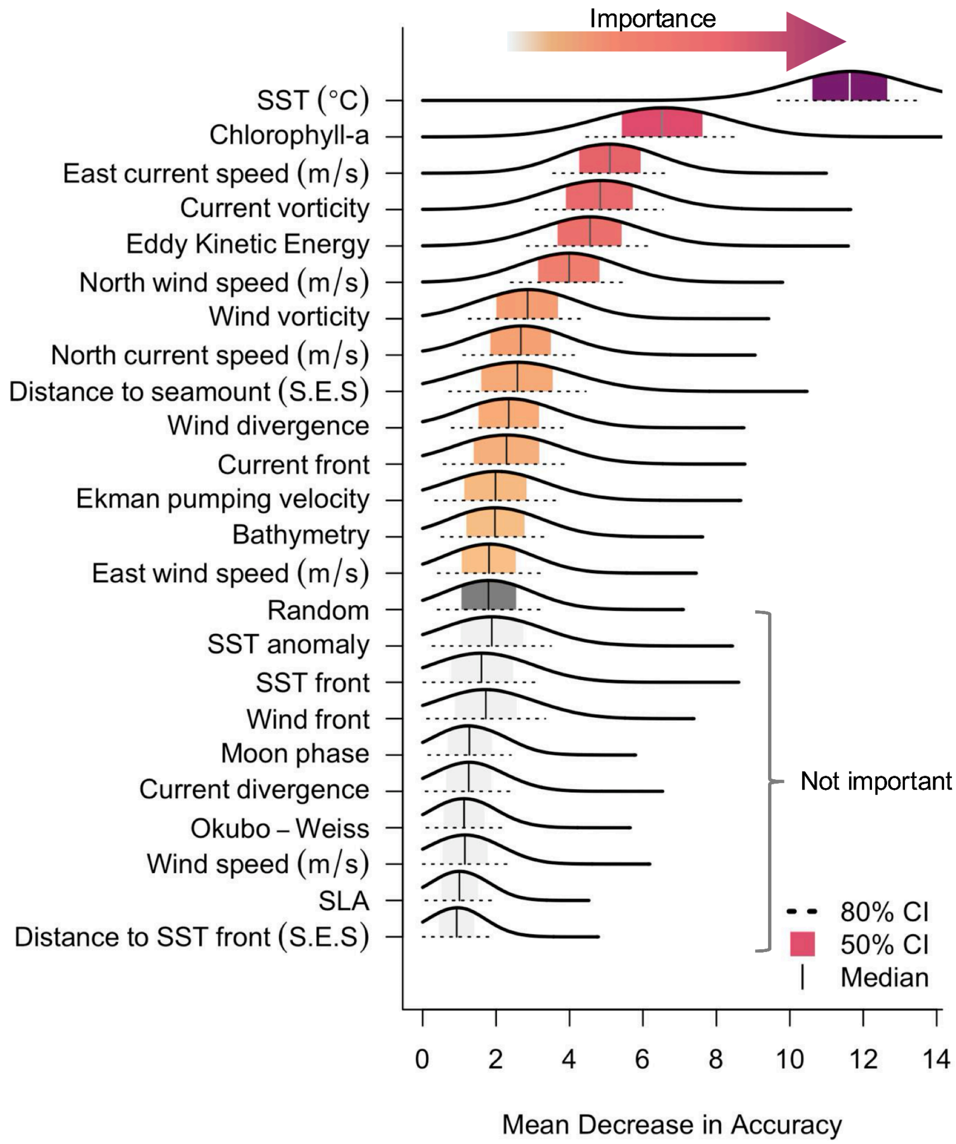



**Figure 6.** Variable importance of covariates included in the Ensemble Random Forests model. The highest ranked variables are the top of the panel and the lowest ranked are the bottom. The solid line for each covariate's empirical distribution is the full range of variable importance metrics across all RFs in the ensemble, the dashed line represents the 10th – 80th percentile interval, while the colored region is the 25th – 75th percentile interval, and the solid vertical line is the median. The random covariate that is included in the model by default is shaded dark gray and all covariates with lower median variable importance than the random are shaded light grey.

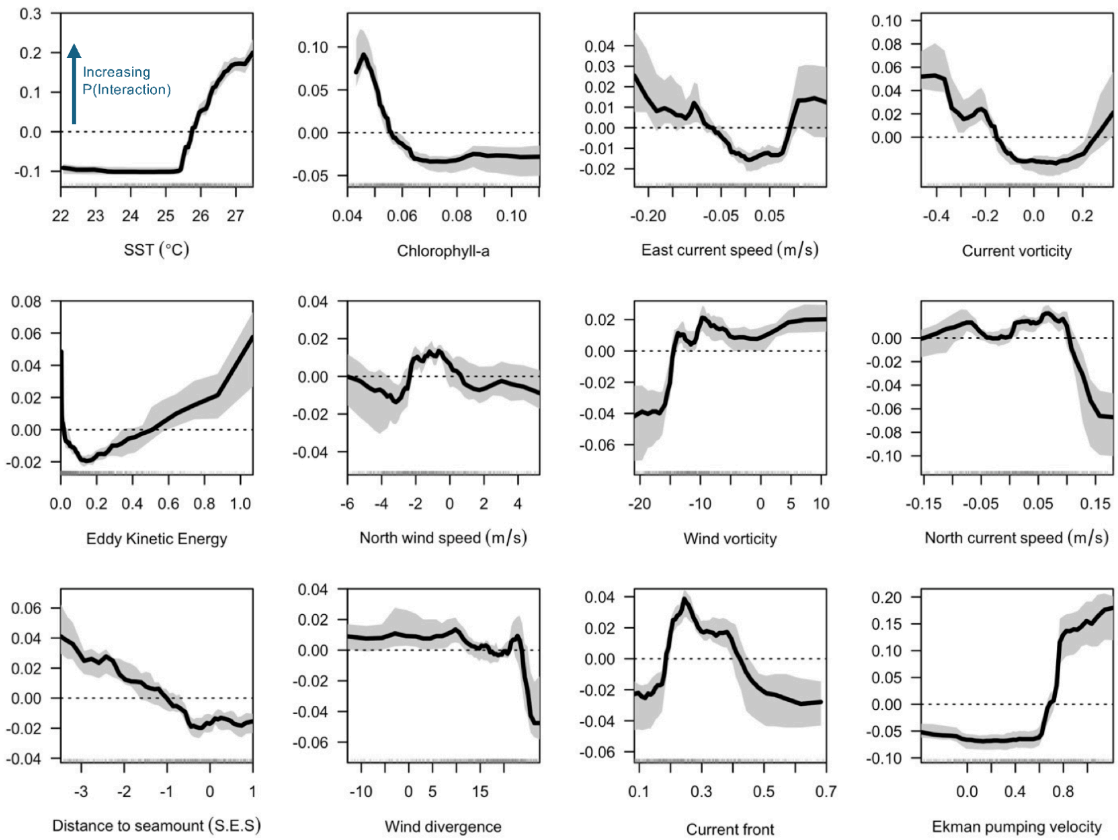



**Figure 7.** Accumulated local effects (ALE) on the ensemble random forest prediction for the top twelve variables in row-order of rank. The black line is the median local effect (change in probability of interaction) as a function of the covariate while the shaded region is the 80% confidence interval. The rug plot at the bottom of each panel demonstrates the distribution and density of longline sets.

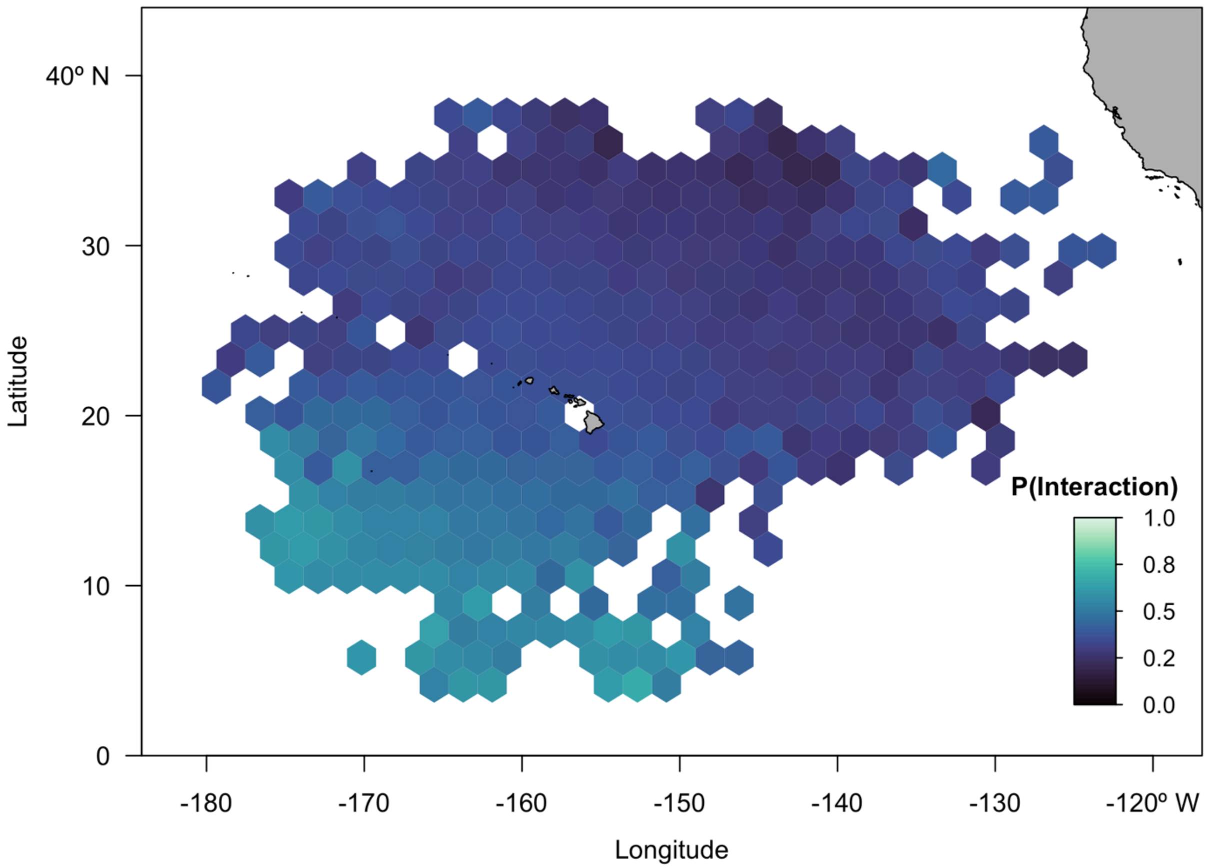



**Figure 8.** Ensemble Random Forest predictions of the Hawaii DSLL observer data. Each grid is the aggregate of individual sets in that cell, with the color indicating the prediction probability of interaction. Cells with less than 3 permitted vessels fishing that cell over the time series are not shown.

## 3.4 Operational ERF Model

PCo and PC biplots included in the operational ERF captured the majority of variance for the respective suite of covariates (Fig. 9-11). The operational ERF model performed slightly worse than the oceanographic-only ERF, with an AUC of 0.585 (Table 4). Gear was the most important variable in the model (Fig. 12). Pairing PCo or PC biplots (Fig. 9-11) with ALE plots (Fig. 13) reveals which suite of characteristics increases interaction probability. Increasing the amount of gear in the water (more hooks and floats) and possibly greater gear movement from longer leaders tend to increase interaction probability (Fig. 9, 13). Hot spots seem to occur in deep to moderately deep water and near sea surface temperature (SST) fronts (Fig. 11, 13). Leatherback interactions are more probable in mesoscale eddies, deformation zones, and areas of strong eastward or westward currents (Fig. 10, 13). On the operational side, using a 16/0 hook, monofilament leader material, and milkfish as bait may be associated with higher interaction risk (Fig. 14).

Predictions for hook type/size were summarized using the MSS threshold of 0.627 (Table 5). The probability of interaction with an offset 16/0 circle hook was 3.6 times greater than that of an offset 15/0 circle hook (Table 5).

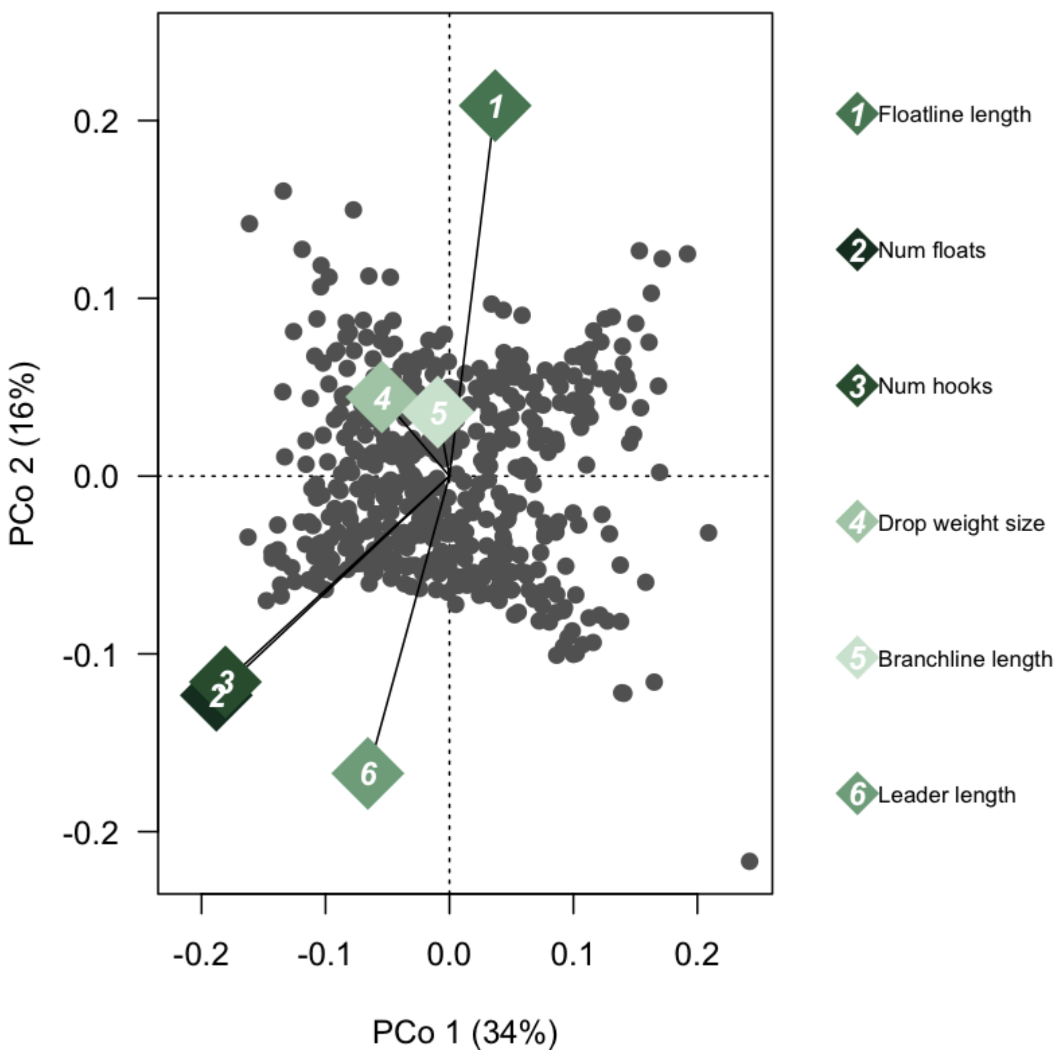



**Figure 9**. Biplot of DSLL gear PCoA. Axis 1 explained 34% of the data variance and Axis 2 explained 16% of the variance. Points represent the 500 gear-configuration cluster centers, where clusters with more similar gear configurations plot closer together. Numbered diamonds represent the 6 loading vectors, colored by strength (light = weak, dark = strong).

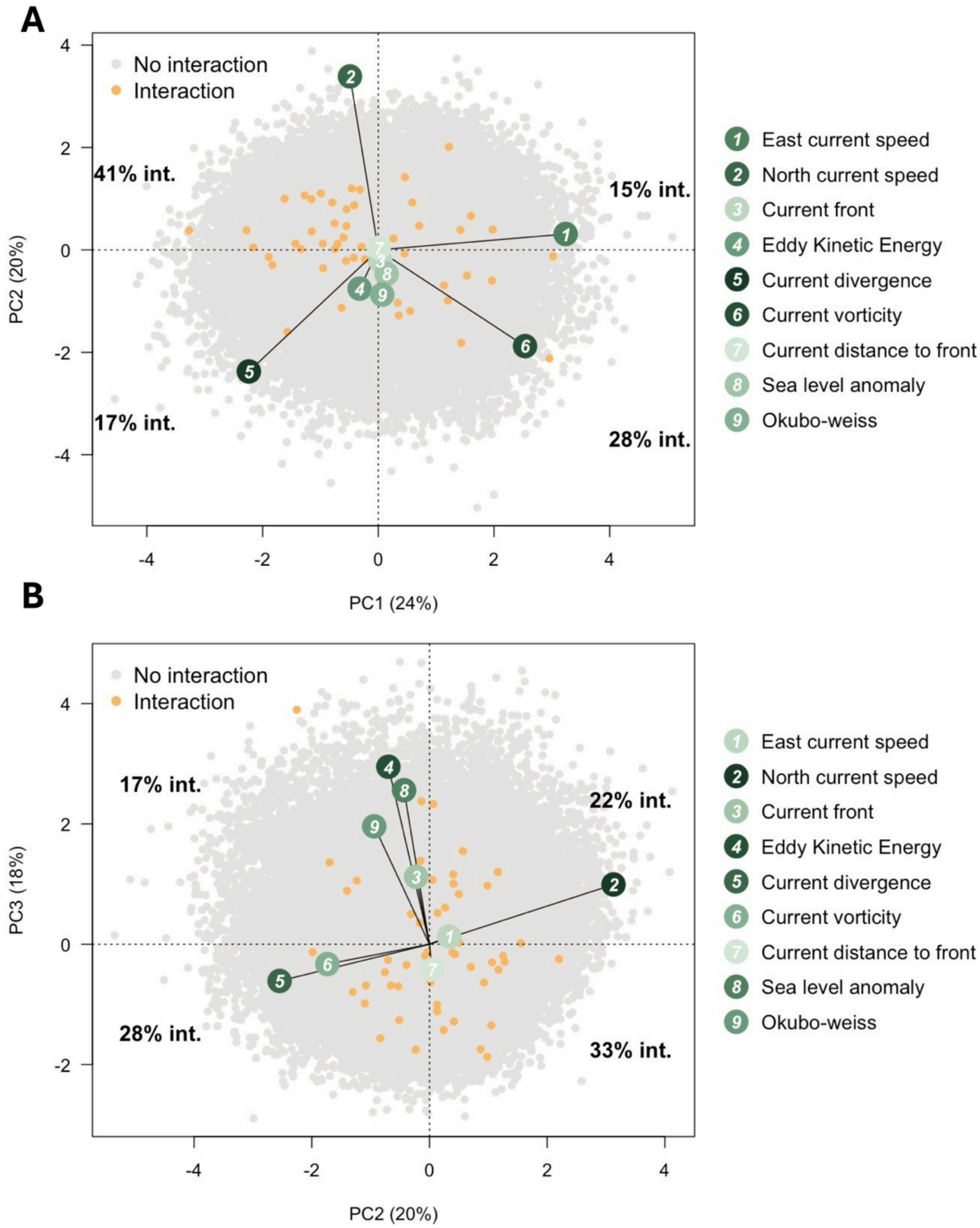
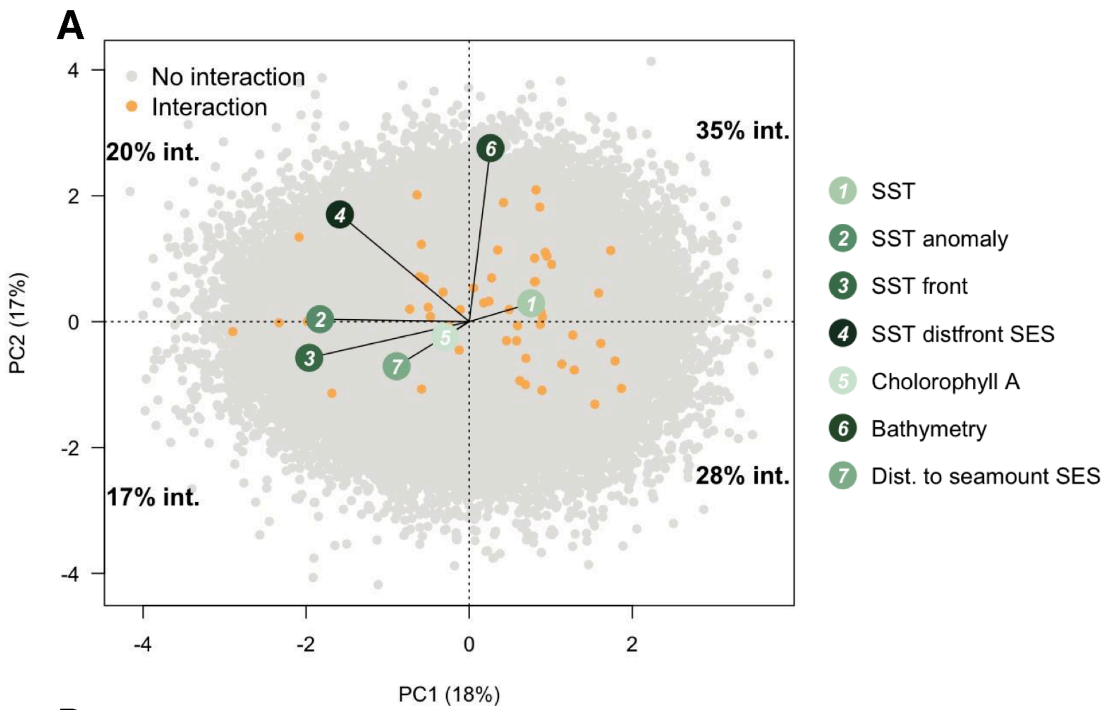



**Figure 10.** Biplots of current and eddy dynamics PCA. (A) Axis 1 explained 24% of the data variance and Axis 2 explained 20% of the variance. (B) Axis 3 explained 18% of the variance. Points represent sets, colored by leatherback interaction (orange) or no interaction (gray). Numbered circles represent the 9 loading vectors, colored by strength (light = weak, dark = strong). The percent of leatherback interactions occurring in each quadrant is included.



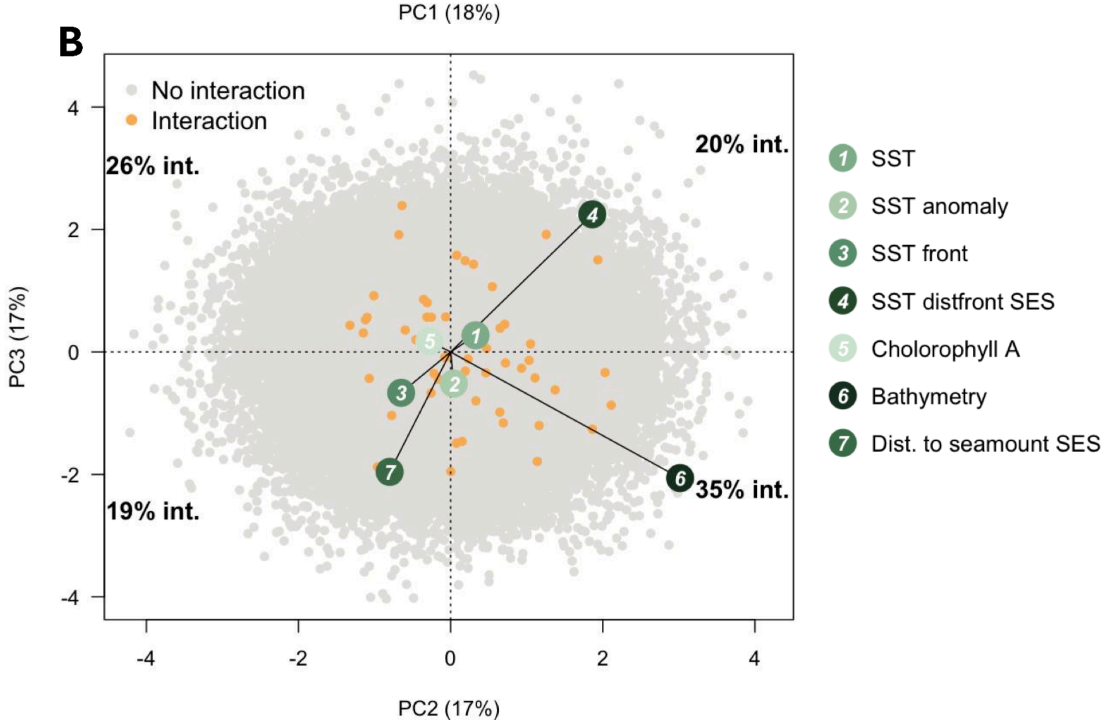




**Figure 11.** Biplots of habitat environmental features PCA. (A) Axis 1 explained 18% of the data variance and Axis 2 explained 17% of the variance. (B) Axis 3 explained 17% of the variance. Points represent sets, colored by leatherback interaction (gold) or no interaction (gray). Numbered circles represent the 7 loading vectors, colored by strength (light = weak, dark = strong). The percent of leatherback interactions occurring in each quadrant is included.

**Table 4.** Ensemble random forest model performance (operational ERF) measured by three threshold-independent metrics: AUC, RMSE, and TSS for training and test datasets.

| Threshold-independent metric | Train | Test |
|---|---|---|
| AUC | 0.997 | 0.585 |
| RMSE | 0.403 | 0.405 |
| TSS | 0.979 | 0.321 |

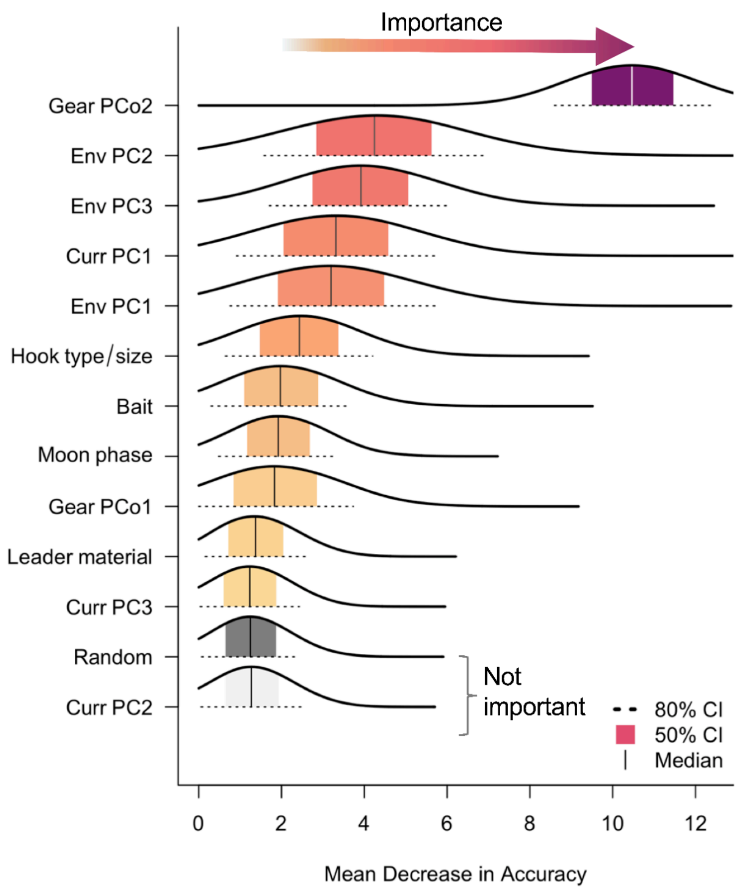



**Figure 12.** Variable importance of covariates included in the Ensemble Random Forests model. The highest ranked variables are the top of the panel and the lowest ranked are the bottom. The solid line for each covariate's empirical distribution is the full range of variable importance metrics across all RFs in the ensemble, the dashed line represents the 10th – 80th percentile interval, while the colored region is the 25th – 75th percentile interval, and the solid vertical line is the median. The random covariate that is included in the model by default is shaded dark gray and all covariates with lower median variable importance than the random are shaded light grey.

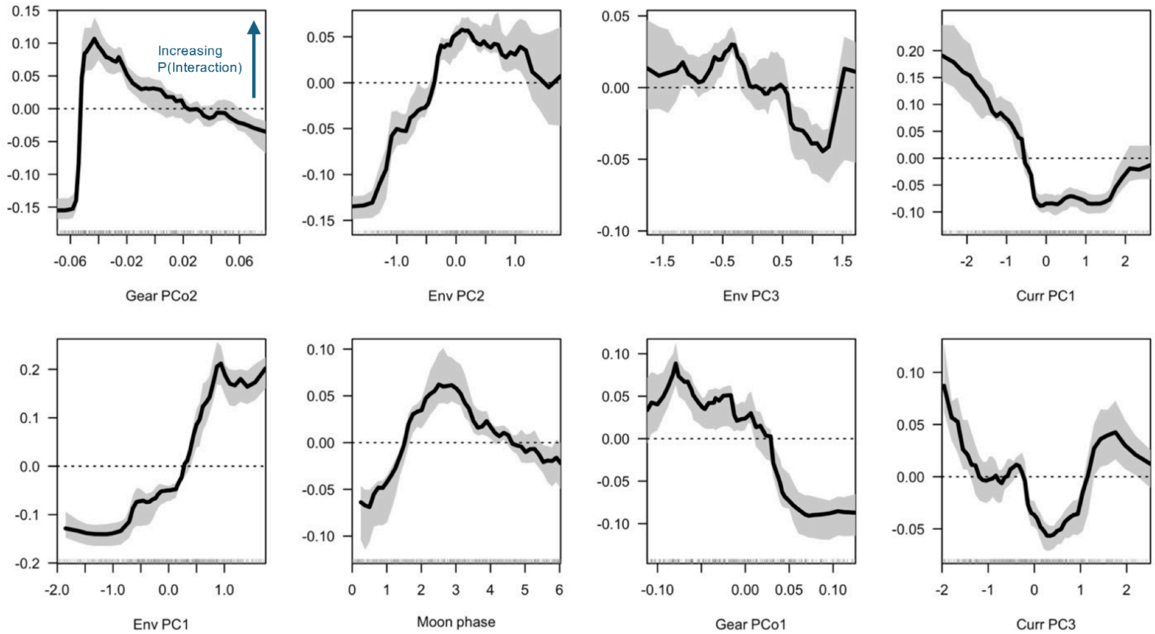



**Figure 13.** Accumulated local effects (ALE) on the ensemble random forest prediction for the top 8 numeric variables in row-order of rank. The black line is the median local effect (change in probability of interaction) as a function of the covariate while the shaded region is the 80% confidence interval. The rug plot at the bottom of each panel demonstrates the distribution and density of longline sets.

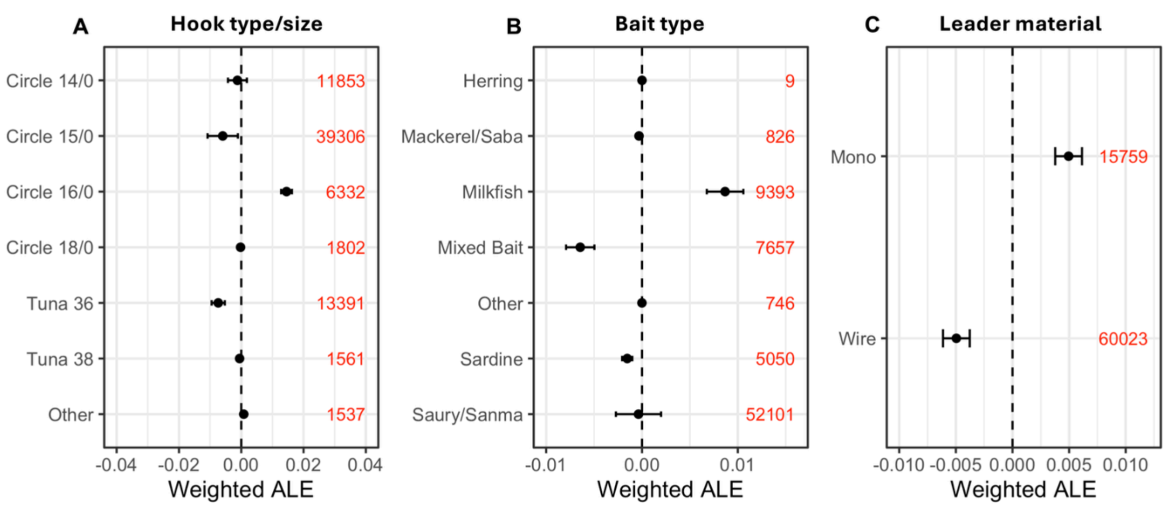



**Figure 14.** Weighted accumulated local effects (ALE) on the ensemble random forest prediction for leatherback interaction for the categorical variables, in row-order of rank (A) Hook type/size, (B) Bait type, and (C) leader material. Points show the median weighted ALE weighted by the proportional frequency in the dataset and horizontal bars represent 95% confidence intervals. The dashed vertical line at zero indicates no effect on the predicted response. Numbers in red indicate number of sets recorded using each.

**Table 5.** Predicted interactions for each hook combination corrected by MSS threshold value of 0.627.

| | Circle 14/0 | Circle 15/0 | Circle 16/0 | Circle 18/0 | Tuna 36 | Tuna 38 | Other |
|---|---|---|---|---|---|---|---|
| 0: no interaction | 0.985 | 0.977 | 0.919 | 0.985 | 0.999 | 0.999 | 0.992 |
| 1: interaction | 0.015 | 0.023 | 0.081 | 0.015 | 0.001 | 0.001 | 0.008 |

# Conclusion

- The majority of leatherback interactions (82%) result from entanglements and/or foul hooking of the body rather than bait ingestion.
- There is no clear leatherback hotspot; instead the interaction gradient appears to be driven primarily by SST.
- Leatherback interactions are more likely with more effort (more hooks per set, floats per set) and possibly greater gear movement (longer leaders).
- Leatherback interactions are more likely in deep or moderately deep water close to SST fronts, near mesoscale eddies (low EKE, low Okubo-Weiss, and negative SLA), and deformations with strong east or west currents.
- Unique patterns to further investigate include increased interaction probability when fishing with offset 16/0 circle hooks (≤ 10°), monofilament, or milkfish.
- There is no single covariate that best predicts interactions, and instead, interactions appear to be effort-driven.
- An expansion of this analysis using ROP data offered by participating nations will further our understanding of environmental and operational factors associated with leatherback turtle bycatch across the WCPFC convention area.

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