The Northern Fulmar (*Fulmarus glacialis*) in Arctic Canada: ecology, threats, and what it tells us about marine environmental conditions

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Abstract: The northern fulmar *Fulmarus glacialis* is a ubiquitous seabird found across the North Atlantic Ocean and into the Canadian Arctic. However, we know little of its ecology in the Arctic, which is unfortunate, because it possesses many traits that make it an excellent biomonitor of the condition of Arctic marine environments. Presently, Arctic fulmars face threats from harvest, bycatch in fisheries, and fouling in oil spills while the birds are in their winter range (the North Atlantic). However, during breeding, migration, and overwintering, they may also experience stress from ecotourism, contaminants, particulate garbage, and climate change. In this paper I review the effects of all of these threats on fulmars and I describe how the ecology of these birds makes them particularly suitable for tracking contaminants, garbage, and the effects of climate change in the Arctic marine ecosystem. I also highlight our key existing knowledge gaps on this species and how additional research will strengthen the utility of fulmars as biomonitors.

Key words: northern fulmar, *Fulmarus glacialis*, Arctic, contaminants, climate change, pollution.

Résumé : Le fulmar boréal, *Fulmarus glacialis*, est un oiseau marin ubiquiste qu'on retrouve sur l'ensemble de l'océan Atlantique nord, et jusque dans l'Arctique canadien. Cependant, on connaît peu de choses sur son écologie dans l'Arctique, ce qui est malheureux parce qu'il possède plusieurs caractères qui en font un excellent biomoniteur de la condition des milieux marins de l'Arctique. Actuellement, les fulmars boréaux sont menacés par la récolte, les prises accidentelles, et les salissures par les déversements d'huile, alors que les oiseaux occupent leur habitat d'hiver (Atlantique nord). Cependant, au cours de la reproduction, de la migration et de l'hivernage, ils peuvent également rencontrer divers stress venant de l'écotourisme, de contaminants, surtout les déchets, et du changement climatique. L'auteur passe en revue les effets de toutes ces menaces qui pèsent sur les fulmars, décrit comment l'écologie de ces oiseaux en font des indicateurs particulièrement fiables pour déceler les contaminants, les déchets et les effets des changements climatiques dans l'écosystème marin arctique. On souligne également les déficiences de connaissances déterminantes actuelles de cette espèce, et comment une recherche additionnelle consolidera l'utilité des fulmars comme biomoniteurs.

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Mots clés : fulmar boréal, *Fulmarus glacialis*, Arctique, contaminants, changement climatique, pollution.

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Introduction

Over the past 30 years, there has been increasing concern over the health of the Canadian Arctic environment. Long considered to be remote and pristine, recent studies in a variety of environmental disciplines are showing that habitats across this vast region are changing, largely in response to a variety of anthropogenic stressors. Climate change, thought to be attributable in part to increasing greenhouse gas emissions, is occurring in the Arctic at a faster rate than elsewhere in North America. Research has already documented trends of increasing air temperatures, increasing sea surface temperatures, declining sea-ice thickness and extent, and reductions in snow cover (ACIA 2004). Contaminants from sources in industrial regions of tropical and temperate zones reach the Arctic via long-range aerial and marine transport. These bioaccumulate in the flora and fauna, with deleterious effects on some species (INAC 2003), and with some substances in wildlife tissues exceeding Health Canada and World Health Organization guidelines for human consumption (Muir et al. 1999). High latitude aquatic ecosystems are also sensitive to ultraviolet (UV) radiation, which is increasing in many areas (Vincent and Pienitz 1996). Moreover, mineral resource extraction and ecotourism are also increasing, potentially affecting long-term land use patterns near many key wildlife sites (Mallory and Fontaine 2004).

How do scientists and resource managers monitor these changes and their effects on Arctic marine ecosystems? Research in the Arctic is extremely expensive, due to the remote, harsh and unpredictable nature of sites, and the high logistic costs of moving supplies to the region, and thus a priority must be cost-effective monitoring solutions. Marine birds have proven to be sensitive and effective indicators of the health or condition of marine ecosystems for a suite of measures (Furness 1993; Nettleship and Duffy 1993; Nisbet 1994; Furness and Camphuysen 1997; Burger and Gochfield 2002; Schreiber 2002). Marine birds are a ubiquitous feature of polar environments, typically feeding at the upper trophic levels, and thus they serve as a proxy for the condition of marine ecosystems because they respond to changes in many levels of the marine food web (Nettleship and Duffy 1993). In particular, most polar marine birds forage over considerable geographic areas, and therefore data gathered from these birds integrate the physical and biological factors that influence the distribution, abundance, and chemical composition of prey species over these regions (e.g., Jenouvrier et al. 2003; Gaston et al. 2005). Many birds also rely on features of sea-ice for feeding (edges, polynyas, underside of ice; Stirling 1997), and thus changes in sea-ice may be detected through effects on marine birds. In years when marine food resources are reduced, aspects of marine bird reproduction are concordantly reduced (e.g., Barbraud and Weimerskirch 2001). Marine birds also offer the advantage of typically being colonial, so multiple samples can be collected at one location and the geographic area represented by those samples can usually be defined.

Canada has an international responsibility to manage large Arctic marine bird populations. In excess of 10 million seabirds inhabit the Canadian Arctic archipelago and surrounding marine zone (Mallory and Fontaine 2004), representing nationally and globally significant populations. The most common and widely-distributed marine birds in the Canadian Arctic are the thick-billed murre (*Uria lomvia*), the black-legged kittiwake (*Rissa tridactyla*), the black guillemot (*Cepphus grylle*), the common eider (*Somateria mollissima*), several species of gulls (*Larus* spp.), and the northern fulmar (*Fulmarus glacialis*). Of these species, significant, broad, regional ecological research and monitoring has only been conducted on the murre (Gaston and Hipfner 2000) and the eider (Goudie et al. 2000); local or specialized research projects have occurred for some other species (e.g., Gilchrist et al. 1998), notably for contaminants monitoring (e.g., Braune et al. 2001; Mallory et al. 2004*a*), but all have been the subject of regional survey efforts (e.g., Brown et al. 1975; Gaston et al. 1986).

While all of these species possess certain unique ecological characteristics that make them potentially useful as monitors of Arctic marine ecosystem health, the northern fulmar is of particular interest. This species is the only petrel (Procellariiformes: Procellariidae) that breeds in the Canadian Arctic, and it has a markedly dissimilar breeding strategy from all of the other Arctic marine birds. Fulmars arrive earlier and depart their colonies later than any of the species above, and they also possess the ability to travel tremendous distances to find food (Falk and Møller 1995; Hatch and Nettleship 1998). In southern, less climatically-extreme parts of the species' range, fulmars are well-studied (Fisher 1952; Hatch and Nettleship 1998), and their populations are known to track or react to certain environmental stressors (e.g., van Franeker 1985; Hatch 1993; Thompson and Ollason 2001); however, this has not been examined in Arctic fulmars. In fact, the ecology of northern fulmars inhabiting true Arctic regions has been examined only intermittently, notably by Salomonsen (1961, 1979), Falk and Møller (1997), and most recently in a substantive review of North American fulmars conducted by Hatch and Nettleship (1998). However, none of these studies considered the fulmar as an indicator species of multiple environmental stressors.

This paper is the second in a series of reviews examining the role that marine birds can play in tracking the health of the Arctic marine ecosystem (the first looked at contaminants in common eiders; Mallory et al. 2004*a*). Here, I review available information on the ecology of northern fulmars breeding in the Canadian Arctic, but because these data are often limited, I refer extensively to studies on fulmars from elsewhere in the North Atlantic Ocean. Fisher (1952) and Hatch and Nettleship (1998) provided excellent reviews of many aspects of fulmar behavior and ecology, and it was not my intention to duplicate those efforts. Instead, after a review of fulmar ecology, I focus on current environmental stressors in Arctic Canada, how these may affect fulmars, and in turn how fulmars may or may not serve as suitable monitors for these threats. Finally, I identify some knowledge gaps on Arctic fulmars and I offer suggestions on studies that would be useful both from an ecological and environmental health perspective.

Fulmar biology

Natural history

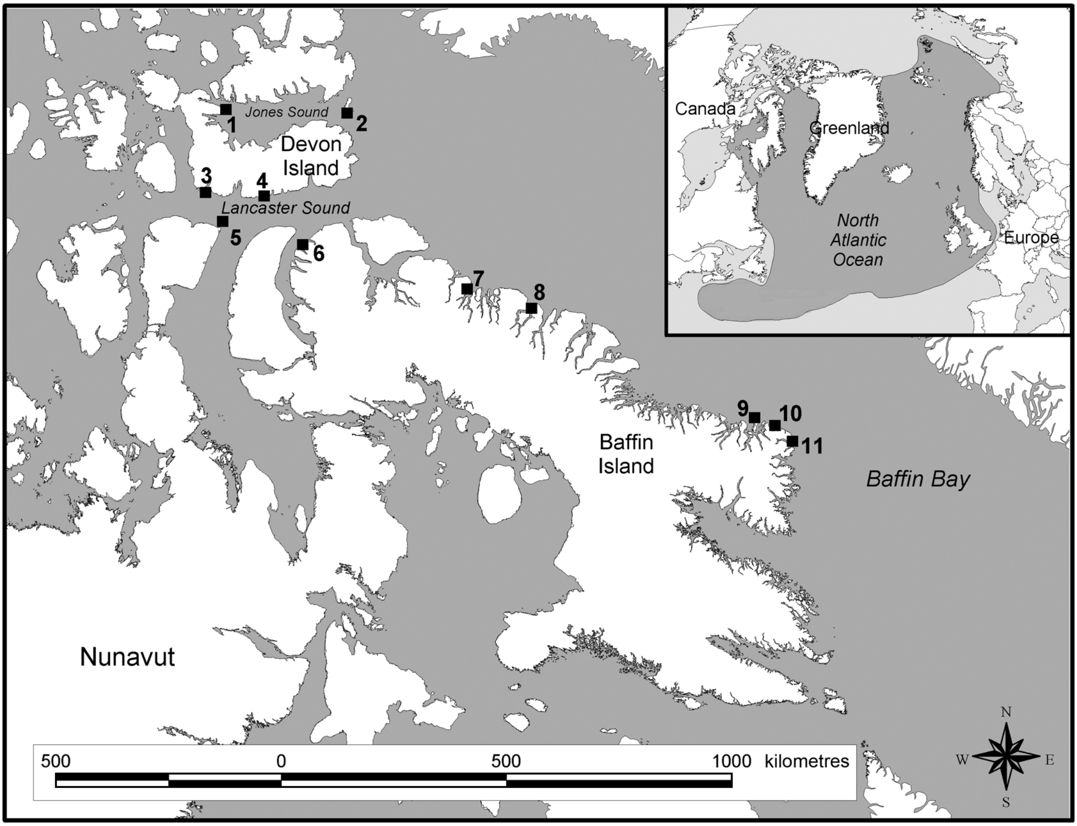
Range

Northern fulmars are ubiquitous, gray and white seabirds found across the North Atlantic Ocean (Fig. 1). They spend most of their time out of sight of land, foraging hundreds of kilometres away from their nest site during the breeding season (Falk and Møller 1995), and moulting and overwintering on the open ocean (Hatch and Nettleship 1998; Huettmann and Diamond 2001). For this reason, most fulmars are seen only by people in ships, and rarely near land except at breeding colonies. In fact, over most of their range, fulmars are well-known to fishermen and whalers, as these birds follow ships and consume discards from whaling and fishing boats (Fisher 1952). So strong is their association with boats that Hobson and Welch (1992*a*) noted the potential bias in studies because fulmars quickly flock to nearby vessels. Safina (2002: 218) described fulmars following a fishing boat this way:

> The increasingly dense crowd of fulmars – now forming a ferocious feathered rabble – already numbers about a thousand. A boat can attract all the birds for many miles around ... In dense packs they churlishly churn the water white around discarded fish, heads, and entrails, screaming, squabbling, pulling gobbets of flesh, and wolfing guts. In appearance and behavior, they seem always just one webbed footstep ahead of starvation.

In Canada, fulmars are found from Ellesmere Island south to waters off of the Maritime Provinces and from Barrow Strait (south of Cornwallis Island) east through Jones and Lancaster Sounds, Baffin Bay, and the Labrador Sea (Fig. 1; occasionally found south to 35°N, Hatch and Nettleship 1998). During the breeding season, fulmars may be found almost everywhere that open water is available (although

Fig. 1. A map showing the distribution of the northern fulmar in Arctic Canada (filled squares), with numbers on sites corresponding to colonies as follows: (1) Cape Vera (last census 2004; 11 000 apparently occupied breeding sites), (2) Princess Charlotte Monument (1998; 300), (3) Cape Liddon (2002; 9000), (4) Hobhouse Inlet (2001; 21 000), (5) Prince Leopold Island (2001; 22 000), (6) Baillarge Bay (2002; 23 000), (7) Buchan Gulf (1986; 25 000), (8) Scott Inlet (1986; 10 000), (9) Cape Searle (2001; 44 000), (10) The Minarets (1985; 20 000), (11) Exeter Island (1971, 2000) (Gaston et al. 2006). The inset shows the common marine range of the northern fulmar in the North Atlantic Ocean (Fisher 1952, Hatch and Nettleship 1998).



uncommonly in Foxe Basin or Hudson Bay), but are particularly common in Lancaster Sound, northern Baffin Bay, and the Labrador Sea (Brown et al. 1975; Huettmann and Diamond 2000). Brown et al. (1975) found that, in summer, fulmar distributions shifted northward, following the northerly advancement of the 10 °C sea temperature isotherm.

Appearance

Fulmars superficially resemble gulls, having gray plumage with lighter feathers on the head. However, these birds posses a distinctive nasal tube on top of the bill, typical of all of the Procellariiformes. In size, fulmars have approximately 1 m wingspans, and show wide variation in body mass, with birds at the same colony ranging from 560 to 1050 g (Hatch and Nettleship 1998). In the Canadian Arctic, fulmars possess an array of plumage colouration from very dark (DD) to very light (LL), which is typically classified into four morphs: DD, D, L, and LL, referring to increasing amounts of white on the breast, neck, and head of birds (Fisher 1952; Salomonsen 1965; van Franeker 1986; Hatch and

Nettleship 1998). Fulmars of the Canadian Arctic are mostly intermediate birds (L and D), while many Pacific fulmars (*F. g. rodgersii*) are very dark (DD) or light (LL), and Greenlandic and European fulmars (*F. g. auduboni*) are principally light morphs (LL). The preponderance of dark Canadian birds and light European birds has been used in part to identify wintering ranges on the open ocean (Brown 1970). Plumage differences, along with distinct markings on the bill, allow experienced observers to distinguish members of a pair that are different morphs at nest sites.

Flight

Fulmars fly with a distinctive, rapid, stiff-winged flapping motion that alternates with long glides (Hatch and Nettleship 1998). They are agile and energy-efficient fliers, and this allows fulmars to operate effectively even in windy conditions (Warham 1990, 1996; Furness and Bryant 1996). Indeed, fulmars can soar near a breeding colony for several minutes without flapping. With such efficient travel capabilities, fulmars can forage over a much broader area than sympatric seabirds (alcids, gulls, eiders), and this may make them less sensitive to environmental conditions near their colony. For example, Gaston et al. (2005) showed that during more severe ice seasons, murres, gulls, and kittiwakes all delayed breeding, but fulmars laid eggs at almost the exact same time each year. Apparently fulmars could travel hundreds of kilometres to reach the nearest open water to feed, whereas the other species had to wait for ice break-up before attempting to nest. Therefore, studying fulmars at a breeding colony (e.g., diet, contaminants, breeding success) provides information on recent environmental conditions over a much larger geographic area than represented by studies of other Arctic seabird species.

Reproduction

Like all petrels, fulmars are long-lived seabirds with delayed breeding maturation and monogamous breeding (Warham 1990). In Europe, fulmars do not begin breeding until they are 8–12 years old, adult survival is high (>0.96 per year; Buckland 1982), and some birds are known to live 30–50 years (Ollason and Dunnet 1988; Dunnet 1991). Ages of initial breeding and typical longevity are unknown for Canadian fulmars.

In the Arctic, northern fulmars first return to their breeding colonies at the start of May (Hatch and Nettleship 1998). Nest sites are typically located on precipitous, eroding cliffs at altitudes of 200–400 m, and are usually confined to cliff ledges that are inaccessible to mammalian predators like arctic foxes (*Alopex lagopus*). This differs somewhat from fulmars in Europe, where many colonies are found on flatter, vegetated sites (Hatch and Nettleship 1998). Depending on the pattern of snow accumulation over the winter, Arctic nest sites may be under snowdrifts when the birds return, and fulmars will dig through drifts to get to their site (Hatch and Nettleship 1998). The nest cups are simple scrapes in loose gravel or on rock, occasionally lined by small pebbles, but at well-established nest sites, long-term nutrient enrichment from guano has led to the development of some graminoid vegetation between scrapes. Carrick and Dunnet (1954) found that fulmars breeding at Eynhallow, Orkney, could breed in successive years whether or not they were successful in the previous year, and this observation has been repeated elsewhere (e.g., Hatch 1990*a*, 1990*c*), including Arctic Canada (Hatch and Nettleship 1998). Wynne-Edwards (1939) suggested that fulmars occasionally skip breeding, but this occurrence has since been deemed as quite uncommon (Lack 1968; Warham 1990; Hatch and Nettleship 1998).

Nest site and mate fidelity are high in fulmars (>90%; Ollason and Dunnet 1978). After returning to the colony, mates spend approximately 2–3 weeks presumably re-establishing their pair bond and selecting or defending nest sites (Hatch and Nettleship 1998). Many non-breeding fulmars also attend the colony, prospecting for future nest sites and gaining experience with conditions on land (Hatch 1989). A unique feature of procellarid breeding biology is the “pre-laying exodus” or “honeymoon” from the colony (Warham 1990). Following their pair bonding period at the nest, the majority of fulmars depart the breeding colony for 1–2 weeks (Hatch 1989; Hatch and Nettleship 1998). Prior to this exodus, fulmar pairs mate and females can store sperm in glands, which allows males and females to forage independently during the exodus (Hatch 1983). After the exodus, the male often returns to the nest first, followed by the female who lays the egg and departs within 24 h. Fulmars lay a single, yolk- and energy-rich egg, and if that egg is lost, they do not relay that year (Hatch and Nettleship 1998). The male incubates the egg for the first shift, which may take up to 16 d (Hatch 1990*a*), after which the male and female take turns incubating or foraging away from the colony, with incubation shifts averaging 4–6 d (Hatch 1990*a*, 1990*c*; Falk and Møller 1997). After 47–49 d, the chick hatches, but is brooded in shifts by parents for another 10–16 d, before both parents depart on provisioning trips. Chicks fledge at 50–53 d old, with minimal provisioning by parents in the last 5 d (Hatch and Nettleship 1998). Over the breeding period (pre-laying through mid-chick rearing), breeding fulmars in Alaska spend 39% of their time at the nest site and 61% of their time at sea (Hatch 1990*b*; proportions unknown for the Canadian Arctic). There is some evidence that fulmars nesting at Arctic colonies have a more compressed breeding season than conspecifics nesting in more southerly, boreal waters (Salomonsen 1979; Falk and Møller 1997; Hatch and Nettleship 1998). Annual breeding success varies, with chicks fledged / egg laid varying from 37 to 47% (Hatch and Nettleship 1998), and is strongly influenced by the previous breeding experience of the nesting pair (i.e., more experienced pairs have higher breeding success; Ollason and Dunnet 1978, 1986; Michel et al. 2003).

Fulmars depart colonies in Arctic Canada in September and October, and are thought to migrate south through Baffin Bay and Davis Strait, to overwinter on the North Atlantic Ocean east of Newfoundland and Labrador (Hatch and Nettleship 1998). This assumption is based in part on the distribution of dark colored birds at sea in the winter (presumed to be principally birds of Canadian origin; Brown 1970), and in part on recoveries of banded fulmars from nearby colonies in Greenland (Lyngs 2003).

Colony locations and population size in Arctic Canada

That some fulmar colonies were located in the Canadian Arctic has been known since the 1800s by European scientists (Kumlien 1879; Boas 1885; Schaanning 1933; Hørring 1937; Wynne-Edwards 1939, 1952), although the sizes and locations of most of these colonies were not well-known until the 1970s (Nettleship 1974; Brown et al. 1975). There are 11 major fulmar colonies in Arctic Canada (Fig. 1), with a few small colonies scattered along the coast of Newfoundland and Labrador comprising $<1\%$ of the Canadian breeding population (Stenhouse and Montevecchi 1999). Most Canadian Arctic colonies are located on sheer cliffs made of eroding, sedimentary rock, and are generally located close to polynyas (areas of open water surrounded by sea-ice) or recurrent leads that open in the sea-ice in the early spring (Brown and Nettleship 1981).

Based on the most current data (Gaston et al. 2006), Cape Searle is the largest colony in Arctic Canada, while Princess Charlotte Monument represents the smallest colony (Fig. 1). However, fulmars are exceedingly difficult to census, because dark phase birds are cryptic against many of the gray cliffs in this region. Estimates of the number of fulmars breeding at some Arctic colonies have varied by more than 200% (Alexander et al. 1991; Hatch and Nettleship 1998; Gaston et al. 2006), so there is considerable uncertainty in the colony estimates. Recently, Gaston et al. (2006) concluded that the Arctic population was approximately 200 000 apparently occupied sites ($\approx$ breeding pairs). Considering that many non-breeding birds attend colonies or feed in waters in this region through the summer (Salomonsen 1979; McLaren 1982), it is reasonable to conclude that perhaps 500 000 individual fulmars inhabit the Canadian Arctic during the breeding season.

Population tends

The North Atlantic population of northern fulmars is estimated at 10 million birds (Lloyd et al. 1991). Fisher (1952) documented a rapid and broad expansion of northern fulmar populations from the mid 18th century through to the late 20th century, although the most recent evidence suggests that some European populations may be in decline (Mitchell et al. 2004). Fisher (1952) attributed this growth to the ability of fulmars to exploit the carcasses from whaling ships, and then as whaling declined, fulmars exploited expanding commercial fishery operations. However, Salomonsen (1965) and Brown (1970) challenged that explanation for the western part of the species' North Atlantic Ocean range, and both argued that the fulmar expansion was better explained by changes in oceanographic conditions. Whatever the cause, the expansion may have affected Canada by establishing small colonies in Newfoundland and Labrador (Hatch and Nettleship 1998; Stenhouse and Montevecchi 1999). Fisher (1952) speculated that colonies previously reported in Cumberland Sound, Nunavut, in the 1800s but subsequently not found may have been extirpated with the decline of whaling in this region, but Wynne-Edwards (1952) questioned whether the colonies ever existed. Thus, it is not known whether Canadian Arctic colonies were affected during the growth of the North Atlantic fulmar population, but Salomonsen (1965) considered that Arctic colonies appeared to have been stable for centuries.

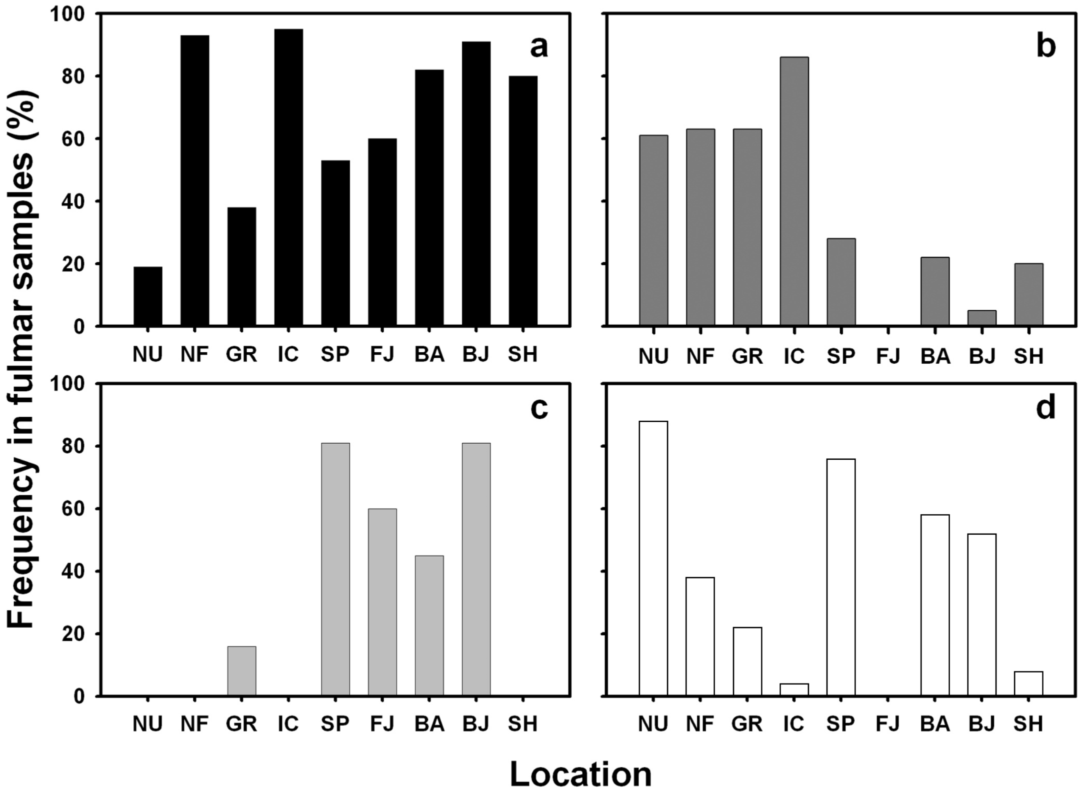
In the North Atlantic Ocean, fulmar populations are dynamic, fluctuating in a 5 year lag behind the North Atlantic Oscillation (NAO), a broad scale, ocean-atmosphere oscillating system that affects northern climates (Thompson and Ollason 2001; Grosbois and Thompson 2005). The mechanism for the fluctuation in fulmar populations is thought to be changes in food availability for the birds. These fluctuations should apply to fulmars from Canada, as it appears that Canadian fulmars winter largely in the Labrador Sea (Brown 1970), but are also scattered across the North Atlantic Ocean (e.g., Lyngs 2003).

In Arctic Canada, Hatch and Nettleship (1998) suggested that the 11 colonies supported about 300 000 pairs of fulmars, but this number has recently been reduced 33% to 200 000 pairs by Gaston et al. (2006). This represents about 2% of the North Atlantic population (Lloyd et al. 1991). However, Gaston et al. (2006) did not believe the apparent changes were indicative of a population trend, but rather were due to different (and perhaps more reliable) techniques used to census colonies in recent years. At two of the better-studied colonies, Prince Leopold Island and Cape Vera, there was no evidence of significant population changes since the 1970s.

Diet

Fulmars are generalist, opportunistic predators and scavengers, eating zooplankton, squid, fish, fisheries discards, and whatever carcasses they can find in the marine environment (Hatch and Nettleship 1998). Virtually all foraging is on the water surface (Hatch and Nettleship 1998), although they are capable of making shallow dives (Hobson and Welch 1992*a*); they are not known to forage on land, even on shore when carcasses are readily available (Hobson and Welch 1992*a*). They occupy upper positions in marine trophic webs, as indicated by stable isotope analyses (δ^{15}N typically 13–17‰ and trophic level 4.0–4.2; Hobson 1993; Hobson and Welch 1992*b*; Hobson et al. 1994, 2002; Thompson and Furness 1995; Atwell et al. 1998; Thompson et al. 1999; Braune et al. 2001; Dahl et al. 2003; Elliott 2005). There have been some conflicting statements in the literature on the importance of fish in fulmar diets. Salomonsen (1950), Fisher (1952), and Belopol'skii (1961) all suggested that fulmars eat relatively few fish. However, more recent studies suggest that breeding fulmars across the North Atlantic Ocean rely on a variety of fish and fisheries discards (Furness and Todd 1984; Camphuysen and Garthe 1997; Hamer et al. 1997; Cherel et al. 2001; Ojowski et al. 2001; Weimerskirch et al. 2001). Near Svalbard, Mehlum and Gabrielsen (1993) found that fulmars consume predominantly invertebrates, but do rely on fish as well, notably Arctic cod (*Boreogadus saida*). Phillips et al. (1999) suggested that the presumed reliance of fulmars on fisheries discards in the southern part of their range (as advocated by Fisher 1952) was overstated, as fulmars in this region also consumed many fish and pelagic zooplankton that they had to catch. Fulmar diets may also shift through the year; Thompson and Furness (1995) found that fulmars shifted to feed lower in the trophic web after the breeding season, as shown by declining stable δ^{15}N values in later-grown primary feathers. Thompson et al. (1995) also showed that fulmars in the Northeast Atlantic have demonstrated a progressive shift to feeding lower in the marine trophic web from the early 1900s, perhaps as an adjustment from consuming offal from whaling.

Fig. 2. Histograms showing the occurrence of food groups ((*a*) fish, (*b*) crustaceans, (*c*) polychaetes, (*d*) squid)) in the diet of northern fulmars sampled in different parts of the North Atlantic Ocean (data from Phillips et al. 1999; Ojowski et al. 2001; Garthe et al. 2004). Sampling locations as follows: NU, Nunavut (Canada); NF, Newfoundland (Canada); GR, Greenland (Denmark); IC, Iceland; SP, Spitzbergen (Norway); FJ, Franz Josef Land (Norway); BA, Barents Sea; BJ, Bjornoya (Norway); SH, Shetland (United Kingdom).



In or near Canadian waters, Garthe et al. (2004) found that fulmars on Funk Island, Newfoundland, fed primarily on capelin (*Mallotus villosus*) and fisheries offal, but also fed on many crustaceans. Similarly, Phillips et al. (1999) showed that fulmars from Greenland consumed many capelin, squid, and crustaceans. In the Canadian Arctic, Bradstreet (1976) found that fulmars in Lancaster Sound foraged heavily on fish during chick-rearing, although amphipods became an increasingly important part of the diet later in rearing. Near Pond Inlet, Baffin Island, Nunavut, Bradstreet and Cross (1982) found that invertebrates, and particularly copepods and cephalopods, dominated fulmar diet numerically, but that fish (notably Arctic cod) and scavenged marine mammal fat dominated fulmar diet in mass. Similarly, at Prince Leopold Island (Lancaster Sound) fulmars fed on Arctic cod, as well as crustaceans (amphipods and copepods) (Hatch and Nettleship 1998). Therefore, based on the limited studies available, it appears that fulmars in the Canadian Arctic rely on fewer fish, or at least fisheries-related materials, and proportionally more marine invertebrates compared to other locations. Overall, there seems to be a tendency for fulmars in the Northeast Atlantic Ocean to rely more on fish and less on crustaceans and squid than fulmars in the Northwest Atlantic and Arctic oceans (Fig. 2). This pattern is probably attributable to the reduced availability of fisheries discards and reduced fish diversity at high latitudes. However, some caution must be exercised in interpreting Fig. 2, because samples sizes differ considerably among studies, and there may be annual differences in diet attributable to season (Thompson and Furness 1995), or perhaps age and gender.

Like other petrels, fulmars produce stomach oil that is stored in a large proventriculus (Warham 1990). Oils from consumed prey are converted to a high-energy stomach oil, and this may occasionally be fed to chicks (along with regurgitated, partially digested prey), or used as fuel for self-maintenance (Hatch and Nettleship 1998). The walls of the proventriculus are muscular, and this adaptation allows fulmars to projectile vomit stomach oil as a defense mechanism against key predators like common ravens (*Corvus corax*) and glaucous gulls (*Larus hyperboreus*), or against conspecifics during competitive interactions (Warham 1990; Hatch and Nettleship 1998).

Environmental threats

Wildlife inhabiting the Canadian Arctic now face a variety of new threats to marine ecosystems, principally attributable to human activities in and south of this region. Threats may be direct, that is, activities that result in the immediate disturbance, impairment or death of birds, and include: harvest, fisheries, ecotourism, and oil spills. Indirect threats are those that may be chronic, accumulating through time, or may affect body condition and health, and include: contaminants, particulate garbage, and climate change. I review how each of these may affect Arctic fulmars below.

Harvest

In Europe, fulmar adults, young, and eggs were formerly harvested in Iceland, the Faeroe Islands, and St. Kilda, UK, but this harvest declined following disease outbreaks (ornithosis) among the fulmars and people eating them in the 1930s (Fisher 1952). However, harvest of adults, young, and eggs has resumed in the Faeroe Islands, with up to 20 000 adult, 100 000 juvenile, and 10 000 eggs harvested annually (Fängström et al. 2005*a*). These birds are all local breeders, and thus would not affect populations in Canada.

In some parts of western Greenland, local communities harvested adults and eggs as food (Salomonsen 1979). In particular, harvest is notably high in the Umanak District (Salomonsen 1967), accounting for 4% of the Greenland fulmar population (est. 200 000 pairs). This harvest continues (Lyngs 2003), but in much lower numbers than other marine birds like eiders, murres, kittiwakes, and gulls (Hansen 2002), and presumably affects Greenlandic fulmars near colonies, and not Canadian fulmars entering offshore Greenland waters. In the Canadian Arctic, there is currently no harvest of fulmars or their eggs (Priest and Usher 2004), although the eggs were consumed by some Inuit communities in the past. Thus, intentional harvest of fulmars does not occur in sufficient numbers to affect Canadian populations, nor to provide samples for scientific study.

Longline fisheries

While fishing activities around the world have had indirect, positive effects on some seabirds by providing increased access to offal and bait, many seabirds are caught and killed by various fishing techniques. Montevecchi (2002) provided a good summary of the interactions between seabirds and fisheries, and in particular he identified the different types of fishing techniques, and which species were more vulnerable to bycatch with each method. For example, pursuit divers (e.g., alcids) were more susceptible to capture in nets, whereas gulls and petrels were more susceptible to capture in longline techniques.

Although fulmars in some regions exploit commercial fisheries for food (Phillips et al. 1999), and these fisheries may have contributed to the increase in fulmar populations of the North Atlantic Ocean (Fisher 1952), there is ample evidence that certain fishing techniques may now be having a significant, deleterious impact on these birds. Relatively few fulmars appear to be caught in drift or gill nets (DeGange and Newby 1980; DeGange and Day 1991), but bycatch in longline fisheries may be very high (Stehn et al. 2001). In the northeastern part of the North Atlantic Ocean, estimates are that 50 000 – 100 000 fulmars may be caught each year in demersal longline fisheries (Dunn and Steel 2001), and

Fig. 3. A northern fulmar hooked through the wing and collected aboard a longline fishery vessel operating in Davis Strait, Nunavut, Canada, 2002. Fulmars often grab bait as it is submerging when lines are being set. Some birds get caught by the hook, and then are dragged underwater and drowned.

fulmars are the most numerous species caught in Alaska (Bakken and Falk 1998; Chardine et al. 2000). This represents about 1% of the world population killed in bycatch each year, which is not considered a threat to overall populations (Dunn and Steel 2001).

Canadian monitoring in Baffin Bay suggests that approximately 500 birds are captured on hooks used in longlines (Fig. 3), mostly fulmars (Chardine et al. 2000). However, Greenlandic fishermen are also active in this region, but they have not reported any bird bycatch, which undoubtedly occurs. Therefore, mortality of fulmars due to bycatch in Arctic Canada is higher than has been reported, but probably insufficient to affect fulmar populations. Despite this, the needless mortality of such large numbers of these birds when successful, mitigative deterrence measures are available (e.g., Løkkeborg and Robertson 2002) should remain a conservation concern (Dunn and Steel 2001).

Oil spills

With increasing levels of ship traffic and resource exploration and extraction underway in Arctic waters, the possibility of oil spills is increasing (Dickins et al. 1990). Oil spilled in marine environments can have devastating effects on marine birds (Piatt et al. 1990; Ford et al. 1996). Even small amounts of oil are capable of killing birds (Burger and Gochfield 2002).

Based on some recent examples, such as the Exxon Valdez spill in Alaska, fulmars do not appear to be heavily affected by oil spills (Piatt et al. 1990; Hatch 1993), especially compared to diving birds like the alcids. Hatch (1993) also postulated that fulmars may be able to avoid oil spills with their good sense of smell (Warham 1990). If an oil spill did occur in Arctic waters, the vast distribution of fulmars (Huettmann and Diamond 2001) suggests that some birds would be affected (many of which could be non-breeders), but probably not on the magnitude expected for murres or eiders (Dickins et al. 1990). The effects would also be dependent on the time of year; a spill during periods when fulmars are aggregated (e.g., spring migration, or close to a colony at fledging) could have catastrophic effects on a local population, whereas a spill during late incubation or chick-rearing might show reduced effects. Moreover, if relatively few breeding birds were oiled, it would be difficult to detect their absence by monitoring at a colony, as the few birds that would be affected (i.e., not return to the nest) might be within the range of normal levels of nest abandonment. Thus, the threat of oil spills to local breeding populations and our ability to detect spill effects might be better monitored with other Arctic seabirds.

Ecotourism

Many governments and agencies in Canada and other polar countries are recognizing the damage that ecotourism can potentially cause to seabird colonies (Hofman and Jatko 2000; Walker et al. 2005). Disturbance may take the form of approaches by people or vehicles that are too close to breeding birds, or alternately loud noises from vehicles, both of which can cause birds to jump from their nests (Ward et al. 2002). These actions can lead to increased physiological stress on the birds (Walker et al. 2005), can expose their eggs or young to predators, or cause the eggs to roll out of the nest (Ward et al. 2002). In the case of many Arctic seabirds, clutch sizes are small, and if damaged or abandoned, often cannot be replaced within that breeding season. Importantly, ecotourism expeditions to the Arctic, especially from cruise ships, are increasing in number (Hall and Johnston 1995), thereby exposing fulmars and other birds to more disturbance during breeding than would be experienced without tourism.

Dunnet (1977) suggested that fulmars were not greatly affected by aircraft flights near colonies, although he examined relatively few nests. During Arctic survey and research work (Gaston et al. 2006), I have also found that fulmars, unlike murres, remain attentive to their nests despite close passes of helicopters or aircraft. However, Ollason and Dunnet (1980) found that more fulmar nests failed in years with greater numbers of observers and consequently higher disturbance of nesting birds at Eynhallow, Orkney. This would be a potential concern for colonies that are visited by tourists, except that in Arctic Canada, fulmars nest on the highest parts of the cliffs, which are inaccessible to most ship- and land-based observers. Of more concern may be disturbance to fulmars foraging on the water surface, but we have no data to assess this possibility.

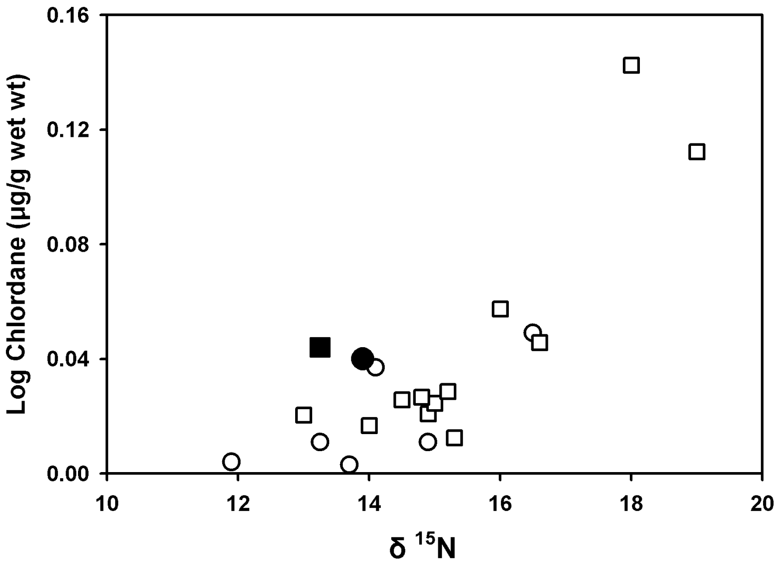
Contaminants

Contamination of Arctic terrestrial and marine environments by persistent organic pollutants (POPs) and trace elements is widespread and circumpolar; almost all Arctic wildlife examined carry some level of contaminant burden (detailed reviews in AMAP 1998, 2004; Braune et al. 2005). The majority of pollutants arrive in the Arctic as a result of long-range transport from regions far to the south (Muir et al. 1992; Bright et al. 1995; Bidleman et al. 2003).

As top predators in marine ecosystems, seabirds tend to bioaccumulate contaminants, and thus have served as good indicators of marine chemical contamination (Burger and Gochfield 2002). Exposure to contaminants like persistent organic pollutants (POPs) or toxic trace elements can affect the immune, endocrine, and nervous systems, as well as internal organs (reviewed in Blus 1996; Hoffman et al. 1996; Peakall 1996; Wiemeyer 1996; Gabrielsen and Henriksen 2001; Burger and Gochfield 2002), and thus these contaminants may pose a concern for the long-term health of fulmars and other seabirds. In particular, POPs are lipophilic and thus accumulate in fatty tissues. Many POPs also accumulate with age, and can be retained in birds for more than a year (e.g., Clark et al. 1987); this may be particularly important (but not yet addressed) in fulmars, because they are amongst the longest lived of any Arctic bird (likely >50 years; Dunnet 1991). These chemicals may affect adult individuals most at times of energetic stress when lipid reserves are low and hence POPs are mobilized (Fisk et al. 2005), such as breeding (Wayland et al. 2002) or periods of starvation (Daoust et al. 1998; Takekawa et al. 2002).

Seabirds have been used since the 1970s to monitor contaminants in the North Atlantic and Arctic oceans (Muir et al. 1992, 1999), with focal species including thick-billed murres, black-legged kittiwakes, fulmars, glaucous gulls, and black guillemots. Unfortunately, fulmars have not been a key component of much of the recent marine environmental health research undertaken in the Barents Sea (e.g., Borgå et al. 2001; Gabrielsen and Henriksen 2001; Hop et al. 2002), so there are relatively few, recent published data on contaminants in fulmars from that region compared to other species (Tables

Fig. 4. $\mathrm{Log}_{10}(x + 1)$-transformed average concentrations of $\sum$chlordanes in livers (circles) and eggs (squares) of seabirds in eastern High Arctic, Canada, compared to $\delta^{15}N$ values of tissues for dovekies *Alle alle*, ivory gulls *Pagophila eburnea*, black-legged kittiwakes *Rissa tridactyla*, thick-billed murres *Uria lomvia*, black guillemots *Cepphus grylle*, and glaucous gulls *Larus hyperboreus*. Northern fulmars (*Fulmarus glacialis*) are indicated by filled circles and squares, and in both cases their values fall well above values for other seabirds feeding at a similar trophic level. Data are from Braune et al. (2001, 2002) and Buckman et al. (2004).



1, 2). Savinov et al. (2003) examined trace elements in 13 marine bird species in the Barents Sea, and found that fulmars had the highest concentrations of Cd and Hg, and were among the species with the highest Zn, As, and Se. Thompson et al. (1998) used fulmar feathers to examine temporal patterns of Hg accumulation over the past century, and to demonstrate that Hg loads differ between colonies, which may be attributable to differences in key prey items at the two locations. F ängström et al. (2001, 2005*a*, 2005*b*) examined contaminants in fulmar eggs and adult tissues from the Faeroe Islands, and found that concentrations of certain POPs are high in Faeroese fulmars, similar to earlier results from Svalbard in the 1970s and 1980s (Mehlum and Bakken 1994; Table 2).

Studies across the Northwest Atlantic Ocean, including the Canadian Arctic, show that northern fulmars carry substantial concentrations of a variety of contaminants (Tables 1, 2), although the most recent data from Greenland is from the 1980s (fulmars have not been part of the recent toxicological assessments in that country; Riget et al. 2004; Vorkamp et al. 2004). In fact, fulmars tend to bioaccumulate proportionally higher levels of most POPs relative to sympatric seabirds and relative to their trophic level (Fig. 4; Braune and Simon 2003; Buckman et al. 2004), similar to ivory gulls (*Pagophila eburnea*), perhaps attributable to the fact that these two species acquire some contaminants by scavenging marine mammal carcasses. Because ivory gull populations appear to be in rapid decline (Gilchrist and Mallory 2005), it may be difficult to sample this species in the future, and thus fulmars will occupy a unique position among Arctic seabirds in relation to their contaminant concentrations and trophic position.

In the Canadian Arctic, fulmar tissues have been analyzed for a variety of trace elements (Table 1), but notably for cadmium (Cd), mercury (Hg), selenium (Se), and zinc (Zn). Between 1975 and 1998, concentrations of Se in fulmars declined, but Hg concentrations increased by 50% (Fig. 5; Braune et al. 2001). Moreover, fulmars had higher concentrations of Cd, Hg, and Se than kittiwakes or murres (Braune and Simon 2004; Campbell et al. 2005). In fact, fulmars had higher concentrations of Cd, Mn,

Table 1. Trace element concentrations (μg/g dry wt) in northern fulmars (values with * are approximations calculated from wet weights, assuming dry weight ~0.33 × wet wt).

Tissue	Al	As	Cd	Cu	Fe	Hg	Mn	Pb	Se	Zn	Reference
Northwest Atlantic											
Muscle			2.8			0.8			7.8	59	1*, 2*
Liver			30.8			6.3			28.5	167	1*, 2*
Egg						0.7–1.4			3.3–4.4		3
Egg		<1.5	<0.24	5.4	135	1.0	<1.5		3.3	45	4
Liver		2.4	30	14	960	6.3	11.4	<0.5	42	144	4
Muscle	36.1	2.2	0.1	14.2	156.6	0.1	1.5	<1.0	2.0	72.6	5
Liver	<33	8.0	5.8	140.8	1786	0.8	16.0	<1.0	4.2	256.0	5
Muscle		8.2	3.5	15.9		1.2	2.0	<1.0	12.3	61.8	6*
Liver		20.8	65.4	18.7		10.2	12.9	<1.0	30.0	189.6	6*
Muscle						0.8					7
Northeast Atlantic											
Feather						0.9–11.5					8
Muscle		1.1–4.8	1.8–8.7	17.0–22.0		0.1–0.7			2.6–8.6	46.0–69.3	9
Liver		2.9–10.2	16.4–109	18.4–22.1		2.0–5.7			10.2–18.8	142–268	9
Liver			57.1	20.8		7.1			10.1	245	10

Note: 1, Neilsen and Dietz 1989; 2, Dietz et al. 1996; 3, Braune et al. 2001; 4, Braune and Simon 2004; 5, Mallory et al. 2004*c*; 6, Campbell et al. 2005; 7, Atwell et al. 1998; 8, Thompson et al. 1998; 9, Savinov et al. 2003; 10, Norheim 1987.
[a]Calculated from wet weights.

Table 2. Persistent organic pollutant concentrations (ng/g lipid normalized means) in northern fulmars.

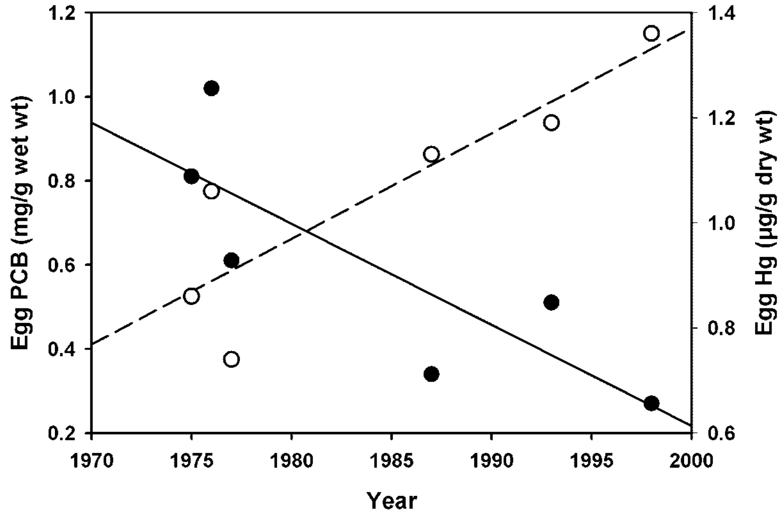
Tissue	ΣPCB	ΣDDT	ΣCHLOR	Dieldrin	ΣPCDD	ΣPCDF	ΣNOPCB	ΣPBDE	ΣMIREX	ΣCBz	ΣHCH	Reference
Canadian Arctic												
Muscle	449	355	204	78					12	178	9	1
Liver	468	306	376	202					11	180	8	1
Egg[a]	2371–8767	1849–7405	860–1240	110–145					90–154	330–634	18–26	2
Liver			2139–3000									3
Liver[a]	4158	4579	2518	539					108	492	47	4
Liver					2.4	7.2	24.1					5
Egg					0.2	0.6	5.5					5
Liver								D[b]				6
Egg								D[b]				6
Northeast Atlantic												
Muscle	5800–24000	1700–20000						6–110		92–590		7
Egg	3300–18000	1000–7000						11–42		74–580		7
Muscle	23400	4500										8
Liver	1800–45700	300–18000								200–1400		8
North Pacific												
Liver	10921	6289	2842	nd					447	500	79	9

Note: D, detected but not quantified; nd, not detected; 1, Mallory et al. 2005; 2, Braune et al. 2001; 3, Fisk et al. 2001; 4, Buckman et al. 2004; 5, Braune and Simon 2003; 6, Braune and Simon 2004; 7, Fängström et al. 2005*a*; 8, Mehlum and Bakken 1994; 9, Elliott 2005.

[a]Calculated from wet weights.

[b]Other halogenated organic compounds detected included toxaphene, polychlorinated terphenyls, and halogenated dimethyl bipyrroles.

Fig. 5. Concentrations and trends in $\sum$PCB (solid circles, solid line) and Hg (open circles, dashed line) in eggs of northern fulmars sampled at Prince Leopold Island, Nunavut (data from Braune et al. 2001).



rubidium, Hg, and Zn than all other seabirds sampled in northern Baffin Bay (Campbell et al. 2005). Collectively, trace element concentrations show considerable variation within and among geographic regions across the Arctic, with little evidence of differences between the Northeast and Northwest Atlantic Ocean, except perhaps for Se (Table 1).

Among the POPs, fulmars have been tested for chlorobenzenes (ΣCBz), hexachlorocyclohexanes (ΣHCH), chlordane-related compounds (ΣCHLOR), DDT and its metabolites (ΣDDT), mirex (ΣMIREX), dieldrin, polychlorinated biphenyls (ΣPCB), polychlorinated dibenzo-*p*-dioxins (ΣPCDD), polychlorinated dibenzo-furans (ΣPCDF), non-*ortho* PCBs (ΣNOPCB), and polybrominated diphenyl ethers (ΣPBDE, in Europe only, Table 2). Concentrations of DDT, PCBs, and ΣCBz declined from the 1970s to the 1990s, while there was no consistent trend in ΣCHLOR, dieldrin, mirex, and ΣHCH (Braune et al. 2001). This general assessment masks some of the patterns, however. For example, although ΣHCH showed no consistent trend, α-HCH showed declines, while β-HCH increased. Between 1975 and 1993, concentrations of PCDDs and PCDFs declined by more than 70% in fulmar livers, but NOPCBs were nearly five times higher in the 1990s than 1970s (Braune and Simon 2003), the latter counter to the pattern observed in kittiwakes and murres. Overall, the contaminant concentrations in fulmar tissues from the Canadian Arctic appear to be lower than those from fulmars in the Northeast Atlantic Ocean or the North Pacific Ocean (Table 2).

The interpretation of chemical data from seabirds requires a careful knowledge of their annual and seasonal habitat use, foraging patterns and body condition, as well as the accumulation and biomagnification processes for various contaminants (Hobson 1993; Braune et al. 2001; Hobson et al. 2002; Buckman et al. 2004). In particular, most Arctic seabirds are migratory, and thus some of the contaminants they carry are picked up in their southern wintering grounds. At present, there is no evidence that fulmar health is being affected by contaminant concentrations presently found in Arctic birds (Braune et al. 2001; Braune and Simon 2003, 2004), but increasing trends in some chemicals like Hg and β-HCH should be cause for concern.

The fact that fulmars accumulate high levels of contaminants causes concern for the health of the species and for the environment in which they feed, but fulmar guano may also be an environmental issue. Blais et al. (2005) showed that sediments in freshwater ponds receiving runoff from cliffs at the Cape Vera fulmar colony had high levels of various contaminants, notably organochlorines like DDT. Because these ponds were eutrophic and were used by other wildlife, Blais et al. (2005) postulated that fulmars act as a conveyor belt, transporting and concentrating contaminants from the marine environment and depositing them for uptake in terrestrial systems.

Particulate garbage

One environmental threat to Arctic fulmars that has received little attention is the ingestion of plastic debris (garbage). Marine plastic debris is now a circumpolar issue affecting a wide range of marine species (Laist 1997). The debris comes from industrial sources around the world, and is dominated by packaging materials (Dixon and Dixon 1981). Ingestion of plastic is a potential problem for birds, and especially for procellariids, because they have the highest incidence of plastic ingestion (Nisbet 1994), and do not regurgitate indigestibles like other seabirds.

Indeed, many procellariids seem particularly vulnerable to the accumulation of plastic (Robards et al. 1995), including fulmars, where 84% of the birds sampled in 1988–1990 in the North Pacific Ocean contained plastic, similar to the 86% found by Moser and Lee (1992) in the Atlantic Ocean off of North Carolina. Van Franeker (1985) found that more than 79% of fulmars in Holland, Bear Island or Jan Mayen contained plastics. He also found that the number of ingested particles was lower in Arctic birds compared to birds near Holland. Furness (1985) showed that plastic pieces comprised 0.1% of fulmar body mass and filled 59% of the volume of the gizzard in some fulmars near Scotland.

Ingested plastic debris can have a variety of effects on host birds (Burger and Gochfield 2002). Sharp pieces can cause internal ulcerations that can become infected. It can also accumulate to the point where debris can completely obstruct the digestive tract, and thus deleteriously affect avian body condition (Ryan 1987). Digestion of plastic debris can also introduce increased contaminant loads to the body of the bird (van Franeker 1985). Disturbingly, levels of plastic debris in the oceans have increased (Ryan and Moloney 1993), and concomitantly, ingestion in seabirds, including fulmars, appears to have increased in both North Atlantic and North Pacific oceans (Robards et al. 1995; van Franeker 1985).

In the Canadian Arctic, there has been no published information on plastic debris in fulmar diets (Hatch and Nettleship 1998), despite studies of regurgitations and of collections of birds (Bradstreet 1976; Bradstreet and Cross 1982). This information was collected in the 1970s and is thus outdated, particularly given that other researchers have found trends of increasing plastic in fulmars elsewhere (Robards et al. 1995). In fact, Mallory et al. (2006) recently found plastic debris in 36% of fulmars caught in 2002 by longline fisheries in Davis Strait, and I found plastic debris (bottle cap liners, adhesive bandages) in fulmars collected at the Cape Vera field site (Fig. 1) in 2003 (M.L. Mallory, unpublished data; Fig. 6).

Climate change

Recent studies have shown that changing climates are affecting terrestrial and marine wildlife (e.g., Planque and Taylor 1998; Post and Stenseth 1999; Post et al. 1999; O'Brien et al. 2000; Kitaysky and Golubova 2000; Barbraud and Weimerskirch 2001). The Arctic marine environment in particular is changing rapidly in response to climate change, best demonstrated by a reduction in sea-ice coverage, and an increase in sea surface temperatures (Vinnikov et al. 1999; Parkinson 2000). These changes are expected to affect many different Arctic species — already deleterious effects have been found for polar bears *Ursus maritimus* (Stirling et al. 1999) and caribou *Rangifer tarandrus* (Miller and Gunn 2003).

Some of the physical products of climate change, such as declining sea-ice extent and increased sea surface temperatures, have now been linked to annual reproduction or population levels in fulmarine petrels. Garthe (1997) and Begg and Reid (1997) found positive correlations between at-sea distributions of fulmars and sea-surface temperatures and salinity. Thompson and Ollason (2001) found that fulmar hatching success, fledging success, and attendance at the Eynhallow colony (Scotland) were all lower in years of higher NAO Index values, and there was a trend of increase in the NAO since the 1960s. Survival of adult fulmars also declined during the period of increasing NAO index (Grosbois and Thompson

Fig. 6. Garbage from the proventriculus of one fulmar collected at Cape Vera, Devon Island, Nunavut, in 2004. Items are principally various forms of plastic, including an adhesive bandage and a bottle cap liner.

2005). In Antarctica, Jenouvrier et al. (2003) showed that the closely-related southern fulmars (*Fulmarus glacialoides*) experienced higher breeding performance in years with greater sea-ice coverage, although they considered year-round ice conditions, and they related annual breeding and long-term demographic parameters to different ice conditions annually and across years.

At a more proximate level, Gaston et al. (2005) found that northern fulmars breeding at Prince Leopold Island, Arctic Canada, had longer incubation shifts and lower nestling survival in years with more extensive ice conditions in Lancaster Sound. They postulated that the increased sea-ice meant further flight distances from the colony to find food, which meant breeding birds incurred higher energetic costs to incubate or rear young (Furness and Bryant 1996). However, the long incubation shifts continued well after sea-ice had broken up, and thus Gaston et al. (2005) also suggested that overall marine productivity was probably reduced in extensive ice years (Welch and Bergmann 1989; Welch et al. 1992), meaning less food was available for fulmars to find.

Collectively, these results are a concern for wildlife management organizations in Canada, because there is conflicting information among studies on the possible effects of climate change on fulmars and other marine birds. Despite the confusion, it is clear that marine conditions are changing (e.g., Vinnikov et al. 1999) and that marine birds will have to respond or adapt to these new conditions.

Suitability of fulmars as monitors of marine ecosystem health

Given the suite of environmental threats currently faced by Arctic marine ecosystems, how might the fulmar serve as a monitor for these issues? To address this question, we must examine how characteristics of the fulmar might be affected by these threats. Here I exclude the issues of harvest, longline fisheries and oil spills. These issues all have the potential to affect Arctic fulmar populations (above) and other Arctic seabirds, and evolving economic development initiatives in Arctic Canada may include hydrocarbon extraction (e.g., Dickins et al. 1990) and increased fishing activity. However, these threats do not occur currently in the Canadian Arctic, or are unlikely to occur at sufficient levels to be detected by colony

Table 3. Summary of the suitability of various physical or reproductive traits of fulmars to monitoring the effects of various marine ecosystem stressors, assessed as poor (P), good (G), and very good (VG).

	Marine ecosystem stressors			
Parameter	Ecotourism	Contaminants	Garbage	Climate change
Diet	P	G	VG	G
Body condition	P	G	G	G
Colony attendance	P	P	P	VG
Reproductive phenology (nest initiation, hatch date)	P	P	P	P
Clutch size	P	P	P	P
Egg size	P	P	P	P
Incubation shift length	P	P	P	VG
Reproductive success	P	P	P	VG
Body tissues	P	VG	P	P

monitoring. Thus, I focus on monitoring the effects of ecotourism, contaminants, garbage, and climate change.

Unlike other birds (e.g., waterfowl; Mallory et al. 1994), certain reproductive traits of fulmars seem to exhibit little variation, and thus would not be sensitive to changes in environmental quality. For example, all fulmars lay a single egg (Warham 1990, 1996), and egg size shows little difference among years (Gaston et al. 2005), so these traits are unlikely to reflect differences in annual habitat conditions. Nest initiation dates also show minimal variation (Hatch and Nettleship 1998). In fact, in his exhaustive review of fulmar breeding, Fisher (1952: 374) wrote:

> It must be the most predictable of all the seabirds of the North Atlantic. Never, in all the literature through which I have laboriously ploughed, have I come across "The fulmar laid early this year".

Given these facts, I have rated clutch size, egg size, and reproductive phenology as "poor" traits for monitoring marine ecosystem stressors (Table 3).

In contrast, monitoring fulmar diet should prove a "good" to "very good" monitoring tool for at least three environmental threats. First, examining fulmar diet will continue to allow researchers to track how contaminants are sourced and how they bioaccumulate in the marine food chain (Braune et al. 2001). This is particularly important because fulmars eat a broad array of items; adjustments in diet could be reflected in long-term changes in contaminant profiles. As well, fulmars appear to be one of the few Arctic marine birds that eat and accumulate particulate garbage (Robards et al. 1995), although this often is found in the gizzard. The drawback, therefore, is that birds may have to be sacrificed to be able to monitor this pattern. Nonetheless, the global pattern of increasing marine particulate debris (Laist 1997) and the lack of debris in fulmar diet samples from the 1970s (Bradstreet 1976) suggests that this is an increasing problem in the Canadian Arctic. At this time there are no data on the source of this garbage. Finally, diet may also give cues to effects of climate change on the marine ecosystem. Fulmars are generalist predators, and thus we expect them to eat what is available. As the relative distribution and abundance of various marine zooplankton or fish change with changing marine conditions (e.g., increasing sea temperatures or reduced ice cover), fulmar diet should reflect these patterns. This will be particularly true if new species invade Arctic waters; Gaston et al. (2003) documented shifts in the marine fish assemblage in northern Hudson Bay by monitoring the diet of murres. Because fulmars are colonial and their foraging range can be determined with current tracking technologies (Falk and Møller 1995), researchers can pinpoint where marine trophic webs are changing by monitoring fulmar diets.

Fulmar body condition varies through the breeding season (Hatch and Nettleship 1998), but there has been relatively little investigation of body condition in relation to stress. As with many other marine birds, adequate body condition is essential for fulmars to enter reproduction (Warham 1990, 1996), and periods of low food availability may result in starvation, reduced attendance at colonies, skipped breeding, or in some cases mortality (e.g., Schreiber 2002). Theoretically, fulmars stressed by high contaminant burdens or deleterious levels of particulate garbage may be in reduced physical condition (Furness 1985); evidence already suggests that climate-induced food reductions affect body condition and survival in fulmars (Thompson and Ollason 2001). However, this may be difficult to assess directly by monitoring colonies, because birds in poor condition may not attend the colony. Thus, given that healthy fulmars attend the colony almost annually to breed (Hatch and Nettleship 1998), variations in colony attendance should be good indicators of ecosystem stress, as has already been shown for factors linked to climate change. However, to directly assess whether the stress was related to food supply, contaminants or garbage, birds would have to be collected and tested for these factors, and this would require sampling at sea, as these birds would not likely show up at colonies. It would seem that the high numbers of birds caught in fisheries bycatch (Dunn and Steel 2001) should prove a useful source of samples to test for effects of contaminants or garbage on body condition, at least by correlation.

During the breeding season, monitoring of colony attendance, incubation shift length, and reproductive success of nesting fulmars should prove to be very good indicators of the effects of climate change and associated long-term change in marine conditions. Already research has shown that some or all of these parameters are related to broad-scale climate patterns, notably the effects of sea-ice (Jenouvrier et al. 2003; Gaston et al. 2005) or winter food supply (Thompson and Ollason 2001; Grosbois and Thompson 2005). Continued monitoring should produce data that will allow for the development of statistical models that can predict long-term trajectories of Arctic fulmar populations in response to climate change (similar to Grosbois and Thompson 2005). However, for the other stressors (contaminants, garbage), there is no evidence that fulmar reproductive parameters measured at the colony will respond to changes in stressor intensity, because body condition would likely be affected first, and thus the birds might not attempt to breed.

Given their role as top predators and scavengers, their general abundance over Arctic waters, and the evidence that concentrations of many contaminants in their tissues are elevated (particularly related to their trophic position; Fig. 4; Braune et al. 2001; Savinov et al. 2003), fulmars fill a somewhat unique position relative to other Arctic marine birds in regards to contaminant monitoring (Fig. 4). Investigating contaminant levels and accumulation pathways in fulmars provides insights into more complex contaminant transfer pathways than in simpler food chains such as found for murres and guillemots. For example, fulmars may be acquiring some contaminants during the digestion of particulate garbage they consume. Importantly, fulmars acquire contaminants from a wide variety of sources, and concentrations of some toxic elements or organic compounds may be reaching levels that have deleterious effects on this species, as has been found for glaucous gulls (Sagerup et al. 2000). Fulmars are also common, such that low intensity but destructive sampling will not have deleterious effects on populations. Thus, as with particulate garbage and climate change, fulmars appear to be highly suitable monitors of contaminants in the Arctic marine environment.

In contrast to these other ecosystem stressors, I suggest that fulmars are not useful as monitors of the effects of ecotourism, at least not in the Canadian Arctic. In this region, fulmars nest high on cliffs (Hatch and Nettleship 1998), and are remote from boats and from land-based access by tourists. Even when loud noises are emitted near colonies or aircraft pass by, fulmars tend to remain on their nests, unlike sympatric breeding seabirds species. Thus, potential deleterious effects of ecotourism stress on colonies are unlikely to manifest themselves in the parameters that we can measure with nesting fulmars (Table 3).

Inuit traditional ecological knowledge

Given that most Canadian fulmars inhabit the Arctic, an area which remains remote and logistically-challenging to conduct research, one form of monitoring that might prove useful for fulmars is examining the information held by Inuit communities of this region. Traditional ecological knowledge (TEK) is gaining increasing attention as an overlooked data source, particularly for remote wildlife populations in the hunting grounds of various aboriginal peoples (Berkes et al. 2000; Mauro and Hardison 2000). Use of TEK is actively advocated in the Arctic (Duerden and Kuhn 1998).

In the case of the fulmar, there was evidence that Inuit may possess TEK on this species, as the fulmar is part of Inuit legend in the "Sedna" mythology (Fisher 1952). Thus, I investigated TEK on fulmars in two communities in Nunavut, Canada, using methods described in Mallory et al. (2003). Between 2000 and 2002, traditional ecological knowledge (TEK) was gathered on fulmars from Inuit living in Qikiqtarjuaq and Arctic Bay, Nunavut (see Gilchrist et al. 2005 for definitions). The fulmar is known as "qaqulluk" to Inuit, and is a familiar bird to Inuit living in communities of eastern Nunavut. However, the fulmar has not often been a key harvested species by Inuit, and as such, TEK was quite limited compared to other birds (Mallory et al. 2004*b*; Gilchrist and Mallory 2005). In Arctic Bay (near the Baillarge Bay colony), interviewees indicated that fulmars were not desired as food, and were consumed only at times when community members were starving. In contrast, at Qikiqtarjuaq (formerly Broughton Island), interviewees indicated that both eggs and adult fulmars were harvested quite heavily in the past, before the community was relocated from Padloping Island (near the Cape Searle colony) to Broughton Island, 100 km north, in the late 1960s. Even while the community was close to the colony, fulmars could only be accessed into part of the incubation period before the sea-ice became too unsafe to travel across; hence, Inuit had limited information on fulmars during chick-rearing. Moreover, for both communities, the vast majority of the fulmars nested high on unsafe cliffs, so relatively few hunters spent much time watching or accessing nests. Thus, interviewees provided little information on nest initiation dates, hatching or fledging dates, diet, or responses to weather patterns.

Collectively, available Inuit TEK on fulmars seems to be of little use for monitoring population trends in Arctic colonies, or for examining potential effects of anthropogenic stressors on these birds. Instead, typical western scientific approaches of surveys (Gaston et al. 2006), colony monitoring (Mallory and Gaston 2005), and specimen sampling (Braune et al. 2001) will prove essential.

Information gaps

Because there has been a paucity of research on fulmars in the Canadian Arctic, there are many aspects of their ecology that remain unknown. Filling in some of these gaps will be essential to allow proper interpretation of information about Arctic marine ecosystem health acquired from monitoring the effects of stressors on Arctic fulmar populations.

Perhaps the key information gap that exists on Arctic fulmars is site-specific data on annual reproductive behaviour, effort and success, and the natural variation that exists in these parameters. For example, we do not know whether there are threshold values for female body condition below which birds do not attempt to lay eggs, or body condition of either parent below which they abandon a nesting attempt. Also unknown is the effect of storms on reproduction, beyond anecdotal observations (Hatch and Nettleship 1998). The unknown factors that determine where birds nest are particularly important: why are there only 11 large and no small fulmar colonies in Arctic Canada, despite thousands of kilometres of cliff coastline? More importantly, what might this mean for the ability of fulmars to initiate new colonies, should conditions become unsuitable at existing sites?

Some aspects of fulmar reproduction from the colony at Prince Leopold Island have been published in summary form in Hatch and Nettleship (1998), but otherwise are unknown. Gaston et al. (2005) provided more recent information on reproductive success of fulmars in relation to climate change, also from the Prince Leopold Island colony, but there are no studies from any of the other major colonies in Nunavut (beyond survey data; Brown et al. 1975; Gaston et al. 2006). It will be critical to understand whether colony-specific differences exist in annual reproduction — we should expect some differences, as some colonies are located near polynyas (Cape Vera), some by broad ice sheets (Prince Leopold Island), and some near moving pack ice or open water (Cape Searle). Intuitively, these differences in the physical foraging environment will mean that, for much of the year, fulmars at various colonies will face considerably different phenology of and accessibility to food supplies. If distances traveled to find food vary, then this could translate into behavioural differences (e.g., incubation scheduling) and breeding success. More importantly, if environmental conditions are changing, fulmars will need to be able to adapt to these changes if colonies are to persist. To assess whether there is potential for these birds to adapt to change, we must determine both the flexibility in their reproductive behaviours, the variation in these behaviours that presently exists within a colony, and the costs and benefits of these behaviours in relation to different environmental conditions.

A second major gap in our knowledge of fulmars in Arctic Canada relates to their foraging, migratory and overwintering movements. We know that many birds forage in Lancaster Sound and Baffin Bay based on at-sea surveys (Huettmann and Diamond 2000), but we do not know what proportion of these birds are breeders and non-breeders. For breeding birds, we have no information on specific foraging locations for the various colonies; presumably many of the birds using colonies in Lancaster Sound also feed in that area. This information is required if we are to assess the effects of alterations to marine habitats that appear remote from a colony, but in fact could form a key foraging area for birds from that colony. Because fulmars at Canadian colonies are difficult to access and are not harvested, relatively few birds have been banded or recovered from studies in this region, thereby precluding information on movements from banding records (Hatch and Nettleship 1998). Banding from nearby colonies in Greenland suggests that birds overwinter south of Greenland and east of Maritime Canada (Lyngs 2003), and it is likely that Canadian birds follow this route. However, Braune et al. (2001) noted that contaminant profiles in fulmars had more European patterns for some compounds, indicating that birds may move across the North Atlantic Ocean in the winter. One Greenlandic fulmar was found dead in France (Salomonsen 1979), suggesting that such movements may occur, and certainly fulmars from British colonies are regularly found on the Grand Banks east of Newfoundland, Canada (Lloyd et al. 1991). A better understanding of habitat use by fulmars during the breeding and non-breeding seasons will be essential for understanding factors influencing population change, and for evaluating the effects of anthropogenic activities (e.g., at-sea oil exploration) on feeding areas of birds.

While the available data on contaminant concentrations in fulmars has allowed for exceptional monitoring of contaminant levels in Arctic marine ecosystems (Muir et al. 1999; Braune et al. 2001), we have little information on potential geographic differences in contaminant concentrations in this species (Braune et al. 2002), the amount of contaminants that are acquired during the breeding (i.e., Arctic) and non-breeding (i.e., North Atlantic) seasons, and whether current concentrations have deleterious effects on the health of birds. Most contaminant concentrations are below levels thought to pose health risks to birds (Braune et al. 2001), but considering concurrent environmental stresses placed on fulmars (Table 3), it is possible that existing contaminant levels could have sublethal effects. Indeed, recent studies on other marine bird species have detected sublethal correlations between contaminant concentrations in wild Arctic birds and indices of their health, notably increased parasite burdens and altered immune responses (e.g., Sagerup et al. 2000; Wayland et al. 2001, 2002, 2003). Similar effects studies on fulmars would be useful in establishing the extent to which existing levels of contaminants are affecting wildlife health, and will help to predict what increasing concentrations of some toxic compounds (Hg, PBDEs) may mean for Arctic wildlife.

Finally, a significant information gap remains on the size and trends in fulmar populations of the Canadian Arctic. As described above, fulmars are particularly difficult to census in this region, and size estimates for certain colonies have varied greatly over the past 50 years (e.g., Wynne-Edwards 1952; Gaston et al. 2006). At a practical level, most colonies in Nunavut have insufficient data to allow determination of population trends unless they involve quick and dramatic population change (as recently found for ivory gulls *Pagophila eburnea*; Gilchrist and Mallory 2005). To fill this information need, long-term monitoring plots need to be established at more colonies, and should be regularly counted to ascertain whether populations are changing (Gaston et al. 2006). Intermittent, full-colony censuses should also be conducted for all colonies, at a less frequent interval than plot monitoring, preferably using high resolution photographs which can be counted precisely.

Conclusions

The northern fulmar is a common, wide-ranging seabird found across the North Atlantic Ocean and into the Canadian Arctic Archipelago. Despite knowing relatively little about the ecology of this species in the Arctic environment, monitoring of fulmar reproductive success, diet, or tissue composition has proven to be a useful tool to monitor some aspects of the condition of the Arctic marine ecosystem (Braune et al. 2001; Gaston et al. 2005). It seems clear, therefore, that long-term observation of fulmars at colonies, and intermittent sampling of fulmar tissues, will allow us to further track trends in the effects of these environmental threats in the Arctic. Our ability to interpret the useful and unique data provided by fulmar monitoring would be greatly enhanced by additional research on the breeding biology, movements, population trends, and response to contaminant concentrations in Arctic fulmars. Indeed, with recent technological advances, devices attached to fulmars may be able to provide simultaneous data on a variety of aspects of both fulmar biology and the environmental characteristics of the Arctic marine ecosystem, as has been conducted with Antarctic seabirds (e.g., Wilson et al. 2002).

Early in the 21st century, available data suggest that the northern fulmar population is healthy in Arctic Canada. Limited, long-term monitoring at two colonies indicates that population trends are stable (Gaston et al. 2006), and contaminant monitoring suggests that levels of most trace elements and POPs are elevated, but generally not at levels thought to pose risks to wildlife health. Despite these apparently benign results, fulmars are sending us some alarming signals. Certain toxic chemicals continue to increase through time in fulmar tissues (Braune et al. 2001), alterations to marine productivity have affected fulmar colony attendance, reproductive behaviour and success, and adult fulmar survival (Thompson and Ollason 2001; Gaston et al. 2005; Grosbois and Thompson 2005), and plastic garbage from the ocean has now appeared in the diet of Arctic fulmars (Mallory et al. 2006). Thus, the northern fulmar is not only a valuable monitor of Arctic marine ecosystem health, it is already indicating that some deleterious changes are underway.

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