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Modelling entanglement rates to estimate mortality of marine birds in British Columbia commercial salmon gillnet fisheries

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ABSTRACT

Incidental mortality of marine birds in fisheries is an international conservation concern, including in Canada where globally significant populations of vulnerable diving species overlap with coastal gillnet fisheries. In British Columbia (BC), commercial salmon gillnet fishing effort was historically very high (>200,000 days fished annually in the early 1950's), and although this fishery has declined, over 6,400 days were fished annually in the 2006–2016 decade. Observations of seabird bycatch within the commercial fishery, however, are limited in both scope (comprising <2% of cumulative effort 2001–2016) and in time (being available only from 1995 onwards and only for a small number of areas). Using onboard fishery observer data from commercial, test and experimental fisheries (1995–2016), we developed two models to estimate the number of marine birds captured per set in sockeye (*Oncorhynchus nerka*) and chum (*O. keta*) salmon gillnet fisheries employing a Generalized Linear Mixed Modeling (GLMM) approach in a hierarchical Bayesian framework, with observer data post-stratified by fisheries management area and year. Using estimates of total commercial fishing effort (estimated number of sets, 2001–2016) we applied the models to extrapolate annual take for the main bird species (or groups) of interest. Multinomial probability estimates of species composition were calculated based upon a sample of 852 birds identified to species that were associated with sockeye or chum fisheries, enabling estimates (with CIs) of potential numbers of the mostly commonly observed species (common murres (*Uria aalge*), rhinoceros auklets (*Cerorhinca monocerata*), and marbled murrelets (*Brachyramphus marmoratus*)) entangled annually in commercial sockeye and chum salmon gillnet fisheries throughout BC. Conservative estimates of annual losses to entanglement were greatest for common murres (2,846, 95% CI: 2,628–3,047), followed by rhinoceros auklets (641, CI: 549–770) and marbled murrelets (228 CI: 156–346). Populations of all three of these alcids species are currently in decline in BC and entanglement mortality is a conservation concern. Gillnet mortality has been identified as a longstanding threat to marbled murrelet populations, which are recognized as *Threatened* in the Canada and the United States of America (USA). In addition, 622 (CI: 458–827) birds from 12 other species were estimated to be entangled annually. We conclude that cumulative mortality from incidental take in salmon gillnet fisheries is one of the largest sources of human-induced mortality for marine birds in BC waters, a conservation concern impacting both breeders and visiting migrants.

1. Introduction

Seabirds are characterized by delayed maturity, long lives, low reproductive output, and generally slow population growth rates. They often exhibit long-distance migrations and can occupy marine habitats over a huge spatial scale, well beyond the Exclusive Economic Zone of a single country. A global review of the monitored portion of the world's seabird population reported an overall decline of 69.7% between 1950

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and 2010 (Paleczny et al., 2015). Seabirds are more threatened, and their conservation status has deteriorated more rapidly than other comparable groups of birds (Croxall et al., 2012). Despite the declines of seabird communities, worldwide seabird-fishery interactions persist (Grémillet et al., 2018). A global assessment of threats to seabirds ranked fisheries bycatch as second, with climate change being the only greater concern for seabirds (Dias et al., 2019).

On the Pacific coast of Canada, British Columbia (BC) has extensive coastlines, hundreds of islands and estuaries, fjordlands, rainforests, and several oceanographic domains, which support over 5.6 million breeding marine birds and millions of seasonal migrants (Rodway et al., 2017). In particular, BC supports important breeding populations of the family Alcidae, marine birds that propel themselves underwater using their wings in search of fish and invertebrate prey. Most alcids nest in colonies, except for the secretive marbled murrelet (*Brachyramphus marmoratus*) which nests solitarily in coastal old growth forests. Canada has significant international stewardship responsibility when a large percentage of a bird's global population breed within its lands. BC supports the majority of the global breeding population of Cassin's auklets (*Ptychoramphus aleuticus,* 75%), ancient murrelets (*Sythliboramphus antiquus,* 54%), rhinoceros auklets (*Cerorhinca monocerata*, 48%), and almost a third of the world's marbled murrelets (28%, EC 2014), in addition to nationally significant populations of common murres (*Uria aalge*), and tufted puffins (*Fratercula cirrhata*; Canadian Wildlife Service, 2019 unpubl. data).

In BC, the largest sources of direct mortality for marine birds are ongoing impacts from acute and chronic oiling, introduced predators, and losses due to fisheries bycatch. In this paper, we focus on mortality of marine birds in gillnet fisheries because it is a global conservation concern (Dias et al., 2019), killing an estimated 400,000 birds per year (Žydelis et al., 2013). A national review of the issue concluded that gillnet fisheries were responsible for the bulk of seabird incidental take within Canadian waters (Ellis et al., 2013; see also Hedd et al., 2015). In BC, fatal light attraction and gillnet fishing in and around Langara Island in the 1950s and 1960s killed an estimated 10,000 ancient murrelets annually (Bertram 1995). In 1980, hundreds of marbled murrelets were killed by gillnet entanglement in the Barkley Sound sockeye fishery (Carter and Sealy 1984), and concerns were voiced for the likely negative population consequences of the hundreds to thousands that may be killed annually along the BC coast (Carter et al., 1995). The first systematic monitoring of seabird entanglements in gillnets did not begin until 1995. From 1995 to 2001, it was estimated that an average of 12,000 (range 1,129-24,002) birds were killed annually in BC gillnet fisheries (Smith and Morgan 2005). The majority of these birds were common murres, followed by rhinoceros auklets, and marbled murrelets.

Here we investigate mortality of marine birds in commercial salmon gillnet fisheries in BC with an emphasis on species of the family Alcidae, which are known to be highly vulnerable to gillnet entanglement (DeGange et al., 1993). We focus on the common murre, rhinoceros auklet, and marbled murrelet which all currently exhibit significant population declines in BC (Hipfner 2005; Rodway and Lemon 2011; Drever et al., 2021). The marbled murrelet is also listed as *Threatened* in the USA (USFWS 1997), and Canada under the Species at Risk Act (EC 2014) due to losses of old growth forest nesting habitat, threats from gillnet mortality, oiling, increased shipping, and ocean climate impacts on prey communities. Observations of seabird bycatch within the commercial salmon fishery are limited in both scope (comprising <2% of cumulative effort 2001–2016) and in time (being available only from 1995 onwards and only for a small number of areas) making analysis challenging. Therefore, we use a hierarchical Bayesian modeling approach (Hatch 2018) to develop estimates of annual gillnet mortality based on existing observer data on bird entanglement in the sockeye and chum salmon applied to fisheries fishing effort.

2. Materials and methods

2.1. Study region

The Department of Fisheries and Oceans Canada (DFO) has jurisdiction of Pacific salmon management encompassing the entire BC coastline. For gillnet vessels, the coast is divided into 30 management areas numbered 1–29, and 121 (Fig. 1). As DFO combines data for management areas 21 and 121, we have included the data for both under management area 21. Management areas 1–29 are also grouped spatially into three larger license areas: C (north and central BC coast, including Haida Gwaii), D (northern Vancouver Island) and E (southern Vancouver Island). License area C includes management areas numbered 1–10; area D: 11–15; 23–27 and area E: 16–22; 28 and 29.

2.2. Historical and current fishing effort

2.2.1. Days fished (1951–2016)

Historical fishing effort as *days fished* was estimated from the number of gillnet landings per week within each management area (courtesy B. Ridgway and J. Davidson, unpubl. data; DFO Fisheries Operations System).

2.2.2. By the set (2001–2016)

Beginning in 2001, information was available from DFO's Fishery Operations System to estimate the total number of gillnet sets for each commercial opening targeting sockeye or chum salmon. For each combination of year and opening, reports from fishers were used to estimate the average number of sets per vessel per day and the average across all vessels was then multiplied by the DFO area manager's independent estimate of the number of vessels operating per opening to estimate the total annual number of sets. Chum and sockeye fisheries had similar net parameters (material type, number of strands, length, weedline depth, hang ratio, net mesh depth; DFO Fisheries Operations System). Mesh size is larger in the chum (mostly 15.24 cm) than the sockeye fishery (mostly 12.38 cm), but bycatch rates of alcids cannot be distinguished between mesh sizes (XJS unpubl. analyses). Fishing effort is mostly during the day with some night fishing in both the chum and sockeye fisheries and will be addressed in a companion paper. Spatio-temporal differences in the chum and sockeye fisheries were the reason for modeling the two fisheries independently (see below).

2.3. Observer reports of seabird bycatch (1995–2016)

Models of marine bird bycatch were developed using data collected by onboard human observers during both commercial and non-commercial salmon gillnet fisheries. Commercial fisheries included those open for fishers holding a license for a specific license area (C, D or E) while non-commercial openings included assessment, selective, exploratory, and test fisheries (data sources: DFO observers and contractors; fishers; Gillnet Associations; Archipelago Marine Research Ltd. 2000; Smith and Morgan 2005). For each observed set, a count of the number of entangled birds and the species were recorded. Also recorded were the set date, time, location and management area. The count of the number of birds entangled per set was the response variable used in the subsequent hierarchical Bayesian models.

2.4. Species composition of bycatch

Not all birds observed entangled were identified to species, but some trained bird observers provided identification. For birds collected (i.e., salvaged) from fishing vessels, species identification was assigned or validated by experts. We categorized birds into four groups, common murres, rhinoceros auklets, marbled murrelets, and 'other' species due to low numbers and the sporadic catch of all other marine birds. Beached birds, and those found floating near gillnet vessels during commercial

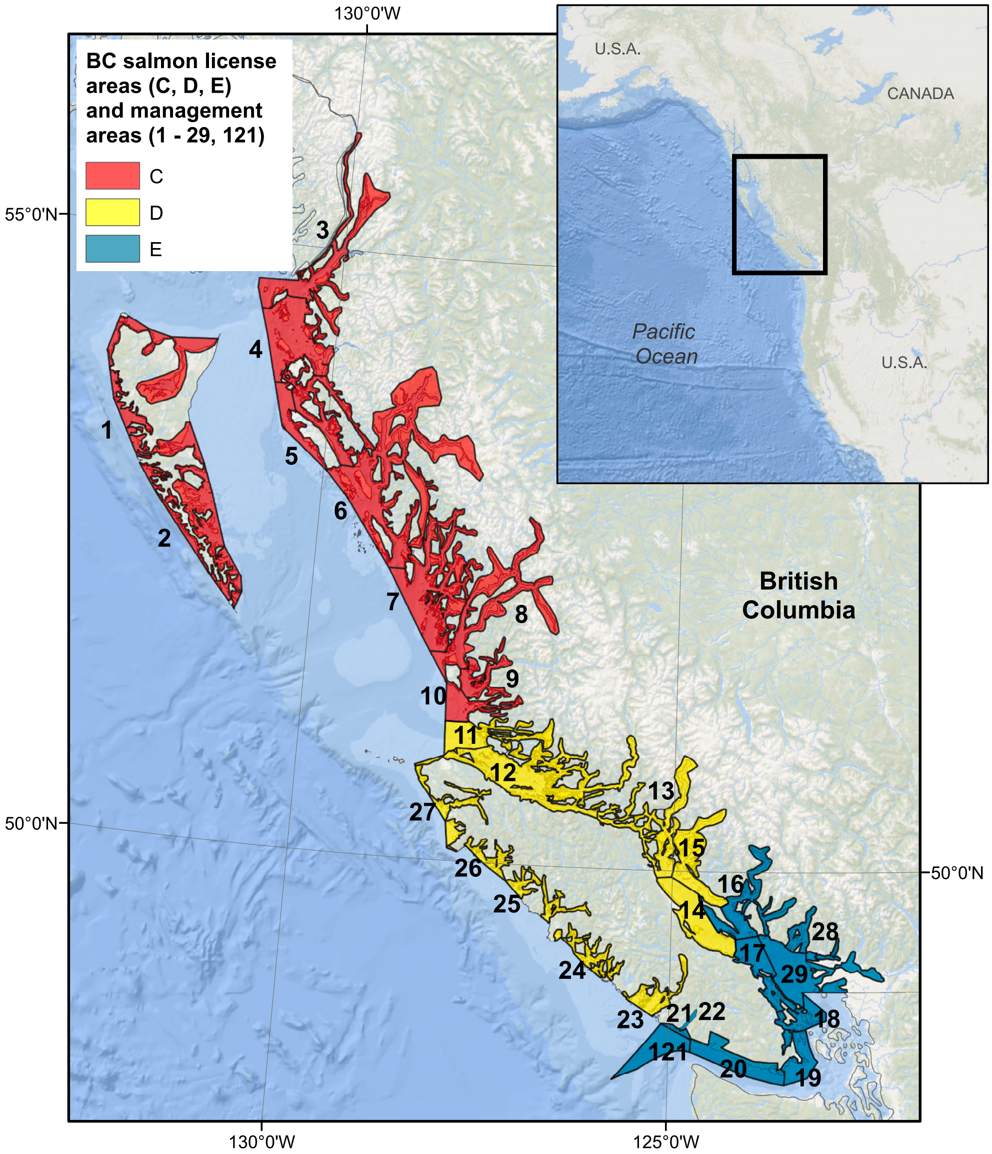

Fig. 1. British Columbia (BC) salmon license and management areas.

gillnet openings were necropsied by veterinarian avian pathologists at the BC Ministry of Agriculture. Those birds deemed to have died via net entanglement were included in estimates of species composition when they could be linked by both date and location to a particular commercial fishery opening.

2.5. Bayesian analyses

Since the data set was relatively sparse, and not balanced across years and management areas, a hierarchical Bayesian analysis framework (e.g., Zuur et al., 2012; Kéry and Royle 2016) was used to estimate seabird bycatch in the BC salmon fisheries. This approach allowed us to estimate bycatch in management areas and years with limited or no seabird bycatch observation efforts, while assigning suitable uncertainty to these estimates given the lack of direct observations. The modeling was conducted in two main steps using two different data sets, a model for the count (numbers of seabirds captured per set) process, and a model assigning those birds to species through a multinomial estimation process. Once the estimation was complete, a large sample of posterior distributions of predicted bird catches and species compositions across observed and unobserved years and management areas were calculated. These were combined with the fishing effort through resampling procedures to obtain distributions of predicted bird catches across the various fisheries.

The count of birds entangled in salmon fishing sets was modeled with a negative binomial Generalized Linear Mixed Model (GLMM) using the standard log link. The distribution of counts was clearly overdispersed with many 0s and some larger counts (up to 59, mean $=$ 0.048, var $=$ 0.552, variance/mean ratio $=$ 11.6), so Poisson distributions were not considered; negative binomial distributions have been used successfully to model seabird bycatch rates in other regions (Bærum et al., 2019). Due to the different timing of the two major fisheries, (chum and sockeye) target species was first considered a fixed effect in the model, however differences between the two target fisheries in both the distribution of seabirds caught per set, and in the distribution of the species composition (see below) were challenging to capture in a single model, so the two fisheries were modeled independently. Year and management area were treated as random effects. Exploration of model fit showed that management area, as a random effect, was not able to completely capture the variation among management areas. This residual variation was further modeled by also including management area as a random effect in the negative binomial dispersion parameter (κ), which gave the model flexibility to allow the dispersion parameter to also vary across management areas. The form of model fit was as follows, where *i* is the management area (*Area*), and *j* is year (*Year*)

$$Count_{ij} \sim NB(\mu ij, \kappa i)$$

$$\mathrm{E}\left(Count_{ij}\right) = \mu_{\mathrm{ij}} \text{ and } \mathrm{var}\left(Count_{ij}\right) = \mu_{\mathrm{ij}} + \mu_{ij}^2 \Big/ \kappa_i$$

$$\log\left(\mu_{ij}\right) = \beta_0 + b_{Ai} \times Area_j + b_{Yj} \times Year_j$$

$$b_{Ai} \sim N\left(0, \sigma_A^2\right)$$

$$b_{Yj} \sim N\left(0, \sigma_Y^2\right)$$

$$\kappa_i \sim LogN\left(\nu,\ \sigma\kappa^2\right)$$

using the standard formulation of the expectation of the mean (E) and variance (var) for the negative binomial (*NB*) distribution. Program JAGS (Plummer 2003), via the r2jags (Su and Yajima 2015) interface, was used to fit this model. Vague priors were used for all parameters. The single fixed parameter (β_0) was assigned normal (*N*) prior distributions with mean 0 and a variance of 100,000. The random effects for management area (σ_A) and year (σ_Y) had priors assigned with uniform distributions between 0.0001 and 10. Priors for the mean and variance on dispersion parameter (κ) needed to be positive, so the mean of the log-normal (*LogN*) distribution (ν) was assigned a uniform prior between −2 and 3 (~0.05–7.4 on the real scale), with the associated variance ($\sigma\kappa^2$) assigned a uniform prior between 0.25 and 10^8. The log-normal mean of the dispersion parameter (ν) was further constrained to be no lower than 0.01: this was done to prevent especially small values of (ν) which led to extremely large and unrealistic predicted counts of seabirds caught in a set (1,000+). Models were run with three Markov Chain Monte Carlo (MCMC) chains, each with 30,000 iterations, and with a burn-in period of 5,000 iterations; good mixing of the MCMC chains was achieved in all models with this burn-in period and number of iterations. Posterior distributions of fixed and random parameters were inferred from these 90,000 MCMC samples. As well, predicted catches in observed and unobserved management area-year combinations were extracted from each MCMC sample. These distributions of 90,000 predicted catches were used in the subsequent analysis which estimated species composition of the bycatch. Bayesian 95% credible intervals, extracted from the posterior distributions of the MCMC chains, are presented for all parameter estimates (Tables S1 and S2).

In the second step, the species composition of the bycatch was estimated with a multinomial mixed model, with a random effect for management area. There was insufficient data to estimate both annual species composition of bycatch and spatial differences (i.e., management areas), and it was felt that spatial variation in the composition of the bycatch would be a larger factor compared to annual differences (Smith and Morgan 2005; Hamel et al., 2009). Sufficient data were available for three species, common murres, rhinoceros auklets, marbled murrelets, and the rest were combined in an 'other' species category, leading to a response variable with four possible outcomes (*K*). In practice, we modeled the categorical distribution (*Cat*) with these four possible outcomes and not the multinomial distribution *per se*, the categorical distribution being simply the equivalent of the Bernoulli distribution with more than two possible outcomes. This model took the form, where *i* is the management area ($Area_i$), *j* is the level of the response (*Species*) excluding the reference level and *J* is the reference level, of:

$$\pi_j = \Pr\{\mathrm{Y} = \mathrm{j}\}, \sum \pi_j = 1$$

$$Y_{ij} \sim Cat\left(K, \pi_{ij}\right)$$

$$\log\left(\pi_{ij}\right) = \beta_{0j} + b_{ij} \times Area_{ij}$$

$$b_{ij} \sim N\left(0, \sigma_j^2\right)$$

Again, vague priors were set for all parameters. The prior for each of the fixed parameters (three intercepts for each species excluding the reference level (β_{0j}), the reference level intercept is simply 1 – sum of the other three) was distributed as normal distribution with a mean of 0 and a variance of 100. The three random effects (σ_j^2) had priors based on a half (positive values only) Student's t distribution, with a mean of 0, a variance of 625 and 4 degrees of freedom. As previously, these models were run with three MCMC chains, each with 30,000 iterations, and with a burn in period of 5000 iterations; good mixing of the MCMC chains was achieved in all models with this burn in period and number of iterations. Posterior distributions of fixed and random parameters were inferred from these 90,000 MCMC samples, as well predicted species compositions in observed and unobserved management areas for each target fishery were extracted from each MCMC sample. Bayesian 95% credible intervals, extracted from the posterior distributions of the MCMC chains, are presented for all parameters modeled (Tables S3 and S4).

Posterior samples of predicted catch and predicted species composition were combined with fishing effort data (total number of sets, per year, per management area and per target species) in a resampling procedure, to obtain estimates of total seabird bycatch across the salmon fisheries. For each fishery, a sample of predicted catches was extracted (with replacement) from the posterior distribution of predicted catches in that year and management area; the size of the sample drawn was equal to the total number of sets fished. This produced a distribution of possible seabird catches across that fishery, which was then summed to obtain total seabird catch in that fishery. To remove unrealistically large, predicted catches of seabirds (notably management area 12 in the chum fishery), predictions over 100 birds caught per set were not included in the resampling procedure. For fisheries in managements areas without direct observations of seabird bycatch, estimates from unobserved management areas were used. This process was repeated across all fisheries to obtain estimates of total seabird bycatch, and the whole process was repeated 10,000 times to provide a distribution of estimates of total seabird bycatch across all fisheries.

To obtain species composition of the seabird bycatch, a similar resampling process was used, whereby one of the 10,000 estimates of catches in each fishery was sampled, and this estimate was apportioned into species based on a random draw of a species composition vector from the 90,000 MCMC samples specific to the appropriate management area and target fishery. As above, if the fishery was from an unobserved management area, then species composition vectors were selected from predictions from unobserved management areas. This process was also repeated 10,000 times, to provide distributions of total estimated seabird bycatches across all fisheries for each of the three species considered and the others group.

3. Results

3.1. Historical and current commercial salmon gillnet fishing effort (1951–2016)

Commercial salmon gillnet fishing effort in *days fished* declined by 92% along the coast of BC between 1951 and 2016 (Fig. 2), from in excess of 200,000 days in the 1950's to less than 20,000 days fished annually over the 2006–2016 decade. During our study period the estimated number of fishing days declined from 42,850 in 1995 to 6,463 in 2016.

The majority of commercial salmon gillnet fishing in BC targets sockeye or chum salmon, and from 2001 to 2016, the estimated cumulative number of sets for sockeye (965,674 sets) was 2.5 times greater

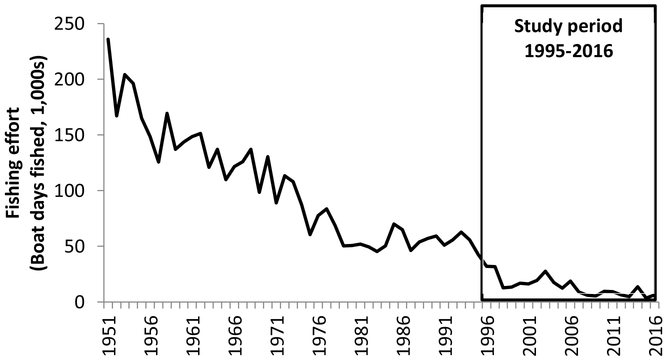

Fig. 2. BC commercial salmon gillnet fishing effort (boat days fished, 1000's), 1951–2016 (courtesy B. Ridgway, J. Davidson, DFO, unpubl. data; DFO Fisheries Operations System).

than for chum salmon (389,006 sets; Table 1). In both fisheries, effort varied spatially and, for sockeye in particular, fishing was concentrated more heavily in the north (license area C) than along the mid-to south coasts (license areas D or E; Table 1). Sockeye salmon is fished by gillnet in summer throughout the coast, while chum salmon is fished in northern regions in summer (license area C) and in southern areas (license areas D and E) during fall. Note that both fisheries occur during marine bird breeding periods, but chum fishing also occurs in non-breeding season, when some species (e.g., common murres) migrate into the region from AK and southern USA while others (e.g., rhinoceros auklets) relocate to areas outside of BC (see Discussion).

Table 1
Estimated cumulative commercial gillnet fishing effort (number of sets, 2001–2016) directed toward sockeye and chum salmon according to license and management area. Also indicated are the number of gillnet sets observed for seabird bycatch within each area. Observations of the sockeye fishery occurred from 1997 to 2016, while observations of the chum fishery were limited to 1995–2007.

		sockeye		chum	
license area	management area	Estimated commercial fishing effort (no. of sets)	No. sets observed	Estimated commercial fishing effort (no. of sets)	No. sets observed
C	1			17	
	2			3503	
	3	292,568	324		
	4	374,928	4822		
	5	5040			
	6	43		36,534	
	7			26,899	
	8			116,198	19
	9				
	10	8675			
D	11	9297	593		
	12	88,237	4384	42,199	390
	13	17,888	318	34,212	206
	14	34	16	31,761	229
	15				
	23	86,865	496	2593	330
	24			344	
	25			15,593	455
	26				
	27			48	
E	16			89	
	17			5989	
	18			10,960	
	19				
	20		1401	4	
	21			30,780	5545
	22				
	28				
	29	82,097	618	31,285	
	Total	**965,674**	**12,972**	**389,006**	**7174**

3.2. *Sets observed for bird entanglement*

Between 1995 and 2016, observations of mortality of marine birds were obtained from 22,056 salmon gillnet sets along the coast of BC; 91.3% (20,146) of these occurred in fisheries targeting sockeye or chum salmon. The number of sets observed for bird bycatch within the sockeye and chum salmon fisheries (20,146) represents < 2% of estimated cumulative commercial fishing effort from 2001 to 2016 (Table 1). In the chum fishery, bycatch observer effort occurred annually from 1995 to 2007 (Table 1) and averaged 552 sets/year (range 133-1,348 sets). In the sockeye fishery, observer effort occurred in 1997 and then annually from 2000 to 2016 (Table 1); annual average coverage in these years was 721 sets (range 141-4,489 sets/year). Between 2008 and 2016, bycatch observer effort in the sockeye fishery has been low and averaged just 200 sets/year (range 141–467 sets).

Commercial fishing effort for sockeye and chum salmon occurs throughout the coast in license areas C, D and E (Fig. 3). While observer effort in the sockeye fishery occurred in all license areas, observer effort in the chum fishery occurred mostly in license areas D and E (Table 1). Observer coverage of the chum fishery in license area C, where fishing effort is greatest, has been extremely limited (Table 1). Management areas 4 (within license area C), 12 (within license area D), and 21 (within license area E) had the greatest number of observations during 1995–2016, with more than 4,000 sets observed for bird bycatch (Table 1). In contrast, commercial fisheries in many management areas (3 of 11 areas for sockeye, and 11 of 18 areas for chum) had no bird observer coverage.

3.3. *Bird catches per set*

Overall, marine birds (n = 1,147) were captured in 2.8% (620 of 22,056) of observed gillnet sets and the catch per set ranged from 1 to 59 birds. Examining the larger catches, 59 rhinoceros auklets were captured in one set in a sockeye selective fishery near the colony on Pine Island (license area D, management area 11) on July 28, 2000. Twenty common murres were captured in a single set in a chum salmon test fishery off the southwest coast of Vancouver Island (license area E, management area 21) in October 2000.

3.4. *Species composition of catch*

A total of 886 birds from 15 species recovered from gillnets or determined through necropsy to have died from net entanglement were identified to species level; 852 of these were associated with the sockeye or chum salmon gillnet fisheries (Table 2). Three species, namely

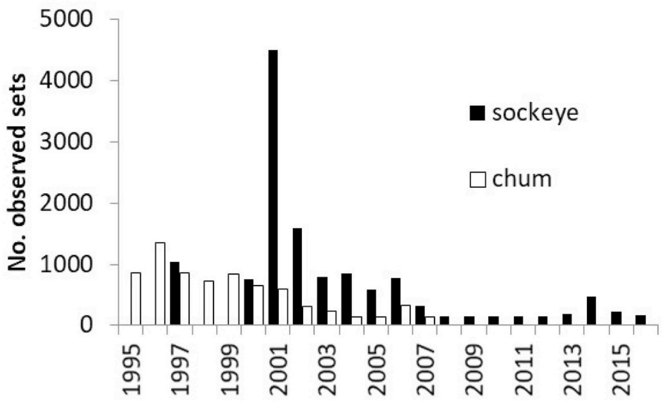

Fig. 3. Number of observed gillnet fishing sets for sockeye and chum salmon in BC, 1995–2016.

Table 2
Species composition of actual identified specimens entangled (n = 852) as seabird bycatch in the sockeye and chum salmon gillnet fisheries in BC, Canada, 1995–2016.

Bird species	sockeye fishery (n = 377)			chum fishery (n = 475)		
	C	D	E	C	D	E
	n = 94	n = 195	n = 88	n = 2	n = 134	n = 339
common murre *Uria aalge*	3	54	73	2	114	287
rhinoceros auklet *Cerorhinca monocerata*	67	136	3		7	11
marbled murrelet *Brachyramphus marmoratus*	22	1			4	4
pigeon guillemot *Cepphus columba*		2	3		3	13
ancient murrelet *Sythliboramphus antiquus*						7
Cassin’s auklet *Ptychoramphus aleuticus*	1	1				1
pelagic cormorant *Phalacrocorax pelagicus*			4		1	6
sooty shearwater *Ardenna grisea*						8
common loon *Gavia immer*		1	3		2	
pacific loon *Gavia pacifica*						1
red-throated loon *Gavia stellata*	1					
western grebe *Aechmophorus occidentalis*			1		1	
red-necked grebe *Podiceps grisegena*					1	
surf scoter *Melanitta perspicillata*			1			1
harlequin duck *Histrionicus histrionicus*					1	

common murres, rhinoceros auklets, and marbled murrelets dominated numbers identified, while other identified species included pigeon guillemots (*Cepphus columba*), other alcids, cormorants, shearwaters, loons, grebes and seaducks (Table 2). Species composition of the marine birds observed in the sockeye fishery showed primarily rhinoceros auklets and marbled murrelets in license area C; mostly rhinoceros auklets and common murres in license area D, and primarily common murres in license area E (Fig. 4A). Most entangled birds were dead but in rare cases fishers retrieved live birds which were released. In the chum fishery, common murres dominated the entanglement mortality in license areas D and E (Fig. 4B). There was limited observer coverage of the chum fishery in license area C.

One common murre, banded on Triangle Island on August 3, 2003 as a breeding adult (J.M. Hipfner, pers. comm.), was recovered from Malcolm Island (management area 12-8, 150 km SE of Triangle Island) on August 29, 2006. No other banded birds were recovered during our study.

3.5. Modeled seabird mortality estimates

The negative binomial GLMM fit to the number of seabirds caught in each set, performed adequately. R-hat values of parameter estimates were all well under 1.1, suggesting sufficient mixing and convergence (Tables S1 and S2). Random effects for management areas were more difficult to estimate, especially for sockeye, while the random effects for year and the random effect of management area on the dispersion parameter readily converged. Similarly, the multinomial model to assign species performed well, and all parameters reached convergence (R-hat $\ll 1.1$, Tables S3 and S4).

From 2001 to 2016, average annual estimated incidental mortality of marine birds in the chum fishery (3,236, CI: 3,144–3,331) was almost 3-times greater than in the sockeye fishery (1,099, CI: 1,065–1,135;

Table 3
Average annual estimated incidental mortality of seabirds (mean and 95% credible intervals) in the commercial sockeye and chum salmon gillnet fisheries along the coast of BC, Canada, 2001–2016.

Bird species/group	mean	LCI	UCI
	sockeye fishery		
common murre	442	383	501
rhinoceros auklet	469	411	539
marbled murrelet	114	76	176
other seabirds	75	51	119
all seabirds	**1099**	**1065**	**1135**
	chum fishery		
common murre	2404	2189	2595
rhinoceros auklet	172	110	282
marbled murrelet	114	62	217
other seabirds	547	387	744
all seabirds	**3236**	**3144**	**3331**

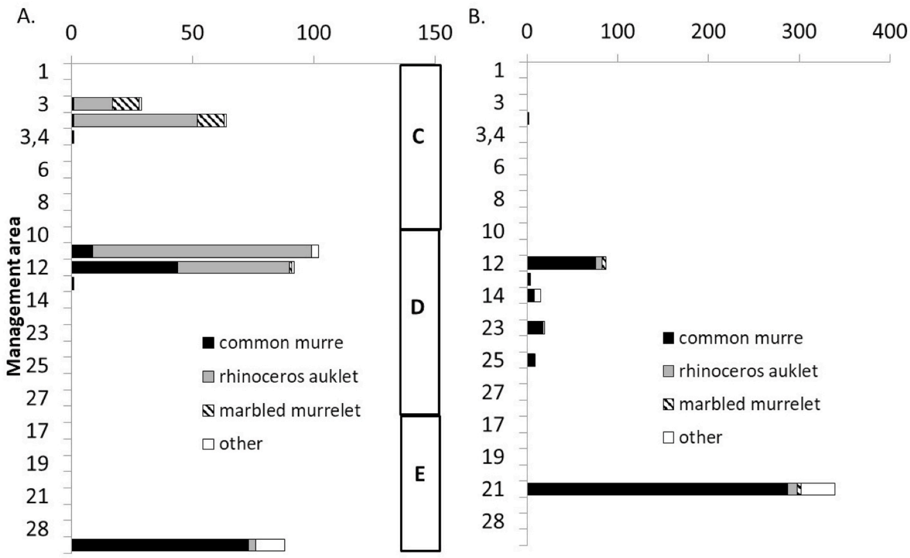

Fig. 4. Number and species composition of the seabird bycatch in sockeye (A) and chum (B) salmon gillnet fisheries along the coast of BC, Canada, 1995–2016. Corresponding license areas are also indicated.

Table 3), despite lower fishing effort for chum (Table 1). Within both fisheries, average annual mortality estimates were greatest within license area C, followed by license areas D, and E (Fig. 5). In the chum fishery, and in all license areas, the common murre was estimated to be the most frequently entangled bird, with a mean annual take of 2,404 individuals (CI: 2,189–2,595), followed by "other" marine birds combined, estimated at 547 individuals per year (CI: 387–744; Fig. 6). Overall, in the sockeye fishery, rhinoceros auklets (469, CI: 411–539) and common murres (442, CI: 383–501) were estimated taken in similar numbers annually on average, with rhinoceros auklets dominating in license area C, and common murres in license area D (Fig. 5). Few birds were estimated taken annually in the sockeye fishery in license area E. Each year, from 2001 to 2016, an average of 114 marbled murrelets were estimated taken in each of the chum (CI: 61–217) and the sockeye (CI: 76–176) salmon gillnet fisheries along the BC coast. Annual variation in the marine bird capture estimates was apparent, and in general was more pronounced within the chum than in the sockeye fishery (Fig. 6). For the chum fishery high estimates of incidental mortality occurred both early and late in the time series but in the sockeye fishery, annual take was predicted to be greatest in 2014, when there was a strong sockeye run in the Fraser River accompanied both by intense fishing effort and onboard observations of marine bird incidental mortality. Despite the high fishing effort for sockeye in 2014, overall gillnet fishing effort was declining during the study period (Fig. 2).

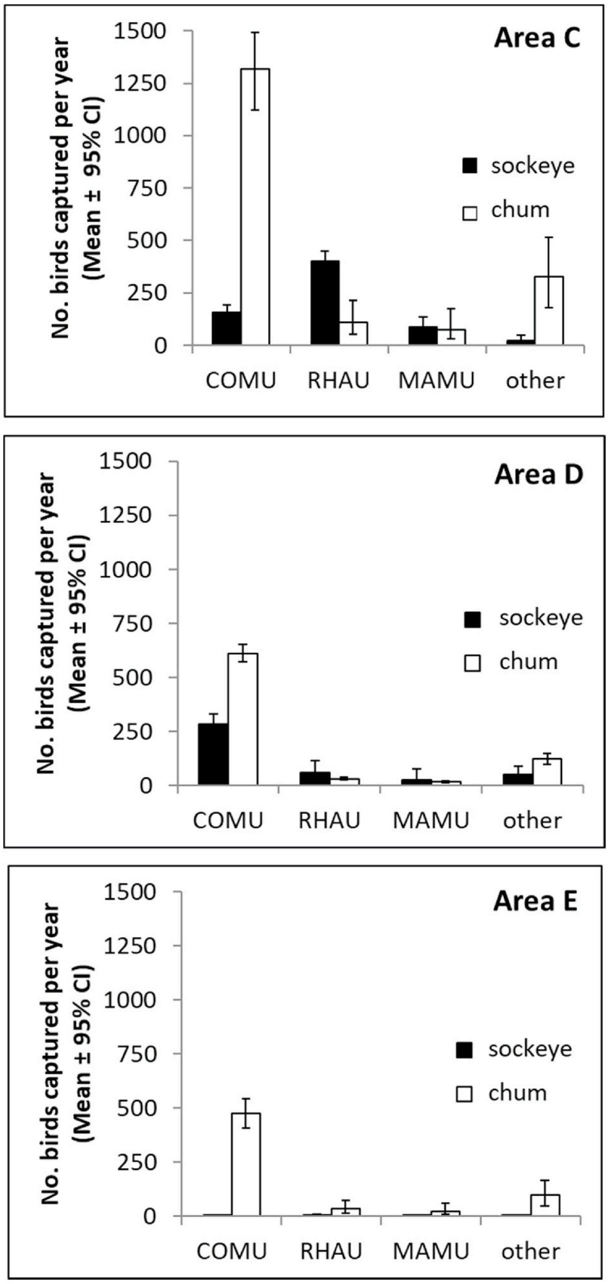

Fig. 5. Estimated mean annual bycatch of seabirds in the commercial sockeye and chum salmon gillnet fisheries, according to license area, along the coast of BC, Canada, 2001–2016. COMU is common murre, RHAU is rhinoceros auklet, MAMU is marbled murrelet, and other is other seabirds.

4. Discussion

4.1. Model performance

In general, our Bayesian hierarchical modeling approach performed adequately, and appeared to capture key aspects of the data available. Even with the abundance of zeros in the data set, the negative binomial distribution fit the count data quite well, and zero-inflation models or hurdle models were not required (Bærum et al., 2019). Treating year and management areas as random effects allowed us to make predictions in unobserved fisheries, with suitably large credible intervals. There were some challenges in the modeling, however, the most notable was obtaining the occasional prediction in the 100s or even 1,000s of birds caught in a set. These predictions were not driven by higher mean numbers of birds caught per set, but by smaller dispersion parameters (and so increasing the variance), which allowed the model to occasionally draw very large values. Treating the dispersion parameter as a random effect assisted with this problem, allowing for a higher dispersion parameter (i.e., less variance) in management areas that did not show large catches of birds. Even so, some hard bounds were imposed on the model and very large and unrealistic predictions of catch were simply removed. The multinomial modeling also performed well, but since this was a limited data set, it was difficult to assess any specific issues with fit. The value of the multinomial model was assigning species to the counts of birds with appropriate uncertainty.

Annual estimates of bird mortality were greatest in license area C, followed by license areas D, and E, and reflect the spatial distribution of fishing effort and observer coverage during the study period. The common murre was the most frequently entangled species, followed by the rhinoceros auklet, and the marbled murrelet. Our annual mortality estimates are lower than the only previous estimates for BC, which were based upon information collected from 1995 to 2001 (Smith and Morgan 2005) when fishing effort was greater than in later years. We note that the variation of our Bayesian modeling estimates based on iterative resampling are much tighter than previous estimates (Smith and Morgan 2005), which were extrapolations from mean values for the entire gillnet fishing fleet and assumed a normal distribution of errors on mean bycatch rates. Since these historic extrapolations were based on the mean bycatch rates and normal distributions, few large catches of birds will inflate the mean. The approach we have employed using random effects and an underlying negative binomial distribution is likely more conservative, but also more accurate because it accounts for the heavily skewed distribution of bird catches in gillnet sets.

In this study we estimated higher bird mortality in the chum fishery than in the sockeye fishery despite lower fishing effort. The difference reflects the amount, timing and location of both fishing effort and observer coverage. For the sockeye fishery, observations occurred throughout our time series (1995–2016) but from 2007 onwards observer coverage was extremely low and confined to a test fishery in a single location (Round Island, see below) where incidental take was minimal. Because there was observer coverage in *all* years for which we have estimates of fishing effort (2001–2016) the model used year-specific observer data to estimate mortality. The low incidence of entanglement post 2007 therefore *deflate* the average annual mortality, and thus likely producing underestimates. In particular, we suggest this

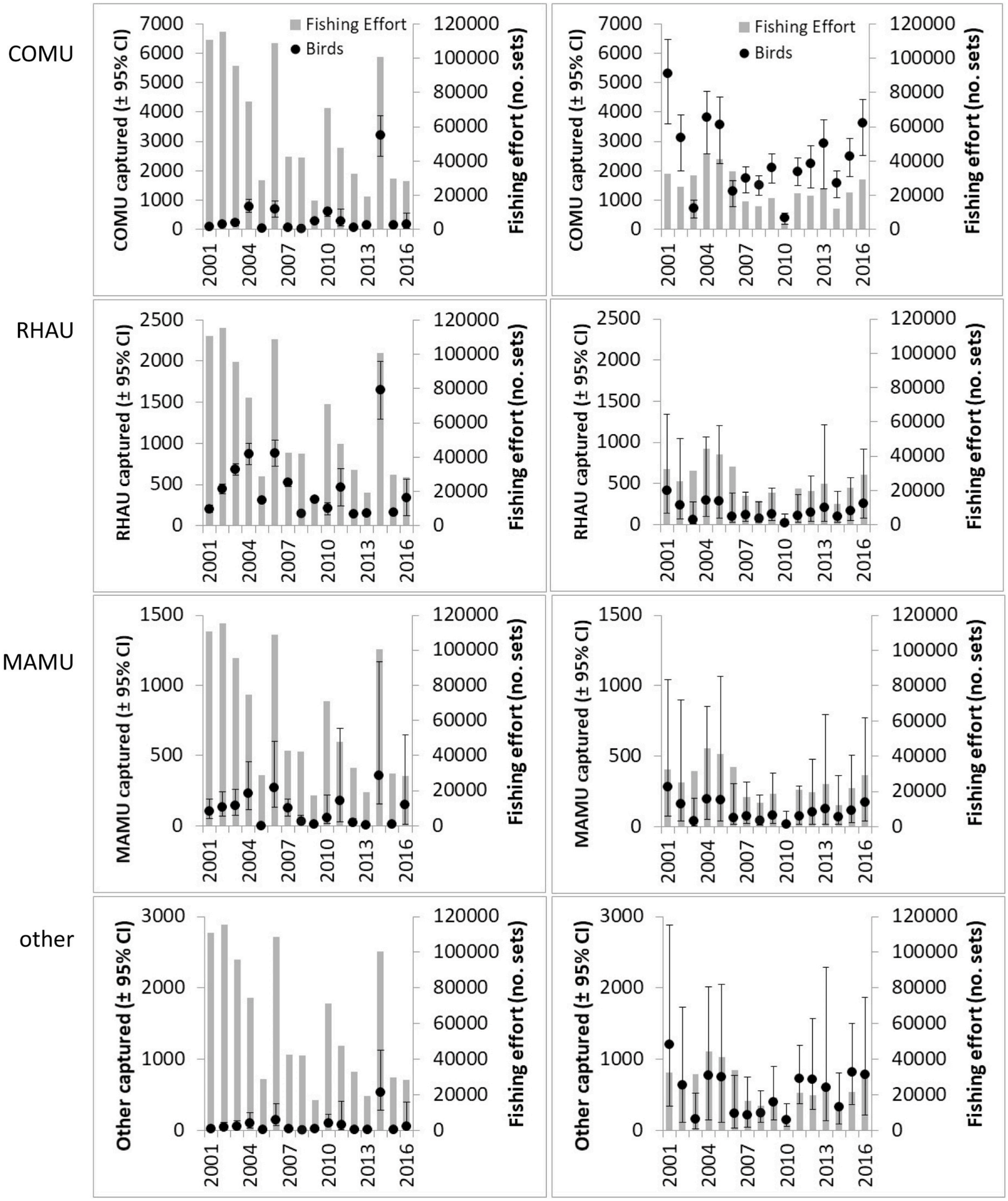

Fig. 6. Estimated annual number of marine birds entangled (points; mean and 95% CI) and annual commercial fishing effort (bars) in the sockeye (left) and chum (right) salmon gillnet fisheries, 2001–2016. COMU is common murre, RHAU is rhinoceros auklet, MAMU is marbled murrelet, and other is other marine birds.

had the effect of vastly underestimating common murre mortality in the sockeye fishery in license area E. An independent study using beached bird surveys in the Salish Sea (which includes license area E) estimated that 2,297 common murre carcasses per year were associated with gillnet fisheries on both sides of the Canada-USA border for a cumulative total of 90,000 birds between 1969 and 2007 (Hamel et al., 2009; see also Kaiser 1993).

The case is different for the chum salmon fishery which had *no* observer coverage after 2007, so the average annual estimates were based upon data from 1996 to 2007 which included the early part of the time series when observer coverage and incidental take levels were relatively high. The locations of the fishery and the observations also influence the bird mortality estimates. The high estimates of common murre bycatch produced for license area C reflect high fishing effort in that area and high levels of bycatch observed in the chum fishery in license area E. When observations for a region are lacking (as is the case for the chum fishery in license area C), the Bayesian model is informed by values and error from other license areas. As common murres are present in high densities within license area C throughout the summer and fall (Fox et al., 2016), the high annual mortality estimates during the fall chum fishery are biologically reasonable. These nuances and uncertainties, and the resulting model predictions, could be tested and improved by systematic deployment of fisheries observers to examine bird entanglement across the salmon gillnet fleet in a manner that captures the spatio-temporal variation in fishing effort.

4.2. Cumulative effects of entanglement mortality

To put our gillnet mortality estimates into a broader conservation context we compare our results to the largest oil spill to impact marine birds in BC waters. In 1988, the *Nestucca* oil spill incident discharged 874,000 L (5,500 barrels) of Bunker C (No. 6) fuel oil in Grays Harbor WA, which subsequently moved into BC waters (USFWS 2004). Beached bird surveys yielded 12,535 dead birds and the total kill was estimated to be 56,000 birds (Ford et al., 1991). In our bycatch investigation, on average, 4,335 birds per year were killed over 16 years for a total 69,360 birds, and thus demonstrates a larger cumulative impact than the *Nestucca* oiling mortality incident.

Commercial gillnet fishing effort declined by 92% along the coast of BC from 1951 to 2016. The reduction in commercial gillnet effort was with associated licence buy-back programs initiated by the Federal Government of Canada (Schwindt et al., 2003). Our estimates of incidental mortality of marine birds are based upon data from a period when fishing effort was at the lowest levels on record (2001–2016). It follows that the historical impacts on marine bird populations along the BC coast must have been significantly greater than the estimates presented here. Seabird monitoring efforts however, were minimal until the 1980s, so matching changes in historic seabird populations cannot be evaluated. We discuss below our gillnet entanglement mortality estimates for common murres, rhinoceros auklets, marbled murrelets, and other diving birds in relation to their distribution, annual cycles, behavior, and population status.

4.3. Common murre

As we confirm here for western Canada, common murres are among the most frequently captured bird in gillnet fisheries year-round throughout northern hemisphere (Žydelis et al., 2013). In southern BC, a study of responses of marine birds to approaching small vessels showed that common murres were the least likely species to react to the disturbance (Hentze 2006). We suggest that a high tolerance for human disturbance is a key behavioural trait which could predispose common murres to greater entanglement risk in gillnets than other marine birds. In addition, it is known that in some regions, both marine birds and gillnet fisheries co-occur because of the locations of forage fish prey. Spatially persistent schools of capelin (*Mallotus villosus*), an important prey species of both common murres and Atlantic cod (*Gadus morhua*) in coastal Newfoundland, can lead to clustering of murres and gillnets set for cod in areas of high capelin density. Such aggregation can lead to large numbers of murres being captured at once within relatively few gillnets (Davoren 2007).

The BC breeding population of common murres in 2004 was 4,704 birds, with most nesting on Triangle Island (Hipfner 2005). In contrast, over 2 million common murres nest in AK, and following breeding, many of the AK birds move into BC coastal waters in late summer and fall (Ainley et al., 2020). Similarly, wintering common murres in the Salish Sea region originate primarily from colonies in OR and WA (Hamel et al., 2008). Consequently, common murres taken in the BC gillnet fisheries likely represent both local and migrant individuals. In license area E, the majority of common murres entangled in gillnets were males and immature fledglings (Smith and Morgan 2005), which is expected because males exclusively provide parental care at sea and they seek coastal areas for rearing (Scott 1990).

Common murre population declines have been documented from breeding colonies in CA, OR, WA, and BC (Manuwal et al., 2001; Thomas and Lyons 2017; Hipfner 2005), and during winter in the Salish Sea (Vilchis et al., 2014). Historic declines were linked to bycatch in gillnet fisheries, oil spills (see also Osterblom et al., 2002; Munilla et al., 2007), and severe ocean warming events (Manuwal et al., 2001; see also Piatt et al., 2020). In BC, the nesting population of common murres on Triangle Island declined 25% to 4327 birds (Hipfner 2005) during 1989–2004, a period when reproductive success was among the *highest* on record (Hipfner et al., 2011). The report of a banded bird from Triangle Island captured in the sockeye gillnet fishery in Johnstone Strait in August 2006, coupled with satellite telemetry results (2006–2007) demonstrated post-breeding movement of common murres from Triangle Island towards Johnstone Strait and the central and northern mainland coasts, within license areas C and D (W.S. Boyd and J.M. Hipfner unpubl. data). The post-breeding movements towards coastal areas highlights the increased likelihood of Triangle Island murres interacting with coastal gillnet fisheries in late summer and fall, when they are no longer tied to the breeding colony (see also Hamel et al., 2008). Gillnet entanglement in coastal BC is potentially contributing to human-induced decline for common murres on Triangle Island as well as for murres from other, much larger populations in AK, OR, and WA which frequent BC following breeding. Our work prompts a review of the extent of gillnet fisheries and risks to alcids in these bordering states.

4.4. Rhinoceros auklet

Canada supports 48% of the global nesting population of rhinoceros auklets, the majority on relatively few large colonies in northern and central BC (Pine Island, Triangle Island, Moore Islands, Lucy Islands, and S'Gang Gwaay, Rodway et al., 2017). There are no major colonies in southern BC, but in neighboring WA there is a large colony at Protection Island, and a small colony on Smith Island (Pearson et al., 2013). Breeding rhinoceros auklets can fly up to 164 km from their colony although most foraging trips are less than 100 km (Cunningham et al., 2018). It is presumed that the large numbers of rhinoceros auklets seen in spring and summer around southern Vancouver Island (Kenyon et al., 2009) are from the colonies in WA, as Canadian waters are easily within their foraging range during breeding.

The rhinoceros auklet was the second most frequently bycaught seabird in our study, with the majority of birds predicted to be taken in the summer sockeye fishery in license area C. Large rafts of thousands of birds often form on the water during breeding (Kenyon et al., 2009) which can result in substantial mortality should they co-occur with gillnet sets. Fishers reported that a particularly bad location in license area D for bird entanglements is Roller Bay, Hope Island, in Queen Charlotte Sound (KC pers. obs.). A recent at-sea survey in July 2018 found multiple thousands of birds near Roller Bay, (DFB pers, obs.) and GPS telemetry tracks of breeding birds from Pine Island in 2016 and 2017 showed extensive use of this regional hotspot (Domalik 2018).

We acknowledge that our prediction likely underestimates the number of rhinoceros auklets killed annually, particularly in the license area D sockeye fishery (see also Appendix B). Large observed catches of rhinoceros auklets in the area in the 1990s, *prior* to the years for which the data enabled mortality estimates (2001–2016), occurred in Roller Bay (license area D, management area 11), a predictable foraging area for breeding birds. In contrast, during 2001–2016 the majority of the observer data was collected at a location where incidental take was minimal, at the Round Island test fishery (license area D, management area 12).

Long-term monitoring (1984–2016) of breeding populations of rhinoceros auklet at four of the largest colonies BC demonstrate an ongoing decline (−1.1% burrow abundance/yr) at Pine Island, the largest BC colony (LW and A. Smith unpubl. analysis; see also Rodway and Lemon 2011). Gillnet entanglement mortality in surrounding waters (license area D) is likely a major contributing factor to the observed population decline at that colony. Populations on Lucy Islands, Triangle Island, and S'Gang Gwaay appear to be stable or increasing, perhaps reflecting lower overlap of foraging areas with gillnet fisheries.

During the post-breeding season, rhinoceros auklets can disperse widely, with many leaving BC waters to winter from CA to AK (Hipfner et al., 2020). The exodus of rhinoceros auklets and influx of common murres during the post breeding season in BC is reflected in their differential bycatch in the license areas D and E summer sockeye fisheries and fall chum fisheries.

4.5. Marbled murrelet

Gillnet mortality has consistently been identified as a threat to marbled murrelets populations (EC 2014) which are in decline throughout most of their range. Long-term monitoring in BC (1996–2018) shows ongoing declines for the southern regions as well as population declines in the central mainland coast and Haida Gwaii (Drever et al., 2021). In neighboring WA, intensive annual at-sea counts of marbled murrelets show a decline of −3.9% per year from 2001 to 2018 (McIver et al., 2019), while smaller populations in OR and CA have stabilized (Raphael et al., 2018).

In AK, historical estimates of gillnet mortality were 3,300 birds per year in 1989 (Piatt and Naslund 1995) and may be linked to population declines (Piatt et al., 2007). Current levels of entanglement mortality in AK are expected to be high for *Brachyramphus* murrelets (e.g., Manly 2007, 2015) which is also a conservation concern for marbled murrelets nesting in BC. Post-breeding, an unknown number of birds that nest in BC move into the Gulf of Alaska (Bertram et al., 2016).

We do not expect large mortalities of marbled murrelets in single sets because they tend to avoid common murres and rhinoceros auklets and are often found near shore in pairs and small groups rather than in large rafts (Burger et al., 2008; Ronconi and Burger 2011). Nets set near shore often caught marbled murrelets where fishing and birds overlapped in time and space (KC pers. obs.). The estimated number of marbled murrelets captured annually in BC salmon gillnet fisheries in this study (228 CI: 156–346) is similar to the previous estimate (278, range 26–552, Smith and Morgan 2005) but is more robust, and now includes credible intervals.

In WA, there is minimal information about marine bird bycatch in gillnet fisheries; however, marbled murrelets are known to be captured (Fry 1995). Telemetry studies of marbled murrelets nesting in the Olympic National Park revealed that home ranges extend into Canada (Lorenz et al., 2016), in management areas 18,19, 20 and 21.

4.6. Other diving birds

Twelve other species of diving birds were identified to have drowned in salmon gillnet fisheries in BC (Table 2). Of these, pigeon guillemots were the most abundant (n = 21), likely reflecting their nearshore foraging habits (Ewins 2020).

A total of seven ancient murrelets were reported captured in license area E management area 21 in a fall chum fishery in 1996. There was almost no gillnet fishing effort in Haida Gwaii (license area C, management areas 1 and 2) during our study period where 54% of the world's ancient murrelet population breeds. In the 1950s and 1960s, gillnet fisheries and troll fisheries operating around Langara Island, Haida Gwaii, killed thousands of ancient murrelets through entanglement and fatal light attraction (Bertram 1995). The seven birds entangled in license area E were post-breeding migrants. During the non-breeding season, ancient murrelets from BC may be killed in the Republic of Korea, where recent estimates of gillnet mortality are in excess of 5,000 birds per year (Choi and Nam 2017). An unknown proportion of ancient murrelets from BC spend part of the non-breeding season in waters off Japan, Korea, and China (Gaston et al., 2017) where they may be at increased risk of being taken as gillnet bycatch (e.g., Otsuki 2013). Ancient murrelets are listed as *Special Concern* in Canada (EC 2015) but the information on losses due to heavy bycatch on the western Pacific portion of the species' wintering grounds has yet to be evaluated.

Three Cassin's auklets were reported killed in gillnets in management area 12 in August, demonstrating that the species use coastal habitats post breeding in addition to their more typical offshore distribution. The world's largest population of Cassin's auklets on Triangle Island has declined significantly (Rodway and Lemon 2011), and is listed as *Special Concern* in Canada (COSEWIC, 2014)). Between May and July Cassin's auklets feed their young primarily on copepods and euphausiids found in bathypelagic, offshore waters where gillnetting does not occur (Bertram et al., 2017). During the post breeding period, birds generally stay offshore, and those that disperse from BC move both north (in summer and fall) and south (fall and winter, Studholme et al., 2019).

4.7. Incidental take of migratory birds and species at risk

In the 1980s in central CA, up to 75,000 common murres died in gillnets (Takekawa et al., 1990), along with hundreds of sea otters (*Enhydra lutris*), and thousands of harbor porpoises (*Phocoena phocoena*). In a precedent setting case, the gillnet mortality was found to be in violation of the Migratory Bird Treaty Act, the Endangered Species Act, and CA state laws. The case was resolved without litigation, and efforts were made to "cushion" regulatory impacts on fishers and the fishery (Atkins and Heneman 1987). Subsequently, a series of restrictions on fishing in shallow waters led to area closures to prevent incidental take of birds and mammals (Wild 1990).

Unlike bird interactions with long-line fishing gear which, with proper mitigation measures, can be deployed with little to no marine bird bycatch (Melvin et al., 2019), gillnets are unselective and regularly catch birds. The problem is compounded because even limited gillnet fishing can result in high mortality rates in areas where diving birds and fisheries co-occur (DFO 2012). The best method to avoid catching birds in nets is to avoid fishing where marine birds are found. Fishery closures (Regular et al., 2013), closures around breeding colonies (Eigner et al., 2012) and bird hotspots (Davoren 2007), coupled with gear modifications, abundance-based fishery openings, and time of day restrictions (Melvin et al., 1999) could greatly reduce bird entanglement mortality (but see Field et al., 2019). Voluntary licence buy-back programs which fairly compensate fishers could also be used to reduce the size of the gillnet fleet, as has been done repeatedly in the past in BC.

5. Conclusion

Through the cumulative effects of many events, incidental take can have long-term consequences for migratory bird populations in Canada. We conclude that the cumulative mortality from entanglement in gillnets is one of the largest sources of human-induced mortality for marine birds, and a major conservation concern, particularly for populations of marbled murrelets, common murres, and rhinoceros auklets, which all show declines in BC.

CRediT authorship contribution statement

Douglas F. Bertram: Funding acquisition, Data curation, Writing - original draft, Project administration. **Laurie Wilson:** Data curation, collection, Writing - review & editing, Project administration. **Kristin Charleton:** Data curation, collection, Investigation, Writing - review & editing. **April Hedd:** Formal analysis, Writing - review & editing, Data curation. **Gregory J. Robertson:** Methodology, Formal analysis, Writing - review & editing. **Joanna L. Smith:** Conceptualization, Data curation, Data collection, Writing - review & editing. **Ken H. Morgan:** Conceptualization, Data curation, collection, Writing - review & editing. **Xiao J. Song:** Data curation, collection, Writing - review & editing, Formal analysis.

Declaration of competing interest

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.

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Appendix A. Supplementary data

Supplementary data to this article (Locations of places named in the text, JAGS code for Multinomial GLMM with one random intercept, and JAGS code for NB GLMM with two random intercepts and one random effect on size.) can be found online at https://doi.org/10.1016/j.marenvres.2021.105268.

Appendix B. Additional entangled birds salvaged during the 2005–2007 “Seabird Recovery Program”

In addition to the observer reports of birds entangled in this study, 93 birds were salvaged by DFO field staff (among the fleet during fishery openings to sample salmon DNA), and volunteer fishers in management areas 3, 4, 8, 11, 12, 13, 14, in 2005, 2006, and 2007. All 93 birds were identified, either by carcass or photograph, and included: 52 rhinoceros auklets, 27 common murres, 8 marbled murrelets, 3 common loons (*Gavia immer*), 1 red throated loon (*G. stellata*), 1 Cassin’s auklet, and 1 pigeon guillemot. Particularly striking was the observation of 46 rhinoceros auklet floating near vessels during a sockeye fishery in management area 4 (July 16, 2006), 23 of which were collected for identification and included in the tally of 93 salvaged birds.

Table S1

Posterior distributions of parameters modeling total number of birds caught in the BC chum fishery (1995–2016), using a negative binomial GLMM. Distributions are based on 90,000 MCMC runs.

	Mean	sd	LCI	UCI	Median	R-hat	Effective sample size
β_0	−3.201	0.622	−4.419	−1.913	−3.197	1.004	740
σ_A	1.357	0.707	0.519	3.146	1.195	1.001	8200
σ_Y	0.897	0.299	0.466	1.621	0.847	1.002	2600
N	−2.36	0.405	−2.952	−1.396	−2.415	1.001	26000
σ_κ	0.891	0.397	0.315	1.825	0.812	1.001	22000
b_{A12}	1.322	0.663	0.074	2.698	1.294	1.003	1100
b_{A13}	0.134	0.66	−1.218	1.458	0.135	1.002	1400
b_{A14}	−1.284	0.76	−2.937	0.077	−1.23	1.002	2500
b_{A21}	0.304	0.61	−0.966	1.517	0.305	1.003	910
b_{A23}	0.242	0.676	−1.131	1.594	0.239	1.002	1700
b_{A25}	−0.891	0.681	−2.359	0.378	−0.859	1.002	2100
b_{Y1995}	−0.093	0.35	−0.769	0.622	−0.1	1.002	5100
b_{Y1996}	−0.245	0.341	−0.897	0.46	−0.254	1.002	4700
b_{Y1997}	0.309	0.344	−0.348	1.014	0.297	1.002	5100
b_{Y1998}	0.079	0.352	−0.598	0.805	0.071	1.002	7800
b_{Y1999}	−0.162	0.353	−0.845	0.558	−0.168	1.002	5000
b_{Y2000}	1.156	0.342	0.513	1.871	1.142	1.002	5100
b_{Y2001}	0.825	0.343	0.168	1.525	0.815	1.002	4400
b_{Y2002}	0.446	0.531	−0.568	1.516	0.435	1.001	6300
b_{Y2003}	−1.67	0.741	−3.321	−0.414	−1.602	1.001	5300
b_{Y2004}	−0.157	0.539	−1.248	0.886	−0.146	1.001	6700
b_{Y2005}	−0.063	0.556	−1.171	1.029	−0.06	1.001	8100
b_{Y2006}	−0.854	0.508	−1.921	0.079	−0.83	1.001	9100
b_{Y2007}	0.377	0.542	−0.674	1.468	0.371	1.001	5100
κ_{A12}	0.043	0.015	0.02	0.078	0.04	1.001	59000
κ_{A13}	0.115	0.085	0.033	0.322	0.094	1.001	90000
κ_{A14}	0.214	0.566	0.018	1.079	0.102	1.001	14000
κ_{A21}	0.155	0.022	0.117	0.203	0.153	1.001	90000
κ_{A23}	0.130	0.140	0.040	0.360	0.105	1.001	50000
κ_{A25}	0.083	0.131	0.013	0.266	0.061	1.001	90000

Table S2
Posterior distributions of parameters modeling total number of birds caught in the BC sockeye fishery (1995–2016), using a negative binomial GLMM. Distributions are based on 90,000 MCMC runs.

	Mean	sd	LCI	UCI	Median	R-hat	Effective sample size
β_0	−5.376	1.243	−8.367	−3.218	−5.23	1.016	150
σ_A	2.933	1.395	1.246	6.714	2.588	1.004	770
σ_Y	0.958	0.226	0.611	1.489	0.926	1.001	29000
N	−2.577	0.36	−2.981	−1.619	−2.673	1.001	90000
σ_κ	0.724	0.449	0.116	1.804	0.619	1.001	12000
b_{A3}	1.134	1.3	−1.128	4.191	1.002	1.013	170
b_{A4}	0.654	1.248	−1.517	3.635	0.508	1.014	160
b_{A11}	3.759	1.241	1.63	6.738	3.6	1.015	160
b_{A12}	1.696	1.227	−0.435	4.645	1.536	1.015	160
b_{A13}	−0.191	1.342	−2.633	2.856	−0.296	1.012	200
b_{A14}	−1.454	2.689	−7.895	2.871	−1.11	1.001	21000
b_{A20}	0.395	1.252	−1.788	3.383	0.25	1.015	160
b_{A23}	−2.811	2.345	−8.666	0.55	−2.387	1.001	16000
b_{A29}	−3.048	2.309	−8.833	0.239	−2.634	1.002	24000
b_{Y1997}	1.634	0.321	1.028	2.286	1.627	1.001	16000
b_{Y2000}	0.7	0.355	0.017	1.413	0.693	1.001	14000
b_{Y2001}	−1.346	0.395	−2.15	−0.594	−1.338	1.001	17000
b_{Y2002}	−0.751	0.417	−1.588	0.052	−0.744	1.001	11000
b_{Y2003}	−0.194	0.413	−1.01	0.616	−0.194	1.001	8600
b_{Y2004}	0.567	0.372	−0.149	1.308	0.563	1.001	7800
b_{Y2005}	−0.359	0.493	−1.356	0.583	−0.348	1.001	8500
b_{Y2006}	−0.013	0.374	−0.741	0.731	−0.017	1.001	17000
b_{Y2007}	0.176	0.509	−0.835	1.167	0.177	1.001	25000
b_{Y2008}	−1.052	0.787	−2.778	0.324	−0.993	1.001	90000
b_{Y2009}	0.704	0.516	−0.286	1.744	0.694	1.001	15000
b_{Y2010}	−0.376	0.638	−1.697	0.827	−0.357	1.001	23000
b_{Y2011}	−0.01	0.568	−1.142	1.099	−0.005	1.001	12000
b_{Y2012}	−0.452	0.629	−1.748	0.736	−0.434	1.001	13000
b_{Y2013}	−0.072	0.559	−1.195	1.012	−0.067	1.001	25000
b_{Y2014}	1.32	0.406	0.549	2.149	1.306	1.001	15000
b_{Y2015}	−0.18	0.542	−1.284	0.853	−0.169	1.001	9400
b_{Y2016}	−0.316	0.629	−1.619	0.866	−0.297	1.001	90000
κ_{A3}	0.073	0.103	0.013	0.223	0.058	1.001	90000
κ_{A4}	0.114	0.132	0.036	0.366	0.083	1.001	20000
κ_{A11}	0.078	0.013	0.056	0.107	0.077	1.001	29000
κ_{A12}	0.043	0.008	0.03	0.061	0.043	1.001	11000
κ_{A13}	0.081	0.148	0.01	0.279	0.058	1.001	36000
κ_{A14}	0.139	0.532	0.011	0.644	0.067	1.001	8400
κ_{A20}	0.194	0.491	0.032	1.016	0.088	1.001	90000
κ_{A23}	0.134	0.363	0.013	0.653	0.069	1.001	26000
κ_{A29}	0.151	0.682	0.013	0.677	0.069	1.001	8900

Table S3
Posterior distributions of parameters modeling species composition of birds caught in the BC chum fishery (1995–2016), using a multinomial GLMM. Distributions are based on 90,000 MCMC runs.

	Mean	sd	LCI	UCI	Median	R-hat	Effective sample size
β_{MAMU}	−4.097	0.898	−6.234	−2.585	−4.003	1.004	750
β_{Other}	−2.851	1.154	−5.499	−0.74	−2.757	1.006	500
β_{RHAU}	−3.605	1.004	−6.227	−2.174	−3.39	1.015	760
σ_{MAMU}	1.304	1.304	0.058	4.75	0.934	1.008	760
σ_{Other}	2.706	1.469	0.964	6.448	2.354	1.002	1800
σ_{RHAU}	1.39	1.286	0.061	4.851	1.013	1.005	960
$b_{4, MAMU}$	−0.268	1.787	−4.344	2.474	−0.034	1.014	4000
$b_{12, MAMU}$	0.709	0.993	−0.756	3.157	0.514	1.004	750
$b_{13, MAMU}$	−0.351	1.702	−4.619	2.189	−0.064	1.003	24000
$b_{14, MAMU}$	−0.482	1.694	−4.756	1.788	−0.123	1.009	3600
$b_{21, MAMU}$	−0.143	0.899	−1.871	1.917	−0.13	1.004	870
$b_{23, MAMU}$	−0.616	1.636	−4.93	1.465	−0.206	1.01	2000
$b_{25, MAMU}$	−0.444	1.614	−4.582	1.817	−0.11	1.011	1600
$b_{4, Other}$	−1.141	2.583	−7.391	2.765	−0.75	1.002	12000
$b_{12, Other}$	−3.157	2.29	−8.815	−0.124	−2.713	1.001	86000
$b_{13, Other}$	−1.446	2.544	−7.608	2.188	−1.024	1.005	8100
$b_{14, Other}$	2.593	1.262	0.355	5.439	2.493	1.006	530
$b_{21, Other}$	0.816	1.163	−1.308	3.484	0.725	1.006	500
$b_{23, Other}$	−0.311	1.432	−3.243	2.577	−0.291	1.002	1500
$b_{25, Other}$	0.356	1.464	−2.571	3.359	0.341	1.003	1100
$b_{4, RHAU}$	−0.331	1.612	−4.36	2.343	−0.069	1.005	4300
$b_{12, RHAU}$	0.943	1.107	−0.503	3.788	0.691	1.012	670

(*continued on next page*)

Table S3 (*continued*)

	Mean	sd	LCI	UCI	Median	R-hat	Effective sample size
$b_{13,\ \text{RHAU}}$	−0.359	1.596	−4.371	2.327	−0.091	1.01	1000
$b_{14,\ \text{RHAU}}$	−0.563	1.634	−5.143	1.763	−0.181	1.013	580
$b_{21,\ \text{RHAU}}$	0.327	0.999	−1.181	2.94	0.097	1.015	940
$b_{23,\ \text{RHAU}}$	−0.734	1.513	−4.838	1.343	−0.325	1.006	3400
$b_{25,\ \text{RHAU}}$	−0.5	1.506	−4.483	1.825	−0.164	1.009	1800

Table S4

Posterior distributions of parameters modeling species composition of birds caught in the BC sockeye fishery (1995–2016), using a multinomial GLMM. Distributions are based on 90,000 MCMC runs.

	Mean	sd	LCI	UCI	Median	R-hat	Effective sample size
β_{MAMU}	−2.161	1.929	−6.17	1.636	−2.122	1.003	820
β_{Other}	−1.783	0.801	−3.38	−0.042	−1.816	1.002	2500
β_{RHAU}	0.493	1.3	−2.167	2.949	0.557	1.007	390
σ_{MAMU}	5.507	2.537	2.374	11.938	4.94	1.001	21000
σ_{Other}	1.463	1.032	0.16	4.064	1.245	1.001	13000
σ_{RHAU}	3.406	1.398	1.621	6.951	3.106	1.002	1600
$b_{3,\ \text{MAMU}}$	4.173	2.086	0.163	8.535	4.106	1.004	790
$b_{4,\ \text{MAMU}}$	4.08	2.053	0.105	8.286	4.026	1.003	1100
$b_{11,\ \text{MAMU}}$	−4.697	4.385	−15.703	1.269	−3.847	1.001	6100
$b_{12,\ \text{MAMU}}$	−1.97	2.167	−6.403	2.282	−1.929	1.003	840
$b_{13,\ \text{MAMU}}$	−2.862	4.817	−14.629	4.183	−2.056	1.001	11000
$b_{29,\ \text{MAMU}}$	−6.075	4.347	−16.849	−0.426	−5.207	1.003	4200
$b_{3,\ \text{Other}}$	0.518	1.147	−1.643	3.081	0.393	1.001	18000
$b_{4,\ \text{Other}}$	0.471	1.137	−1.727	2.959	0.366	1.001	16000
$b_{11,\ \text{Other}}$	0.374	0.91	−1.473	2.312	0.331	1.002	3500
$b_{12,\ \text{Other}}$	−1.44	1.133	−4.122	0.194	−1.28	1.001	7600
$b_{13,\ \text{Other}}$	−0.402	1.731	−4.295	2.304	−0.153	1.016	6000
$b_{29,\ \text{Other}}$	−0.054	0.821	−1.841	1.598	−0.018	1.002	3100
$b_{3,\ \text{RHAU}}$	1.915	1.476	−0.817	5.025	1.832	1.004	660
$b_{4,\ \text{RHAU}}$	3.009	1.468	0.309	6.121	2.918	1.005	460
$b_{11,\ \text{RHAU}}$	1.805	1.329	−0.698	4.534	1.748	1.006	410
$b_{12,\ \text{RHAU}}$	−0.412	1.312	−2.899	2.266	−0.475	1.007	390
$b_{13,\ \text{RHAU}}$	−2.463	2.86	−9.243	2.04	−2.074	1.001	9000
$b_{29,\ \text{RHAU}}$	−3.673	1.38	−6.392	−0.914	−3.68	1.005	520

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