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Exploring seabird interactions in Hawai'I's deep-set and shallow-set longline fisheries

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Abstract

We used a multivariate categorical ensemble random forest model to investigate the role of various environmental and operational factors, including mitigation measures, influencing rates of interaction and mortality of seabirds in Hawaiʻi's longline fisheries. Using the Pacific Islands Regional Observer Program data collected from 2005–2023, we assessed Laysan (*Phoebastria immutabilis*) and black-footed (*P. nigripes*) albatross bycatch risk in Hawaiʻi's deep-set (DSLL) and shallow-set (SSLL) longline fisheries, which are separately managed fisheries. The SSLL generally targets swordfish and is a night-time fishery and was associated with higher rates of seabird interaction but lower rates of mortality as compared to the DSLL, where gear is set during daylight hours. Albatross interaction rates were lower in the DSLL fishery (Catch Per Unit Effort [CPUE]: 0.0023 Laysan, 0.0053 black-footed) than in the SSLL (CPUE: 0.021 Laysan, and 0.0198 black-footed) fishery. However, 93% of albatrosses captured in the DSLL died at-vessel compared to 26% in the SSLL fishery. Notably, the percentage of SSLL interactions resulting in an at-vessel mortality increased to ~40% around the full moon, suggesting that higher moon illumination appears to compromise the effectiveness of night setting in reducing seabird bycatch, night setting may be less effective as a seabird bycatch mitigation technique when the moon is brightest, which also is when ~61% of SSLL sets occur. Our analyses also identified that discarding offal or spent bait during haulback was associated with increased seabird interactions by up to 73% in the SSLL fishery and 35% in the DSLL fishery. Seabird mortality and injury are further discussed in relation to various mitigation measures regulated for United States North Pacific longline fisheries.

Introduction

The incidental capture and mortality of seabirds in various fisheries is a concern both domestically as well as internationally, especially given the potential for population declines. It is well established that even low bycatch rates pose a serious threat to long-lived seabirds like albatrosses and petrels, which are some of the most threatened group of seabirds (Phillips et al. 2016; Dias et al. 2019; IUCN 2021). As such, great effort has been made to fish in ways that reduce seabird bycatch rates. Given the complexity of fisheries and seabird ecology and behaviors, regulations with domestic and international management generally offer a menu approach of mitigation options, including but not limited to, use of tori lines, line weighting schemes, specific offal and bait management, and night-setting. Based on a variety of factors, including human safety to fishing crew, fishers often have strong preferences regarding their choice of required mitigation method employed, and the United States has long advocated for this option-menu to enhance compliance and hence conservation value.

Seabird bycatch mitigation has been a focus in the Hawaiʻi longline (HI LL) fishery for decades and experiments conducted in the United States (U.S.) and foreign longline fisheries have informed management decisions in Hawaiʻi and throughout U.S. fisheries (Gilman et al. 2025). Due to concerns regarding bycatch mitigation efficacy as well as human safety concerns for the fishing crew, efforts have been undertaken to review and update regulations. Of particular interest internationally is to identify means to effectively reduce bycatch while minimizing disturbance of fishing operations, which would result in increased adoption and use by the industry. As such, bycatch management often includes menu options to allow fishers to choose measures based on preferences. In Hawaiʻi's deep-set longline (DSLL) fishery, for example, tori lines were shown to be significantly more effective at reducing seabird bycatch than blue-dyed bait (Chaloupka et al. 2021; Gilman et al. 2021; WPRFMC). Based on these findings, the Western Pacific Fishery Council recommended replacing the existing requirement for thawed, blue-dyed bait and strategic offal discharge with the use of a tori line. This regulatory change was finalized on March 1, 2024 (89 FR 15062).

Conditions and interactions with seabirds differ between the Hawaiʻi shallow-set longline (SSLL) and DSLL fisheries and among seabird species given their unique ecology and behaviors. As such, mitigation measure effectiveness differs across fisheries and bycatch species. The SSLL targets swordfish (*Xiphias gladius*), whose behavior is influenced by diel vertical migration and lunar illumination. Historically the fishery has adjusted their set times based on lunar phases to improve efficiency and catch rates. Seabird avoidance has been largely achieved due to operational and regulatory factors such as night-setting. However, experimental efforts have aimed to provide greater flexibility in the time period for gear setting, which may help to optimize catch efficiency and crew safety (86 FR 71234). One trial tested the use of tori lines as a daytime mitigation measure, but seabird interactions increased compared to night setting with blue-dyed fish bait, suggesting it was not a viable option for further exploration (Chaloupka et al. 2024). Therefore, the SSLL fishery would benefit from further bycatch mitigation research (WPRFMC 2023).

We assessed environmental variables with a focus on (1) the role of the lunar phase with respect to Laysan and black-footed albatross interactions and mortality in Hawaiʻi's longline fisheries. This factor is especially relevant when evaluating the effectiveness of night-setting as a standalone mitigation measure, and this subject has been the focus of extensive scientific discussion. (2) We also evaluated the effectiveness of various mitigation strategies (in concert and alone, based on the current data available to us) used in both fisheries. The results of this project will demonstrate the effectiveness and limitations of night-setting as a stand-alone measure and collectively with other mitigation strategies, potentially informing revisions to the suite of allowable mitigation measures under both domestic (e.g., Pacific Islands Region) and international fisheries management frameworks, such as the Western and Central Pacific Fisheries Commission (WCPFC).

Methods

Fisheries

The Hawai'i longline fleets consist of the Deep-Set (DSLL) and Shallow-Set (SSLL) fisheries, which are separately managed. The DSLL is a year-round fishery that primarily targets tuna (*Thunnus* spp.) and accounts for more than 95% of total longline effort. Gear setting generally takes place during the daylight hours and gear is hauled in during nighttime hours. The SSLL primarily targets swordfish (*Xiphias gladius*) and is more seasonal, with most fishing activity taking place in the first and last quarter of the calendar year. Gear setting begins at a minimum one hour after local sunset and is completed before sunrise. Gear is hauled in the following day during daylight hours.

Observer data

NOAA Fisheries maintains the Pacific Islands Region Observer Program (PIROP) which oversees data on target catch and bycatch in Hawai'i's longline vessels collected from human observers. From 2005-2023, the program maintained ~20% and 100% (human) observer coverage in the DSLL and SSLL, respectively. The bycatch data presented here therefore do not represent the entire HI DSLL fishery, whereas it is fully representative of the HI SSLL fishery. In both the DSLL and SSLL, observers monitor the first hour of the set and the entire gear haulback. Observers record longline gear configuration, seabird mitigation measures employed, seabird bycatch to ensure compliance with existing regulations (Title 50 CFR § 665.815), and to fulfill agency requirements for reporting and monitoring seabird mitigation use and effectiveness.

Our analysis includes the Laysan albatross (*Phoebastria immutabilis)* and black-footed albatross (*P. nigripes*), the seabird species with the highest interaction rates with the HI longline fisheries. If a seabird becomes hooked or entangled, observers record species, hook number on the line (relative to the buoy), whether a light device was used and its proximity to the branch line, entanglement or hook location (e.g., ingested, head/beak, wing, body, tail), how the gear was removed, any gear remaining on bird prior to release, and the bird's disposition or fate (e.g., released alive with an injury or died).

Gear covariates for random forest model

Recorded longline gear configuration includes details on hook and floats, bait type, light devices, and the specifications of the main line, float line, branch line, and leaders. To strengthen model outputs, we collapsed the raw gear configuration per set to clusters of gear combinations for decomposition. We tested the number of gear configuration clusters ranging from 20 to 1000 and found the ratio of the between cluster sum of squares to the total sum of squares reached an asymptote around 100 clusters; thus, we used 100 gear configuration clusters moving forward. We then did Principal Coordinates Analysis (PCA) on a Gower dissimilarity matrix of the 100 cluster means by fishery. We visualized the first two principal coordinates (PC) and retained the first six PCs that accounted for more than 75% of the total variance in the gear configuration cluster means. We then back-calculated the principal coordinate scores for each set based on the set's cluster identity.

Environmental data

We extracted 23 environmental variables associated with each fishing set for the observer data (Table S1). These variables are associated with the temporally dynamic conditions (lunar phase), different spatiotemporally dynamic attributes (e.g. sea surface temperature (SST), sea surface height (SSH), ocean currents and winds, chlorophyll-a concentrations) and static attributes (distance to seamount). To isolate the effects of lunar phase, gear, and mitigation measures, we reduced the influence of environmental covariates by conducting a PCA on all environmental covariates with the exception of lunar phase and included the component scores (PC1-PC10) in the multivariate categorical model for each fishery. Prior to the PCA, all environmental variables were transformed using bestNormalize (Peterson, 2021).

Mitigation measures

Seabird mitigation measures (Title 50 CFR § 665.815) have been required for Hawai'i's pelagic longline fishing vessels since 2001 but amended in 2006 (70 FR 75075) and 2024 (89 FR 15064). For sets north of 23°N (deep and shallow set), and south of 23°N (shallow set), vessels must side-set by deploying gear from the side of the vessel, deploy bird curtains, and use weighted branch lines and ensure bait is submerged, or vessels must follow alternative techniques outlined below. For deep sets, vessels not side-setting must use tori lines with streamers, a line shooter, and a weighted branch line (as of April 1 2024; Title 50 CFR § 665.815; 89 FR 15064). Prior regulations for deep-set vessels (not side-setting) mandated the use of thawed, blue-dyed bait, a line shooter, weighted branch lines, and strategic offal and bait management when the gear is being set or hauled (effective Jan 18 2006; 70 FR 75075). HI DSLL vessels fishing south of 23°N are not required to employ seabird mitigation measures. For shallow sets, vessels not side-setting must set only at night, using thawed, blue-dyed bait, and when seabirds are present, strategically discharging offal (fish parts) and spent bait on the opposite side of the vessel from where the longline gear is being set or hauled. Other mitigation measures are optional and include using weighted branch lines, a towed buoy, or water sprayers.

Multivariate categorical Ensemble Random Forest Model (ERF)

To identify seabird interaction rate and fate within each fishery (DSLL, SSLL), we modeled the probability of the type of interaction outcome that could occur for each set (set with no interaction, set with black-footed albatross at-vessel mortality, set with Laysan albatross at-vessel mortality, set with black-footed albatross interaction but no mortality, or set with Laysan albatross interaction but no mortality) using a variant of an ensemble random forest (ERF) that allows for the modeling of categorical outcomes (Lipscomb et al., 2025). We included the generated environmental covariate PCA scores, gear PCoA scores, bycatch mitigation covariates, lunar phase, and a random variate. Given that seabirds are nesting in known breeding colonies that are non-equidistant from every fishery set, we accounted for spatial location by calculating the latitudinal and longitudinal standardized anomaly from each set by fishery.

We fit the ERF model using 100 random forests using 1000 decision trees for each, trying 5 covariates at each node, with a balanced number of records from each disposition outcome for the training sets provided to each tree. To evaluate model performance, we calculated threshold-independent metrics, including area under the curve (AUC), root mean squared error (RMSE), and true skill statistic (TSS). We assessed the variable importance as a function of mean decrease in accuracy following Siders et al. (2020). For variables that were more important than the random variate, we calculated accumulated local effects (ALE), which quantify how changes in a specific covariate influence the model's predicted probability of presence/absence. The ALE predictions facilitated mapping the change in probability of a seabird bycatch interaction as a function of covariates for each categorical outcome.

Results

Fishery operations

The DSLL fishery operates year round and remains fairly constant throughout each lunar phase whereas the SSLL fishery has greater effort around the full-moon and less effort around the new moon (Fig. 1). Gear configuration in the DSLL and SSLL fisheries has marginally changed from 2005 to 2023. In the DSLL fishery, drop weight size and floatline length have decreased, whereas the number of floats and number of hooks per set have increased (Fig. 2). Since 2005, the floatline length, number of floats, and number of hooks per set have increased in the SSLL fishery (Fig. 2).

The gear PCoAs demonstrate variability in gear configuration used in the DSLL (Fig. S1) and SSLL (Fig. S2) fisheries. The DSLL fishery has greater variability in gear configurations than the SSLL fishery. The first two PCs of the PCoA of gear in the DSLL fishery explained 39% of the total variance (Fig. S1). Negative PC1 scores are driven by thicker branch line and leaders, more floats, and more hooks per set (Fig. S1) whereas positive PC2 scores are driven by thicker branch line, more floats, and more hooks per set (Fig. S1). The first two PCs of the PCoA of gear in the SSLL fishery explained 48% of the total variance (Fig. S2). Negative PC1 scores are associated with larger drop weights, longer branch lines, and certain hook types. It is also associated with greater effort (more floats, longer float lines, and more hooks per set) (Fig. S2). Larger drop weights drive the positive PC2 scores (Fig. S2).

Mitigation measures implemented

The DSLL fishery sets gear during the daylight hours. During gear setting, 21% of the DSLL sets employed strategic discarding of bait or offal and of the strategic bit discard, only 36% of the sets used blue-dyed bait. The use of blue-dyed bait has varied since 2005, but discarding bait has become more typical than discarding offal in recent years (Fig. 3). Essentially all sets used both a line shooter and weighted branch line (Table 1; Fig. 3). Tori lines and towed buoys were used in only 2% and 1% of sets, respectively while 21% employed side-setting (Table 1). Seabirds were recorded as present during 43% of DSLL sets. Gear is hauled in 1 h before dusk and is finished overnight after approximately 11 h. During haulback, most data for mitigation measures is not reported (Table 1). Seabirds were observed in 55% of DSLL hauls (Table 1).

In contrast, the SSLL fishery sets gear at night approximately 1 h after dusk and is complete before sunrise. Most SSLL sets used thawed, blue-dyed bait deployed outside the vessel wake (Table 1; Fig. 4). Only 12% of the sets included discarding of bait and/or offal; and discarding offal has become rare in recent years, whereas discarding bait is slightly more common (Table 1; Fig. 4). The fishery rarely used tori lines, towed buoys, or water spray during the setting of gear, but consistently used weighted branch lines (Table 1; Fig. 4). Seabirds were recorded as present during only 13% of the SSLL sets (Table 1). Haulbacks in the SSLL fishery occur during the daytime, beginning approximately 1 h after dawn, and are completed after about 9 h. Most data was not available for SSLL haulbacks; though some SSLL haulbacks employed discard practices (4%), blue-dyed bait (4%), and a weighted branch line (4%) (Table 1; Fig 4). Most haulbacks (96%) that used blue dye also discarded offal. Seabirds were recorded present during most (81%) of SSLL haulbacks (Table 1).

Albatross bycatch

Between 2005 and 2023, 94,556 longline sets were observed (Table 2). The SSLL fishery comprised 21,214 observed sets, or 22% of the total observed sets (Table 2). Of these SSLL sets, 2% had at least one interaction with the black-footed albatross, 2.2% had at least one interaction with the Laysan albatross, and 0.33% had an interaction with at least one of each species (Table 2). The DSLL fishery had 73,342 observed sets (Table 2). Of these observed DSLL sets, 1.3% had at least one interaction with a black-footed albatross, 0.57% had at least one interaction with the Laysan albatross, and 0.12% had at least one interaction with each of these species (Table 2). In the DSLL, catch per unit effort (CPUE; per 1000 hooks) was 0.0053 for black-footed albatross, 0.0023 for Laysan albatross, and 0.0005 for both species, whereas rates were 0.0198, 0.021, and 0.0031, respectively, in the SSLL (Table 2).

There were a total of 1,157 observed black-footed albatross interactions in the DSLL and 509 observed interactions in the SSLL (Table 3). In the DSLL fishery, Laysan albatross interactions were less common, with only 547 observed Laysan albatross interactions, while there were 639 observed interactions in the SSLL (Table 3). Across both fisheries and albatrosses, most sets with an interaction had only a single interaction; multiple captures of the same species in a single set were uncommon (Table 3).

In our analyses, we investigated the disposition, or fate, of the seabirds that interacted with the longline fisheries to determine or predict injuries and mortality. In the DSLL fishery, 92% of black-footed albatross and 94% of Laysan albatross interactions result in mortality (Table 4). In contrast, the SSLL fishery shows much lower at-vessel mortality rates, with 31% for black-footed albatross and 18% for Laysan albatrosses. Instead, the majority of interactions in the SSLL fishery lead to injured releases (74%), from 67% for black-footed albatross to 79% for Laysan albatross (Table 4).

In both fisheries, the majority of individuals of both species were hooked rather than entangled or both hooked and entangled, comprising 75 to 87% of observed interactions (Table 5). Most hook interactions occurred on the head, beak, or mouth across both fisheries for both seabird species, accounting for 42-63% of hook interactions (Table 6). In the DSLL fishery, ingestion was the second most common hook interaction, observed in 26% of black-footed and 27% of Laysan albatrosses (Table 6). In contrast, only 13% of black-footed and 11% of Laysan albatrosses ingested hooks in the SSLL fishery, where the second most common hook interaction involved the wing or front flapper (21% and 28%, respectively; Table 6).

In the DSLL fishery, nearly all hookings to the head, beak, or mouth, or through ingestion resulted in at-vessel mortality for both albatross species (Table 7). In contrast, in the SSLL fishery, most head, beak, or mouth hookings did not result in at-vessel mortality (58% for black-footed albatrosses, 68% for Laysan albatrosses; Table 7). However ingestion of the hook led to high at-vessel mortality rates in the SSLL fishery (85 and 62% mortality, respectively; Table 7). Wing or front flipper hookings were typically non-fatal in the SSLL fishery, with 93% and 94% survival for black-footed and Laysan albatrosses, respectively (Table 7).

In the DSLL fishery, the percent of observed at-vessel mortalities across moon phases were similar for both albatross species (Table 8; Fig. 5). Of the observed interactions, most seabirds were recorded as at-vessel mortalities regardless of moon phase (Table 8; Fig. 6). Mortality rate ranged from 0.0053 to 0.0061 per 1000 hooks for black-footed albatross and 0.0025 to 0.0034 for Laysan albatross in the DSLL (Table 8; Fig. 5).

In the SSLL fishery, the percent of observed at-vessel mortalities varied across lunar phase and was greatest during the first quarter to full moon phase ($\pi/2$ to π radians) for both black-footed albatross and Laysan albatross, increasing from a 24% mortality rate in the prior moon phase to 40% for the black-footed albatross and from 6% to 26% for the Laysan albatross (Table 8). Taking effort (by sets) into account, the rate of mortalities is greatest during the first quarter to full moon phase, with interaction rates increasing from 0.0037 in the prior moon phase to 0.0128 for the black-footed albatross, and from 0.0012 to 0.0107 for the Laysan albatross (Table 8). Similarly, for effort (by 1000 hooks), the rate of mortality is greatest during the first quarter to full moon phase (Table 8; Fig. 5). The rate of injury is higher across all moon phases for both species, but remains relatively the same (Fig. 6).

Model performance

The ensemble random forests models had high threshold-independent performance, with an average area under the curve of 1.00 and 0.97 (1 is perfect), an average root mean squared error of 0.10 and 0.22 (0 is perfect), and an average true skill statistic of 0.99 and 0.86 (1 is perfect), for SSLL and DSLL, respectively, across disposition outcomes (Table 9). In the DSLL, the probability of injury for either seabird had near-perfect performance across the disposition outcomes (e.g., at vessel-mortality or released injured), whereas the probability of no interaction or an at-vessel mortality for either seabird performed marginally worse (Table 9). The probability of seabird mortality or no interaction performed well across disposition states for the SSLL (Table 9).

Factors affecting albatross disposition in the DSLL fishery

In the DSLL fishery, the top covariate for the ERF model specific to seabird fate was strategic offal discard during the haulback, followed by the latitude anomaly of the set, gear axis 2, and the use of blue-dyed bait (Fig. 7). Multiple principal components from the gear PCA were important, highlighting the relevance of gear configuration. In contrast, the lunar phase contributed little to model accuracy in the DSLL, where the lunar phase increased black-footed albatross injury risk by less than half a percent, particularly in darker phases (last quarter to new moon), while other outcomes remained relatively unaffected (Fig. 8).

The current regulation in the DSLL fishery is the deployment of a tori line during the set (as of April 1 2024; Title 50 CFR § 665.815; 89 FR 15064) and serves as the baseline to mitigation measures described below (Fig. 9). The additional mitigation measure of discarding bait during the set increases the probability of interaction with either albatross species by 6%, and by 8% if it is blue-dyed (Fig. 9). Other measures such as using a bird curtain, towed buoy, or discarding offal during the set increase interaction probability by less than 2%, while side setting has no effect (Fig. 9). In contrast, discarding offal or bait during the gear haulback substantially increases the probability of interaction with either species by 35% and 23% respectively, with greater risk observed for the black-footed albatross compared to the Laysan albatross (Fig. 9).

Factors affecting albatross disposition in the SSLL fishery

In the SSLL fishery, the top covariate for the ERF model that predicts probability of seabird interaction and fate was strategic offal discard during haulback, followed by gear axes 1 and 5 (Fig. 10). Bait discard during haulback also was a top covariate (Fig. 10). Unlike DSLL, lunar phase emerged as a key covariate in the SSLL model, indicating sensitivity in disposition to moonlight conditions. Additionally, several components of the environmental PCoA showed high importance, suggesting broader influences on seabird bycatch disposition in the SSLL fishery (Fig. 10). The SSLL had almost no change in predicted probability of interaction around the full moon but the probability of mortalities vs. injuries changed—during the full moon, more birds arrived dead at-vessel and less birds arrived injured at-vessel. This was true for both species (Fig. 11).

In the SSLL fishery, the most common mitigation measure used is night setting with thawed, blue-dyed bait (77% of sets) and serves as the baseline to mitigation measures described below (Fig. 12). Additional measures during setting, such as discarding bait or offal, using a shooter, bird curtain, or side setting, have minimal effect on the probability of interaction with either albatross species (Fig. 12). In contrast, discarding offal during haulback increases the probability of interaction by 73%, with a higher risk of injury for blackfoot-footed albatross (Fig. 12). Discarding bait during haulback also elevates interaction risk, particularly for black-footed albatross, which are more than twice as likely to interact with the fishery than the Laysan albatross (Fig. 12). The use of a towed buoy during haulback increases the probability of interacting with either species by 15% (Fig. 12).

Conclusions

The multivariate categorical ERF was useful in determining the impacts of various environmental and operational factors that predict probabilities of interaction with seabirds in both Hawaiʻi's DSLL and SSLL fisheries, as well as predict the likelihood of disposition outcome (e.g., at-vessel mortality or released injured) from such interactions. Since observers collect data only for 1 hour of gear-setting, whereas the entire haulback process is observed, we are unable to definitively investigate interactions during the setting process versus during the haulback process. Given setting and haulback operations, birds that were observed injured at-vessel must have interacted with the fishery during the gear haulback while birds observed dead at-vessel likely interacted with the fishery during gear setting. To better minimize interactions and at-vessel mortalities, future research would benefit from identifying the specific stages of fishing operations during which the interactions occurred.

Lunar phase

Operationally, the DSLL and SSLL fisheries differ with regard to level of effort in relation to the moon's phases, whereby DSLL remains constant throughout lunar phases while effort in the SSLL is highest around full moon phase. In terms of seabird interactions, the predicted probability of an interaction increases slightly (less than half a percent) in the DSLL fishery between the last quarter and new moon, which seems mostly associated with an increase in injured Laysan albatrosses. The SSLL had almost no change in predicted probability of interaction around the full moon but did see a swap in the disposition of those interactions—more birds arriving dead at-vessel and less birds arriving injured at-vessel. While these changes are small, the overall average predicted probability of a dead at-vessel albatross was 3.4% and 2.3% for black-footed and Laysan, respectively. This means the full moon associated changes in the SSLL ERF predicted probabilities represent a 14% and 22% increase in at-vessel mortalities. In contrast, the same small change in predicted probabilities of interaction around the full moon in the DSLL fishery only corresponds to a 1.1% change in interaction risk. These ERF predictions comport with the changes in the ratio of observed at-vessel dead to injured seabirds associated with moon phase.

Seabird bycatch mitigation strategies

Per regulations in Hawaii's fisheries, if vessels are not side-setting (Title 50 CFR § 665.815), the required seabird mitigation measure in the DSLL fishery is deployment of a tori line during setting, while in the SSLL fishery, mitigation consists of night setting combined with thawed, blue-dyed bait, and if seabirds are present, discharging offal (fish parts) and spent bait during setting or haulback. Our analyses suggest that in the DSLL fishery, additional mitigation measures beyond the baseline strategy of deploying a tori line during setting did not reduce the overall probability of seabird interactions. However, in both fisheries, offal and bait discards during haulback were predicted to have increased seabird interaction risk, with black-footed albatross having disproportionately higher rates.

The SSLL fishery currently requires the strategic discard of offal discharge or spent bait during setting or haulback if seabirds are present. Since this additional measure occurs when birds are present, the ERF may be spuriously associating this mitigation with increased interactions rather than the naïve assumption that bait discards are counterproductive to reducing bycatch of the black-footed and Laysan albatross. Either way, it is clear from the data that birds are present the majority of time during the haulback and discard of offal discharge or spent bait during the haulback is associated with elevated at-vessel mortalities of both seabird species.

Final remarks

Our analyses highlight the value of use of a multivariate categorical ensemble random forest models to help identify factors that impact seabirds' risk to incidental capture and mortality in fisheries. Empirical evidence to support management actions is critically important in order to enhance conservation efficiencies and minimize implementation of regulations with limited value.

Tables and Figures

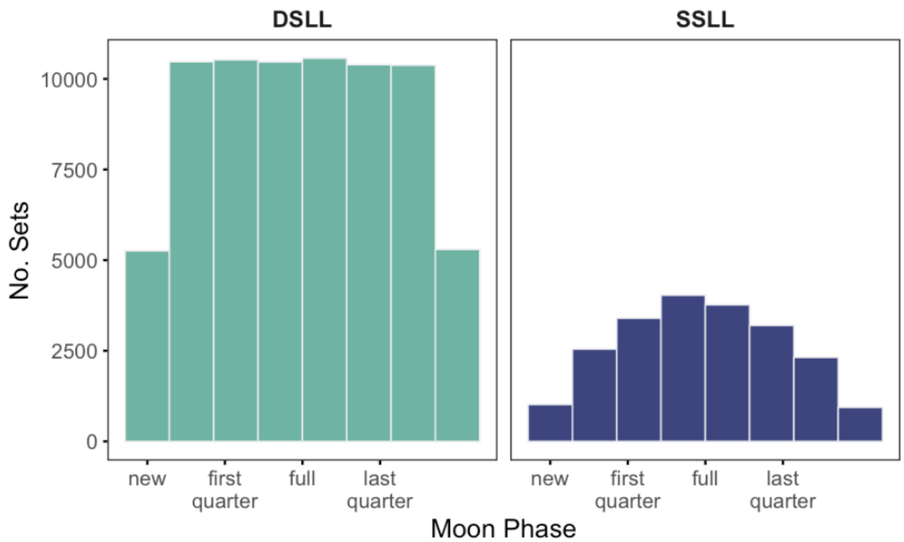

Figure 1. Longline fishing effort in relation to lunar phases in the DSLL and SSLL fisheries from 2005 to 2023.

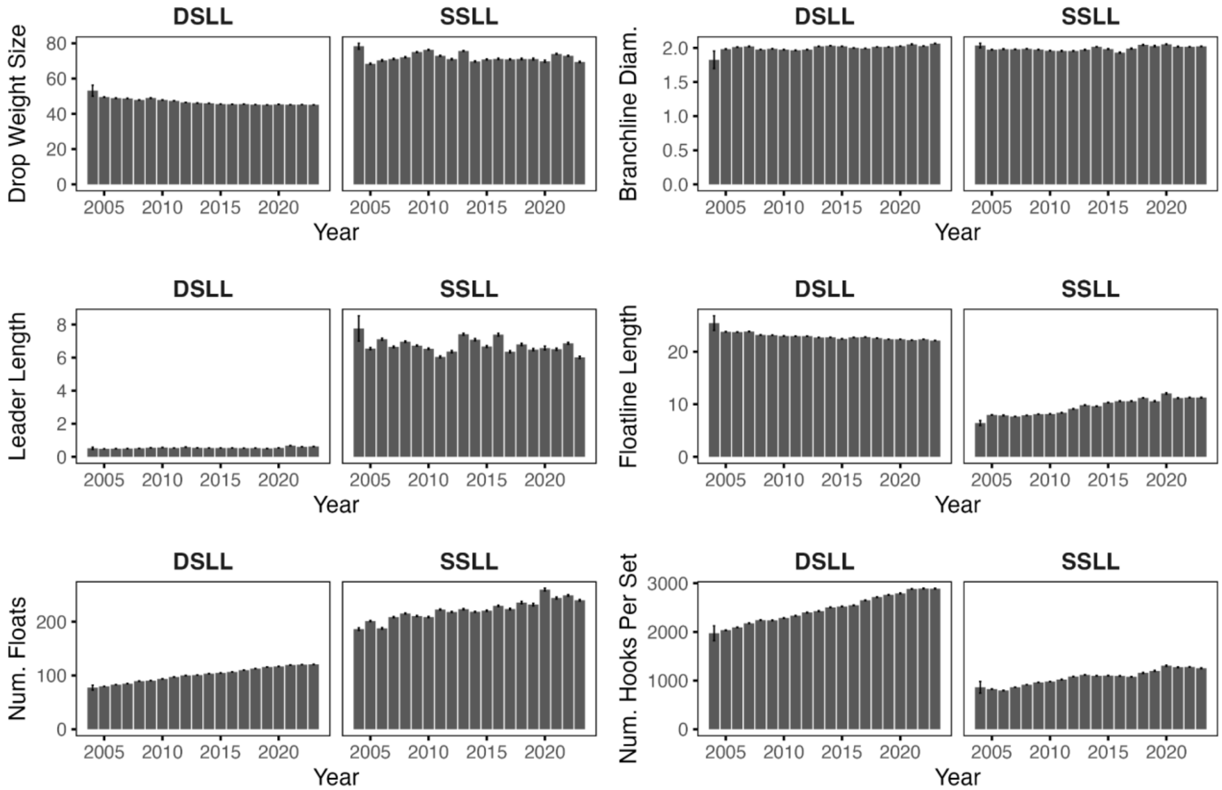

Figure 2. Mean and standard error of gear configuration in the observed DSLL and SSLL fisheries from 2005 to 2023.

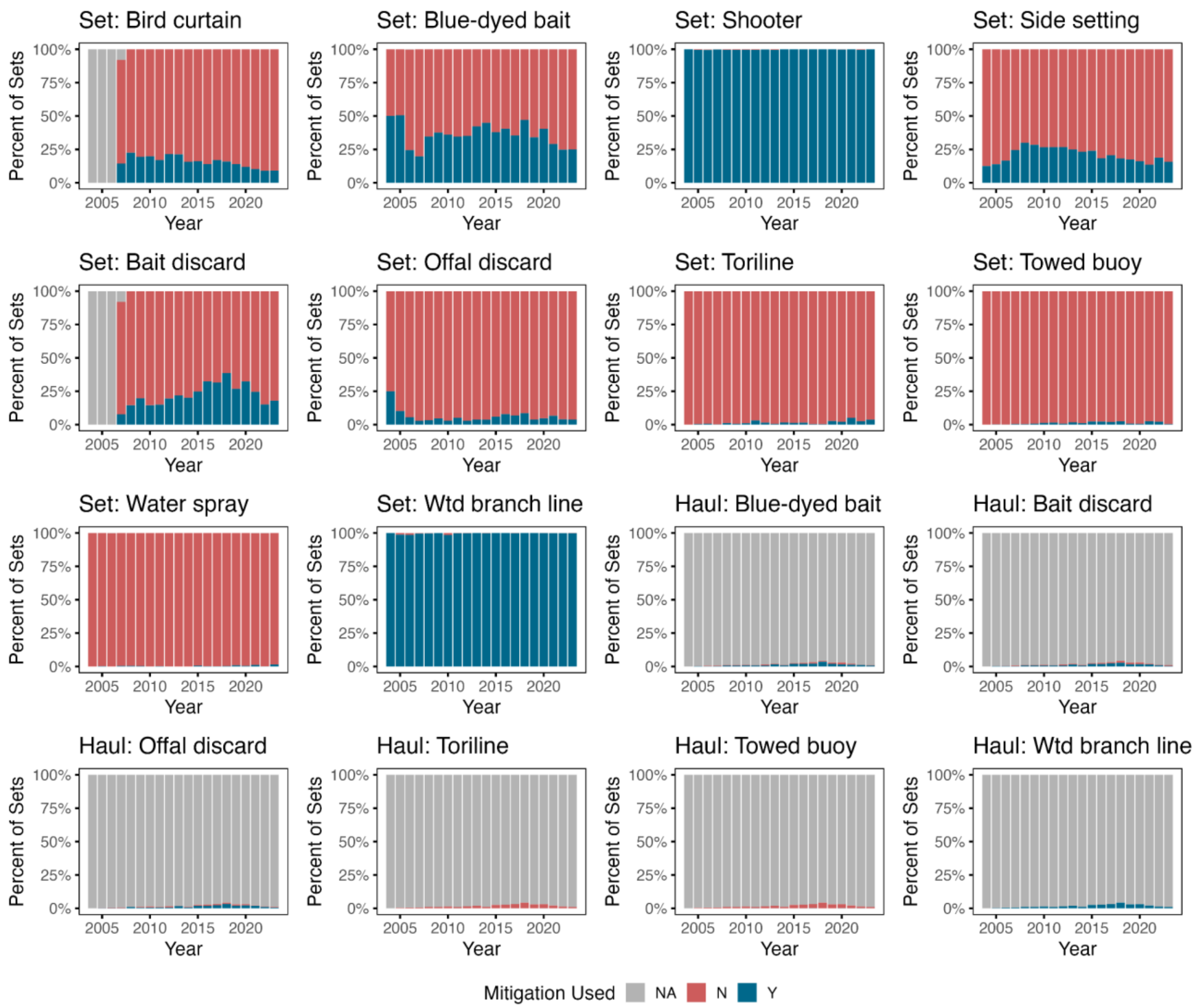

Figure 3. Annual implementation of each mitigation strategy during set or haul in the observed DSLL fishery from 2005 to 2023.

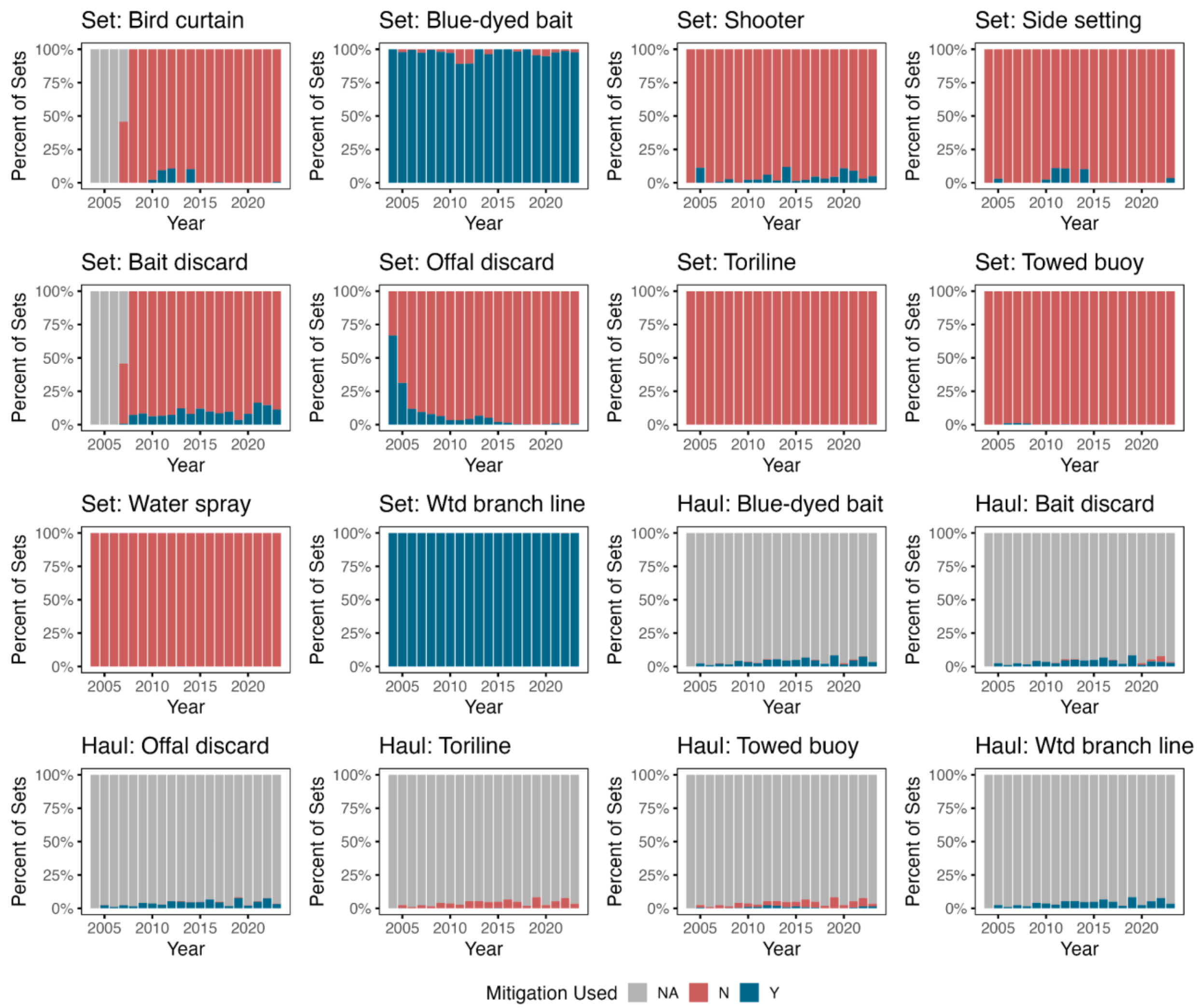

Figure 4. Annual implementation of each mitigation strategy during set or haul in the observed SSLL fishery from 2005 to 2023.

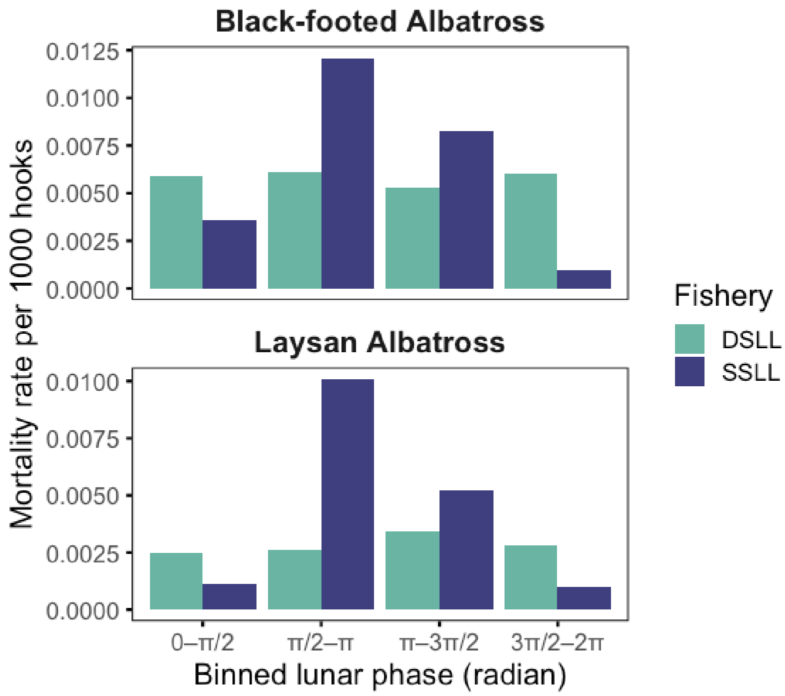

Figure 5. At-vessel mortality rate per 1000 hooks binned within each moon phase for black-footed and Laysan albatross in the observed DSLL and SSLL fisheries. Lunar phases are: 0 to π/2 (new moon to first quarter), π/2 to π (first quarter to full moon), π to 3π/2 (full moon to last quarter), and 3π/2 to 2π (last quarter to new moon).

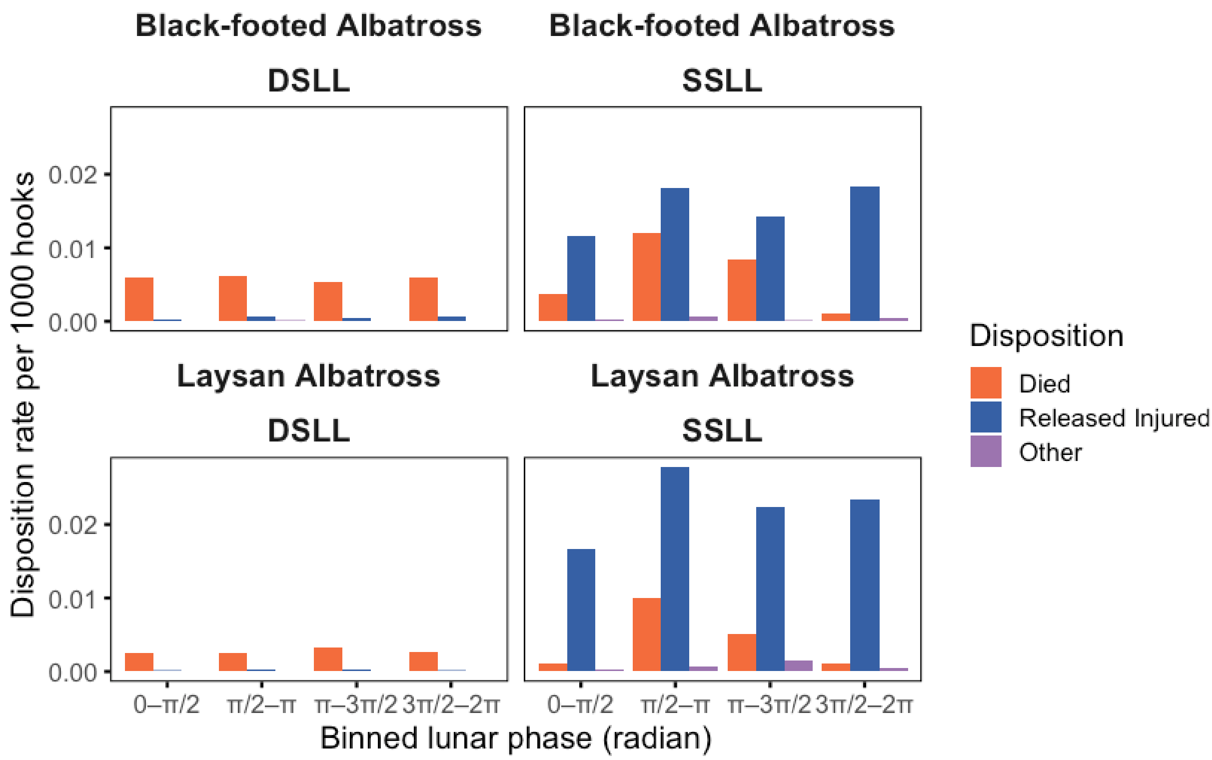

Figure 6. Disposition rate per 1000 hooks binned within each moon phase for black-footed and Laysan albatross in the observed DSLL and SSLL fisheries. Moon phases are: 0 to π/2 (new moon to first quarter), π/2 to π (first quarter to full moon), π to 3π/2 (full moon to last quarter), and 3π/2 to 2π (last quarter to new moon).

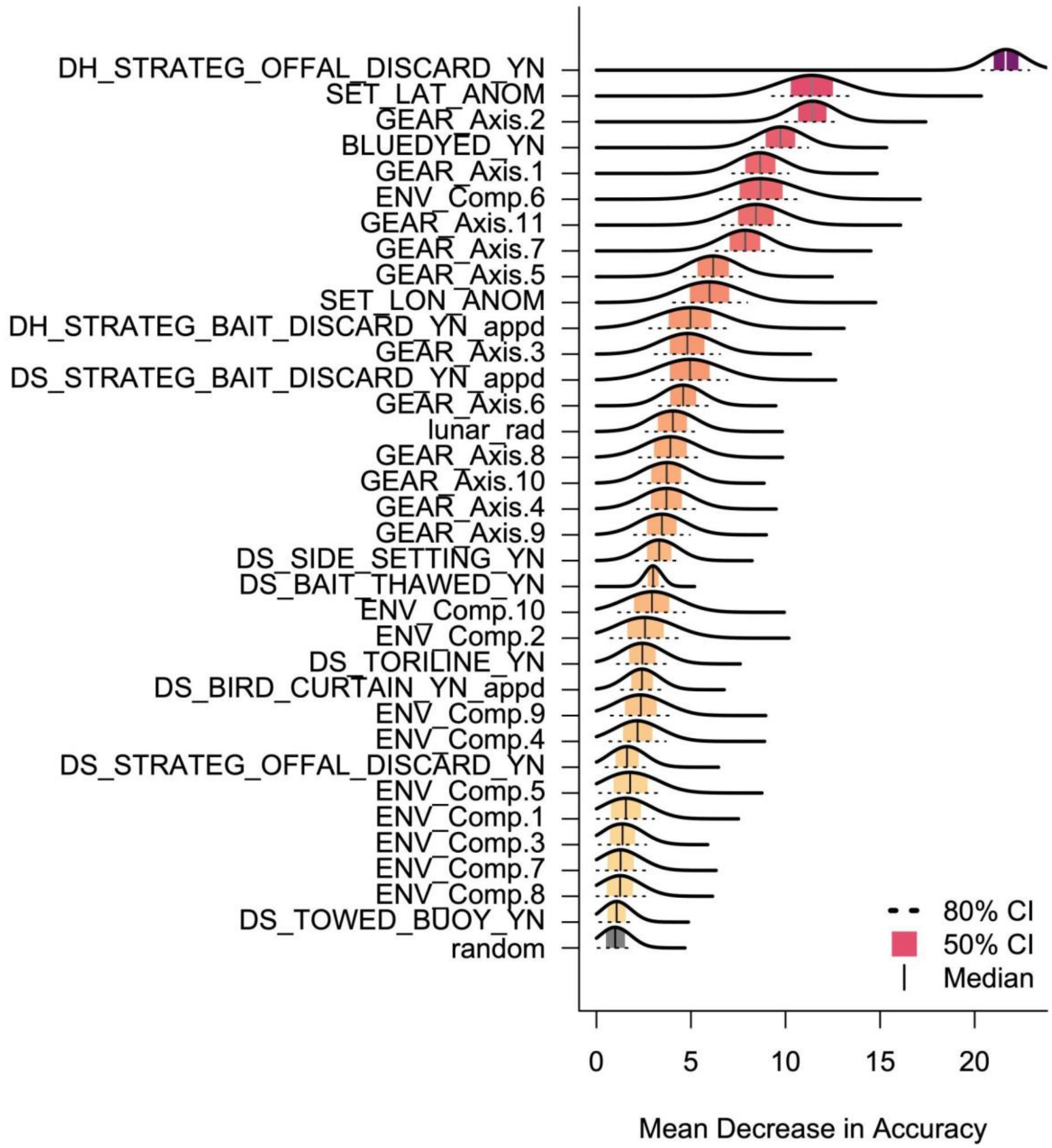

Figure 7. Variable importance of covariates included in the Ensemble Random Forests models in the DSLL fishery. Variables are in order from highest ranking to lowest from top to bottom. The solid line for each covariate's empirical distribution is the full range of variable importance metrics across 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. DS = during gear set, DH = during haul.

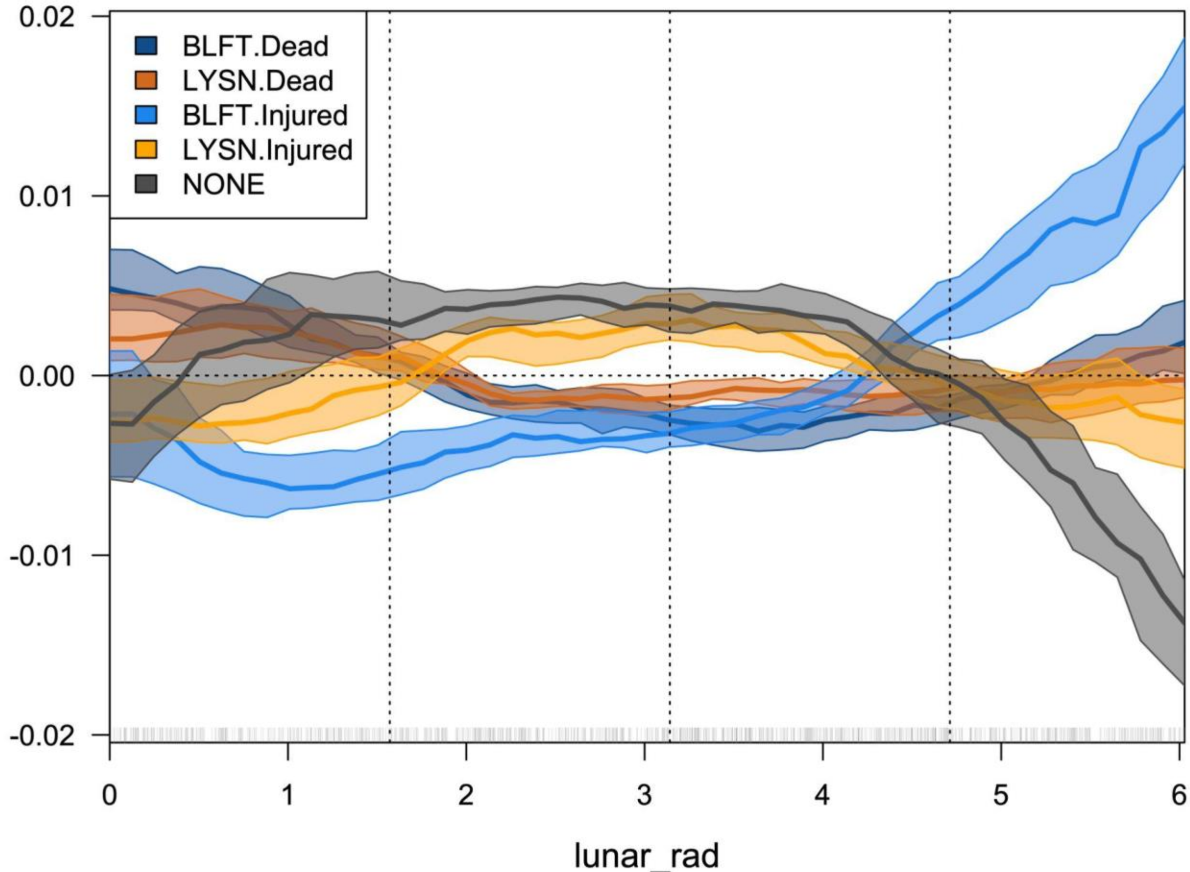

Figure 8. Accumulated local effects of lunar phase (radians) on probability for each disposition outcome for the DSLL fishery. The dashed vertical lines are associated with moon phases: 0 (new moon), 1.57 (first quarter), 3.14 (full moon) 4.71 (last quarter), 6.28 (new moon). Each solid line is the median local effect (change in probability of interaction) as a function of lunar phase while the shaded region is the 80% confidence interval. Rug (black vertical tick marks at bottom) are the observed moon phase of deep-set sets.

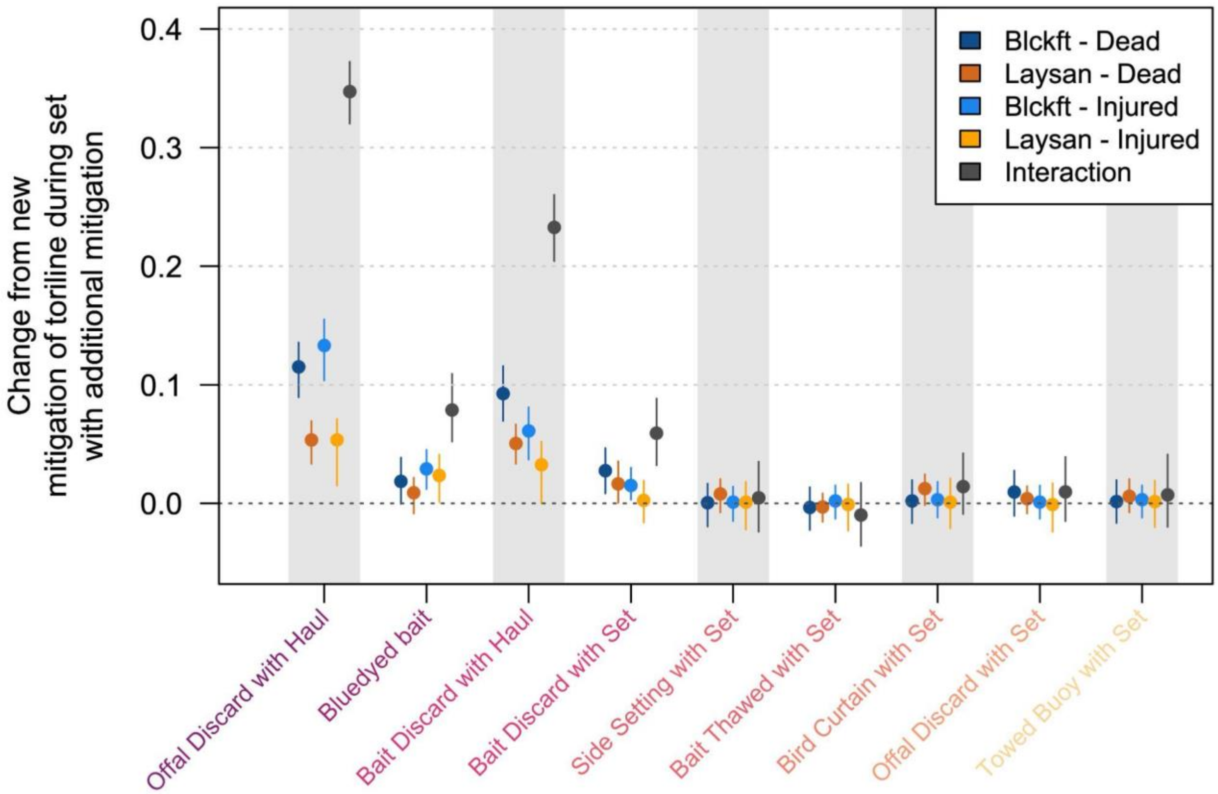

Figure 9. Accumulated local effects of each mitigation factor on probability for each disposition outcome for the DSLL fishery. Values are represented as the change in probability from the current regulation in the DSLL fishery: tori line during set. Points are median with segments indicating the 90% interval. Variables are in order from highest ranking to lowest from left to right. Note the change in gray data point representing the disposition outcome of any interaction (mortality or injury) with either species.

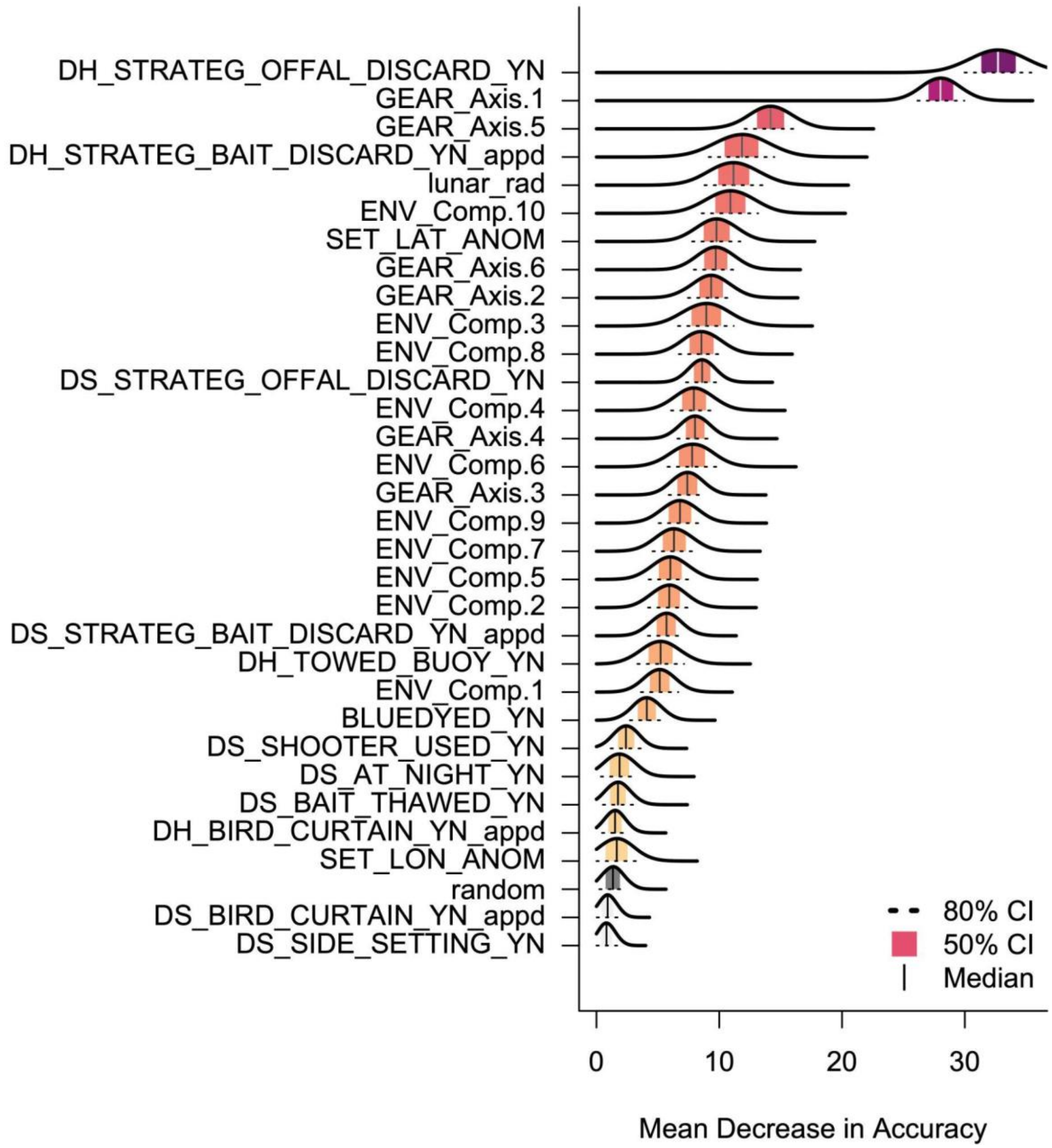

Figure 10. Variable importance of covariates included in the Ensemble Random Forests models in the SSLL fishery. Variables are in order from highest ranking to lowest from top to bottom. The solid line for each covariate's empirical distribution is the full range of variable importance metrics across 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. DS = during gear set, DH = during haul.

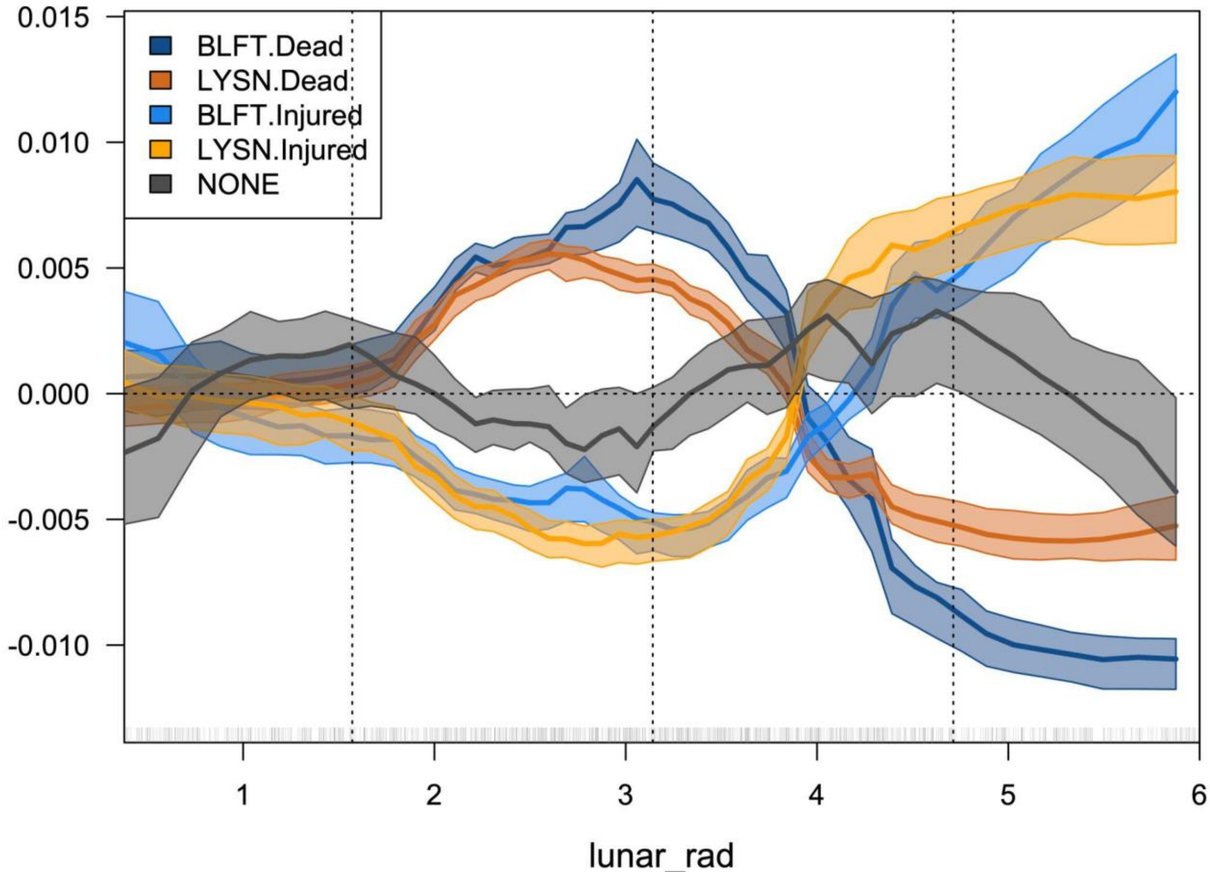

Figure 11. Accumulated local effects of lunar phase (radians) on probability for each disposition outcome for the SSLL fishery. The dashed vertical lines are associated with moon phases: 0 (new moon), 1.57 (first quarter), 3.14 (full moon) 4.71 (last quarter), 6.28 (new moon). Each solid line is the median local effect (change in probability of interaction) as a function of lunar phase while the shaded region is the 80% confidence interval. Rug (black vertical tick marks at bottom) are the observed moon phase of shallow-set sets.

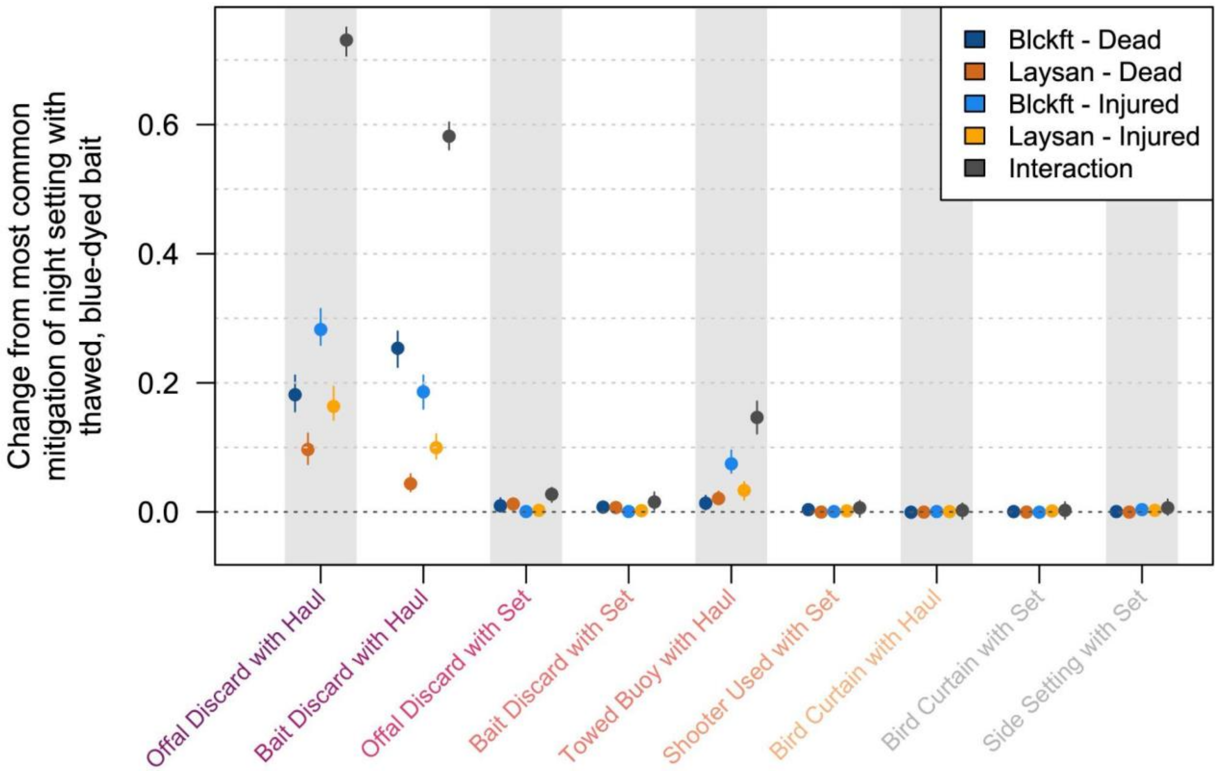

Figure 12. Accumulated local effects of each mitigation factor on probability for each disposition outcome for the SSLL fishery. Values are represented as the change in probability from the most common mitigation measure in the SSLL fishery: night setting with thawed, blue-dyed bait. Points are median with segments indicating the 90% interval. Variables are in order from highest ranking to lowest from left to right. Note the change in gray data point representing the disposition outcome of any interaction (mortality or injury) with either species.

Table 1: Percent of mitigation measures used within each observed fishery from 2005-2023.

		DSLL			SSLL		
Timing	**Mitigation measure**	**Y (%)**	**N (%)**	**Unknown (%)**	**Y (%)**	**N (%)**	**Unknown (%)**
Set	At night	0	100	0	97	3	0
	Bait discard	20	69	12	7	77	16
	Bait outside wake	99	1	0	99	1	0
	Bait thawed	87	13	0	99	1	0
	Bird curtain	14	74	12	2	82	16
	Birds recorded as present	43	45	11	13	72	16
	Blue-dyed bait	36	64	0	97	3	0
	Offal and/or bait discard	21	68	11	12	76	12
	Offal discard	5	95	0	6	94	0
	Shooter used	100	0	0	4	96	0
	Side setting	21	79	0	3	97	0
	Tori line	2	98	0	0	100	0
	Towed buoy	1	99	0	0	100	0
	Water spray	0	100	0	0	100	0
	Weighted branch line	100	0	0	100	0	0
Haul	Bait discard	1	1	98	3	0	96
	Birds present	55	33	11	81	3	16

Blue-dyed bait	1	1	98	4	0	96
Offal and/or bait discard	1	0	98	4	0	96
Offal discard	1	1	98	4	0	96
Tori line	0	2	98	0	4	96
Towed buoy	0	2	98	1	3	96
Water spray	0	2	98	0	4	96
Weighted branch line	2	0	98	4	0	96

Table 2: Overview of observed sets with at least one albatross interaction in each fishery from 2005-2023.

	DSLL (73,342 sets)			**SSLL** (21,214 sets)		
Species	**n**	**Percent (per set)**	**Rate (per 1k hooks)**	**n**	**Percent (per set)**	**Rate (per 1k hooks)**
Black-footed albatross	972	1.3	0.0053	434	2	0.0198
Laysan albatross	420	0.57	0.0023	462	2.2	0.021
Both birds	89	0.12	0.0005	69	0.33	0.0031

Table 3*:* Total observed albatross bycatch from 2005-2023. Organized by the number of sets with 1 interaction, 2 interactions, 3 interactions, and 4 or more.

	DSLL					**SSLL**				
Species	**Total**	**1**	**2**	**3**	**4+**	**Total**	**1**	**2**	**3**	**4+**
Black-footed albatross	1157	836	103	23	10	509	374	48	9	3

Laysan albatross	547	344	49	17	10	639	365	63	18	16

Table 4: Total number and percent of disposition outcomes within each observed fishery from 2005-2023. The majority of mortalities occur during the set and released injuries occur during the haulback.

		DSLL		SSLL	
Species	**Fate**	**n**	**Percent**	**n**	**Percent**
Black-footed albatross	Died	1064	92	159	31
	Released Injured	90	8	343	67
	Other	3	0	8	2
Laysan albatross	Died	516	94	114	18
	Released Injured	28	5	508	79
	Other	3	1	17	3

Table 5: Total number and percent of seabirds entangled, hooked, or both, in each observed fishery from 2005-2023.

		DSLL		SSLL	
Species	**Hook vs entangle**	**n**	**Percent**	**n**	**Percent**
Black-footed albatross	Entangled only	42	4	57	11
	Hooked only	995	87	381	76
	Hooked and entangled	103	9	65	13
Laysan albatross	Entangled only	35	6	88	14
	Hooked only	447	83	461	75

Hooked and entangled	57	11	65	11

Table 6: Total number and percent of birds hooked in each body location within each observed fishery from 2005-2023.

		DSLL		SSLL	
Species	**Hook location**	**n**	**Percent**	**n**	**Percent**
Black-footed albatross	Body/Shell	10	1	22	5
	Head/Beak/Mouth	697	63	232	52
	Ingested	291	26	59	13
	Leg/Foot/Rear flipper	8	1	37	8
	Tail	2	0	1	0
	Wing/Front flipper	95	9	95	21
	Unknown	6	1	1	0
Laysan albatross	Body/Shell	4	1	26	5
	Head/Beak/Mouth	309	61	226	42
	Ingested	138	27	61	11
	Leg/Foot/Rear flipper	3	1	66	12
	Tail	0	0	5	1
	Wing/Front flipper	52	10	149	28
	Unknown	4	1	1	0

Table 7: Total number and percent of birds hooked in each body location and their disposition outcome within each observed fishery from 2005-2023.

			DSLL		SSLL	
Species	**Hook location**	**Disposition**	**n**	**Percent**	**n**	**Percent**
Black-footed albatross	Body/Shell	Died	2	20	1	5
		Released Injured	8	80	20	91
		Other	0	0	1	5
	Head/Beak/Mouth	Died	681	98	96	41
		Released Injured	14	2	135	58
		Other	2	0	1	0
	Ingested	Died	289	99	50	85
		Released Injured	1	0	9	15
		Other	1	0	0	0
	Leg/Foot/Rear flipper	Died	4	50	1	3
		Released Injured	4	50	35	95
		Other	0	0	1	3
	Tail	Died	2	100	0	0
		Released Injured	0	0	1	100
	Wing/Front flipper	Died	47	49	6	6
		Released Injured	48	51	88	93

		Other	0	0	1	1
	Unknown	Died	6	100	1	100
Laysan albatross	Body/Shell	Died	2	50	2	8
		Released Injured	1	25	24	92
		Other	1	25	0	0
	Head/Beak/Mouth	Died	306	99	67	30
		Released Injured	2	1	154	68
		Other	1	0	5	2
	Ingested	Died	137	99	38	62
		Released Injured	1	1	23	38
	Leg/Foot/Rear flipper	Died	1	33	0	0
		Released Injured	2	67	65	98
		Other	0	0	1	2
	Tail	Released Injured	0	0	5	100
	Wing/Front flipper	Died	33	63	5	3
		Released Injured	19	37	140	94
		Other	0	0	4	3
	Unknown	Died	4	100	0	0
		Released Injured	0	0	100	100

Table 8: Black-footed and Laysan albatross at-vessel mortalities that occur within each moon phase in the observed DSLL and SSLL fishery: percent of mortalities within the lunar phase in relation to others, percent of total interactions that resulted in mortalities within each lunar phase for the species, mortality rate by set, and mortality rate by hooks (per 1000 hooks) within each lunar phase. Lunar phases are: 0 to π/2 (new moon to first quarter), π/2 to π (first quarter to full moon), π to 3π/2 (full moon to last quarter), and 3π/2 to 2π (last quarter to new moon).

		DSLL						SSLL					
Species	**Lunar phase (radians)**	**N morts.**	**N sets**	**Percent of mortalities (%)**	**Percent of total interactions that died (%)**	**Mortality rate (per set)**	**Mortality rate (per 1k hks)**	**N morts.**	**N sets**	**Percent of mortalities (%)**	**Percent of total interactions that died (%)**	**Mortality rate (per set)**	**Mortality rate (per 1k hks)**
Black-footed albatross	0–π/2	272	18381	26	95	0.0148	0.0059	16	4336	10	24	0.0037	0.0036
	π/2–π	279	18413	26	90	0.0152	0.0061	85	6657	54	40	0.0128	0.0121
	π–3π/2	241	18279	23	92	0.0132	0.0053	54	6241	34	36	0.0087	0.0083
	3π/2–2π	272	18266	26	91	0.0149	0.0060	4	3980	3	5	0.0010	0.0010
	0–π/2	116	18381	22	95	0.0063	0.0025	5	4336	4	6	0.0012	0.0011

	π/2–π	118	18413	23	94	0.0064	0.0026	71	6657	62	26	0.0107	0.0101
Laysan albatross	π–3π/2	153	18279	30	93	0.0084	0.0034	34	6241	30	18	0.0054	0.0052
	3π/2–2π	129	18266	25	96	0.0071	0.0028	4	3980	4	4	0.0010	0.0010

Table 9: Threshold-dependent performance of the multivariate categorial ERF models of disposition outcomes for black-footed and Laysan albatross in the DSLL and SSLL fisheries. The metrics include area under the curve (AUC), root mean squared error (RMSE), and true still statistic (TSS). There were five possible dispositions for the model in each fishery: at-vessel mortality for black-footed albatross, at-vessel mortality for Laysan albatross, black-footed albatross injury but released alive, Laysan albatross injury but released alive, or no interaction.

Fishery	Disposition	AUC	RMSE	TSS
DSLL	Black-footed albatross- Dead	0.92	0.19	0.69
	Laysan albatross- Dead	0.97	0.16	0.82
	Black-footed albatross- Injured	1	0.12	0.99
	Laysan albatross- Injured	1	0.10	1
	No interaction	0.96	0.51	0.80
SSLL	Black-footed albatross- Dead	1	0.08	0.99
	Laysan albatross- Dead	1	0.06	0.99
	Black-footed albatross- Injured	1	0.10	0.98
	Laysan albatross- Injured	1	0.10	0.98
	No interaction	1	0.17	0.99

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Supplementary Information

Table S1: Environmental covariates included in the environmental principal component analysis.

Covariate category	Covariate	Definition	Spatial resolution	Temporal resolution	Citation
Temporal	lunar_rad	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_anom	sea surface temperature anomaly	4 km	8 days	OceanWatch-ERDDAP
	sst_front	strength of the SST front			Derived
	sst_distfront_ses	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_zonal	zonal current speed (W-E)	0.33 °	5 days	PO.DAAC-JPL
	current_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
	current_distfront_ses	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	ssh_sla	sea level anomaly	0.17 °	5 days	PO.DAAC-JPL
	ssh_okuboweiss	Okubo Weiss value	0.17 °	5 days	Derived
	ssh_eke	eddy kinetic energy	0.17 °	5 days	Derived
Sea Wind Attributes	wind_zonal_mean	mean zonal wind speed across 6 h intervals of set soak (W-E)	0.25 °	1 day	NOAA NCEI

	wind_meridional_mean	mean meridional wind speed across 6 h intervals of set soak (N-S)	0.25 °	1 day	NOAA NCEI
	wind_front_mean	mean wind front across 6 h intervals of set soak	0.25 °	1 day	NOAA NCEI
	wind_divergence_mean	mean wind divergence across 6 h intervals of set soak	0.25 °	1 day	Derived
	wind_vorticity_mean	mean vorticity across 6 h intervals of set soak	0.25 °	1 day	Derived
	wind_ekmanpumpvel_mean	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
	seamt_dist_ses	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

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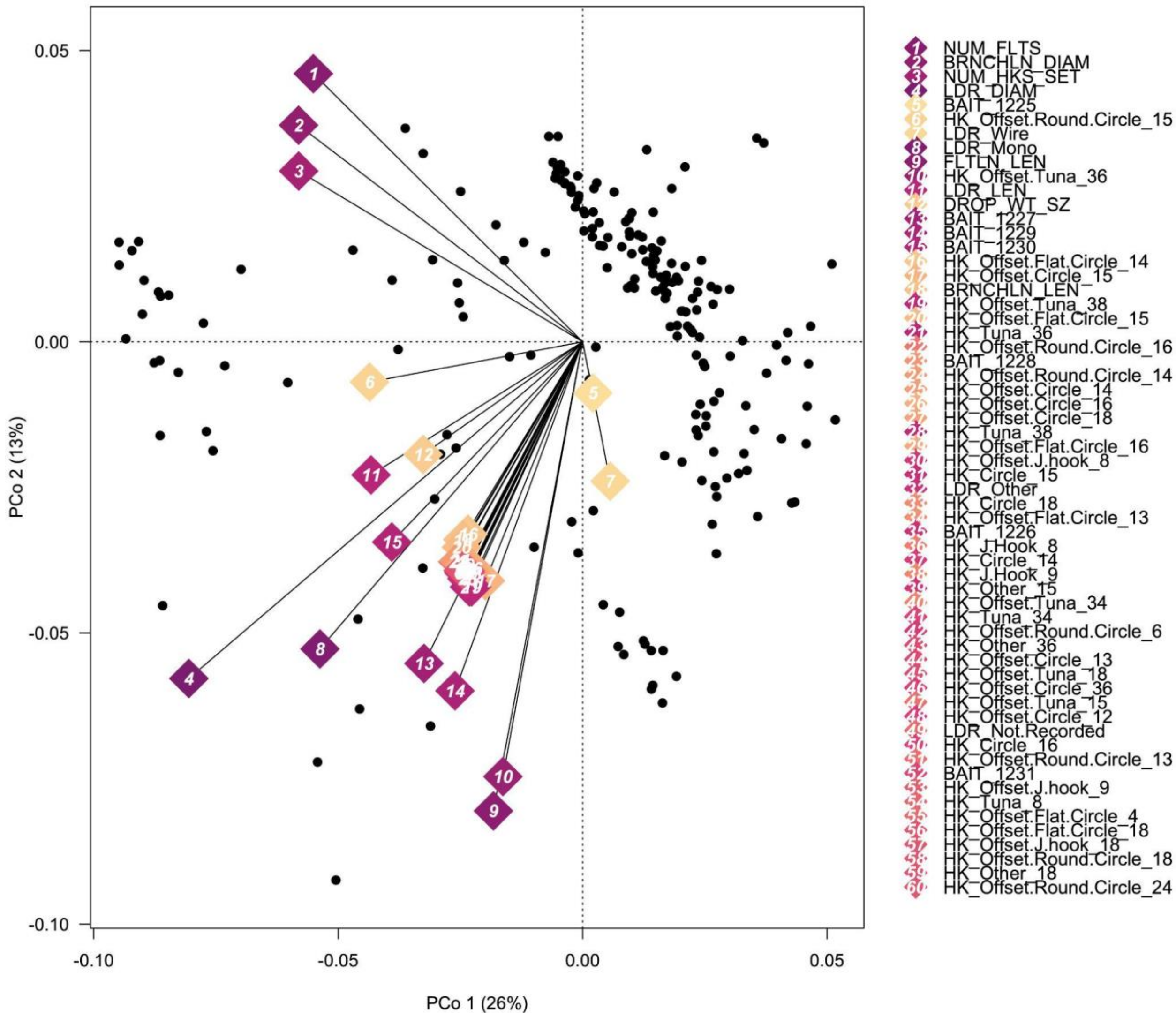

Figure S1. The first and second principal components from a Principal Coordinates Analysis (PCoA) of the gear used in the DSLL fishery from 2005 to 2023. Each point represents a configuration combination's first and second principal components score. Vectors indicate the loadings of each gear type in the first and second principal components, darker colors indicate higher ranked loading values across both PCs.

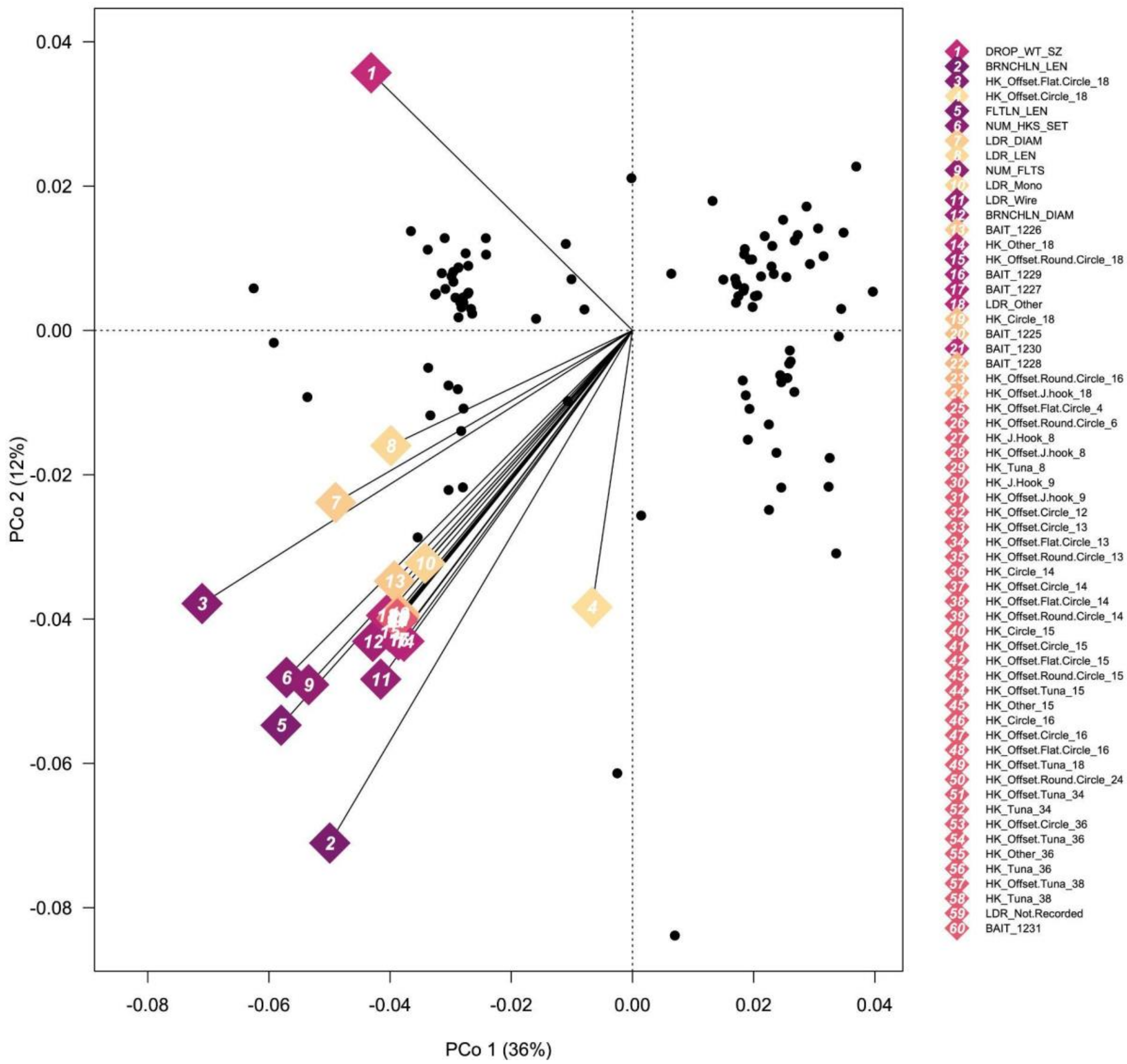

Figure S2. The first and second principal components from a Principal Coordinates Analysis (PCoA) of the gear used in the SSLL fishery from 2005 to 2023. Each point represents a configuration combination's first and second principal components score. Vectors indicate the loadings of each gear type in the first and second principal components, darker colors indicate higher ranked loading values across both PCs.