Animal Conservation

Animal Conservation. Print ISSN 1367-9430

Reducing uncertainty on the Grand Bank: tracking and vessel surveys indicate mortality risks for common murres in the North-West Atlantic

A. Hedd[1], W. A. Montevecchi[1], L. McFarlane Tranquilla[1], C. M. Burke[1], D. A. Fifield[1], G. J. Robertson[2], R. A. Phillips[3], C. Gjerdrum[4] & P. M. Regular[1]

1 Cognitive and Behavioural Ecology Program, Department of Psychology, Memorial University, NF, Canada
2 Wildlife Research Division, Environment Canada, NF, Canada
3 British Antarctic Survey, Natural Environment Research Council, Cambridge, UK
4 Canadian Wildlife Service, Environment Canada, Dartmouth, NS, Canada

Keywords
common murre; at-sea distribution; anthropogenic risk; offshore oil pollution; fisheries bycatch; murre harvest; year-round tracking.

Correspondence
April Hedd, Cognitive and Behavioural Ecology Program, Department of Psychology, Memorial University, St. John's, NF, Canada A1C 3C9. Tel: +1 709 864 3461; Fax: +1 709 864 2430
Email: ahedd@mun.ca

Editor: Todd Katzner
Associate Editor: Todd Katzner

Received 16 September 2010; accepted 18 April 2011

doi:10.1111/j.1469-1795.2011.00479.x

Abstract

Seabirds and other marine animals are at risk from anthropogenic activities that target them directly and those that can harm them incidentally. We integrate year-round tracking and vessel studies to assess risks for a globally important seabird population in the North-West Atlantic. The eastern Canadian Grand Bank has a rich and diverse food web that supports an abundance of apex predators. Major resource extraction industries (hydrocarbon production and fisheries) operate in the area, and, in addition to shipping and hunting, pose risks for marine birds. Understanding the relative risks has been hampered by poor information on bird distribution at sea. Here, we deployed global location sensors (loggers or geolocators) on common murres *Uria aalge* at Funk Island, the species' largest North American breeding colony. Adults ($n=10$) were resident on the Grand Bank and in adjacent pelagic waters year round. Within 10 days of leaving the colony, males dispersed offshore ($<50°$W), south–south-east of Funk Island. Females departed later and spent 10–47 days in coastal waters before moving offshore. All birds were in the vicinity of offshore oil platforms during November and December, but remained outside the area of the coastal Newfoundland and Labrador murre hunt. Three of six tracked females, but only one of four tracked males moved closer to shore during January and February where vulnerability to the hunt may have increased. Vessel-based surveys confirmed the importance of offshore, shelf-edge habitats for murres in winter. Our results highlight the relative risk to wintering murres from different human activities, providing a sound scientific rationale for focusing conservation and management actions. This information is particularly timely given the continued expansion of deep-water drilling in the North-West Atlantic and increasing risk of oil pollution for seabirds attracted to platforms.

Introduction

Understanding the potential risks that industrial and other anthropogenic activities pose to wildlife is hampered by gaps in our knowledge about species' distributions throughout the year (Wiese *et al*., 2001; Phillips *et al*., 2004, 2005; Montevecchi, 2006). When wildlife distribution and human activity overlap, conflict often results (e.g., bycatch in fishing gear, oil pollution; Lewison *et al*., 2004; Votier *et al*., 2005; Kaluza *et al*., 2010). Failure to understand the seasonal movements of animals also compromises our ability to assess mortality risks and to promote sustainable harvesting and resource extraction practices. The recent miniaturization of tracking devices, particularly global location sensors (GLS), for deployment on species weighing substantially <1 kg, has revolutionized our capacity to understand the dynamics of seasonal movements for a broad range of marine species (Phillips *et al*., 2005, 2006; Shaffer *et al*., 2006; Guilford *et al*., 2009; Egevang *et al*., 2010; Harris *et al*., 2010).

The global marine environment is a heterogeneous matrix of biologically rich patches interspersed with vast areas of comparatively unproductive habitat. Productive marine areas thus tend to attract a diversity and abundance of marine predators (Davoren, 2007; Amorim *et al*., 2009; Pichegru *et al*., 2009). The productive waters of the Grand Bank of Newfoundland, Canada provide critical habitat for a variety of vertebrate predators, including an estimated 40 million seabirds annually (Barrett *et al.*, 2006). Globally significant concentrations of thick-billed murres *Uria lomvia*, common murres *Uria aalge* and dovekies *Alle alle* overwinter on the bank, while in summer millions of southern hemisphere shearwaters (*Puffinus* spp.) and storm-petrels enter the area (Brown, 1986; Barrett *et al.*, 2006). Breeding populations include both the world's largest colony of Leach's storm-petrels *Oceanodroma leucorhoa* and the largest common murre colony in North America (Evans & Nettleship, 1985; Sklepkovych & Montevecchi, 1989). The Grand Bank is also an area where a suite of resource extraction and industrial activities pose risks to seabirds (see Fig. 1), including: (1) commercial gillnet and longline fisheries that take seabirds as bycatch (Piatt, Nettleship & Threlfall, 1984; Davoren, 2007; Department of Fisheries and Oceans, 2007; Benjamins, Kulka & Lawson, 2008); (2) dense, heavily used international shipping routes, contributing to one of the world's worst chronic oil pollution problems (Wiese & Ryan, 2003); (3) an expanding offshore oil and gas industry that poses mortality risks from collisions (including birds attracted by artificial lights) and flaring, in addition to operational and accidental discharges of hydrocarbons (Wiese *et al.*, 2001; Burke *et al.*, 2005; Fraser, Russell & Von Zharen, 2006; Montevecchi, 2006; Wilhelm *et al.*, 2007). Oil pollution is particularly problematic in the region due to high numbers of vulnerable diving seabirds (particularly auks, Family Alcidae) present year-round (Lock, Brown & Gerriets, 1994; Wiese & Ryan, 2003). In coastal waters there is a directed legal hunt for murre (*Uria* spp.) that occurs during fall and winter (Fig. 1;

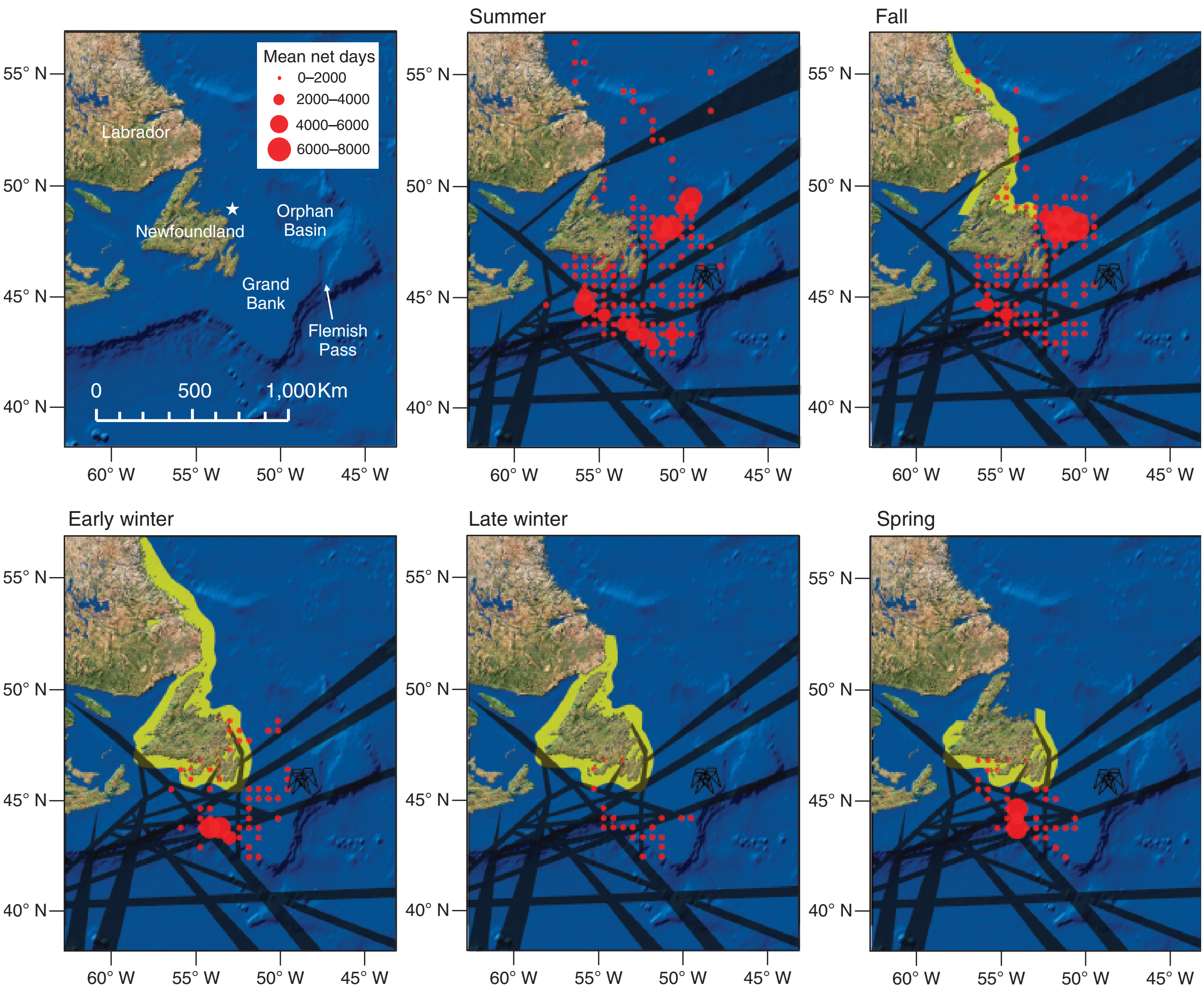

Figure 1 Diagram of study area and study site (Funk Island; star) showing the location of operating oil platforms along with seasonal variation in shipping lanes (black lines; adapted from Lock *et al.*, 1994), hunting zones (yellow shading; zones outlined at http://www.ec.gc.ca/rcom-mbhr/default.asp?lang=en&n=13B4C8EE-1) and gillnet fishing activity expressed as mean annual net days (per 30′ latitude × 30′ longitude block) for Atlantic cod, monkfish, white hake, Greenland halibut and lumpfish gillnets set <200 m since 1991 (red circles; data from Canadian Department of Fisheries and Oceans, Fisheries Statistics Branch).

Elliot, 1991; Montevecchi, Chaffey & Burke, 2007; Chardine, Robertson & Gilchrist, 2008). A lack of information on spatio-temporal distributions of seabirds, particularly outside the summer breeding period, hampers our ability to assess the relative and cumulative impacts of these risks for vulnerable species.

As part of an ongoing study, we addressed this information gap for common murres breeding at Funk Island off the north-east Newfoundland coast; a species expected to remain largely resident in the region year-round (Brown, 1986; Lock *et al.*, 1994) and therefore vulnerable to all the mortality sources described above. Using GLS to track non-breeding season movements of individual birds, and vessel surveys to quantify relative abundance at sea, we document the overlap of common murres with anthropogenic activities and propose research and monitoring efforts needed to quantify the associated risks.

Materials and methods

Logger data

British Antarctic Survey archival light, temperature and immersion loggers (Mk5/Mk7; mass = 3.6 g), attached to plastic leg bands (logger, band and cable tie mass = 5.4 g, ~0.6% adult body mass), were fitted to 20 breeding common murres between 31 July and 2 August 2007 at Funk Island (49°45′N, 53°11′W), Newfoundland, Canada (Fig. 1). This colony holds ~400 000 breeding pairs (Chardine *et al.*, 2003). Between 21 and 30 July 2008, 14 (70%) of these birds were re-sighted breeding at the colony, and 10 loggers were retrieved. At retrieval, 0.5 mL of blood was collected, from which sex was determined using W-chromosome analysis (Fridolfsson & Ellegren, 1999). There was no significant difference in the mean body mass ± SD of seven birds weighed at deployment (920 ± 29 g) and retrieval (919 ± 30 g; paired *t*-test: $t_6 = 0.18$, $P = 0.91$), nor between the mass of birds from which loggers were retrieved (902 ± 37 g, $n = 10$) and controls (922 ± 49 g, $n = 57$; two sample *t*-test: $t_{65} = -1.25$, $P = 0.22$).

The 10 loggers were successfully downloaded, providing data from July 2007 to July 2008 for four males and six females. Light data were processed according to Phillips *et al.* (2004) using MultiTrace Geolocation software (Jensen Software Systems, Laboe, Germany), with the correction factor for day/night movement set to 0.7, a threshold of 1 and an angle of elevation of –5.5. Day/night length is used to provide an estimate of latitude, and the timing of local midday/midnight relative to GMT is used to estimate longitude. This procedure produces two locations per day, corresponding to local midday and midnight. Mean positional error ± SD of similar devices deployed on free-ranging albatrosses was 186 ± 114 km (Phillips *et al.*, 2004). Latitudes cannot be accurately estimated from light levels during equinox periods (Hill, 1994), so when possible we obtained (during equinox) or improved latitude estimates by reconciling temperature data recorded by the loggers with remotely sensed satellite sea surface temperatures (SSTs) (Teo *et al.*, 2004). Light-based latitude data were retained both when tag-derived temperatures were unavailable (Mk7 devices; as the temperature sensor was omitted at manufacture), and when the SST algorithm performed poorly. Largely, the latter encompassed the winter and spring periods (mid-November through April) for birds that inhabited offshore Grand Bank and adjacent shelf slope waters, presumably due to the lack of a strong SST gradient and cloud cover in the region. Light-based latitude data that were clearly affected by proximity to equinoxes (8 September–31 October vernal equinox, 25 February–31 March spring equinox) were excluded. Longitude estimates, however, are unaffected by equinox and were used to ascertain east–west movement during these times. Clearly erroneous locations resulting from light level interference, locations that represented unrealistic movements ($>500\ \mathrm{km\ day^{-1}}$), and locations outside the likely range of the species were also removed (Brown, 1986; Lock *et al.*, 1994). Overall, the resulting dataset included 3844 validated locations (272–496 per individual; Table 1). Validated locations were smoothed twice, with raw fixed positions maintained around periods of missing data (Phillips *et al.*, 2004). Locations were

Table 1 Colony departure, offshore movement and maximum (great circle) distance from the colony during the nonbreeding season for common murres *Uria aalge* tracked via geolocation from Funk Island, Newfoundland, 2007–2008

Logger	Sex	No. of locations	Colony departure date	Date of offshore arrival (≤ 50°W)	Time to move offshore (days)	Maximum distance from colony during nonbreeding (km)
4238	M	295	11-Aug-07	17-Aug-07	6	970
4240	M	309	14-Aug-07	21-Aug-07	7	980
5220	M	496	19-Aug-07	24-Aug-07	5	965
5229	M	449	9-Aug-07	18-Aug-07	9	865
Male (mean ± SD)			13-Aug ± 4 days	20-Aug ± 3 days	7 ± 1.7	945 ± 54
4234	F	272	18-Aug-07	9-Sept-07	22	805
5221	F	415	21-Aug-07	7-Oct-07	47	850
5230	F	404	24-Aug-07	10-Sept-07	17	1040
5231	F	477	21-Aug-07	25-Sept-07	35	1045
5232	F	397	23-Aug-07	7-Sept-07	15	1060
5233	F	330	19-Aug-07	29-Aug-07	10	1065
Female (mean ± SD)			21-Aug ± 2 days	14-Sept ± 14 days	24 ± 14.0	978 ± 117

mapped in ArcGIS 9.3 (ESRI, Redlands, CA, USA), and Spatial Analyst and Hawth's Tools, respectively, were used to create kernel density surfaces (North Pole Lambert azimuthal equal-area projection; cell size = 50 km, search radius = 200 km) and per cent volume contours to describe the bird's utilization distribution (Phillips *et al.*, 2005). Kernel density maps were produced for each of four nonbreeding periods: (1) *fall/post-breeding*, spanning colony departure in August to the end of October; (2) *early winter*, November and December; (3) *late winter*, January to the start of the spring equinox (late February); (4) *spring/pre-breeding*, from the end of the spring equinox (31 March) to the end of April. Birds began visiting the breeding colony again during May. For kernel analyses, locations were weighted such that each individual contributed equally to the surfaces produced; 50% contours were used to describe seasonal 'core' or high use areas.

Vessel survey data

Distributions and densities of murres *Uria* spp. were quantified from vessels of opportunity operating within eastern Canadian continental shelf waters under the Eastern Canadian Seabirds at Sea (ECSAS) program 2006–2011. All birds seen were counted during 5 or 10 min observation periods (watches) from the bridge of the ship, scanning a 90° arc from one side of the vessel forward to the bow, using a survey width of 300 m (Tasker *et al.*, 1984; C. Gjerdrum, D. Fifield, S. Wilhelm, unpublished data.). All birds observed on the sea surface were continuously recorded throughout each watch. Flying birds were recorded using instantaneous counts at regular intervals to avoid overestimation of bird density (Tasker *et al.*, 1984; Gaston, Collins & Diamond, 1987). Position and time were recorded for each watch. Data were compiled into a series of bins (30′ latitude × 30′ longitude), each containing the total number of murres (flying and on the water combined) and the total area of ocean surveyed (km^2), and expressed as birds per km^2. Vessel data were compiled seasonally to correspond with presentation of the geolocator data.

Results

Tracking data

Birds were distributed within ~1050 km of the Funk Island colony throughout the nonbreeding period (colony departure – April; Table 1), implying that breeding-aged individuals from this population remain resident in Grand Bank and adjacent pelagic waters year-round. Despite the small sample size, there was an apparent sex difference in the timing of movement away from the colony and the relative use of near shore (coastal) and offshore waters during the nonbreeding period (Table 1).

Fall/post-breeding period (August–October)

Males ($n = 4$) left the colony at the end of the breeding season between 9 and 19 August 2007 and rapidly dispersed to offshore waters (offshore is defined here as $\leq 50°$W, near shore as $> 50°$W) south of Funk Island (Table 1 and Fig. 2). The transition from near shore to offshore waters (~260–380 km from the colony) took 7 ± 1.7 days (Table 1). Females ($n = 6$) left the colony slightly later than males, between 18 and 24 August 2007, and spent 24 ± 14 days (range 10–47 days) in more near shore, coastal waters before also moving offshore (Table 1 and Fig. 2). Different patterns of movement away from the colony resulted in a partial spatial separation of fall high use areas by sex (Fig. 3). For males, there was a single core area offshore in the vicinity of the shelf edge on the southern Grand Bank, while females had two core areas; one over the continental shelf off Newfoundland's north-east coast, and a second which partially overlapped with that of males offshore.

Early winter (November–December)

In November and December all birds were centered offshore, in the vicinity of the shelf edge on the northern or southern Grand Bank, or in the pelagic waters of the Orphan Basin and Flemish Pass (Fig. 2). Five birds spent some or all of the early winter period within the Orphan Basin. Birds were relatively sedentary during this period and overlaps in core areas of males and females were high. Females did, however, tend to be distributed slightly further north, reflecting greater use of the Orphan Basin (Fig. 3).

Late winter (January–February)

After spending the early winter period relatively concentrated and centered offshore, some birds dispersed in January and February with increased use of areas nearer to shore. The tendency to disperse in late winter appeared greater for females (three of six) than males (one of four; Fig. 2) in our dataset. Female (4234) used nearer shore regions from southern Labrador to south-eastern Newfoundland, 5230 spent early January close to the east coast and then moved to the southern Grand Bank for the rest of winter, while 5231 moved to the shelf edge off the south coast of Newfoundland where it stayed until late April. The other three females were relatively sedentary during winter, and occupied similar offshore regions between November and February. Just one of four males (5220) relocated. This bird moved to the east coast of Newfoundland in late January and then on to offshore waters off southern Newfoundland where it remained until mid-April (Fig. 2). The other males stayed offshore, near the shelf edge throughout winter. The core areas of females during this period were more expansive than those of males, extending from the east coast offshore, with a secondary pocket off southern Newfoundland (Fig. 3). The core area of males remained offshore.

Spring (April)

For the majority of birds, the distribution in April mirrored that in January and February (Fig. 2), and kernel density plots during late winter and spring were therefore similar

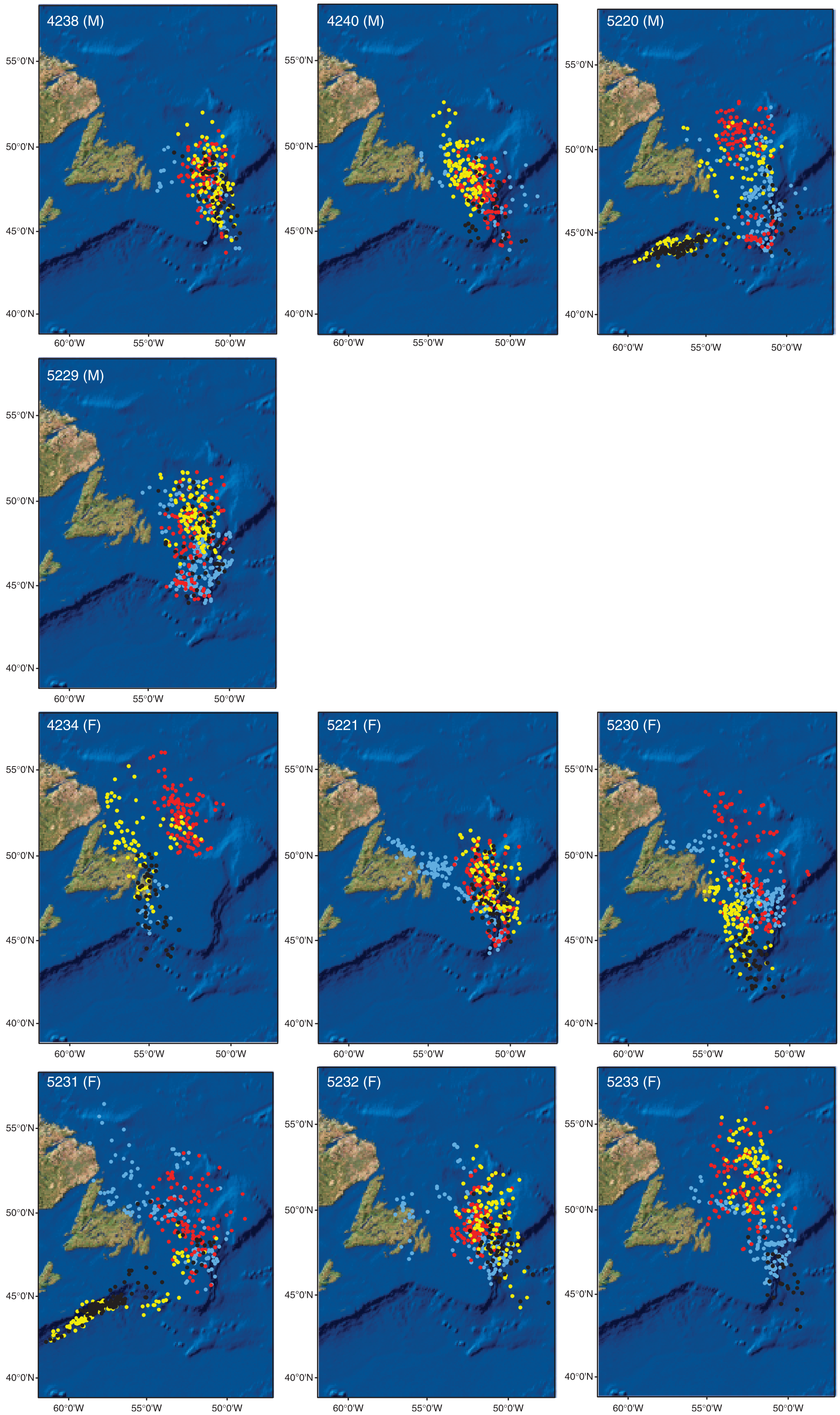

Figure 2 Distribution of individual common murres *Uria aalge* during the fall/post-breeding (August–October; blue points), early winter (November–December; red points), late winter (January–February; yellow points) and spring/pre-breeding (April; black points) periods. Individuals are identified by geolocator number, with M and F indicating male and female, respectively.

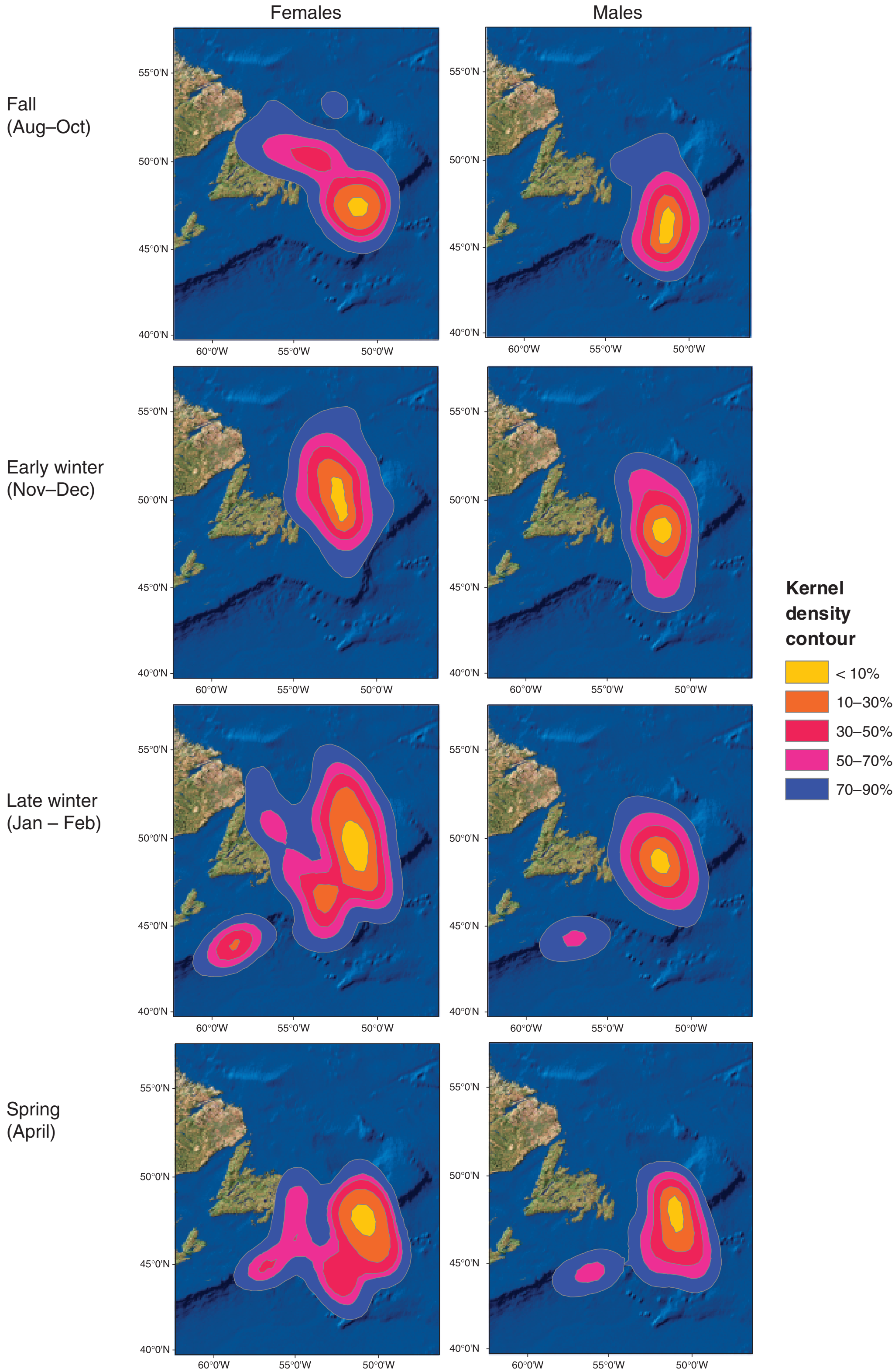

Figure 3 Kernel density contours of male and female common murres *Uria aalge* during the fall (August–October), early winter (November–December), late winter (January–February) and spring (April) periods. Note that kernels for fall only include the subset of individuals (i.e. $n=2$ males and $n=5$ females) for which we had spatial information extending from August through October. All 10 individuals are represented during the remaining periods.

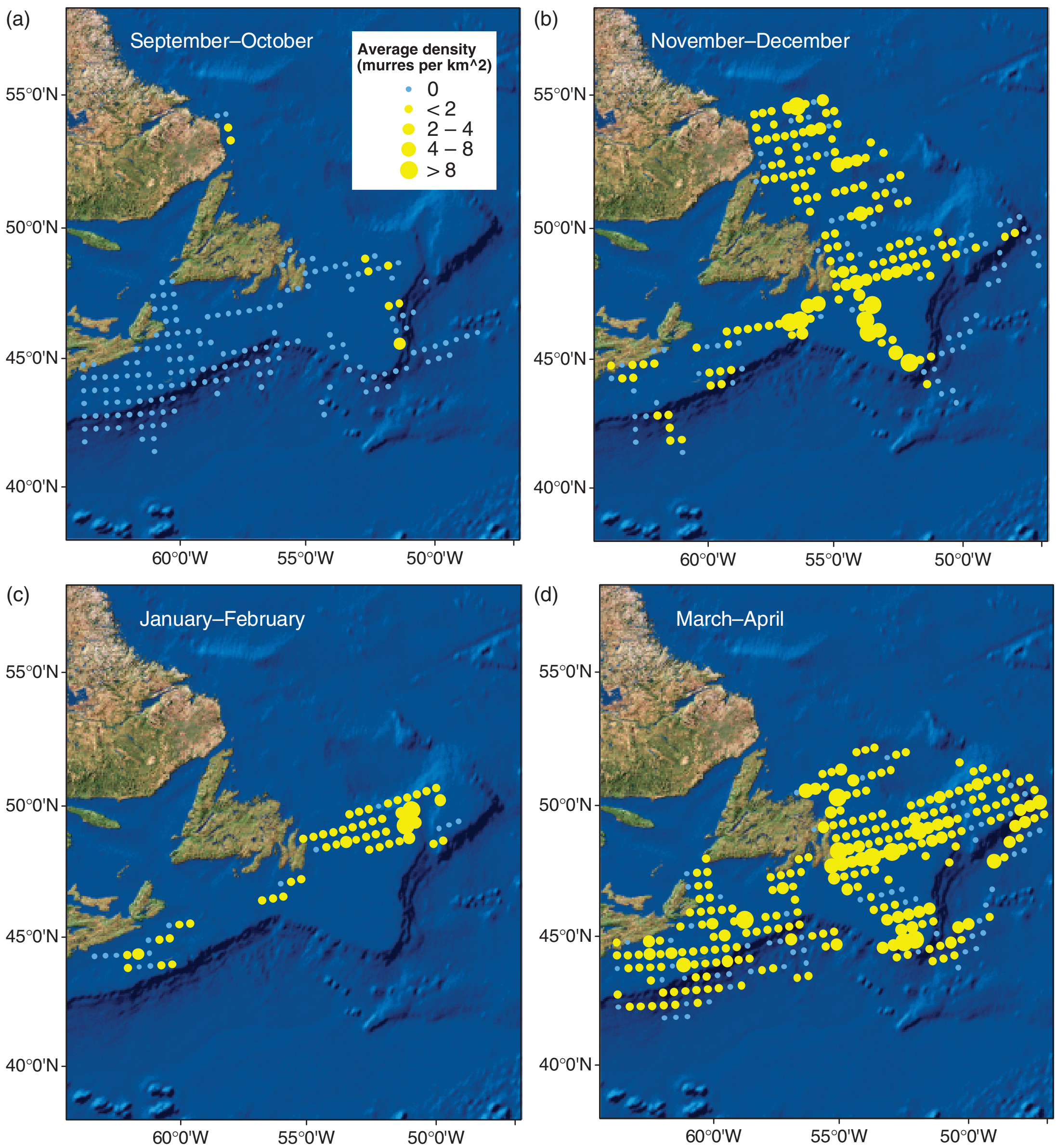

Figure 4 Seasonal at-sea distribution of murres (*Uria* spp.) from the Eastern Canadian Seabirds at Sea (ECSAS) Program, 2006–2011. (a) September–October, (b) November–December, (c) January–February, (d) March–April.

(Fig. 3). Although some locations (and resulting kernels) are slightly further south in spring, this likely reflects the residual influence of the equinox rather than bird movement.

Vessel data

Murres were absent from southern survey areas (Scotian Shelf and regions south of Newfoundland) in September and October (Fig. 4a), and observed only in offshore areas of the Grand Bank and near southern Labrador. During November and December, murres were more widely distributed over continental shelf waters north, east and south of Newfoundland, and to a lesser extent on the Scotian Shelf (Fig. 4b). Highest densities (5.55 ± 1.55 birds km^{-2}) were observed on the southern Grand Bank, with clusters of high abundance also evident in offshore areas along the shelf break off southern Labrador. Murres were present in the Orphan Basin in early winter. Few surveys were conducted during January and February, however, the density of murres observed near the shelf edge on the northern Grand Bank was high (Fig. 4c). More extensive coverage in March and April indicated that murres were widely distributed over continental shelf and adjacent pelagic waters east and south of Newfoundland, with greater numbers occurring on the Scotian Shelf (Fig. 4d). High densities were observed inshore along the east and north-east coasts, in continental shelf waters off the south coast, along the southern Grand Bank as well as in pelagic waters offshore of the Flemish Cap.

Discussion

Electronic data loggers have revolutionized research in marine ornithology and ecology by providing information on spatio-temporal distributions of marine predators, with direct application to conservation (Burger & Shaffer, 2008). This technology has enabled unparalleled insights into the movement and behavior of marine birds, information that is both timely and essential for understanding exposure to anthropogenic risks at sea. Using GLS loggers, we demonstrated that breeding common murres were year-round residents of the Grand Bank and adjacent pelagic waters off eastern Canada (see Fort *et al*., 2010 for similar year-round residency of common murre in the Barents and Norwegian Seas). These data on long-term movement and residency patterns of individuals enable the first risk assessment in the Newfoundland and Labrador region, where birds are vulnerable to mortality from a variety of human activities (Fig. 1).

Bycatch in gillnet fisheries is a major threat to the common murre throughout its range (Piatt & Nettleship, 1987; Falk & Durinck, 1991; Melvin, Parrish & Conquest, 1999; Smith & Morgan, 2005; Davoren, 2007). Losses were likely to have been unsustainable in gillnet fisheries for cod *Gadus morhua* and salmon *Salmo salar* off Newfoundland before the early 1990s, when tens of thousands of birds drowned each summer (Piatt *et al*., 1984; Piatt & Nettleship, 1987). Overall bycatch mortality presumably declined in 1992 when a groundfish moratorium resulted in an immediate, large-scale decrease in gillnet fishing effort. Recent (2000–2003) estimates of seabird bycatch derived using data from DFO Fisheries Observers and commercial fishermen, indicate that 2000–7000 murres die per year in the Newfoundland and Labrador region, largely in near shore fisheries targeting cod and lumpfish *Cyclopterus lumpus* and often in nets set close to seabird breeding colonies (Benjamins *et al*., 2008). Given the spatial distribution of adult murres, their potential for overlap with gillnets posing entanglement risk (i.e. those set <200 m deep, Fig. 1; Hedd *et al*., 2009; Regular *et al*., 2010) is highest during summer and fall, and relatively low in winter and spring. During the summer breeding season murres are densely aggregated foraging within $\sim$100 km radius of the colonies, and nets set within colony foraging areas likely pose the greatest risks. Indeed, Davoren (2007) estimated that from 2000 to 2003, 3000–14 000 murres died annually within a single small biological hotspot off the north-east coast of Newfoundland. This level of bycatch could have potentially major local population impacts, despite the overall regional reduction in fishing effort (Davoren, 2007). As in other productive marine areas with high spatiotemporal overlap of seabirds and fisheries (Pichegru *et al*., 2009), the situation off Newfoundland and Labrador calls for close monitoring (including continued deployment of independent observers on fishing vessels), as the distribution of fishing effort and target species continue to change.

A legal, shore-based fall-winter hunt for murres occurs off Newfoundland and Labrador (Elliot, 1991; Chardine *et al*., 2008;Fig. 1). Annual estimated kills of 600 000–900 000 birds throughout the 1970s and 1980s dropped substantially with the adoption of hunting restrictions in 1993 (Elliot, 1991). Estimates from Murre Harvest Surveys (Environment Canada, Canadian Wildlife Service) in the mid 1990s indicated annual harvests of 200 000–300 000 birds (Chardine *et al*., 1999), and further declines in 2001–2002 to 160 000–190 000 birds per year (Chardine *et al*., 2008). At the height of the harvest, 95% of hunted birds were thick-billed murres, with common murres comprising just 5% of the kill overall (Elliot, 1991). With respect to where murres were taken, in the 1980s the proportions of common murres harvested were highest in early season (October–November) hunts off the north coast (up to 15%) and throughout the winter along the south coast (up to 30%; Elliot, 1991); data from hunts throughout the 2000s suggests that proportions are similar today (G. J. Robertson, Environment Canada, unpubl. data). Historically, inexperienced first-year birds appeared to be more vulnerable, representing 53% of those shot, despite comprising just 20% of the wintering population (Elliot, 1991). Recent banding efforts indicate that young common murres, especially from Labrador colonies, are being shot at much higher rates than thick-billed murre chicks banded in the Canadian Arctic (Gaston & Robertson, 2010). It is unclear whether this represents a change through time in the species composition of the hunt, as previous research and management has focused primarily on thick-billed murres, the species that historically comprised the bulk of hunted birds (Chardine *et al*., 2008). As the murre hunt is conducted from small open boats, much of the effort is concentrated in inshore areas and within bays (Elliot, 1991; Fig. 1). While our data indicate that Funk Island adults (and females, in particular) may be vulnerable to fall (north coast) and late season (January–March; north, east and south coast) hunts when inshore (Figs 2 and 3), the relatively coarse resolution of our GLS data do not preclude the possibility that they are distributed sufficiently far from shore as to be beyond the range of hunters. Indeed, the little information available suggests that adult common murres are very rarely taken in the murre hunt (Robertson, Storey & Wilhelm, 2006; G. J. Robertson, Environment Canada, unpubl. data). Continued collection of information from hunted birds and banding of murres at colonies will help clarify the species, populations, sexes and age classes most vulnerable to hunting.

Newfoundland and Labrador has one of the world's worst chronic marine oil pollution problems as ships travelling busy international traffic routes between Europe and North America illegally dump oily bilge and ballast water as they traverse the east coast of Canada (Wiese & Ryan, 2003). Between 1998 and 2000, it was estimated that $315\,000 \pm 65\,000$ murres (25 000–40 000 of which were common murres) and dovekies were killed annually off south-eastern Newfoundland as a result of illegal discharge of oil from ships (Wiese & Robertson, 2004). Despite a significant reduction between 1984 and 2005, the current density of oiled seabirds observed during systematic beached bird surveys still exceeds those reported elsewhere in the world

(Wilhelm *et al*., 2009). Diving seabirds, including murres and other auks (Family Alcidae), are the most common victims of oil pollution as they spend much of their time on the water surface (Lock *et al*., 1994; Camphuysen, 1998; Wiese & Ryan, 2003). Residency on the Grand Bank suggests that adult common murres are vulnerable to chronic ship-source oil pollution year round. Fall and winter are expected to be particularly sensitive periods for many reasons. First, common murres have an 'intermediate' chick development strategy, whereby the male parent accompanies the flightless young to sea at *c*. 3 weeks of age (Ainley *et al*., 2002). Parent–young pairs then undertake a swimming migration to foraging or nursery areas where parental care continues for at least the next 1–2 months (Varoujean *et al*., 1979; Harris & Birkhead, 1985). Satellite tracking of dispersing males and young from Funk Island in 2009 (C. Burke, W. Monterecchi, A. Hedd, unpublished data) indicated that pairs crossed international shipping lanes and oil fields as they swam from the colony to nursery areas on the southern Grand Bank. Adult murres also undergo a rapid, almost synchronous moult of flight feathers, rendering them flightless for many weeks during autumn (Ainley *et al*., 2002). With little or no dispersal potential, flightless young and moulting adults are highly vulnerable to oil on the water. In cold regions such as the North-West Atlantic, winter is expected to be the season in which oil imposes the greatest mortality as aromatic hydrocarbon toxins evaporate slowly and even very small amounts of oil on the feathers can compromise thermoregulation, leading to death (Levy, 1980; Leighton, 1985).

Through both operational discharges and accidental spills, oil platforms on the Grand Bank pose another risk for seabirds. Adult murres from Funk Island spend the early winter offshore either in the vicinity of oil platforms, or within the deep waters of the Orphan Basin where numerous exploration licenses have been issued (http://www.cnlopb.nl.ca/maps/onl_2010.pdf), and where high-risk deep water drilling activity has occurred [e.g. Stena Carron completed drilling of the deepest well in Canadian history (in 2600 m of water) in August 2010; http://www.reuters.-com/article/2010/09/01/chevron-canada-idUSN0112807720 100901] and is expected to increase in the coming years. Our findings suggest particularly that males may be vulnerable to offshore oil pollution, as most are resident offshore from November through February. Current (Fig. 4) and previous vessel surveys (Brown, 1986; Lock *et al*., 1994) support our tracking data, and confirm the importance of offshore, shelf-edge habitats for murres in winter.

Vessel surveys on the Grand Bank also indicate that *overall* seabird densities (but not those of auks, specifically) are higher adjacent to offshore platforms relative to the surrounding areas (Wiese & Montevecchi, 2000; Wiese *et al*., 2001; C. Burke *et al*. unpubl. data). Increased densities can result from seabirds using platforms as roosting sites, birds utilizing increased food concentrations near the artificially created reefs, and for planktivorous species, due to their natural attraction to light (including night-lighting and flares; Tasker *et al*., 1984; Reed *et al*., 1985; Baird, 1990; Montevecchi, 2006). Regardless of the concentrating mechanisms, however, once in the vicinity of platforms, seabirds are at risk from both the operational and accidental discharge of hydrocarbons into the ocean (Wiese *et al*., 2001; Wilhelm *et al*., 2007). Low-volume and low-concentration hydrocarbon discharge during drilling (e.g. produced water) is a common ongoing practice in the east coast offshore industry that periodically results in the presence of oily sheens on the water. Fraser *et al*. (2006) estimated that between 156 and 4332 auks are likely killed annually as a result of oil sheens produced by the three platforms currently operating on the Grand Bank and suggested that uncertainty around these estimates could be reduced with increased information on seasonal seabird densities in the region (currently being collected via Environment Canada's ECSAS Program), access to information from industry on the occurrence of oil sheens at platforms, and an understanding of the negative impact of tiny amounts of oil on plumage. Since that time it has been shown that feather structure can be damaged by tiny quantities of oil absorption (O'Hara & Morandin, 2010) and as a result, seabirds on the Grand Bank may be impacted by the thin (barely visible) sheens that form around offshore production facilities from produced water containing currently admissible concentrations of hydrocarbons (Canada–Newfoundland Offshore Petroleum Board, 2002). Given the demonstrated importance of offshore waters for wintering adult common murres coupled with the information gap surrounding interactions of seabirds with Newfoundland and Labrador's offshore oil and gas installations (Burke *et al*., 2005), we reemphasize the need for mandatory placement of independent observers on these platforms to evaluate environmental impacts (Wiese & Montevecchi, 2000; Wiese *et al*., 2001; Burke *et al*., 2005). Having observed the environmental disaster that resulted from the explosion of the *Deepwater Horizon* in the Gulf of Mexico in 2010, such data are required to evaluate the sustainability of existing extraction practices, and critically, to enhance stewardship and protection of this globally significant marine ecosystem.

In conclusion, continued comprehensive research and multi-site monitoring will be required to understand population-level impacts of the various anthropogenic pressures facing common murres and other vulnerable seabirds off eastern Canada. Through provision of colony- and age-specific spatial residency times, information from GLS (and other types of tracking) devices is likely to be an important component of the toolset we use to unravel the relative risks. While the overall pressure on eastern Canadian murre populations from hunting, fisheries bycatch and chronic oil pollution has likely been reduced in recent decades, cumulative annual mortality for common murre remains substantial (~60 000 individuals) and its allocation between age-classes and colonies is poorly known (Robertson *et al*., 2006). As oil pollution is a persistent source of increased mortality and decreased fecundity for seabirds worldwide (Ford *et al*., 1982; Piatt *et al*., 1990; Votier *et al*., 2005; Wilhelm *et al*., 2009; Wolfaardt *et al*., 2009), filling the local information gap surrounding seabirds and the offshore oil and gas industry has been highlighted as a conservation priority.

Acknowledgements

Thanks to Larry Easton and family for safely transporting us to and from Funk Island, and to Anna Russell at DFO for providing the fishing effort data presented in Fig. 1. We are grateful to the Newfoundland and Labrador Parks Division for granting a research access permit to the Funk Island Provincial Seabird Ecological Reserve and to Memorial University's Institutional Animal Care Committee for granting approval for the protocols used in this study Comments from two anonymous reviewers improved an earlier draft of this manuscript. This research was supported by an NSERC Discovery Grant, the Murre Fund of the Newfoundland and Labrador Legacy Nature Trust and the Government of Canada's Program for International Polar Year to W.A.M., and by support to G.J.R. and D.A.F. from Environment Canada through the Environmental Studies Research Fund. This research represents a contribution to the British Antarctic Survey Ecosystems Programme.

References

Ainley, D.G., Nettleship, D.N., Carter, H.R. & Storey, A.E. (2002). Common murre (*Uria aalge*). In *The birds of North America online*. Poole, A. (Ed.). Ithaca: Cornell Lab of Ornithology. Available at http://bna.birds.cornell.edu/bna/species/666 doi:10.2173/bna.666.

Amorim, P., Figueiredo, M., Machete, M., Morato, T., Martins, A. & Serrao Santos, R. (2009). Spatial variability of seabird distribution associated with environmental factors: a case study of marine Important Bird Areas in the Azores. *ICES J. Mar. Sci.* **66**, 29–40.

Baird, P.H. (1990). Concentrations of seabirds at oil-drilling rings. *Condor* **92**, 768–771.

Barrett, R.T., Chapdelaine, G., Anker-Nilssen, T., Mosbech, A., Montevecchi, W.A., Reid, J.B. & Veit, R.R. (2006). Seabird numbers and prey consumption in the North Atlantic. *ICES J. Mar. Sci.* **63**, 1145–1158.

Benjamins, S., Kulka, D. & Lawson, J. (2008). Incidental catch of seabirds in Newfoundland and Labrador gillnet fisheries, 2001–2003. *Endang. Species Res.* **5**, 149–160.

Brown, R.G.B. (1986). *Revised atlas of eastern Canadian seabirds: shipboard surveys*. Ottawa: Government Publishing Centre.

Burger, A.E. & Shaffer, S.A. (2008). Application of tracking and data-logging technology in research and conservation of seabirds. *Auk* **125**, 253–264.

Burke, C.M., Davoren, G.K., Montevecchi, W.A. & Wiese, F.K. (2005). Seasonal and spatial trends of marine birds along support vessel transects and at oil platforms on the Grand Banks. In *Offshore oil and gas environmental effects monitoring*: 587–614. Armsworthy, S.L., Cransford, P.J. & Lee, K. (Eds). Columbus: Battelle Press.

Camphuysen, C. (1998). Beached bird surveys indicate decline in chronic oil pollution in the North Sea. *Mar. Poll. Bull.* **36**, 519–526.

Canada–Newfoundland Offshore Petroleum Board. (2002). *Offshore waste treatment guidelines*. St. John's: National Energy Board, Canada–Newfoundland Offshore Petroleum Board & Canada–Nova Scotia Offshore Petroleum Board, 21pp.

Chardine, J.W., Collins, B.T., Elliot, R.D., Lévesques, H. & Ryan, P.C. (1999). Trends in the annual harvest of murres in Newfoundland and Labrador. *Bird Trends* **7**, 11–14.

Chardine, J.W., Robertson, G.J. & Gilchrist, H.G. (2008). Harvest of seabirds in Canada. In *Seabird harvest in the Arctic. CAFF Technical Report No. 16*: 20–29. Merkel, F. & Barry, T. (Eds). Akureyri: CAFF International Secretariat, Circumpolar Seabird Group (CBird).

Chardine, J.W., Robertson, G.J., Ryan, P.C. & Turner, B. (2003). *Abundance and distribution of common murres breeding at Funk Island, Newfoundland in 1972 and 2000. Can. Wildl. Serv. Tech. Rep. Ser. No. 404*. Atlantic Region: Canadian Wildlife Service.

Davoren, G.K. (2007). Effects of gill-net fishing on marine birds in a biological hotspot in the Northwest Atlantic. *Conserv. Biol.* **21**, 1032–1045.

Department of Fisheries and Oceans. (2007). *National plan of action for reducing the incidental catch of seabirds in longline fisheries*. Ottawa: Department of Fisheries and Oceans.

Egevang, C., Stenhouse, I.J., Phillips, R.A., Petersen, A., Fox, J.W. & Silk, J.R.D. (2010). Tracking of Arctic Terns *Sterna paradisaea* reveals longest animal migration. *Proc. Natl. Acad. Sci. USA* **107**, 2078–2081.

Elliot, R.D. (1991). The management of the Newfoundland turr hunt. In *Studies of high-latitude seabirds. 2. Conservation biology of thick-billed murres in the Northwest Atlantic. Can. Wildl. Serv. Occ. Paper No. 69*: 29–35. Gaston, A.J. & Elliot, R.D. (Eds). Ottawa: Canadian Wildlife Service.

Evans, P.G.H. & Nettleship, D.N. 1985. Conservation of the Atlantic Alcidae. In *The Atlantic Alcidae. The evolution, distribution and biology of the auks inhabiting the Atlantic Ocean and adjacent water areas*: 427–488. Nettleship, D.N. & Birkhead, T.R. (Eds). London: Academic Press.

Falk, K. & Durinck, J. (1991). The by-catch of thick-billed murres in salmon driftnets off west Greenland in 1988. In *Studies of high-latitude seabirds. 2. Conservation biology of thick-billed murres in the Northwest Atlantic. Can. Wildl. Serv. Occ. Paper No. 69*: 23–28. Gaston, A.J. & Elliot, R.D. (Eds). Ottawa: Canadian Wildlife Service.

Ford, R.G., Wiens, J.A., Heinemann, D. & Hunt, G.L. (1982). Modelling the sensitivity of colonially breeding marine birds to oil spills: guillemot and kittiwake populations on the Pribilof Islands, Bering Sea. *J. Appl. Ecol.* **19**, 1–31.

Fort, J., Steen, H., Strøm, H., Tremblay, Y., Pettex, E., Gabrielsen, G., Le Maho, Y., Porter, W., Grønningsæter, E. & Grémillet, D. (2010). Contrasted migratory strategies in a sympatric high-Arctic seabird duet. Abstracts of the 1st World Seabird Conference, Victoria, September 2010.

Fraser, G., Russell, J. & Von Zharen, W. (2006). Produced water from offshore oil and gas installations on the Grand Banks, Newfoundland and Labrador: are the potential effects to seabirds sufficiently known? *Mar. Ornithol.* **34**, 147–156.

Fridolfsson, A.-K. & Ellegren, H. (1999). A simple and universal method for molecular sexing of non-ratite birds. *J. Avian Biol.* **30**, 116–121.

Gaston, A.J., Collins, B.L. & Diamond, A.W. (1987). The snapshot count for estimating densities of flying seabirds during boat transects: a cautionary comment. *Auk* **104**, 336–338.

Gaston, A.J. & Robertson, G.J. (2010). Trends in the harvest of Brünnich's Guillemots in Newfoundland: effects of regulatory changes and winter sea-ice conditions. *Wildl. Biol.* **16**, 47–55.

Guilford, T., Meade, J., Willis, J., Phillips, R.A., Boyle, D., Roberts, S., Collett, M., Freeman, R. & Perrins, C.M. (2009). Migration and stopover in a small pelagic seabird, the Manx Shearwater *Puffinus puffinus*: insights from machine learning. *Proc. Roy. Soc. Lond. Ser. B: Biol. Sci.* **276**, 1215–1223.

Harris, M.P. & Birkhead, T.R. (1985). Breeding ecology of the Atlantic Alcidae. In *The Atlantic Alcidae. The evolution, distribution and biology of the auks inhabiting the Atlantic Ocean and adjacent water areas*: 155–204. Nettleship, D.N. & Birkhead, T.R. (Eds). London: Academic Press.

Harris, M.P., Daunt, F., Newell, M., Phillips, R.A. & Wanless, S. (2010). Wintering areas of adult Atlantic Puffins *Fratercula arctica* from a North Sea colony as revealed by geolocation technology. *Mar. Biol.* **157**, 827–836.

Hedd, A., Regular, P.M., Montevecchi, W.A., Buren, A.D., Burke, C.M. & Fifield, D.A. (2009). Going deep: common murres dive into frigid water for aggregated, persistent and slow-moving capelin. *Mar. Biol.* **156**, 741–751.

Hill, R.D. (1994). Theory of geolocation by light levels. In *Elephant seals: population ecology, behavior, and physiology*: 227–236. Le Boeuf, B.J. & Laws, R.M. (Eds). Berkeley: University of California Press.

Kaluza, P., Kölzsch, A., Gastner, M.T. & Blasius, B. (2010). The complex network of global cargo ship movements. *J. R. Soc. Interf.* **7**, 1093–1103.

Leighton, F.A. (1985). Oil and arctic marine birds: an assessment of risk. In *Petroleum effects in the arctic environment*: 183–215. Engelhardt, F.R. (Ed.). London: Elsevier.

Levy, E.M. (1980). Oil pollution and seabirds: Atlantic Canada 1976–77 and some implications for northern environments. *Mar. Poll. Bull.* **11**, 51–56.

Lewison, R.L., Crowder, L.B., Read, A.J & Freeman, S.A. (2004). Understanding impacts of fisheries bycatch on marine megafauna. *Trends Ecol. Evol.* **19**, 598–604.

Lock, A., Brown, R. & Gerriets, S. (1994). *Gazetteer of marine birds in Atlantic Canada*. Dartmouth: Canadian Wildlife Service.

Melvin, E.F., Parrish, J.K. & Conquest, L.L. (1999). Novel tools to reduce seabird bycatch in coastal gillnet fisheries. *Conserv. Biol.* **13**, 1386–1397.

Montevecchi, W.A. (2006). Influences of artificial light on marine birds. In *Ecological consequences of artificial night lighting*: 94–113. Rich, C. & Longcore, T. (Eds). Washington: Island Press.

Montevecchi, W.A., Chaffey, H. & Burke, C.M. (2007). Hunting for security: changes in the exploitation of marine birds in Newfoundland and Labrador. In *Resetting the kitchen table: food security in Canadian coastal communities*: 99–116. Parrish, C.C., Turner, N.J. & Solberg, S.M. (Eds). New York: Nova Science Publishers.

O'Hara, P.D. & Morandin, L.A. (2010). Effects of sheens associated with offshore oil and gas development on the feather microstructure of pelagic seabirds. *Mar. Poll. Bull.* **60**, 672–678.

Phillips, R.A., Silk, J.R.D., Croxall, J.P. & Afanasyev, V. (2006). Year-round distribution of white-chinned petrels from South Georgia: relationships with oceanography and fisheries. *Biol. Conserv.* **129**, 336–347.

Phillips, R.A., Silk, J.R.D., Croxall, J.P., Afanasyev, V. & Bennett, V.J. (2005). Summer distribution and migration of nonbreeding albatrosses: individual consistencies and implications for conservation. *Ecology* **86**, 2386–2396.

Phillips, R.A., Silk, J.R.D., Croxall, J.P., Afanasyev, V. & Briggs, D.R. (2004). Accuracy of geolocation estimates for flying seabirds. *Mar. Ecol. Prog. Ser.* **266**, 265–272.

Piatt, J.F., Lensink, C.J., Butler, W., Kendziorek, M. & Nysewander, D.R. (1990). Immediate impact of the 'Exxon Valdez' oil spill on marine birds. *Auk* **107**, 387–397.

Piatt, J.F. & Nettleship, D.N. (1987). Incidental catch of marine birds and mammals in fishing nets off Newfoundland, Canada. *Mar. Poll. Bull.* **18**, 344–349.

Piatt, J.F., Nettleship, D.N. & Threlfall, W.T. (1984). Net mortality of common murres *Uria aalge* and Atlantic Puffins *Fratercula acrtica* in Newfoundland, 1951–1981. In *Marine birds: their feeding ecology and commercial fisheries relationships. Canadian Wildlife Service Special publication*: 196–207. Nettleship, D.N., Sanger, G.A. & Springer, P.F. (Eds). Ottawa: Canadian Wildlife Service.

Pichegru, L., Ryan, P.G., LeBohec, C., van der Lingen, C.D., Navarro, R., Peterson, S., Lewis, S., van der Westhuizen, J. & Gremillet, D. (2009). Overlap between vulnerable top predators and fisheries in the Benguela upwelling system: implications for marine protected areas. *Mar. Ecol. Prog. Ser.* **391**, 199–208.

Reed, J.R., Sincock, J.L. & Hailman, J.P. (1985). Light attraction in endangered Procellariiform birds: reduction by shielding upward radiation. *Auk*, **102**, 377–383.

Regular, P.M., Davoren, G.K., Hedd, A. & Montevecchi, W.A. (2010). Crepuscular foraging by a pursuit-diving seabird: tactics of common murres in response to the diel vertical migration of capelin. *Mar. Ecol. Prog. Ser.* **415**, 295–304.

Robertson, G.J., Storey, A.E. & Wilhelm, S.I. (2006). Local survival rates of common murres breeding in witless bay, Newfoundland. *J. Wildl. Mgmt.* **70**, 584–587.

Shaffer, S.A., Tremblay, Y., Weimerskirch, H., Scott, D., Thompson, D.R., Sagar, P.M., Moller, H., Taylor, G.A., Foley, D.G., Block, B.A. & Costa, D.P. (2006). Migratory shearwaters integrate oceanic resources across the Pacific Ocean in an endless summer. *Proc. Natl. Acad. Sci. USA* **103**, 12799–12802.

Sklepkovych, B. & Montevecchi, W.A. (1989). The world's largest known nesting colony of Leach's storm-petrels on Baccalieu Island, Newfoundland. *Am. Birds* **43**, 38–42.

Smith, J. & Morgan, K. (2005). *An assessment of seabird bycatch in longline and net fisheries in British Columbia. Can. Wildl. Serv. Tech. Rep. Ser. No. 401*. Pacific and Yukon Region: Canadian Wildlife Service.

Tasker, M.L., Hope-Jones, P., Dixon, T. & Blake, B.F. (1984). Counting seabirds at sea from ships: a review of methods employed and a suggestion for a standardized approach. *Auk* **101**, 567–577.

Teo, S.L.H., Boustany, A., Blackwell, S., Walli, A., Weng, K.C & Block, B.A. (2004). Validation of geolocation estimates based on light level and sea surface temperature from electronic tags. *Mar. Ecol. Prog. Ser.* **283**, 81–98.

Varoujean, D.H., Sanders, S.D., Graybill, M.R. & Spear, L.B. (1979). Aspects of common murre breeding biology. *Pac. Seabird Group Bull.* **6**, 28.

Votier, S.C., Hatchwell, B.J., Beckerman, A., McCleery, R.H., Hunter, F.M., Pellatt, J., Trinder, M. & Birkhead, T.R. (2005). Oil pollution and climate have wide-scale impacts on seabird demographics. *Ecol. Lett.* **8**, 1157–1164.

Wiese, F.K. & Montevecchi, W.A. (2000). Marine bird and mammal surveys on the Newfoundland Grand Banks from offshore supply boats 1999–2000. Unpublished Husky Oil Contract Report, St. John's, Newfoundland

Wiese, F.K., Montevecchi, W.A., Davoren, G., Huettmann, F., Diamond, A.W. & Linke, J. (2001). Seabirds at risk around offshore oil platforms in the North-west Atlantic. *Mar. Poll. Bull.* **42**, 1285–1290.

Wiese, F.K. & Robertson, G.J. (2004). Assessing seabird mortality from chronic oil discharges at sea. *J. Wildl. Mgmt.* **68**, 627–638.

Wiese, F.K. & Ryan, P.C. (2003). The extent of chronic marine oil pollution in southeastern Newfoundland waters assessed through beached-bird surveys 1984–1999. *Mar. Poll. Bull.* **46**, 1090–1101.

Wilhelm, S.I., Robertson, G.J., Ryan, P.C. & Schneider, D.C. (2007). Comparing an estimate of seabirds at risk to a mortality estimate from the November 2004 *Terra Nova* FPSO oil spill. *Mar. Poll. Bull.* **54**, 537–544.

Wilhelm, S.I., Robertson, G.J., Ryan, P.C., Tobin, S.F. & Elliot, R.D. (2009). Re-evaluating the use of beached bird oiling rates to assess long-term trends in chronic oil pollution. *Mar. Poll. Bull.* **58**, 249–255.

Wolfaardt, A.C., Williams, A.J., Underhill, L.G., Crawford, R.J.M. & Whittington, P.A. (2009). Review of the rescue, rehabilitation and restoration of oiled seabirds in South Africa, especially African penguins *Spheniscus demersus* and Cape Gannets *Morus capensis*, 1983–2005. *Afr. J. Mar. Sci.* **31**, 31–54.