BYCATCH AND BEACHED BIRDS: ASSESSING MORTALITY IMPACTS IN COASTAL NET FISHERIES USING MARINE BIRD STRANDINGS

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SUMMARY

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In most of the world's coastal fisheries, bycatch of marine birds is rarely monitored, and thus the impact on populations is poorly known. We used marine bird strandings to assess the impact of entanglement in Pacific Northwest coastal net salmon fisheries. We compared the magnitude and species composition of fisheries-associated strandings (FAS) to baseline data collected at beaches monitored by citizen-science programs in Washington State and British Columbia, and to seabirds salvaged from gillnets during observer programs. Carcass encounter rates were 16.4 carcasses/km [95% confidence interval (CI): 11.2 to 21.7] for FAS and 1.00 carcasses/km (95% CI: 0.87 to 1.14) for baseline data. Declines in fisheries effort were associated with decreasing FAS, although declines in at-sea seabird abundance may also be at play. Common Murres *Uria aalge* comprised most of the carcasses in both the FAS (86%) and bycatch studies (71%). Although the total count of murre FAS represented a small fraction (1.3%–6.6%) of baseline mortality accumulated for the Salish Sea over the same period, murre FAS added 0.2%–2.9% to annual mortality rates. Considering the effects of other natural and anthropogenic mortality agents on murres in the region, this species might benefit from further protection. Given the complexity of salmon fisheries management and the ubiquitous distribution of seabirds in the Salish Sea, we recommend the comprehensive adoption of gillnet gear modification to reduce seabird bycatch, a solution that may prove to be beneficial for the vitality of seabird populations and of the fishing industry.

Key words: Common Murre, *Uria aalge,* Salish Sea, beached bird surveys, seabird bycatch, British Columbia, Washington

INTRODUCTION

Bycatch in fisheries gear is one of the most common sources of anthropogenic at-sea mortality for marine birds (Wilcox & Donlan 2007, Finkelstein *et al.* 2008). Among the gear types known to capture marine birds, gillnets—with fisheries landings of nearly eight million metric tons per year worldwide (Watson *et al.* 2006)—take pursuit-divers (Tasker *et al.* 2000) including alcids (Artyukhin & Burkanov 2000, Österblom *et al.* 2002, Benjamins *et al.* 2008), shearwaters (Uhlmann *et al.* 2005), loons (Dagys & Žydelis 2002) and penguins (Taylor *et al.* 2002), and benthic feeders such as sea ducks (Dagys & Žydelis 2002), with some fisheries estimated to take thousands of seabirds annually (Davoren 2007). Although the population impacts of gillnet fisheries remain largely unknown (Uhlmann *et al.* 2005, but see Davoren 2007), Hall *et al.* (2000) speculated that seabird bycatch in gillnet fisheries is "probably more common than suggested by the literature" because gillnet fisheries—many of which operate in coastal areas using small boats that land catches daily—have rarely been observed (Hall *et al.* 2000, Lewison *et al.* 2004).

Bycatch is a conservation concern because, for long-lived species with low fecundity and delayed maturity, such as many marine birds, even slightly elevated adult mortality can lead to population decline (Nur & Sydeman 1999, Russell 1999). From a fisheries management and industry perspective, bycatch is problematic because the take of protected or charismatic species can lead to fisheries closures and can create a political climate that is unsympathetic to commercial fishing (Salzman 1989, Kelleher 2005).

The most accurate assessments of bycatch typically come from data collected by independent shipboard observers (Kelleher 2005, Miller & Skalski 2006). However, the cost and logistics demands of observer programs make them rare (Lewison *et al.* 2004). As a result, accurate estimation of non-target catch is mostly lacking throughout the world's fisheries (Lewison *et al.* 2004, Kelleher 2005, Read *et al.* 2006). When attempting to assess the impacts of coastal fisheries on regional non-target populations, a possible alternative or complement to vessel-based observer programs is animal stranding surveys. To date, marine mammal, turtle and seabird stranding survey data have been used to track oil pollution (Camphuysen & Heubeck 2001, Wiese & Ryan 2003); to document sources of mortality (Chaloupka *et al.* 2008), effects of biotoxins (Scholin *et al.* 2000), anomalous mortality events (Parrish *et al.* 2007), vessel strikes (Hazel & Gyuris 2006) and the prevalence of ingested marine debris (Bugoni *et al.* 2001); to assess local and regional biophysical coupling (Parrish *et al.* 2007); and to monitor the effects of bycatch in coastal fisheries (Forney *et al.* 2001, Lewison *et al.* 2003, Žydelis *et al.* 2006, Peckham *et al.* 2007). With respect to fisheries mortality, strandings can be particularly useful sources of information because carcasses can be assessed for signs of entanglement or hooking (Cox *et al.* 1998, Žydelis *et al.* 2006, Byrd *et al.* 2008). However, the relative importance of anthropogenic sources of mortality as signaled by beached animals is difficult to assess in the absence of background mortality rates or known population size (Eguchi 2002, Ford 2006). Therefore, beached animal monitoring programs can be useful, particularly if carcass data are recorded over the long term, systematically and over a wide geographic area, providing an index of baseline mortality with which anomalous mortality events, including acute fisheries-associated mortality, can be compared (Ford 2006, Žydelis *et al.* 2006, Parrish *et al.* 2007, Chaloupka *et al.* 2008, Nevins *et al.* 2008).

In the Pacific Northwest, marine bird strandings have periodically been linked to entanglement in fisheries gear (Kaiser 1993, Wilson *et al.* 1995). In October 2007, more than two hundred marine birds, mostly Common Murres *Uria aalge,* washed up on a single beach in Puget Sound, Washington, (Dunagan 2007a) following a fishery opening. Necropsy results pointed to drowning as the suspected cause of death, although the diagnosis was not definitive (National Wildlife Health Center 2008, K. Schuler pers. comm.). Several fleets of net fisheries, namely gillnet, purse seine and reef nets, operate in the inland marine waters of the Pacific Northwest that include the Strait of Juan de Fuca, the Strait of Georgia and Puget Sound (collectively referred to as the "Salish Sea"; Fraser *et al.* 2006). Fleets include Canadian and US non-tribal and tribal commercial fisheries, as well as test fisheries that monitor the size and migration status of fish stocks (DFO 2001, WDFW 2008, WDFW 2009). Commercial and test fisheries target salmon in late summer and fall, including Sockeye (*Oncorhynchus nerka*), Chum (*O. keta*), Pink (*O. gorbuscha*), Coho (*O. kisutsh*) and Chinook (*O. tshawytscha*). Observer programs and scientific studies have demonstrated the spatiotemporal overlap between seabirds and fisheries (Troutman *et al.* 1991, Hamel *et al.* 2008) and bycatch in gillnets, primarily in the Fraser River non-tribal fisheries for Sockeye and Pink Salmon in late summer (July and August) and in the Puget Sound and Strait of Juan de Fuca Chum fisheries in the fall (October and November; Pierce *et al.* 1994, Erstad *et al.* 1996b, Melvin *et al.* 1999, Smith & Morgan 2005). In the Fraser River, Sockeye and Pink Salmon non-tribal gillnet sector alone, estimates of mortality suggested that hundreds to thousands of birds, principally Common Murres and Rhinoceros Auklets *Cerorhinca monocerata,* were caught in one year (Pierce & Alexandersdottir unpubl. data in Thompson *et al.* 1998). Out of concern for Marbled Murrelets *Brachyramphus marmoratus,* a species listed as Threatened under the US Endangered Species Act and the Canadian Species at Risk Act, regulations to reduce seabird bycatch went into effect in 1999, but only in the commercial Sockeye and Pink Salmon non-tribal gillnet fishery in Washington [Washington Administrative Code (WAC) 220-47-302; Harrison 2001].

Despite regional declines in both fleet size and landings, gillnet fisheries have persisted in the Salish Sea and were worth an average of $25 million annually from 2000 to 2006 in British Columbia and Washington combined (L. Hoines, Washington Department of Fish and Wildlife [WDFW], pers. comm.; DFO 2007; Jording *et al.* 2007). In southern British Columbia, 393 licenses for commercial salmon gillnetting fisheries were issued in 2008 for the Strait of Georgia and Juan de Fuca fisheries (i.e. in Area E and including First Nations; DFO 2008). Since 2002, Puget Sound and Strait of Juan de Fuca, Washington, commercial non-tribal gillnet fishing licenses have averaged almost 200 (Jording *et al.* 2007), although only a fraction of licensees actually participate in any fisheries opening (J. Jording pers. comm.). The US tribal fleet is not taken into account in the aforementioned licenses; however, treaty tribes in Washington are entitled to 50% of the harvestable salmon at all usual and accustomed fishing areas (Shepard & Argue 2005). Thus, tribal fishing effort may rival that of the non-tribal fleet.

To date, observer programs specifically designed to monitor marine bird bycatch in Pacific Northwest gillnet fisheries have been short-term projects, lasting from two to six years at most (between 1993 and 1996 in Washington and from 1995 to 2001 in British Columbia) depending on the fishery (Pierce *et al.* 1994, Erstad *et al.* 1994, Melvin 1995, Melvin & Conquest 1996, Melvin *et al.* 1997, Smith & Morgan 2005). Spatially and temporally comprehensive observer data do not exist for Salish Sea gillnet fisheries. The goal of our study was to use beached bird data to assess marine bird bycatch in the Salish Sea. To that end, we compiled records of stranded marine birds where the cause of death was associated with net fisheries [each individual bird hereafter called a fisheries-associated stranding (FAS)]. We compared the magnitude and species composition of FAS events with baseline data collected systematically by beached bird monitoring programs at sites across the Salish Sea and with results from short-term bycatch studies. We discuss whether trends in beached bird densities could be related to fishing effort and ocean conditions. Finally, using the baseline data, we examine the importance of fisheries-associated mortality relative to all mortality causes combined and suggest that this approach may be useful in cases in which unobserved small-scale coastal fisheries operate along populated and accessible coastlines amenable to beach survey programs.

METHODS

Study area

Our study focused on beached birds and commercial gillnet fisheries in the Salish Sea (Fig. 1). Winds, currents, tides, freshwater runoff and heterogeneous bathymetry in the Salish Sea interact to fuel a productive and diverse ecosystem (Thomson 1981, Strickland 1983) supporting many top-level piscivorous predators such as salmon and marine birds (Vermeer *et al.* 1992, Lichatowich 1999, Zamon 2003, Lance & Thompson 2005, Ruckelshaus & McClure 2007). More than 100 species of marine birds breed, migrate, or overwinter in the Salish Sea (Speich & Wahl 1989, Vermeer & Ydenberg 1989, Puget Sound Action Team 2007, Rice 2007). Six species of seabirds regularly nest in the Salish Sea: Rhinoceros Auklet, Glaucous-winged Gull *Larus glaucescens* or hybrids of the Glaucous-winged and Western Gull *Larus occidentalis,* Pigeon Guillemot *Cepphus columba,* Tufted Puffin *Fratercula cirrhata,* Pelagic Cormorant *Phalacrocorax pelagicus* and Double-crested Cormorant *Phalacrocorax auritus.* Rhinoceros Auklet and Glaucous-winged Gull are the most abundant (Speich & Wahl 1989, Vermeer & Ydenberg 1989). In mid- to late summer, diversity of marine birds increases because of the arrival of overwintering species and the passage of migrants, particularly Common Murres and loon, grebe, gull and scoter species groups (Manuwal & Carter 2001, Nysewander *et al.* 2001).

Breeding (e.g. Rhinoceros Auklets) and overwintering (e.g. Western Grebes *Aechmophorus occidentalis* and Common Murres) species have both suffered notable declines in the Salish Sea based, respectively, on estimates of colony size and regional at-sea counts (Mahaffy 1994, Carter *et al.* 2001, Nysewander *et al.* 2001, Parrish *et al.* 2001, Wilson 2005, Puget Sound Action Team 2007). As a result, 14 species of seabirds and sea ducks are listed as Endangered, Threatened or Sensitive species, or are candidates for any of the former designations in Washington State and British Columbia combined (Brown & Gaydos 2007).

Data compilation

Fisheries-associated strandings

Most of the marine bird strandings that were eventually characterized as fisheries-associated were opportunistic sightings first reported by members of the public, as distinct from systematic beached bird surveys. Once strandings were known to wildlife management authorities, birds were enumerated by direct count or by estimation. Searches for additional carcasses may have been conducted on neighboring beaches or waters, and may have been repeated the following days or weeks. In some cases, a subset of carcasses was collected for necropsies to determine the most probable cause of death (Table 1). Drowning was inferred by pathologists from one or more of the following indications: lung congestion; serosanguinous fluid in mouth, trachea and abdominal and thoracic air sacs; carotid arteries and jugular veins engorged with blood; pulmonary edema.

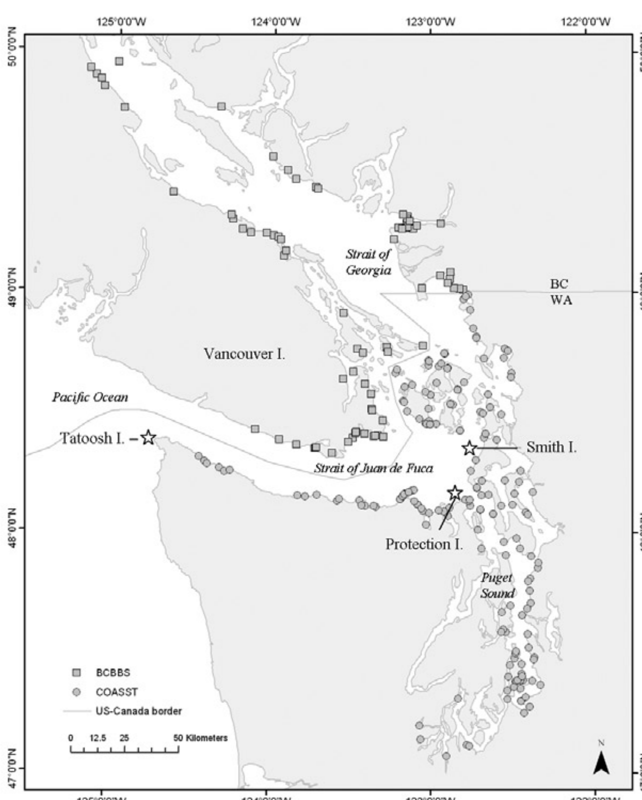

Fig. 1. Location of baseline survey sites in the Salish Sea (Strait of Juan de Fuca, Strait of Georgia and Puget Sound), including the BC Beached Bird Survey (BCBBS—filled squares) in British Columbia and the Coastal Observation Seabird Survey Team (COASST) surveys (filled circles) in Washington State.

Diagnoses consistent with net capture included wing fractures, skin contusions and hemorrhage of subcutaneous tissue at the neck and shoulders (Table 1). In addition, bacteriology, virology and parasitology results were usually negative (i.e. disease was not a factor), and body condition was not consistent with starvation.

Information sources for FAS included scientific articles, technical reports, agency mortality records, newspapers and personal communications. We specifically contacted agencies responsible for processing wildlife remains and diagnosing cause of death, including the National Wildlife Health Center (Madison, WI), the Washington Animal Disease Diagnostic Laboratory at Washington State University (Pullman, WA), and the US Fish and Wildlife Service Forensics Laboratory (Ashland, OR). For each record found across all sources, we listed the number of carcasses found by species, date, survey distance (when available), how cause of death was determined, observer name, data source and a description (latitude and longitude, when available) of the location. When beached birds were not counted, the number of FAS were estimated to the nearest hundred or as a range (Table 1). In most cases, the method of species identification, the number of people searching, start and end times for each search, and the number of times a location was patrolled were unknown.

Baseline beached birds

Within the Salish Sea, the incidence of beached birds has been monitored systematically by two citizen-science programs, the Coastal Observation and Seabird Survey Team (COASST) and the British Columbia Beached Bird Survey (BCBBS). In both programs, skilled volunteers monitored a predefined section of beach at least once per month to count and identify any beached carcass encountered (provided there were identifiable or measurable parts). In both programs, cause of mortality was not diagnosed, although volunteers did record presence of oil or fisheries gear on the carcasses. Collectively, these programs have monitored approximately 230 km of coastline in Washington State and British Columbia annually since 2002 (Fig. 1). We used beached bird data collected by COASST and BCBBS volunteers to establish baseline patterns of beached carcass abundance and species composition.

COASST

COASST volunteers were asked to collect data monthly and to space their surveys at regular intervals, but could decide on which day or days to conduct their survey. All survey sites have set start and turnaround points. Volunteers worked mostly in pairs, searching in a sinusoidal pattern from the water to the edge of the vegetation. Depending on beach width, sites were surveyed on the outward leg only (narrow beaches) or both legs (wide beaches), without duplicating effort spatially. Each carcass was measured (wing chord, culmen, tarsus), uniquely marked and photographed. Identifications to the lowest taxonomic level were made on site using Hass & Parrish (2002) and were later verified by experts using foot type, measurements and photographs. Across the program, volunteers were able to identify carcasses correctly to the level of species and family 85% and 92% of the time respectively (present study).

BCBBS

BCBBS surveyors conducted monthly surveys on approximately the same day of the month (1986–1997) or in the last week of

TABLE 1
Summary of seabird strandings in the Salish Sea where probable cause of death was entanglement in net fisheries gear[a]

Event	General location	Date	Reported carcass count	Count quality[b]	Diagnosis method[c]	Source
1	Birch Bay	1 Nov 1969	Hundreds	Medium	4	Wahl 1969
2[d]	East Boundary Bay	16 Aug 1978	Unspecified	Low	4	Wilson *et al.* 1995
3[d]	Sooke	11 Aug 1982	>70	Medium	2	Wilson *et al.* 1995
4	North Boundary Bay	4 Aug 1983	>40	Medium	4	Wilson *et al.* 1995
5	Sooke	11 Sep 1983	12	High	2	Wilson *et al.* 1995
6[d]	Sooke	8 Oct 1990	Estimated 500	Medium	3	Wilson *et al.* 1995
7	East Boundary Bay	15 Aug 1992	200 murres, few rhinos	Low	2	Wilson *et al.* 1995, Kaiser 1993
8	North Boundary Bay	17 Aug 1993	250	High	3	CWS unpubl. data
9	North Boundary Bay	18 Aug 1993	321	High	4	CWS unpubl. data
10	Iona Island	20 Aug 1993	50–100	Medium	4	CWS unpubl. data
11	Wreck Beach	20 Aug 1993	50–100	Medium	4	CWS unpubl. data
12	East Boundary Bay	22 Aug 1993	100–200	Medium	4	CWS unpubl. data
13	North Boundary Bay	23 Aug 1993	128	High	4	CWS unpubl. data
14	North Boundary Bay	25 Aug 1993	79	High	4	CWS unpubl. data
15	East Boundary Bay	5 Sep 1993	50–100	Medium	4	Kaiser 1993
16	Nanaimo	25 Oct 1994	1	High	2	Wilson *et al.* 1995
17	North Boundary Bay	18 Aug 2003	6	High	1	CWS unpubl. data
18	North Boundary Bay	19 Aug 2003	10	High	1	CWS unpubl. data
19	North Boundary Bay	19 Aug 2003	8	High	4	CWS unpubl. data
20	North Boundary Bay	22 Aug 2003	9	High	4	CWS unpubl. data
21	North Boundary Bay	26 Aug 2003	20	High	4	CWS unpubl. data
22	North Boundary Bay	26 Aug 2003	2	High	4	CWS unpubl. data
23	North Boundary Bay	27 Aug 2003	2	High	4	CWS unpubl. data
24	North Boundary Bay	28 Aug 2003	10	High	4	CWS unpubl. data
25	North Boundary Bay	2 Sep 2005	70	High	2	CWS unpubl. data
26	North Port Madison Bay	2006	46	High	4	Dunagan 2007b, G. Shirato WDFW unpubl. report
27	North Port Madison Bay	22 Oct 2007	105	High	4	G. Shirato WDFW unpubl. report
28	North Port Madison Bay	23 Oct 2007	87	High	2[e]	National Wildlife Health Center 2008, G. Shirato WDFW unpub. report
29	North Port Madison Bay	28 Oct 2007	16	High	4	G. Shirato WDFW unpub. report
30[d]	Central Puget Sound	30 Oct 2007	100	Medium	2[e]	Dunagan 2007a, G. Shirato WDFW pers. com.
31	North East Bainbridge Island	29 Oct 2007	12	High	4	G. Shirato WDFW unpub. report
32	North Port Madison Bay	29 Oct 2007	16	High	4	G. Shirato WDFW unpub. report

[a] Rows describe single events, defined by the day when and beach where carcasses were encountered.
[b] How the size of a stranding event was assessed: direct count of carcasses (High); carcass count estimated as one number or a range (Medium); only nonnumeric data available (e.g. "birds found") (Low).
[c] Basis for diagnosing fisheries as probable cause of death: (1) necropsy results indicated drowning; external examination showed contusions or broken bones or both; (2) necropsy results indicated drowning; external examination showed no contusions or broken bones; or no external examination made; (3) external examination showed contusions or broken bones, or both; no necropsy; (4) no necropsy or external examination, but active fishery known in the area or site had a history of strandings. Not all carcasses in one event were subject to necropsies.
[d] Birds found on the water.
[e] Drowning suspected, but no definite diagnosis.
CWS = Canadian Wildlife Service; WDFW = Washington Department of Fish and Wildlife.

each month (2002–2005) following a tested protocol (Ainley *et al.* 1980). One or two observers conducted direct outward- and return-leg routes above and along the wrack line. Many observers were experienced naturalists and familiar with coastal and pelagic bird species, and all observers were equipped with beached bird identification guides [Ainley *et al.* (1980) during 1986–1997; Hass & Parrish (2002) during 2002–2005]. Identification was made to the lowest taxonomic level possible, and carcasses were generally marked with unique tags or removed from the beach. Measurements were not taken, but during 1986–1997 only, many carcasses were collected, frozen and sent to program managers for identification (Burger 1993, Stephen & Burger 1994).

Gillnet fisheries and salvaged birds

Commercial gillnet fishing gear consists of mono- or poly-filament nylon webbing. Nets have a maximum length of 550 m in Washington State (with the exception of one small bay where maximum net length is 180 m) and are either 375 m or 550 m long in British Columbia, depending on the fishery management unit (DFO 1993, WDFW 2008). One end is attached to the vessel (length usually less than 15 m); the other is supported by a buoy, extending the net in a straight line (Pierce *et al.* 1994, Smith & Morgan 2005). In both countries, nets must be attended at all times, and soak time (length of time nets are in the water) is generally around two hours (Pierce *et al.* 1994, Smith & Morgan 2005, WDFW 2008).

The Washington State and British Columbia gillnet fisheries are open to any license holder, and the number of participating vessels is unrestricted. Fisheries openings occur on discrete days and typically last between 12 and 24 hours. The fishing schedule (dates and times of openings) depends on preseason forecasts of fish returns and is agreed upon by tribal, state and federal agencies in an extensive and complex rule-making process (e.g. North of Falcon public meetings; http://wdfw.wa.gov/factshts/harvest.htm). However, openings may be adjusted based on in-season estimates of fish returns. In addition, Fraser River Sockeye and Pink Salmon fisheries management takes into account regulatory advice and recommendations from the Pacific Salmon Commission charged with implementing the Pacific Salmon Treaty, an international agreement between the United States and Canada. In Washington State, the WDFW manages non-tribal fisheries. Each Washington tribe manages its own tribe's fisheries and coordinates management and planning at the local, regional and national levels by participating in the Northwest Indian Fisheries Commission. In British Columbia, the federal Department of Fisheries and Oceans (DFO) is responsible for managing all commercial fisheries.

In Washington, entangled seabirds were recorded and salvaged by observers in the non-tribal commercial Sockeye and Pink (eastern Strait of Juan de Fuca, July–September) and Chum (Puget Sound, October–November) gillnet fleet from 1993 to 1996, as part of bycatch observer programs directed by WDFW (Erstad *et al.* 1994, Pierce *et al.* 1994, Pierce *et al.* 1996, Erstad *et al.* 1996a) and during research specific to seabird bycatch mitigation (Melvin 1995; Melvin & Conquest 1996; Melvin *et al.* 1997, 1999). In British Columbia, observer data on seabird entanglements were collected in the Chum test gillnet fisheries (north shore of the western Strait of Juan de Fuca, September–October) between 1995 and 2001 (Smith & Morgan 2005). In most cases, observers had received expert training in seabird identification. In addition, birds were salvaged from nets and species identification was confirmed during necropsies. We used these direct observations of birds salvaged from nets for comparisons of species composition. A total of 2348 and 1051 gillnet sets were respectively observed in the non-tribal Sockeye/Pink and Chum fisheries in Washington, and 5425 sets were observed in the British Columbia Chum fishery.

Data analysis

Because birds could have washed up on shore as a result of one or more sequential interactions with fisheries, and because we had no information on the timing or location of these interactions, we categorized FAS in discrete events, which we defined at the daily level and by the location. For instance, bird carcasses encountered daily on a single beach over a period of three consecutive days would count as three individual events.

Carcass encounter rate

For both baseline and FAS data, we defined carcass encounter rate (r_{smy}) as the average number of dead beached birds detected at a survey site (s) in a given month (m) and year (y), standardized for survey distance:

$$r_{smy} = \frac{\sum_{1}^{n} \beta_{smy}}{l_s n_{smy}} \qquad (1)$$

where β_{smy} is the sum of bird carcasses detected on each survey at site s in month m in year y, l_s is the distance surveyed in kilometers and n is the number of replicate surveys conducted during the month. To ensure that baseline carcass encounter rates reflected recent mortalities, birds marked the previous month were not included in the numerator. However, birds marked and re-encountered within the same month were included in the numerator, a situation only possible for a site with more than one replicate survey in a month. When survey distance was missing for FAS observations, we estimated shoreline distance on a satellite image using the measuring tool in Google Earth (Google, Mountain View, CA, USA). If start and end locations of the search were not well defined (n = 12 FAS events), we conservatively included the entire length of the beach where the search was conducted. When precise counts were not available and data were reported as a range (e.g. 50–100), we chose the minimum number as the numerator. If data were reported as "hundreds," we used 200 to represent the count. If FAS event size was reported as "a few," we used two, and if unspecified, we used one. Overall, this approach would tend to underestimate mortality during FAS events.

We summarized carcass encounter rates for each program using both an arithmetic mean (i.e. mean of carcass encounter rates associated with each site–month–year sample over all survey sites and years) and a pooled encounter rate (i.e. sum of the average carcass count detected each month at each survey site divided by the sum of the monthly distance surveyed at each site). The pooled encounter rate takes into account the fact that the distance surveyed varied (0.1–6 km, Table 2), and thus longer survey sites contributed more to the mean than did shorter survey sites. To compare carcass encounter rates between the baseline data and FAS data, we filtered the baseline data as follows: We constrained the baseline data to only the fishing season (July–December). Because the nature of the FAS bird mortality data means that zero-bird events were not possible, we selected only those baseline survey site–month–year samples with carcass encounter rates greater than zero. We explored the effect of survey distance on baseline carcass encounter rates because even a single bird found on a short beach can inflate carcass encounter rates standardized to a kilometer. To determine the effect of survey distance, we plotted carcass encounter rates resulting from each survey site–month–year sample as a function of survey distance and visually determined the intersection point at which an ensemble of carcass encounter rates of small survey sites was greater than that of the majority of long survey sites. We created two subsets of data, one with all samples (n = 947), and another in which we removed the samples for which small survey sites had high carcass encounter rates (i.e. sites of 0.75 km or less in length, with more than three birds per kilometer; n = 931). We observed no significant difference in mean carcass encounter rates between those treatments ($t = 1.01$, df = 1876, $P = 0.31$). Therefore, for the analyses presented here, we used all data, regardless of survey distance.

Baseline beached birds reflect the local at-sea avifauna and also integrate across all sources of mortality—that is, natural and anthropogenic. In the Salish Sea, beached carcass patterns may signal the seasonal shift in bird abundance (from a breeding to an overwintering and migrating community), all else being equal. We used generalized linear models (GLMs) to determine whether temporal differences were evident in baseline carcass encounter rates. Baseline data contained a large number of survey site–month–year samples with zero counts. That situation led to excessive overdispersion, which we remedied with the use of a negative binomial model (Crawley 2007). We used a negative binomial error distribution with year, month and program as factor covariates, and we report the main effect as significant relative to all other months, years and program if the absolute value of the coefficient divided by its sandwich standard error is greater than 1.96 (i.e. the standard *Z*-test; Zar 1999, Diggle *et al.* 2002).

We fit the following full model:

$$\log(\mu_i) = \alpha + \beta 1(Yi) + \beta 2(Mi) + \beta 3(Pi) + offset[\log(Li)], \quad (2)$$

where $\log(\mu i)$ is the log of the mean encounter rate in the *i*th survey site–month–year; α is the intercept; *Yi*, *Mi*, *Pi* are the year, month and program of the *i*th survey site–month–year, and β1, β2 and β3 are their respective coefficients; and *Li* is the distance surveyed for the *i*th survey. We included an offset term to account for differences in survey effort as indexed by survey distance (Crawley 2007). Our candidate model set included all models nested within the full model, and we used the Akaike information criterion (AICc) to select the most parsimonious model from which the coefficients were extracted (Burnham & Anderson 2002). We used the "glm.nb" function available in the MASS library in program R (R Development Core Team 2008).

TABLE 2
Summary statistics[a] for survey effort (mean ± standard deviation) and carcasses during beached bird surveys in British Columbia (BCBBS), 1990–1997 and 2002–2007, and Washington State (COASST), 2000–2007

Programs	Survey sites per year	Surveys per year	Surveys per site	Distance surveyed per site (km)	Total distance surveyed[b] (km)	Total carcasses[c]	Surveys with carcasses	Encounter rate[d] [birds/km (confidence limits)]
BCBBS								
All months	21.1±12.1 Range: 1–41	130.6±77.9 Range: 1–225	23.4±20.7 Range: 1–112	2.3±1.6 Range: 0.2–10	4024	1025 Refinds: 23	0.20 n=396	1.03 (0.86, 1.20) n=377 Pooled: 0.91
Fisheries months	18.0±11.0 Range: 1–34	65.9±43 Range: 1–119	12.1±10.5 Range: 1–56	2.3±1.6 Range: 0.2–10	2067	633 Refinds: 13	0.25 n=228	1.09 (0.83, 1.35) n=215 Pooled: 1.03
COASST								
All months	77.6±49.4 Range: 5–138	757.6±502.5 Range: 10–1409	33.1±37.8 Range: 1–292	1.3±0.9 Range: 0.1–6	8381	968 Refinds: 117	0.10 n=709	0.89 (0.79, 0.99) n=570 Pooled: 0.62
Fisheries months	64.9±44.0 Range: 5–128	389.8±230.3 Range: 10–663	18.0±19.7 Range: 1–147	1.3±0.9 Range: 0.1–5	4282	641 Refinds: 73	0.14 n=433	0.95 (0.80, 1.10) n=344 Pooled: 0.91
Fisheries-associated strandings[e]	2.5±2.0 Range: 1–6	3.4±3.2 Range: 1–8	1.5±0.8	4.1±2.9 Range: 0.3–10	97	1916	1.00	16.4 (11.2, 21.7) n=21 Pooled: 16.4

[a] Data summarized over all months of the year and for months (July to December) when gillnet fisheries operate. Statistics on fisheries-associated strandings listed last for comparison.
[b] For all surveys and all years.
[c] Carcasses found over all surveys and all years, including refound birds.
[d] Mean rate as calculated for beaches with >0 birds found. Sample size and lower and upper confidence limits provided. Pooled encounter rate also shown.
[e] Beached carcasses only.

Species composition

To examine species composition between FAS, baseline beached birds and birds salvaged from nets during fisheries observer programs, we pooled years and calculated the count of each species within each data type. To reduce the number of species categories and to highlight abundant species, we combined the less numerically abundant species into taxonomic groups (e.g. Common Loons *Gavia immer* and Pacific Loons *Gavia pacifica* were assigned to "Loons"). Species found in the baseline or salvage programs, but not represented in FAS data, were placed in the category "Other." Unidentified birds were assigned to "Unknown." To assess how the distribution of species–group counts varied between programs, we applied a GLM framework to three subsets of data, each of which contained a different combination of programs:

- FAS and bycatch,
- bycatch and baseline, and
- baseline and FAS.

We used GLMs with Poisson-distributed errors to fit the full models (species group and data type as main effects, and their interaction). To assess similarity between distributions, we compared the deviance [obtained from analysis of variance (ANOVA)] explained by the addition of the interaction term in each of the three models. For instance, a pair of programs with a smaller deviance was more closely matched than a pair with a larger deviance. As with the negative binomial GLM described earlier, statistical modeling of species composition was done in program R.

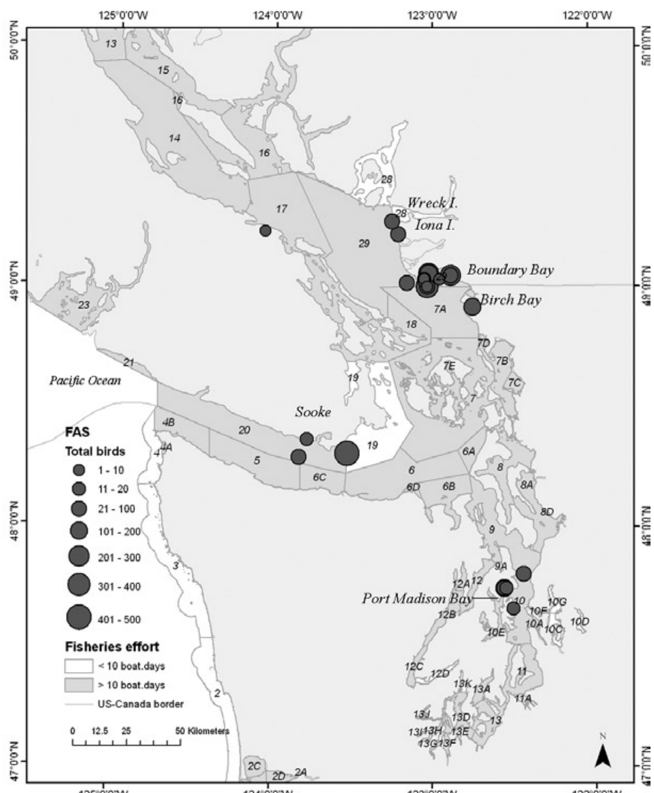

Fig. 2. Location of Salish Sea fisheries-associated strandings (FAS) and fisheries management units in British Columbia and Washington State. Filled circles representing FAS events (n = 32) are scaled to the number of bird carcasses counted and or estimated. Management units in which the annual average fishing effort (1970–2005) was greater than 10 boat–days are shaded in gray and identified by number–letter code.

Gillnet fisheries effort

In British Columbia, all fish sales must be reported to DFO via "fish slips," which include the number of days of fishing ("days fished") in a given fishery management unit. Data from 1965 to 2006 were available from the DFO database PACHARV3 (L. Biagini, DFO, pers. comm.). We used the annual sum of days fished as our proxy of fishing effort in the Strait of Georgia and the Strait of Juan de Fuca in British Columbia (management units 13–21 and 28–29; Fig. 2). In Washington State, any commercial transaction of fish must be reported to WDFW via "fish receiving tickets." Only fishery management unit, not days fished, were available from the tickets. We therefore used the number of transactions of fish as a proxy for fishing effort and assumed one transaction per boat per day. We summarized fishing effort for Puget Sound and the Strait of Juan de Fuca (all contiguous units between 4b and 6a in the Strait of Juan de Fuca and all units south of and including unit 7a; Fig. 2). A complete dataset was available from WDFW for the period 1977 to 2005 (L. Hoines, WDFW, pers. comm.). We used a linear regression model to describe the interannual trends of fishing effort.

Ocean conditions

In the Pacific Northwest, the timing and strength of upwelling is a major driver of productivity at all levels of the food web (Bakun 1996). For seabirds, in particular, anomalous ocean conditions may result in breeding failure and low survival (Hodder & Graybill 1985, Bayer *et al.* 1991, Wilson 1991) or in changes in migration timing and local population abundance, or both. We examined the correlation between ocean conditions and the annual pattern of beached birds for both FAS and baseline data. Spring transition refers to the shift from persistent downwelling to persistent upwelling in the California Current, and delayed transitions have been associated with delayed primary and secondary production, lower fish survival and late onset of breeding of seabirds (Logerwell *et al.* 2003, Peterson *et al.* 2006, Sydeman *et al.* 2006). Spring transition dates, which are derived from the daily upwelling indices averaged from 42 degrees to 48 degrees north and from sea level measured at Neah Bay (48°22.1′N, 124°37.0′W) were obtained from http://www.cbr.washington.edu/data/trans_data.html (with permission from L. Logerwell). In addition, the strength of spring upwelling was indexed by the sum of daily index values from March through June measured at 48 degrees north and 125 degrees west (http://las.pfeg.noaa.gov/las6_5/servlets/dataset?catitem=1626; Schwing *et al.* 2006). For both indices, we computed the anomalies (annual value – annual average from 1969 to 2007) and correlations with baseline encounter rates and number of fisheries-associated beached carcasses (Pearson correlation coefficients, *r*).

Mortality impacts of FAS

To assess the relative importance of fisheries mortality, we calculated the cumulative magnitude of beached carcasses from all mortality sources. Specifically, we summed the program-specific mean monthly baseline encounter rates (averaged over all years) and extrapolated the annual rates over the length of shoreline on which carcass deposition was possible in the Salish Sea. We thus estimated the number of carcasses encountered per year had all beaches been surveyed (cf. Wiese & Robertson 2004). Shoreline suitable for carcass deposition was determined from shoreline inventories in Washington State and British Columbia (Nearshore Habitat Program 2001) and included segments classified as rock, gravel, sand or mud of any width, but with slopes less than 20 degrees. Finally, we multiplied the Salish Sea annual carcass count by the number of years (39) since the first FAS record to give the cumulative beached carcasses. To bracket our estimates, we used the minimum and maximum of mean monthly encounter rates each multiplied by 12, as the lower and upper limits of annual rates. To ensure that cumulative beached carcasses represented a minimum of acute fisheries-related mortality, we removed those baseline surveys within 20 km and in the same month as known FAS. Finally, we assumed that deposition, persistence and detection probabilities were the same across all mortality factors.

To determine whether net fisheries mortality is a conservation concern, we focused on the species with the highest FAS. We converted the fraction of beached birds associated with fisheries bycatch into mortality rates under three scenarios of fisheries mortality:

- *low* fisheries mortality, in which the annual mortality as a result of fisheries was the annual mean of FAS over all 39 years;
- *average* fisheries mortality, in which the annual mortality as a result of fisheries was the mean of years in which at least one FAS was reported; and
- *high* fisheries mortality, in which the annual mortality as a result of fisheries was the highest FAS ever reported in a year.

We also considered whether fisheries mortality was compensatory (i.e. the reduction of population size is accompanied by an increase in natural survival such that the annual survival rate remains relatively stable; Boyce *et al.* 1999) or additive (no density-dependent response to mortality, and thus fisheries takes are additional to all other sources of mortality; Boland & Litvaitis 2008). First, we calculated the proportion of mortality resulting from fisheries in each scenario (*Fi*), and then the mortality rate resulting from fisheries under the assumptions of compensatory ($f_{compensatory}$) and additive ($f_{additive}$) mortality, as follows:

$$F_i = \frac{FAS_i}{B+FAS_i} \tag{3}$$

$$f_{i,\,compensatory} = F_i \times m \times 100 \tag{4}$$

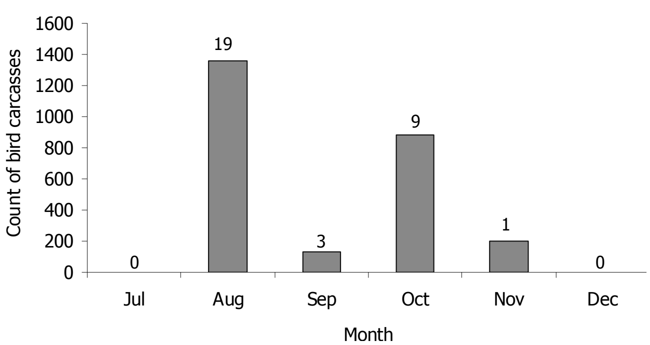

Fig. 3. Total monthly fisheries-associated strandings counted or estimated from 1969–2007. The number of events is shown over each bar.

$$f_{i,\,additive} = \frac{F_i \times m}{1-F_i} \times 100 \tag{5}$$

where *FASi* is the total annual FAS under scenario *i* (low, average, high), *B* is the number of baseline carcasses encountered per year in the Salish Sea on average (estimated by extrapolating the mean annual baseline encounter rate over the entire coastline as described above) and *m* is the species' annual mortality rate, taken from the literature. We multiplied by 100 to present results as percentages.

RESULTS

Fisheries-associated stranding patterns

We compiled records from water or on land of 32 FAS events in 12 separate years between 1969 and 2007 (Table 1). Approximately 2576 carcasses were found, either on beaches or floating in the water. Average event size was 80.5 ± 110 [standard deviation (SD)] birds (1–500 birds). Carcasses were specifically enumerated in 21 events (69%). In only two events did necropsies diagnose drowning specific to nets. In eight other events, necropsies indicated drowning, but did not specify the cause. Reports stated that birds collected from two events showed signs of struggle, presumably in net gear, but lack of necropsies prevented a clinical diagnosis of drowning. No necropsies were available for the remaining 20 events. In those cases, reports indicated that mortality in fisheries gear was inferred from circumstances—that is, any one or a combination of net fisheries being active in close proximity, or a history of fisheries-related marine bird die-offs at that time of year at that site, or carcasses being recorded on consecutive days (Table 1). The large proportion of events lacking confirmation of cause of death (Table 1) was an artifact stemming, in part, from follow-up searches on consecutive days being considered to be separate events, whereas birds were mostly collected for necropsies on the first day only.

Fisheries-associated strandings were principally reported from three general areas in the Salish Sea: southeastern Strait of Georgia (Boundary Bay, Birch Bay, Wreck Beach, Iona Island; 21 events and 86% of reported birds); the north shore of the Strait of Juan de Fuca in the vicinity of Sooke (three events or 6% of reported birds); and in Port Madison Bay in central Puget Sound (seven events and 9% of reported birds; Fig. 2, Table 1). The number of events and total number of birds summed across all years was

TABLE 3
Selection scores of the top four models of baseline carcass encounter rate[a]

Model[b]	K	AICc	ΔAICc
$\alpha + \beta1(Yi) + \beta2(Mi) + \beta3(Pi) + offset[\log(Li)]$	**28**	**6989**	**0**
$\alpha + \beta1(Yi) + \beta2(Mi) + offset[\log(Li)]$	27	6990	1
$\alpha + \beta2(Mi) + \beta3(Pi) + offset[\log(Li)]$	13	7070	81
$\alpha + \beta1(Yi) + \beta3(Pi) + offset[\log(Li)]$	17	7098	99

[a] Number of parameters (K), corrected Akaike information criterion (AICc) and difference in AICc between the given model and the best model (ΔAICc). Full model scores shown in bold type.

[b] α is the intercept; *Yi*, *Mi*, *Pi* are year, month and program of the *i*th survey (site–month–year), and β1, β2 and β3 are their respective coefficients; *Li* is distance surveyed on the *i*th survey.

greatest in August (53% of encountered carcasses and 59% of events), followed by October (34% carcasses and 28% of events; Fig. 3). No FAS were reported in July or December, the first and last months of commercial gillnet fishing and the months with the lowest fishing effort.

Baseline survey patterns

More than 12 000 km of coastline were surveyed across all months, years and beached bird programs, resulting in approximately 2000 detected carcasses. Only 7% of carcasses were found again within the month (Table 2). Approximately 100 sites were monitored during an average of 900 surveys per year for both programs pooled. However, relative to the BCBBS, COASST covered approximately four times more survey sites and conducted approximately six times more surveys per year (Table 2; Fig. 1). Differences between programs can be partly explained because BCBBS surveys were focused from fall to spring between 2002 and 2007. Because the programs progressively added or removed survey sites over the years, considerable variation occurred in the number of sites surveyed annually and the number of surveys conducted per site (Table 2). Survey distance varied from 0.1 km to 10 km, with an overall mean of 1.9 ± 1.4 km (SD). When restricting the baseline survey effort to the fishing season only (July–December), metrics of survey effort and number of carcasses decreased by about half (Table 2).

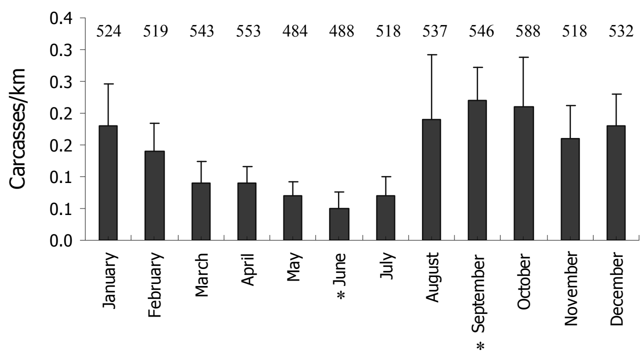

Fig. 4. Mean carcass encounter rate of baseline data, per month, with sample sizes (site–month–year) indicated over the bars. Error bars show the 95% confidence intervals. June was significantly lower than all other months, and September was significantly higher than all other months except August ($P < 0.05$; denoted by asterisks). See Table 4 for pairwise comparisons of months.

Carcass encounter rate

Despite the apparent elevation in carcass encounter rate in the baseline data from BCBBS as compared with that from COASST, we observed no significant effect of program on encounter rates in the full model ($\beta_3 = -0.19$; 95% confidence interval [CI]: 1.12 to 0.75; $Z = -1.55$; $P = 0.06$; Table 2). This result is echoed by the synonymy between the full model, including year, month and program terms, and a slightly more parsimonious model without the program term (Table 3). We therefore pooled program data when comparing against FAS.

Bird carcasses were detected in all months during baseline surveys (Fig. 4). Encounter rates were significantly higher in all months from August to January relative to all months from March to July, with the highest encounter rates in September and the lowest, in June (Fig. 4, Table 4), potentially reflecting the increase in size of the autumn migrating and overwintering marine bird community in the Salish Sea. Of 6350 survey site–month–year samples pooled from both beached bird programs, a preponderance (85%) reported zero birds (Table 2). The mean carcass encounter rate over all survey sites, months and years was 0.14 carcasses/km (95% CI: 0.12 to 0.15; n = 6350; pooled encounter rate: 0.16 birds/km).

Restricting baseline samples to surveys in which at least one bird was detected and to fisheries months only, we found that the carcass encounter rate increased by a factor of almost seven to 1.00 carcass/km (95% CI: 0.87 to 1.14; n = 559). By contrast, the mean carcass encounter rate of FAS was nearly 17 times greater (Table 2). More than 75% of filtered baseline samples had encounter rates of less than 1 carcass/km; the minimum FAS encounter rate was

TABLE 4
Difference in mean encounter rates (± standard error) between months, derived from the exponentiation of model coefficients (i.e. e^{β_2}; see equation 2)[a]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Feb	0.9±1.2										
Mar	**0.5±1.2**	0.6±1.0									
Apr	**0.6±1.2**	**0.6±1.0**	1.1±1.0								
May	**0.5±1.2**	**0.6±1.0**	1.0±1.0	0.9±1.0							
Jun	**0.3±1.3**	**0.3±1.0**	**0.6±1.1**	**0.5±1.0**	**0.6±1.1**						
Jul	**0.5±1.2**	**0.6±1.0**	0.9±1.0	0.9±1.0	0.9±1.0	**1.6±1.0**					
Aug	1.2±1.2	1.3±1.0	**2.2±1.1**	**2.0±1.0**	**2.2±1.0**	**3.8±1.1**	**2.3±1.0**				
Sep	**1.5±1.2**	**1.6±1.0**	**2.7±1.0**	**2.5±1.0**	**2.8±1.0**	**4.8±1.0**	**3.0±1.0**	1.3±1.0			
Oct	1.4±1.3	1.6±1.1	**2.7±1.1**	**2.5±1.1**	**2.7±1.1**	**4.7±1.1**	**2.9±1.1**	1.2±1.1	1.0±1.1		
Nov	1.0±1.2	1.1±1.0	**1.9±1.0**	**1.8±1.0**	**2.0±1.0**	**3.4±1.1**	**2.1±1.0**	0.9±1.1	0.7±1.0	0.7±1.1	
Dec	1.1±1.2	1.2±1.0	**2.1±1.0**	**1.9±1.0**	**2.1±1.0**	**3.7±1.0**	**2.3±1.0**	1.0±1.0	0.8±1.0	0.8±1.1	1.1±1.0

[a] Reference months in top row (e.g. encounter rates in September averaged 1.5 times those in January). Statistically significant values ($P < 0.05$) shown in bold type.

1.1 carcasses/km (Fig. 5). To remove the possible influence of known fisheries-associated mortality on baseline carcass encounter rates, we further filtered the baseline dataset by excluding any survey conducted in the same month and within 20 km of a FAS event. As a result, seven baseline samples were excluded, and the overall encounter rate decreased to 0.92 carcasses/km (95% CI: 0.84 to 1.00; n = 552), suggesting that beached bird monitoring captures a fisheries signal.

Annual trends

Despite minimal and noisy data, the magnitude of FAS events appeared to track fisheries effort (Fig. 6). Over the decades in which FAS were reported, fisheries effort declined significantly in British Columbia (linear regression 1965–2006: $B_1 = -0.89$, $r^2 = 0.79$, $P < 0.001$) and in Washington State (1977–2005: $B_1 = -0.95$, $r^2 = 0.90$, $P < 0.001$; Fig. 6). Between the 1970s and the 2000s, annualized boat–days dropped to one tenth in both jurisdictions. Before 1999, the year in which bycatch mitigation measures went into effect in the non-tribal Sockeye and Pink Salmon fishery in Washington, mean carcass encounter rates for FAS were twice those for FAS reported subsequently (22 ± 14 carcasses/km [SD] compared with 11 ± 7 carcasses/km [SD] respectively; n = 11 samples in each treatment, $t = 2.5$, df = 20, $P = 0.02$). Baseline data were not available before 1990, but even so, long-term trends were apparent in the baseline dataset as well. Baseline encounter rates in the 1990s were almost twice those in 2007, and the differences in all pairwise comparisons between years from 1991 to 1994 with years from 2002 to 2007 were significant, with 1993 having significantly higher encounter rates than any other year (Fig. 7, Table 5). The same pattern held when restricting the data to BCBBS samples only: 0.24 carcasses/km in the 1990s (95% CI: 0.09 to 0.39; n = 103) compared with 0.14 carcasses/km in the 2000s (95% CI: 0.06 to 0.22; n = 155). We observed no significant difference between programs after 2001, when data from both COASST and BCBBS were available ($\beta program = -0.12$; 95% CI: 0.87 to 1.12; $Z = -1.03$; $P = 0.15$). Therefore, the decadal difference is unlikely to be a program effect.

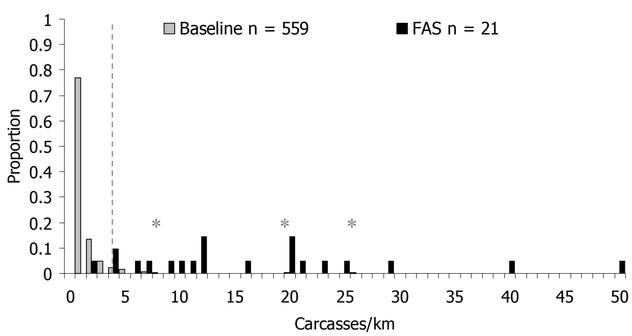

Fig. 5. Frequency distribution of site–month–year samples as a function of beached bird carcass encounter rate (binned in increments of one carcass per kilometer) for baseline and fisheries-associated strandings (FAS). Baseline rates based on filtered data [i.e. surveys conducted between July and December (fisheries months) with at least one bird found in a month]. Sample size (n) is number of survey site–month–year samples used to generate encounter rates. Dotted line indicates the baseline mean plus two standard deviations (four carcasses per kilometer). The three highest baseline encounter rates are denoted by arrows.

Annual trends in carcass encounter rates, in either the FAS or baseline dataset, may also reflect regional oceanographic conditions affecting foraging conditions, reproductive success and timing of post-breeding migration. We observed a negative relationship between the spring transition anomaly and strength of upwelling from 1969 to 2007 (Pearson $r = -0.46$, $P = 0.003$, n = 39; Fig. 8). That is, late spring transitions tended to be associated with years of weaker spring–summer upwelling. FAS coincided with later-than-average spring transition during eight of 12 years (Fig. 8), and the four highest mean annual FAS encounter rates were during

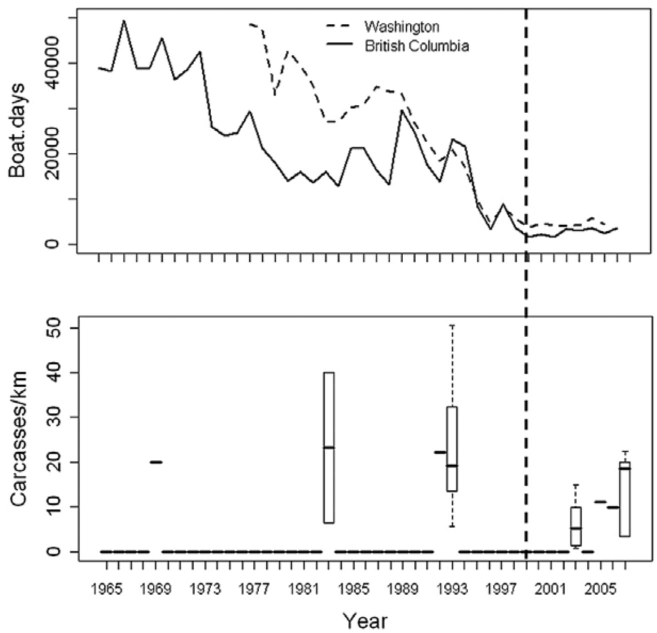

Fig. 6. Top panel: Commercial gillnet fisheries effort for the treaty and non-treaty fleet in Washington State (1977–2005) and British Columbia (1965–2006). Bottom panel: Box plot of Salish Sea annual carcass encounter rate of birds counted or estimated during fisheries-associated strandings events (1969–2007, n = 32). Vertical dotted line denotes the year (1999) when seabird bycatch mitigation rules went into effect in the Sockeye *Oncorhynchus nerka* and Pink Salmon *Oncorhynchus gorbuscha* non-treaty gillnet fishery in Washington State.

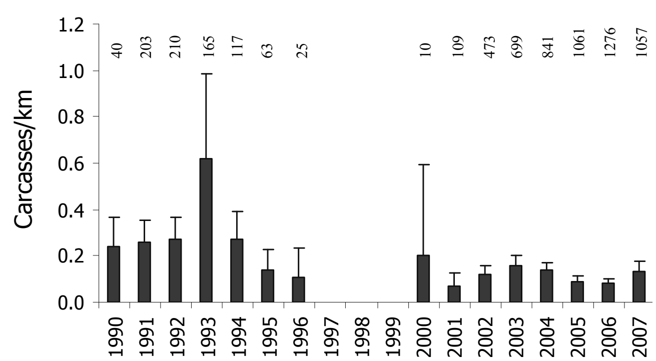

Fig. 7. Mean carcass encounter rate per year in baseline data; sample sizes (units site–month–year) shown above bars. Error bars show 95% confidence intervals. Encounter rate in 1993 (asterisk) was significantly higher than in any other year ($P < 0.05$). No meaningful data in 1997 because of the small sample size (one survey). See Table 5 for pairwise comparisons.

years when the date of spring transition was among the latest 25% (1969, 1983, 1992 and 1993). However, no significant relationship was apparent between spring transition, or upwelling, and the total number of birds encountered during FAS events ($r = 0.34$, $P = 0.28$ and $r = -0.37$, $P = 0.24$ respectively). Furthermore, the relationship between annual baseline encounter rates and both ocean indices was not significant (spring transition: $r = 0.40$, $P = 0.16$; upwelling: $r = 0.002$, $P = 1.00$).

Species composition

The species composition of FAS was similar to that of birds salvaged from nets during fisheries observer/scientific programs (deviance explained by addition of the interaction term 302.5, as compared with 2165.2 in comparisons with baseline program data; Fig. 9). Of the 2576 FAS, 93% were divers, including alcids (Common Murres, Rhinoceros Auklets, Marbled Murrelets, Pigeon Guillemots), loons (Common and Pacific Loons), cormorants (Pelagic Cormorants), grebes (Western Grebes, Red-necked Grebes *Podiceps grisegena,* and scoters; Fig. 9). By contrast, only 44% of the 1274 carcasses found in baseline surveys during fisheries months were divers. The diversity of baseline carcasses was greater, with 93 species or species groups, including marine birds (seabirds, seaducks and shorebirds), raptors, and passerines, compared with 15 species in both the FAS and bycatch samples.

Most of the divers found in both FAS and bycatch samples were Common Murres (0.86 and 0.71 respectively; Fig. 9). By contrast, murres represented only 0.21 of the baseline samples (Fig. 9). Gulls were the most abundant species found in baseline surveys (0.32). No gulls were salvaged from nets, and that group constituted only 0.01 of the FAS total. Excluding the multispecies category "Unknown," Rhinoceros Auklets were the second-most abundant species in the FAS (0.03) and bycatch (0.16) datasets. The proportion of Rhinoceros Auklets in the baseline sample (0.04) was similar to that in the FAS. This species was no more prevalent than was any other baseline diver category (Fig. 9). Only two Marbled Murrelets were found in FAS; eight were documented as birds salvaged from nets, and nine were detected during baseline surveys. The "Other" category—56 taxa, including other seabirds, shorebirds, dabbling ducks, passerines and raptors—was the third largest in the beached bird baseline dataset. Approximately 5%–9% of carcasses across all three datasets were not identified.

Mortality impacts of FAS

We calculated that more than 10 000 marine bird carcasses would have been found per year on the shores of the Salish Sea had volunteers been able to conduct monthly surveys of the entire 6218 km coastline on which carcass deposition was possible (2663 km in British Columbia and 3556 km in Washington State respectively; Table 6). Over the 39 years that FAS were reported (1969–2007), this result scales proportionately to nearly 427 000 carcasses (Table 6). For Common Murres, the single most abundant species in the FAS and bycatch datasets, we estimated that 2298 carcasses would have been encountered in an average year in the Salish Sea, for a cumulative total of nearly 90 000 carcasses between 1969 and 2007 (Table 6).

Given that murres were disproportionately affected by bycatch, we assessed the potential demographic impact of fisheries mortality on adults of this species. To estimate the number of adult murres in the FAS dataset, we applied the age composition of murres salvaged in the Sockeye, Pink and Chum net fisheries during two years (63% adults; Thompson *et al.* 1998). We assumed an adult murre annual mortality of 10%, a rate documented for murres breeding elsewhere in the California Current System (Lee *et al.* 2008). As a result, compensatory fisheries mortality would constitute no more than 2.3%

TABLE 5
Difference in mean encounter rates (± standard error) between years, derived from the exponentiation of model coefficients (i.e. $e^{\cap_1}$; see equation 2)[a]

	1990	1991	1992	1993	1994	1995	1996	2000	2001	2002	2003	2004	2005	2006
1991	1.5±1.1													
1992	1.5±1.1	1.0±1.1												
1993	**3.2±1.2**	**2.1±1.1**	**2.2±1.1**											
1994	1.6±1.1	1.1±1.1	1.1±1.1	**0.5±1.1**										
1995	0.9±1.2	0.6±1.1	0.6±1.1	**0.3±1.2**	0.6±1.1									
1996	0.8±1.5	0.5±1.4	0.5±1.4	**0.2±1.5**	0.5±1.4	0.8±1.5								
2000	0.4±3.1	0.2±3.0	0.2±3.0	**0.1±3.1**	0.2±3.0	0.4±3.2	0.5±3.9							
2001	0.7±1.2	0.5±1.2	0.5±1.2	**0.2±1.2**	**0.4±1.2**	0.8±1.2	0.9±1.5	2.0±3.2						
2002	0.6±1.1	**0.4±1.1**	**0.4±1.1**	**0.2±1.1**	**0.4±1.1**	0.6±1.1	0.8±1.4	1.6±2.9	0.8±1.1					
2003	0.8±1.1	**0.6±1.1**	**0.6±1.1**	**0.3±1.1**	**0.5±1.1**	0.9±1.1	1.1±1.4	2.3±2.9	1.2±1.1	1.4±1.0				
2004	0.8±1.1	**0.5±1.1**	**0.6±1.0**	**0.3±1.1**	**0.5±1.1**	0.9±1.1	1.1±1.4	2.3±2.9	1.2±1.1	1.4±1.0	1.0±1.0			
2005	**0.5±1.1**	**0.3±1.1**	**0.3±1.1**	**0.2±1.1**	**0.3±1.1**	0.6±1.1	0.7±1.4	1.4±2.9	0.7±1.1	0.9±1.0	**0.6±1.0**	**0.6±1.0**		
2006	0.6±1.1	**0.4±1.1**	**0.4±1.1**	**0.2±1.1**	**0.3±1.1**	0.6±1.1	0.7±1.4	1.6±2.9	0.8±1.1	1.0±1.0	**0.7±1.0**	**0.7±1.0**	1.1±1.0	
2007	0.8±1.4	**0.6±1.3**	**0.6±1.3**	**0.3±1.4**	**0.5±1.3**	0.9±1.4	1.1±1.8	2.3±2.8	1.2±1.5	1.4±1.3	1.0±1.3	1.0±1.2	**1.6±1.2**	1.5±1.2

[a] Reference years in top row (e.g. encounter rates in 1993 averaged 2.2 times those in 1992). Statistically significant values ($P < 0.05$) shown in bold type.

of total adult murre mortality (Table 7). If fisheries bycatch were an additive source of mortality, the annual mortality rate would increase by an additional 2.9% at most, for a total of 12.9%; Table 7).

DISCUSSION

Clearly, the number of FAS in the Salish Sea (approximately 2600 between 1969 and 2007) underrepresented bycatch mortality because approximately 3500 birds were estimated caught on average in a single year (1994) in the Washington State non-tribal, Sockeye and Pink Salmon fishery (Pierce & Alexandersdottir unpubl. data in Thompson *et al.* 1998). Of the animals that die at sea, only a portion wash up on shore because offshore flow (Hart *et al.* 2006) and local winds (Flint & Fowler 1998) may carry drifting carcasses away from shore, and carcasses may sink or be scavenged before reaching shore. Once onshore, beached carcasses may not persist long enough to be detected (Wiese & Robertson 2004). For example, drift block recovery rates in the Salish Sea have ranged from 27%–59%, values that integrate persistence on the beach and detection processes (Klinger & Ebbesmeyer 2002, Sauers *et al.* 2004). How seabird recovery rates compare is unknown, but they are presumably lower given that carcasses are subject to decomposition and scavenging. Finally, personal communication with wildlife managers indicated to us that records of FAS events, particularly in the 1980s, may have been lost (L. Leschner, WDFW, pers. comm.). Despite the effects of physical processes and sampling on the probability of encountering beached birds—caveats that apply to both FAS and baseline birds—the FAS encounter rate (17 carcasses/km) was an order of magnitude greater than that of the filtered baseline dataset (1 carcasses/km, calculated over fisheries months and non-zero samples). Thus, FAS events were much more severe than was background mortality at the level of daily surveys, and establishing baseline animal stranding rates is therefore useful for signaling acute mortality events. However, integrating site, season and species-specific differences in deposition rates may further improve the accuracy of FAS and baseline beached birds as indicators of at-sea mortality (Epperly *et al.* 1996, Hart *et al.* 2006, Wiese & Elmslie 2006, Parrish *et al.* 2007).

Mortality impacts of FAS

Although the baseline incidence of beached birds was chronically low (Table 2; Fig. 5), surveys were spread over hundreds of sites collectively, indicative of all regions and beach types in the Salish Sea (Fig. 1). By contrast, FAS events were relatively acute, but their reporting was infrequent (12 years since 1969; Figs. 5 and 6) and simultaneously restricted in space (Fig. 2). Despite the severity of FAS events [e.g. 81 ± 110 carcasses per event (SD); Fig. 5], the cumulative FAS carcass count was smaller by two orders of magnitude than the cumulative number of beached birds that we estimated would have been found in the Salish Sea over these 39 years (Table 6). Thus, the low frequency and limited geographic distribution of FAS events rendered cumulative fisheries-associated

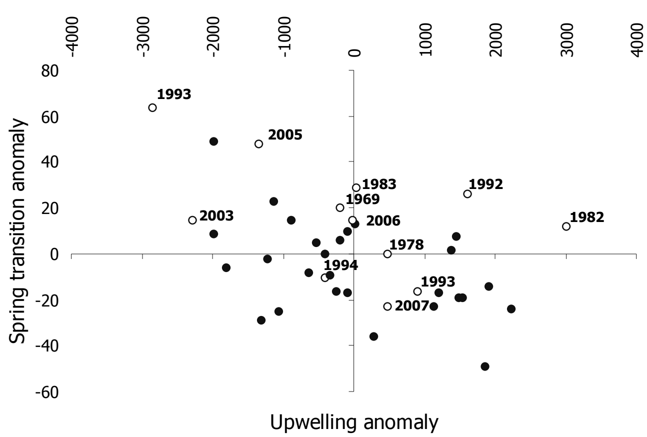

Fig. 8. Relationship between spring transition and upwelling anomalies from 1969 to 2007 (Pearson $r = -0.46$, $P = 0.003$). Years with fisheries-associated strandings (FAS) labeled with open circles.

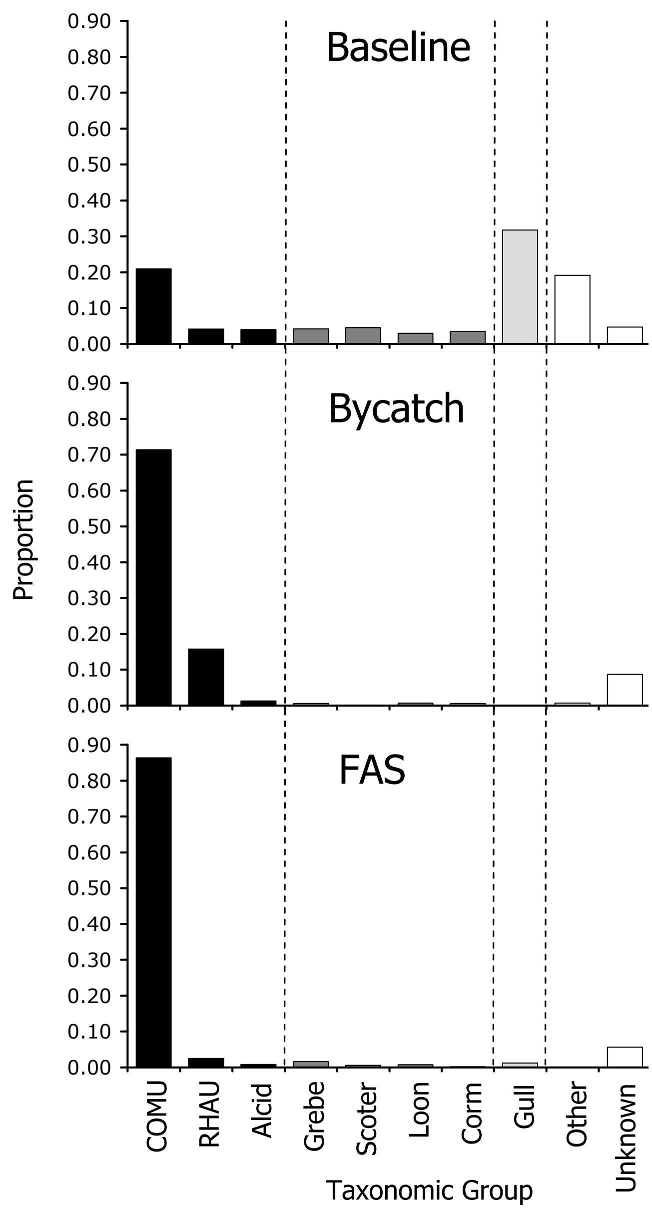

Fig. 9. Taxonomic composition of baseline dataset (top panel), salvaged birds from nets (middle panel) and fisheries-associated strandings (FAS; bottom panel) in the Salish Sea. Proportions calculated using all birds found (including birds found more than once) during fisheries months only (July–December). COMU = Common Murre *Uria aalge*; RHAU = Rhinoceros Auklet *Cerorhinca monocerata*; CORM = cormorant. Dashed lines separate groups by taxonomic family and foraging mode: i.e. divers (alcids: black bars; other divers: dark gray bars) and surface-feeding gulls (light gray bars).

beached carcasses a minor portion of total beached bird carcasses (0.3%–1.7%; Table 6). However, for Common Murres, the species making up the vast majority of the fisheries mortality in both the FAS and the bycatch datasets (Fig. 9), fisheries-associated mortality made up a larger fraction of total baseline mortality (1.3%–6.6%; Table 6).

Murres are susceptible to fisheries throughout their range (Artyukhin & Burkanov 2000, Österblom *et al.* 2002, Žydelis *et al.* 2006, Davoren 2007, Benjamins *et al.* 2008). For a species with low fecundity, delayed maturity and a long life span, such as murres, population status is much more sensitive to a slight elevation in adult mortality than even a large decrease in breeding success (Russell 1999, Lee *et al.* 2008). Elevated mortality may cause population declines. In Central California, where the Common Murre population size was 220 000 birds in the late 1970s, bycatch mortality by a gillnet fleet of 70 boats was estimated at 10% per year for seven years and was linked to a 53% population decline in less than a decade (Salzman 1989, Takekawa *et al.* 1990). However, the impact of bycatch may be less substantial, depending on the population growth rate. For instance, thousands of birds were estimated taken in each of two years in the Newfoundland coastal gillnet fishery for Capelin *Mallotus villosus* (0.4%–1.7% of the local breeding population of 830 000 individuals; Davoren 2007), a value that was not associated with a population decline; rather, it resulted in a stable local population (Wiese *et al.* 2004, Davoren 2007).

TABLE 6
Total beached bird carcasses in the Salish Sea per year, and cumulative total between 1969 and 2007, extrapolated from baseline carcass encounter rates 1990–1997 and 2000–2007[a]

	Baseline carcasses		FAS
	Per year	1969–2007	1969–2007
All marine bird species	10 943 (3 876–20 894)	426 761 (151 159–814 884)	2 576
Common Murres *Uria aalge*	2 298 (814–4 388)	89 620 (31 743–171 126)	2 225

[a] Extrapolated monthly mean totals (minimum and maximum monthly values in parentheses).
FAS = fisheries-associated strandings (included for comparison).

TABLE 7
Mortality of adult Common Murres *Uria aalge* attributable to net fisheries under three scenarios of annual fisheries-associated strandings (FAS)[a]

FAS scenario	Total murre FAS	Adult murre FAS	Proportion of total (equation 3)	Compensatory mortality (equation 4)	Additive mortality (equation 5)
Low	57	36	0.02	0.2%	0.2%
Average	223	140	0.06	0.6%	0.7%
High	945	595	0.23	2.3%	2.9%

[a] Calculations use the mean of annual baseline mortality of adult murres (2022 adults) and assumed an annual mortality rate of 10% (Lee *et al.* 2008). We also assume that 63% of total murre FAS were adults, as found in salvaged murres during two years in the Sockeye *Oncorhynchus nerka,* Pink *Oncorhynchus gorbuscha* and Chum Salmon *Oncorhynchus keta* fisheries (Thompson *et al.* 1998).

In general, demographic models demonstrate that the percentage by which adult mortality increases is matched by a concomitant decrease in population growth rate (Nur & Sydeman 1999, Wiese *et al.* 2004). However, the impact of elevated mortality may not be noticed from population censuses alone because of compensatory mechanisms such as increases in recruitment or increases in annual survival in the remaining population (Boland & Litvaitis 2008, Delord *et al.* 2008, Votier *et al.* 2008). Thus, in some years, the effect of bycatch mortality on population growth of murres in the Salish Sea may be negligible (e.g. the "low" scenario, adding 0.2% mortality; Table 7); in other years, the effect may be more substantial, possibly tipping the balance from a positive to a negative net growth (e.g. the "high" scenario, adding 2.9% mortality; Table 7; Piatt *et al.* 1984; Nur & Sydeman 1999). Ultimately, the effect of fisheries will depend on whether the mortality is being incurred long term, whether density-dependent factors are at play, and whether the population has the capacity to buffer against all sources of anthropogenic and natural mortality.

When considering the impact of fisheries bycatch, it is important to take into account other sources of mortality (Russell 1999, Ainley *et al.* 2002, Votier *et al.* 2005). Off the coasts of Spain and Portugal, Common Murres constituted the largest seabird population, with approximately 20 000 individuals in seven main colonies during the first half of the 20th century. Because of a combination of coastal net fisheries, oil pollution and shooting, with net mortality contributing the largest share of mortality, Common Murres were essentially extirpated from the region in 50 years despite favorable oceanic conditions and prey abundance (Munilla *et al.* 2007).

Murres in the Salish Sea originate primarily from colonies in Oregon and Washington (Manuwal & Carter 2001, Hamel *et al.* 2008), where the combined population fluctuates around 700 000 breeding birds (Carter *et al.* 2001, Parrish *et al.* 2001, Wilson 2003, Naughton *et al.* 2007). West Coast murres are susceptible to oil spills, which have killed tens of thousands of birds (Ford 1991, *Tenyo Maru* Oil Spill Natural Resource Trustees 2000). Chronic oiling, also a factor for murres in the Salish Sea (Burger 1993), can affect seabird populations perhaps even more than acute oil spills (Gandini *et al.* 1994, Wiese *et al.* 2004). Anomalous ocean conditions associated with El Niño episodes or weak spring upwelling can lead to breeding failure and mass mortality of seabirds (Hodder & Graybill 1985, Bayer *et al.* 1991, Wilson 1991, Sydeman *et al.* 2006, Parrish *et al.* 2007). Finally, the direct and indirect effects of predators such as Bald Eagles *Haliaeetus leucocephalus* have caused colony-wide reproductive failure and colony abandonment (Parrish *et al.* 2001, R. Lowe pers. comm., J. Parrish unpubl. data) at some of the largest murre colonies in Washington State—Tatoosh Island, thousands of birds—and Oregon—Three Arch Rocks complex, hundreds of thousands of birds—which may reduce future recruitment to the regional population. In Washington, murre colony counts declined drastically between 1982 and 1983, but were relatively stable at one third of pre-1983 levels throughout the 1990s and early 2000s (Carter *et al.* 2001, Wilson 2003, Warheit & Thompson 2004). In Oregon, population trends were stable throughout the 1980s and 1990s, but total population size decreased by 4% between 1988 and 2004 (Carter *et al.* 2001, Naughton *et al.* 2007). Clearly, Common Murres are vulnerable to a suite of mortality agents operating simultaneously. The impact of fisheries will thus also depend on whether bycatch mortality affects colonies disproportionately, and the source–sink dynamics that govern population trends (Inchausti & Weimerskirch 2002).

Rhinoceros Auklets appeared to be the species second-most susceptible to entanglement, and were the second-ranked group among identified taxa in the cumulative FAS sample (Fig. 9). As with murres, Rhinoceros Auklets are pursuit divers that target dense prey aggregations (Gaston & Dechesne 1996). Unlike murres, this species breeds until late August (Wilson & Manuwal 1986) on Protection Island (approximately 24 000 breeding birds; Wilson 2005) and Smith Island (approximately 2588 birds; Speich & Wahl 1989; Fig. 1). Both islands lie within active gillnet fisheries grounds (Figs. 1 and 2), and thus Rhinoceros Auklets are vulnerable to fisheries during the breeding season. However, their abundance diminishes greatly after the breeding season; they are thought to migrate south to California (Briggs *et al.* 1992). Our baseline data corroborated this inferred natural history. Rhinoceros Auklet strandings occurred only from March to September in the baseline data and were limited in the FAS dataset to August and early September in Boundary Bay. By contrast, fisheries-associated murre strandings were found throughout the Salish Sea from August to October. Therefore, the spatial and temporal exposure to net fisheries of Rhinoceros Auklets breeding in the Salish Sea may be narrower than for murres.

Spatial distribution of FAS

Gillnet fisheries operate throughout the Salish Sea (Fig. 2), yet FAS events were localized. FAS occurred repeatedly in three general areas, namely Boundary Bay, near Sooke on the north shore of San Juan de Fuca, and in Port Madison Bay in Puget Sound. The spatial pattern of carcass deposition is influenced by local winds, currents and tides (Flint & Fowler 1998, Wiese & Ryan 2003, Parrish *et al.* 2007). Marine bird carcasses can stay afloat for a week (Wiese 2003), during which time they may get carried away from the mortality source by currents and winds (Engie & Klinger 2007). In the Salish Sea, drift card deployment and particle models showed that floating material can be carried more than tens of kilometers within a few days from release (Hlady & Burger 1993, Klinger & Ebbesmeyer 2002, Engie & Klinger 2007). Therefore, tying FAS to a particular fishery opening or fishery sector ranges from difficult to impossible with only beached bird data at hand.

Fishing effort and regulations

Fisheries-associated strandings in the Salish Sea have declined since 1969, perhaps as a result of decreased fishing effort or implementation of bycatch mitigation rules in Washington State in 1999—or both (Fig. 6). For example, the introduction of fishing regulations in the eastern US gillnet fishery for Spiny Dogfish *Squalus acanthias* resulted in both decreased fishing effort and decreased Bottlenose Dolphin *Tursiops truncatus* stranding (Byrd *et al.* 2008). The same study showed that bycatch estimates were positively correlated with stranding rates. In the Salish Sea, "seabird strips"—white nylon substituted for monofilament mesh in the upper 20 meshes of a gillnet—coupled with fishing that avoids sunrise, have been mandatory in the non-tribal sector of the US Sockeye and Pink Salmon fisheries in the eastern Strait of Juan de Fuca since 1999 (WAC 220-47-302 and 220-47-410; Harrison 2001). However, the non-tribal gillnet sector of the Sockeye and Pink fisheries represents only 10% of the combined landings from the Washington State, British Columbia and tribal Sockeye and Pink Salmon gillnet fisheries (Harrison 2001). Thus, the decrease in fishing effort over time is more likely to have resulted in a change in fisheries strandings than has the introduction of bycatch reduction measures.

Ocean conditions

Despite the fact that net fisheries have operated every year in the Salish Sea for several decades (Shepard & Argue 2005; Fig. 6), FAS were reported for only 12 years (Table 1), supporting our claim that fisheries stranding patterns are not entirely predictable from fishing effort alone. It appeared that fisheries mortality may have been related to late spring transition (Fig. 8). We hypothesized that large-scale ocean-climate phenomena may alter fisheries effects through a change in migration timing, such that during poor years, failed breeders may enter the Salish Sea earlier, putting a larger number of birds at risk of bycatch during the Sockeye and Pink Salmon fisheries (Hamel *et al.* 2008). In general, poor reproductive performance and low attendance were documented in 1983, 1992, 1993, 1998 and 2005 in the California Current (Hodder & Graybill 1985, Wilson 1991, Parrish *et al.* 2001, Sydeman *et al.* 2001, Sydeman *et al.* 2006, Parrish *et al.* 2007). Of those five years, FAS were documented in four (1983, 1992, 1993 and 2005), supporting our hypothesis. However, there were years of late spring transition (e.g. 1997), weak upwelling (e.g. 1999) or low reproduction or attendance (e.g. 1998) without FAS, and years with FAS in which ocean conditions were "normal" (e.g. 1990, 2007). Thus, while poor ocean conditions may exacerbate fisheries-associated mortality, it is not a necessary precondition.

Changes in bird abundance and distribution

It is also possible that fewer FAS events in recent decades reflect regional changes in live bird abundance. For instance, a large-scale seasonal shift from a summer to winter seabird community resulted in a tripling in density of live seabirds in the southern North Sea, a change mirrored by the pattern of seabird deposition rates at an adjoining beach (Camphuysen & Heubeck 2001). In our study region, abundance of marine bird species declined by 27%–47% between 1978/79 and 2003–2005 (Bower *et al.* unpubl. data in Puget Sound Action Team 2007). For murres, colony declines have been documented in Washington State, Oregon and British Columbia (Parrish *et al.* 2001, Carter *et al.* 2001, Wilson 2003, Hipfner 2005, Naughton *et al.* 2007), and abundance in Puget Sound dropped at least 20% (Bower *et al.* as reported in Puget Sound Action Team 2007). The number of Rhinoceros Auklets breeding on Protection Island in the Strait of Juan de Fuca (Fig. 1), dropped by 30% between 1975 and 2000 (Wilson 2005). Pacific Loons (52%), Western Grebes (81%–95%), and Surf Scoter *Melanitta perspicillata* (64%) have also experienced marked declines in the Salish Sea (Bower *et al.* as reported in Puget Sound Action Team 2007, Puget Sound Action Team 2007). Finally, for gulls, the largest share of the baseline dataset (Fig. 9), local breeders (Glaucous-winged Gulls) and overwintering birds (Bonaparte's Gulls *Larus philadelphia* and Heermann's Gulls *Larus heermanni* decreased in abundance by at least 60% (Bower *et al.* unpubl. data in Puget Sound Action Team 2007, Puget Sound Action Team 2007). To conclusively determine the relationship between fisheries strandings and bird distribution in our system, concurrent monitoring of live and beached marine bird densities and fisheries effort would be needed at similar space and time scales.

CONCLUSIONS

Most fisheries in the world are poorly studied and few estimates of bycatch are available (Lewison *et al.* 2004). This situation holds particularly true in small-scale fisheries, which may have a disproportionate impact on coastal fauna relative to industrial fisheries (Peckham *et al.* 2007). In the absence of vessel-based observations, beached bird monitoring can highlight mortality pulses (Seys *et al.* 2002), frame the geographic scope of bycatch and identify species involved (Žydelis *et al.* 2006). Our study also demonstrates that baseline encounters can factor in mortality rate estimates, provided that beached bird monitoring programs have a broad geographic and temporal scope, and that fisheries-associated strandings are accounted for separately from baseline surveys. Further investigation into local biophysical factors leading to deposition patterns, persistence rates and detection probabilities of strandings will strengthen the linkage to location and magnitude of absolute mortality during fisheries operations (Ford 2006, Hart *et al.* 2006, Wiese & Elmslie 2006, Žydelis *et al.* 2006, Parrish *et al.* 2007).

Management recommendations

Much of the attention paid worldwide to seabird bycatch has arisen from a conservation concern for populations (Finkelstein *et al.* 2008). Even when bycatch exists without a demonstrated impact on populations, as may be the case with Common Murres in the Salish Sea, incidental mortality constitutes a waste of biodiversity (Crowder & Murawski 1998 and Morgan & Chuenpagdee 2003), a violation of the Migratory Bird Treaty Act, to which both countries sharing the Salish Sea are signatories (Harrison 2001). Further, such bycatch may inflict a time burden and loss of revenue for the industry because nets must be cut or disentangled to release animals. Mass mortality attracts the attention of the public and the media (Dunagan 2007a, Dunagan 2007b), and contributes to a political climate unfavorable to fishing industries and governments (Salzman 1989). Therefore, whether the goal in reducing seabird bycatch in the Salish Sea is to avoid population decline, to preserve individuals or to avoid damage to the fisheries, effective measures exist that may prove beneficial for the vitality both of seabird populations and of the fishing industry.

Commercial salmon fisheries management in the Salish Sea involves multiple government agencies, tribal nations and marine species, many populations of which are listed under the US Endangered Species Act (Gustafson *et al.* 2007). This situation results in complex negotiations about fishing quota allocations and timing of fisheries. Management considerations coupled with the ubiquitous distribution of diving seabirds across the Salish Sea throughout the late summer and winter (Nysewander *et al.* 2001) do not lend themselves well to time-of-year and area closures. Instead, we suggest that a technological solution such as gear modification (e.g. Melvin *et al.* 1999) is most appropriate for the Salish Sea biomanagement system. Gear modification is likely to protect a suite of species and does not require predictions of where and when birds and fisheries will interact. Fisheries mortality appears to have occurred in all principal regions of the Salish Sea (i.e. Strait of Juan de Fuca, Puget Sound and the Strait of Georgia), across fisheries (late summer and fall fisheries) and across years regardless of ocean conditions. Therefore, to prevent future fisheries-associated seabird mortality, we recommend that bycatch avoidance measures such as the "seabird strip"—preferably in conjunction with daytime fishing only—be adopted comprehensively, extending to all Salish Sea gillnet fisheries regardless of country or tribal status.

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