Seabird bycatch loss rate variability in pelagic longline fisheries

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1   Abstract:

2   The incidental mortality of seabirds from fisheries ranks as the greatest threat impacting

3   seabirds globally. However, its impact on seabird populations may have been

4   substantially underestimated due to lost, undetected bycatch. To estimate the full extent

5   of the bycatch problem, knowledge about the magnitude and variability of lost bycatch is

6   necessary. Based on a long-term dataset, this study aims to facilitate the loss-corrected

7   bycatch estimates for pelagic longline fisheries that do not have a concurrent bycatch loss

8   observation component. We analyze information from all types of fishery interactions of

9   seabirds to improve the estimate of bycatch loss rate and also reveal its variability.

10   Specifically, we analyze how environmental and ecological factors affect seabird bycatch

11   loss rate using Bayesian state-space models. Results show strong species effects in the

12   bycatch loss rate. Inclement weather and strong competition among seabird species also

13   affect bycatch loss rate. Estimates of the species-specific bycatch loss rate indicate that,

14   for some species, the loss can well exceed the average loss rate, suggesting that seabird

15   bycatch loss cannot be further ignored in assessing the fishery impact on seabird

16   populations. To gauge the full scale of seabird bycatch, it is critical to account for this

17   lost bycatch in bycatch assessments, at minimum, using an average loss rate with the

18   ultimate goal of species-specific loss-corrected assessments.

19   Keywords: Bayesian statistics; state-space models; bycatch assessment; cryptic bycatch

20

1 Introduction

The seabird bycatch problem in pelagic longline fisheries has been exposed for only about three decades (Brothers 1991), and yet bycatch in fisheries ranks as the top threat by impact to populations of albatrosses, large petrels/shearwaters and penguins (Anderson et al. 2011; Croxall et al. 2012; Dias et al. 2019). The incidental mortality from fisheries is currently recognized as a serious global concern (ACAP 2019a). It threatens 17 of the 22 albatross species with extinction and puts an additional 7 petrel species under elevated risk (ACAP 2019b; Anderson et al. 2011; IUCN 2019; Robertson and Gales 1998).

Seabirds foraging near a longline fishing vessel are vulnerable to being incidentally caught primarily during two windows of opportunity/risk, when the baited hook is accessible to seabirds either in the line-setting stage or in the line-hauling stage (Brothers et al. 2010). Many seabirds are surface-scavengers that take baits from hooks, and this behavior makes them vulnerable to longline fishing operations (Camphuysen et al. 1995). Those hooked or entangled at the setting stage are subject to loss during set, soak and haul (Brothers et al. 2010). Almost all fishery observer protocols to date only record bycatch at the haul, and consequently those caught at the setting stage that drop off the gear before they can be observed, i.e., cryptic bycatch (Gilman et al. 2013), are not included in the records. Due to this, the actual seabird bycatch in pelagic longline fisheries could well exceed what is reported (Anderson et al. 2011; Brothers et al. 2010). Cryptic seabird bycatch has also been documented in trawl fisheries, such as mortalities from warp strikes (Maree et al. 2014; Sullivan et al. 2006; Watkins et al. 2008).

43   In order to recover the cryptic seabird bycatch in pelagic longline fisheries, it is

44   necessary to consider a much broader class of seabird-fishery interactions, which

45   themselves are observable and cover both the apparent and cryptic bycatch events (Figure

46   1). Seabird-fishery interactions can be classified into different types based on whether the

47   sequence of interactions leads to a bycatch event and the associated observation

48   uncertainty (Figure 2A) (Brothers et al. 2010). Based on the seabird interactions with the

49   highest certainty of getting caught or entangled by the fishing gear (observed caught type;

50   also type O in Figure 2A), more than 50% of the observed caught seabirds were not

51   retrieved at the haul (Brothers et al. 2010). Similar estimates of loss rate were also

52   reported in Brothers (1991); Gilman et al. (2007) and Gilman et al. (2003). For this type

53   of interaction (observed caught type), observation uncertainty, i.e., mistakenly classifying

54   an interaction of an uncaught seabird into a caught category, is relatively low and can be

55   ignored to a first approximation. However, only a small fraction of all recorded

56   interactions qualifies as this type, e.g., less than 2.9% of all interactions were classified as

57   observed caught (Brothers et al. 2010), with the majority of interactions unutilized in the

58   estimation of loss rate, thus substantially limiting the inferential power of the analysis.

59   Pooling information from all recorded interactions has the potential to improve

60   the estimate of bycatch loss rate and also reveal its variability. A recent study based on

61   the same set of observation records as in Brothers et al. (2010) but making use of all

62   interaction types estimates the average bycatch loss rate at 29.8% with a 95% credible

63   interval of [0.24%, 51.88%] (Zhou et al. 2019a). The estimate is consistent with two

64   regional bycatch loss rate estimates: 27% for the Japanese longline tuna vessels operating

65   in the region of Tasmania, Australia (Brothers 1991) and 28% for the Hawaii longline

66 tuna and swordfish fisheries (Gilman et al. 2003; Gilman et al. 2007). Regional

67 differences in the percentages of observed seabirds caught during setting and

68 subsequently retrieved at the haul were noted in Brothers et al. (2010); however, it is

69 unclear whether regional differences contribute significantly to the variability of loss rate.

70   Since revelation of the bycatch loss problem at the global scale (Brothers et al.

71 2010), little has been done to try to estimate the lost portion of seabird bycatch in bycatch

72 assessments, with a few notable exceptions. In the assessment of seabird bycatch risk

73 from New Zealand commercial fisheries, a multiplier of 2.08 was used for all the

74 observed bycatches on pelagic longlines (Richard et al. 2017), taking into account the

75 sampling effect but still ignoring observation uncertainty. Such an approach is useful in

76 gauging the approximate scale of the total bycatch. The multiplier approach has also been

77 developed for trawl and demersal longline fisheries (Richard et al. 2017; Watkins et al.

78 2008). To avoid the problem of over-estimation, an integrated bycatch assessment model

79 built for the US Western North Atlantic pelagic longline fishery incorporates both

80 observation uncertainty in the bycatch loss process and bycatch origin (Zhou et al. 2019a).

81 By comparison with results from this integrated model, the corresponding loss-free

82 assessment model substantially under-estimated both total bycatch and the associated

83 uncertainty in that fishery. A loss-free assessment model is thus harmful both in

84 discounting the actual impact of bycatch and in making that false statement

85 overconfidently.

86   The aim of this study is to facilitate loss-corrected bycatch estimation based on

87 existing data for pelagic longline fisheries that do not have a concurrent bycatch loss

88 observation component (most qualify as such). The strategy is to extend models to test

89   variability of the bycatch loss rate among alternative factors and conditions to improve

90   our understanding of loss rate and the seabird bycatch process in longline fisheries. Using

91   Bayesian state-space models we analyze how environmental factors at the time of the

92   bait-taking interaction and ecological traits of seabirds affect bycatch loss rate.

93   2 Material and methods

94   2.1 Bait-taking attempts and outcome confirmation

95   The seabird bait-taking attempt and confirmation observations data in pelagic

96   longline fisheries was collected by XX from 11 fishing vessels. over a 15-year period,

97   from 1988 to 2003, in four geographical regions: Indian Ocean, Coral Sea, Southern

98   Ocean and Central Pacific. This data set contains a total of 5,969 observed seabird

99   interactions on a total of 726,626 baited hooks. The same data were previously presented

100   in Brothers et al. (2010).

101   The focal point of Brothers et al. (2010) was interacting seabirds, whereas, in this

102   study, the focus is instead on the baited hooks. A baited hook may be pursued by a single

103   individual or multiple individuals. When multiple individuals compete over the same

104   baited hook, the bait-taking attempt of each individual registers as a separate count of

105   interaction. While multiple bycatch incidences on the same hook are theoretically

106   possible, they have not been observed in the field, and in this study, we assume that a

107   baited hook may catch at most one individual. Due to this change of focus, the count of

108   different types of bait-taking attempts (Table 1) differs from that of Brothers et al. (2010).

109   The seabird interaction methodology was developed in 1988 by Brothers (1991).

110   Here, we present the methodology on a conceptual level and refer the reader to Gilman et

111   al. (2003) for a detailed description. The seabird interaction methodology involves two

112   linked observation components (Figure 2), one at the line setting stage and one at the

113   hauling stage. Time and other positional aids, such as the interaction location relative to

114   line surface floats distances, which provide time intervals, are used to link an observed

115   seabird interaction at the line setting stage to a retrieved carcass during the haul. In

116   contrast, a traditional observer protocol only involves observations at the hauling stage.

117   Multiple hooks are observed simultaneously and independently of each other; for

118   simplicity, the following description only pertains to the observations of a single baited

119   hook. At the line setting stage, a bait-taking attempt is classified into one of five types

120   based on whether the sequence of interactions that lead to a bycatch event and also the

121   classification uncertainty (Figure 2A). Indeterminate (I) will be assigned if an individual

122   is seen to successfully take the bait but circumstances do not allow further confirmations;

123   a possibly caught (P) individual is seen to successfully take the bait, display one of the

124   typical capture responses momentarily but circumstances do not allow the final

125   confirmation of the capture; an observed caught (O) individual displays clear evidence of

126   struggle and its inability to escape the line. I, P and O bait-taking attempts, in decreasing

127   uncertainty, eventually lead to a bycatch event. On the other hand, the attempt is

128   successful (S) if an individual was seen to successfully remove the bait from the hook

129   and not be caught in the process; it is unsuccessful (U) if the individual made no contact

130   with the fishing gear during the attempt. Multiple individuals may attempt to interact with

131   the same hook, and all attempts were recorded, but in this study, we are only concerned

132   with the last observed attempt. At the line hauling stage, a carcass is either retrieved from

133 the observed hook or not, and this result is recorded as the final confirmation of the

134 interaction (Figure 2B).

135   Note that all observations are based on behavioral responds of seabirds towards

136 baited hooks above the surface of the water, and underwater attacks cannot be observed

137 *directly*. However, each underwater attack attempt, i.e., the underwater dive pursuit, and

138 its outcome, e.g., successful or unsuccessful bait take when the bird that dived returns to

139 the surface, can be observed and accounted for in the model.

140 2.2 Probability model of the seabird bycatch and observation processes

141   To remove observation uncertainty from the estimation of bycatch loss rate and

142 also to pool information from different stages of bait-taking attempts (I, P and O) leading

143 to a bycatch event, a state-space probability model was developed. In this model, other

144 attempts and bycatch events are two hidden states, upon which two sets of observations

145 are made (Figure 2). The probability of classifying a bait-taking attempt (A) that does not

146 lead to a bycatch event as one of five types is

147 $Prob(A=i)=\beta_i,$

148 where $i \in \{O, P, I, S \text{ and } U\}$ with the constraint $\sum_i \beta_i = 1$, and similarly for an attempt

149 leading to a bycatch event, the classification probability is

150 $Prob(A=i)=\gamma_i,$

151 with the constraint $\sum_i \gamma_i = 1$. For a no-bycatch event, no carcass will be retrieved, and for

152 a bycatch event, a carcass will be retrieved with a probability of $1-p_{loss}$. Non-

153 informative Dirichlet priors, i.e., Dirichlet (1,1,1,1,1), were used for both the vectors of

154 β_i s and γ_i s for $i \in \{$O, P, I, S and U$\}$. It is assumed that the observations for different

155 hooks are independent and identically distributed.

156 ## 2.3 Predictors of the loss rate

157 Two sets of predictors were tested for their performance to predict bycatch loss

158 rate in this study: 1) environmental factors and 2) ecological traits. Environmental factors

159 include physical conditions and also biological competition, and these factors were

160 recorded concurrently with the bait-taking observations; ecological traits of seabirds were

161 extracted from published literature.

162 For the environmental factors, three variables were analyzed, i.e., *reg*: the four

163 fishing regions where the interaction is taking place, *phy*: the physical oceanic condition

164 at the time of the bait-taking attempt and *cmp*: the risk score at the nearest bird abundance

165 count interval. Variable *phy* is the sum of the wind score and sea score at the time of the

166 bait-taking attempt. It measures the roughness of the oceanic condition. The wind score is

167 a combination of wind speed and wind direction with respect to the vessel to determine

168 the score with a range from 1 (calm) to 8 (rough), and the sea score is based on the

169 Douglas sea scale with a score of 2 denoting slight waves and 8 denoting very rough

170 conditions. Three levels of *phy* representing calm, intermediate and rough conditions

171 were used, i.e., $phy \leq 4$, $4 < phy \leq 8$, and $8 < phy$. Most of the observed interactions

172 occurred when the condition was calm, and the least interactions occurred when the

173 condition was rough. Variable *cmp* is the sum of the counts of seabirds by species around

174 the vessel weighted by their respective bycatch risk score. Spot counts of seabird

175   abundance around the vessel were recorded mostly at either 15- or 30-min intervals

176   throughout the duration of line sets. The weight for each observed seabird species ranges

177   from 0 to 10 based on their tendency to engage in bait-taking interactions, with 0

178   denoting species that do not interact with fishing operations and 10 denoting species most

179   adept at bait locating and recovery. Four levels of competition severity were used, i.e.,

180     $cmp \leq 200$, $200 < cmp \leq 400$, $400 < cmp \leq 600$, and $600 < cmp$. See supplementary

181   material for a detailed description of the bycatch risk score for each species.

182   For the ecological traits, three variables were analyzed, i.e., *spp*: the species

183   identity of the seabird making the final bait-taking attempt, *diver* and *scavenger*: the

184   primary feeding strategies of the species. While all seabirds are capable of taking baits

185   close to the surface, some species regularly dive to snatch items at some distance below

186   the surface and some species are regular scavengers. These different feeding strategies

187   may have incurred different forms of hooking and/or entanglement, which consequently

188   led to different loss rates.

189   2.4 Hypotheses

190   Eight hypotheses on the variability of the bycatch loss rate were tested (Table 2).

191   The null hypothesis (H0) assumes a constant loss rate ($p_{loss} = p_0$). Here, the domain of p_0

192   is on the interval [0, 1], and we used the probit link function to transform the domain

193   from [0, 1] into the entire real line, i.e., $probit(p_{loss}) = c$. The use of probit link simplifies

194   the choice of the non-informative prior for c, which is the standard normal because of the

195   probability integral transformation between variables c and p_{loss}. All the following

196   hypotheses were constructed by adding covariates (predictors) to $probit(p_{loss})$.

197   The first three hypotheses test for the effect of environmental factors on loss rate.

198   Hypothesis H1 tests for the effect of the fishing region on loss rate. In H1, the loss rate of

199   an interaction occurred in region i with a probit link of $probit(p_{loss}[i]) = reg_i$, where the

200   prior of region effect is the standard normal for each region i=Central Pacific, Coral Sea,

201   Indian Ocean and Southern Ocean. In addition. the physical oceanic condition and

202   competitive species circumstances at the time of the interaction may affect the form of

203   hooking and/or entanglement and subsequently affect the bycatch loss rate. H2 tests for

204   the effect of oceanic condition on the loss rate. In H2, the loss rate of an interaction with

205   physical condition phy_j at the time of the interaction and a probit link is modeled as

206    $probit(p_{loss}[j]) = phy_j$, where the prior of the effect of physical condition is the

207   standard normal for each condition j=calm, intermediate and rough. H3 tests for the effect

208   of the severity of competition on loss rate. In H3, the loss rate of an interaction with risk

209   level cmp_k at the time of interaction and a probit link is $probit(p_{loss}[k]) = cmp_k$, where

210   the prior of the risk level effect is the standard normal for each bycatch risk level.

211   The other four hypotheses test for the effects of ecological traits of seabirds on

212   loss rate. The species-specific hypothesis (H4) assumes that each species has a species-

213   specific loss rate. In H4, the loss rate of species l with a probit link is

214    $probit(p_{loss}[l]) = spp_l$, where the prior of the species effect spp_l is the standard normal

215   for each species. Next, the hierarchical species hypothesis (H5) postulates an average

216   bycatch loss rate among all species, from which the loss rate for each species deviates. In

217   H5, the loss rate of species m with a probit link is $probit(p_{loss}[m]) = c + spp_m$, where the

218   prior for the average effect is $c \sim Normal(0, v[1])$, the prior for the species effect is

219    $spp_m \sim Normal(0, v[2])$, and the prior for the variance components is $v \sim Dirichlet(1,1)$

220   to ensure non-informativity on p_{loss}. H5 estimates both an average loss rate based on the

221   entire data set and the species effect for each species without partitioning the data set. H5

222   is a compromise between H0 and H4 in the sense that H0 assumes a constant loss rate

223   across all bait-taking attempts and estimates the loss rate based on the entire data set,

224   while H4 assumes a separate loss rate for each species and partitions the data according

225   to species identity.

226   In the next two hypotheses, we try to decompose the species effect into

227   components based on seabird ecological traits. Differences in primary feeding strategies

228   among different species may affect loss rate. Specifically, we test whether regular divers

229   and scavengers have a different loss rate than primarily surface feeding species. In H4e1,

230   the loss rate of species n with a probit link is $probit(p_{loss}[n]) = diver(n)$, where $diver(n)$ is

231   an indicator function of species n,

232    $$diver(n) = \begin{cases} 1, \text{ if species } n \text{ regularly dives for food} \\ 2, \text{ otherwise} \end{cases},$$

233   and in H4e2, the loss rate of species n with a probit link is

234    $probit(p_{loss}[n]) = scavenger(n)$, where $scavenger(n)$ is an indicator function of species n,

235    $$scavenger(n) = \begin{cases} 1, \text{ if species } n \text{ regularly scavenges for food} \\ 2, \text{ otherwise} \end{cases},$$

236   and the prior for each factor level is the standard normal for both hypotheses. Results

237   show that none of the environmental factors improved model performance, and therefore,

238   environmental factors were not included in H4e1 and H4e2.

239 2.5 Model fitting and selection

240   A Bayesian approach was used for parameter estimation. We used exclusively

241 non-informative priors for model coefficients. To simulate MCMC (Markov Chain

242 Monte Carlo) samples from the posterior distribution, we used JAGS 4.3 (Plummer 2003)

243 in the statistical program R 3.6.1 (R Development Core Team 2016).

244   Model performance was measured based on deviance information criterion (DIC,

245 (Plummer 2002)),

246 $DIC = \bar{D} + pD$,

247 where deviance D is twice the negative log-likelihood, $\bar{D}$ is the posterior mean of the

248 deviance, and pD is an estimate of the effective number of parameters in the model

249 based on the algorithm proposed by (Plummer 2002). The model with the minimum DIC

250 is the recommended model, and as a rule of thumb, a less than 2 difference in DIC

251 relative to the recommended model suggests substantial evidence for the model,

252 differences between 3 and 7 indicate that the model has considerably less support,

253 whereas a larger than 10 difference indicates that the model is very unlikely (Burnham

254 and Anderson 2003; Burnham et al. 2011).

255 3 Results

256   Species identity has a significant effect on the bycatch loss rate. Based on DIC,

257 the species-specific model H4 has the best performance in modeling bycatch loss rate

258 (Table 2). The selected model incorporates species identity as a fixed effect with a

259 reduction of 8.6 points with respect to the null model. Efforts to decompose the species

260   effect into ecological components were not successful. The species effect cannot be

261   explained by either the dive feeding behavior or the scavenging behavior, the

262   incorporation of which did not improve model fit against the null model. The inclusion of

263   the fishing region and physical oceanic conditions did not improve model fit against the

264   null model (Table 2). In addition, we did not find any effect of environmental factors on

265   bycatch loss rate.

266   Based on the null model H0, the posterior estimate of the average bycatch loss

267   rate peaks around 42.82% (Figure 3). The posterior estimate has a mean of 31.02% and a

268   95% credible interval [2.17%, 54.19%]. Compared to an earlier estimate of the average

269   bycatch loss rate on the same data set but based on the counts of bait-taking attempts in

270   three aggregate types (Zhou et al. 2019a), the posterior estimate in this study is more

271   concentrated around the region with the highest posterior density (Figure 3), suggesting

272   more information on the loss rate in the unaggregated form of the data. Both the mean

273   and interval estimates of the loss rate were slightly higher than the earlier estimate.

274   Based on the selected model (H4), species-specific bycatch loss rates were

275   estimated for 22 albatross, petrel and shearwater species (groups) encountered as bycatch

276   during the entire period of the experiment. The estimates of median and interquartile

277   range varied considerably among species (Figure 4). Among all 22 seabird species

278   (groups), grey petrel, great-winged petrel and white-chinned petrel were the top three

279   species (groups) with the highest median bycatch loss rate ($p_{loss} > 70\%$). Flesh-footed

280   shearwater, grey-headed albatross and northern royal albatross were among the bottom

281   three with the lowest median bycatch loss rate ($p_{loss} < 20\%$). Posterior estimates for

282 black petrel, Buller's petrel, Salvin's albatross, sooty albatross, soft-plumaged petrel and

283 wandering albatross did not differ much from the prior distribution due to the limited

284 number of observations available for these species. The species-specific bycatch loss rate

285 of these species is therefore inconclusive based on the available observations.

286   The median loss rate for a given fishing operation can well exceed 50% or more.

287 Although the posterior density of the average loss rate drops significantly in the range of

288 values larger than 50% (Figure 3), e.g., the posterior probability of $\bar{p}_{loss} > 60\%$ is less

289 than 0.001, the median loss rate for the top three species (groups) with the highest loss

290 rate exceeds 60%. The reason for this apparent contradiction is that the entire sample is

291 dominated by two species (groups), i.e., black-browed albatross and Laysan albatross,

292 which constitute 39% of all the recorded bait-taking attempts, and both species (groups)

293 have a similar median loss rate between 30% and 40% (Figure 4).

294   Stressful environmental conditions at the time of bait-taking interaction generally

295 result in a lower bycatch loss rate. Based on model H2, median estimates of the loss rate

296 under different physical conditions reveal that the loss rate is relatively stable at calm and

297 intermediate physical conditions but is actually lower when physical conditions are rough

298 (Figure 5). More competitive species situations also lead to slightly lower loss rates

299 according to the median estimate of loss rate at different levels of competition (Figure 6).

300   The dive feeding and scavenging behaviors failed to explain the majority of the

301 species effect on loss rate. Compared with the prior distribution (dotted line segments in

302 Figure 7) of the difference in loss rate between divers and non-divers, the posterior (solid

303 curve in Figure 7) only shifted slightly to the negative range, and on average, diving

304 species have a loss rate 7.26% lower in value than non-diving species. Similarly,

305 scavenging species on average have a loss rate 4.48% lower in value than non-scavenging

306 species (Figure 8).

4 Discussions and conclusion

308 Results from this study indicate that the loss component of seabird bycatch in

309 pelagic longline fisheries cannot be further ignored in assessing population impacts of

310 fishing on seabirds. The loss rate strongly depends on the species identity of the bycatch,

311 and for some species, species loss rate can well exceed average loss rate, which had a

312 medium value of 31.02% in this study and 50% in earlier studies (Anderson et al. 2011;

313 Brothers et al. 2010). Nevertheless, estimates based on average loss rate are an under-

314 estimate for some species. Notably, the posterior median loss rate of grey petrel is

315 77.84%. Species having a higher bycatch loss rate experience more impact from the

316 fishery than expected. Considering how little progress has been made to incorporate even

317 the average loss rate into seabird bycatch assessments, the first step forward would be to

318 recover lost bycatch using the average loss rate in order to gauge the approximate scale of

319 the total bycatch with the ultimate goal of species-specific loss-corrected assessments.

320 Estimated seabird species-specific bycatch loss rates provided here account for

321 fishery removals and are directly applicable to seabird conservation management. Efforts

322 to support bycatch loss observations are critically important given the high loss rate and

323 large variations among species found in this study. While the applicability of the study

324 results to data-deficient fisheries or regions remains open to question, use of indicative

325 information, such as the posterior average bycatch loss rate [see Zhou et al. (2019a) for

326 an example], is more appropriate from a seabird conservation perspective than to simply

327 ignore the fact of seabird bycatch losses entirely. This is increasingly important when

328 Potential Biological Removal methodology (Sharp et al. 2009) could be used to manage

329 fishery impacts and seabird populations.

330   It would be *wrong* to assume that, in general, the loss rate only rarely exceeds

331 54.19% (the upper boundary of the 95% credible interval of the average loss rate). By

332 itself, the average loss rate is misleading, and the only reason why it is presented here is

333 to accommodate data-poor scenarios where species identity of the bycatch is not available.

334 The estimated average bycatch loss rate is only *specific* to the experiment (Brothers et al.

335 2010), and in fact, it is the weighted average of all the seabird bycatches encountered

336 during the experiment. Thus, it does not represent the average bycatch loss rate in general.

337 Species identity plays a significant role in determining the actual average bycatch loss

338 rate for a particular fishery; whenever possible, the species-specific rates should be used

339 without making any unfounded assumptions on the sampling behavior. To incorporate the

340 bycatch loss process into assessment of the impact of bycatch on seabird populations, e.g.,

341 using the methods demonstrated in Zhou et al. (2019a), a species-specific approach is

342 recommended.

343   The primary forms of seabird bycatch are hooking in the bill/throat and

344 entanglement by the line (Brothers 1991). According to a recent study (Baker et al. 2019),

345 the retention rate is almost 100% for a hooked/entangled dead bird carcass. It is probable

346 that many birds caught that ultimately are lost successfully break loose while still alive.

347 Hooking and entanglement under stressful conditions may reduce successful escape

348 prospects. Even those that successfully escaped may have incurred injuries, e.g., a broken

349   lower bill, that can impact their long-term survival. Albatrosses have been observed that

350   have died on their nests from hook wounds (Weimerskirch and Jouventin 1987). Other

351   potential sources of hook wounds include discarded hooks in the offal and hooks

352   remaining on cut off branch lines attached to birds (Brothers 1995).

353   The loss of bycaught birds from fishing gear can be due to predation, currents and

354   other mechanical action during line soak and haul (Brothers et al. 2010; Gilman et al.

355   2003). Around one third of the seabird carcasses hauled aboard tuna fishing vessels in the

356   Australian Fishing Zone were damaged and partially eaten (Brothers et al. 1998; Gales et

357   al. 1999). Blue (*Prionace glauca*) and shortfin mako (*Isurus oxyrinchus*) sharks are

358   commonly caught as bycatch species on pelagic longlines (Gilman et al. 2008; Vega and

359   Licandeo 2009), and sharks in the vicinity, after the birds were hooked, including those

360   sharks later hooked themselves, may have caused removal of an entire seabird carcass

361   from a hook. In another study, , a large tear through the soft tissue in retrieved albatross

362   carcasses was often found in the region where the hook was lodged, suggesting that the

363   drag from currents might tear hooks free from the carcass (Trebilco et al. 2010). The

364   removal might also come from unobserved discarding of bycaught seabirds by the crew,

365   but it is not a factor in the current study due to the bycatch loss observations employed

366   (Brothers et al. 2010). Gales et al. (1998) found that the seabird catch rate in Tasmania

367   was 95% higher when accounting for the bycatch deliberately not hauled aboard due to

368   crew flicking or cutting the branch line along the side of the vessel.

369   The majority of the species effect remains unexplained. Some species, e.g., great-

370   winged petrel (Brothers et al. 2010), which is among the top three species with the

371   highest loss rate, are more skilled than others in successfully removing bait from hooks.

372   These species may be more likely to break free from otherwise fatal entanglement with

373   the fishing gear. Great-winged petrels, in particular, have a relatively small bill and gape,

374   which is likely to minimize their capture risk on the generally larger hook sizes in use by

375   pelagic longline vessels. Aggression and competition among individuals may be another

376   factor separating species according to successful outcomes and tendency to stay in place

377   once hooked. It has been observed that a seabird is capable of successfully removing bait

378   without being hooked or entangled in a relatively stress-free environment, e.g., when the

379   seabird is the only individual attempting to take the bait and the ocean is relatively calm.

380   When multiple individuals (possibly from multiple species) are competing for baits, a

381   higher number of individuals are caught (Brothers et al. 2010). Some species may

382   compete more aggressively for bait than others. In particular, northern royal albatross

383   often compete aggressively for baits already seized by other species (Brothers et al. 2010).

384   Such aggressive behavior may result in more secure capture circumstances and,

385   subsequently, relatively lower loss rate for this species (Figure 4).

386   This study did not find substantial evidence for divers having a different loss rate

387   from surface feeders and scavengers. Some proficient deep diving species are capable of

388   taking baits at even 200 m astern with an unweighted branchline (Keitt et al. 2000;

389   Weimerskirch and Cherel 1998), which is approaching the maximum reliable observation

390   distance across all sea state conditions under the current observation protocol, i.e., naked

391   eye with binocular assisted vision for more distant observations (Brothers et al. 2010). If

392   successful bait taking that can result in death was regularly occurring at depth beyond

393   observation distance, one would expect there to be a lot more inexplicable observed

394 bycatch, whereas the data contains few observed (carcasses hauled aboard) bycatch that

395 couldn't be ascribed to a particular interaction observation.

396   Geographically, the bait-taking observations in this study did not cover the West

397 Indian and Atlantic Ocean sectors, where the species composition of the bycatch is

398 substantially different from the regions covered in this study. Greater shearwater

399 (*Puffinus gravis*), northern gannet (*Morus bassanus*) and gulls (*Larus spp.*) dominate the

400 bycatch in the Western North Atlantic (Zhou et al. 2019b; Zhou et al. 2018), but none of

401 these species were bycaught in this study. Based on the strong species effect found in this

402 study, it is reasonable to suspect those bycatch species of the Atlantic may have a

403 different loss rate than explored here. It is therefore necessary to conduct a similar

404 experiment in the Atlantic (and elsewhere) to collect observations on seabird bait-taking

405 attempts in order to estimate the loss rate of additional species. Moreover, further

406 observations are needed for the seabird species (asterisked in Figure 4) that are already

407 covered in this study but with limited sample sizes.

408   The findings of the current study are consistent with previous studies on bycatch

409 loss rate (Baker et al. 2007; Brothers 1991; Brothers et al. 2010; Gilman et al. 2003;

410 Gilman et al. 2007; Zhou et al. 2019a), and the analysis of species-specific rates revealed

411 that the loss rate can reach as high as 70% for some species. An adequate bycatch

412 assessment should document the full impact of a fishery on seabird populations by trying

413 to recover the lost bycatch through the observation of both the set and haul. Continuing to

414 ignore bycatch loss in bycatch assessments may lead to eventual loss of biodiversity.

5 Acknowledgements

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536

Tables and figures

538 *Table 1 Number of bait-taking interactions by the extent of confirmation of outcome and*
539 *whether or not carcass was retrieved*

	Carcass retrieved	
Bait-taking attempts	No	Yes
Observed caught	90	85
Possibly caught	65	14
Indeterminate	238	13
Successful	1152	2
Unsuccessful	1331	0

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542 *Table 2 Candidate models based on different hypothesis on the loss rate and the model*
543 *selection results based on DIC. The selected model is marked in bold.*

Hypotheses	Covariates	ΔDIC
H0	-	8.6
H1	Fishing region	9.5
H2	Physical condition	8.9
H3	Bycatch risk score	11.1
H4	**Species-specific effect**	**0**
H5	Hierarchical species effect	2.5
H4e1	Diver or not	9.5
H4e2	Scavenger or not	10.1

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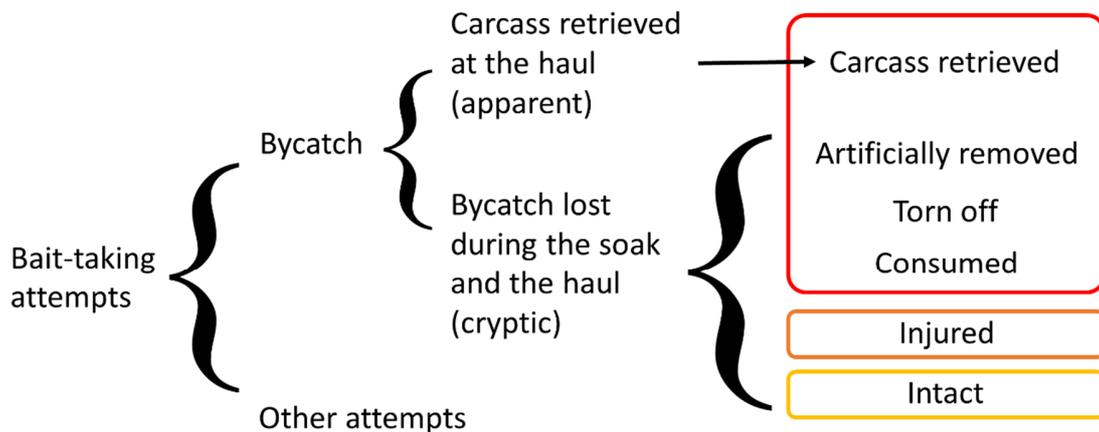
Seabird-fishery interactions   Outcome

Figure 1 Seabird-fishery interactions and the outcome of apparent and cryptic bycatch events in pelagic longline fisheries.

The outcome of the seabird-fishery interactions can be classified into three groups based on the severity of the impact. The high impact group (red) entails the immediate death of the seabird, and it includes carcasses retrieved, carcasses removed by cutting off the branch lines, those torn off the hook due to water pressure and those consumed whole by sharks or other predatory fish. The intermediate impact group (orange) and the low impact group (yellow) include those entangled seabirds that managed to escape with or without inflicting any injuries. Note that only the outcome of a retrieved carcass can be directly observed based on the existing observation protocol.

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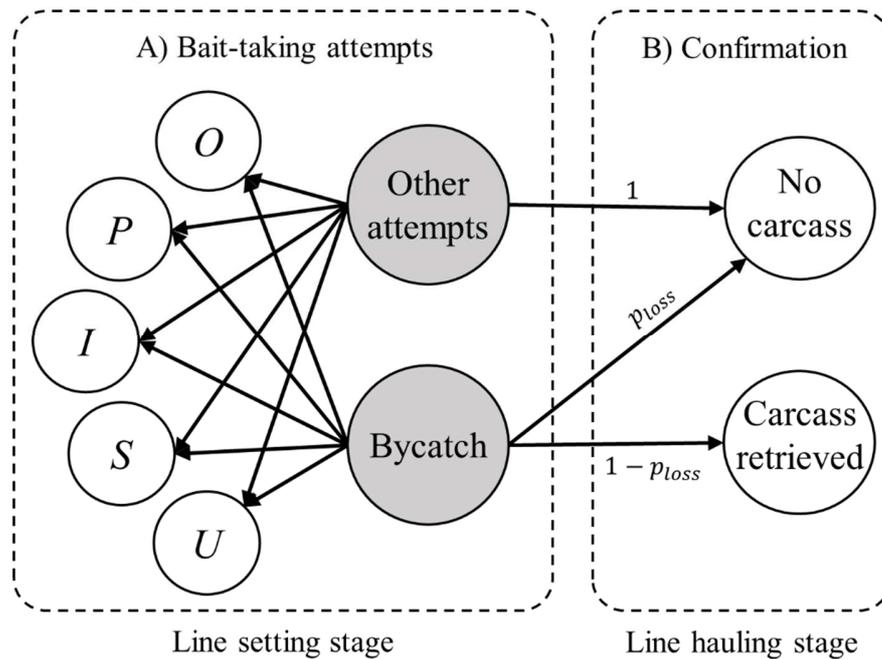
Figure 2 Observation of bait-taking interactions (A) at the line setting stage and outcome confirmation at the line hauling stage (B) with respect to a baited hook.

There are two types of bait-taking attempts (Panel A), those leading to a bycatch (lower gray circle), either through hooking or entanglement, and other attempts (upper gray circle). An observer classifies the interactions into one of five types (white circles to the left), observed caught (O), possibly caught (P), indeterminate (I), successful (S) and unsuccessful (U).

Bycatch events (Panel A) have two possible outcomes at the line hauling stage (Panel B): Either the carcass is retrieved at the hauling stage (lower white circle) or the captured seabird may separate from the hook with probability p_{loss} and become unobservable to the observer at the hauling stage (upper white circle). All the other attempts (Panel A) lead to the event of no carcass retrieved (Panel B). The expressions on the arrows are the associated state transition probabilities.

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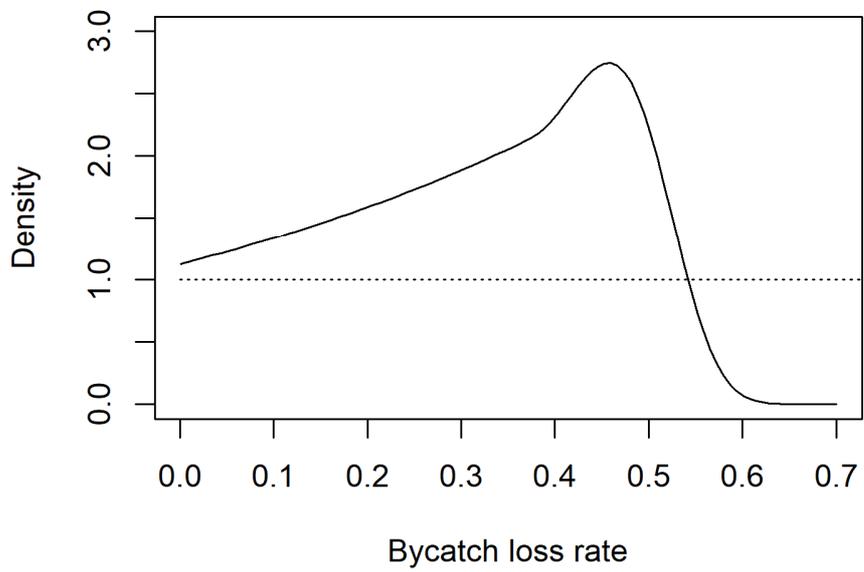
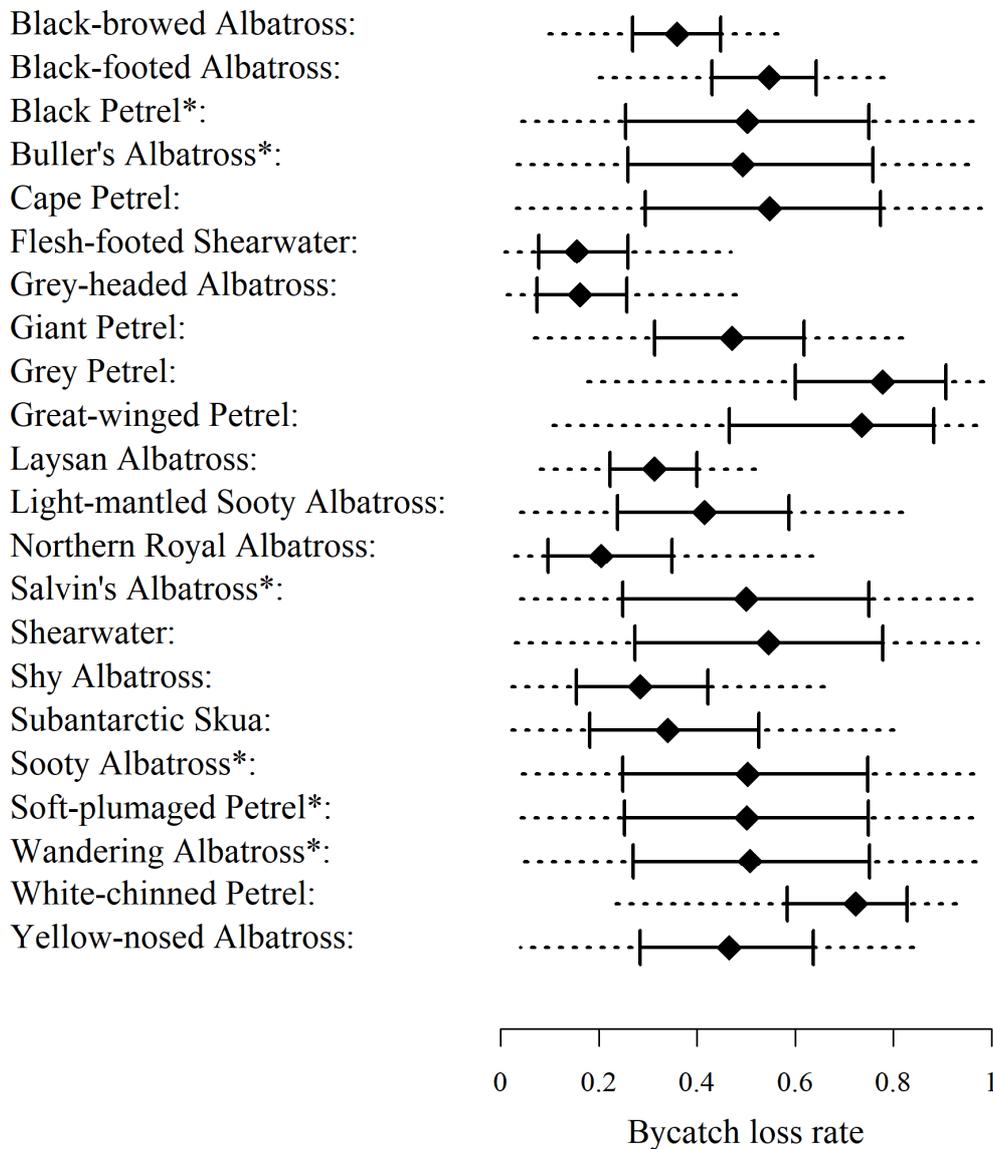Figure 3 Prior (dotted line) and posterior estimate (solid curve) of the average bycatch loss rate based on model H0.

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*Figure 4 Bycatch loss rates of common seabird species (groups) in pelagic longline fisheries. For each line, the solid diamond marks the median posterior estimate, the solid intervals mark the interquartile range of the posterior estimate, and the dashed line marks the 95% credible interval. Seabird species (groups) are ordered alphabetically. Black-browed albatross includes Thalassarche melanophris and T. impavida; Black petrel includes Procellaria parkinsoni, and P. westlandica; giant petrel includes Macronectes giganteus and M. halli; shearwater includes A. grisea, P. tenuirostris and P. pacificus; shy albatross includes T. cauta and T. steadi; wandering albatross include Diomedea exulans, D. antipodensis, D. dabbenena and D. amsterdamensis ; yellow-nosed albatross includes T. chlororhynchos and T. carteri. Species or species groups marked with * have no more than 10 observed records, and their results are inconclusive.*

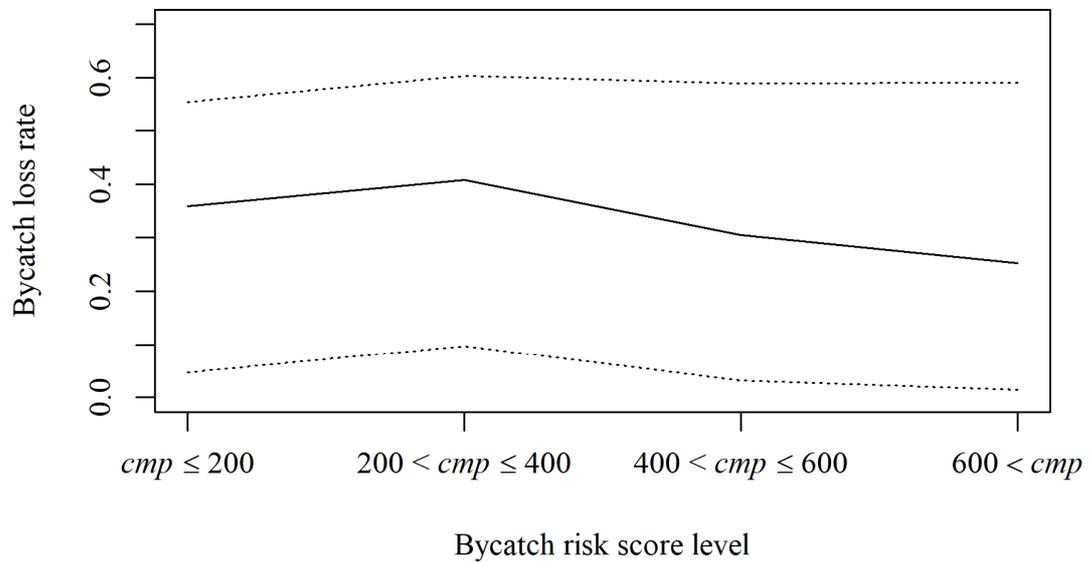594   [Production instructions: 1.5 or 2 columns; no color needed in print]

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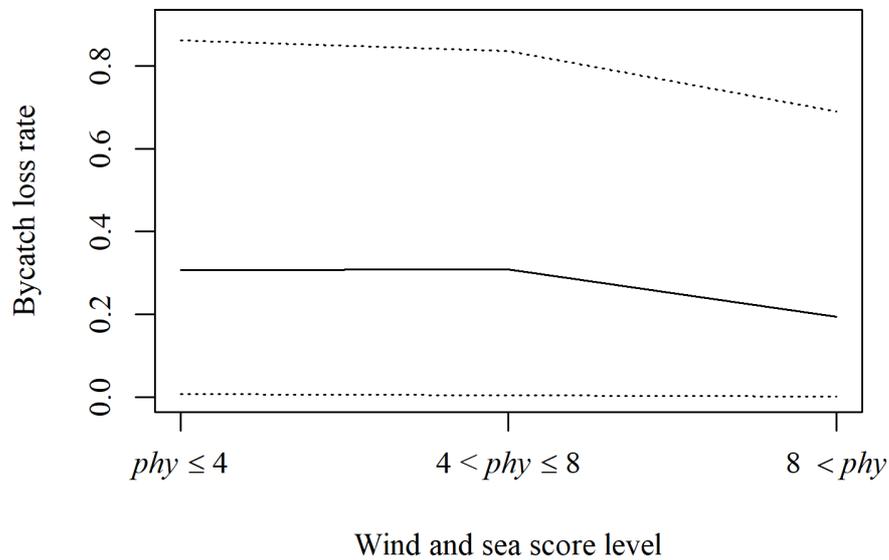
Figure 5 Median (solid line) and 95% credible interval (dotted lines) of the posterior estimate of the bycatch loss rate at calm ($phy \leq 4$), intermediate ($4 < phy \leq 8$) and rough ($8 < phy$) physical conditions based on model H2.

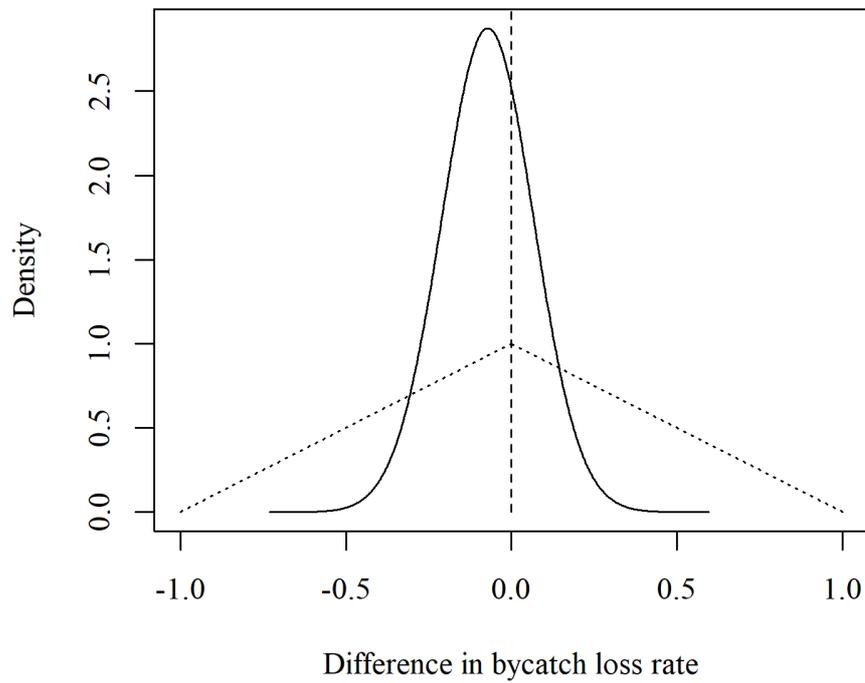[Production instructions: 1 column; no color needed in print]

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Figure 6 Median (solid line) and 95% credible interval (dotted lines) of the posterior estimate of the bycatch loss rate at different levels of bycatch risk score based on model H3.

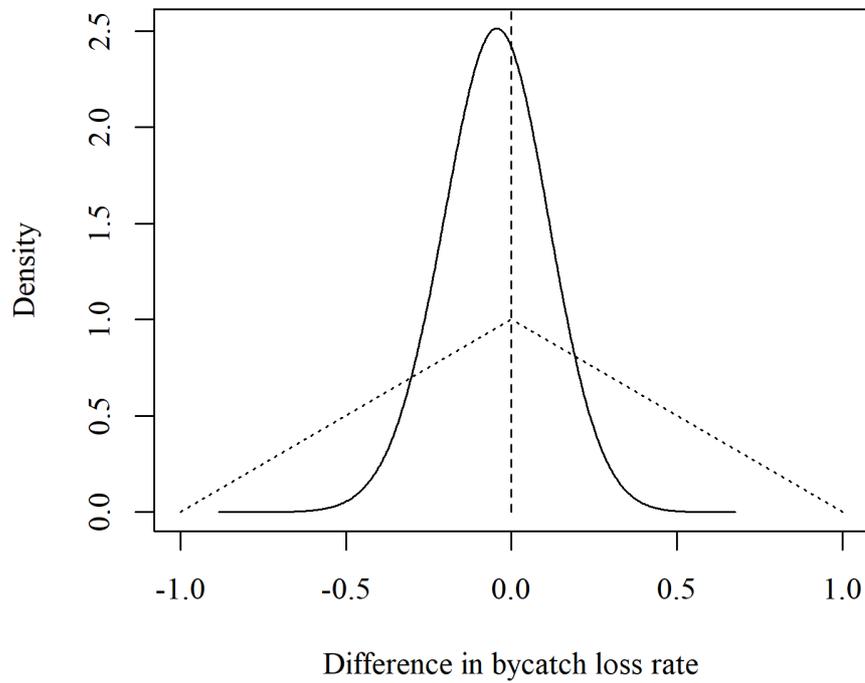[Production instructions: 1 column; no color needed in print]

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Figure 7 Prior (two dotted line segments) and posterior (solid curve) of the difference in bycatch loss rate between divers and non-divers based on model H4e1. A negative value indicates a lower loss rate for divers, and the vertical dashed line separates negative values and positive ones.

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Figure 8 Prior (two dotted line segments) and posterior (solid curve) of the difference in
bycatch loss rate between scavengers and non-scavengers based on model H4e2. A
negative value indicates a lower loss rate for scavengers, and the vertical dashed line
separates negative values from positive ones.

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