Could tori lines replace blue-dyed bait to reduce seabird bycatch risk in the Hawaii deep-set longline fishery?

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EXECUTIVE SUMMARY

The comparative efficacy of tori lines and blue-dyed fish bait as seabird bycatch mitigation measures was assessed for the Hawaii deep-set tuna longline fishery. Tori lines have been shown to be an effective seabird bycatch mitigation measure for many pelagic and demersal longline fisheries, but the effectiveness of blue-dyed bait remains equivocal (Gilman et al 2021b).

The Western Pacific Regional Fishery Management Council is considering whether to replace blue-dyed fish bait with tori lines in the prescribed suite of bycatch mitigation measures available to the Hawaii-based deep-set tuna longline fishery. The efficacy of three seabird bycatch mitigation measures (tori line, blue-dyed fish bait, strategic offal discharge) for this fishery has been previously evaluated but the blue-dyed bait effect was equivocal because it was a confounded treatment with offal discharge due to regulatory restrictions (Gilman et al 2021b).

A partial factorial experiment that was exempt from the blue-dyed fish bait and offal discharge regulatory restrictions was commissioned to evaluate the comparative efficacy of tori lines and blue-dyed bait to reduce seabird interactions in this deep-set longline fishery - where interactions are attempts to contact a baited hook or actual contacts with a baited hook. The study was conducted under a NOAA Fisheries Experimental Fishing Permit issued to the Hawaii Longline Association on January 27, 2021. The purpose was to support evidence-informed seabird bycatch mitigation policy in this fishery.

The field experiment comprised 87 sets deployed during 7 trips from 3 Hawaii-based commercial longline vessels. The partial factorial design involved random assignment on each trip to one of the two treatments (tori line, blue-dyed fish bait) for the initial set and then alternating the two treatments for each subsequent set in the trip. All the sets were deployed with lines shooters, similar branchline weights and no offal discharge during setting operations. Nearly 99% of all the seabird interactions during this experiment were for black-footed (*Phoebastria nigripes*) and Laysan albatrosses (*Phoebastria immutabilis*).

We used a Bayesian modelling workflow to model statistically the albatross interactions (attempts to contact a baited hook, actual contacts with a baited hook) recorded using onboard stern-view video-based electronic monitoring. This modelling approach supports robust statistical inference about the comparative efficacy of the two mitigation measures evaluated (tori lines, blue-dyed bait).

The number of albatrosses captured on the hook (drownings) was also recorded during the gear haulback — only 13 albatrosses were hook-caught in this experiment.

We found that tori lines worked as an effective seabird bycatch mitigation measure in this trial fishery, which is consistent with previous findings for this fishery (Gilman et al 2021b). More importantly, we found that tori lines were a far more effective seabird bycatch mitigation measure than blue-dyed fish bait. In contrast to Gilman et al (2021b), we were able to unequivocally determine the comparative efficacy of tori line and blue-dyed fish bait as seabird bycatch mitigation measures in this fishery.

Specifically, we found that:

- albatrosses were 1.5 times (95% HDI[1]: 1-2.2) less likely to attempt to contact a baited hook when tori lines were deployed compared to sets deployed with blue-dyed fish bait

[1] HDI = highest posterior density interval (the shortest uncertainty interval)

- albatrosses were ca 4 times (95% HDI: 1.5-9.2) less likely to contact a baited hook when tori lines were deployed compared to sets deployed with blue-dyed fish bait

- albatrosses were ca 14 times (95% HDI: 7.8-18.6) less likely to be captured on a baited hook when tori lines were deployed compared to sets deployed with blue-dyed fish bait

It has been shown elsewhere and for this fishery that tori lines tend to increase the median distance from the vessel stern that seabird attacks occur on sinking longline gear (Gilman et al 2021a). The point being that the further astern that a gear/bait interaction can be deterred the better for reducing capture risk, since the further astern, the more likely the baited hook has sunk to a depth inaccessible to a surface foraging albatross.

We found albatross interactions with longline gear deployed with tori lines occurred significantly further astern than for those sets deployed with blue-dyed bait. This finding further reinforces the benefits of using tori lines rather than blue-dyed bait as an effective seabird bycatch mitigation measure.

1. INTRODUCTION

Fisheries that target productive species such as tunas can profoundly affect co-occurring bycatch species with low fecundity, delayed maturation and other life history traits that make them vulnerable to anthropogenic sources of mortality (Hall et al 2000, Chaloupka 2002, Dulvy et al 2014). Bycatch in longline and other fishing gear types is a serious threat to albatrosses and petrels, which are two of the three most threatened groups of seabirds (Dias et al 2019, IUCN 2021).

Of 29 albatross and large petrel species listed under the Agreement on the Conservation of Albatrosses and Petrels (ACAP), 19 are categorized as threatened (Phillips et al 2016, IUCN 2021). Thus, a range of gear technologies have been recommended to help mitigate seabird bycatch in pelagic longline fisheries (ACAP 2019).

Seabird bycatch of the Hawaii-based deep-set tuna longline fishery operating in the central North Pacific comprises mainly the Laysan (*Phoebastria immutabilis*) and the black-footed albatrosses (*Phoebastria nigripes*), with stable and increasing population trends, respectively (Gilman et al 2016, IUCN 2021). There was a 67% decline in standardized seabird catch rates in the tuna fishery following the introduction of seabird regulations (Gilman et al 2008).

However, the albatross catch level has been significantly increasing over the past decade (Gilman et al 2016, WPRFMC 2020). The most recent seabird bycatch estimate in 2019 for the fishery was ca 1000 captures, of which 96% were retrieved dead (NMFS, 2021) and were most likely were captured during setting rather than during haulback (Gilman et al 2016).

The increasing trend in annual bycatch levels is attributable to increasing fishing effort and increasing black-footed albatross nominal catch rates, which was linked to an increase in the number of black-footed albatrosses attending vessels. This increase in black-footed albatross density around the fishing vessels might be a response to changes in seasonal and spatial distribution of fishing effort, variability in environmental conditions and in ocean productivity linked to inter-annual and decadal climate cycles, and also to the increasing population trend of black-footed albatrosses (Kappes et al 2015, Gilman et al 2016, Wren et al 2019).

Regulations to mitigate seabird bycatch in the Hawaii-based deep-set tuna longline fishery require the implementation of one of two alternative suites of measures when fishing north of 23° N: (1) set gear from the side of the vessel, deploy a bird curtain, and attach weights ≥45 g within 1 m of the hook; or (2) use blue-dyed and thawed bait, 'strategically' discharge offal during setting or hauling, use a mainline line shooter, and attach weights ≥ 45 g within 1m of the hook (NMFS 2005). The US regulations for the deep-set fishery differ from the seabird management measure adopted by tuna RFMOs such as WCPFC and IATTC, which allow parties to choose one or two alternative mitigation methods depending on the location of fishing grounds and vessel length.

While the side setting suite of measures is understood to produce significantly lower seabird catch rates relative to the alternative suite of measures (Gilman et al 2007, Gilman et al 2016), most vessels choose the option that includes blue-dyed bait (for example, 82% of vessels used the blue-dyed bait suite of measures in 2019, NMFS 2021). This fishery primarily uses forage fish species for the bait (NMSF 2021).

In the 1970s, US East Coast longline fishers experimented with colored squid baits to attempt to increase swordfish catch rates (McNamara et al 1999). Importantly, it was further presumed that blue-dyed bait might make it more difficult for seabirds to detect at the sea surface or that seabirds might be disinterested in unnatural-colored baits (Boggs 2001, Gilman et al 2007). Thawed fish bait may sink faster than frozen and partially thawed fish bait, thus reducing seabird access to baited hooks (Brothers et al 1999, Robertson & van den Hoff 2010). Interestingly, blue-dyed bait was found to be ineffective at reducing marine turtle bycatch in an experimental pelagic longline fishery (Swimmer et al 2005).

Another seabird bycatch mitigation strategy includes the use of tori-lines. A tori line is a line with streamers that is towed from the stern of the vessel as crew set baited hooks (Melvin et al 2013). The forward movement of the fishing vessel creates drag on the streamer line, so that a section of the line is in the air above the sea surface. This aerial portion of the streamer line can have streamers attached at various intervals to contribute to protecting baited hooks from scavenging seabirds.

Several previous studies have found that tori lines, perhaps co-applied with other bycatch mitigation measures such as blue-dyed bait, can achieve substantial reductions in seabird interactions with longline gear (Yokota et al 2011, Melvin et al 2013, Sato et al 2016, Domingo et al 2017, Gladics et al 2017, Gilman et al 2021b).

However, there have been very few experimental assessments of blue-dyed fish bait effectiveness for seabird bycatch mitigation (Brothers et al 1999, McNamara et al 1999, Cocking et al 2008, Ochi et al 2011, Gilman et al 2016). Gilman et al (2021b) found that the efficacy of blue-dyed fish bait for the Hawaii-based tuna longline fishery was equivocal because of the regulatory constraints that restricted the sampling design that could be applied (Figure 1: top right panel).

Gilman et al (2021b) recommended that additional field trials be conducted to further clarify whether blue-dyed bait was an effective seabird bycatch mitigation measure. The Western Pacific Regional Fishery Management Council is currently exploring whether tori lines might in fact be a suitable replacement for blue-dyed fish bait in the prescribed suite of bycatch measures available to the Hawaii-based deep-set tuna longline fishery (WPRFMC 2020).

So, the Western Pacific Regional Fishery Management Council has sponsored an additional field experiment using commercial longline vessels coupled with stern-view video-based electronic monitoring to evaluate unequivocally the comparative efficacy of tori lines and blue-dyed thawed fish bait as seabird bycatch mitigation measures for the US central North Pacific tuna longline fishery.

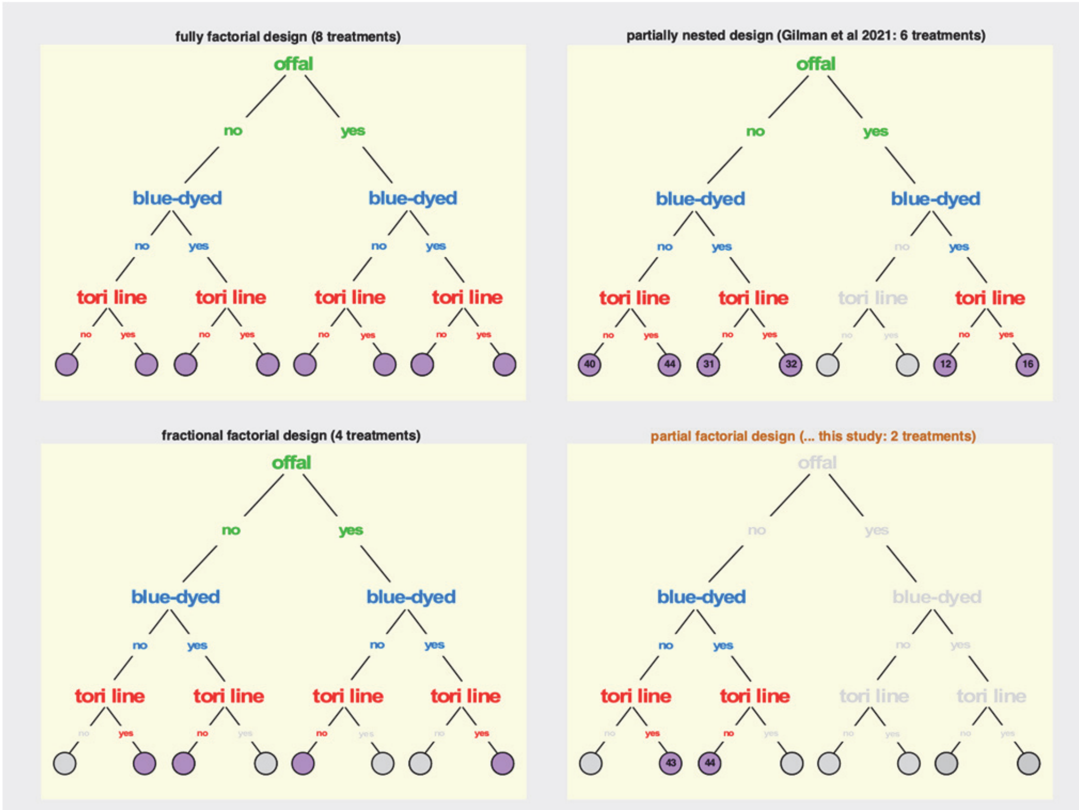


Figure 1 Experimental design options for evaluating the efficacy of 3 seabird bycatch mitigation measures in the Hawaii deep-set longline fishery. (*Top left*) shows the full factorial design for a 3-factor study for strategic offal discharge, blue-dyed bait and tori lines assuming exemption from regulatory requirements applicable to this fishery. (*Top right*) shows the partially nested or partially clustered design used in Gilman et al (2021b) — terminal nodes show that number of sets deployed with that treatment where nodes with no sets shows those treatment arms that did not occur in that study, due to regulatory requirements. (*Bottom left*) shows a fractional factorial design to address the efficacy of the 3 mitigation measures (offal, blue-dyed bait, tori line) that requires less sampling effort that the full factorial design and supports estimation of the main-effects but not any interactions — it is a strategic subset of the full factorial shown in the top left panel. (*Bottom right*) shows the partial factorial design adopted here to compare the efficacy of two bycatch mitigation measures (tori line, blue-dyed bait) given funding constraints and an exemption for the regulatory requirements — there were 43 sets deployed with tori lines only and 44 sets deployed with blue-dyed bait only.

2. METHODS

2.1. Experimental Design Options

Various experimental designs to disentangle the effects of seabird bycatch mitigation measures were considered for this trail (Figure 1) — including full factorial and fractional factorial designs that are strategic subsets of full factorial designs (Cochran & Cox 1957, Montgomery 2000). Specifically, the full factorial design applicable to this field experiment comprises the 3 bycatch mitigation measures or treatments (strategic offal discharge, tori line, blue-dyed bait), which were addressed in Gilman et al

(2021a) where the partially nested design was applied due to regulatory constraints (Figure 1 top right). The full 3-factor design (Figure 1 top left) and a main-effects only fractional factorial design (Figure 1 bottom left) would have enabled all 3 treatments to be evaluated but these 2 designs were considered infeasible here due to funding considerations.

Moreover, the main policy focus for the Western Pacific Regional Fishery Management Council was on comparing the comparative efficacy in a field trial of tori lines and blue-dyed bait as seabird bycatch mitigation measures. Comparing the 2 bycatch measures (tori lines, blue-dyed bait) results in the partial factorial design shown in Figure 1 (bottom right) — which is also a main-effects only design (like the fractional factorial design) but lacks an explicit control treatment unlike the fractional factorial design (Figure 1 bottom left): [offal=yes, blue-dyed=yes, tori=yes]). The partial factorial design (Figure 1: bottom right) was subsequently selected in this field experiment to evaluate the comparative efficacy of the two seabird bycatch mitigation measures (tori line, blue-dyed thawed fish bait).

2.2. Experimental Setting

The field experiment comprised 87 longline sets deployed during 7 trips from 3 commercial longline vessels undertaken between February and June 2021. All 3 vessels used 45 g lead-centered swivels attached about 0.6 m from the hook, monofilament leaders, thawed milkfish (*Chanos chanos*) and saury (*Cololabis saira*) for bait and a mix of 14/0 and 15/0 circle hooks. One of the vessels used both 'weak' hooks with a narrower 4.2 mm wire diameter and conventional hooks with a 4.5 mm wire diameter.

A previous analysis found, for these types of data for this fishery using the models applied here, that a study with between 25-63 sets should have sufficient statistical power to detect a moderate to strong effect (Chaloupka 2019). All 3 vessels operate in the Hawaii-based deep-set longline fishery that targets mainly bigeye and yellowfish tunas. The experiment comprised 2 treatments: (1) tori line and (2) blue-dyed thawed fish bait. Tori lines were deployed for 43 of the 87 sets and blue-dyed bait for 44 sets (Figure 1: bottom right). No tori line entanglements were encountered during the trials.

Branchline weighting and line shooter seabird bycatch mitigation measures were used for all 87 sets and no offal or bait were discharged during setting operations. Here the longline set is the fundamental sampling unit or blocking factor (Bergh et al 1990, Jensen et al 2018) that is nested within trip, which is itself nested within vessel. So, the sampling design comprises 3 crossed random effects: set, trip, vessel. This multilevel or hierarchical random-effects structure needs to be accounted for in any statistical modeling of the estimated treatment-specific effects on albatross bycatch rates.

2.3. Tori Line Design and Electronic Monitoring System

The tori line design and deployment used here were described in detail in Gilman et al (2021a). The application of electronic monitor systems for fisheries related management has been promoted by van Helmond et al (2020) and Gilman et al (2020) with the specific onboard video-based EM system used here described in Gilman et al (2021a). The EM analyst estimated that the tori line aerial extent was 50 m throughout for all the 43 tori line treatment sets. The protocol for recording seabird attempts and contacts with baited hooks was the same as applied in Gilman et al (2021a, 2021b) with the description of the data fields and data collection methods summarised in Appendix 1.

2.4. EM-derived Data

2.4.1. Interactions with the Gear/Bait (or Baited Hook)

The data comprised the number of seabird interactions, which were for either the black-footed albatross or the Laysan albatross exposed to the Hawaii-based deep-set longline fishery. For most analyses here, the 2 albatross species records were combined into a generic albatross species category as there were too few data to estimate species-specific interaction rates with baited hooks. Importantly, the black-footed albatross accounted for 91% of attempts to contact a baited hook and ca 55% of the actual contacts with a baited hook. So, any inference regarding attempts to contact a baited hook metric is based mainly on data for the black-footed albatross rather than the Laysan albatross. There were 5 Laysan and 8 black-footed albatross captures recorded during the gear haulback with all 13 albatross captures retrieved from sets deployed with thawed blue-dyed fish bait.

Here the focus was on the following albatross-specific interactions or response metrics (Figure 2): (1) number of albatrosses recorded as hook-caught ("captured") on each set, (2) the number of albatross attempts to contact a baited hook recorded for each set and (3) the number of albatross contacts with a baited hook recorded for each set. The recorded albatross attempts and contacts with baited hooks were determined for each set using the onboard video-based electronic monitor system using pre-determined criteria for classifying an interaction as an attempt or a contact (Gilman et al 2021a). There were too few attempts or contacts > 2 or 3 to model meaningfully (Figure 2), so these response metrics were more appropriately restructured as a binary or Bernoulli response (0,1) variable with the attempt rate being recoded as either 0 for no attempts and 1 for one or more attempts. The same procedure was applied to the albatross contacts data.

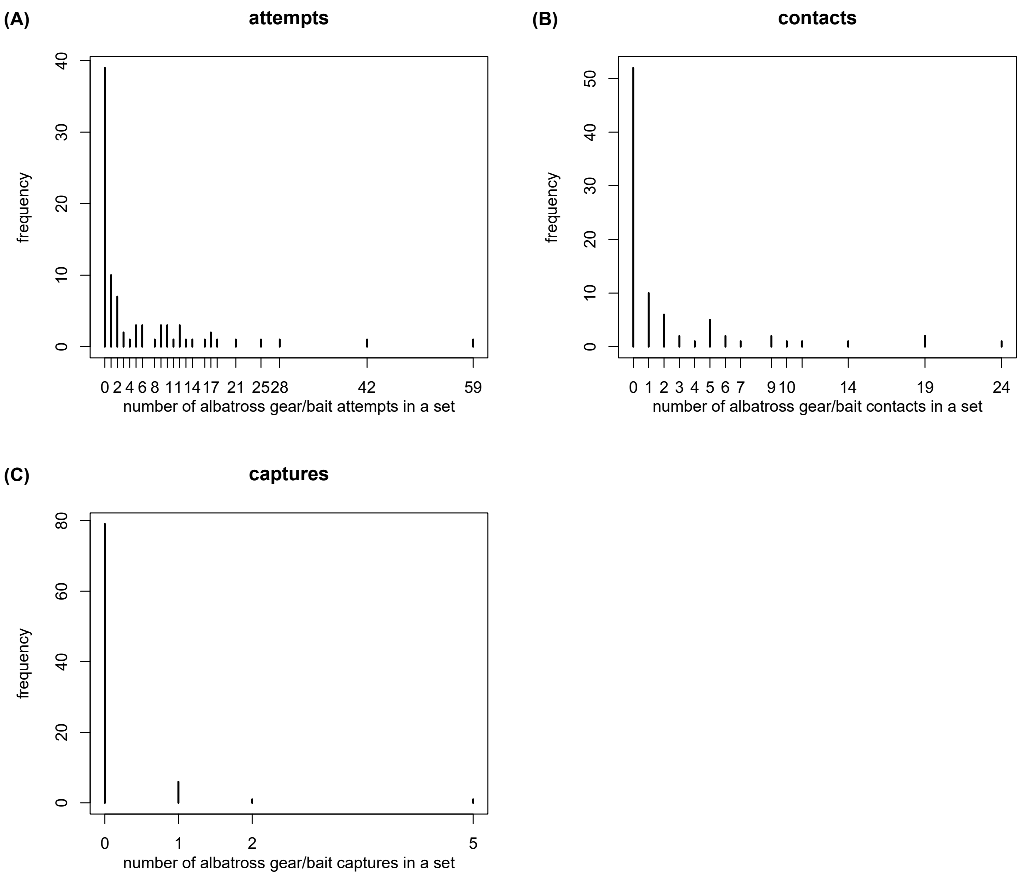


Figure 2 Summary of albatross interactions for each of the 87 sets. (Panel A) shows frequency of albatross attempts for each set. (Panel B) shows frequency of albatross contacts for each set. (Panel C) shows frequency of albatross captures (drownings) for each set.

2.4.2. Distance astern observations

It has been shown that tori lines tend to increase the distance astern that seabird attacks occur on sinking longline gear (Melvin et al 2001, Cortés & González-Solís 2018). The main point of interest here being that the further astern that a gear/bait interaction can be deterred the better for reducing interaction rates (especially contacts and captures), since the gear has probably sunk to a depth no longer readily accessible to a diving or surface foraging seabird (Melvin et al 2014). The EM analysts in this field experiment recorded 646 distance astern observations from 49 of the 87 sets for the albatross interactions with baited hooks. Treatment-specific interactions were recorded as either an attempt or a contact with a baited hook and were also recorded separately for each of the 2 seabird species encountered (black-footed albatross, Laysan albatross).

2.5. Statistical Modelling Approaches

2.5.1. Modelling the albatross attempt and contact rates

The statistical modelling approach used here was based on a Bayesian inference workflow (Gabry et al 2019) based on a spatially-explicit generalised additive mixed regression model structure (geoGAMM: Fahrmeir & Lang 2001, Kammann & Wand 2003) with an appropriate response-specific likelihood for the various forms of interaction rate data (see Gilman et al 2020 or Gilman et al 2021b for recent fishery related examples). The Bayesian approach to statistical modelling provides a powerful way to account for uncertainty in the data, the model parameters and the model structure using probability theory (Gelman et al 2020).

The Bayesian modelling workflow used here comprised: (1) prior predictive checks to assess the adequacy of the priors used for (2) a robust statistical model accounting for experimental design constraints and potential predictors of interaction rates followed by (3) posterior predictive checks of the adequacy of the statistical model(s) fitted to the interaction data.

Here the response metrics are binary data (for example: 0 = no attempts, 1 = at least one attempt to contact a baited hook) and so are sampled from a Bernoulli probability distribution and so appropriately modelled using a regression model with Bernoulli likelihood — which is a special case of a binomial likelihood but now with a single trial (Congdon 2003).

Specifically, geoGAMMs with Bernoulli likelihood were fit to the albatross interaction data (ATTEMPT = at least 1 albatross attempt to attack the gear, CONTACT = at least 1 albatross contact with a baited hook) while accounting for potentially informative predictors using the Stan computation engine (Carpenter et al 2017) via the `brms` interface (Bürkner 2017). All models here were implemented using weakly informative regularizing priors (Lemoine 2019, Ott et al 2021) with prior predictive graphical summaries used to assess adequacy of the priors (Gabry et al 2019).

The predictors included treatment (tori line, blue-dyed bait), wind force category (< Beaufort 4 or ≥ Beaufort 4), cloudiness (overcast or not), mean density of seabirds observed attending the vessel and the specific set geolocation. Cubic smoothing splines (Wood 2006) were used to account for possible nonlinear functional form of the covariates such as seabird density near the vessel. The structured spatial effect of the individual set geolocations was estimated in the geoGAMMs using a 2D Gaussian Process structure (Gelfand & Schliep 2016, see Gilman et al 2020b for a recent fishery related example).

The random effect structures (intercepts-only) included in the geoGAMMs were the identity of the 7 trips and the identity of the 3 vessels to account for any correlated or trip- and/or vessel-specific heterogeneity in the interactions rates not accounted for by the other predictors.

Model selection was based on leave-one-out cross-validation metrics to estimate any comparative difference in expected predictive accuracy between the various models fitted such as whether to include an explicit spatial effect or not or whether including a vessel-specific random effect was necessary (Vehtari et al 2017). The weight of evidence in favour of one model over any other candidate models was also assessed using Bayesian stacking, which is the Bayesian analogue of model averaging (Yao et al 2018).

The posterior samples for all models were sourced from 4 chains and 20,000 iterations after a warmup of 1000 iterations per chain. Therefore, the posterior for each estimate comprised 16,000 samples or draws that were used to derive the uncertainty intervals (HDIs or highest posterior density intervals: Kruschke & Liddell 2018) using the `tidybayes` package for R (Kay 2020a). This summary display showing both the full posterior distribution of the parameter coupled with the summary metrics (median, 95% HDI) helps to support a more precise form of communicating parameter uncertainty (van der Bles et al 2019).

Model convergence was assessed using parameter-specific diagnostics such as multiple chain rank plots, bulk and tail effective sample size metrics and a rank-based *Rhat* statistic (Vehtari et al 2021) — all diagnostics reflected convergence of all models used here. Further evaluation of the best-fit-model was assessed using graphical posterior predictive checks (Gelman et al 2014, Gabry et al 2019). All inference was made using the best-fit model.

In any experimental setting it is important to be able to conclude that there was an effect, when there really was an effect. And it is equally as important to be able to conclude that there was no effect, when there was no effect. This can be done using indices of existence and significance in a Bayesian setting (Makowski et al 2019). A probability statement about the *existence* of a particular effect and its direction, such as tori line effects, can be determined with those 16,000 draws using the probability of direction metric proposed recently by Makowski et al (2019) — also known as the maximum probability of an effect.

The *significance* (rather than just existence) of any such effect (or parameter estimate) was then assessed using the HDI+ROPE approach (Kruschke & Liddell 2018). The region of practical equivalence (ROPE) has been proposed as a robust procedure to determine the significance of a meaningful effect in a Bayesian setting using the posterior draws from the best-fit model along with the calculated 95% HDIs of those draws (Kruschke & Liddell 2018). An appropriate ROPE range or "null hypothesis" region for a regression model with Bernoulli likelihood has been defined by Kruschke & Liddell (2018) as [-0.18,0.18].

The decision rule is that if the HDI lies entirely outside the ROPE then reject the "null hypothesis" that the sampled groups are the same or equivalent (Kruschke & Liddell 2018). If the HDI is lies entirely within the ROPE, then accept the "null". Otherwise, the decision to reject or accept is "undecided". This is called the HDI+ROPE decision rule (Kruschke & Liddell 2018). Kelter (2020) suggested recently that using a 100% HDI based on the entire posterior distribution (aka full ROPE) could be used for a more robust decision. The existence and significance metrics were derived here using the `BayestestR` package for R (Makowski et al 2019).

Finally, the estimated effects summaries based on the best-fit conditional regression models were then adjusted for variable sample size of the treatments using the marginal means approach (Searle et al 1980, Lenth 2016) and implemented using the `emmeans` package for R (Lenth 2020) — here however, we specifically use the median rather than the mean. The `ggplot2` (Wickham 2016) and `colorspace` (Zeileis et al 2020) packages for R were used for all summary graphics while the `patchwork` package for R (Pedersen 2020) was used for all multi-panel arrangements.

2.5.2. Albatross captures

There were only 13 albatrosses captured (hooked) in the 87 sets based on monitoring the catch during gear haulback: 8 black-footed albatrosses and 5 Laysan albatrosses These data are too few to warrant any more comprehensive statistical analysis other than some robust form of modelled statistical summary. So, here the median posterior albatross capture rate and highest posterior density interval (HDI) was summarised by sampling from a binomial likelihood with a Bayes-Laplace prior (Tuyl et al 2008) using the `binom` R package (Dorai-Raj 2014) — rather than merely using the raw or naïve summaries. Specifically, the number of sets with at least 1 capture for those sets with or without tori lines deployed were sampled from a binomial likelihood with 1000 simulation trials, which were then summarised as the median and highest posterior density intervals (80%, 95%) using the `tidybayes` package for R (Kay 2020a) and the stat_halfeye() function from the `ggdist` package for R (Kay 2020b) to display the full posterior distribution to support a more precise form of communicating parameter uncertainty (van der Bles et al 2019).

The posterior ratio (and 95% HDI) based on the 1000 trials for the 2 densities was then used to assess any apparent difference between the capture rate for sets deployed with or without tori lines. The posterior ratio summary was also included in the observed capture summary plot. The `ggplot2` (Wickham 2016) and `colorspace` (Zeileis et al 2020) packages for R were used for the summary graphics while the `patchwork` package for R (Pedersen 2020) was used for the multi-panel arrangements.

2.5.3. Modelling the distance astern observed for seabird interactions with the gear

A GLMM regression model with zero-truncated Gaussian likelihood (Williams et al 2020) was fit to the 646 distance astern observations for the species-and treatment-specific gear/bait attempt and contact response metrics. The 646 observations were recorded from 49 of the 87 sets with each set used as an intercept-only random effect structure in the GLMM. No distance astern measurement could be < 0 from the stern with the observed distances ranging from ca 0-65m. Hence, the applicability of a left truncated Gaussian likelihood model with a lower bound imposed at zero was appropriate here — no upper bound was set here (say at 65m) but this is readily accounted for using this modelling approach that is also known in the econometric literature as a limited dependent variable model (Judge et al 1985).

The GLMM with left truncated Gaussian likelihood was fit within a Bayesian inference framework using the Stan computation engine (Carpenter et al 2017) via the brms interface (Bürkner 2017) with weakly informative priors (Lemoine 2019, Ott et al 2021). Model fit was assessed using graphical posterior predictive checks (Gabry et al 2019). The `ggplot2` (Wickham 2016) and the `colorspace` (Zeileis et al 2020) packages for R were used for the summary graphics while the `patchwork` package for R (Pedersen 2020) was used for multi-panel arrangements.

3. RESULTS

3.1. Modelling the Albatross Attempt Rates

Figure 3 shows the density distributions for the weakly informative priors used in the geoGAMMs used for modelling the albatross interaction rate data (attempt or contact) — the top panel shows density summaries for the key fixed effect parameters while the prior used for the spatial effect is shown in the bottom panel. These are all sensible priors and widely used in most Bayesian modelling (Gelfand & Schliep 2016, Lemoine 2019). The fitted models were not sensitive to either of the inverse Gamma priors used for the 2D spatial effect of set geolocations, so the IG (1.49,0.057) prior was used in all subsequent models fitted. These are similar to the priors used in Gilman et al (2021b) for fitting various Bayesian geoGAMMs.

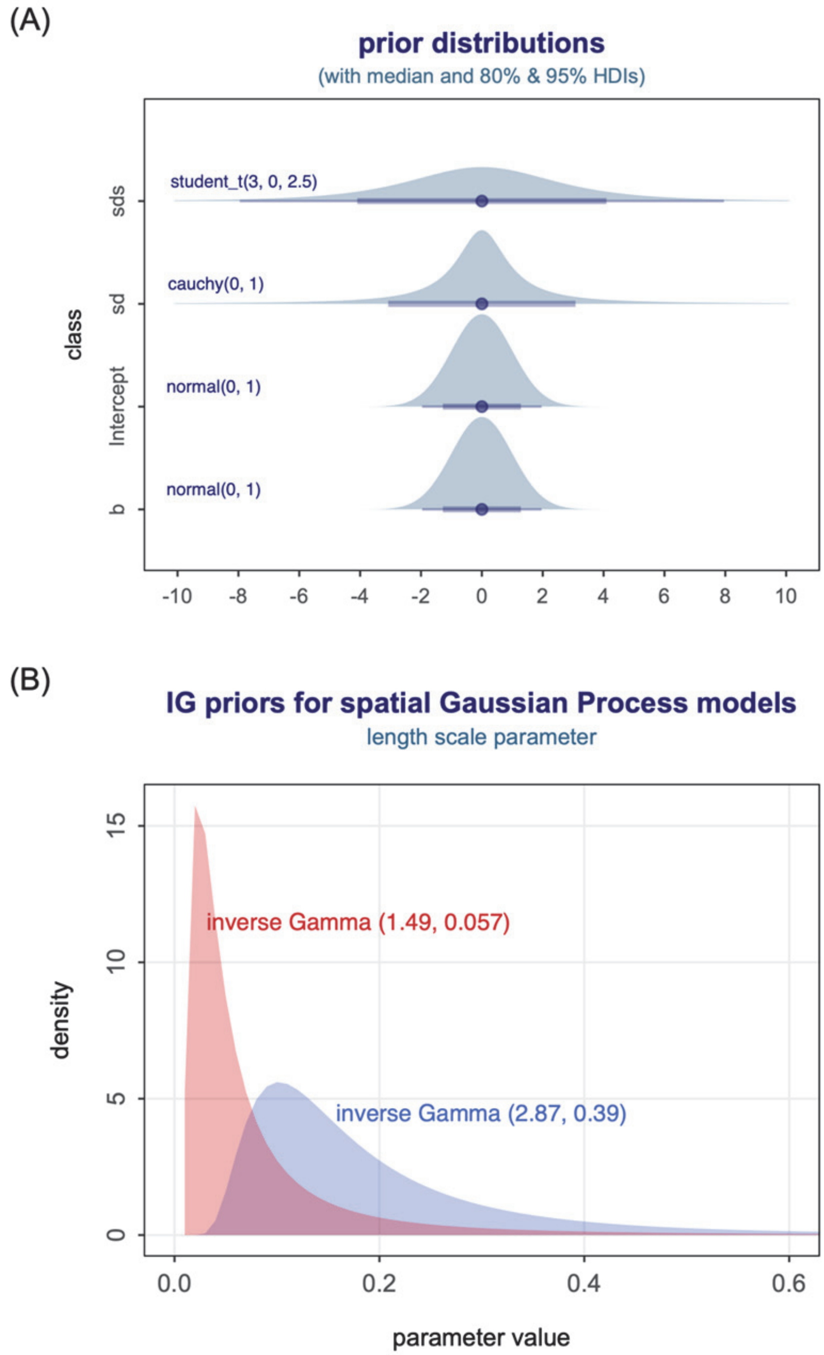


Figure 3 PRIOR SUMMARIES (Panel A) shows prior density polygons for the model parameter classes used in the geoGAMMs (b = fixed effect parameters, intercept = overall model intercept, sd = standard deviation for various parameters, sds = standard deviation for the smoothing effects). solid dot = median summary of that density, thick horizontal line under each density polygon = 80% highest posterior density interval, thin horizontal line = 95% HDI). (Panel B) shows the density polygons for the 2 inverse Gamma priors considered here for the spatial Gaussian Process structure of the geoGAMMs — model fit was found to be insensitive to which of those two IG priors were used.

Here the best-fit geoGAMM fitted the attempt rate data well conditional on the fixed effects or predictors (treatment, overcast, windy force, seabird density, season, set geolocation) and the trip- and vessel-specific random effects included in the model — all inference for the attempt rate (at least one attempt to attack the gear) is based on this model with the predicted GAMM-adjusted marginal treatment effect summarised in Figure 4 for sets deployed with tori lines or blue-dyed bait. It is apparent that predicted attempt rate was lower for sets deployed with tori lines than for sets deployed with blue-dyed bait. It was estimated that albatrosses were 1.5 times (95% HDI: 1-2.2) less likely to attempt to contact a baited hook when tori lines were deployed compared to sets deployed with blue-dyed fish bait. More details of model structure and predicted covariate functional form is considered below for the contact rate metric.

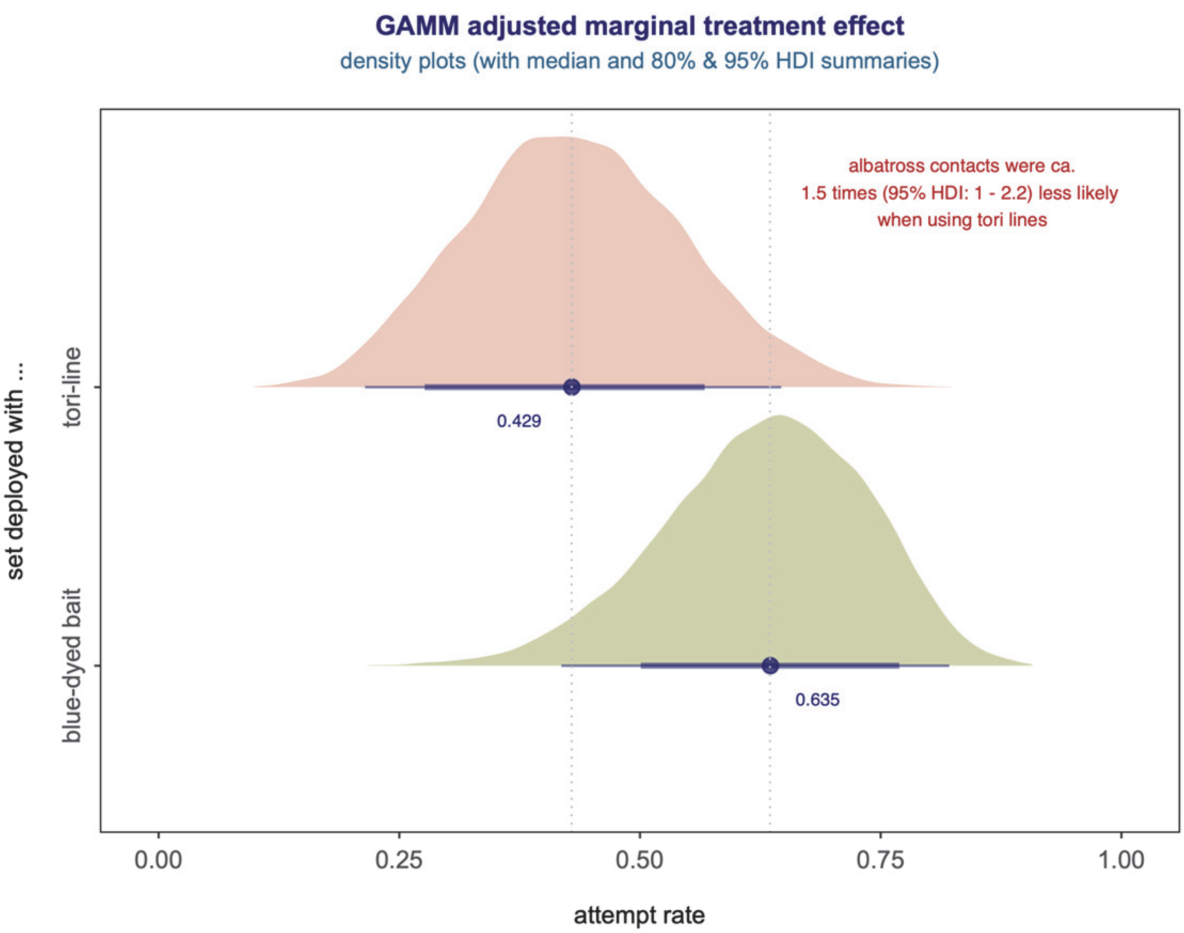


Figure 4 ATTEMPT RATE Summary of the estimated marginal median treatment effect derived from the best-fit geoGAMM for the albatross bait/gear attempt rate. Coloured polygon shows the density distribution summary, solid dot (+ numeric label) = median estimated of the density polygon, thick horizontal line below each polygon shows the 80% highest posterior density interval for the density polygon while the thin horizontal line is the 95% HDI.

3.2. Modelling the Albatross Contact Rates

A summary of some of the potentially informative predictors for all the geoGAMMs fitted to the albatross interaction data is shown in Figure 5 for the contact rate data. The top panel shows the significant seabird density effect where it is apparent that albatross contact rate increased nonlinearly with increasing seabird density. The residual spatial effect is shown in the bottom panel where it is apparent that contact rates varied considerably over the region that the 87 sets were deployed — importantly model selection based on leave-one-out cross-validation (LOOcv) and the Bayesian stacking suggest that the spatial effect was a significant effect and was relevant for any model inference. The residual spatial effect probably reflects where seabirds are more likely to occur and then interaction with any fishing effort in the area.

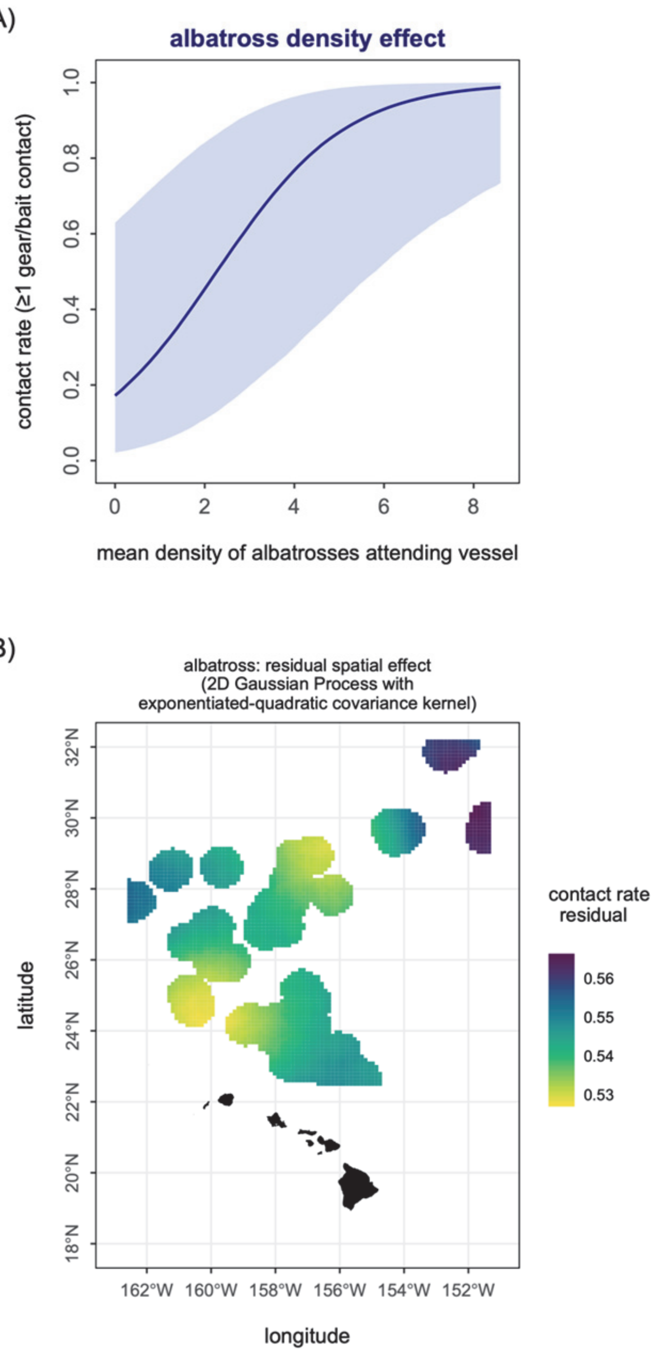


Figure 5 Estimated functional form for 2 continuous predictors included in the best-fit geoGAMM to estimate albatross contact rate conditional on potentially informative predictors. (Panel A) shows the nonlinear functional form for the estimated effect for the density of seabirds attending the vessel: solid curve = median effect, shaded polygon = 95% credible interval. (Panel B) shows the residual spatial effect from an albatross contact rate geoGAMM. Black polygons show the main Hawaiian Islands.

The best-fit geoGAMM identified by the LOOcv and Bayesian stacking metrics fitted the data well as shown for example by the posterior predictive check tests summarised in Figure 6 for the contact rate data model. All inference is based on this geoGAMM conditional on the fixed effects or predictors (treatment, overcast, windy force, seabird density, season, set geolocation) and the trip- and vessel-specific random effects included in the model.

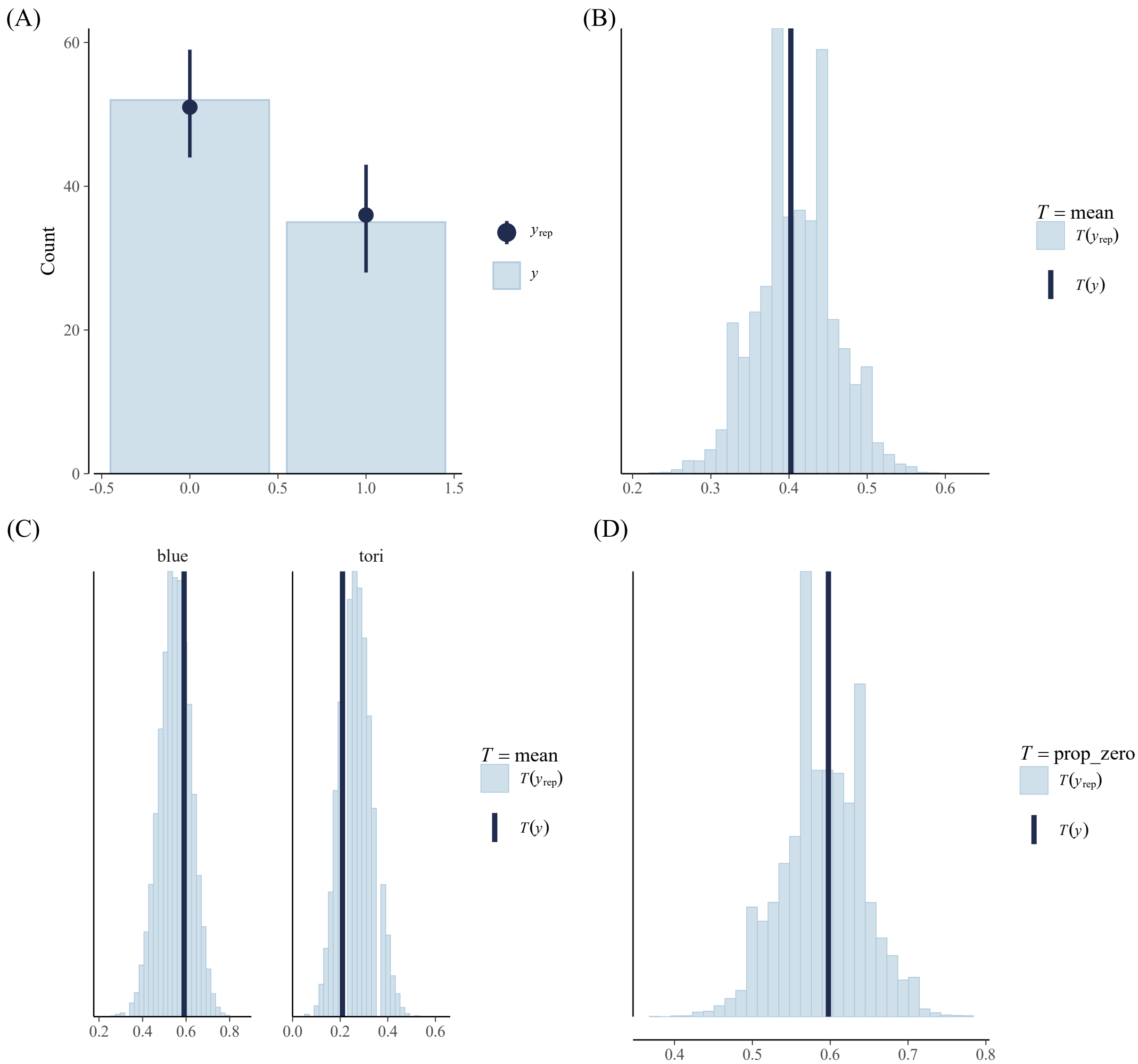


Figure 6 CONTACT RATE Posterior predictive check tests for 10,000 draws from the best-fit albatross contact rate geoGAMM. (Panel A) shows the posterior predictive check for the response variable where *yrep* is the model-based summary of the expected rates (mean, 95% credible interval) while the bars show the observed. (Panel B) shows check for the mean observed rate (solid vertical line) and the histogram of the expected rates (T(y)). (Panel C) shows the same check as for (B) now conditional on whether tori lines were deployed or not. (Panel D) shows the observed (solid line) and expected proportion of zeroes in the data.

Figures 7 and 8 show the existence and significance of the modelled conditional treatment effect based on the posterior draws from the best-fit contact rate geoGAMM. Specifically, Figure 7 shows that the treatment effect for tori lines had a > 0.999 probability of being negative compared to the treatment effect for blue-dyed bait. On the other hand, we can be >99% sure that the seabird density effect was a positive. Figure 8 shows that the treatment effect can indeed be considered as statistically significant using either a full (100%) HDI+ROPE or a 95% HDI+ROPE metric. So, Figures 7 and 8 show that it was unequivocal that the albatross contact rate was significantly lower for sets deployed with tori lines compared to sets deployed with blue-dyed bait.

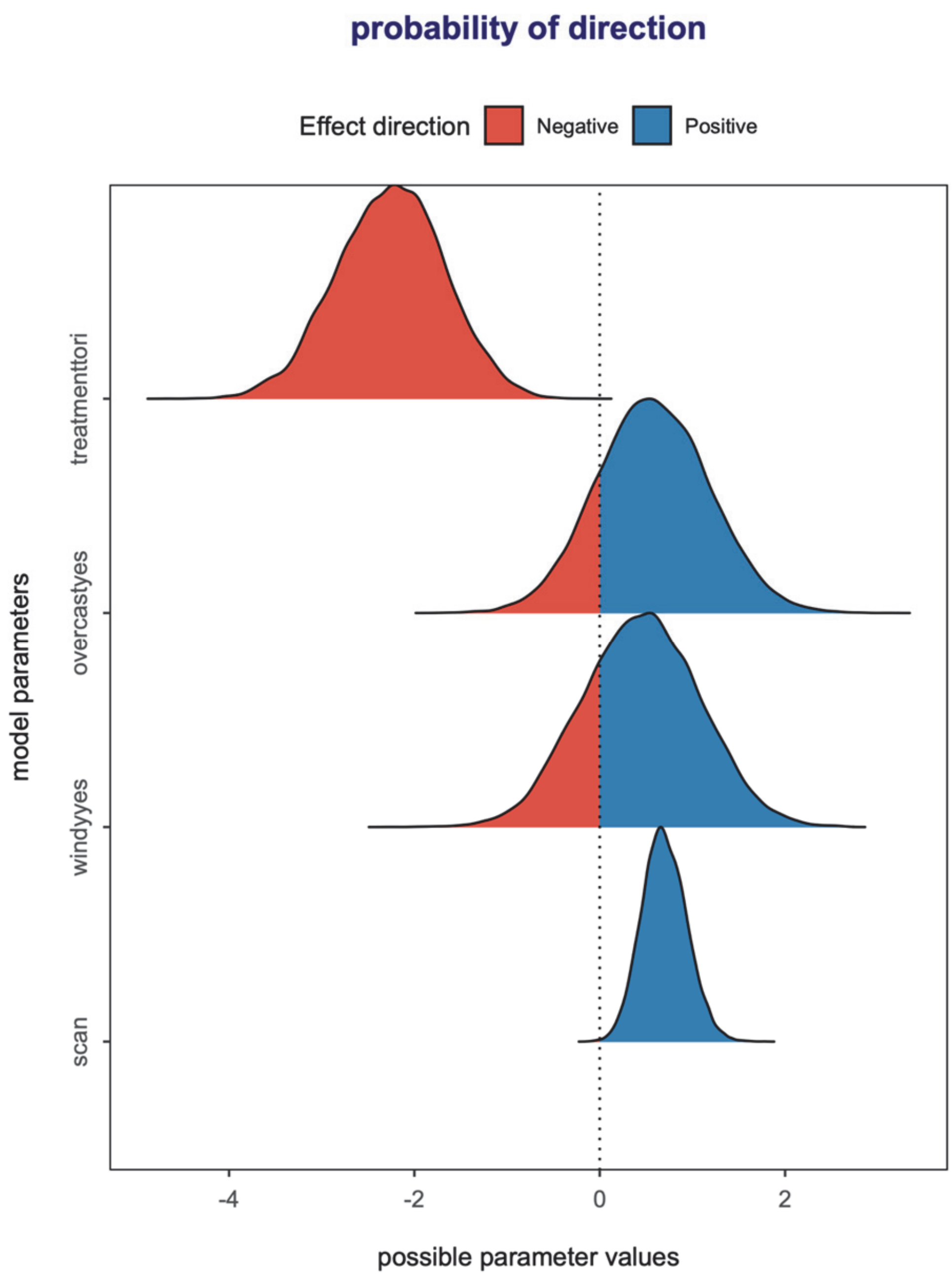


Figure 7 CONTACT RATE Probability of direction plot for selected parameters estimated from the best-fit GAMM for the albatross bait/gear contact rate (scan = seabird density attending the vessel). Polygons show the density summary of the posterior draws and coloured given the estimated direction (positive or negative) of the effect or parameter. The proportion of the polygon that does not include zero is a statement about the probability of the proposed direction of the effect.

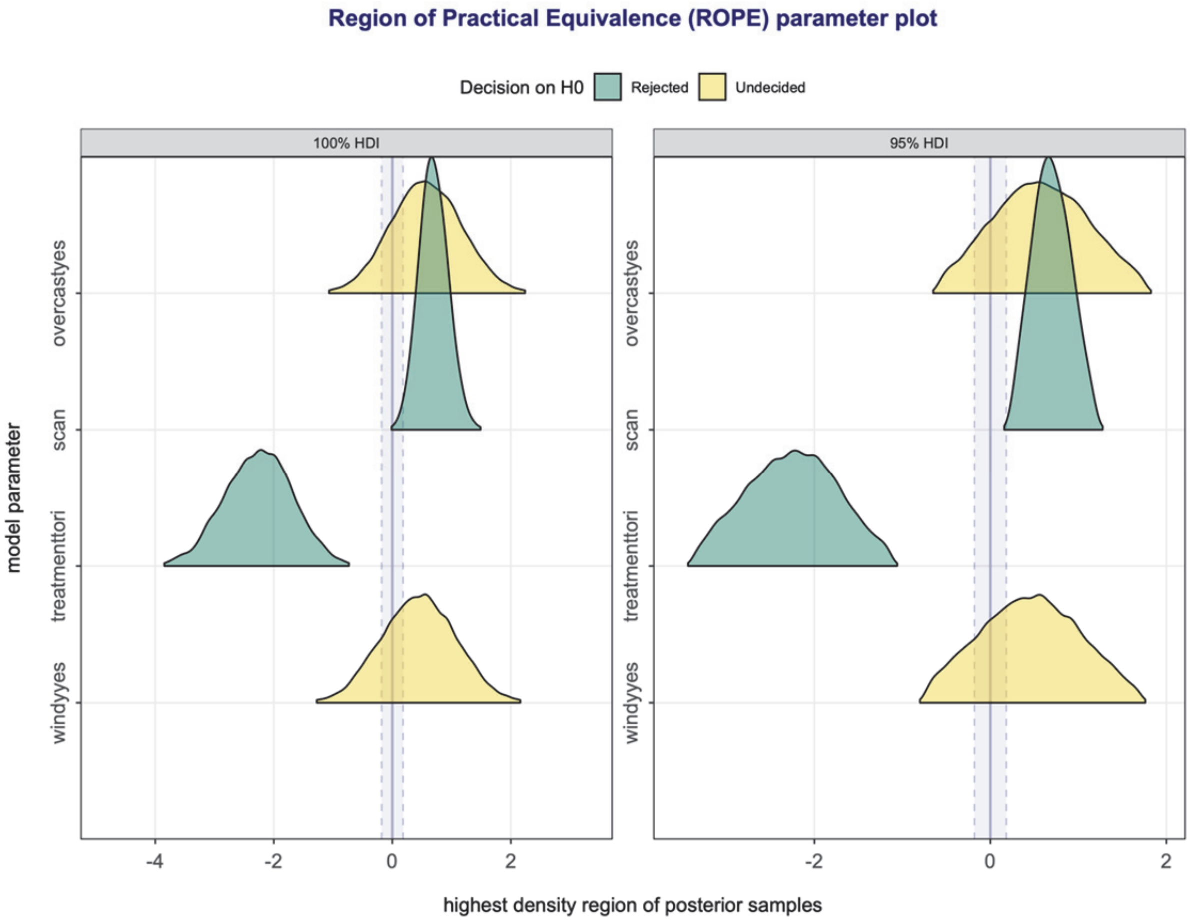


Figure 8 CONTACT RATE ROPE-based summary of the significance of the various fixed effects derived from the best-fit geoGAMM for the albatross bait/gear contact rate. (Panel A) shows the effects given a full ROPE based on a 100% highest posterior density interval. (Panel B) shows the effects given a ROPE based on a 95% highest posterior density interval. Green polygon indicates a significant effect.

The predicted geoGAMM-adjusted marginal treatment effect for contact rate is summarised in Figure 9 for sets deployed with tori lines or blue-dyed bait. It was estimated that albatrosses were 4.1 times (95% HDI: 1.5-9.2) less likely to contact a baited hook when tori lines were deployed compared to sets deployed with blue-dyed fish bait.

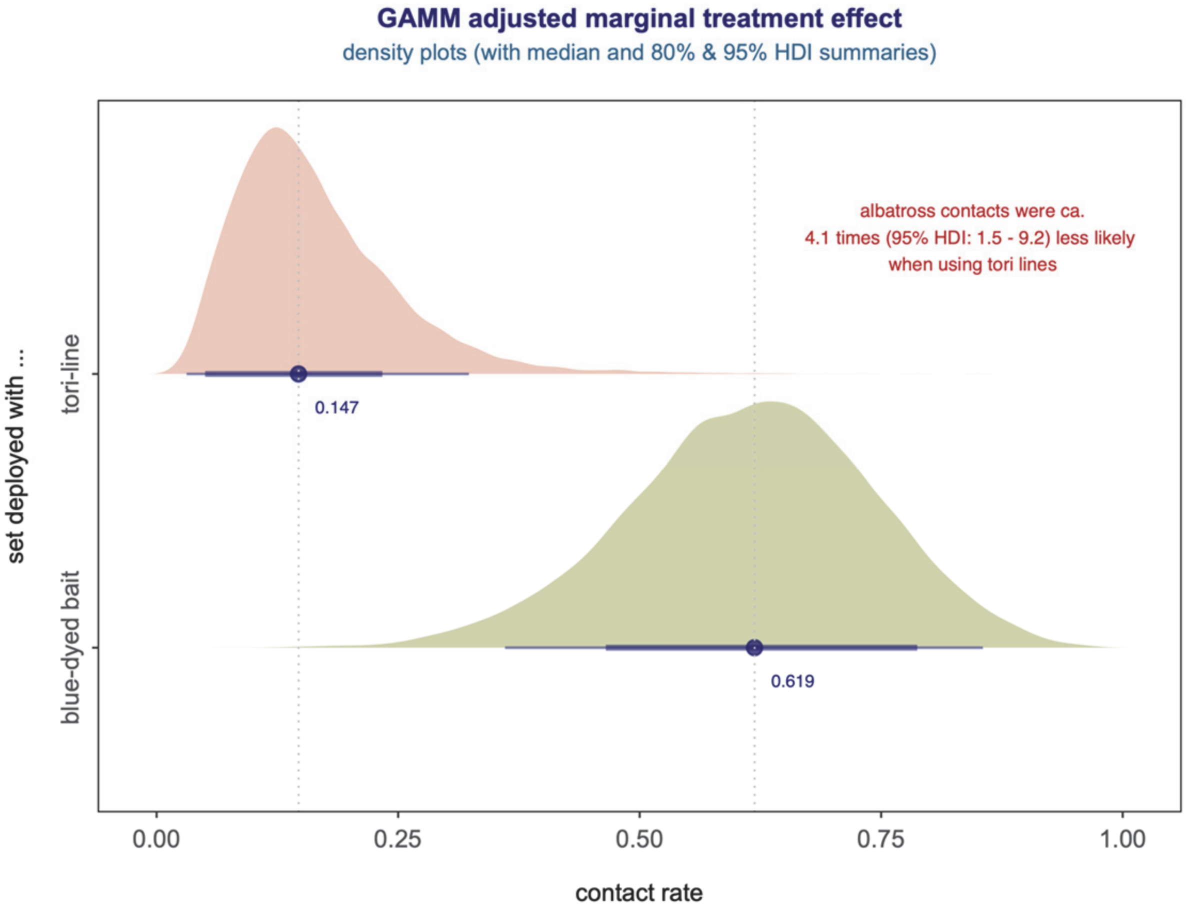


Figure 9 CONTACT RATE Summary of the estimated marginal mean (or median) treatment-specific effect derived from the best-fit geoGAMM for the albatross bait/gear contact rate. Coloured polygon shows the density distribution summary, solid dot (+ numeric label) = median estimated of the density polygon, thick horizontal line below each polygon shows the 80% highest posterior density interval for the density polygon while the thin horizontal line is the 95% HDI.

3.3. Albatross Captures

The simulation-based statistical summary for albatross captures for sets deployed with tori lines or with blue-dyed fish bait is shown in Figure 10. It is important to recall that there were only 13 albatrosses caught on the gear in this study. This suggests that albatross capture in this fishery is a rare event, which is a finding consistent with previous estimates of seabird bycatch rates in the Hawaii-based deep-set pelagic longline fishery (Gilman et al 2016, Gilman et al 2021b). We estimated that albatrosses were in fact 13.7 times (95% HDI: 7.8-18.6) less likely to be captured when tori lines were deployed compared to sets deployed with blue-dyed fish bait

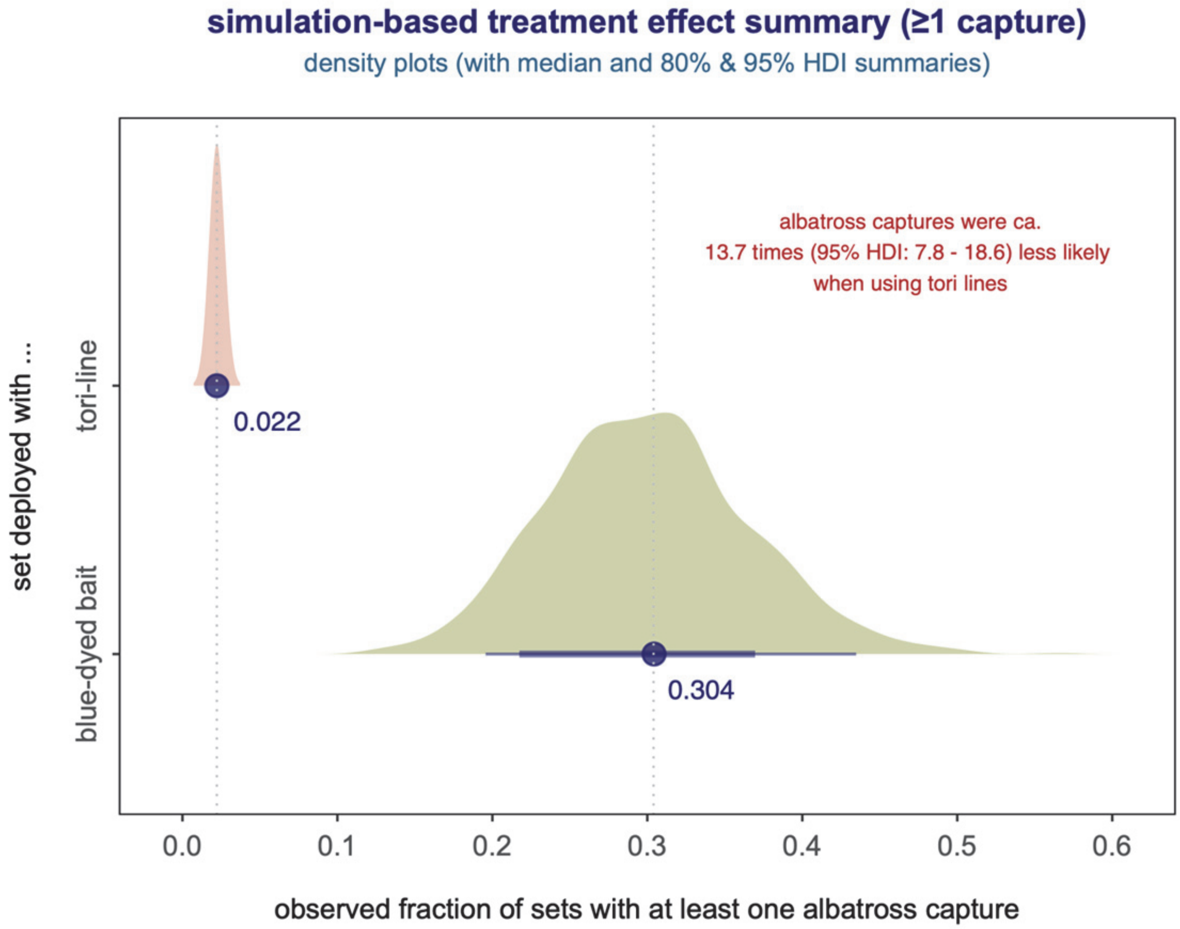


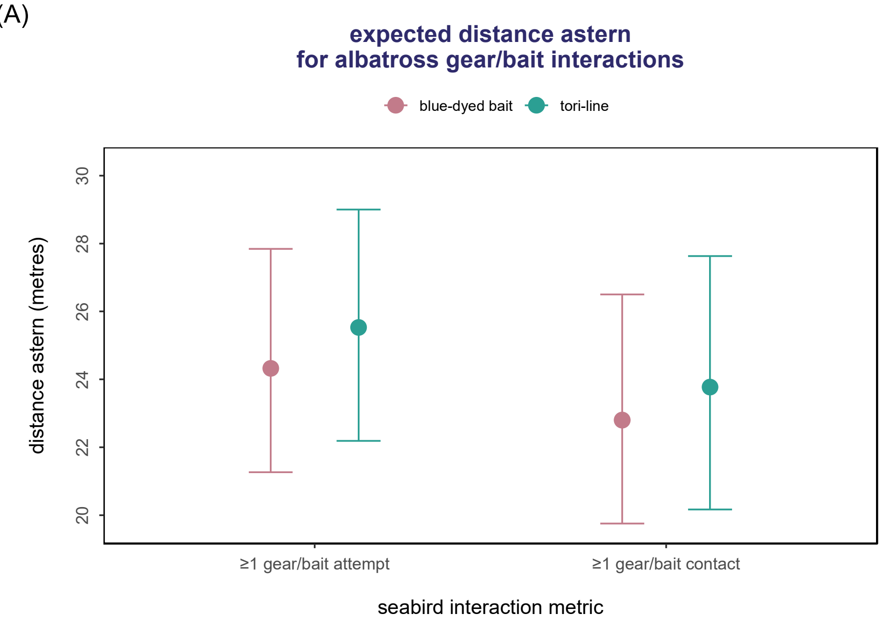
Figure 10 CAPTURE RATE Simulation-based summary of 13 albatross captures on the 87 longline sets. Coloured polygon shows the density distribution summary of the 1000 simulations for the sets deployed with or without tori lines, solid dot = median estimated of the density polygon (estimate also shown as a numeric label), thick horizontal line below each polygon shows the 80% highest posterior density interval for the density polygon while the thin horizontal line is the 95% HDI.

3.4. Distance astern observed for seabird interactions with the gear

Less than 1% of the 646 observed distance astern records for albatross interactions with the baited hooks were >50 m astern or outside of the estimated protective aerial portion of the tori line. Around 27% of the 646 records occurred within 10m of the stern. We found that the expected or estimated albatross interactions with longline gear deployed with tori lines occurred significantly further astern than for those sets deployed with blue-dyed bait (Figure 11a). This finding further reinforces the benefits of using tori lines rather than blue-dyed bait as an effective seabird bycatch mitigation measure.

However, it is worth noting that 84% of the 646 distance astern observations sourced from the 49 sets were recorded from the 30 sets deployed with blue-dyed bait. Attempts also occurred further astern than contacts (Figure 11a). It was also apparent that blacked-footed albatross longline gear/bait interactions occurred further astern than did the Laysan albatross interactions (Figure 11b) — but this species-specific effect is not strong inference as black-footed albatross interactions accounted for 89% of the 646 distance astern observations derived from the onboard electronic monitoring systems by the EM analyst.

(A)



(B)

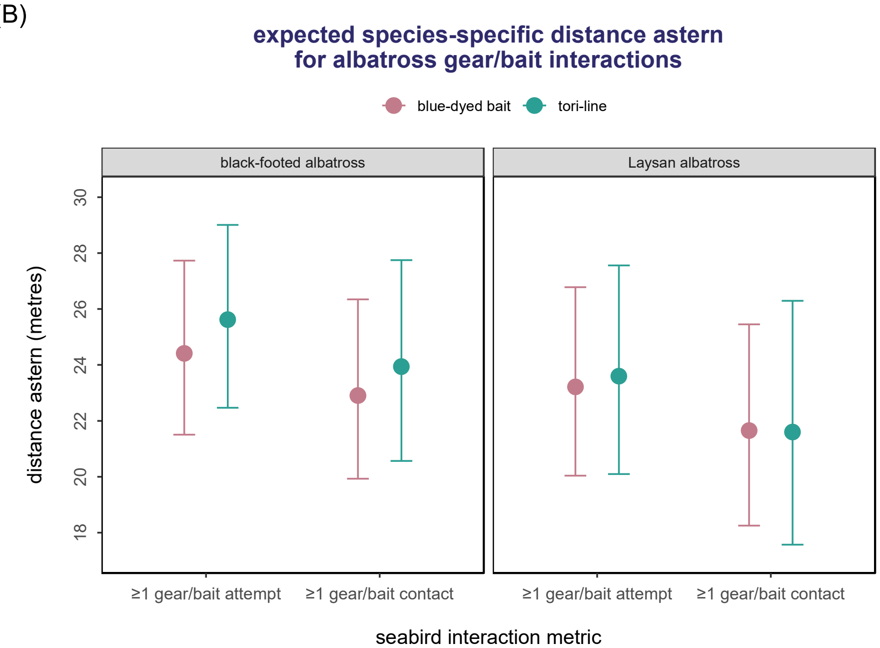


Figure 11 DISTANCE ASTERN (Panel A) shows the estimated distance astern conditioned on treatment and gear/bait interaction type. (Panel B) shows the estimated species-specific distance astern conditioned on treatment and gear/bait interaction type. solid dot = estimated median and vertical bar = 95% credible interval.

4. DISCUSSION

4.1. Tori line vs. blue-dyed bait effect on seabird interaction risk

Using a Bayesian structured workflow, we found that the use of tori lines resulted in substantially lower albatross interaction rates than blue-dyed and thawed fish bait in this US central north Pacific tuna longline fishery. We can be 100% certain that this effect occurred for the contact rates in our experimental trial.

The implications for this fishery are that replacing thawed blue-dyed fish bait with tori lines would achieve a substantial reduction in seabird catch rate. More broadly, regional fisheries management organizations should evaluate the evidence for including blue-dyed fish bait as an option in meeting seabird conservation and management measures. Fisheries management authorities should develop and implement robust criteria for the adoption of bycatch mitigation methods that provide robust evidence that the estimated effect size warrants the adoption of a bycatch mitigation intervention, and that the estimated effect is generalizable and relevant over diverse settings such that the measure is suitable for adoption regionally.

Several past studies have found blue-dyed fish bait to significantly reduce seabird interaction rates relative to a control (McNamara et al 1999, Cocking et al 2008, Gilman et al 2008, Ochi et al 2011) as well controlled experiments of tori lines (McNamara et al 1999, Boggs 2001, Domingo et al 2017). But only one previous study was identified that compared the seabird interaction rates of blue-dyed fish bait and tori lines: contrary to our findings, McNamara et al (1999) found blue-dyed fish bait had a lower seabird attempt rate than tori lines in the Hawaii-based deep-set longline fishery. McNamara et al (1999) set baits outside of the white, turbulent, propellor wash where a high contrast with the dyed fish bait would occur (and setting in the propeller and hull wash also reduces baited hook sink rates, Brothers et al 1999). In the current study, while fishers were not directed to alter their conventional fishing practices to avoid setting in the prop wash, they conventionally throw the baited hooks outside of this area as well.

There is evidence suggesting that seabirds may rapidly habituate to blue-dyed bait. Cocking et al (2008) found the effect of blue-dyed fish bait on reducing seabird contact rates declined over the study period: during the initial two days of a field trial, seabirds contacted 48% of blue-dyed fish bait, increasing to 90% during the final three days of the trial.

Fishers typically do not set gear with fully frozen bait because this can make it difficult to thread the bait onto a hook, and the frozen bait may break (McNamara et al 1999). The small difference in sink rates between partially and fully thawed bait estimated by Robertson & van den Hoff (2010) may not significantly affect seabird catch risk (Gilman & Ishizaki 2019). Furthermore, there was no significant differences in sink rates between frozen, partial- or full-thawed fish bait with 60 g weights were attached 0.2 m from the hook (Robertson & van den Hoff 2010), suggesting that the small effect of bait thaw status on sink rates is exceeded by the effect from branchline weighting when weights, exceeding a threshold mass, are located sufficiently close to the hook.

4.2. Seabird Density

The experiment found that the density of seabirds attending vessels significantly explained interaction rates, and we are over 99% certain that this effect occurred for contact rates. This finding is consistent with several previous studies in Hawaii's longline fisheries, for both the effect of this variable on seabird catch risk during setting and hauling (Gilman et al 2014, Gilman et al 2016). Local abundance during setting and hauling affects catch rates due to the effect of animal density on catchability (Gilman et al 2005). Local abundance can also affect scavenging behavior, where, up to some threshold, the larger the seabird density, the more intense the competitive scavenging behavior and capture risk will be (Gilman et al 2016).

This finding indicates that the proposal by Melvin et al (2014) to not standardize effort to explicitly account for seabird density in assessing seabird catch risk is inappropriate in this region and possibly other regions with similar conditions of minimal hierarchical competitiveness and no secondary interactions (Gilman et al 2016). However, it has been found elsewhere that seabird competition for baits (a food subsidy) and secondary interactions, due to smaller diver-diving species making baits available to surface foragers, often have larger effects on catch rates than seabird density (Jimenez et al 2012, Melvin et al 2014).

4.3. Distance Astern

The ca 50 m-long streamer line aerial section covered >99% of the attempts and contacts by Laysan and black-footed albatrosses and is consistent with observations during a 2020 experiment (Gilman et al 2021). Therefore, the tori line aerial coverage is considered adequate for this fishery. The diving capacity of the seabirds that interact with a fishery, and hence how far astern they are able to access baited hooks, determines the effective length of the tori line aerial section. All three genera of small-bodied albatrosses (*Phoebetria, Thalassarche, Phoebastria*) make infrequent and short dives to a mean depth < 1.4 m (Bentley et al 2021). Laysan and black-footed albatrosses, in particular, have limited diving capacities (Prince et al 1994), typically only making body thrusts to reach prey near the surface.

Black-footed albatrosses make dives to a mean depth of 0.6 m (± 0.2 m) and have a maximum diving depth of about 2.5 m (Kazama et al 2019). This is consistent with Melvin et al (2001) who estimated that Laysan albatrosses rarely reached beyond 2m depth when scavenging from demersal longline fishing vessels, based on observations that they rarely submerged themselves, and when they did, they remained submerged briefly for < 2 seconds.

Furthermore, unlike in other regions, secondary interactions, where deep-diving seabird species access baited hooks at depth, is understood to not occur in North Pacific pelagic longline fisheries (Gilman et al 2016). Secondary interactions occur when, unable to consume the bait at depth, these deep-divers bring the baited hook back to the sea surface where larger surface foraging seabird species have a second opportunity to access the terminal tackle and become captured (Jimenez et al 2012, Melvin et al 2014).

Gilman et al (2021a) also found that > 50% of seabird interactions occurred within 10 m of the vessel stern. It has been proposed elsewhere that using longer and more brightly colored streamers constructed with materials that result in erratic streamer movement might reduce seabird interactions near the vessel where baited hooks are most vulnerable (Goad & Debski 2017, ACAP 2019) — however, these tori line modifications could increase the risk of entanglement with the gear and then require a longer drag section to maintain the protective aerial coverage.

The further distance astern of seabird interactions with a tori line suggests that the tori line deterred albatrosses from scavenging close to the vessel relative to setting with blue-dyed bait. As expected, attempts occurred further astern than contacts, as the further from the vessel, the deeper the baited hooks are and less successful the birds are at contacting them.

The observation of black-footed albatross interactions being further astern relative to the Laysan albatross might be a result of black-footed albatrosses being less agile, making them less capable of scavenging near the vessel hull, and making them less competitive than the Laysan albatross.

Or, perhaps compared to Laysans, black-footed albatrosses dive deeper when scavenging for baits and thus attempt to contact and contact baited hooks further astern. There may also be differences in behavioral traits between the species related to their vessel scavenging. For instance, black-footed albatrosses may be less likely to pass under or near the protective aerial portion of the tori line than Laysan albatrosses.

5. CONCLUSION

We found that tori lines were a more effective seabird bycatch mitigation measure in this trial compared to the use of blue-dyed fish bait? Specifically:

- albatrosses were 1.5 times (95% HDI[2]: 1-2.2) less likely to attempt to contact a baited hook when tori lines were deployed compared to sets deployed with blue-dyed fish bait
- albatrosses were ca 4 times (95% HDI: 1.5-9.2) less likely to contact a baited hook when tori lines were deployed compared to sets deployed with blue-dyed fish bait
- albatrosses were ca 14 times (95% HDI: 7.8-18.6) less likely to be captured on a baited hook when tori lines were deployed compared to sets deployed with blue-dyed fish bait

While blue-dyed fish bait to known to reduce seabird bycatch risk (McNamara et al 1999, Gilman et al 2016), this study demonstrated unequivocally that it is not as effective a seabird bycatch mitigation method as tori lines in this fishery.

5.1. Policy implications for consideration …

Local scale: replacing thawed blue-dyed fish bait with tori lines would achieve substantial reductions in seabird bycatch rates and drownings

Regional scale: fisheries management authorities should develop and implement robust, explicit criteria for the adoption of bycatch mitigation measures

Global scale: tuna RFMOs should re-evaluate the evidence for the current inclusion of blue-dyed fish bait as an option in their seabird conservation and management measures

[2] HDI = highest posterior density interval (the shortest uncertainty interval)

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Appendix 1: Data fields and collection protocols employed by the EM analyst

Data Field	Collection Protocol
Seabird bycatch mitigation methods during setting	
Tori line deployed	Record 'yes' if a tori line was deployed during the entire set, from the deployment of the first to final hook; 'no' if a tori line was not deployed during any of the set; and 'partial' if a tori line was deployed during a segment but not the entire set.
Tori line aerial extent	Record the estimated length of the aerial section of the tori line to the closest meter, from the vessel stern to the first point where the tori line contacts the sea surface.
Tori line maintained over area where baited hooks enter water	At the start of the set and every hour thereafter during the set, record yes or no as to whether the aerial portion of the tori line was over the area of the sea surface where crew were setting baited hooks.
Bait dyed blue or untreated	Record yes or no as to whether baits were untreated or dyed blue.
Offal and spent bait management	Record 'no' if no offal or spent bait were discharged during the entire set, or 'yes' if offal or spent bait were discharged during the set.
Other fishing methods	
Date and time of start and end of set	Record the date and time at the start and end of the set, based on when the first and last baited hooks enter the water. Collected by the EM system using an integrated GPS.
Set duration	Record the duration of the set, calculated from the data on the date and time of day of the start and end of the set.
Latitude and longitude at the start and end of the set	Record the latitude and longitude of the vessel position when the first and last baited hooks enter the water. Collected by the EM system using an integrated GPS.
Wind direction in relation to the vessel setting direction	Record the wind direction in relation to the vessel setting direction (e.g., wind from the stern, wind from the port).
Hooks per set	Record the hooks deployed per set, estimated as the average number of hooks per minute for a 10-minute period raised according to the total duration of the set
Seabird attempts and bait contacts during the set	
Number of seabird attempts to take bait from hooks	Record the number of seabird species-specific attempts to contact a bait attached to a hook. An attempt is when a seabird plunges underwater or completely

	submerges but does not contact a bait attached to a hook. A bird sitting on the sea surface looking underwater was not considered an attempt – the seabird must have conducted a submerged or partially submerged body thrust to be recorded as an attempt. Only one attempt was recorded per individual bait, regardless of whether multiple birds made attempts to scavenge the same bait or an individual bird made multiple attempts to contact the same bait. If a bait was contacted by a seabird, then attempts to contact that bait were not recorded.
Number of seabird contacts with baited hooks	Record the number of species-specific seabird contacts with baited hooks. A contact is when a seabird grasps a bait in its beak while the bait is attached to a hook. Only one contact was recorded per individual bait. If a seabird contacted a bait held by another bird, this was not counted as a second contact. If a bird contacted a bait held by another bird and successfully stole the bait from the other bird, this also is not counted as a second contact. If an individual bird contacted the same baited hook multiple times during separate events (i.e., the bird released the baited hook, and subsequently grasped the same baited hook in its beak), and if multiple birds contacted the same baited hook during separate events, each event was not counted as separate contacts.
Distance astern of seabird attempts and contacts	Record the distance astern that each seabird attempt and contact occurred, estimated to the meter.
Seabird scan counts	
Number of seabirds, by species, attending the vessel during the set	Within an area 100 m astern, conduct scan counts during every attempt and contact during the set to estimate the number of seabirds to the species level (*see* Gilman et al 2016, Gilman et al 2021a). For sets with no attempts or contacts, estimate the average number of seabirds present during the entire set.
Environmental variables that potentially significantly explain seabird catch risk	
Beaufort wind force scale	Following the Hawaii longline observer program protocols (NMFS 2017), record the Beaufort scale based on the sea surface state and wave height, from Beaufort scale of 0 – surface like a mirror, 0 m wave height, to 10 – sea looks white, foam blown in dense streaks obscuring visibility, wave height between 8.8 m and 12.5 m.
Illumination	Following the Hawaii longline observer program protocols for assessing weather conditions (NMFS 2017), record condition category (clear, partly cloudy, cloudy – one or more layers, drizzle, showers, rain, thunderstorm, rain and fog, fog and thick haze, snow or snow and rain).