A New Framework for Assessing the Effects of Anthropogenic Sound on Marine Mammals in a Rapidly Changing Arctic

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The recent loss of Arctic sea ice provides humans unprecedented access to the region. Marine mammals rely on sound as a primary sensory modality, and the noise associated with increasing human activities offshore can interfere with vital life functions. Many coastal communities rely on marine mammals for food and cultural identity, and subsistence hunters have expressed strong concerns that underwater sound from human activities negatively affects both the animals and hunting success. Federal regulations require scientists and oil and gas operators to acquire incidental harassment authorizations for activities that may disturb marine mammals. Currently, authorization requests are focused on the impacts of sound from activities considered in isolation of one another, and this precludes any possibility of a meaningful analysis of the cumulative impacts from multiple sources. We propose a new assessment framework that is based on the acoustic habitats that constitute the aggregate sound field from multiple sources, compiled at spatial and temporal scales consistent with the ecology of Arctic marine mammals.

Keywords: Arctic, marine mammals, acoustic habitats

The Arctic Ocean is rich with natural sound. Some sources are abiotic (e.g., wind, waves, precipitation, surf, tectonic activity, sea ice) and others biological (e.g., crustaceans, fish, mammals; Bass and Clark 2002). Sea-ice sounds are highly variable and result from three physical drivers: (1) temperature changes that induce cracking (thermal stress), (2) currents and winds that compress or break up ice (mechanical stress), and (3) tiny exploding air bubbles in melting icebergs (seltzer noise). Ice-related sound levels vary from very low under the relatively stable conditions of land-fast ice to comparatively high at active pressure ridges (Greene 1995). In the absence of sea ice, wind is the primary driver of ambient noise in all regions of the world's oceans (Zhang et al. 2006).

The dramatic loss of sea ice over the past decade provides humans with unprecedented access to the Arctic. Projections of an ice-free summer by 2040 (Serreze 2011) have stimulated plans for a wide variety of offshore activities, including shipping, oil and gas development, tourism, commercial fishing, and scientific research. Commercial shippers have begun to use the Northern Sea Route along Siberia and across northern Russia. In 2010, commercial vessels transported 2 million tons of cargo along this route, a load expected to increase to 40 million tons by 2020 (see the Artic Marine Shipping Assessment's executive summary at *www.arctic.gov/publications/AMSA/exec_summary.pdf*). In time, shippers will also use the Northwest Passage, albeit seasonally, to move supplies and to support expanding resource development and tourism, especially in the Canadian Arctic (*www.pame.is/amsa*). Resource development includes oil and gas exploration and prospecting for hard minerals. In 2008, oil companies paid a record $2.6 billion for leases in the Alaskan Chukchi Sea. The companies have since increased the number and geographic extent of seismic surveys between July and December; exploratory drilling is planned in that region within the next few years. The seasonal opening of Arctic waters also has prompted countries to increase military training activities at high latitudes and to define or extend their continental shelf boundaries (Berkman and Young 2009). The expansion of commercial fisheries is expected to follow the seasonal sea-ice retreat. In US waters, the National Marine Fisheries Service has prohibited the development of new fisheries but only until information on potential target stocks is sufficient to allow sustainable management

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of the fishery. Scientists have demonstrated a strong interest in characterizing the present environmental conditions and variability, as well as changes occurring in the Arctic ecosystem, with intensive research directed toward that end during the 2007–2008 International Polar Year (Krupnik et al. 2011).

All of these offshore activities generate sound, ranging from the low-frequency drone of ship propellers to the powerful impulses from icebreaking, seismic survey airguns, and sonars (Hildebrand 2009). Overall, the increase in human activities precipitated by sea-ice loss is generating an increasing level of underwater noise (hereafter, *anthropogenic sound*) in the Arctic marine environment, including in areas that have previously not experienced anything approaching these levels of activity. International reviews (*www.pame.is/amsa*) and US federal agencies concerned with mitigating the environmental impacts of human activities have identified anthropogenic sound as an important consideration for the Arctic ecosystem and one that will require a framework for coordinated monitoring in order for that ecosystem to be understood and effectively managed (Southall et al. 2009).

Effects of anthropogenic sound on marine mammals

The effects of anthropogenic sound on marine mammals have been the focus of numerous scientific reviews and workshops over the past 40 years (e.g., Payne and Webb 1971, Fletcher and Busnel 1978, Richardson et al. 1995, NRC 2005 and the citations therein, MMC 2007, Nowacek et al. 2007, Southall et al. 2007, Weilgart 2007, Tyack 2008, Southall and Nowacek 2009). Concern arises because cetaceans (whales, dolphins, and porpoises) and pinnipeds (sea lions, seals, and walruses) rely on sound to sense their environment, particularly underwater (Richardson et al. 1995). Sound travels extremely well in water, and marine mammals have exceptional capabilities for both generating and detecting sounds, principally for communication, echolocation, and predator avoidance. All species produce a variety of sounds; calls from baleen whales are generally in the low-frequency range (below 1 kilohertz [kHz]) and those from pinnipeds and toothed cetaceans are at higher frequencies. Rather than presenting a tutorial here on sources, measurement, or transmission of underwater sound, we refer the reader to Bradley and Stern (2008), Richardson and colleagues (1995), and *www.dosits.org* for background and additional information.

Anthropogenic sounds can affect marine mammals in a number of ways, including (a) disruption of behavior (e.g., feeding, breeding, resting, migration), (b) masking of important sounds, (c) temporary or permanent hearing loss, (d) physiological stress or physical injury, and (e) changes to the ecosystems that result in a reduction of prey availability. Southall and colleagues (2007) reviewed the state of science pertaining to behavioral disruption and hearing loss and provided provisional exposure criteria for use in preventing auditory injury. Quantifying behavioral responses to anthropogenic sound is a complex task and, although numerous field studies have been conducted, their results are often ambiguous because measurable effects are highly dependent on context, because measurements of acoustic exposures are often inadequate, or because these studies lacked sufficient statistical power to detect changes (see MMC 2007). Consequently, attempts to mitigate behavioral disruption are based on establishing safety zones, the radii of which are derived solely on the basis of an anticipated received level from a given source, an approach that is inconsistent with current scientific understanding of how noise affects marine mammal behavior (Nowacek et al. 2007, Southall et al. 2007, Ellison et al. 2011). Although physiological stress caused by noise exposure has been documented for fish in laboratory settings, which may have implications for questions about whether and how noise affects prey availability, no relevant data on stress are available for marine mammals. Conversely, *masking*, defined as the reduction in the area over which marine mammals can hear and communicate, has been the focus of several recent studies (e.g., Clark et al. 2009, Jensen et al. 2009).

Masking results from chronic increases in the low-frequency sound from the combined noise of anthropogenic activities. It degrades marine-mammal acoustic habitat much like fog or smoke obscures important visual signals for terrestrial animals (Slabbekoorn et al. 2010). To a degree, marine mammals may be able to compensate for masking, either by increasing the amplitude of their calls or by altering other signal characteristics (see Parks et al. 2010 and the references therein). Commercial shipping is the largest contributor to masking noise, with documented increases of 10–12 decibels (dB) in some areas of the eastern North Pacific since the advent of propeller-powered vessels (Andrew et al. 2002, McDonald et al. 2008). Sound from seismic surveys also contributes to basin-wide masking (Hildebrand 2009) and has been detected at distances of thousands of kilometers from its sources in the North Atlantic (Nieukirk et al. 2004). In the Arctic, airgun sounds are common during the open-water season and were detected in the Fram Strait throughout the International Polar Year (Moore et al. 2011). Clark and colleagues (2009) quantified the loss of acoustic habitat due to masking from commercial ship noise by developing a model of communication space for three species of baleen whales on the basis of the temporal and frequency characteristics of their calls. Further development of such communication-space models would be a significant contribution to efforts to understand and manage the impacts of anthropogenic sound on Arctic species and ecosystems.

Regulating anthropogenic sound in the Arctic marine environment

Arctic whales, seals, and walruses produce sounds and are likely to hear well in the frequency band of sounds from the most common anthropogenic activities (figure 1). Arctic subsistence hunters are concerned that anthropogenic

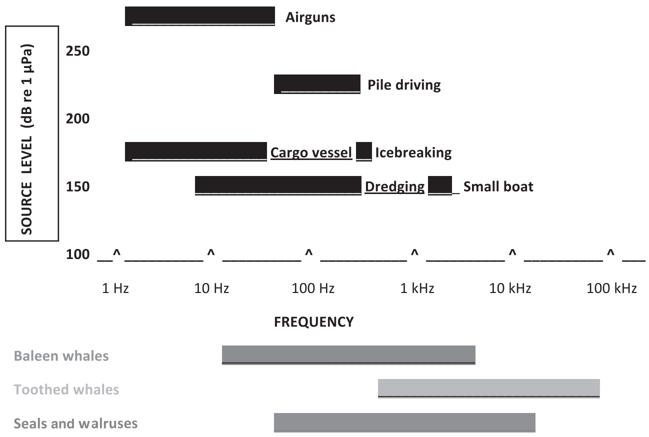

Figure 1. Approximate frequency bands and source levels for common offshore activities in the Arctic (Greene 1995, Hildebrand 2009) relative to frequencies used by Arctic baleen and toothed whales, seals, and walruses. Abbreviations: dB, decibels; Hz, hertz; kHz, kilohertz; μPa, micropascals.

sound will displace marine mammals and thereby restrict their access to these animals for food and cultural identity (e.g., Hoag 2010). Since the early 1980s, scientists have conducted studies to determine the displacement distances and to document the behavioral disruption of bowhead whales (*Balaena mysticetus*) caused by seismic surveys (see the summary in Richardson et al. 1995), but there is still no consensus on whether, how, or to what extent marine seismic survey activities negatively affect the whales or interrupt subsistence hunting. The contentious atmosphere regarding the impacts of anthropogenic sound has focused the development of regulations on the limitation of the exposure of marine mammals to loud sounds that can be associated with specific projects or activities. In this context, sounds from offshore scientific research and industrial activities fall under regulatory scrutiny far more often than sounds from other activities, including shipping and tourism.

In US waters, three statutes provide the legal framework for addressing concerns regarding the effects of anthropogenic sound: the Marine Mammal Protection Act (MMPA), the Endangered Species Act (ESA), and the National Environmental Policy Act (NEPA). The MMPA established requirements for activities that incidentally harass or harm (i.e., *take*) marine mammals. Authorizations are granted for not more than five consecutive years for activities expected to (a) occur in a specified geographic region, (b) involve the harassment of or harm to no more than a small number of marine mammals, (c) have a negligible impact on the affected marine-mammal species or populations, and (d) not have an unmitigable adverse impact on the availability of marine mammals for subsistence uses. The ESA (section 7) requires all federal agencies to carry out programs for the conservation of species or populations listed as *threatened* or *endangered* and to "[e]nsure that any action authorized, funded, or carried out… is not likely to result in the destruction or adverse modification of habitat of such species." A section 7 consultation on a proposed activity that may affect listed species must take into account the cumulative effects of the activity, together with other activities that are occurring or are reasonably likely to occur as a consequence of that activity. Finally, the NEPA requires an analysis of the potential effects of proposed activities and alternatives to them and explicitly requires consideration of cumulative effects.

Although they are required by legislation, assessments of the cumulative effects and impacts of anthropogenic sound from multiple sources on marine mammals and their habitat have proven difficult to carry out. Thus, such requirements have yet to result in practical responses. Because these laws and the regulations that implement them must be applied to multiple types of activities, the US Congress included within them standards that are general rather than specific. Interpreting general standards such as "small number," "negligible impact," "jeopardy," and "adverse modification" has proven to be a challenge made even more complex by the difficulty of quantifying the effects of any single sound source. It is often extremely difficult to determine the effects of sound-generating activities on marine mammals. In the face of this regulatory dysfunction, activity-specific mitigation and monitoring programs are often required (box 1). Mitigation measures are intended to reduce the effects of a proposed activity, whereas monitoring is meant to determine what effects occur irrespective of mitigation. Individually, most mitigation and monitoring methods have serious shortcomings, primarily because marine mammals vary markedly in their natural history and behavior such that the probability of detecting an impact is often low and varies widely as a function of the density and activity of the marine mammals and of relevant environmental conditions. Monitoring methods are also generally limited in scope and do not provide a basis for measuring and evaluating the full effects of a given activity in concert with those of other activities. Therefore, there are no ready means of estimating the contribution of a specific activity to the cumulative effects of all human activities on a species or population. For that purpose, resource managers need a comprehensive framework for evaluating the effects of sound.

Creating acoustic habitats to assess anthropogenic sound and its effects

The sounds that marine mammals hear and generate vary in characteristics such as dominant frequency, bandwidth, energy, temporal pattern, and directionality. The environment often contains multiple cooccurring sounds and, like all animals, marine mammals must be able to discriminate a signal (meaningful sound) from noise. Just as many terrestrial animals integrate multiple stimuli from their visual landscape, marine mammals must be able to discriminate among multiple stimuli in their acoustic seascape. An

Box 1. Common mitigation and monitoring practices used to address the effects of anthropogenic sound on marine mammals.

Mitigation

The following practices are used for mitigating the effects of anthropogenic sounds. (a) Sound-generating activities are scheduled to limit co-occurrence with marine mammals. (b) The minimum required sound source (e.g., the smallest amount of airgun energy needed to acquire the sought-after geophysical data) is used or the source is buffered with sound-attenuation devices (e.g., bubble curtains). (c) Preactivity surveys are conducted to determine whether marine mammals are in the vicinity, and the activity or the schedule is adjusted accordingly. (d) Visual observers or passive acoustic monitors are used to maintain safety zones around the sound source. The radii of such zones can be set to prevent serious injury or death (Level A taking under the Marine Mammal Protection Act [MMPA], where *taking* refers to the harassment of or harm to marine mammals) or to minimize disruption of behavior (Level B taking under the MMPA). Sound verification studies are conducted to establish safety zones, which are based on the dissipation of sound energy with distance from the source, a process that varies with environmental conditions. (e) The power of a sound source (i.e., powering down) is reduced or shut off (i.e., shut down) when marine mammals are detected in or near the safety zones; the power of a sound source can also be ramped up once the safety zone is deemed clear of marine mammals.

Monitoring

The monitoring of anthropogenic sound and its effects on marine mammals is achieved through the following procedures. (a) Sound-source levels or received levels are monitored, to the extent feasible, depending on the relevant circumstances. (b) Visual observers or passive acoustic monitoring systems are used to detect marine mammals in or near safety zones, and their responses are described to the extent that this is feasible. (c) Postactivity surveys of marine mammals that were exposed to, and thus may have been affected by, the activity are conducted. The nature of such surveys (e.g., aerial surveys, shore-based visual surveys, passive acoustic surveys) can vary on the basis of the activity and environmental conditions.

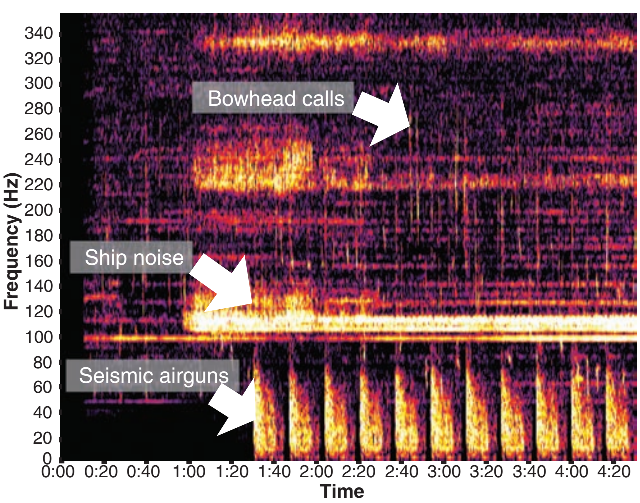

Figure 2. Example spectrogram depicting an acoustic habitat comprising bowhead calling, a ship transiting, and airgun pulses as a function of time (in minutes:seconds). Abbreviation: Hz, hertz.

acoustic habitat is composed of the acoustic energy from all contributing sources, natural and anthropogenic (figure 2). In the Arctic, acoustic habitats vary by region and season primarily in response to the type and extent of sea-ice cover and the concomitant human activities. We anticipate that increasing levels of commercial shipping and cruise-based tourism will contribute greater amounts of low-frequency noise into the acoustic habitat. Noise from oil and gas activities (e.g., seismic surveys, pile driving, drilling, and production operations) will also contribute to background levels, particularly in the low-frequency band. Coastal development will add vessel noise, as well as impulsive sounds from pile driving. If commercial fisheries develop, there will be a cumulative increase in low-frequency vessel noise, and fish-finding sonars will contribute high-frequency sound energy. Given these and a range of possible noise sources associated with military operations, involving vessels, sonars, and aircraft, acoustic habitats in the Arctic are certain to change dramatically in the foreseeable future. This imposition will occur in two basic ways: increases in background noise levels and increases in acoustic clutter, where *clutter* includes discrete acoustic events, such as airgun pulses.

In some recent summaries (e.g., Ragen et al. 2008, Huntington 2009), ways of reducing the impacts of increasing human activity on Arctic marine mammals have been suggested, but none has been focused on how to address the aggregate increase in anthropogenic sound. We propose an approach in which sounds from multiple sources are mapped and integrated with information about the distribution, density, movement patterns, and ecology of marine mammals to estimate where and when they are likely to be most at risk from sound-generating activities (box 2). This approach would incorporate scientific information that is often available in regulatory documentation but not integrated into a comprehensive understanding of the acoustic habitat for the purpose of analyzing potential acute effects and chronic influences. Creating an acoustic-habitat framework would (a) provide a means of accounting for the cumulative contributions from multiple anthropogenic sound sources, (b) identify areas of sound–mammal overlap, (c) aid in the identification of data gaps, and thereby (d) guide research. Additional steps, such as modeling the loss of communication space (e.g., Clark et al. 2009), can be

Box 2. Steps for the creation of acoustic habitats as a framework to guide research and to evaluate the effects of anthropogenic sound on marine mammals.

Science foundation

In order to create an acoustic-habitat framework, science foundations must (a) summarize natural and anthropogenic sound sources by region and period; (b) map the sound fields generated by each source; (c) merge the sound field maps to depict the overall acoustic habitat and highlight areas in which cumulative effects are likely to occur; (d) list marine-mammal species and all proposed offshore activities by region and period; and (e) summarize the behavioral ecology for marine-mammal species by region and season and map distribution, relative abundance, and ecologically important areas (e.g., those used for feeding, breeding and migration).

Acoustic-habitat framework

The acoustic-habitat framework must (a) overlay acoustic-habitat maps with maps of marine-mammal distribution patterns, relative abundance, and ecological importance and (b) identify areas or periods of concern and data gaps, including limitations on the understanding of sound sources and propagation, as well as the behavioral ecology of potentially affected marine mammals.

Research and evaluation

In research and evaluation efforts, (a) data gaps must be prioritized, and the research needed to close such gaps must be conducted. (b) Precautionary measures must be incorporated in order to ensure that marine mammals are protected while uncertainties are being resolved. (c) Regular reviews of progress must be conducted to adjust management measures as required and research results must be used to develop allowable thresholds of exposure.

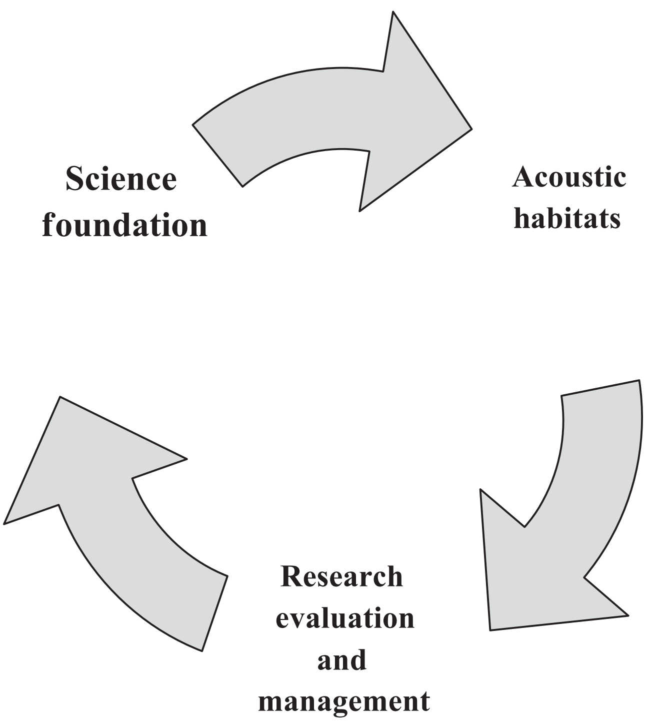

Figure 3. Cycle of constructing acoustic-habitat frameworks based on foundational science and culminating in focused research, evaluation, and management of outcomes with regard to reducing marine-mammal exposures to anthropogenic sounds.

applied in order to quantify the level of spatial, temporal, and spectral overlap and to elucidate likely impacts.

Ideally, the 10 steps supporting the three principal activities (box 2) would be completed at a regional level each year (figure 3). In this way, the prior year's research and evaluation would contribute directly to the scientific foundation and the resultant acoustic-habitat framework in the following year. An acoustic habitat comprises all sound sources and thereby provides a means of addressing their cumulative effects over a range of temporal and spatial scales—an oft-stated goal in reviews and workshop reports (e.g., MMC 2007). Specifically, the development of acoustic habitats would provide managers with a pragmatic and adaptive means of addressing concerns about the impacts of anthropogenic sound on marine mammals and, in doing so, would improve the assessment of the "human footprint" both on regional scales (Hatch and Fristrup 2009) and throughout the world's oceans (e.g., Halpern et al. 2008).

Contribution to national and international Arctic marine conservation

In 2007, the Arctic passed a dramatic physical threshold with an extreme reduction in summer sea ice (Serreze 2011). Marine environmental and acoustic conditions common in the 1970s, when the NEPA, ESA and MMPA came into force, are not likely to be seen again in the foreseeable future. A new approach to management is required if we are to avoid a deterioration in the acoustic habitats of Arctic marine ecosystems, as has been demonstrated in regions of the North Atlantic and North Pacific basins (e.g., Hildebrand 2009). Characterization and measurement of acoustic habitats at ecological scales could provide the foundation for assessing marine-mammal vulnerability to anthropogenic sound and for building an environmentally responsible process for managing underwater sound in a rapidly changing Arctic marine environment. Development of an acoustic-habitat framework would be consistent with the US National Policy for the Stewardship of the Ocean, which considers the ecosystem as a whole and includes among its scientific program goals ecosystem mapping and characterization and ecological modeling and forecasting (White House Council on Environmental Quality 2010). With regard to acoustics, the US National Oceanic and Atmospheric Administration is now developing cetacean density and distribution and underwater-sound-mapping tools to inform conservation management decisions, a process that is consistent with and will contribute to the description of acoustic habitats at regional scales.

Concern regarding the effects of anthropogenic sound on marine mammals is international, as was reflected in the Arctic Marine Shipping Assessment (*www.pame.is/amsa/amsa-2009-report*), academic and activist reviews (e.g., Jasny et al. 2005), reports on specific regional issues (e.g., Reeves et al. 2005) and various European guidelines (e.g., Boyd et al. 2008; *www.accobams.org/index. php?option=com_docman&task=cat_view&gid=37&Itemid=50&limitstart=5*). In 2010, the Standing Working Group on Environmental Concerns (SWGEC) of the International Whaling Commission's (IWC) Scientific Committee reviewed the evidence for masking from anthropogenic sound across ocean basins, with an emphasis on low-frequency sounds (less than about 1 kHz) from ships and airguns. The SWEGEC recommended (a) that the masking potential of anthropogenic sources be quantified and acoustic measurements be standardized and (b) that IWC member governments work to develop a quantitative approach for assessing cumulative impacts of anthropogenic sound on cetaceans. The SWGEC also noted progress in working with the Environment Protection Committee of the International Maritime Organization toward a goal of global underwater noise reduction from shipping by 3 dB in 10 years and by 10 dB in 30 years (IWC 2011). The truly international character of the Arctic demands this type of collaborative approach if the goal of anthropogenic sound reduction is to be realized.

As in US waters, various efforts are under way at an international level to map the current and anticipated human footprint in the Arctic. For example, the International Union for Conservation of Nature, in partnership with the Natural Resources Defense Council, is developing maps that depict ecologically and biologically sensitive areas to facilitate ecosystem-based management in the Arctic (*www.iucn.org/about/work/programmes/marine/marine_our_work/polar_activities/arctic/?7347/IUCNNRDC-Arctic-Marine-Ecosystem-Based-Management-Project-February-2011*). Maps of marine-mammal movement patterns and habitat are central to this effort and build on an existing atlas for Arctic subregions (Smith et al. 2010). At the same time, the Conservation of Arctic Flora and Fauna working group of the Arctic Council has prepared a marine Circumpolar Biodiversity Monitoring Program to promote long-term monitoring of Arctic wildlife, including marine mammals, and their habitats. This effort complements that by the Protection of the Arctic Marine Environment working group of the Arctic Council, which produced the Arctic Marine Shipping Assessment (AMSA) report (see *www.pame.is/images/stories/AMSA_Status_on_Implementation_of_the_AMSA_2009_Report_Recomendations-May_2011_copy_copy_copy_copy.pdf*).

There is an opportunity, if we act quickly and collaboratively, to channel global interests in Arctic energy, fishing, shipping, tourism, and science toward an ecosystem-based, precautionary development path with a strong scientific foundation (e.g., Berkman and Young 2009). This will require the concordance of national and international law in a manner in which the authority of the eight Arctic-rim countries is recognized over their coasts and continental shelves, while the need for collaboration is also recognized in order to ensure a coordinated conservation and management approach. With regard to the anthropogenic sound footprint in the Arctic, the scientific tools exist to guide the development of holistic acoustic-habitat frameworks for effective assessment and management at biologically meaningful spatial and temporal scales. The key will be to link those frameworks to strategies of Arctic marine conservation at national and international levels. As is outlined in the AMSA scenarios matrix (*www.arctic.gov/publications/AMSA/scenarios.pdf*), the choices made now will strongly influence the direction and sustainability of development in the Arctic over the next decade and beyond. Action to reduce anthropogenic sound in the marine environment can act as a catalyst for an ecosystem-based approach to Arctic resource management, but time is of the essence.

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