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

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Edited by Janet Franklin, University of California, Riverside, CA, and approved June 4, 2018 (received for review February 27, 2018)

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 impassible, 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*), walruses (*Odobenus rosmarus*), and polar bears (*Urus 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.

Author contributions: D.D.W.H., K.L.L., and H.L.S. designed research; D.D.W.H., K.L.L., and H.L.S. performed research; D.D.W.H. analyzed data; and D.D.W.H., K.L.L., and H.L.S. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1803543115/-/DCSupplemental.

adopted a semiquantitative spatial vulnerability approach that capitalizes on the rich methodological history of risk and vulnerability assessments (14–22). We measured the vulnerability (V; range, 1–9) of each subpopulation i based on the multiplicative effects of spatially explicit exposure (E; scored 1–3, low-high) and several aspects of sensitivity to vessels (S; scored 1–3, low-high): $V_i = (E_i) \times (S_i)$. We identified the relative risk, as well as uncertainty (U; scored 1–3, low-high), across Arctic regions, AMM species, and subpopulations to enhance decision-making for environmentally sound marine traffic practices within the context of a rapidly warming and increasingly accessible Arctic.

Results

Forty-two (53%) of the 80 AMM subpopulations were exposed to portions of either one of or both the NWP and NSR, with exposure scores ranging from 1.01 to 3.0 (*SI Appendix*, Table S1). Sensitivity scores for these subpopulations ranged from 1.63 to 2.50, resulting in subpopulation-specific vulnerability scores ranging from 1.76 to 7.50 (Figs. 2 and 3). Of the subpopulations that overlap with the sea routes, the Eclipse Sound narwhal subpopulation was most vulnerable to vessel traffic largely because of a combination of high exposure to the NWP and biological (species-specific) traits that increased vulnerability. The Hudson Bay–James Bay ringed seal subpopulation was least vulnerable. We found an intermediate vulnerability level among all AMM species (mean score = 4.20) exposed to Arctic sea route traffic, reflecting relatively high vulnerability among narwhal, walrus, bowhead, and beluga subpopulations (mean scores = 5.59, 5.34, 5.16, and 5.06, respectively) compared with intermediate vulnerability of bearded seals (mean score = 4.01) and relatively low vulnerability of polar bears and ringed seals (mean scores = 2.95, 3.52, respectively; Table 1). However, uncertainty was generally greater for the least vulnerable subpopulations, particularly among ice seals and polar bears (Fig. 3). Walruses were the outlier among pinnipeds, with relatively high vulnerability and low uncertainty.

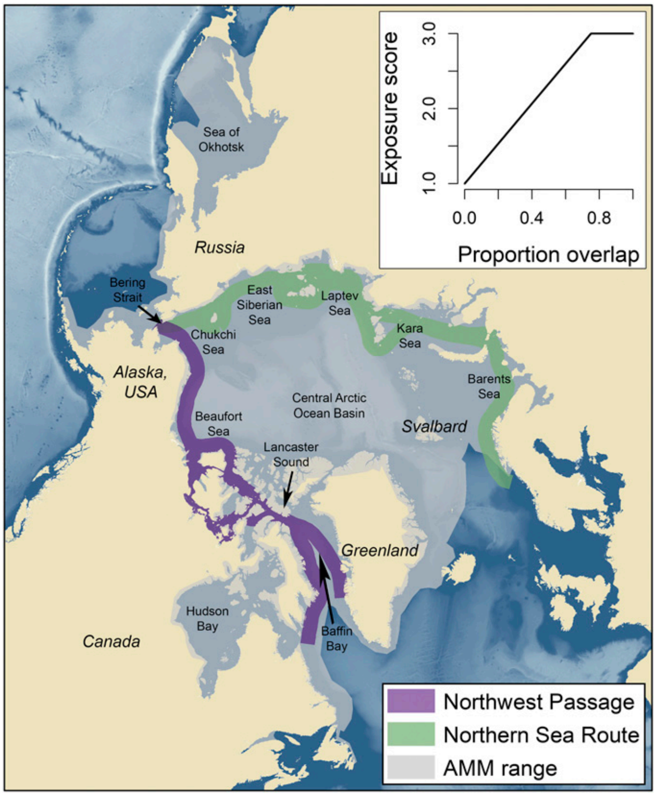

Fig. 1. Map of the Northwest Passage, Northern Sea Route, and extent of the September range of 80 AMM subpopulations. Polar bears range onto land during the open-water period, as reflected by gray shading overlapping land. (*Inset*) Illustration of how the proportion of the sea routes that overlap each subpopulation's range was converted to an exposure score.

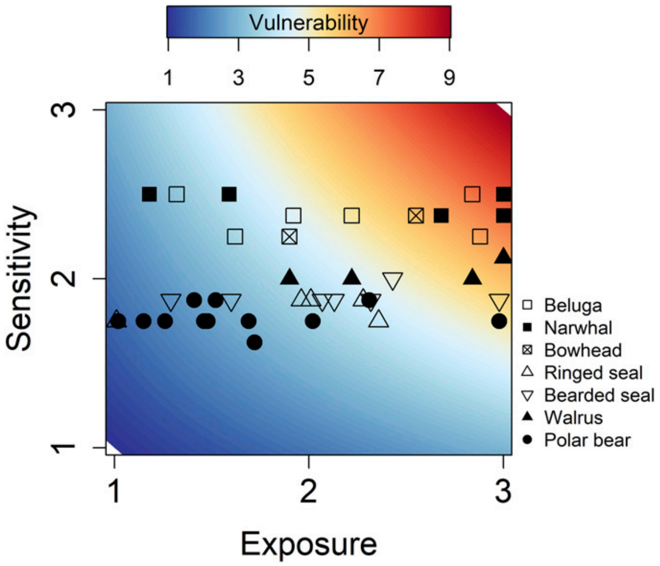

Fig. 2. Vulnerability plot expressing sensitivity and exposure scores across Arctic marine mammal subpopulations exposed to the Northwest Passage or Northern Sea Route. Vulnerability is the product of exposure and sensitivity.

The spatial distribution of AMM vulnerability and uncertainty varied regionally and by taxonomic group (Figs. 4 and 5). Regions of the Pacific Arctic (i.e., Bering Strait, Chukchi, Beaufort, and East Siberian seas), Russian Arctic (Laptev Sea), and eastern Canadian Arctic (Lancaster Sound, eastern Baffin Island, Barrow Strait, Gulf of Boothia) were characterized by high vulnerability scores, which corresponded to cetacean and pinniped subpopulations with high vulnerability. Several of these regions were also characterized by particularly high uncertainty (i.e., Russian Arctic, eastern Canadian Arctic). In contrast, subpopulations distributed north and south of the NWP in the central Canadian Arctic and near Baffin Bay, Greenland, and the Barents Sea generally had lower vulnerability scores, although the number of exposed subpopulations was also low in these regions compared with up to 10 subpopulations using the Bering Strait-Chukchi Sea region (*SI Appendix*, Fig. S2). Polar bears had the lowest vulnerability scores, with the exception of the Northern Beaufort Sea subpopulation. Cetaceans were characterized by relatively low uncertainty despite their high vulnerability in comparison with pinnipeds, which had high uncertainty across the Arctic sea routes.

Discussion

A suite of ecological impacts are emerging as a result of unprecedented sea ice loss across Arctic marine systems (23, 24), but the consequences of increasing human access in the face of environmental change have not been comprehensively considered across AMMs. Here, we have performed an analysis of the vulnerability of some of the most sensitive Arctic species to an anthropogenic risk factor that is primed to expand in the absence of sea ice. We used the extensive literature available about vessel effects on marine mammals in more temperate regions, and ultimately we provide a comprehensive assessment of the combined effects of vessel exposure and sensitivity across all populations of AMMs under increasingly navigable Arctic sea

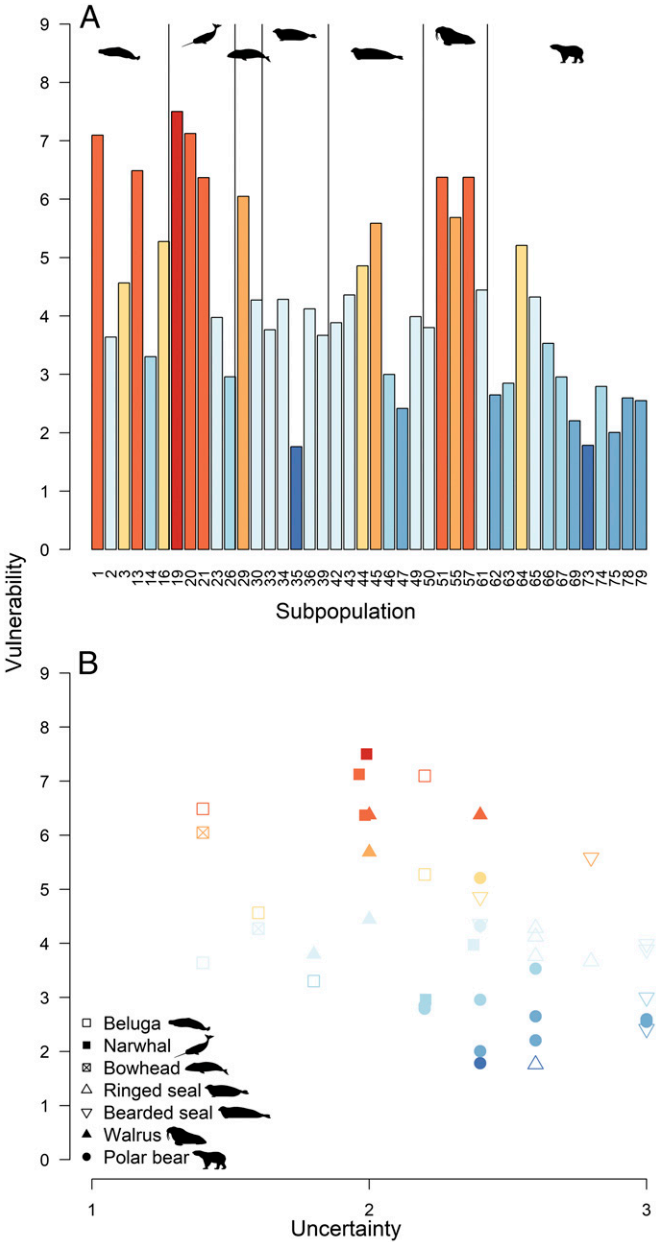

Fig. 3. Vulnerability scores across (*A*) subpopulations (numbers correspond to *SI Appendix*, Table S1) and (*B*) relative to uncertainty scores of each AMM species (shapes correspond to Fig. 2). Color shading corresponds to the vulnerability plot in Fig. 2.

routes during open-water conditions. Understanding the heterogeneity of risk across this remote seascape provides useful insights for developing best practices for maritime industries, as well as species and regions to prioritize.

Planning for risk avoidance is complicated by the highly mobile nature of AMMs and the fact that vessels also move (10). However, sea ice loss is forecasted to continue for several decades even if aggressive mitigation is immediately implemented (25), so prudent marine spatial planning would aim to implement risk abatement measures in advance of the development of extensive commercial shipping. We found greater variability in exposure than sensitivity, but cetaceans were particularly vulnerable to vessel effects based on relatively high exposure, as well as sensitivity scores. Arctic cetaceans are migratory, often following genetically based migration routes and exhibiting site fidelity to productive regions with extensive summer foraging opportunities (e.g., refs. 26 and 27) that are experiencing variable impacts to changing sea ice habitat (e.g., refs. 28–30). The NWP and NSR have extensive overlap with the same foraging areas and fall migration routes of these cetacean species. In addition, we found that cetaceans are particularly sensitive to vessel disturbance, acoustic effects, and in the case of bowhead whales, ship strikes. Cetacean-oriented mitigation strategies developed elsewhere suggest that avoiding key habitats by routing, detecting, and deviating from whales visible at the surface and minimizing sound production could be effective ship-based measures, all of which can be further enhanced by restricting speed (11, 31–34). Specific maximum noise level thresholds, or noise budgets, have also been proposed as a solution for highly sensitive areas and species (35). Another approach called dynamic spatial management, based on a fluid spatial and temporal management framework, has been proposed in some Arctic regions and has shown promise elsewhere (36, 37).

Understanding where knowledge gaps exist can help target future research and monitoring efforts to minimize vessel threats, and we found that uncertainty varied among regions, species, and subpopulations. Some of the species and regions identified as the least vulnerable were also characterized by high uncertainty, highlighting areas that need additional data and monitoring. The highest uncertainty occurred throughout Russia in the NSR and in some portions of the Atlantic Arctic. There are large data gaps on AMM subpopulation status, trends, and distribution (3), which contributed to much of the uncertainty in species exposure and sensitivity. We found a disproportionate focus on cetacean sensitivity to vessel effects, whereas few studies examined vessel effects on ice seals or polar bears. Walruses also scored relatively high vulnerability compared with the other pinniped species, largely because of their higher climate change sensitivity and several small subpopulations that had high sea route exposure in comparison with the ice seals, which are characterized by high uncertainty in subpopulation size and structure. Ice seals are presumably focused on foraging during the open-water period, and many data gaps exist on the summer ecology, behavior, and in turn, impacts of vessels on ringed or bearded seals in particular (38, 39). For many of these subpopulations, there was a paucity of information, or we relied on studies of sister species. Our focus on the open-water period precluded examination of ice-breaking vessel activities during the ice-covered season, which would potentially alter vulnerability scores for some species, especially those that rely on sea ice as a platform for reproduction, molting, and foraging (i.e., seals and polar bears). For example, icebreakers can negatively affect ice-breeding seals during pupping and lactation periods by direct collision, as well by separating mothers and pups (40). Examination of potential vessel impacts to sub-Arctic species was also beyond the scope of this analysis, even though more temperate marine mammal species appear to increasingly use Arctic regions in summer. Additional research is warranted to understand the seasonal distribution, abundance, and potential vulnerability of sub-Arctic species to vessels.

Our analysis focused on the NWP and NSR, where recent vessel transit data were available, but there is important AMM habitat in other regions with vessel exposure (e.g., Svalbard, Sea of Okhotsk). Although our study used open data on full transits of the two sea routes, vessel traffic in much of the Arctic is not well-documented (7, 10). Nearly 65% of the Arctic marine environment experienced vessel traffic in a recent snapshot of 2015 ship tracks, although most was focused in the Barents, Bering, and Norwegian seas during open-water periods (41). Broader data on vessel type and tracks would enable more quantitative analyses of exposure and associated impacts, such as probabilistic modeling of vessel noise propagation (42), individual exposure estimates (43), and overlap with ecologically significant

Table 1. **Mean vulnerability assessment scores of AMMs to vessel traffic during the open-water period, averaged across subpopulations exposed to either or both the NWP or NSR**

Species	Proportion of subpopulations exposed	Exposure	Sensitivity	Vulnerability	Uncertainty
Beluga	0.33	2.13	2.38	5.06	1.77
Narwhal	0.50	2.29	2.45	5.59	2.12
Bowhead	0.50	2.22	2.31	5.16	1.50
Ringed seal	0.63	1.92	1.83	3.52	2.64
Bearded seal	0.78	2.12	1.89	4.01	2.80
Walrus	0.42	2.59	2.05	5.34	2.04
Polar bear	0.63	1.67	1.77	2.95	2.52
All AMMs	0.53	2.05	2.02	4.20	2.32

Subpopulations with no exposure to the sea routes are excluded from the estimation of means.

areas (32). Regions such as the Bering Strait and the Chukchi Sea, which we identify as areas with high AMM vulnerability, are at the crossroads of the NWP and NSR and are also of substantial biological and cultural importance; as such, they are ripe for more focused research on vessel impacts (11).

A population's resilience or capacity to adapt affects vulnerability, yet this is often excluded from vulnerability analyses because of the inherent challenges associated with scoring adaptive capacity (14) and limited information (e.g., refs. 19, 20, and 44). Slow intrinsic growth rates, long generation

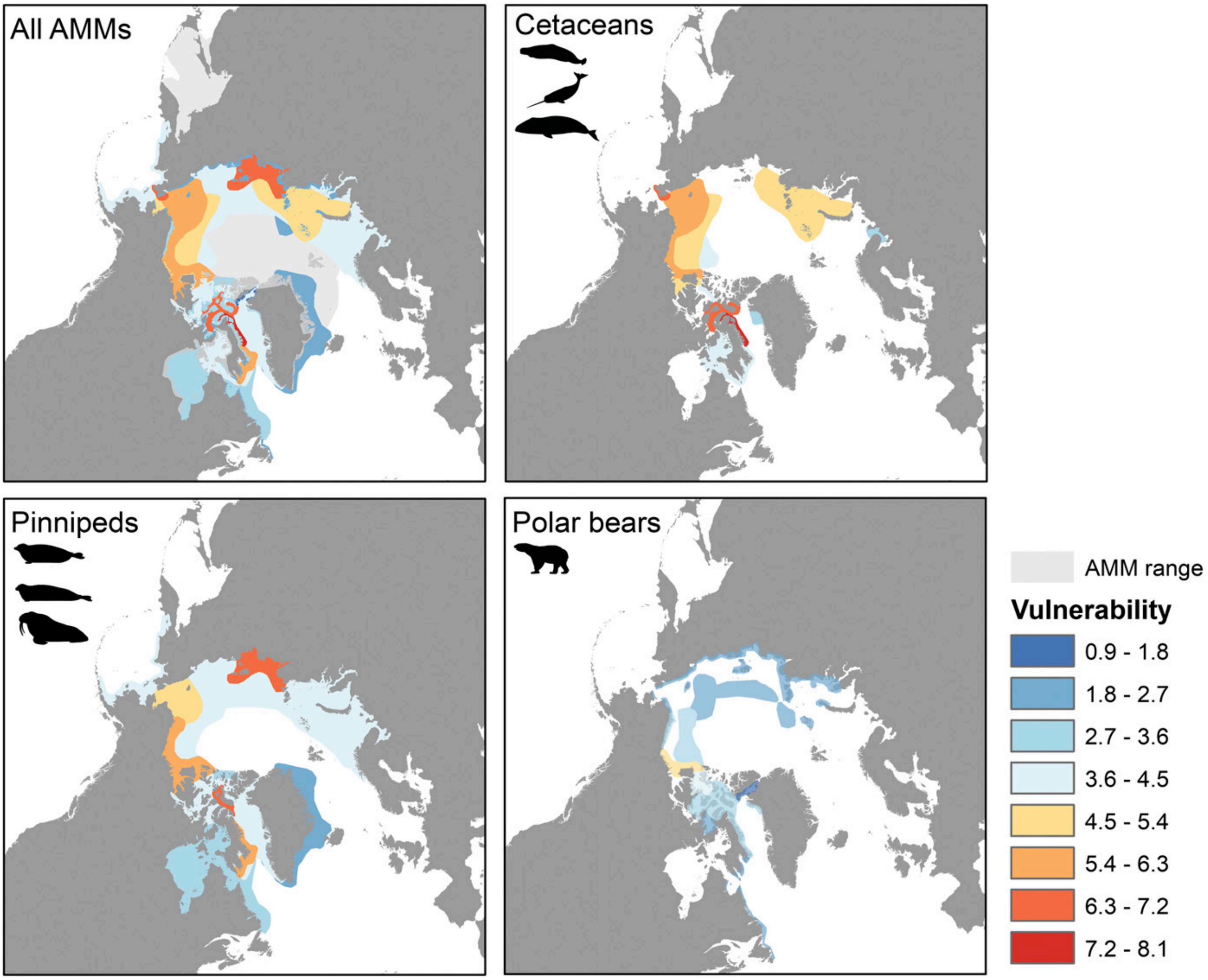

Fig. 4. Maximum vulnerability scores for all AMM species (*Top Left*) and taxonomic groups exposed to the Arctic sea routes. Vulnerability color shading corresponds to the vulnerability plot in Fig. 2. The combined ranges of all other AMM subpopulations that did not overlap the Arctic sea routes are shown in gray in the *Top Left*, including portions of polar bear subpopulations that range onto land during the open-water period.

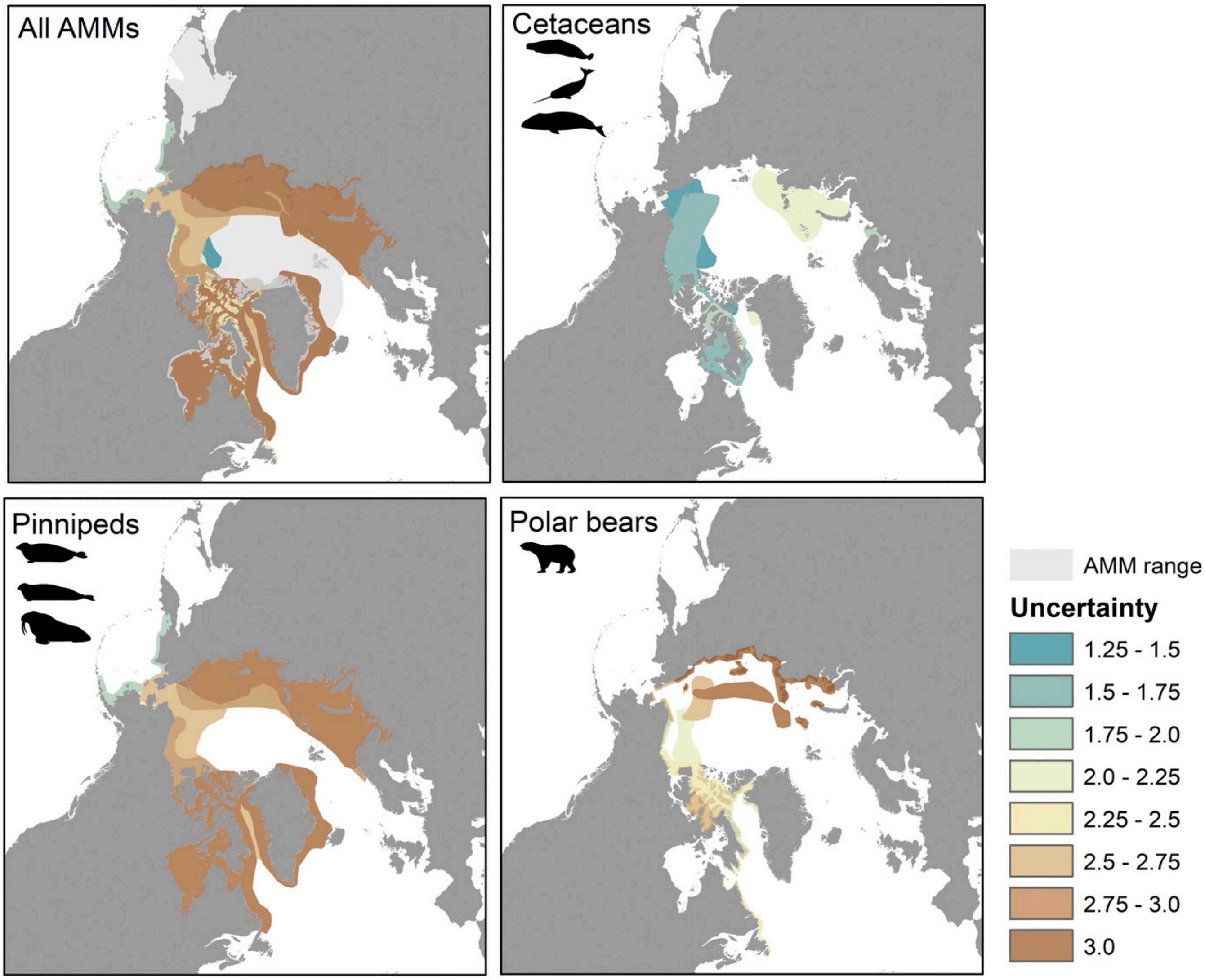

Fig. 5. Maximum uncertainty scores for all AMM species (*Top Left*) and taxonomic groups exposed to the Arctic sea routes. The combined ranges of all other AMM subpopulations that did not overlap the Arctic sea routes are shown in gray in the *Top Left*, including portions of polar bear subpopulations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

ACKNOWLEDGMENTS. Thanks to Peter Westley for reviewing an earlier draft, Richard McGovern for assisting in mapping sea routes, and Sheila Ocoma and Kathryn Koo for entering vessel transit data. Two anonymous reviewers improved the paper. This work was primarily funded by NASA Grant NNX16AG33G (to H.L.S. and K.L.L.), with additional support for D.D.W.H. from the Collaborative Alaskan Arctic Studies Program.

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