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## Research

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## Conservation biology

# Canadian fishery closures provide a large-scale test of the impact of gillnet bycatch on seabird populations

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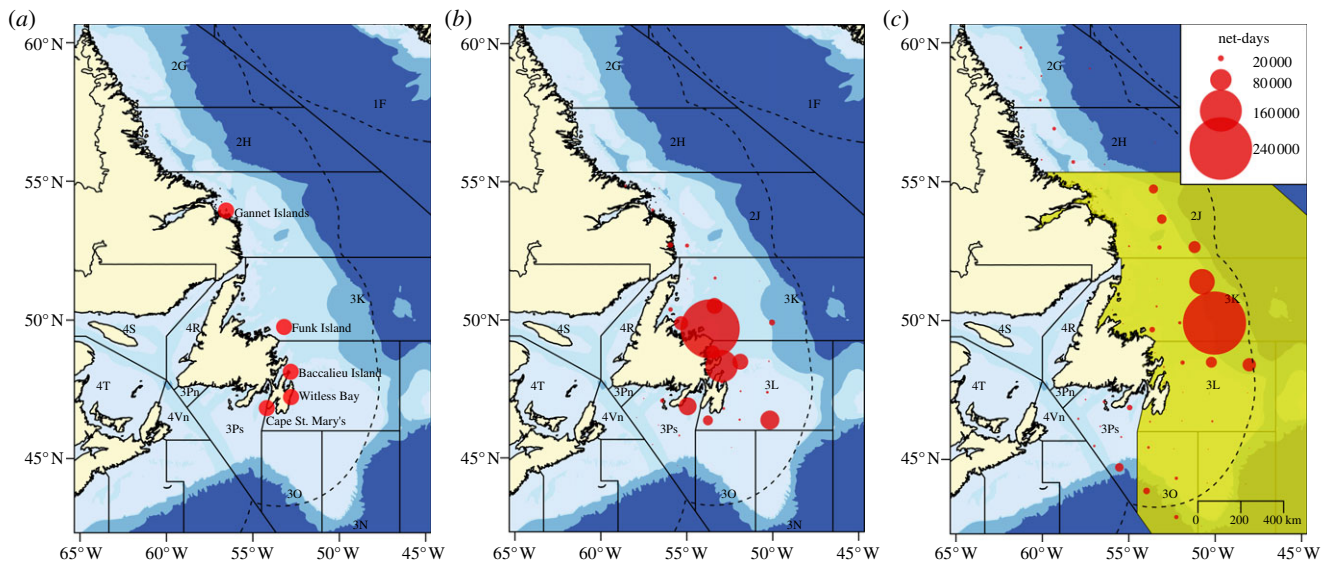
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In 1992, the eastern Canadian gillnet fisheries for northern cod and Atlantic salmon were largely closed. These large-scale fishery closures resulted in the removal of tens of thousands of gillnets known to inflict high levels of seabird mortality. We used this unprecedented opportunity to test the effects of gillnet removal on seabird populations. Consistent with predictions, we show that the breeding populations of divers (auks, gannets; susceptible to gillnet bycatch) have increased from pre-closure levels, whereas the populations of scavenging surface-feeders (gulls; low vulnerability to gillnet bycatch but susceptible to removal of fisheries discards) have decreased. Using the most complete series of seabird census data for the species most vulnerable to bycatch, we demonstrate a positive population response of common murres to reduction in gillnet fishing within its foraging range. These findings support the widespread but seldom documented contention that fisheries bycatch negatively impacts populations of non-target large vertebrates.

## 1. Introduction

Incidental take, or bycatch, of non-target species in fishing gear carries negative consequences for marine animals around the globe [1–4]. Yet, robust interrogations of the population effects of bycatch mortality have been precluded by data deficiencies [2,3]. Most assessments of seabird bycatch mortality and its population implications have been directed at incidental take on baited hooks within longline fisheries of the Southern Ocean [4]. Bycatch in gillnet fisheries has received less attention but has long been recognized as a global conservation concern. In the early 1970s, high levels of seabird mortality imposed by salmon driftnets (free floating gillnets) in Greenland exceeded levels considered sustainable for local seabird populations [5]. These findings resulted in the closure of the Greenland driftnet fishery in 1972 [6] and contributed to a United Nations ban on high seas driftnet fishing in 1992 (Resolution 46/215). Since the 1970s, global effort in fixed (set-net) gillnet fisheries, especially in northern oceans, have increased substantially, yet there have been few recent assessments of associated seabird mortality and population responses [3,7].

Fishing activity in the northwest Atlantic has entailed substantial bycatch mortality [8,9] and the closure of the eastern Canadian northern cod (*Gadus morhua*) and Atlantic salmon (*Salmo salar*) gillnet fisheries in 1992 [10,11] provided an unprecedented opportunity to assess the effects of gillnet bycatch on seabird population trends. Since these moratoria, some limited gillnet fishing for cod continued in small-scale sentinel and commercial fisheries, though most gillnet fishing now occurs offshore and is directed towards



**Figure 1.** Seabird ecological reserves (red; *a*) and average annual fishing effort (net-days; number of gillnets  $\times$  days set (gillnets typically 91 m long and soaked for 1 day)) from gillnet fisheries before (1987–1991; *b*) and after (1992–2009, closure zone shown in yellow; *c*) the fishery closures. NAFO divisions and Canada's exclusive economic zone are shown with solid and dotted black lines, respectively. The inshore cod fishery dominated pre-moratoria fishing efforts and the offshore halibut fishery has dominated following the closures.

Greenland halibut (*Reinhardtius hippoglossoides*; [12]). Thus, since 1992, tens of thousands of gillnets that were set annually within the foraging ranges of seabirds at major breeding colonies in eastern Canada are no longer deployed (figure 1). The fishery closures have likely resulted in reduced seabird bycatch throughout the region over the past 20 years. In response to changes in fishing effort, we predicted positive population responses by diving seabird species (gillnet-vulnerable auks, gannets). Surface-feeding seabirds (gulls) are not at significant risk of bycatch in gillnets, though their reliance on offal and discards made them susceptible to the fishery closures [13]. As the fishery moratoria also entailed removal of hundreds of thousands of tonnes of offal and discards from inshore waters, we predicted that surface-feeding seabirds would exhibit negative population trends via reduced breeding success and emigration. Given seabird life-history traits (e.g. long-lived, delayed maturity), the intervening period provided ample time to detect potential changes in diving and surface-feeding seabird populations.

## 2. Material and methods

Gillnet fishing data from 1987 to 2009 were obtained from Fisheries and Oceans Canada (DFO) for May–September, when gillnet fishing effort peaks and nesting seabirds occupy coastal colonies. Given the fact that nets are set for variable periods, a diving bird's risk of entanglement is a function of soak time and the number of nets set; therefore, our effort index was net-days (i.e. one net-day equals one standard length net (typically 91 m) fishing for 24 h). These data were aggregated by year and Northwest Atlantic Fisheries Organization (NAFO) unit area (e.g. unit area 3 Lg within division 3 L), and average annual fishing effort for each unit area was calculated for pre- and post-moratoria periods.

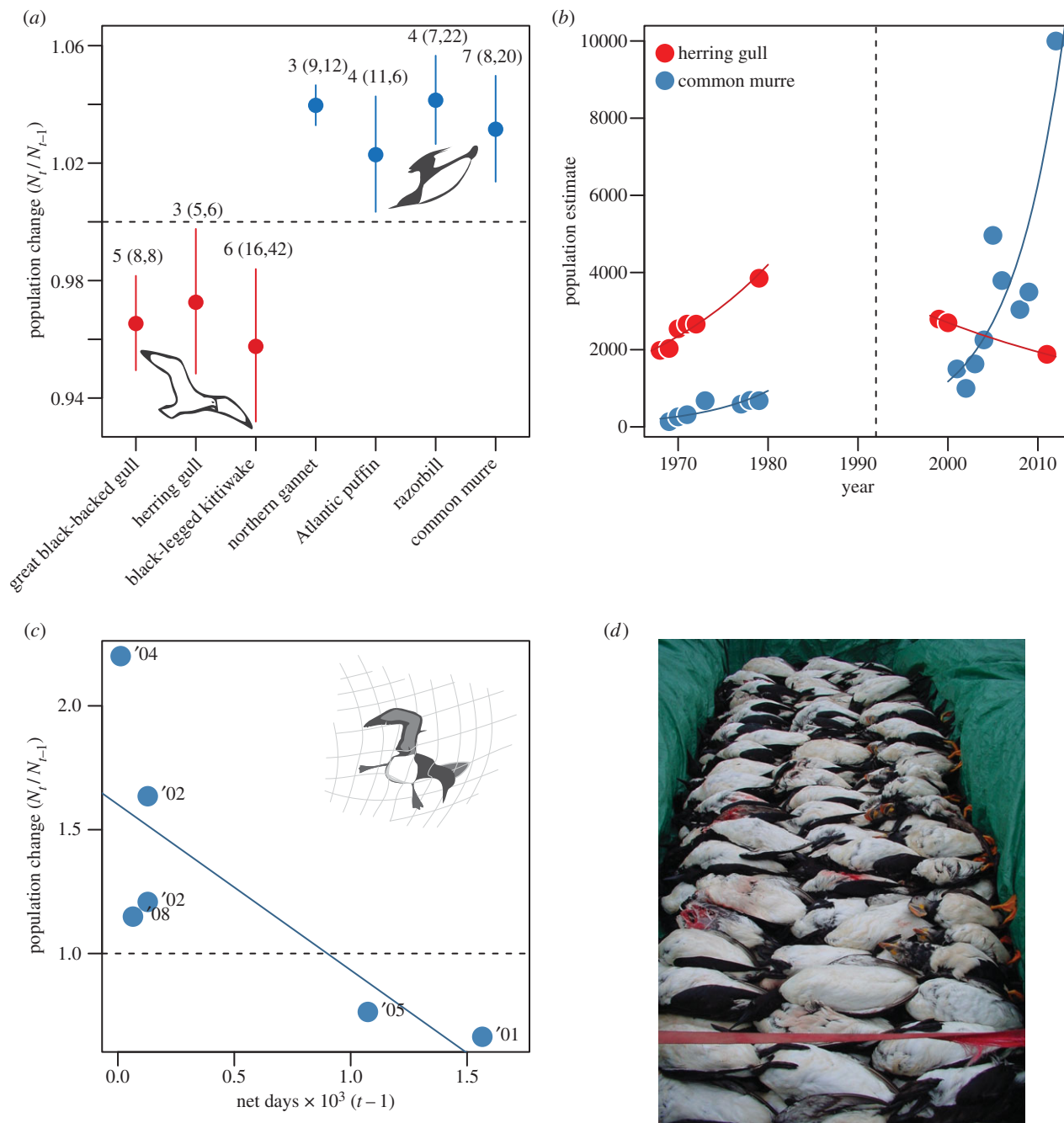
Using Canadian Wildlife Service, colony-based census data collected from 1968 to 2012, we compared population trends of diving seabirds (common murre, razorbill (*Alca torda*), Atlantic puffin (*Fratercula arctica*), northern gannet (*Morus bassanus*)) with surface-feeding seabirds (herring gull (*Larus argentatus*), great black-backed gull (*Larus marinus*), black-legged kittiwake

(*Rissa tridactyla*) at Newfoundland and Labrador's five major seabird ecological reserves (SERs; figure 1*a*). These reserves host greater than 90 per cent of the regional seabird population. In general, three census counts were conducted for each species at each colony before and after the closures. Population trends from 1975 to 2012 for each species were estimated using lognormal-Poisson generalized linear-mixed models with census count as the response, year as an explanatory variable and colony as a random effect; model residuals were weighted by  $\ln(\text{count})$  to reduce heterogeneity due to smaller populations being less stable. Lognormal-Poisson models were used to account for overdispersion. Data limitations precluded pre- and post-moratoria-specific trend assessment. There were, however, sufficient data to estimate pre- and post-moratoria population trends of common murres and herring gulls from Gull Island (Witless Bay SER) using generalized linear models with a negative binomial distribution to account for overdispersion. Similarly, continuous count data from Gull and Great Island (Witless Bay SER) between 2002 and 2009 enabled a more focused post-moratoria analysis of population responses of common murres (annual change;  $\ln(N_t/N_{t-1})$ ) to gillnet fishing effort within their foraging ranges (approx. 100 km; unit areas 3Lg, 3Lj, 3Ls). For this analysis, effort data were restricted to Atlantic cod, lumpfish (*Cyclopterus lumpus*), Greenland halibut and winter flounder (*Pseudopleuronectes americanus*) as these fisheries incur significant bycatch of murres [8,9]. Owing to the common murre's maximum dive depth of approximately 180 m [14], effort data were truncated to gillnets set less than 200 m. Confidence intervals around the slope estimate for this normal regression were calculated using a parametric bootstrap (10 000 replicates).  $N_t/N_{t-1}$  was calculated by taking the exponent of slope estimates and confidence intervals from all models. All analyses were run in R [15].

This paper relied on two federal government databases (Fisheries and Oceans Canada and Environment Canada) that can be accessed through a formal request.

## 3. Results

Following the fishery closures in NAFO Divisions 2J3KLMNO, gillnet fishing activity decreased substantially



**Figure 2.** Population trend estimates  $\pm$  CIs of surface-feeding (red) and diving seabirds (blue) breeding at seabird ecological reserves (SERs) from 1975 to 2012 ( $n$  colonies ( $n$  pre-,  $n$  post-moratoria counts) indicated; *a*); pre- and post-moratoria population trends of Herring gulls and common murres breeding at Gull Island, Witless Bay SER (*b*); inter-annual population change of common murres breeding at Gull and Great Islands, Witless Bay, in response to local post-moratoria gillnet fishing effort (year  $t-1$  indicated; *c*); and, boatload of murres and puffins caught in gillnets in Witless Bay in 2002 (photo credit: Environment Canada; *d*).

in inshore regions where seabirds forage from breeding colonies (figure 1). These radical fishery changes, from peak activity in the 1970s to its minimum in the 2000s, are coincident with increasing populations of diving seabirds and decreasing numbers of surface feeders (figure 2*a*). At Gull Island, Witless Bay SER, common murre and herring gull populations were increasing before the moratoria ( $\beta = 1.13$  (LCI: 1.06, UCI: 1.21) and 1.06 (LCI: 1.05, UCI: 1.07), respectively; figure 2*b*). Following the fishery closures, the common murre population increased, possibly at a greater rate than pre-moratoria growth ( $\beta = 1.18$  (LCI: 1.11, UCI: 1.27); figure 2*b*), and the herring gull population decreased ( $\beta = 0.97$  (LCI: 0.96, UCI: 0.97); figure 2*b*). Further, annual population changes of breeding common murres at Witless Bay are

negatively associated with local fishing effort ( $\beta = -0.67$  (LCI:  $-0.81$ , UCI:  $-0.20$ ),  $R^2 = 0.49$ ; figure 2*c*).

#### 4. Discussion

Reductions in inshore gillnet fishing effort coincided with population increases of diving and decreases of surface-feeding seabirds throughout eastern Canada. These trends are likely due to substantial reductions in bycatch mortality for divers and reductions in breeding success by surface-feeders, owing to the elimination of discards and offal around breeding colonies following the fishery closures. During the 1990s, large gulls exhibited reduced breeding success,



increased predation rates on smaller seabirds [16] and engaged in widespread scavenging on human refuse. Comparative analyses of trends before and after the moratoria for the seabird most reliant on discards, the herring gull, and the seabird most vulnerable to bycatch, the common murre, further indicate that discard availability affects gull population growth and bycatch mortality slows murre population growth. The latter is supported by the direct negative association between common murre population change and continued local gillnet fishing efforts. Adult murre are highly susceptible to bycatch in gillnets [17], especially when they are set within the foraging range of colonies [9,18]. Murre exhibit obligate bi-parental care, so every drowned adult also results in offspring mortality. As such, localized fishing efforts can entail considerable demographic consequence. To our knowledge, this is the first demonstration of a bycatch-related breeding population response.

Other significant factors have also led to reductions in murre mortality since the early 1990s. Reductions in mortality associated with illegal ship-source hydrocarbon discharges have coincided with increased surveillance [19]. Common murre are legally hunted in Newfoundland and Labrador, and regulations established in 1993 resulted in subsequent reductions in murre kills [20]. These sources of winter mortality are not easily associated with colony of origin [19,20], as is the case between breeding population trends and spatially explicit gillnetting efforts during summer. Geolocator tracking indicates that adult murre from eastern Canadian colonies winter largely outside coastal hunting zones, reducing this mortality risk [21]. The primary anthropogenic risk to the other diving seabirds (northern gannets, Atlantic puffins and razorbills) is bycatch, and their

populations have increased from pre-moratoria levels. The release from gillnet mortality is evident despite a pervasive bottom-up regime shift in the northwest Atlantic which had a profound negative influence on capelin (*Mallotus villosus*), a major forage fish that supports the large vertebrate food-web, including seabirds [22].

Reduced inshore gillnet fishing in eastern Canada creates opportunity to explore alternative, more selective fishing gear (e.g. cod pots) and to establish marine protected areas to aid population recoveries. Current offshore fishing efforts incur large incidental takes of non-breeding summer residents (e.g. shearwaters [8]); the population consequences of such bycatch is unknown. Although inshore gillnet fishing has largely disappeared, limited summer efforts continue to kill many seabirds, especially when gillnets are set in hotspots that concentrate fishes, mammals and seabirds ([18]; figure 2*d*). Bycatch persists in the Witless Bay area thereby suggesting that post-moratoria fishing activity continues to slow the growth rate of local seabird populations. This result is telling given post-moratoria inshore fishing efforts are an order of magnitude lower than pre-moratoria efforts. We conclude that large-scale reductions in fishing effort had pervasive consequences and our findings support the widely accepted, but rarely documented, contention that fisheries bycatch negatively impacts seabird population trends.

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