Using Bayesian time series models to estimate bycatch of an endangered albatross

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ABSTRACT

Developing unbiased estimates of incidental bycatch poses a challenge for species where fishing-induced mortality is a rare occurrence. Expanding rare mortality events using ratio estimators or bycatch of proxy species can result in highly variable estimates based on untested and often untestable assumptions. We estimated short-tailed albatross bycatch in a U.S. West Coast groundfish fishery using Bayesian time series modeling. The best model used a constant bycatch rate and inferred annual expected bycatch and variability using a Poisson distribution, given specified levels of observed effort. Fleet-wide bycatch estimates varied annually and peaked at 1.35 birds in 2011 (the year of the only observed mortality). The probability of exceeding the limit of five estimated takes in a 2-year period was very low throughout the time series, and estimated takes in the unobserved portion of the fleet are more likely with lower observer coverage and higher fishing effort. The Bayesian model-based approach avoids assumptions inherent in ratio estimators and proxy methods; it incorporates uncertainty, reduces volatility, and enables comparisons of bycatch estimates to management thresholds. This analytical approach offers natural resource managers a framework for estimating bycatch in data-limited contexts, which can result in better guidance for management actions and mitigation strategies.

Keywords:

Bayesian times series modeling
Bycatch
Short-tailed albatross
Take threshold

1. Introduction

Incidental mortality (bycatch) of seabirds in fisheries is one of the top threats contributing to the decline of seabirds worldwide. The number of globally threatened species affected by bycatch has increased from 40 species (Croxall et al., 2012) to 50 in recent years (Dias et al., 2019), and many seabird populations have declined since 1950 (Paleczny et al. 2015). Albatrosses are particularly imperiled, with 15 of 22 species classified by the International Union for Conservation of Nature as globally threatened (Critically Endangered, Endangered, or Vulnerable) and six other species as near threatened (IUCN, 2022). All 15 of the imperiled albatross species are caught as bycatch in fisheries, which has, in part, contributed to their population declines (IUCN, 2022).

Estimating seabird bycatch can be challenging for a variety of reasons. Seabirds typically have little economic value for fishers and therefore, seabird bycatch is almost always discarded at sea and not available for dockside sampling. To document seabird and other at-sea discards, fishery managers often employ at-sea observers onboard fishing vessels, or, in more recent years, electronic monitoring equipment such as video cameras. Because these monitoring programs can be costly, monitoring of fishing activities is often less than 100%, and bycatch is thus sampled on only a subset of vessels within a fleet. Observed bycatch on sampled vessels is used to estimate fleet-wide bycatch by expanding the sampled portion of the fleet to the unsampled portion of the fleet, assuming the bycatch rate on sampled vessels reflects the rate on unsampled vessels. Expanding bycatch estimates to the entire fleet requires data on the size of the fleet and some metric of fishing effort (e.g., number of trips, number of gear deployments, number of hooks, etc.) which might not always be available or accessible.

Sampling biases also present a challenge to accurate bycatch estimates. Some sampling biases are inherent in the bycatch process. For example, cryptic mortality, where bird mortalities are not observed and therefore go unsampled, is a form of sampling bias (Gilman et al., 2013). In trawl fisheries, birds in flight can strike aerial cables and rigging, which can cause injury or death; however, these interactions are largely unobserved and go unrecorded (Tamini et al., 2015, Melvin et al., 2011). In hook-and-line fisheries, birds hooked during deployment of gear and subsequently drowned might become dislodged from the hook prior to gear retrieval, which can result in them going unrecorded (Zhou et al., 2020). Other sampling biases can arise from non-random deployment of observers on vessels; these can result from hidden spatial or temporal strata in the fishery, observer coverage waivers resulting from safety concerns, or just from reluctance of fishing captains to carry observers. There is also the potential for "observer effects", when vessels change their fishing behavior or locations due to the presence of fishery observers (Benoît and Allard, 2009). Finally, observer programs are sometimes not designed to focus on seabirds but rather on documenting bycatch and discard of non-target fish species.

The method employed to estimate bycatch can also introduce assumptions about the data and the underlying bycatch process. Historically, ratio estimators have been widely used to expand the observed bycatch estimate to the unobserved portion of the fleet (Stratoudakis et al., 1999; Borges et al., 2005; Walmsley et al., 2007). However, using observer samples to estimate bycatch in the unsampled portion of the fishery relies on the assumption that bycatch is proportional to some fishing effort metric common to both observed and unobserved vessels.

This assumption is often not supported by data, as bycatch might vary nonlinearly or even be unrelated to the ratio denominator (Rochet and Trenkel, 2005).

Bycatch estimates produced using ratio estimators have also been shown to be biased, particularly when observer coverage is low (Carretta and Moore, 2014, Martin et al., 2015). Under such circumstances, relatively minor differences in observed bycatch could result in greatly disparate fleet-wide estimates. For example, the absence of bycatch events in the observed portion of the fleet results in a fleet-wide estimate of zero, despite the fact that the real estimate could be something greater than zero. Alternatively, one or a few bycatch events could result in unrealistically large estimates, when the true value is likely lower. Thus, ratio estimators are considered unsuitable for rare events (Carretta and Moore, 2014; Martin et al., 2015).

1.1 Short-tailed albatross and West Coast sablefish fisheries

The short-tailed albatross (*Phoebastria albatrus*) was likely once the most abundant of the North Pacific albatrosses, along with black-footed albatross, *P. nigripes,* and Laysan albatross, *P. immutabilis*, with 14 known historical breeding colonies in the northwestern Pacific Ocean (USFWS, 2008). In the late 19th and early 20th centuries, millions of short-tailed albatross were hunted for feathers, oil, and fertilizer, and, by 1949, the species was thought to be extinct (USFWS, 2008). The species has been recovering since the 1950s, and their present range encompasses the Pacific Rim from southern Japan through Alaska and British Columbia to northern California. Individuals spend time primarily along continental shelf margins, which lead to extensive overlap with many commercial fishing operations (Guy et al., 2013).

Despite conservation efforts resulting in a steady population increase over the last decade (USFWS, 2020), bycatch of short-tailed albatrosses in commercial fisheries continues to be a major conservation concern, especially for younger age classes. Since 1983, 21 short-tailed albatross mortalities have been documented throughout the North Pacific, and 2/3 of them have been individuals younger than 4 years old (Table 1). Considered globally threatened and listed as Vulnerable by the International Union for Conservation (Birdlife International, 2022), the short-tailed albatross was listed as endangered under the U.S. Endangered Species Act (ESA) throughout its range, including the United States, by the U.S. Fish and Wildlife Service (USFWS, 2000). The Short-tailed Albatross Recovery Plan (USFWS 2008) and subsequent reviews summarizing the status of the species (USFWS, 2009, 2014, 2020), have identified fisheries bycatch as a major and continuing threat.

Sablefish (*Anoplopoma fimbria*) is one of the most commercially valuable species for U.S. west coast groundfish fisheries. From 2000-2019, sablefish landings averaged 5,571 metric tons and revenue averaged $29.4 million USD; while this represented only 5% of annual groundfish landings, it represented 37% of annual revenue on average (PFMC 2020). Sablefish is targeted using trawl and fixed gear, with the latter (longline, pot) being prosecuted under multiple permits, including Limited Entry, Limited Entry Daily Trip Limits, Open Access, and Catch Shares sectors (see Somers et al., 2022 for fishery descriptions). Demersal longline gear in these sectors overlaps with albatrosses off the U.S. West Coast, particularly in shelf-slope habitats north of 36° N latitude (Guy et al. 2013). Most seabird bycatch, including of albatrosses, occurs in sablefish longline fisheries, particularly the Limited Entry (LE) sablefish demersal longline fishery (Jannot et al. 2020).

Estimating short-tailed albatross bycatch in U.S. West Coast groundfish fisheries has been a challenge because documented short-tailed albatross mortalities are extremely rare. In April 2011, a single, sub-adult short-tailed albatross was recorded taken off the coast of Oregon (USFWS, 2012) in the LE sablefish demersal longline fishery. To overcome the shortcomings of ratio estimators, we explore model-based methods for estimating short-tailed albatross bycatch in the LE sablefish longline fishery. Model-based methods are particularly useful when bycatch is dominated by zeroes; there is reduced bias from rare events, and the methods incorporate uncertainty (Martin et al., 2015). Model-based estimation of bycatch done in a frequentist or Bayesian setting can reduce variability by using all of the information contained in the time series and can preclude arbitrary decision-making about how many years of data to combine. We use a Bayesian approach because it enables probabilistic inference for bycatch and mortality within years, conditional on fishing effort; this approach has been demonstrated with other rare bycatch species, such as cetaceans, delphinids, pinnipeds, sea turtles, and sharks (Martin et al., 2015; Cosandey-Godin et al., 2015; Jannot et al., 2021a). Bayesian approaches have recently been applied to seabirds (Hatch, 2018; Parsa et al., 2020), including to understand spatiotemporal patterns and locations of seabird bycatch hotspots (Rujia et al., 2021). We use this modeling framework to predict annual short-tailed albatross bycatch in the Limited Entry sablefish longline sector off the U.S. West Coast for the years 2002-2019.

2. Methods

2.1 Data

We applied Bayesian time-series models to short-tailed albatross bycatch using fisheries-dependent data from the LE sablefish longline fleet of the U.S. West Coast groundfish fishery (Table 2) provided by the Fisheries Observation Science Program at the National Oceanographic and Atmospheric Administration (NOAA) Northwest Fisheries Science Center. The fisheries observer program collects independent, at-sea fisheries data by deploying trained fisheries observers on commercial fishing vessels along the U.S. west coast (NWFSC, 2020a). A subset of the ~90 permitted vessels are randomly selected and monitored during the fishing season (April - October). The observed portion of the fleet was used to estimate bycatch for the entire fleet (observed + unobserved). While the program strives to deploy observers on 30% of LE sablefish longline fishery trips using a spatially stratified sampling scheme, realized annual observer coverage averages 28% and ranges from 7 - 46% (Somers et al., 2020). Observer coverage is calculated as the percentage of fleet-wide landings (by weight) estimated from landing receipts, called fish tickets, that are generated when the fish is purchased at the dock (see Supplemental Text for description of fish ticket processing).

During fishing trips, fisheries observers record interactions with and bycatch of seabirds and other protected species as well as information on catch and fishing effort, including fishing location and depth. For West Coast groundfish fisheries, observers prioritize documenting interactions of short-tailed albatross and other ESA-listed species with fishing vessels (NWFSC, 2020a). On hook-and-line vessels such as those in the LE sablefish longline fleet, observers sample 30 - 100% of the catch from each set/haul during a fishing trip to determine its species composition. In many cases, 100% of the set/haul is sampled, and seabird counts represent a complete census of the set/haul (see NWFSC, 2020b). When less than 100% of the catch was sampled, seabird counts were expanded to the set/haul level prior to modeling. Serious injury and mortality designations were determined by seabird experts. Under the ESA, a 'take' of a short-tailed albatross is defined as any act that harasses, harms, pursues, hunts, shoots, wounds, kills, captures, or collects, or attempts to engage in any such conduct (USFWS, 2017). Fisheries observer notes and data, and, when available, photographs and video, recorded at the time of interactions, informed take designations. Observers typically detail the nature of the injury and changes in the animal's behavior following its release, and notes indicating a potential mortality could include evidence of bleeding, broken bones, wounds, trailing gear, vomiting, and abnormal behavior (NWFSC, 2020a). For the purposes of our models and estimating bycatch, all interactions designated as takes were considered mortalities and therefore, bycatch.

2.2 Statistical Model

We used Bayesian generalized linear models (GLMs) to estimate annual means and variability of short-tailed albatross bycatch within the LE longline fleet, for both the observed and unobserved portions of the fleets. The simplest version of our estimation model used assumes that the number of observed bycatch events for each year follows a Poisson distribution,

$$n_{take,y} \sim Poisson\left(\lambda_y = \theta \cdot E_y\right)$$

where:

$n_{take,y}$ = the number of observed bycatch events (or take events) in year y
λ_y = expected observed bycatch (# of animals)
θ = estimated observed bycatch rate
E_y = observed effort in year y.

This formulation is identical to that of widely used GLMs, where a log-link is used to estimate θ and E_y is included as an offset term, $\log(\lambda_y) = log(\theta) + log(E_y)$. The unobserved bycatch rate can be calculated similarly, replacing E_y with the unobserved effort in year y. In this formulation, the estimated bycatch rate θ is not time-varying, but does include parameter uncertainty that is propagated through calculations of mean bycatch, $\theta \cdot E_y$. Variability in estimated observed bycatch rates over time is thus driven by changes in observed effort. Additional factors such as albatross distribution in space or time, or major changes in fisheries gear may also affect observed bycatch rates, but those quantities are assumed constant here.

We considered several extensions to the base model described above. First, we evaluated models where observed bycatch was drawn from alternative distributions (negative binomial, Poisson hurdle model), which can be appropriate for zero-inflated datasets. Second, we evaluated the potential to fit models that allowed the bycatch rate to be variable through time. To simulate that bycatch rate variability through time, we modeled bycatch rate as a random walk in log-space, $\theta_y \sim Normal\left(\theta_{y-1}, \sigma_\theta\right)$, where σ_θ is an added parameter that controls the variability of the random walk. Finally, we explored how two alternative measures of fishing effort (number of observed hooks, mass of observed retained catch) affected inference and model performance.

Due to the paucity of bycatch events, covariates of interest, such as year or environmental effects, were not included.

Estimation was done using Stan and the R package *rstan* (Stan Development Team, 2016), which implements Markov chain Monte Carlo (MCMC) using the No-U Turn Sampling (NUTS) algorithm (Hoffman and Gelman, 2014; Carpenter et al., 2017). Weakly informative Student-t (3, 0, 2) priors were used for all fixed effect parameters. For each model considered, we ran three parallel MCMC chains for 4000 iterations each, discarding the first 50% of the samples. Convergence was assessed using $\hat{R}$ and effective samples size (Gelman et al., 2013) along with trace plots. To evaluate models with the highest predictive accuracy, we used the Leave One Out Information Criterion (LOOIC, Vehtari et al., 2017, 2022) as a model selection tool, which approximates leave-one-out cross-validation. Code to perform these analyses is available as an R package (*bycatch*, https://ericward-noaa.github.io/bycatch/; Ward and Jannot, 2021; Jannot et al., 2021b).

2.3 Expanding bycatch to the unobserved portion of fleet

Observer coverage is < 100% and variable through time, therefore observed bycatch estimates need to be expanded to the unobserved portion of the fleet to estimate total bycatch. There are a number of ways to calculate bycatch in the unobserved part of the fleet, including dividing $\theta \cdot E_y$ by the observer sampling rate; however, this ignores uncertainty in the expansion. To fully propagate uncertainty forward, we used the posterior predictive samples from the observed portion of the LE sablefish longline fleet to expand to the unobserved portion of the fleet (Jannot et al., 2021b), which was derived by subtracting observed fishing effort from total fishing effort. These posterior predictive estimates of the unobserved portion of the fleet were then added to observed bycatch to estimate total albatross bycatch.

2.4 Evaluating management thresholds

We used the simulated values from the posterior predictive distribution to generate 95% credible intervals (CIs) for the predicted total bycatch in each year to evaluate existing management thresholds. The incidental take of short-tailed albatross in this fishery is expected to be no more than one observed or a mean of five estimated albatross over a 2-year period (USFWS, 2017). As the management threshold based on observed data is known, we focused on the probability of Bayesian estimates of total fleetwide bycatch exceeding this threshold. In addition to evaluating the probability of exceeding this management-set threshold, we also evaluated the probability of exceeding a more conservative threshold of three or four animals/2-year period.

2.5 Sensitivity analysis

To understand how the likelihood of detecting future bycatch events in the unobserved portion of the fleet is affected by changes in observer coverage, fishing effort, and observed bycatch events, we used the Bayesian framework described above and the Poisson data model with a constant bycatch rate to explore fishery scenarios. We varied fishing effort within the range of historically observed values (300 - 900 sets/year) and annual observer coverage from 0 - 100%. For each of these cases, we used the existing observations of bycatch to estimate the bycatch rate. We then varied the observed takes in a future year; as these are generally rare events, we only explored future observations of 0 mortalities or 1 mortality. We fit the Bayesian model to each permutation (4 MCMC chains, 40,000 iterations to better approximate posterior predictive frequencies). The posterior predictive distributions were then used to estimate the probabilities of unobserved takes occurring in the unobserved portion of the fleet. The total estimated bycatch is simply a sum of observed and predicted bycatch for the unobserved portion of the fleet,

$$N_{obs} + Poisson(\theta \cdot U_y),$$

where N_{obs} is the number of observed bycatch events, θ is the estimated bycatch rate using historical data, and U_y is the unobserved effort in year *y*.

3. Results

3.1 Model Diagnostics and Selection

Models employing a constant bycatch rate and drawn from a Poisson distribution did converge, and the model with the highest predictive accuracy for short-tailed albatross bycatch (with the lowest LOOIC) used observed sets for fishing effort (Table 3). Models using observed hooks or retained catch for fishing effort resulted in lower predictive accuracy (ΔLOOIC = 0.3, 0.5 respectively); these differences were smaller than the LOOIC estimates' standard errors (7.6 - 8.1), and the models were qualitatively similar. Of the models using a time-varying bycatch rate and drawn from alternative distributions, only a single negative binomial model and two Poisson hurdle models demonstrated convergence (Table 3). Despite the increased flexibility of those alternative error distributions, the LOOIC statistics indicated that the Poisson model with observed sets for fishing effort and a constant bycatch rate had slightly better predictive accuracy than the Poisson hurdle model (Table 3). The best model resulted in a bycatch rate θ of 0.139 takes per 1000 sets (95% CIs = 0.007 - 0.452).

3.2 Estimated bycatch of short-tailed albatross

Annual expected mortalities for the observed portion of the fleet varied over the course of the times series, generally increasing from around 0.05 birds from 2002-2004 to around 0.10 from 2017-2019. Estimated mortalities peaked at nearly 0.10 birds in 2005, averaged around 0.07 for three years, bottomed out at 0.04 in 2009, peaked above 0.10 in 2010, trended downward for three years, and trended upward since 2013, peaking in 2018 (Fig. 1a). Mean estimated bycatch, and associated uncertainty with that estimate, for the observed fleet was greatest in years with more observed effort (2005, 2010, 2018; Fig. 1a).

Fleetwide bycatch estimates (unobserved estimates plus documented observed mortalities) also varied annually; estimates did not trend upward or downward over the times series, but peaked at 1.35 birds in 2011, the year of the only observed mortality (Fig. 1b). The total fleetwide bycatch and upper confidence limit estimates were relatively high in 2009 (0.52). In addition, 2019, as well as 2004 (0.28), 2006 (0.26), 2010 (0.3), and 2012 (0.26), had relatively high bycatch estimates for the unobserved portion of the fleet (Table 4). The expanded estimates of total bycatch from models using observed hooks or retained catch for fishing effort (see Table 2) were qualitatively similar to estimates using observed sets.

As expected, the posterior predictive distributions for unobserved sets is highly skewed with the majority at 0, resulting in 95% credible intervals that are not variable for many years (*e.g.* the upper 95% credible interval for total bycatch is 1.0 for the last five years; Fig. 1b). The posterior distribution of total positive takes [Pr(takes ≥1), the probability of non-zero takes occurring] is an alternative measure of uncertainty or risk. In most years the probability of more than 0 takes occurring was < 0.20; this probability was 1.0 in 2011, when an actual take occurred, and 0.36 in 2009, when observer coverage was very low (Table 4).

3.3 Evaluating management thresholds and likelihood of future STAL takes

The probability of the fleetwide estimate of short-tailed albatross bycatch exceeding five takes in a 2-year period was low throughout the time series (< 0.02), but was elevated during the period from 2009-2012 (Fig. 2), with a peak of approximately 0.018 in 2011. Exceeding lower thresholds of three or four estimated takes in a 2-year period had higher probabilities, especially during the 2009-2012 period, with peaks of 0.15 and 0.05, respectively (Fig. 2). The probability of reaching the five takes/2-year period threshold was approached only under conditions of very low observer coverage, very high fishing effort, and multiple takes in the observed portion of the fleet (Fig. 3).

The probability of short-tailed albatross takes in the unobserved portion of the fleet in a future year increased, as expected, with lower observer coverage and higher fishing effort (Fig. 4). Having at least one take in the observed portion of the fleet (as compared with zero) also increased the estimated bycatch rate, translating into a higher probability of a take in the unobserved portion of the fleet (Fig. 4). For the relatively high observer coverage spanning the last five years (~37%), this probability ranged from 0.07 - 0.16 with no observed takes to 0.11 - 0.27 with one observed take, depending on the level of fishing effort.

4. Discussion

Estimating rare mortalities has been a challenge in fisheries monitoring because of untested assumptions of ratio estimators and proxy methods as well as the volatility of estimates from ratio estimators (Rochet and Trenkel, 2005; Martin et al., 2015). This challenge hinders assessing the impacts of fisheries on rarely caught seabirds. The Bayesian approach we used here to expand and estimate total bycatch of short-tailed albatross in the U.S. West Coast LE sablefish longline fleet overcomes these challenges. We found that expected mortalities, while variable, are effectively zero for most years, and thus below the management threshold established for this endangered species. Challenges remain, however, due to sampling biases from cryptic mortality or non-random distribution of fishing effort in time or space.

We found that estimates and uncertainty around total bycatch in a given year were sensitive to how bycatch rates were modeled. In addition to the positive influence of effort on bycatch, changes in observer coverage also affected bycatch estimates. Higher observer coverage rates decrease uncertainty in the model and reinforce the rarity of observed bycatch, thus reducing uncertainty in the likelihood of bycatch overall and resulting in lower expected bycatch in the unobserved portion of the fleet. That is, the more samples showing zero bycatch, the more likely unsampled portions of the fleet also encountered zero bycatch. By contrast, low observer coverage increases uncertainty and thus inflates estimates of total bycatch; historically low observer coverage in 2009 (7%) resulted in a greater estimate for the unobserved portion of the fleet and thus total bycatch for that year. High fishing effort in 2010 and 2018 also resulted in higher estimates for the observed portion of the fleet; however, lower observer coverage in 2010 relative to 2018 led to greater fleetwide estimates in 2010 compared to 2018.

Fisheries with rare-event bycatch and low observer coverage create unique problems for estimating bycatch over time and space, especially where estimates are compared with conservation thresholds, such as delisting criteria, or management thresholds, such as incidental mortality limits. Our analyses demonstrate that Bayesian time series modeling is an effective method for estimating bycatch of a rarely caught seabird, making our approach preferable to simple ratio estimation. Uncertainty intervals from the Bayesian method can be interpreted as probability distributions, the probability of exceeding thresholds can be easily calculated, and modeling is robust to future potential mortality in the context of fisheries and endangered species management. Simple bycatch-generating processes (*i.e.*, Poisson) work well when data are rare but not over-dispersed, whereas over-dispersed data can be accommodated by more complex distributions (Jannot et al., 2021a). Using information from the entire time series, our modeling resulted in reduced bias and reporting uncertainty, which are useful when using the precautionary principle to craft management policies.

Unlike ratio estimators, which can produce highly volatile and unrealistic results when bycatch is rare (data sets are zero-inflated), our Bayesian modeling produced predicted annual means and credible intervals that are more realistic, given the extent of short-tailed albatross bycatch documented throughout the North Pacific. Estimates of bycatch produced through ratio expansion result in many years with zeroes and a few years with alarmingly high values if any bycatch is observed. For example, using ratio estimation on this dataset would result in a point estimate of 4.8 short-tailed albatross mortalities for 2011 and zeroes for every other year. This estimate did not include any estimates of error around the point estimates, which implies certainty that we do not have, given observer coverage levels of less than 100%. Bayesian estimation of bycatch for seabirds in these fisheries are much less volatile compared to ratio estimation, which oscillates between low and high annual estimates with no estimated uncertainty (Jannot et al., 2018).

Bayesian modeling also enabled exploration of probabilities associated with having a fishery that has a substantial portion of the fleet that is unobserved. Our analyses showed that the probability of reaching the management threshold of five short-tailed albatross takes/2-year period is extremely low (< 0.02), except under the exceedingly unlikely conditions of very low observer coverage, very high fishing effort, and multiple takes in the observed portion of the fleet; this was true even for a year with a documented take (2011). To clearly link probability of STAL bycatch to population recovery, it would be advisable to consider insights from the sensitivity analyses presented here in any revised bycatch thresholds set using Bayesian modeling.

Our Bayesian modeling approach also enabled us to show that the probability of short-tailed albatross takes in the unobserved portion of the fleet increased, as expected, with lower observer coverage, higher fishing effort, and documented takes in the observed portion of the fleet. As the bycatch rate (θ) is assumed constant over time, future observed takes will increase both the mean bycatch rate and the probability of unobserved takes occurring, because the rate is increased. For a given level of risk (*e.g.*, a 5% chance of an unobserved bycatch rate occurring), our simulations highlight the changes in effort or changes in observer coverage that would be necessary to achieve the acceptable risk level. Like any model framework that assumes a constant bycatch rate, if short-tailed albatross experience non-stationary dynamics (future population growth and/or distributional changes), inference from our current model may not yield unbiased estimates.

Probability-based methods are advantageous where bycatch is dominated by zeroes -- they reduce bias from rare events, incorporate uncertainty, and have less reliance on assumptions. The model-based Bayesian approach has been employed with other rare bycatch species, including marine mammals, sea turtles, and sharks (Martin et al., 2015). While we believe these methods show promise, as in any modeling situation, it is possible to overfit a particular dataset; especially in data-poor situations, we suggest analyses start with simpler models.

These methods also reduce volatility by using all information in the time series, reduce arbitrary decisions about how many years of data to combine, and enable probabilistic inference for bycatch conditional on fishing effort. This is particularly important for translating bycatch estimates into probabilities of exceeding management thresholds, which is conceptually simpler and can also be more easily interpreted by resource managers. These qualities highlight why these methods are important for understanding bycatch patterns and responding to years of high bycatch; accurate and properly bounded estimates of bycatch are critical for both adaptive fisheries management and conservation and recovery of listed species.

As with many bycatch expansion methods, a limitation of our modeling approach is that it is much more informative if there is at least one observed mortality in the time series to estimate bycatch (with no takes, the modeling produces large variance estimates). There is interest in estimating short-tailed albatross bycatch in other longline fishing fleets along the U.S. West coast, including the Limited Entry Daily Trip Limit and Open Access fleets. However, differences in areas fished, targeted species, quotas and catch limits make it inappropriate to apply bycatch rates estimated for the LE sablefish longline fleet to these other fleets or to simply combine these fleets into a single analysis. Non-injurious encounters, such as feeding on offal and bait, and sightings of short-tailed albatross have been recorded by observers on actively fishing vessels in these fleets (Jannot et al., 2021b). These interactions raise concerns with resource managers and conservation practitioners because of the potential for serious injury or mortality. Therefore, assessing bycatch risk to short-tailed albatross from other U.S. West Coast fishing fleets continues to be a priority.

Data availability is another limitation of these or any expansion methods, as we rely exclusively on observer data. In the LE sablefish longline fleet, observers collect information that might provide insight into seabird bycatch risk in general, such as fishing depth, latitude, setting speed, set duration, etc. Without comparable data from the unobserved portion of the fleet, our analyses cannot fully utilize the rich data sets provided by observers. Rather, our analyses must assume that the spatio-temporal aspects of fishing are similar among observed and unobserved vessels, and such assumptions limit our understanding of the causes of bycatch. The "observer effect" posits that observed vessels can behave quite differently than unobserved vessels (Benoît and Allard, 2009; Faunce and Barbeaux, 2011); therefore, any inferences about seabird bycatch in general must be tempered by the limited data available from unobserved vessels and the potential for an observer effect.

In the future, data from unobserved vessels in this fleet may be obtained through increased use of vessel logbooks (not yet required but are being developed for U.S. West Coast longline fisheries) or the expanded use of electronic monitoring. These data would not only increase our understanding of the substantial unobserved portion of the fleet, but they might also reveal any spatial and temporal strata in the fishery that could affect bycatch estimates. Still, any estimates of seabird bycatch will still be affected by sampling biases from unobserved and unrecorded mortality (Gilman et al., 2013; Zhou et al., 2020) as well as from constraints from observer programs designed to document bycatch and discard of non-target fish species.

That said, the Bayesian method has been adopted by management agencies (Good et al., 2021; Jannot et al., 2021b), tailoring analyses to particular fisheries, assumptions, and management thresholds. For example, analyses of humpback whales (*Megaptera novaeangliae*) bycatch in the West Coast sablefish pot fishery built on the Bayesian estimation by including a simulation component that examined model support for alternate distributions of sparse data (Jannot et al. 2021a). The analyses presented here built upon the Bayesian estimation by including analyses exploring how fishing effort variation and potential future bycatch affected inferences about exceeding the management threshold.

Potential future analyses include modeling the effects of covariates on bycatch estimates. These include factors based on known or suspected operational or environmental factors, time-varying bycatch rates (which might result from shifts in population distribution for example), or a steadily increasing short-tailed albatross population. While our limited data precluded modeling the effects of covariates for estimating bycatch, recent analyses of black-footed albatross bycatch in U.S. West Coast groundfish fisheries (Wuest et al., pers, comm) suggest there is merit to exploring covariate effects for more commonly bycaught species (Jannot et al., 2021b). One covariate of particular interest to explore in more populated bycatch time series (such as for black-footed albatross) is that of streamer line use. While the single instance of a short-tailed albatross mortality occurred on a set where streamer lines were deployed, this seabird dissuasion technique has proven to be effective for albatross bycatch reduction in many longline fisheries. Streamer lines are included in best practices to reduce bycatch in longline fisheries worldwide, and their use is mandated in U.S. West Coast longline fisheries (USFWS, 2017).

Seabird bycatch, particularly when rare, is challenging for fisheries management organizations to estimate, but its estimation is a necessary first step toward mitigating any bycatch-related impacts on the population. Conservation efforts require accurate accounting of fisheries-related mortality, which can be difficult when not all fisheries are monitored or not all vessels in a fishery are observed. The Bayesian modeling described here addresses this latter challenge and provides estimates of observed as well as unobserved bycatch in such partially monitored fisheries. These modeling efforts are flexible and applicable to commonly used generalized linear models; they can produce uncertainty estimates around means as well as estimates of undetected bycatch when observed bycatch in a given year is zero. Interactions of short-tailed albatross and fisheries throughout the North Pacific may increase as the species continues to recover, and distributional shifts may occur in the species and fisheries due to climate change, which could lead to increased bycatch risk. The modeling framework presented here provides managers and analysts with an important tool to more accurately assess the impacts of fishing on rarely caught and endangered seabirds.

Data availability statement

The data that support the findings of this study are available in the tables of this article.

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Table 1. Short-tailed albatross mortalities associated with North Pacific fisheries (Alaska, West Coast U.S., Russia, Japan) since 1983, including report date, fishery, if reported in observer program, age of bird, and source.

Report Date	Location	Fishery	Observer program	In sample*	Bird age	Source
7/15/1983	Bering Sea	Net	No	n/a	4 months	USFWS (2008)
10/1/1987	Gulf of Alaska	Halibut	No	n/a	6 months	USFWS (2008)
8/28/1995	Aleutian Islands	IFQ sablefish	Yes	No	1 year	USFWS (2008)
10/8/1995	Bering Sea	IFQ sablefish	Yes	No	3 years	USFWS (2008)
9/27/1996	Bering Sea	Pacific cod Hook-and-line	Yes	Yes	5 years	USFWS (2008)
4/23/1998	Bering Sea, Russia	Russian salmon drift net	n/a	n/a	< 1 year	USFWS (2008)
9/21/1998	Bering Sea	Pacific cod hook-and-line	Yes	Yes	8 years	USFWS (2008)
9/28/1998	Bering Sea	Pacific cod hook-and-line	Yes	Yes	Sub-adult	USFWS (2008)
7/11/2002	Sea of Okhotsk, Russia	Russian**	n/a	n/a	3 months	YIO (2011)
8/29/2003	Bering Sea, Russia	Russian demersal longline	n/a	n/a	3 years	YIO (2011)
8/31/2006	Kuril Islands, Russia	Russian**	n/a	n/a	1 year	YIO (2011)
8/27/2010	Bering Sea/Aleutian Islands	Pacific cod hook-and-line	Yes	Yes	7 years	NOAA Fisheries (2010)
9/14/2010	Bering Sea/Aleutian Islands	Pacific cod hook-and-line	Yes	Yes	3 years	NOAA Fisheries (2010)
4/11/2011	Pacific Ocean/Oregon	Sablefish demersal longline	Yes	Yes	1 year	USFWS (2012)
10/25/2011	Bering Sea	Pacific cod hook-and-line	Yes	Yes	1 year	NOAA Fisheries (2011)
5/24/2013	Pacific Ocean, Japan	Hook-and-line seabird bycatch research	No	n/a	1 year	YIO, pers. comm.
9/7/2014	Bering Sea/Aleutian Islands	Greenland turbot hook-and-line	Yes	No	5 years	NOAA Fisheries (2014a)
9/7/2014	Bering Sea/Aleutian Islands	Greenland turbot hook-and-line	Yes	Yes	Sub-adult	NOAA Fisheries (2014b)
12/16/2014	Bering Sea/Aleutian Islands	Pacific cod hook-and-line	Yes	Yes	< 1 year	NOAA Fisheries (2015)
9/26/2020	Bering Sea/Aleutian Islands	Pacific cod demersal longline fishery	Yes	Yes	9 years	NOAA Fisheries (2020a)
10/16/2020	Bering Sea/Aleutian Islands	Pacific cod demersal longline fishery	Yes	Yes	2 years	NOAA Fisheries (2020b)

* “In sample” refers to whether specimen was in catch sample analyzed by a fisheries observer

** Specifics regarding the type fishery are unknown

n/a = not applicable

Table 2. Data for calculating short-tailed albatross bycatch, including observed fishing effort (number of observed sets, hooks, and retained catch), observer coverage (proportion of fleet-wide catch observed), and short-tailed albatross (STAL) takes in the LE sablefish longline fishery from 2002–2019 (data from the West Coast Groundfish Observer Program).

Year	Observed Sets (#)	Observed Hooks (#)	Observed Retained Catch (MT)	Observer Coverage (%)	Observed STAL takes (#)
2002	391	779,624	190.8	24	0
2003	351	733,602	222.8	21	0
2004	326	492,009	180.0	14	0
2005	678	1,456,102	481.5	36	0
2006	470	939,951	295.9	21	0
2007	517	1,034,046	298.5	27	0
2008	540	1,244,141	338.1	31	0
2009	287	648,980	97.8	7	0
2010	762	1,761,173	345.8	27	0
2011	673	1,405,444	240.7	21	1
2012	532	1,580,075	239.3	22	0
2013	353	1,047,526	166.4	22	0
2014	495	1,200,615	203.2	27	0
2015	632	1,536,820	397.8	41	0
2016	671	1,743,233	338.1	33	0
2017	701	2,107,656	396.8	37	0
2018	839	2,411,652	467.2	46	0
2019	673	1,791,897	359.3	39	0

Table 3. Model diagnostics (convergence, LOOIC, LOOIC Standard Error [SE]) for 18 combinations of fishing effort metric, bycatch rate, and bycatch process model choice. LOOIC statistics not reported for models that did not converge or had many divergent transitions.

Fishing effort metric	Bycatch rate	Bycatch process	Model convergence	LOOIC	LOOIC SE
Number of sets	Constant	Poisson	Yes	10.4*	7.6
Number of hooks	Constant	Poisson	Yes	10.7	8.1
Observed landings	Constant	Poisson	Yes	10.9	8.0
Number of sets	Time-varying	Poisson	No	-	-
Number of hooks	Time-varying	Poisson	No	-	-
Observed landings	Time-varying	Poisson	No	-	-
Number of sets	Constant	Negative binomial	No	-	-
Number of hooks	Constant	Negative binomial	No	-	-
Observed landings	Constant	Negative binomial	Yes	11.4	8.3
Number of sets	Time-varying	Negative binomial	No	-	-
Number of hooks	Time-varying	Negative binomial	No	-	-
Observed landings	Time-varying	Negative binomial	No	-	-
Number of sets	Constant	Poisson hurdle	Yes	11.4	7.4
Number of hooks	Constant	Poisson hurdle	No	-	-
Observed landings	Constant	Poisson hurdle	No	-	-
Number of sets	Time-varying	Poisson hurdle	No	-	-
Number of hooks	Time-varying	Poisson hurdle	No	-	-
Observed landings	Time-varying	Poisson hurdle	Yes	11.7	7.7

* model that both converged and had the lowest LOOIC

Table 4. Estimated annual bycatch of short-tailed albatross in the U.S. West Coast limited entry longline sablefish fishery, including mean bycatch for observed sets (bycatch rate multiplied by effort), mean total bycatch for observed and unobserved portions of the fleet (plus actual takes from Table 2), 95% credible intervals for mean total bycatch, and probability of ≥ 1 total takes for combined observed and unobserved sets.

Year	Expected bycatch (observed)	Mean total bycatch	95% CIs	Pr (≥ 1)
2002	0.054	0.179	0 - 1	0.151
2003	0.049	0.189	0 - 1	0.157
2004	0.045	0.281	0 - 2	0.223
2005	0.094	0.172	0 - 1	0.147
2006	0.065	0.255	0 - 2	0.203
2007	0.072	0.199	0 - 1	0.167
2008	0.075	0.168	0 - 1	0.145
2009	0.040	0.525	0 - 3	0.361
2010	0.106	0.299	0 - 2	0.229
2011	0.094	1.351	1 - 3	1.000
2012	0.074	0.263	0 - 2	0.214
2013	0.049	0.175	0 - 1	0.150
2014	0.069	0.189	0 - 1	0.160
2015	0.088	0.128	0 - 1	0.114
2016	0.093	0.187	0 - 1	0.165
2017	0.097	0.166	0 - 1	0.145
2018	0.117	0.138	0 - 1	0.121
2019	0.094	0.149	0 - 1	0.129

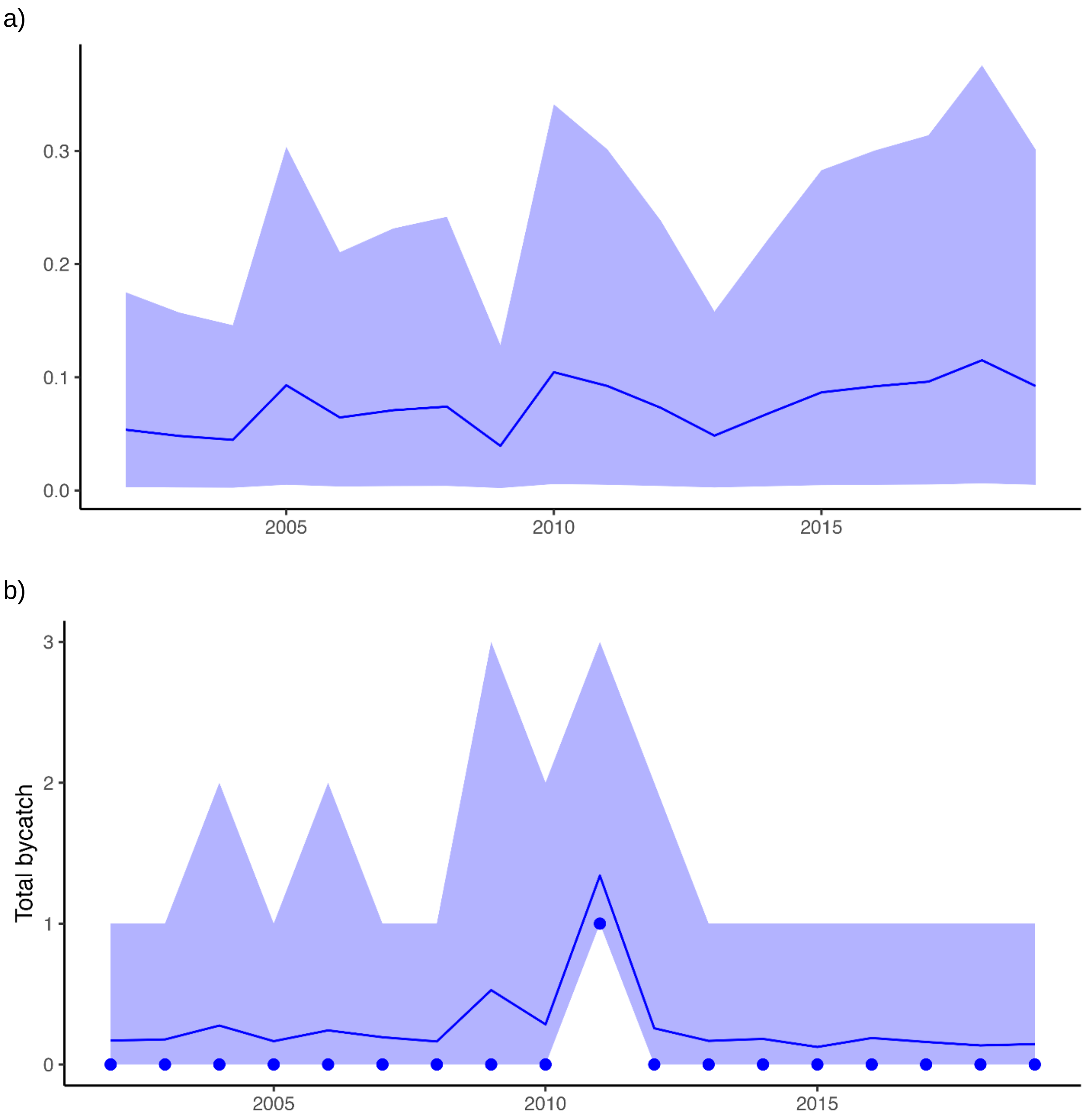

Figure 1. Estimated (a) mean short-tailed albatross bycatch (λ_y) in the observed fleet and (b) total short-tailed albatross bycatch in the entire LE sablefish longline fleet from 2002-19 using a constant bycatch rate, a Poisson distribution for bycatch, and observed sets as the measure of effort. Mean bycatch is calculated as the bycatch rate multiplied by observed effort (sets), where effort varies through time (Table 4). Solid lines represent the posterior mean, the shaded area represents the 95% credible interval, and dots represent observed bycatch.

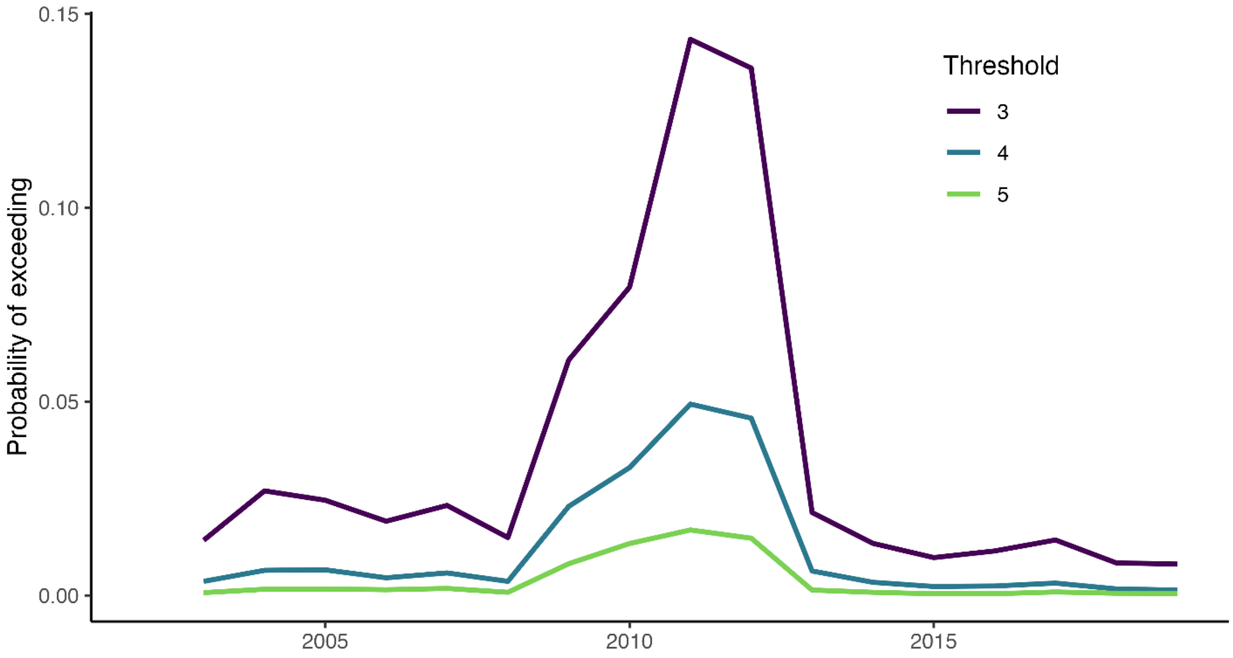

Figure 2. Probability of meeting or exceeding estimated bycatch threshold of 3, 4, or 5 short-tailed albatross over a 2-year window. The model used a constant bycatch rate, a Poisson distribution for bycatch, and the number of sets as effort.

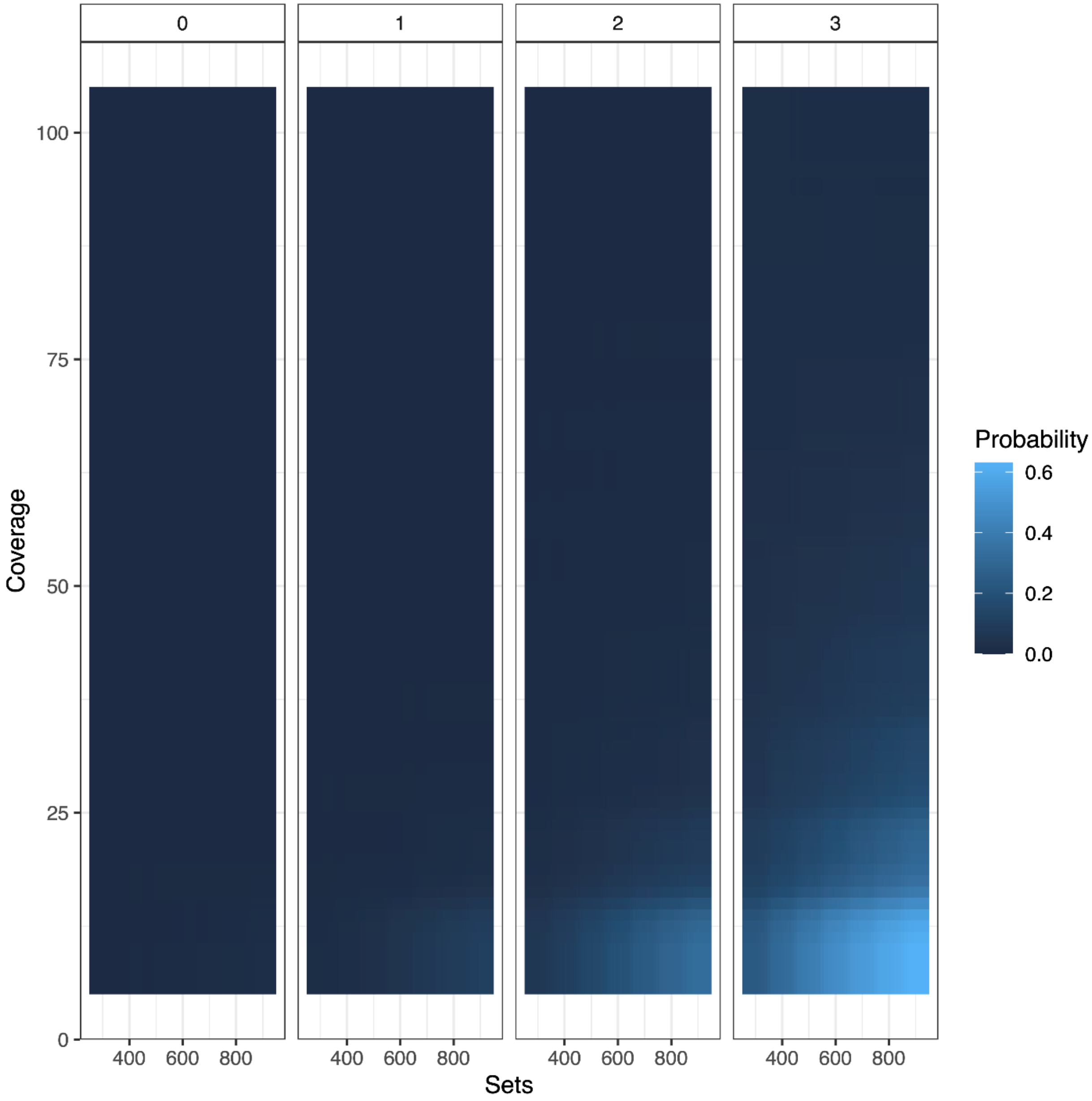

Figure 3. Probability of exceeding the take threshold (fleet-wide estimate of 5 short-tailed albatross over a 2-year period) in the U.S. West Coast sablefish longline fleet. This threshold is estimated across future observed effort (x-axis), observer coverage (y-axis) and future observed takes (facets). As these probabilities are variable by year, the year with the highest 2-year probability is shown (2011-2012).

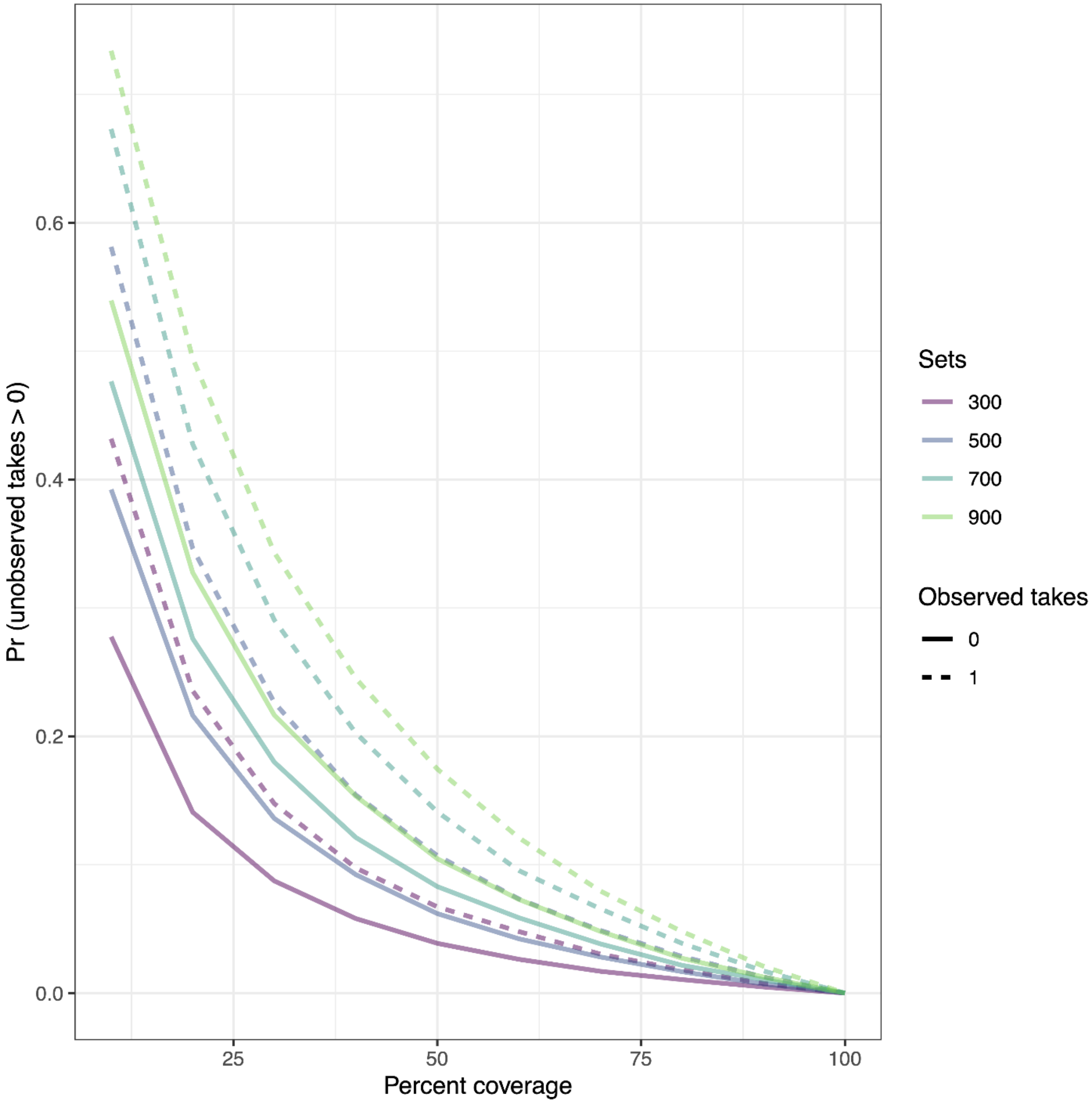

Figure 4. Probability of non-zero takes in the unobserved portion of the fishery, in a future year, based on bycatch estimates from 2002-2019. The posterior probability of takes being greater than 0, Pr(takes > 0) is shown for levels of observer coverage, future effort (measured in numbers of sets), and future takes in the observed portion of the fleet (0, 1).

Credit Author Statement

Thomas Good: Conceptualization, Writing –Original Draft, Writing - Review and Editing, Project Administration; **Jason Jannot:** Conceptualization, Methodology, Data Curation, Formal Analysis, Writing - Review and Editing; **Kayleigh Somers:** Validation, Writing - Review and Editing; **Eric Ward:** Conceptualization, Methodology, Formal analysis, Visualization, Writing - Review and Editing

Declaration of Interest Statement

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: