



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

Donna D. W. Hauser^{a,1,2}, Kristin L. Laidre^a, and Harry L. Stern^a

^aPolar Science Center, Applied Physics Laboratory, University of Washington, Seattle, WA 98105

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 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.

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.

Published under the PNAS license.

¹Present address: International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK 99775.

²To whom correspondence should be addressed. Email: dhauser2@alaska.edu.

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

Published online July 2, 2018.

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

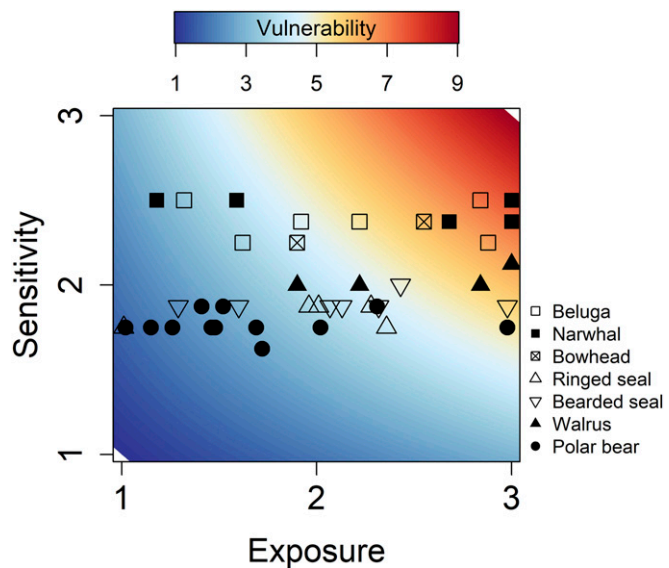


Fig. 2. Vulnerability plot expressing sensitivity and exposure scores across Arctic marine mammal subpopulations exposed to the Northwest Passage or Northern Sea Route. Vulnerability is the product of exposure and sensitivity.

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.

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

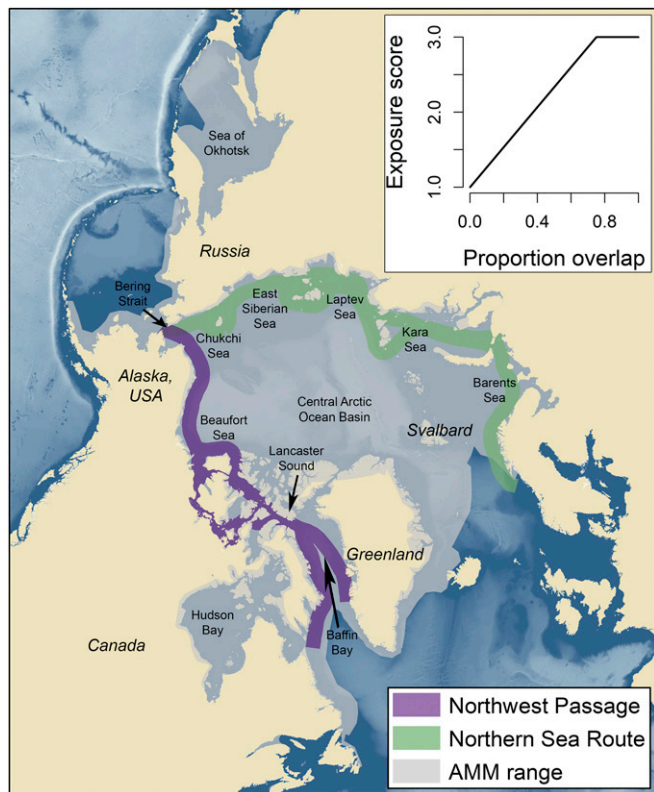


Fig. 1. Map of the Northwest Passage, Northern Sea Route, and extent of the September range of 80 AMM subpopulations. Polar bears range onto land during the open-water period, as reflected by gray shading overlapping land. (Inset) Illustration of how the proportion of the sea routes that overlap each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

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

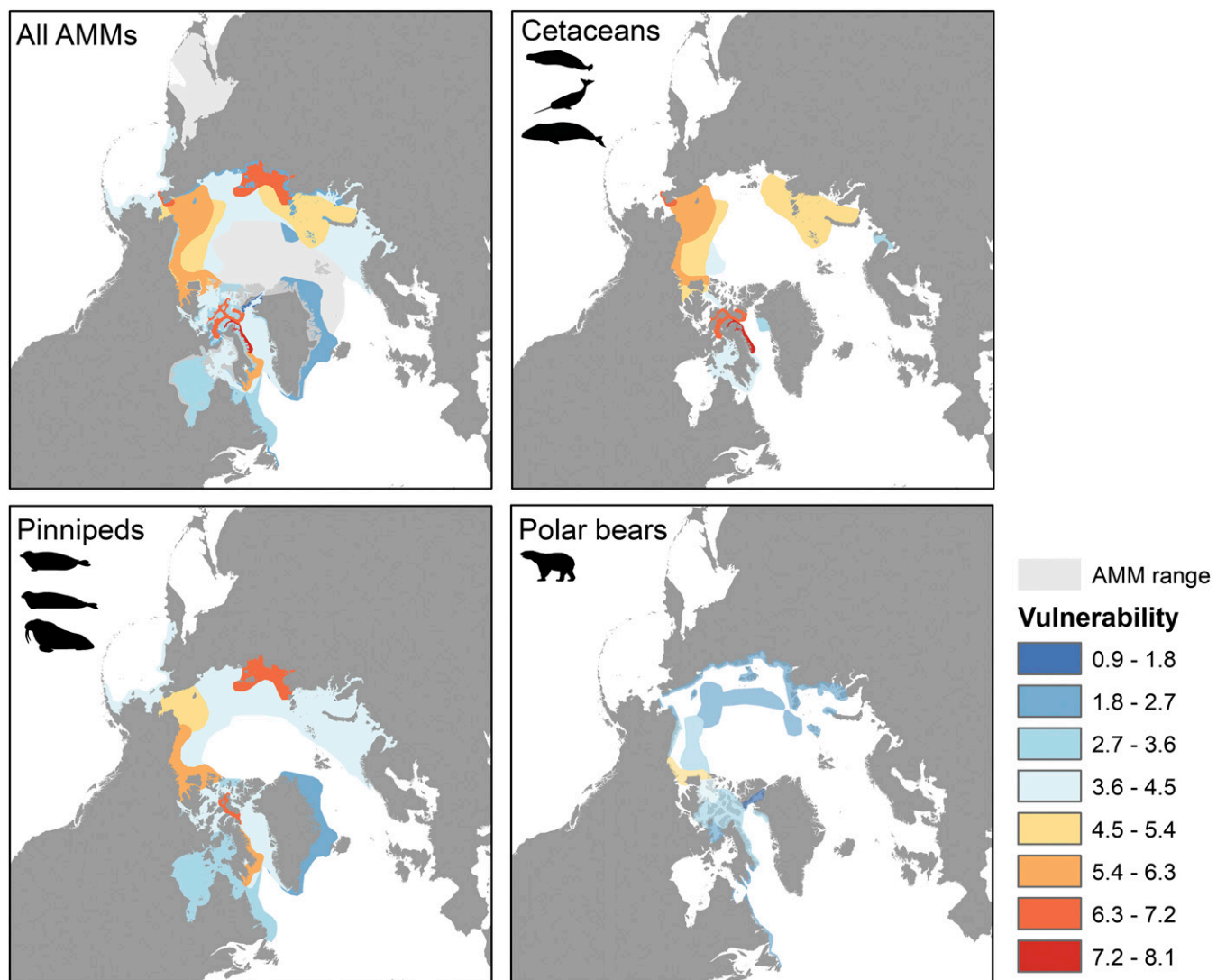


Fig. 4. Maximum vulnerability scores for all AMM species (*Top Left*) and taxonomic groups exposed to the Arctic sea routes. Vulnerability color shading corresponds to the vulnerability plot in Fig. 2. The combined ranges of all other AMM subpopulations that did not overlap the Arctic sea routes are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

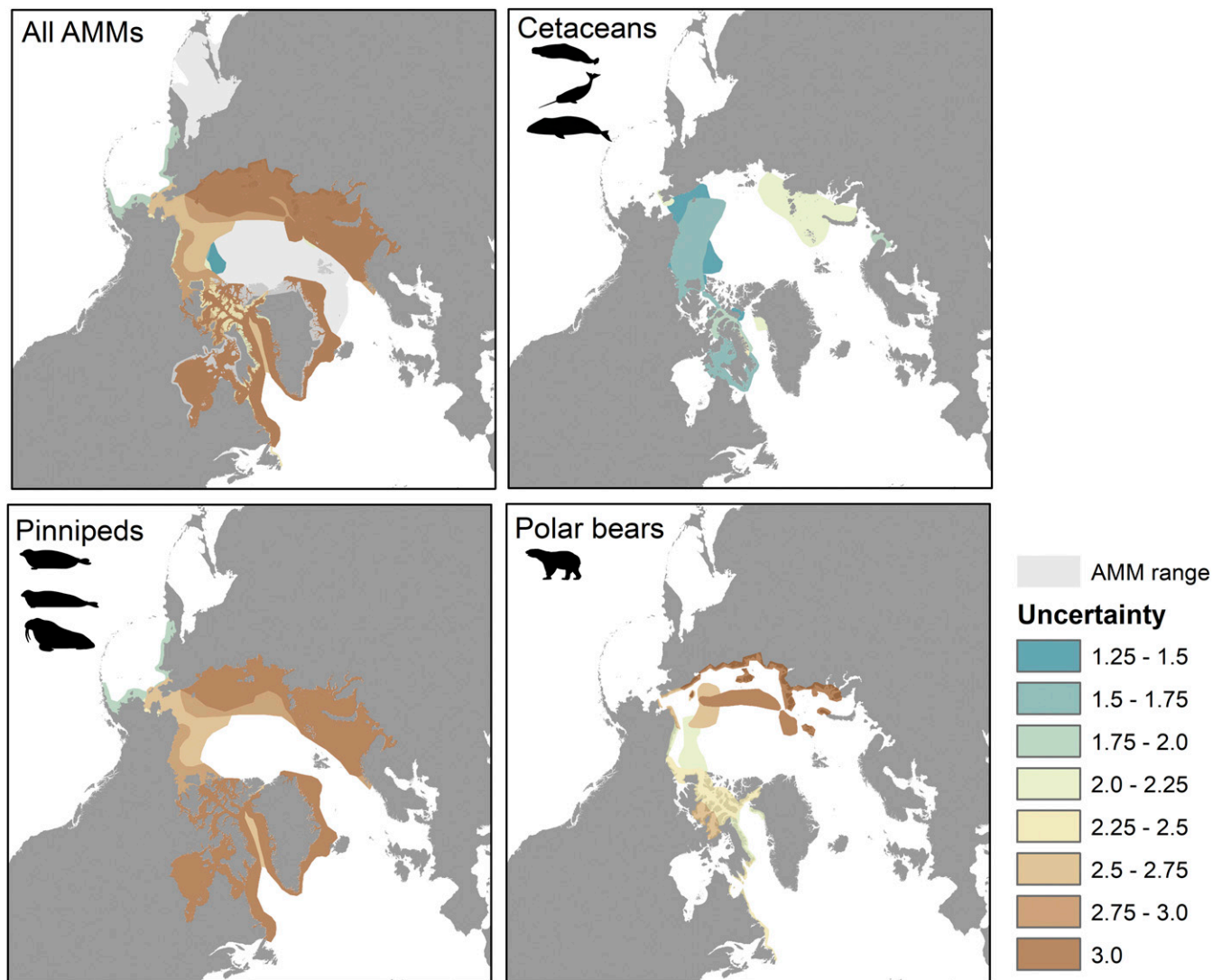


Fig. 5. Maximum uncertainty scores for all AMM species (*Top Left*) and taxonomic groups exposed to the Arctic sea routes. The combined ranges of all other AMM subpopulations that did not overlap the Arctic sea routes are shown in gray in the *Top Left*, including portions of polar bear subpopulations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

- Comiso JC, Hall DK (2014) Climate trends in the Arctic as observed from space. *Wiley Interdiscip Rev Clim Change* 5:389–409.
- Stroeve JC, Markus T, Boisvert L, Miller J, Barrett A (2014) Changes in Arctic melt season and implications for sea ice loss. *Geophys Res Lett* 41:1216–1225.
- Laidre KL, et al. (2015) Arctic marine mammal population status, sea ice habitat loss, and conservation recommendations for the 21st century. *Conserv Biol* 29:724–737.
- Overland JE, Wang M (2013) When will the summer Arctic be nearly sea ice free? *Geophys Res Lett* 40:1–5.
- Wassmann P (2011) Arctic marine ecosystems in an era of rapid climate change. *Prog Oceanogr* 90:1–17.
- Grebmeier JM (2012) Shifting patterns of life in the Pacific Arctic and sub-Arctic seas. *Annu Rev Mar Sci* 4:63–78.
- AMSA (2009) *Arctic Marine Shipping Assessment* (Arctic Council, Tromsø, Norway).
- Smith LC, Stephenson SR (2013) New trans-Arctic shipping routes navigable by mid-century. *Proc Natl Acad Sci USA* 110:E1191–E1195.
- Stephenson SR, Brigham LW, Smith LC (2014) Marine accessibility along Russia's Northern Sea Route. *Polar Geogr* 37:111–133.
- Reeves RR, et al. (2014) Distribution of endemic cetaceans in relation to hydrocarbon development and commercial shipping in a warming Arctic. *Mar Policy* 44:375–389.
- Huntington HP, et al. (2015) Vessels, risks, and rules: Planning for safe shipping in Bering Strait. *Mar Policy* 51:119–127.
- Kovacs KM, Lydersen C, Overland JE, Moore SE (2011) Impacts of changing sea-ice conditions on Arctic marine mammals. *Mar Biodiversity* 41:181–194.
- Moore SE, Huntington HP (2008) Arctic marine mammals and climate change: Impacts and resilience. *Ecol Appl* 18(Suppl 2):S157–S165.
- Adger WN (2006) Vulnerability. *Glob Environ Change* 16:268–281.
- Halpern BS, et al. (2008) A global map of human impact on marine ecosystems. *Science* 319:948–952.
- Williams SE, Shoo LP, Isaac JL, Hoffmann AA, Langham G (2008) Towards an integrated framework for assessing the vulnerability of species to climate change. *PLoS Biol* 6:2621–2626.
- Allison EH, et al. (2009) Vulnerability of national economies to the impacts of climate change on fisheries. *Fish Fish* 10:173–196.
- Turner BL, 2nd, et al. (2003) A framework for vulnerability analysis in sustainability science. *Proc Natl Acad Sci USA* 100:8074–8079.
- Gardali T, Seavy NE, DiGaudio RT, Comrack LA (2012) A climate change vulnerability assessment of California's at-risk birds. *PLoS One* 7:e29507.
- Hodgson EE, Essington TE, Kaplan IC (2016) Extending vulnerability assessment to include life stages considerations. *PLoS One* 11:e0158917.
- Davidson AD, et al. (2012) Drivers and hotspots of extinction risk in marine mammals. *Proc Natl Acad Sci USA* 109:3395–3400.
- Maxwell SM, et al. (2013) Cumulative human impacts on marine predators. *Nat Commun* 4:2688.
- Post E, et al. (2013) Ecological consequences of sea-ice decline. *Science* 341:519–524.
- Bhatt US, et al. (2014) Implications of Arctic sea ice decline for the Earth system. *Annu Rev Environ Resour* 39:57–89.
- Overland JE, Wang M, Walsh JE, Stroeve J (2014) Future Arctic climate changes: Adaptation and mitigation time scales. *Earth's Future* 2:68–74.
- Nielsen NH, Laidre K, Larsen RS, Heide-Jørgensen MP (2015) Identification of potential foraging areas for bowhead whales in Baffin Bay and adjacent waters. *Arctic* 68:169–179.
- Dietz R, et al. (2008) Movements of narwhals (*Monodon monoceros*) from Admiralty Inlet monitored by satellite telemetry. *Polar Biol* 31:1295–1306.
- Hauser DDW, Laidre KL, Stern HL, Suydam RS, Richard PR (2018) Indirect effects of sea ice loss on summer-fall habitat and behaviour for sympatric populations of an Arctic marine predator. *Diversity Distrib* 24:791–799.
- Laidre KL, et al. (2016) Use of glacial fronts by narwhals (*Monodon monoceros*) in West Greenland. *Biol Lett* 12:20160457.
- George JC, Druckenmiller ML, Laidre KL, Suydam R, Person B (2015) Bowhead whale body condition and links to summer sea ice and upwelling in the Beaufort Sea. *Prog Oceanogr* 136:250–262.
- Redfern JV, et al. (2017) Assessing the risk of chronic shipping noise to baleen whales off Southern California, USA. *Endanger Species Res* 32:153–167.
- Redfern JV, et al. (2013) Assessing the risk of ships striking large whales in marine spatial planning. *Conserv Biol* 27:292–302.
- McKenna MF, Katz SL, Condit C, Walbridge S (2012) Response of commercial ships to a voluntary speed reduction measure: Are voluntary strategies adequate for mitigating ship-strike risk? *Coast Manage* 40:634–650.
- Silber GK, et al. (2012) The role of the International Maritime Organization in reducing vessel threat to whales: Process, options, action and effectiveness. *Mar Policy* 36:1221–1233.
- Merchant ND, Faulkner RC, Martinez R (October 24, 2017) Marine noise budgets in practice. *Conserv Lett*, 10.1111/conl.12420.
- Siders A, Stanley R, Lewis KM (2016) A dynamic ocean management proposal for the Bering Strait region. *Mar Policy* 74:177–185.
- Maxwell SM, et al. (2015) Dynamic ocean management: Defining and conceptualizing real-time management of the ocean. *Mar Policy* 58:42–50.
- Cameron M, et al. (2010) *Status Review of the Bearded Seal (Erignathus barbatus)*, NOAA Technical Memorandum NMFS-AFSC (US Department of Commerce, Springfield, VA), Vol 211.
- Kelly BP, et al. (2010) *Status Review of the Ringed Seal (Phoca hispida)*, NOAA Technical Memorandum NMFS-AFSC (US Department of Commerce, Springfield, VA), Vol 212.
- Wilson SC, et al. (2017) Assessment of impacts and potential mitigation for ice-breaking vessels transiting pupping areas of an ice-breeding seal. *Biol Conserv* 214: 213–222.
- Adams J, Silber GK (2017) *2015 Vessel Activity in the Arctic*, NOAA Technical Memorandum NMFS-OPR (National Oceanic and Atmospheric Administration Fisheries, Silver Spring, MD), Vol 57, 171 p.
- Aulanier F, Simard Y, Roy N, Gervaise C, Bandet M (2017) Effects of shipping on marine acoustic habitats in Canadian Arctic estimated via probabilistic modeling and mapping. *Mar Pollut Bull* 125:115–131.
- Jones EL, et al. (2017) Seals and shipping: Quantifying population risk and individual exposure to vessel noise. *J Appl Ecol* 54:1365–2664.
- Hobday AJ, et al. (2011) Ecological risk assessment for the effects of fishing. *Fish Res* 108:372–384.
- Laidre KL, et al. (2008) Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecol Appl* 18(Suppl 2):S97–S125.
- CAFF (2017) *State of the Arctic Marine Biodiversity Report* (Conservation of Arctic Flora and Fauna International Secretariat, Akureyi, Iceland).
- Headland RK (2010) Ten decades of transits of the Northwest Passage. *Polar Geogr* 33: 1–13.
- Havbase (2017) Map of Arctic and Shipping (Norwegian Coastal Administration, Ålesund, Norway). Available at https://havbase.no/havbase_arktis. Accessed June 18, 2018.
- Williams A, Dowdney J, Smith ADM, Hobday AJ, Fuller M (2011) Evaluating impacts of fishing on benthic habitats: A risk assessment framework applied to Australian fisheries. *Fish Res* 112:154–167.
- Halpern BS, Selkoe KA, Micheli F, Kappel CV (2007) Evaluating and ranking the vulnerability of global marine ecosystems to anthropogenic threats. *Conserv Biol* 21: 1301–1315.