Vulnerability of Arctic marine mammals to vessel traffic in the increasingly ice-free Northwest Passage and Northern Sea Route

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The fabled Northwest Passage and Northern Sea Route that were once the quests of early Western explorers are now increasingly sea ice-free, with routine vessel transits expected by midcentury. The potential impacts of this novel vessel traffic on endemic Arctic marine mammal (AMM) species are unknown despite their critical social and ecological roles in the ecosystem and widely recognized susceptibility to ice loss. We developed a vulnerability assessment of 80 subpopulations of seven AMM species to vessel traffic during the ice-free season. Vulnerability scores were based on the combined influence of spatially explicit exposure to the sea routes and a suite of sensitivity variables. More than half of AMM subpopulations (42/80) are exposed to open-water vessel transits in the Arctic sea routes. Narwhals (*Monodon monoceros*) were estimated to be most vulnerable to vessel impacts, given their high exposure and sensitivity, and polar bears (*Ursus maritimus*) were estimated to be the least vulnerable because of their low exposure and sensitivity. Regions with geographic bottlenecks, such as the Bering Strait and eastern Canadian Arctic, were characterized by two to three times higher vulnerability than more remote regions. These pinch points are obligatory pathways for both vessels and migratory AMMs, and so represent potentially high conflict areas but also opportunities for conservation-informed planning. Some of the species and regions identified as least vulnerable were also characterized by high uncertainty, highlighting additional data and monitoring needs. Our quantification of the heterogeneity of risk across AMM species provides a necessary first step toward developing best practices for maritime industries poised to advance into this rapidly changing seascape.

risk analysis | resilience | vessel impacts | climate impacts | Arctic marine mammal

The Arctic is the scene of the most profound environmental changes on Earth, where warming has been two to three times greater than the global mean and contributed to exceptional reductions in sea ice cover (1). Most exaggerated during the summer–fall open-water season, the extent of September sea ice cover has retreated 14% per decade since 1979, and the duration of the open-water period has increased 5–10 wk (2, 3). Projections suggest the Arctic will be sea ice-free during summer by 2040 (4). Effects of declines in seasonal sea ice are propagating through Arctic marine ecosystems and are increasingly juxtaposed with expanding anthropogenic interests in the region (5, 6).

Navigability of previously inaccessible Arctic sea routes has increased in conjunction with Arctic sea ice loss, sparking commercial interests in the development of more direct connections among global markets (7). Once impassable, the Northwest Passage (NWP) has recently seen the advance of commercial traffic and may provide new open shipping routes by midcentury (8). The Northern Sea Route (NSR), through the Russian coastal seas, already supports economically viable transits by both ice-strengthened and open-water ships (9). Even the North Pole may be passable within decades (8), raising questions of how to juggle economic development and environmental protection in Arctic

marine environments. The Arctic Council recommended that areas of ecological importance be identified and assessed for measures that will minimize the effects of a developing shipping industry (7), leading to the adoption of a new Polar Code by the International Maritime Organization that went into effect on January 1, 2017. Despite general provisions, limited data hamper the implementation of specific guidelines to minimize environmental consequences.

The potential effects of vessels on marine mammals are widely recognized, and correspondingly, the seven endemic Arctic marine mammal (AMM) species are presumed to be among the most at risk from increased marine traffic in the Arctic sea routes (10, 11). However, there has not been a circumpolar assessment of vulnerability for these species: beluga whales (*Delphinapterus leucas*), narwhals (*Monodon monoceros*), bowhead whales (*Balaena mysticetus*), ringed seals (*Pusa hispida*), bearded seals (*Erignathus barbatus*), walrus (*Odobenus rosmarus*), and polar bears (*Ursus maritimus*). AMMs are sentinel species adapted to sea ice environments, key constituents of short Arctic food chains, critical cultural and subsistence resources to coastal indigenous communities, generally data poor, and increasingly susceptible to climate change impacts (3, 12, 13). To understand the implications of the development of Arctic sea routes and support implementation of environmental protection and conservation efforts, we examined the vulnerability of 80 AMM subpopulations to vessel traffic in the increasingly navigable Arctic sea routes during the open-water season (Fig. 1). We

Significance

The Arctic is experiencing unprecedented rates of sea ice loss in concert with expanding anthropogenic activities that may have compounding effects on marine ecosystems. The Northwest Passage and Northern Sea Route have recently seen the advent of commercial traffic, raising questions of how to juggle economic development and conservation. Here we show the vulnerability of 80 subpopulations of seven endemic Arctic marine mammal species to vessel traffic across the Northwest Passage and Northern Sea Route during the open-water season, accompanied by estimates of uncertainty that highlight additional research needs. As global, national, and local organizations sharpen their focus on the Arctic, our results provide a framework to evaluate environmental impacts to the region's most iconic and sensitive species.

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Fig. 5. Maximum uncertainty scores for all AMM species (*Top Left*) and taxonomic groups exposed to the Arctic sea routes. The combined ranges of all other AMM subpopulations that did not overlap the Arctic sea routes are shown in gray in the *Top Left*, including portions of polar bear subpopulations that range onto land during the open-water period.

time, habitat specificity, several foraging specializations, and small population sizes suggest that most AMM species are susceptible and have limited ability to respond to large changes in their environment (3, 45). Our inclusion of variables corresponding to sensitivity to sea ice loss, as well as subpopulation size and trends, provide some assessment of potential adaptive capacity, yet we recommend additional research to assess AMM resilience, to vessels or otherwise, under climate change scenarios.

We have provided the framework and initial assessment of the developing threats associated with increasing navigability of the Arctic environment for key wildlife species that range widely across international boundaries, use regional habitats, are critical and traditional resources for indigenous communities, and are at the forefront of climate change impacts. Our direct measures of vulnerability may inform policy decisions, as well as guide future research, regarding upcoming economic and conservation challenges associated with vessel presence in this newly accessible, rapidly changing, and data-poor ecosystem.

Materials and Methods

Subpopulation Exposure. We estimated subpopulation-specific exposure to potential vessel traffic based on the spatial overlap of the NWP and NSR with each subpopulation's distribution, which relied on mapping subpopulation-specific ranges during September. Based on review of the peer-reviewed and gray literature, we delineated shapefiles describing the ranges of 80 AMM subpopulations (*SI Appendix, Fig. S1*) that make up internationally recognized subpopulations or summer-fall aggregations (3, 46). We selected September because it represents the annual sea ice minimum, when vessel traffic will presumably be greatest (7). We also digitized Arctic sea routes (9, 47), applying a buffer to account for ship deviations from the core route (e.g., see ref. 48) and for possible detours resulting from sea ice conditions. We applied a 100-km buffer on either side of the core route except where the route is naturally constrained by geography, in which case the full width of the strait or channel is the buffer (Fig. 1).

We then calculated what fraction of subpopulation-specific September ranges overlapped with each sea route. We translated the fraction of subpopulation range overlap with sea routes into an exposure score (E) ranging 1–3, assuming that a threshold ≥ 0.75 overlap corresponds to a uniformly high exposure level (score = 3) and that no overlap corresponds to an exposure score of 1. Fractional overlap values between 0 and 0.75 were assigned scores between 1 and 3 on a linear scale (Fig. 1), as implemented elsewhere (20, 49).

Subpopulation Sensitivity. We conducted a broad review of the literature and developed a scoring system to account for potential effects of AMM exposure to marine traffic (*SI Appendix, Sensitivity Scoring*). We examined seven variables affecting AMM sensitivity. Variables in our sensitivity assessment focused specifically on the potential biological effects of vessel traffic during the open-water season (variables 1–3; i.e., literature reviews of potential for vessel disturbance, vessel collision, or acoustic impacts), the frequency of exposure (variable 4; measured as recent transits of the NWP and NSR), and the biological and ecological characteristics that affect subpopulation response to vessels (variables 5–7; specifically sensitivity to climate change, relative abundance, and subpopulation status). Although sampling expert opinion is one approach to scoring sensitivity (e.g., ref. 50), we scored each sensitivity variable on a three-point scale (e.g., similar to refs. 19 and 20), with 1 as the least sensitive and 3 as the most sensitive, based on our extensive literature review (*SI Appendix, Sensitivity Scoring*). We combined scores across variables by calculating mean sensitivity scores for each subpopulation.

Uncertainty. We assessed uncertainty in both the exposure and sensitivity components of the vulnerability analysis. We ranked exposure uncertainty (U_e) according to our confidence in mapped distributions of each subpopulation (*SI Appendix, Table S2*). We calculated mean uncertainty in sensitivity (U_s) based on scores separately assigned to four sensitivity variables. First, we scored uncertainty in sensitivity variables 1–3 (i.e., potential

for disturbance, collision, or acoustic impact) based on uncertainty in the literature (19, 20, 50), as defined in *SI Appendix, Table S2*. We also assigned uncertainty scores in relative abundance (sensitivity variable 6) as 1 for subpopulations for which abundance estimates have associated error estimates, 2 for those with an abundance estimate but no error, and 3 for subpopulations with unknown abundance.

Vulnerability Analyses. We calculated mean vulnerability and uncertainty scores for each subpopulation and species. We excluded subpopulations that had no spatial overlap with the NWP or NSR, as lack of exposure to the sea routes would bias their vulnerability estimate low. We mapped scores to assess spatial variability in vulnerability and associated uncertainty and identified key regions of interest. This was conducted by assigning vulnerability and uncertainty scores to each subpopulation's September range and using ArcGIS 10.4 (ESRI) Cell Statistics tool to estimate the spatial distribution of maximum vulnerability and uncertainty scores across all species and among taxonomic groups (Figs. 4 and 5).

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