Polar lessons learned: long-term management based on shared threats in Arctic and Antarctic environments

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The Arctic and Antarctic polar regions are subject to multiple environmental threats, arising from both local and ex-situ human activities. We review the major threats to polar ecosystems including the principal stressor, climate change, which interacts with and exacerbates other threats such as pollution, fisheries overexploitation, and the establishment and spread of invasive species. Given the lack of progress in reducing global atmospheric greenhouse-gas emissions, we suggest that managing the threats that interact synergistically with climate change, and that are potentially more tractable, is all the more important in the short to medium term for polar conservation. We show how evidence-based lessons learned from scientific research can be shared between the poles on topics such as contaminant mitigation, biosecurity protocols to reduce species invasions, and the regulation of fisheries and marine environments. Applying these trans-polar lessons in tandem with expansion of international cooperation could substantially improve environmental management in both the Arctic and Antarctic.

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The Arctic and Antarctic are profoundly different environments. The southern portion of the Arctic is dominated by continental land masses, many of which are seasonally ice-free, whereas the Arctic Ocean and its associated sea ice prevail in the highest northern latitudes. In contrast, Antarctica is a continental land mass surrounded by the Southern Ocean, and only about 0.3% of the Antarctic land area is seasonally ice-free (Shaw *et al.* 2014). The isolation and extreme cold of the Antarctic have contributed to pronounced ecological differences from the Arctic, including the absence of terrestrial megafauna and a continental shelf ecosystem nearly devoid of post-Paleozoic predators (Aronson *et al.* 2011).

In a nutshell:

- Climate change is the most important environmental threat to both the Arctic and Antarctic
- However, until the greenhouse-gas emissions that drive climate change can be reduced, it is crucial to address other threats (including pollution, fisheries overharvesting, and invasive species) that interact with climate change
- International cooperation and the sharing of scientific lessons between the Arctic and Antarctic will allow resource managers to more effectively mitigate these threats and to better protect polar environments

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The intensity and governance of human activities also vary greatly between the Arctic and Antarctic. The Arctic has been continuously inhabited, albeit sparsely, for millennia, and most Arctic land masses belong to sovereign states. While much of the Antarctic has also been claimed by various states, it is governed by the international Antarctic Treaty System, which sets issues of sovereignty aside. The Treaty includes the Protocol on Environmental Protection (the "Madrid Protocol"), which commits Treaty Parties to "comprehensive protection" of the Antarctic environment and prohibits mineral resource exploitation. The Antarctic is also much less explored than the Arctic, and our understanding of broad-scale biogeographic patterns there is still developing.

Despite these differences, the Arctic and Antarctic share characteristics that make them vulnerable to anthropogenic change, including low temperatures that can delay recovery from disturbance, lack of functional redundancy in ecosystems, and potential long-term attractiveness for resource exploitation as more accessible resources are depleted elsewhere. Here, we examine some of the major environmental issues common to both polar regions: climate change, pollution, fisheries overexploitation, and incursion by invasive species (Figure 1). Principal among these is climate change, which interacts with and exacerbates other threats. There is little doubt that addressing climate change is essential for protecting polar environments. Over the short to medium term (ie years rather than decades), however, we suggest that focusing on these interacting threats is crucial to Arctic and Antarctic environmental protection. By sharing research outputs and lessons learned across the poles, we can more easily counteract these problems.

Climate change – the greatest threat

Anthropogenic climate change not only directly affects the environment but also exacerbates other environmental stressors (Panel 1 and Figure 2; IPCC 2014a). Overwhelmingly, it represents the greatest long-term threat to polar ecosystems.

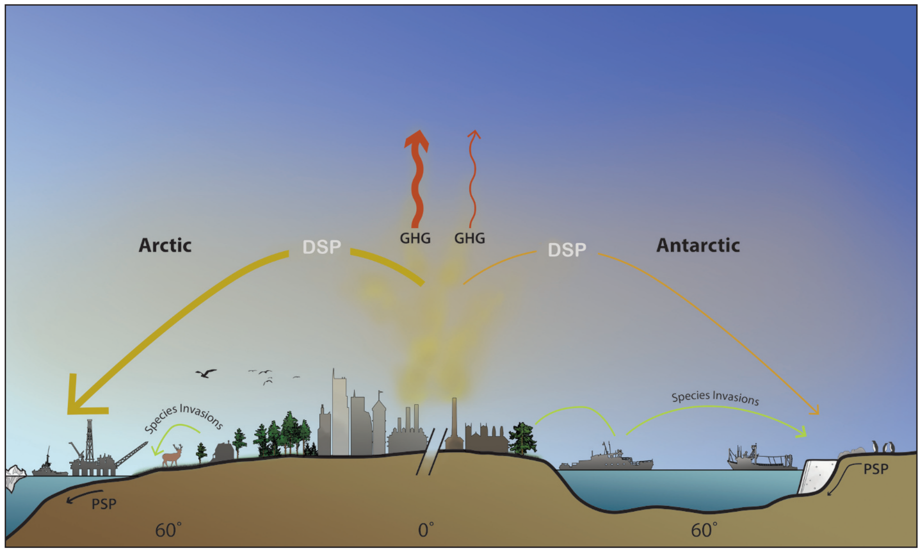

Figure 1. *Shared threats to polar environments. Greenhouse gases (GHGs, red arrows) are the major causes of climate change, the principal threat to polar environments. Climate change interacts with other threats, including diffuse-source pollutants (DSPs) such as persistent organic pollutants and ozone-depleting chemicals that migrate from lower latitudes. It also raises the risk of more localized point-source pollutants (PSPs), as well as fisheries overexploitation (represented by fishing boats) and species invasions (green arrows).*

Arctic warming is widespread, with measurable ecological impacts. For example, shorter and milder Arctic winters have coincided with rapid greening and reduced variation in photosynthetic activity during the growing season (Xu *et al.* 2013). This has led to apparent mismatches between caribou (*Rangifer tarandus*) migration, which is triggered by day length, and temperature-controlled emergence times for forage species, resulting in reduced food availability and increased calf mortality (Post and Forchhammer 2008). Climate change has also promoted seasonal desiccation of many high-Arctic ponds that had been permanent water bodies for millennia, diminishing potential habitat for waterfowl and aquatic organisms (Smol and Douglas 2007).

Changes in Arctic sea-ice cover, snow cover, and greenhouse-gas (GHG) emissions (including methane) from permafrost thaw may induce positive feedbacks that exacerbate anthropogenic warming (Euskirchen *et al.* 2013). Soil warming by only 1°C in the vast Arctic peatlands will increase respiration of carbon (C) stored in peat, potentially releasing up to 100 megatons of C annually, providing further positive feedbacks with anthropogenic warming (Dorrepaal *et al.* 2009). However, permafrost thaw increases nitrogen availability at the thaw front, potentially either increasing biomass production – which could partially offset carbon dioxide (CO_2) release from peat respiration – or facilitating decomposition and subsequent CO_2 release via higher litter quality (Keuper *et al.* 2012). The balance among such opposing influences on atmospheric CO_2 will likely be an important factor in the trajectory of future global climate change.

Sea-ice retreat in the Arctic Ocean has led to increased primary productivity (Pabi *et al.* 2008) but decreased habitat for ice-dependent marine invertebrates, fish, and mammals (Laidre *et al.* 2008; Meier *et al.* 2014). Among Arctic mammals, the hooded seal (*Cystophora cristata*), polar bear (*Ursus maritimus*), and narwhal (*Monodon monoceros*) appear to be the most vulnerable to sea-ice retreat (Laidre *et al.* 2008). In addition, poleward migration of temperate fish species has prompted range shifts and dietary changes for marine birds, including the thick-billed murre (*Uria lomvia*), and mammals such as the harbor seal (*Phoca vitulina*), the northern populations of which specialize on prey such as Arctic cod (*Boreogadus saida*) (Meier *et al.* 2014).

Climate change in Antarctica has been characterized by pronounced regional differences. Parts of east and central Antarctica have experienced decreased annual temperatures. This is due to the loss of ultraviolet-light-absorbing ozone causing stratospheric cooling over the South Pole, resulting in the polar jet stream strengthening and shifting south, and an increased thermal gradient between polar latitudes and mid-latitudes (Robinson and Erickson 2014). Yet the Western Antarctic Peninsula – the repository of most Antarctic terrestrial biodiversity – and Central West Antarctica are warming rapidly (Nicolas and Bromwich 2014), also in part due to the southern shift in the polar jet stream (Robinson and Erickson 2014). Recent research has identified the initial stages of the collapse of the West Antarctic Ice Sheet (Joughin *et al.* 2014). In Antarctic terrestrial ecosystems, climate-related changes are difficult to predict given the paucity of basic data on biodiversity. While differences between the two polar terrestrial systems can complicate direct comparisons, the potential for positive feedbacks from soil temperature changes is likely to be lower in the Antarctic than in the Arctic because of the generally colder climate, lower productivity, and low soil C content; changes to

Antarctic vegetation and associated invertebrate fauna may therefore be less dramatic (Nielsen and Wall 2013).

In the Western Antarctic Peninsula region of the Southern Ocean, sea-ice retreat may have been caused by enhanced meridional winds (Stammerjohn *et al.* 2012), as well as by a southern shift in the polar jet stream (Robinson and Erickson 2014). Sea-ice retreat has been linked to reductions in Antarctic krill (*Euphausia superba*) populations in this region (Meyer 2012). Retreating coastal sea ice may also promote increased primary production by benthic macroalgae and could lead to decreased invertebrate biodiversity in previously ice-covered, low-light, invertebrate-dominated habitats (Clark *et al.* 2013). Moreover, synergistic effects of decreased sea ice and smaller regional krill populations may threaten populations of crabeater seals (*Lobodon carcinophaga*) in the future (Siniff *et al.* 2008).

Ocean acidification, another threat linked to rising CO_2 levels, may lower hatch rates of krill (Kawaguchi *et al.* 2013) and cause shell dissolution in pteropods (Bednaršek *et al.* 2012), potentially inducing population collapses for these key mid-trophic-level organisms. These changes may lead to decreased fecundity and range contractions in Adélie (*Pygoscelis adeliae*) and chinstrap (*Pygoscelis antarctica*) penguins (Trivelpiece *et al.* 2011). Climate-related collapses in Antarctic silverfish (*Pleuragramma antarcticum*) populations may also be responsible for local declines in Adélie penguins (Sailley *et al.* 2013), although the exact nature of climate impacts on Antarctic marine ecosystems in general is still highly uncertain (Constable *et al.* 2014).

Diffuse-source pollution

Many toxic organic compounds released in lower latitudes tend to concentrate in polar regions as a result of condensation in cooler atmospheric temperatures and decreased degradation in cooler environments (Wania and McKay 1996). Chemical contaminants can also be transported considerable distances via ocean currents, and may reach peak levels in the Arctic long after their production has ceased (Gouin and Wania 2007). Hazards to Arctic fauna likely include behavioral modification and reduced fecundity (Jenssen 2006). In addition,

Panel 1. Climate change as a threat multiplier

Anthropogenic climate change is exacerbating many threats to polar environments. In the Arctic, melting ice sheets are leading to increased shipping, potential port developments, and greater militarization (Borgerson 2013), all of which elevate the risk of habitat loss, point-source pollution, and species invasions. Permafrost thaw is also increasing the risk of point-source pollution through damage to oil storage facilities and pipelines that are either anchored to or resting on permafrost (Instanes *et al.* 2005). In the Prudhoe Bay Oil Field of Alaska, permafrost thaw is further accelerated by road dust, leading to greater erosion and more abundant ponds and thermokarst pits (Raynolds *et al.* 2014).

As climate warms and ice sheets retreat, the availability of persistent organic pollutants (POPs) to ecosystems may be prolonged by re-volatilization (Ma *et al.* 2011). The ecological stress of climate change may interact with endocrine-disrupting organic pollutants to further disrupt breeding and reduce fecundity of marine mammals and birds (Jenssen 2006). Moreover, although concentrations of several known POPs in the environment have gradually decreased, polycyclic aromatic hydrocarbons (PAHs) associated with fossil-fuel combustion have increased (De Laender *et al.* 2011).

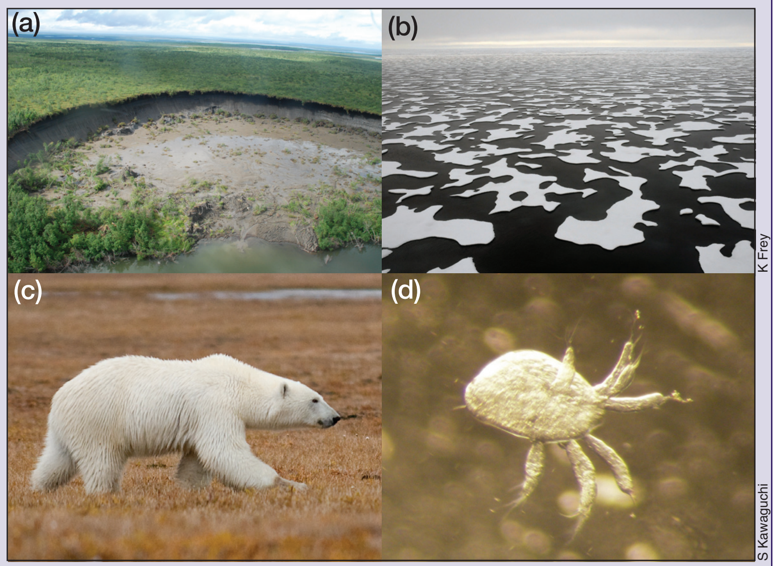

Figure 2. *Examples of impacts of climate change in polar regions. (a) In terrestrial environments, thawing of ice-rich continuous permafrost, as shown here near the Mackenzie Delta in northern Canada, causes retrogressive thaw slumps. These land disturbances result in changes to surface water chemistry in adjacent rivers and lakes, alter local vegetation, and can damage infrastructure, such as pipelines for oil and gas, increasing the risk of point-source pollution. (b) Melting sea ice is reducing habitat for ice-dependent animals including (c) polar bears (*Ursus maritimus*) in the Arctic and (d) larval krill (*Euphausia superba*) in the Antarctic.*

Higher temperatures at both poles will likely result in the decline of marine fish and invertebrate species with life-cycle stages linked to sea ice; in the Arctic Ocean in particular, this may open niches for invasions from cold temperate areas. For instance, at least 77 Pacific mollusk species may potentially be capable of colonizing the Atlantic Ocean if sea-ice extents decrease as predicted (Vermeij and Roopnarine 2008). New fisheries may also open, which could lead to ecological stress through impacts on both target and bycatch species (Cheung *et al.* 2010).

On the Western Antarctic Peninsula, climate change, in concert with increasing visitation by tourists and scientists, is exacerbating the risk of terrestrial invasions (Chown *et al.* 2012). In the Scotia Sea of Western Antarctica, decreased krill abundance may be due to an interactive combination of climate change, harvesting, and recovery of marine mammal populations from overexploitation (Trivelpiece *et al.* 2011).

"emerging" diffuse-source contaminants, such as long-chain perfluorinated carboxylates, may be affecting hormone levels and hatchling success of Arctic birds, although there is a paucity of information available about the effects of these chemicals (Tartu *et al.* 2014).

Diffuse-source pollutant levels are generally much lower in the Antarctic than in the Arctic because of the lower emission rates of these substances in the Southern Hemisphere and the greater isolation of polar air masses in the Antarctic (Bargagli 2008). Nevertheless, increased chemical use in developing Southern Hemisphere countries, together with relatively little regulatory capacity or use of abatement technologies, has promoted the transfer of pollutants – such as pesticides – to the Antarctic (Bargagli 2008). Furthermore, despite a reduction in ozone-depleting chemical emissions since the Montreal Protocol entered into force in 1989, depleted stratospheric ozone over the South Pole continues to exert a strong influence on the Antarctic climate, which may persist for the next 50 years or so (Robinson and Erickson 2014).

Point-source pollution

The contrasting human histories of the polar regions have led to a greater legacy of point-source pollution in the Arctic. In the North American Arctic, the Distant Early Warning (DEW) Line of 63 military radar stations and associated smaller sites – stretching from Greenland to western Alaska – created many point sources of heavy metals, polychlorinated biphenyls (PCBs), and other contaminants. Remediation of 21 sites managed by the Canadian Department of National Defence is expected to cost CAD$575 million (DND 2014). Moreover, increasing petroleum extraction and shipping in the North American Arctic is raising the risk that a major oil spill will occur in this region (Grabowski *et al.* 2014). In Russia, although both legacy and contemporary military sites are present, aging oil infrastructure is a larger problem, with many spills going unreported (Jernelöv 2010). Poland *et al.* (2003) estimated that 5–15% of oil production in the Russian Arctic was lost due to spills.

In contrast, Antarctica is very sparsely populated, with little history of terrestrial resource exploitation. Pollutants are also regulated; the Madrid Protocol bans release of pesticides and other harmful substances, and heavy fuel oil was banned in 2011 (IMO 2011). While the Antarctic therefore has less point-source pollution than the Arctic, human activity in the Antarctic is concentrated in coastal ice-free areas, which contain important wildlife habitat (Shaw *et al.* 2014). Furthermore, Antarctic research stations do not have the capacity to respond effectively to a major hydrocarbon spill, such as that associated with the grounding of a ship carrying a year's fuel supply for a station.

For both regions, there is still a lack of information on the sensitivity of local species to contaminants as the basis for objective environmental standards (Chapman and Riddle 2005; Scheuhammer *et al.* 2015). In addition, the consensus approach of the Antarctic Treaty System resulted in the insertion of ambiguous language in the Madrid Protocol, such as the phrase "minor or transitory impact", and frequent qualifying phrases to soften environmental obligations, such as "wastes...shall be reduced as far as practicable". Consequently, there is a risk that best management practices are not universally adhered to and may differ to those applied domestically. By comparison, several Arctic nations, including Canada and the US, have national environmental legislation that applies equally to their high-latitude territories and that contains stringent clean-up criteria. Looking ahead, submissions to the UN Commission on the Limits of the Continental Shelf have been interpreted to suggest some countries may be anticipating future interest in Southern Ocean offshore hydrocarbon resources (Joyner 2011), which would lead to increased risk of point-source pollution.

Fisheries overexploitation

Polar fisheries are generally less exploited than many temperate ones (eg Zeller *et al.* 2011); however, they are not insulated from overexploitation. As more accessible stocks in lower latitudes have diminished, polar fisheries have come under increased pressure, and some stocks are now severely depleted (Ainley and Pauly 2013; Kjesbu *et al.* 2014). For example, depletion of finfish stocks along the Antarctic continental margin likely contributed to the increasing focus on krill that began in the late 1970s (Ainley and Pauly 2013).

Arctic fisheries are generally managed both cooperatively and nationally. Several stocks are reasonably well-managed (eg Barents Sea stock of Atlantic cod [*Gadus morhua*]; Kjesbu *et al.* 2014), although future climate change and overexploitation elsewhere will increase pressure on these resources (Cheung *et al.* 2010). Antarctic fisheries are managed collectively through the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). This management regime uses a precautionary, ecosystem-based approach that aims to ensure long-term fishery stability and ecosystem protection (CCAMLR 2012). Nevertheless, Antarctic fish stocks have still experienced overfishing, including illegal and unreported fishing for species such as the Antarctic toothfish, *Dissostichus mawsoni* (Ainley and Pauly 2013).

Threats to Antarctic krill – the largest Antarctic fishery and a vital forage species for several iconic Southern Ocean predators – are complex, interactive, and still poorly understood. Krill distributions are difficult to map and characteristically patchy (Miller 2014). Additionally, the krill fishery has the potential to compete with predator species in areas where there are concentrated krill populations, making its impact disproportionate to the percentage of total stock harvested (Woehler *et al.* 2014).

Climate change (see Panel 1) and ocean acidification exacerbate the vulnerability of krill and krill-dependent trophic networks.

Species invasions and range expansions

In the Arctic, connectivity to more temperate regions, via terrestrial land masses and ocean currents, is far greater than in the Antarctic. Thus, the distinction between invasion and climate-driven range expansions in the Arctic is often blurred; most species movements to higher latitudes are range expansions, rather than direct introductions by humans. The "shrubification" of Arctic tundra (Myers-Smith *et al.* 2011), for instance, is driven by dispersal and phenological changes due to warming. This phenomenon will likely diminish the habitat of tundra grassland specialists, such as the migratory Lapland longspur (*Calcarius lapponicus*), with the degree of impact depending on the pace of climate change and the dispersal abilities of shrub species (Boelman *et al.* 2015). However, invasive species directly introduced by humans are likely to increase in both terrestrial and marine Arctic ecosystems (Ware *et al.* 2012, 2014), and climate warming will interact with expanded human activity to synergistically increase the risk of human-mediated species invasions in the Arctic (see Panel 1).

Isolation, harsh conditions, and relatively sparse human activity have somewhat insulated the Antarctic from species invasions (Hughes *et al.* 2014). Despite these natural barriers and a formal ban on species introductions, human-facilitated introductions to the Antarctic include two grasses and several terrestrial invertebrates. A recent risk assessment for species introductions to Antarctica (Chown *et al.* 2012) found that approximately 24% of human visitors to Antarctica unintentionally transport seeds on clothing and equipment. Less is known about introduced marine species in the region, mostly due to a lack of baseline biodiversity data (Griffiths *et al.* 2013). Ships traveling to Antarctic waters have been found to transport non-native species (Lewis *et al.* 2005) and Arctic marine species can survive in Antarctic waters (Tavares and De Melo 2004), raising the possibility of human-mediated invasions between the poles.

Cooperative effort and shared lessons learned

In contrast to threats elsewhere on the planet, the most important environmental threats to both polar regions originate from ex-situ human activities, making international cooperation essential if conservation is to be successful. In particular, effective action to reduce GHG emissions is critical if large-scale impacts on polar environments are to be avoided. The lack of progress in reducing global GHG emissions (IPCC 2014b), however, suggests that immediate strategies focusing on threats that interact with climate change may be crucial for improving environmental protection. Such threats may be easier to address in the short to medium term and, unlike reduction of GHG emissions, are often directly within the influence of existing governance structures for both the Arctic and Antarctic. Fostering international cooperation and sharing lessons learned between the poles will be imperative in effectively engaging these threats (Table 1).

New information on emerging persistent organic pollutants should be quickly translated into coordinated action in countries of both hemispheres, given the propensity of these chemicals to accumulate even after production has ceased. The rapid phase-out of perfluoroalkyl sulfonamide production after the discovery of potential toxicity and broad environmental distribution suggests that coordinated action is possible, although in this case phase-out was facilitated by the availability of alternatives and there being only one principal manufacturer (Giesy and Jones 2015). For point-source pollution, technology developed in the Arctic to accelerate remediation has already been transferred to the Antarctic (Figure 3).

To reduce the risk of chemical spills and the need for remediation in the Antarctic, we argue that the best spill

Table 1. Summary of shared lessons learned to improve Arctic and Antarctic environmental protection

Threat	*Shared lesson*	*Knowledge transfer*
Climate change	Reduce GHG emissions; address additional threats interacting with climate change	Arctic <–> Antarctic
Diffuse-source pollution	Translate new information on impacts of emerging contaminants into swift reductions or bans in both northern and southern hemispheres	Arctic <–> Antarctic
Point-source pollution	Incorporate best national practices from Arctic nations into Antarctic spill prevention and response programs; improve spill prevention programs in both polar regions	Arctic –> Antarctic
Fisheries overexploitation	Apply ecosystem-based precautionary principles similar to those of CCAMLR to Arctic fisheries; encourage international cooperation on fisheries protection and MPAs; recognize limits of collective management by consensus and prepare to make difficult decisions when managing the krill fishery	Arctic <–> Antarctic
Invasive species	Adapt biosecurity protocols used in Antarctic to key Arctic points of entry	Arctic <– Antarctic

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Figure 3. *Examples of lessons learned that can be exchanged between the poles to improve environmental protection. (a) Collaboration between Canadian and Australian scientists has led to the deployment of geosynthetic liners and biopiles to remediate contamination at Casey Station, Antarctica. (b) Spill prevention and response protocols in Alaska are stringent and include an integrated network of spill-response units designed to react quickly to spills, such as this oil tank overflow. The adoption of a similar integrated strategy among Antarctic research stations would reduce the risk of environmental contamination. (c) Biosecurity protocols in the Antarctic are strict and continually improving. (d) Analogous techniques could be adopted in Arctic points of entry, such as Iqaluit, Canada, to reduce the considerable risk of species invasions due to propagule introduction and climate change.*

prevention and response standards from Arctic nations could be incorporated into protocols for Antarctic stations. For example, Alaska has strong regulations for preventing oil spills and an integrated network of units designed to respond to a large spill, including a joint spill response and training program with Canada (Grabowski *et al.* 2014). At present, there is no hydrocarbon extraction in the Antarctic, and the volumes of oil being shipped on any single vessel are small relative to those transported by bulk carriers in the Arctic. Nonetheless, with the small resident population and scattered stations belonging to various nations, mounting an effective response to a major marine oil spill would be extremely difficult. This emphasizes the critical importance of developing an integrated prevention, response, and mitigation plan among Antarctic Treaty Parties, similar to that used by Alaska and Canada.

In general, there are many challenges in responding to an oil spill in either polar region. These include the vast distances involved, extended periods of darkness, cold temperatures (which create logistical difficulties and impede hydrocarbon degradation), potential jurisdictional issues in international waters, and a paucity of basic knowledge on the chemical and biological implications of oil in polar environments (Grabowski *et al.* 2014). Thus, preventive measures such as strict shipping codes and improved navigational charts are vital in both regions.

As climate change alters the distributions of commercially important fisheries (eg Cheung *et al.* 2010), effective regulation of new fishing areas – supported where appropriate by the establishment of marine protected areas (MPAs) – will help to ensure that those fisheries are properly maintained. Currently, coverage of MPAs in the Arctic is inadequate, with most of the region falling far below the UN Convention on Biological Diversity's target of 10% protection of coastal and marine areas (Watson *et al.* 2014).

Recent recovery of Barents Sea cod stocks due to effective cooperative management and increased ocean temperature (Kjesbu *et al.* 2014), and CCAMLR's success at reducing illegal, unreported fish catches (eg Patagonian toothfish, *Dissostichus eleginoides*; Woehler *et al.* 2014), show that successful cooperative management of polar fisheries is feasible. Attempts to establish MPAs in Antarctic waters have met with limited success, but designating new MPAs remains high on the agenda of many nations. Given the demonstrable conservation outcomes associated with well-designed MPAs (eg Edgar *et al.* 2014), establishing a network of such protected areas in collectively managed polar seas should be a priority.

Because krill serve as crucial prey for many fish, seabirds, and marine mammals, krill harvest has been banned in the US Pacific Northwest (US Federal Register 2009). Although the Antarctic krill fishery may be relatively underexploited according to current abundance estimates, caution is also required in its management, and further research is warranted given the uncertainties in the response of krill to climate change and ocean acidification (Constable *et al.* 2014). The collapse and subsequent recovery of the Atlantic herring (*Clupea harengus*) fishery in the subarctic North Sea provides a relevant cautionary example. Before its collapse during the 1970s, the fishery was exploited by several countries, with collective catch limits agreed upon by all parties (Dickey-Collas *et al.* 2010). Increased prices linked to diminishing catches in the 1970s temporarily insulated fishers from the economic effects of an impending collapse, and contributed to a lack of consensus on catch reductions. Only after the expansion of exclusive economic zones (EEZs), the unilateral closure of the British fishery within its EEZ, and the near-total collapse of the fishery was the stage set for a wider moratorium, subsequent recovery, and more effective collective management (Dickey-Collas *et al.* 2010).

Biosecurity measures will be necessary at both poles to slow the rate of non-native species introductions; reducing this rate may provide time for action to address climate change and thus limit the spread of invasive species. Antarctic biosecurity for marine and terrestrial environments is continually improving and incorporates visitor education, ballast-water management guidelines, and inspection and cleaning procedures that substantially reduce invasion risk (CEP 2011). Adopting more stringent protocols for the main ports in Arctic ecosystems would also decrease the risk of invasions. The challenge will be greater for controlling invasive marine organisms, which are generally more dispersive than their terrestrial counterparts and more difficult to detect and eradicate. National requirements for ballast-water management to minimize invasive species transfer already exist in some Arctic nations, such as the US, Canada, and Norway, but not in Russia, Sweden, Denmark, or Finland. Even though Russia, Sweden, and Denmark have acceded to the International Convention for the Control and Management of Ships' Ballast Water and Sediments, ballast-water management in much of the Arctic Ocean remains voluntary until the treaty comes into force, 12 months after ratification by the 30 countries representing 35% of global shipping.

Conclusions

Globally, habitat loss and degradation directly caused by local human activities appear to be the greatest threats to biodiversity (eg Vié *et al.* 2009). In polar environments, although human-caused habitat loss is important, the primary threats are largely a result of human activities in distant lower latitudes, particularly as a result of CO_2 emissions and other pollutants, and increased pressure to exploit polar resources as those elsewhere become depleted. Anthropogenic climate change is the predominant threat, directly precipitating massive ecological change and interacting synergistically with other threats. In light of the key role that polar regions play in regulating global climate and oceanic currents, addressing global GHG emissions is imperative (IPCC 2014b); otherwise feedbacks between altered polar climate and ice regimes will affect lower latitudes. However, dealing with additional threats that interact with climate change is also essential, given that managing these threats has a higher likelihood of success in the short to medium term. Establishing a robust and systematic network of protected areas to conserve ecosystems and species, removing threats of chemical pollution, and improving cooperative multinational fisheries management are all achievable goals that would have measurable environmental benefits globally (eg CCAMLR 2012; DND 2014; Edgar *et al.* 2014). Sharing and incorporating lessons learned between the poles will help to successfully respond to these shared challenges.

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References

Ainley DG and Pauly D. 2013. Fishing down the food web of the Antarctic continental shelf and slope. *Polar Rec* **50**: 92–107.

Aronson RB, Thatje S, McClintock JB, and Hughes KA. 2011. Anthropogenic impacts on marine ecosystems in Antarctica. *Ann NY Acad Sci* **1223**: 82–107.

Bargagli R. 2008. Environmental contamination in Antarctic ecosystems. *Sci Total Environ* **400**: 212–26.

Bednaršek N, Tarling GA, Bakker DCE, *et al.* 2012. Extensive dissolution of live pteropods in the Southern Ocean. *Nat Geosci* **5**: 881–85.

Boelman NT, Gough L, Wingfield J, *et al.* 2015. Greater shrub dominance alters breeding habitat and food resources for migratory songbirds in Alaskan arctic tundra. *Glob Change Biol* **21**: 1508–20.

Borgerson S. 2013. The coming Arctic boom – as the ice melts, the region heats up. *Foreign Aff* **92**: 76–89.

CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources). 2012. Fisheries. Hobart, Australia:

CCAMLR. www.ccamlr.org/en/fisheries/fisheries. Viewed 4 Jun 2015.

CEP (Committee for Environmental Protection). 2011. Non-native species manual. Buenos Aires, Argentina: Secretariat of the Antarctic Treaty. www.ats.aq/documents/atcm34/ww/atcm34_ww004_e.pdf. Viewed 4 Jun 2015.

Chapman PM and Riddle MJ. 2005. Toxic effects of contaminants in polar marine environments. *Environ Sci Technol* **39**: 200A–07A.

Cheung WWL, Lam VWY, Sarmiento JL, *et al.* 2010. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Glob Change Biol* **16**: 24–35.

Chown SL, Huiskes AHL, Gremmen NJM, *et al.* 2012. Continent-wide risk assessment for the establishment of nonindigenous species in Antarctica. *P Natl Acad Sci USA* **109**: 4938–43.

Clark GF, Stark JF, Johnston EL, *et al.* 2013. Light-driven tipping points in polar ecosystems. *Glob Change Biol* **19**: 3749–61.

Constable AJ, Melbourne-Thomas J, Corney SP, *et al.* 2014. Climate change and Southern Ocean ecosystems I: how changes in physical habitats directly affect marine biota. *Glob Change Biol* **20**: 3004–25.

De Laender F, Hammer J, Hendriks AJ, *et al.* 2011. Combining monitoring data and modeling identifies PAHs as emerging contaminants in the Arctic. *Environ Sci Technol* **45**: 9024–29.

Dickey-Collas M, Nash RDM, Brunel T, *et al.* 2010. Lessons learned from stock collapse and recovery of North Sea herring: a review. *ICES J Mar Sci* **67**: 1875–86.

DND (Department of National Defence). 2014. The Distant Early Warning (DEW) line remediation project. Ottawa, Canada: DND. www.forces.gc.ca/en/news/article.page?doc=the-distant-early-warning-dew-line-remediation-project/hgq87xvs. Viewed 4 Jun 2015.

Dorrepaal E, Toet S, van Logtestijn RSP, *et al.* 2009. Carbon respiration from subsurface peat accelerated by climate warming in the subarctic. *Nature* **460**: 616–19.

Edgar GJ, Stuart-Smith RD, Willis TJ, *et al.* 2014. Global conservation outcomes depend on marine protected areas with five key features. *Nature* **506**: 216–20.

Euskirchen ES, Goodstein ES, and Huntington HP. 2013. An estimated cost of lost climate regulation services caused by thawing of the Arctic cryosphere. *Ecol Appl* **23**: 1869–80.

Giesy JP and Jones PD. 2015. Vignette 2.3: perfluoroalkyl substances in the environment: history of an environmental issue. In: Newman MC (Ed). Fundamentals of ecotoxicology (4th edn). Boca Raton, FL: CRC Press.

Gouin T and Wania F. 2007. Time trends of Arctic contamination in relation to emission history and chemical persistence and partitioning properties. *Environ Sci Technol* **41**: 5986–92.

Grabowski MR, Coolbaugh T, Dickins DF, *et al.* 2014. Responding to oil spills in the US Arctic marine environment. Washington, DC: National Academies Press.

Griffiths HJ, Whittle RJ, Roberts SJ, *et al.* 2013. Antarctic crabs: invasion or endurance? *PLoS ONE* **8**: e66981.

Hughes KA, Convey P, and Huiskes AHL. 2014. Global movement and homogenisation of biota: challenges to the environmental management of Antarctica? In: Tin T, Liggett D, Maher PT, and Lamers M (Eds). Antarctic futures: human engagement with the Antarctic environment. Dordrecht, the Netherlands: Springer.

IMO (International Maritime Organization). 2011. Antarctic fuel oil ban and North American ECA MARPOL amendments enter into force on 1 August 2011. London, UK: IMO. www.imo.org/MediaCentre/PressBriefings/Pages/44-MARPOL-amends.aspx#.U0uFIfmSz0c. Viewed 4 Jun 2015.

Instanes A, Anisimov O, Brigham L, *et al.* 2005. Infrastructure: buildings, support systems, and industrial facilities. In: Arctic Climate Impact Assessment. Cambridge, UK: Cambridge University Press.

IPCC (Intergovernmental Panel on Climate Change). 2014a. Summary for policymakers. In: Field CB, Barros VR, Dokken DJ, *et al.* (Eds). Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

IPCC (Intergovernmental Panel on Climate Change). 2014b. Summary for policymakers. In: Edenhofer OR, Pichs-Madruga Y, Sokona E, *et al.* (Eds). Climate change 2014: mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

Jenssen BM. 2006. Endocrine-disrupting chemicals and climate change: a worst-case combination for Arctic marine mammals and seabirds? *Environ Health Persp* **114**: 76–80.

Jernelöv A. 2010. The threats from oil spills: now, then, and in the future. *Ambio* **39**: 353–66.

Joughin I, Smith BE, and Medley B. 2014. Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica. *Science* **344**: 735–38.

Joyner CC. 2011. Potential challenges to the Antarctic Treaty. In: Berkman PA, Lang MA, Walton DWH, and Young OR (Eds). Science diplomacy: Antarctica, science and the governance of international spaces. Washington, DC: Smithsonian Institution.

Kawaguchi S, Ishida A, King R, *et al.* 2013. Risk maps for Antarctic krill under projected Southern Ocean acidification. *Nat Clim Change* **3**: 843–47.

Keuper F, van Bodegom PM, Dorrepaal E, *et al.* 2012. A frozen feast: thawing permafrost increases plant-available nitrogen in subarctic peatlands. *Glob Change Biol* **18**: 1998–2007.

Kjesbu OS, Bogstad B, Devine JA, *et al.* 2014. Synergies between climate and management for Atlantic cod fisheries at high latitudes. *P Natl Acad Sci USA* **111**: 3478–83.

Laidre KL, Stirling I, Lowry LF, *et al.* 2008. Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecol Appl* **18**: S97–S125.

Lewis PN, Riddle MJ, Smith SDA, *et al.* 2005. Assisted passage or passive drift: a comparison of alternative transport mechanisms for non-indigenous coastal species into the Southern Ocean. *Antarct Sci* **17**: 183–91.

Ma J, Hung H, Tian C, and Kallenborn R. 2011. Revolatilization of persistent organic pollutants in the Arctic induced by climate change. *Nat Clim Change* **1**: 255–60.

Meier WN, Hovelsrud GK, van Oort BEH, *et al.* 2014. Arctic sea ice in transformation: a review of recent observed changes and impacts on biology and human activity. *Rev Geophys* **51**: 185–217.

Meyer B. 2012. The overwintering of Antarctic krill, *Euphausia superba*, from an ecophysiological perspective. *Polar Biol* **35**: 15–37.

Miller DGM. 2014. Antarctic marine living resources: "the future is not what it used to be". In: Tin T, Liggett D, Maher PT, and Lamers M (Eds). Antarctic futures: human engagement with the Antarctic environment. Dordrecht, the Netherlands: Springer.

Myers-Smith IH, Forbes BC, Wilmking M, *et al.* 2011. Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities. *Environ Res Lett* **6**: 045509.

Nicolas JP and Bromwich DH. 2014. New reconstruction of Antarctic near-surface temperatures: multidecadal trends and reliability of global reanalyses. *J Climate* **27**: 8070–93.

Nielsen UN and Wall DH. 2013. The future of soil invertebrate communities in polar regions: different climate change responses in the Arctic and Antarctic? *Ecol Lett* **16**: 409–19.

Pabi S, van Dijken GL, and Arrigo KR. 2008. Primary production in the Arctic Ocean, 1998–2006. *J Geophys Res* **113**: C08005.

Poland JS, Riddle MJ, and Zeeb BA. 2003. Contaminants in the

Arctic and the Antarctic: a comparison of sources, impacts, and remediation options. *Polar Rec* **39**: 369–83.

Post E and Forchhammer MC. 2008. Climate change reduces reproductive success of an Arctic herbivore through trophic mismatch. *Philos T Roy Soc B* **363**: 2369–75.

Raynolds MK, Walker DA, Ambrosius KJ, *et al.* 2014. Cumulative geoecological effects of 62 years of infrastructure and climate change in ice-rich permafrost landscapes, Prudhoe Bay Oilfield, Alaska. *Glob Change Biol* **20**: 1211–24.

Robinson SA and Erickson DJ. 2014. Not just about sunburn – the ozone hole's profound effect on climate has significant implications for Southern Hemisphere ecosystems. *Glob Change Biol* **21**: 515–27.

Sailley SF, Ducklow HW, Moeller HV, *et al.* 2013. Carbon fluxes and pelagic ecosystem dynamics near two Western Antarctic Peninsula Adélie penguin colonies: an inverse model approach. *Mar Ecol-Prog Ser* **492**: 253–72.

Scheuhammer A, Braune B, Chan HM, *et al.* 2015. Recent progress on our understanding of the biological effects of mercury in fish and wildlife in the Canadian Arctic. *Sci Total Environ* **509–510**: 91–103; doi:10.1016/j.scitotenv.2014.05.142.

Shaw JD, Terauds A, Riddle M, *et al.* 2014. Antarctica's protected areas are inadequate, unrepresentative and at risk. *PLoS Biol* **12**: e1001888.

Siniff DB, Garrott RA, Rotella JJ, *et al.* 2008. Projecting the effects of environmental change on Antarctic seals. *Antarct Sci* **20**: 425–35.

Smol JP and Douglas MSV. 2007. Crossing the final ecological threshold in high Arctic ponds. *P Natl Acad Sci USA* **104**: 12395–97.

Stammerjohn S, Massom R, Rind D, and Martinson D. 2012. Regions of rapid sea ice change: an inter-hemispheric seasonal comparison. *Geophys Res Lett* **39**: L06501.

Tartu S, Gabrielsen GW, Blévin H, *et al.* 2014. Endocrine and fitness correlates of long-chain perfluorinated carboxylates exposure in Arctic breeding black-legged kittiwakes. *Environ Sci Technol* **48**: 13504–10.

Tavares M and De Melo GAS. 2004. Discovery of the first known benthic invasive species in the Southern Ocean: the North Atlantic spider crab *Hyas araneus* found in the Antarctic Peninsula. *Antarct Sci* **16**: 129–31.

Trivelpiece WZ, Hinke JT, Miller AK, *et al.* 2011. Variability in krill biomass links harvesting and climate warming to penguin population changes in Antarctica. *P Natl Acad Sci USA* **108**: 7625–28.

US Federal Register. 2009. Fisheries off West Coast states; coastal pelagic species fishery; Amendment 12 to the Coastal Pelagic Species Fishery Management Plan. Washington, DC: US Federal Registry. www.gpo.gov/fdsys/pkg/FR-2009-07-13/html/E9-16531.htm. Viewed 5 Jun 2015.

Vermeij GJ and Roopnarine PD. 2008. The coming Arctic invasion. *Science* **321**: 780–81.

Vié J-C, Hilton-Taylor C, and Stuart SN. 2009. Wildlife in a changing world – an analysis of the 2008 IUCN Red List of Threatened Species. Gland, Switzerland: IUCN.

Wania F and McKay D. 1996. Tracking the distribution of persistent organic pollutants. *Environ Sci Technol* **30**: 390a–96a.

Ware C, Bergstrom DM, Müller E, and Alsos IG. 2012. Humans introduce viable seeds to the Arctic on footwear. *Biol Invasions* **14**: 567–77.

Ware C, Berge J, Sundet JH, *et al.* 2014. Climate change, non-indigenous species and shipping: assessing the risk of species introduction to a high-Arctic archipelago. *Divers Distrib* **20**: 10–19.

Watson JEM, Dudley N, Segan DB, and Hockings M. 2014. The performance and potential of protected areas. *Nature* **515**: 67–73.

Woehler EJ, Ainley D, and Jabour J. 2014. Human impacts to Antarctic wildlife: predictions and speculations for 2060. In: Tin T, Liggett D, Maher PT, and Lamers M (Eds). Antarctic futures: human engagement with the Antarctic environment. Dordrecht, the Netherlands: Springer.

Xu L, Myneni RB, Chapin III FS, *et al.* 2013. Temperature and vegetation seasonality diminishment over northern lands. *Nat Clim Change* **3**: 581–86.

Zeller D, Booth S, Pakhomov E, *et al.* 2011. Arctic fisheries catches in Russia, USA, and Canada: baselines for neglected ecosystems. *Polar Biol* **34**: 955–73.

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