ASSESSING THE RISK OF NON-NATIVE MARINE SPECIES IN THE BERING SEA

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Marine Invasive Species Risk Assessment

Assessing the Risk of Non-Native Marine Species in the Bering Sea

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Executive summary

Invasive species are one of the leading global conservation concerns, which can have strong, negative impacts on ecosystems, vulnerable species, and valuable natural resources. Arctic regions have experienced a relatively low number of biological introductions to date. Their geographical remoteness, cold waters, and presence of sea ice present challenging conditions for both non-native organisms and the vessels that transport them, presumably leading to low rates of introduction and establishment. However, observed increases in water temperatures reductions in sea ice, and projected increases in shipping traffic are expected to render arctic marine regions more susceptible to the arrival and colonization of marine invasives. Risk assessments for these Arctic regions are important to inform management and monitoring priorities by determining which species pose the greatest risk. To this end, we developed a ranking system for non-native marine species and used this system to assess the risk of non-native species to the Bering Sea. Using species' published physiological tolerances, we mapped habitat suitability under current and future climate scenarios to identify geographic areas of current and future concern. In addition, we described shipping traffic from commercial and fishing vessels to identify ports of entry for non-native species. Collectively, these analyses identify which marine species have the greatest risk for invasion, where in the Bering Sea invasion risk and species establishment is greatest, and which ports are most likely to serve as an entry point for marine invasives into Alaska's Bering Sea.

The ranking system we developed for non-native marine species consists of 33 questions grouped into five categories. The first four categories evaluate a species' ability to arrive and establish in the Bering Sea, its reliance on humans for introductions, its biology, and its impacts on ecological and human systems. The fifth category is not included in the total ranking score, but provides information on management considerations. The ranking system has methods to account for data deficiencies and calculates these deficiencies to allow readers to weigh the lack of knowledge with the ranking score. We prioritized non-native species for ranking based on their geographic proximity to the Bering Sea. We evaluated 46 species and ranking scores ranged from 29.1 to 74.3 (out of a possible 100), with highest scores indicating greatest risk. Taxonomy at the level of phylum did not explain variation in ranking values, likely due to the substantial biological variation relative to our ranking criteria among members of the same phylum.

To investigate where non-native species may survive and persist in the Bering Sea, we compared species' temperature and salinity thresholds to environmental conditions of the Bering Sea. Environmental conditions were obtained from three Regional Ocean Modeling Systems (ROMS) and investigated under two time periods: current (2003-2012) and mid-century (2030-2039). We identified potential habitat for survival for 42 species, and potential habitat for reproduction for 29 species. Under current conditions, all species had temperature and salinity thresholds that would allow survival in the Bering Sea for at least part of the year, and most species (79% to 83%) had thresholds that would allow for survival year-round. For species with temperature and salinity thresholds unsuitable for survival in the Bering Sea, winter temperatures appear to be the limiting factor. Most species had six to nine weeks of suitable conditions for reproduction. Future increases in water temperatures are expected to open more habitat for

marine invasives. Two of the three ROMs project an increase in the number of non-native species that would be able to survive year-round by mid-century. Moreover, models project between 37% and 60% of the Bering Sea shelf habitat to become more suitable under mid-century climate conditions. Across all marine invasive species assessed in this study, habitat suitability is currently highest in the southeastern Bering Sea, along the Aleutian Islands and the northwestern tip of the Alaska Peninsula, and is generally expected to expand northwards from the Alaska Peninsula and eastward into Bristol Bay, tracking projected increases in water temperature.

To investigate which ports are the likeliest points of introduction for marine invasives to the Alaskan Bering Sea, we assessed both vessel traffic and ballast water volume. Vessel traffic patterns indicate a high degree of connectivity between Dutch Harbor and ports from both the eastern and western Pacific Ocean. Dutch Harbor receives the greatest amount of both vessel traffic and ballast water exchange, and is therefore the most likely port of entry for shipborne marine invasive species. Not only is Dutch Harbor at greatest risk for the arrival of marine invasives, but our analysis of habitat suitability indicates that Dutch Harbor also lies within some of the most suitable habitat for marine invasive species. Additional ports with relatively high volumes of vessel traffic capable of introducing marine invasives include Akutan, which receives a high portion (approximately 26%) of fishing vessel traffic, and Nome, which receives a moderate amount (approximately 10%) of ballast water discharge.

I. INTRODUCTION

The Bering Sea is a highly productive sea that lies between the Pacific and Arctic Oceans, supporting half of the United States' seafood harvest, and generating more than $1 billion USD in revenues each year through the commercial fishing industry (Fissel et al. 2015; Alaska Marine Conservation Council 2008). The Bering Sea is also a key corridor for global shipping traffic and for expanding development in the Arctic. Further, the remote communities of the Bering Sea are largely dependent on access to subsistence foods for sustenance and cultural preservation (Bering Sea Elders 2011; Mathis et al. 2015). Low human population levels and challenging abiotic conditions have likely kept introductions of marine invasive species relatively low to date; however, new patterns in global shipping and rising ocean temperatures are likely to increase the rate of introductions and render habitat more suitable for the establishment of non-native species.

The Bering Sea is a high-traffic region for both commercial and fishing vessels, and the frequency of marine vessel traffic along the Northern Great Circle Route through the southern Bering Sea is ranked among the world's highest (Halpern et al. 2008). Using these traffic routes, non-native species may be unintentionally transported and introduced to Alaska's marine areas by commercial and fishing vessels, and from vessels supporting arctic development (Ellis and Brigham 2009). Large, commercial ships may introduce species when discharging ballast water that was sourced from another region (Fofonoff et al. 2003a), and by inadvertently transporting fouling organisms, which can survive on submerged or wet vessel surfaces such as hulls, anchors, propellers, and sea chests (Moser et al. 2017). The commercial fishing fleet may also act as a transportation vector for invasive species, particularly fouling organisms (Moser et al. 2017). In addition to the southern traffic routes, trans-oceanic shipping through the Arctic (and through the Bering Sea) is anticipated to increase tenfold by 2020 (Barents Observer 2010).

Climate-mediated changes in the Bering Sea are leading to altered landscapes and habitats. A reduction in sea ice, as well as warming water temperatures, has been observed for several decades in the region (Stroeve et al. 2007; Overland and Wang 2010). Sea ice cover in the Bering Sea has decreased significantly since 1954, and surface water temperatures have increased by 0.23°C per decade over the same time period (Mueter and Litzow 2008). This warming trend has resulted in major changes in the distribution and abundance of native species (e.g. Brodeur et al. 1999; Grebmeier et al. 2006; Mueter and Litzow 2008). Moreover, several native species including mollusks, salmonids, and crabs have shown decreased fitness as a result of ocean acidification (Fabry et al. 2009; Kroeker et al. 2013), which may impact the Bering Sea's ability to resist invasions. Lastly, warming conditions and reductions in sea ice increase the feasibility and incentive for additional human activity and shipping traffic in the region (Ricciardi et al. 2017).

The economy and community resilience of the Bering Sea is particularly susceptible to the negative impacts of invasive species given the geographic isolation of communities and their dependence on intact, productive ecosystems. In the Bering Sea, invasive species have the potential to cause environmental and economic problems with profound implications for commercial fishing and subsistence communities, including:

- Competition and predation – such as competition between Atlantic salmon (*Salmo salar)* and native Pacific salmon (*Oncorhynchus* spp.) for spawning or rearing habitats and food (ADF&G 2002a, Wing et al. 1992); or competition between European green crab (*Carcinus maenas)* and commercially important native crabs (ADF&G 2002a, Davidson et al. 2009);
- Alterations to Alaska's commercial fishing, and subsistence economy, as well as its profound cultural connections, due to species declines and/or changes in species distribution (ADF&G 2002a, Pimentel et al. 2005). For example, the tunicate *Didemnum vexillum* can affect commercial groundfish fisheries (Valentine et al. 2007);
- Damage to equipment and infrastructure – such as fouling of aquaculture equipment, fishing gear, and port/dock infrastructure by tunicates (Shaw 2010); and
- Ecosystem conversions – such as the conversion of mudflat ecosystems to salt marsh by the cordgrass *Spartina* spp., decreasing habitat important for shorebirds and many species of fish, clams, and crabs (Daehler 2000, ADF&G 2002a, WAPMS 2004).

To safeguard against the ecological and economic impacts of marine invasive species, a well-coordinated management effort is warranted in Alaska. Since the number and distribution of known marine invasive species in the Bering Sea (and in Alaska waters in general) are still relatively limited, this region has the opportunity to avoid some of the problems that plague more heavily invaded areas farther south such as British Columbia, Washington, California, and Hawaii. Although Alaska currently has fewer invasive species than these nearby states and provinces, some non-native species are already present in Alaska (McClory and Gotthardt 2008). Recently, the Alaska Invasive Species Working Group (AISWG) compiled a list of more than 70 aquatic invasive species that either occur, or have the potential to occur, in Alaska waters based on proximity of species in neighboring states and provinces, similarity of habitats, and potential vectors that could lead to unintentional introductions (AISWG 2010). A key recommendation from AISWG was the need for a ranking system to strategically determine the most ecologically threatening species in order to target coordination, monitoring, and prevention efforts.

Over the past decade, a wide variety of invasive risk assessment models have sought to provide an objective and systematic mechanism to prioritize non-native species for research, prevention, and monitoring (e.g. Carlson et al. 2008, Davidson et al. 2017, Drolet et al. 2016). Published marine invasive species models have been developed for more southern regions (e.g. Drolet et al. 2015, Mandrake and Cudmore 2015); we build upon these models by incorporating criteria with greater relevance in the subarctic Bering Sea, where few invasive species have been observed. To investigate the potential for future invasions of the Bering Sea, we performed a risk assessment that identifies and ranks the threat of non-native and invasive species in nearby regions, assesses the potential for a non-native species to survive and establish in the Bering Sea, and identifies potential arrival points based on marine vessel traffic into the Bering Sea region.

The risk assessment we developed consists of three components:

1) A semi-quantitative ranking system that evaluates the risk of non-native species to the Bering Sea ecosystem. Our system includes questions for evaluating the threat of individual species based on spatial and biological characteristics, known or potential

impacts, and feasibility of management or eradication. Cumulative scores produce an index value that may be used to rank species such that managers and researchers may prioritize species for action.

2) A habitat suitability analysis that examines the potential for non-native species to survive and reproduce within the Bering Sea. Specifically, we examine whether species can survive year-round, identify which weeks are most suitable for their survival, and assess if conditions exist to support reproduction. We consider the potential effects of climate change on invasion risk by generating and comparing current (2003-2012) and mid-century (2030-2039) habitat suitability models. This analysis is based on species-specific temperature and salinity thresholds for both survival and reproduction, and uses regional ocean models developed by the NPRB Bering Sea Project (Hermann et al. 2013; Hermann et al. 2016).
3) A description of vessel traffic and ballast water movement patterns in the Bering Sea from both commercial and fishing vessels. We describe the number of ships and the volume of ballast water discharged in ports of the Bering Sea, and where these ships originate, allowing the identification of ports that are most at risk from marine invasives.

Collectively, these components help identify species to target for early detection and prevention efforts, establish a method for managers elsewhere in the state to evaluate risk, and raise awareness about the threat from invasive marine species.

II. SPECIES RANKING SYSTEM

Methods

Developing a list of potential invasive species

We downloaded or digitized spatially-explicit occurrence records for non-native species in surrounding regions from the National Exotic Marine and Estuarine Species Information System (NEMESIS; Fofonoff et al. 2003b) and the Nonindigenous Aquatic Species Database (NAS; Fuller and Benson 2013). For each record, we assigned each species a 'proximity rank' based on the geographic proximity of closest known occurrence records to the Bering Sea. We defined proximity to the Bering Sea using the Marine Ecoregions of the World classification by Spalding et al. (2007). Species present in an ecoregion that encompassed the Bering Sea (Aleutian Islands, Eastern Bering Sea, and Kamchatka shelf) received a proximity value of 0; species present in an ecoregion adjacent to the Bering Sea received a proximity value of 1; species present in an ecoregion once-removed from the Bering Sea received a proximity value of 2, and so on (Figure 1). Species with a proximity value of 0 to 3 were included in the potential invasive species list. We included marine species (salinity tolerance > 30 ppt.) and species that spend a portion of their lifecycle in a marine environment (diadromous and brackish species). We did not include plants.

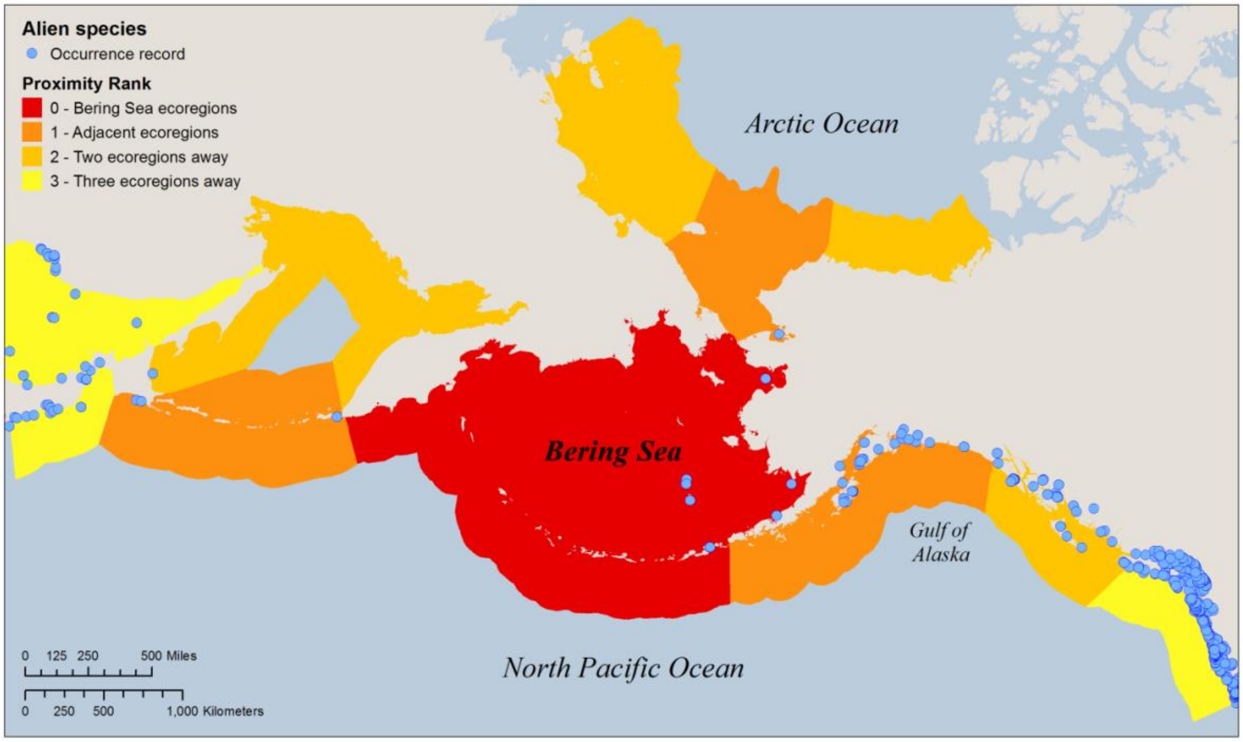
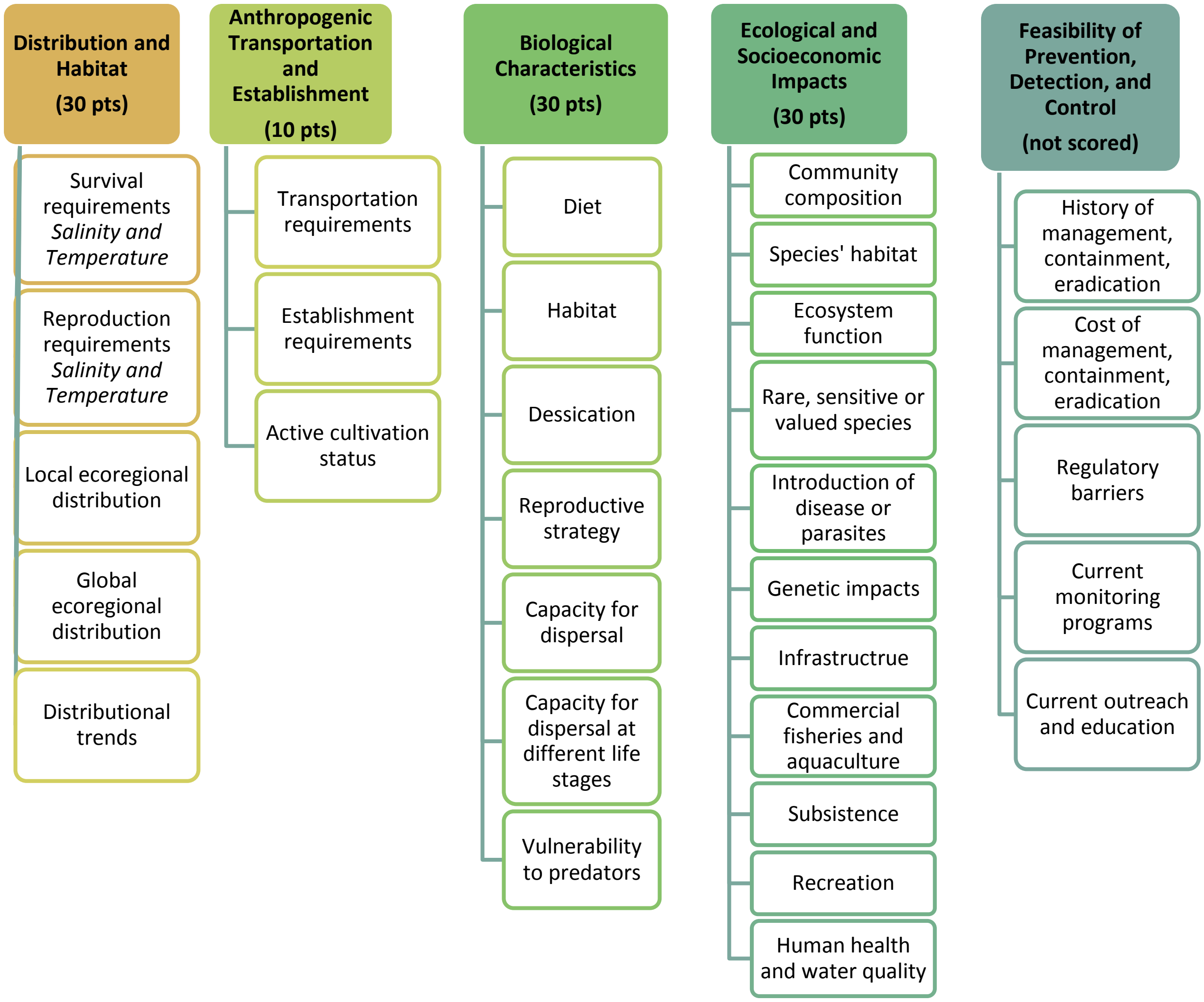


Figure 1. Occurrence records (blue dots) for non-native species and their geographic proximity to the Bering Sea. Ecoregions are based on the classification system by Spalding et al. (2007). Data source: NEMESIS and NAS databases.

Ranking system structure

We compiled, selected, and modified elements from nine ranking systems[1]. The draft ranking system and potential invasive species list were distributed for expert review to 20 researchers. We received sufficient feedback on potential invasive species and ranking criteria from seven individuals at six organizations[2].

The ranking system developed includes 33 assessment questions grouped into five categories (Figure 2). The fifth category is meant to be a stand-alone indicator for managers, and is not included in the species' total rank score.



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[1] Ranking systems considered include: Gotthardt and Walton 2011; Gallardo et al. 2015; Molnar et al. 2008; Halpern et al. 2007; Drolet et al. 2015; Mandrak and Cudmore 2015; Copp et al. 2005; Morse et al. 2004; Washington Invasive Species Council, Invasive species impact and prevention/early action assessment tool.

[2] Expert feedback was provided by: Danielle Verna, Portland State University; Linda Shaw, National Oceanic and Atmospheric Administration; Lindsey Flagstad, Alaska Center for Conservation Science; Catie Bursch, Kachemak Bay Research Reserve; Mark Systma, Portland State University.

Figure 2. Overview of the ranking system variables (and points) organized by category.

Criteria and score distribution

Questions are scored based on the selection of multiple-choice answers, and points are evenly distributed across criteria within each category. The cumulative score can range from 0 to 100, with 100 indicating high invasion and impact potential. See Appendix A for a copy of our ranking system, including detailed criteria and point distributions.

SECTION I. DISTRIBUTION AND HABITAT – 5 questions, 30 points

This section addresses the species' local and global distribution, climatic tolerances, and the presence of suitable habitat in the Bering Sea. This section is based on the premise that species with widespread ranges are more likely to establish additional populations than species with restricted ranges due to a wide niche tolerance and increased sources of introduction (Carlton 1996; Ehrlich 1986; Rouget and Richardson 2003). This section also takes into consideration the climatic similarity between locations where the species is already established and those where it could potentially establish in Alaska. Although a species may be globally widespread, if it is unable to survive and successfully reproduce in climates similar to the Bering Sea, the ecological threat is greatly reduced.

SECTION II. ANTHROPOGENIC TRANSPORTATION AND ESTABLISHMENT – 3 questions, 10 points

This section addresses the ability of a species to travel via anthropogenic means (e.g. ballast water, biofouling), and to establish at anthropogenic sites (e.g. on marine infrastructure). This section is based on the premise that species that use vessels or other human infrastructure as a mode of transportation can travel longer distances and have a higher likelihood of arriving in the Bering Sea. In addition, species that are able to establish in both anthropogenic and undisturbed natural areas are more of a threat to native biodiversity than those species that are restricted to human disturbed sites. This section is given less weight than the others based on (1) the potential to inflate the risk of species that may frequently use anthropogenic vectors but are unlikely to survive in the cold waters of the Bering Sea; and (2) precedent set by other non-indigenous ranking systems in which anthropogenic factors were similarly down-weighted or not considered (Carlson et al. 2008, Gallardo et al. 2016, Gotthardt et al. 2011, Molnar et al. 2008, Morse et al. 2004).

SECTION III. BIOLOGICAL CHARACTERISTICS – 8 questions, 30 points

This section addresses core life history characteristics that may increase the potential for a species to spread and become established. Species that have generalist dietary and habitat needs are more likely to survive and thrive in new areas. Additionally, species that reproduce throughout the year and have a high population growth rate are more likely to quickly produce offspring creating a viable population in the new area. Species with the capacity for frequent, long-distance movement are more likely to be invasive due to repeated introductions to a new area.

SECTION IV. ECOLOGICAL AND SOCIOECONOMIC IMPACTS – 12 questions, 30 points

This section addresses the severity of the threat of a non-native species based on impacts that have been reported for this species elsewhere. The questions are divided into two sections: ecological impacts that address effects to populations, biological communities, habitats, and ecosystem processes; and socioeconomic impacts that address effects to commercial and subsistence activities, recreation, and human health and water quality.

SECTION V. FEASIBILITY OF PREVENTION, DETECTION, AND CONTROL – 5 questions, not scored

This section addresses the feasibility of controlling a species once it becomes invasive. The questions consider the history and cost of management elsewhere, and the regulations and monitoring efforts currently being implemented in Alaska. Since few invasive species have established in the Bering Sea, and the feasibility of control is largely unknown in Alaskan systems, this section was created to inform managers as a supplement to the invasiveness rank.

Adjusted ranks and data deficiencies

Final ranks are calculated as:

$$\left(\frac{\text{Total score}}{\text{Total possible score}}\right) \text{x } 100 = \text{Final rank}$$

This ranking system requires clear documentation for answers to each variable, but allows for species to be evaluated when information is lacking. In such cases, the data-deficient criterion is removed from the scoring system and the score is calculated using a reduced “total possible score”. The species also receives a ‘data deficiency’ score that sums the number of criteria that are removed from the scoring system. For example, if a species is lacking information for three criteria, weighted at 2.5 points each, 7.5 points will be subtracted from the ‘total possible score’ and the species will receive a ‘data deficiency’ score of 3. This allows readers to understand any data deficiencies when interpreting a species’ rank (Figure 3).

Final Rank: 47.4
Data Deficiency: 8.8

Category Scores and Data Deficiencies

Category	Score	Total Possible	Data Deficient Points
Distribution and Habitat	20	26	3.8
Anthropogenic Influence	4.7	10	0
Biological Characteristics	16.05	25	5
Social and Economic Impacts	2.5	30	0
Totals	43	91.25	8.8

Figure 3. Example of final rank calculations for a marine invasive species in the Bering Sea.

Species scoring process

A revised list of potential invasive species was generated to prioritize ranking and expedite the process in light of timely management needs. Priority species were those with a geographic proximity value from 0 to 2, and a subset of species with a proximity value of 3 (Figure 1). The 'proximity 3' subset included all proximity 3 species west of the Bering Sea, and species on the North American coast occurring within or north of the mouth of the Columbia River (Washington-Oregon border). These geographic restrictions reduced the initial list of 129 species to 46 species.

For each species on the priority list, we performed a literature review[3] to inform each ranking criterion. Because the evaluation of the 46 species required substantial scholarly review, we divided this review amongst four researchers. Prior to ranking, we controlled for consistency in interpretation and scoring of criteria by collectively scoring an initial five 'test' species, chosen to represent different levels of expected invasiveness, proximity, and information availability. After each researcher scored a species separately, the group compared ranks, discussed discrepancies, and detailed standards for answering questions with recurring discrepancies among the group (see Appendix B). The scores generated for the five test species were discarded and final evaluation of these species was performed by individual researchers along with the remaining species.

Once species were ranked, draft scores and ranking reports were sent to individual reviewers with marine invasive expertise. Feedback primarily consisted of providing missing literature or data to better inform criteria answers and rank decisions. We contacted 39 expert reviewers and received feedback from seven reviewers[4] for 21 of the highest ranked species.

Final criteria choices and supporting information were entered into a database, which facilitated quick calculation of cumulative and categorical (i.e., Distribution and Habitat, Anthropogenic Influence, Biological Characteristics, and Impacts) scores. The species status reports, which include each criterion selection and scores, as well as ranking information and rationale, is available online[5].

Evaluation of ranking system and scores

Data Deficiencies

To determine if any variables were disproportionally answered as "unknown", the proportion of questions scored as unknown was calculated for all species within each ranking category.

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[3] The NEMESIS, NAS, and Nature Conservancy (Molnar et al. 2008) databases were used as starting points, and supplemented by literature searches conducted using Web of Science and Google Scholar.

[4] Expert feedback was provided by: Christina Simkanin, Smithsonian Environmental Research Center; Linda McCann, Smithsonian Environmental Research Center; Jenn Dijkstra, The Center for Coastal and Ocean Mapping; Kelly Krueger, Sun'aq Tribe of Kodiak; Linda Shaw, National Oceanic and Atmospheric Administration; Nora Foster, NRF Taxonomic Services; and Peter Westley, University of Alaska Fairbanks.

[5] http://accs.uaa.alaska.edu/invasive-species/bering-sea-marine-invasives/ranking-system

Category Score Correlations

During the development of the ranking system, we sought to avoid duplicating the information captured, by creating informative, diagnostic questions, with explicit answer choices, such that a single characteristic would not influence the scores of multiple questions or categories. To assess redundancy within the system, we measured the strength of association between the four ranking categories using Spearman's rank correlations. Some level of correlation (weak to moderate) is to be expected between categories based on common biological relationships between characteristics – e.g. species with widespread distributions are more likely to have broad environmental tolerances (Gröner et al. 2011; Zerebecki and Sorte 2011). Strong correlations however, indicate consistent scoring patterns between categories, suggesting redundancy in the system, and that questions or answer choices in the ranking system repeat information rather than capturing the full range of species' traits and variability, as intended.

Category Contributions to Overall Scores

Spearman's rank correlation coefficients were also used to evaluate the relative contribution of each categorical score to overall score. Specifically, to mitigate autocorrelation a separate score [Rank score] – [Category score] was calculated for each unique species-category combination, and Spearman's rank correlations coefficients were calculated between these scores and ranking category scores.

Taxonomic Bias

To assess whether the ranking system was biased towards certain taxonomic groups, we pooled and compared overall scores at the phylum-level. The diversity of species within our species list made it impractical to summarize trends across lower taxonomic levels, because at these finer scales, many taxonomic groups are represented only by a single species. To assess differences among phylum-level scores, we used a Kruskal-Wallis rank sum test. We did not perform multiple comparison tests because the Kruskal-Wallis rank sum test indicated no significant differences among groups.

Results

Potential invasive species list and ranking scores

We identified 149 species of potential marine invasive species that have been observed within areas up to three ecoregions away from the Bering Sea (Appendix C). From this list, we prioritized and evaluated a total of 46 species including four species previously observed in the Bering Sea, nine species observed in habitat one ecoregion away from the Bering Sea, 11 species observed in habitat two ecoregions away from the Bering Sea and 22 species observed in habitat three ecoregions away from the Bering Sea. Species evaluated included three annelids, three bryozoans, four cnidarians, 15 crustaceans, two fish, 11 mollusks and eight tunicates. The ranking scores of these species ranged from 29.1 to 74.3 (out of a possible 100), and were normally distributed with majority of the points falling around the mean (Shapiro-Wilk test, $p = 0.82$). Species-specific ranking scores are detailed in Appendix D.

Ranking system evaluation

Data deficiencies

Data deficiency scores ranged from 0 to 26.25 per species (mean: 6.08; maximum possible: 100) with the categories "Distribution and Habitat" and "Biological Characteristics" receiving the highest total data deficiency scores (8 to 10%, *n* = 46 species; Table 1). Data deficiencies within "Distribution and Habitat" were typically related to unknown temperature and salinity thresholds for reproduction.

Table 1. Ranking criteria themes and the total points scored as unknown for all ranked species.

Criteria Category	Data Deficient Points	% Data Deficient	Species with data deficiencies (out of 46)
Distribution and Habitat	95	6.9	18
Anthropogenic Transportation and Establishment	8	1.7	2
Biological Characteristics	112.5	8.1	21
Ecological and Socioeconomic Impacts	64	4.6	15

Category Score Correlations

We identified significant correlations ($p < 0.01$) between three of the six category pairings (Table 2); however, these correlations were moderate in strength and occurred between categories with conceptual similarities, indicating that it is possible within the structure of the ranking system for a species to score highly in one of these categories but not the other. These results suggest that the correlation is representative of relationships between a species' characteristics rather than redundancy in the ranking system.

The strongest relationships were identified among 'Biological Characteristics', 'Distribution and Habitat' and 'Ecological and Socioeconomic Impact' scores (Table 2). These relationships suggest that species capable of rapid spread or colonization, with broad environmental tolerances were more likely to score high for 'Ecological and Socioeconomic Impacts'. Since these traits facilitate spread and establishment, both of which are necessary stages for a non-native species to become widely distributed and invasive (i.e. impact native systems), these results are not surprising. In addition, the relationship between distribution and impacts may be based on probability, whereby species that are widespread have more opportunities to impact ecosystems to which they are introduced.

The 'Anthropogenic Transportation and Establishment' category was not significantly correlated with any other category. For many taxa, their global range depends almost exclusively on transport via anthropogenic vectors, and in many cases, the survival and establishment of these non-native species are almost exclusively associated with the presence of anthropogenic infrastructure such as piers and marinas (Ruiz et al. 2009). Therefore, we would have expected a mild to moderate correlation with ‘Distribution and Habitat’ and potentially ‘Ecological and Socioeconomic Impacts’; however, this section is comprised of only three questions. We therefore suspect that the variability observed is not sufficient enough to be captured by the Spearman’s rank correlations.

Table 2. Spearman’s rank correlations between each category of variables.

	Categories			
	Distribution and Habitat	Anthropogenic Transportation & Establishment	Biological Characteristics	Ecological and Socioeconomic Impacts
Distribution and Habitat		0.317	0.473*	0.495*
Anthropogenic Transportation & Establishment			0.250	0.188
Biological Characteristics				0.544*
Ecological and Socioeconomic Impacts				

* Correlation is significant at the 0.01 level (2-tailed)

Ranking Category Contributions to Overall Ranking Scores

Total variance within species’ rank scores was relatively equally distributed across all ranking categories except ‘Anthropogenic Influence’. ‘Biological Characteristics’ was the best predictor of overall score (r^2 = 0.40), followed by ‘Social and Economic Impacts’ (r^2 = 0.36) and ‘Habitat and Distribution’ (r^2 = 0.31) which contributed similarly to overall scores (Figure 4).

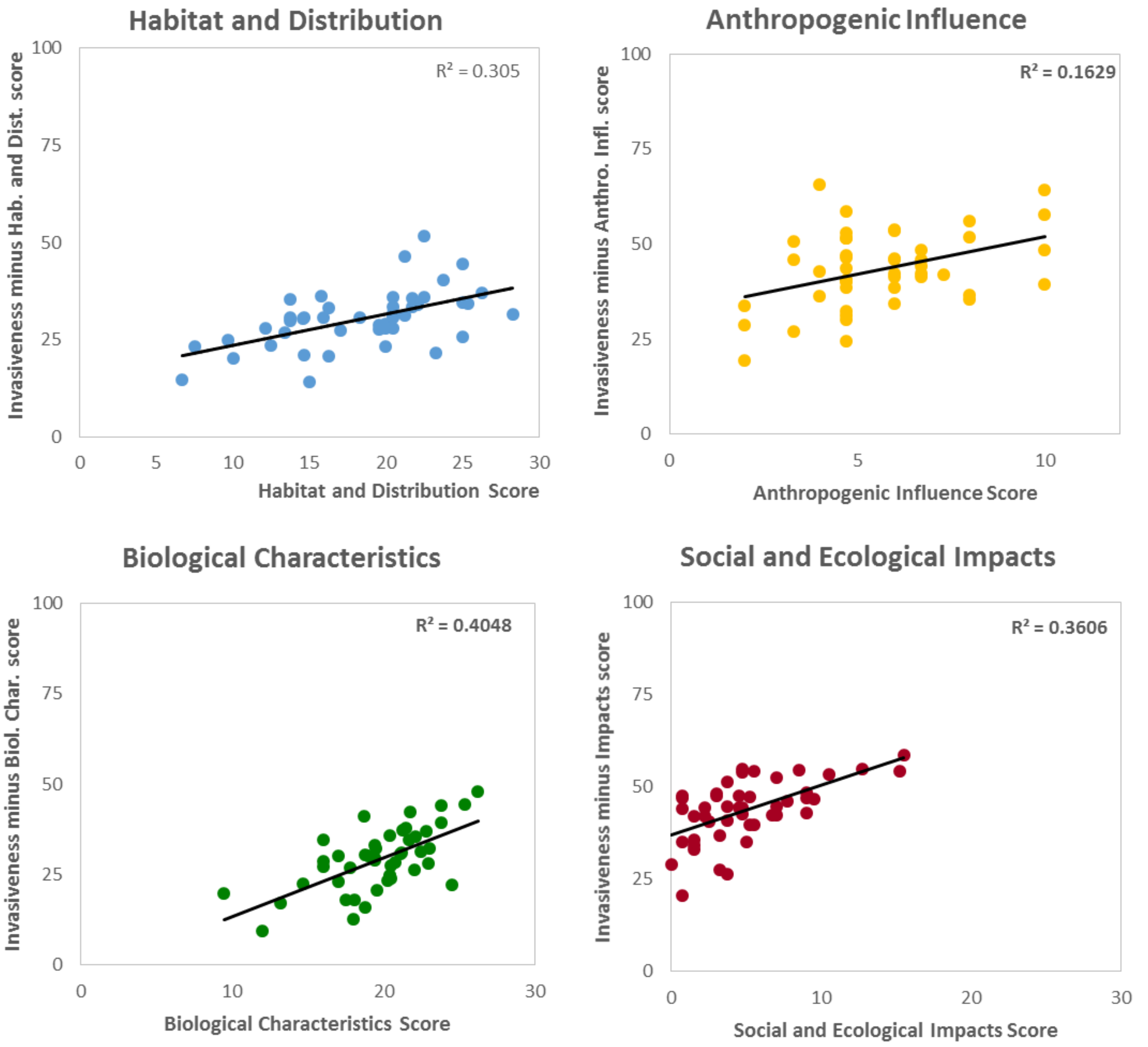

Figure 4. Species' scores for each ranking category relative to the sum of the remaining category scores. For each comparison, the r^2 value represents the proportion of the total variance accounted for by that ranking category's score.

Taxonomic Bias Results

There was no detectable difference among scores for phyla (Kruskal-Wallis, $X^2 = 4.76$, $df = 5$, $p = 0.446$; Figure 5). This is likely due to the high biological variation at this high taxonomic level. For example, the phylum Chordata includes both fish, which are large and highly mobile organisms, and tunicates, which are relatively small and sessile during adulthood.

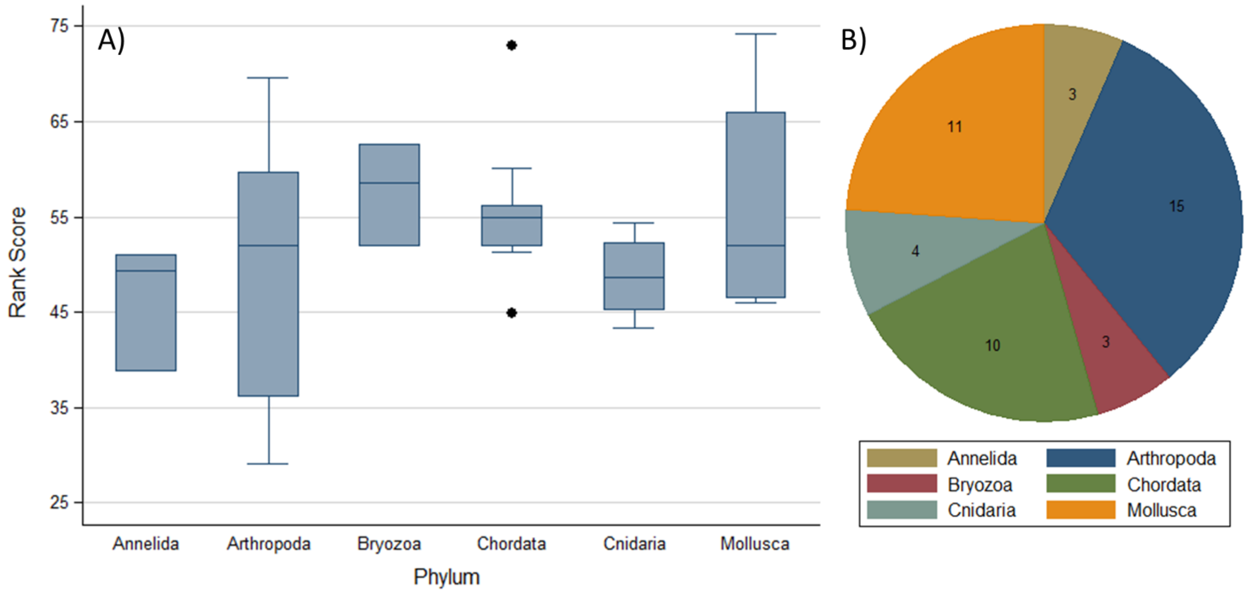

Figure 5. A) Ranking scores for all species by phylum; B) composition of species' phyla considered by our ranking process.

Discussion

Species ranks – top ten watch list

We developed a semi-quantitative ranking system to assess the potential risk of non-native marine species to the Bering Sea. This system assesses the potential risk of each species based on criteria and characteristics that would promote arrival, establishment, expansion and damage in the Bering Sea. Specifically, these criteria encompass current habitat and distribution, biological characteristics, transportation and establishment associated with anthropogenic activities, and the potential ecological and socioeconomic threat of each species.

Of the 46 species ranked, the top ten non-native species of concern are: Pacific oyster (*Crassostrea gigas*), European green crab (*Carcinus maenas*), Mediterranean mussel (*Mytilus galloprovincialis*), carpet sea squirt (*Didemnum vexillum*), bay barnacle (*Amphibalanus improvisus*), Japanese skeleton shrimp (*Caprella mutica*), Manila clam (*Venerupis philippinarum*), brown bryozoan (*Bugula neritina*), softshell clam (*Mya arenaria*) and red-rust bryozoan (*Watersipora subtorquata* complex) (Appendix D). Of these species, the Japanese skeleton shrimp and the soft-shell clam, currently inhabit regions in the Bering Sea (see Fofonoff et al. 2003b). The European green crab and the carpet sea squirt have both been observed within two ecoregions away from the Bering Sea, and are both well-known invasive species that are currently on local watch lists and are considered species of great concern (ADF&G 2002b).

Species on the top ten list are evenly distributed across four phyla: Arthropoda, Mollusca, Bryzoa, and Chordata. The top three species are all mollusks and are ranked relatively high due to the general biology of mollusks, such as their capacity for long distance dispersal (Branch and Steffani 2004) and survival in a variety of environments (Padilla 2010). The Pacific oyster in particular is ranked relatively high due to its ability to modify habitats, and the environmental damage reported in places where wild populations have established (Padilla 2010, Troost 2010, Herbert et al. 2016). Our ranking system does not however, consider the economic benefit of species, such as the Pacific oyster, which may be high (see Herbert et al. 2016).

Data deficiencies

The utility of a prioritization scheme depends on the availability and quality of data. While we conducted extensive literature searches and contacted numerous experts to obtain current information, for some species, we were unable to answer all of the questions with justification and certainty. To address this issue, we constructed a mechanism for handling unknown ranking criteria that still allowed for the species to be scored by removing the question from the scoring criteria and identifying it as an 'unknown' (see Carlson et al. 2008). By identifying data deficiencies for each species, we were able to highlight species-specific data gaps while still allowing for a rank score to be calculated. In the case of high data deficiencies, this mechanism also indicates to the reader that a given species rank and status report has limitations.

Assessment of the ranking system

Tests assessing the influence of each rank criteria category revealed that no single category dictated the overall ranking score, rather, the ranking score was influenced by a cumulative increase (or decrease) across all categories. This is consistent with the positive correlations observed among each of the pairwise category comparisons. In addition, there appears to be no taxonomic bias in the ranking system, likely due to the wide array of species and biological characteristics within each phyla.

Ranking System - General remarks

This ranking system and potential invaders list allows managers to make informed decisions about which species are likely to arrive, establish and/or cause economic or ecological damage in the Bering Sea. In addition, the species status reports establish a baseline for future comparisons and the ranking criteria creates a framework that can be updated as new information becomes available. The scope and uses of the marine invasive species ranking system exceed the results contained within this report. An Access database includes all the species information gathered and ranks calculated during this effort. The database can be easily updated as new information and funding become available, and is available on request[6]. To ensure consistency in future updates to the database, we developed an instruction manual that details how common scenarios are addressed during the ranking process (Appendix B).

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[6] Available on request from the Alaska Center for Conservation Science: http://accs.uaa.alaska.edu/request-data/

III. HABITAT SUITABILITY ASSESSMENT

Methods

Determining species’ environmental tolerances

We characterized regional habitat suitability based on published species-specific physiological thresholds for the marine invasive species identified through our ranking process. A species’ environmental tolerances were defined by temperature (T) and salinity (S) thresholds, both of which are strong predictors of aquatic species’ distribution and their invasion potential (Barry et al. 2008; Hewitt and Hayes 2002). We considered thresholds for a) survival and b) reproduction, which represent the two limiting life stages required for colonization (Blackburn et al. 2011). Of the 46 species included in the ranking system, we compiled T-S survival tolerances for 42 species and T-S reproductive tolerances for 29 species (Appendix E).

We defined survival thresholds for each species as the minimum and maximum T-S reported across all life stages. If the maximum temperature threshold was unknown, but survival had been observed in temperatures higher than the maximum temperature of the Bering Sea (approximately 17°C), we set the maximum temperature to an arbitrary value of +999 to ensure its inclusion in our analysis. If salinity thresholds were not available, but a species was known to be marine, we set its salinity range to average seawater values (31 to 35 ppt), which would confer salinity survival to almost all areas of the Bering Sea. For reproduction, if multiple thresholds were published for different life stages (e.g. spawning, larval development), we chose the narrowest T-S range. If T-S thresholds were available from experimental studies, we selected these in favor of thresholds inferred from a species’ geographic distribution. Although thresholds based on distribution alone may be biased or incomplete, we considered this source of data to be superior to no data.

Environmental covariates: Water temperature and salinity

Values for the T-S regimes of the Bering Sea were obtained from three Regional Ocean Modeling Systems (ROMS) for the most recent time period (current; 2003-2013) and farthest forecasted time period (mid-century; 2030-2039) (Hermann et al. 2013; Hermann et al. 2016). Each ROMS was generated by downscaling one of three general circulation models (GCM): 1) CGCM3-t47, 2) ECHO-G, and 3) MIROC3.2 (Hermann et al. 2016). The GCMs used to develop the ROMS were selected for their ability to hindcast observed conditions in the Bering Sea and the northeastern Pacific (Wang et al. 2010; Hermann et al. 2016). These GCMs were developed for the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4), and were based on the A1B emissions scenario (Nakićenović et al. 2000). The A1B scenario implies moderate greenhouse forcing mitigation relative to other scenarios; however, because all scenarios generally track each other in the short-term, results from A1B GCMs do not differ substantially from other emission scenarios over the study period we considered (2003-2039; Nakićenović et al. 2000).

ROMS outputs provide weekly values of temperature and salinity throughout the Bering Sea with a 6-nautical mile spatial resolution and 10 vertical depth levels (Hermann et al. 2016). Because most species we considered are coastal or intertidal organisms, we restricted our analysis to the Bering Sea continental shelf, defined by waters less than 200 m depth (Stabeno et al. 1999), and to the top seven ocean layers (surface and 5, 10, 15, 20, 30, 40 m depths). We summarized the depth dimension into a single value by taking the maximum T-S values from across these depths for each pixel. To explore potential changes in habitat suitability over time, we considered two 10-year study periods: current (2003-2012) and mid-century (2030-2039).

Classifying Habitat Suitability

Our habitat suitability analyses consisted of three components: 1) year-round survival, 2) weekly survival, and 3) weekly reproduction. Habitat suitability was analyzed separately for each species, ROMS, and study period (current, 2003-2012 and mid-century, 2030-2039), and results were summarized across species. All analyses were conducted in R version 3.3.2 (R Core Team 2016) with support from the following packages: ddply, doSNOW, dplyr, ggplot2, ncdf4, maptools, plyr, rgdal, raster, rasterVis, rgeos, sp, viridis.

Year-Round Survival

For each species, we defined a 6-nautical mile pixel as 'suitable' if the pixel's T-S values remained within the species' survival range for every week of a given year. We classified the pixel as 'suitable year-round' if it remained suitable for survival year-round for at least 7 years out of the 10-year study period. Cumulative species habitat suitability for a given pixel was then determined by summing the number of species that had suitable habitat in that pixel. We also expressed the change in number of species predicted to have year-round habitat by calculating the difference in number of species from current to mid-century projections for each model.

Weekly Survival

For each week of the year, we classified a species as having suitable survival habitat if its T-S requirements were met in at least one 6-nautical mile pixel of the Bering Sea. Unlike our year-round habitat analysis, where the same pixel had to remain suitable year-round, in this analysis we allowed suitable habitat to move in space from one week to the next. Habitat suitability was determined for each week of a 10-year study period. Weekly survival was defined as the number of weeks per year identified as having suitable survival habitat, averaged across each 10-year study period. In addition, we summarized overall weekly habitat quality for all non-native taxa in the Bering Sea. This was calculated for each pixel by using the cumulative weekly averages for all 42 taxa; pixel values therefore represent 'average suitable week x number of taxa', with a theoretical maximum value of 2184 (52 weeks x 42 taxa). This habitat quality assessment was performed for each study period and ROMS.

Reproductive Suitability

For each species, we determined a pixel as having suitable reproductive habitat if the T-S values for that pixel were within the species' reproductive T-S thresholds. We then calculated the number of consecutive weeks in a year that could support suitable reproductive habitat, such that pixel values could range from 0 to 52. For our analysis, we used the maximum number of consecutive weeks identified as suitable reproductive habitat within each 10-year study period as our metric; this value was calculated for each species and ROMS.

Results

Year-round Survival

Under current conditions (2003-2012), our habitat models estimate that 33 to 35 (of the 42 non-native species assessed) can survive year-round in the Bering Sea (Figure 6). For most species, suitable habitat currently exists in the southeastern Bering Sea, and specifically along the Aleutian Islands, the northwestern tip of the Alaska Peninsula, and the western region of Bristol Bay (Figure 7). Both CGCM3-t47 and MIROC3.2 models project mid-century (2030 – 2039) conditions that would enable one additional species to survive year-round (Table 3). Across all three models, the amount of suitable habitat is also expected to increase. By mid-century, the ROMS estimate that between 37% and 60% of currently unsuitable habitat will become suitable for at least one of the modeled species (Table 3). The ROMS also estimate a small amount of habitat switching from suitable to unsuitable, however, this is less than 7% (Table 3). In general, the ROMS project a northward expansion of habitat in the southeastern Bering Sea, along the Aleutian Islands and the northwestern tip of the Alaska Peninsula (Figure 6). A band of relatively high habitat suitability for assessed species is visible, and species are expected to shift northwards relative to current suitable habitat. This band tracks the northward shift of 0°C water temperatures (Figure 7). The northern Bering Sea (above 58°N) remains unsuitable for nearly all assessed species, with very little change from current to mid-century conditions (Figure 7).

Table 3. Change in the number of species and percent area projected to have year-round suitable habitat for non-native marine species (42 assessed) between current (2003-2012) and mid-century (2030-2039).

Model	Current species count	Mid-century species count	Habitat gained	Habitat lost
CGCM3-t47	35	36	59.88%	6.70%
ECHO-G	33	33	36.78%	6.17%
MIROC3.2	34	35	52.52%	3.65%

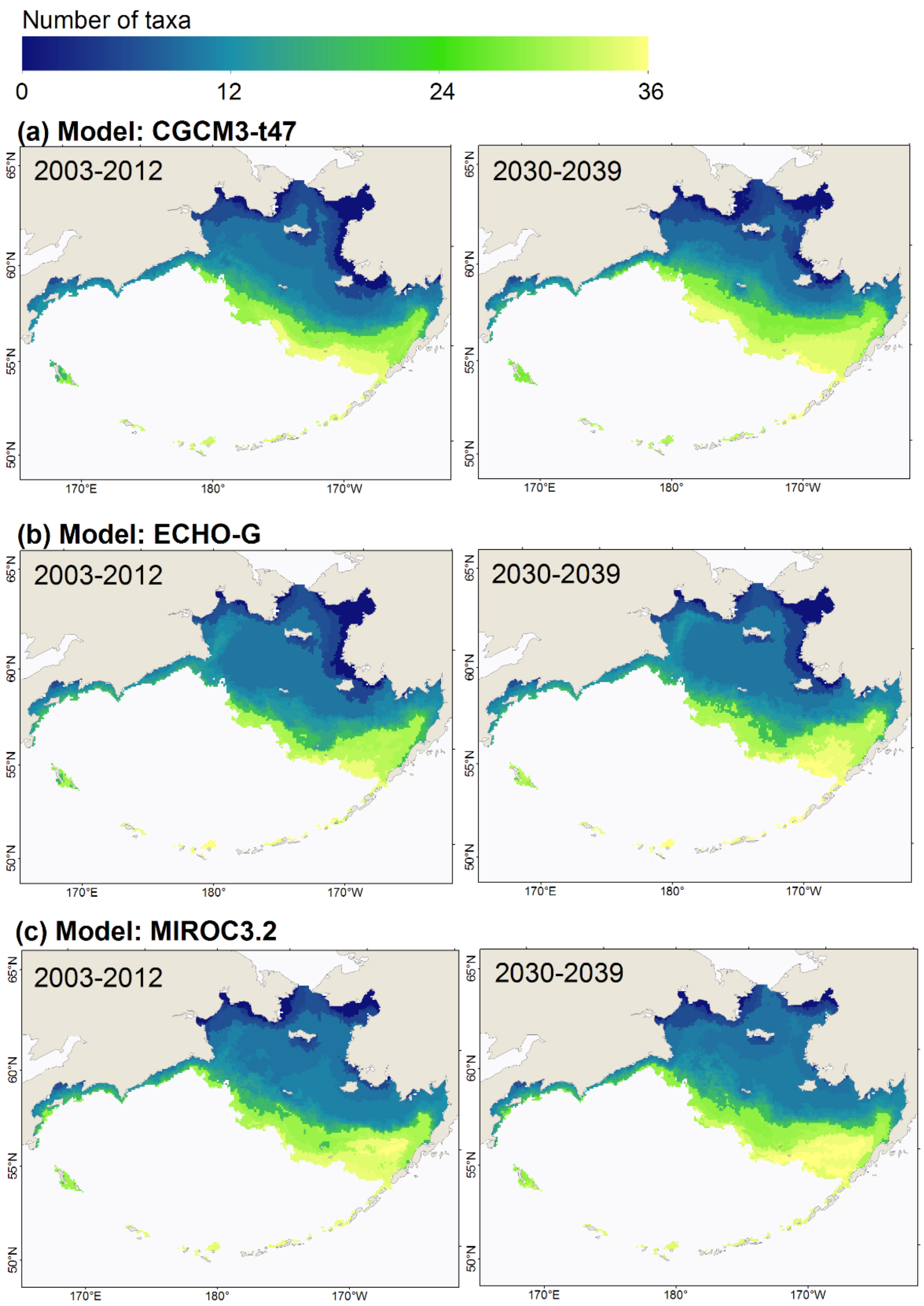
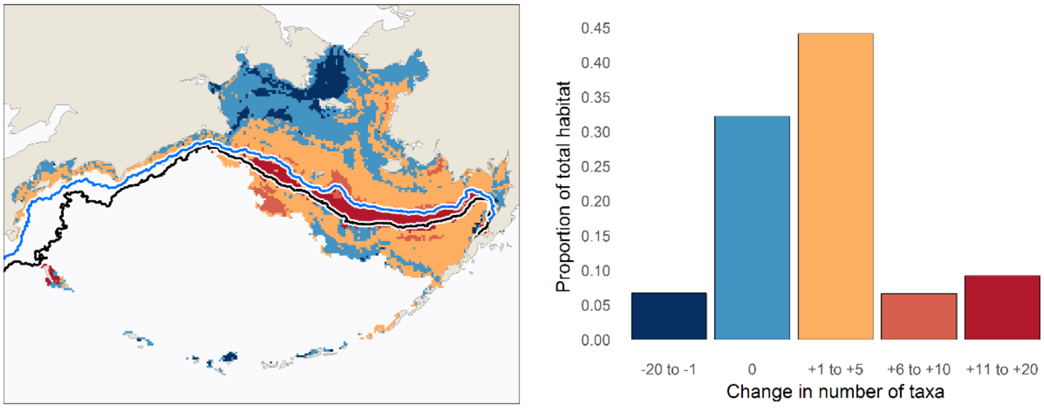
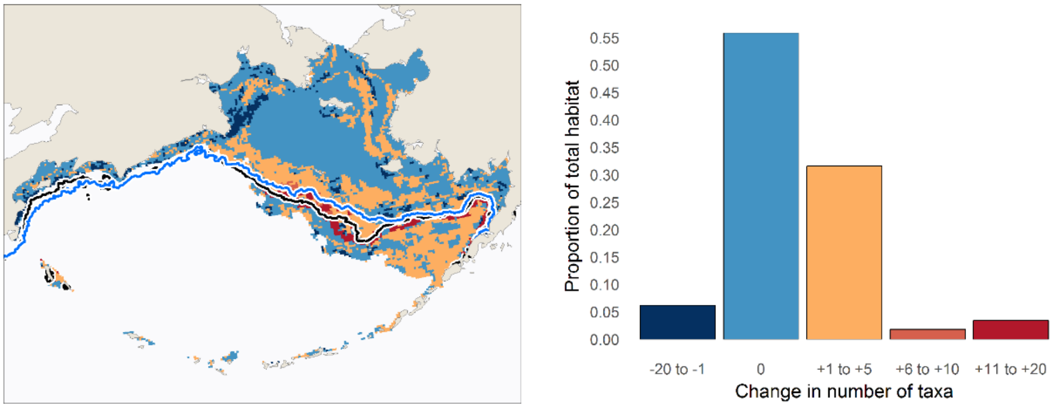


Figure 6. Number of non-native species (out of 42 assessed) predicted to have year-round suitable habitat in the Bering Sea under current (2003-2012) and future (2030-2039) climate conditions. Suitable habitat was assessed for each species by comparing physiological or geographic thresholds to the water temperature and salinity values of the Bering Sea as predicted by three different ROMS models: a) CGCM3-t47, b) ECHO-G, and c) MIROC3.2.

(a) Model: CGCM3-t47



(b) Model: ECHO-G



(c) Model: MIROC3.2

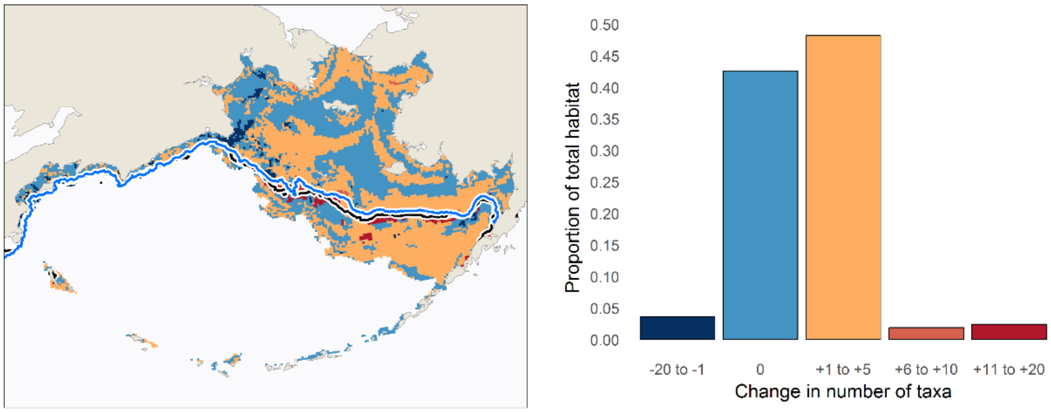


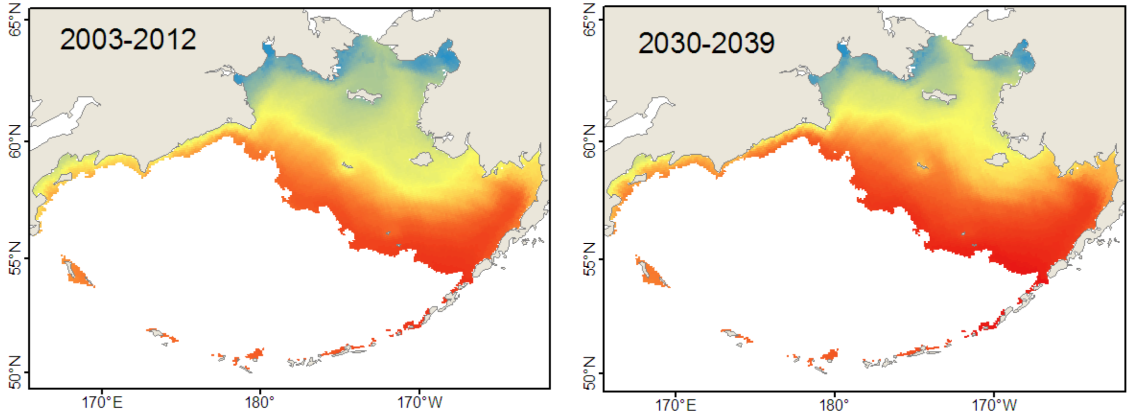
Figure 7. Projected change in the number of invasive species (out of 46) characterized to have year-round suitable habitat by mid-century (2030 – 2039). Suitable habitat was assessed using three ROMS: a) CGCM3-t47, b) ECHO-G, and c) MIROC3.2. Histograms show the proportion of the study area projected to become less suitable (dark blue), more suitable (orange and reds), or undergo no change in species richness (medium blue) by the mid-century relative to current conditions. The black line shows current 0˚C isocline and the blue line shows the predicted mid-century 0˚C isocline.

Weekly survival

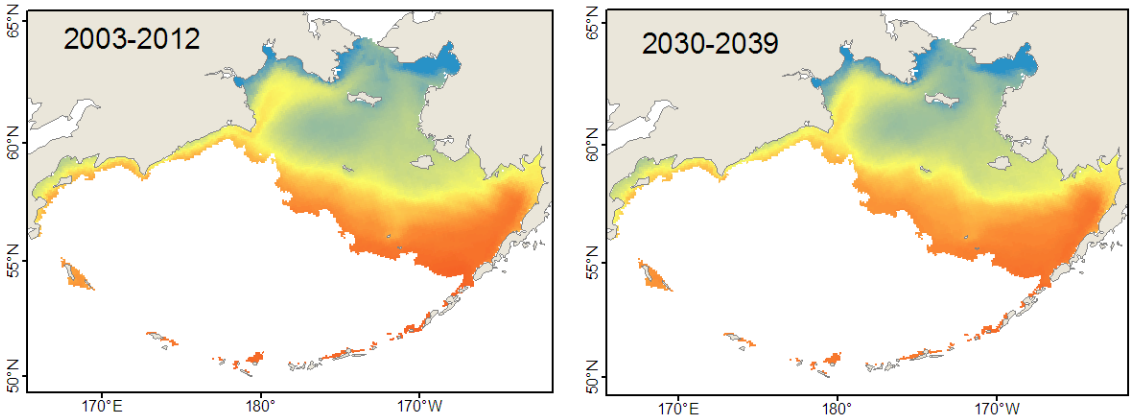
Trends in weekly suitability follow a similar spatial pattern as year-round survival, with a few important distinctions. When examined on a per-week basis, suitable habitat for many species extends farther north and west where it meets the edge of the continental shelf (Figure 8). In contrast to our year-round survival models, the majority of Bristol Bay was classified as highly suitable habitat; Norton Sound and the Gulf of Anadyr remain unsuitable for almost all species. The ROMS project a slight northward expansion of suitable habitat by mid-century (Figure 8).

Our analysis identified seven modeled species that have suitable habitat in the Bering Sea for some weeks of the year, but cannot survive year-round under current (2003-2012) conditions. These species are: a clam worm (*Hediste diadroma*), a copepod (*Limnoithona tetraspina*), a sea grape (*Molgula manhattensis*), Mediterranean mussel (*Mytilus galloprovincialis*), onyx slippersnail (*Crepidula onyx*), orange ripple bryozoan (*Schizoporella japonica*) and the red-rust bryozoan (*Watersipora subtorquata* complex). During the current study period, suitable habitat was identified for all seven species for at least six weeks during early July to mid-August (weeks 28 to 33; Figure 9). However, less than half of these species had suitable survival habitat classified in the ROMS during the 5-month period from December to early May (weeks 49 to 19), when average temperatures are below 1°C (Figure 9). The ROMS indicate that winter habitat is expected to remain sparse for most of these species through the mid-century; however, summer habitat is projected to remain relatively abundant, and to remain suitable for longer periods of the year (Figure 9).

(a) Model: CGCM3-t47



(b) Model: ECHO-G



(c) Model: MIROC3.2

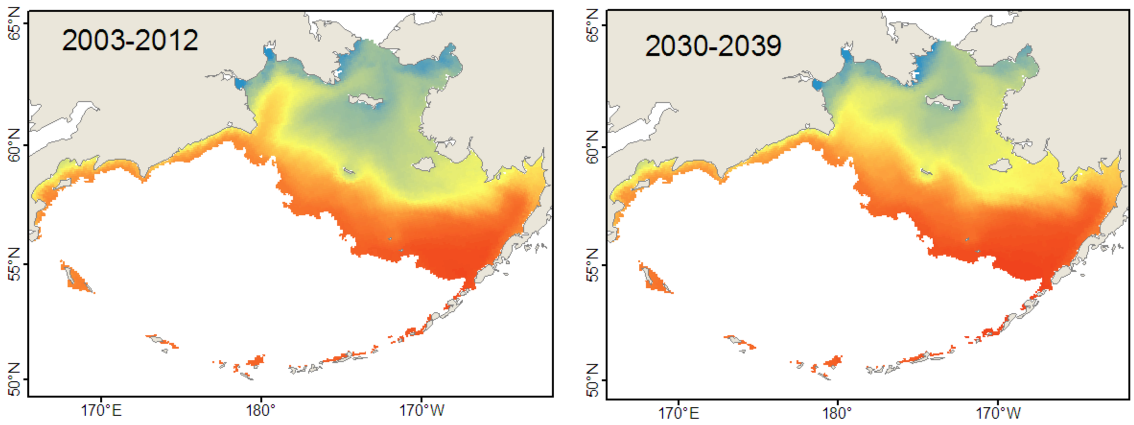


Figure 8. Weekly suitable habitat in the Bering Sea for 42 non-native species, under current (2003-2012) and mid-century (2030-2039) climate conditions. Predictions are shown for three ROMS models: a) CGCM3-t47, b) ECHO-G, and c) MIROC3.2.

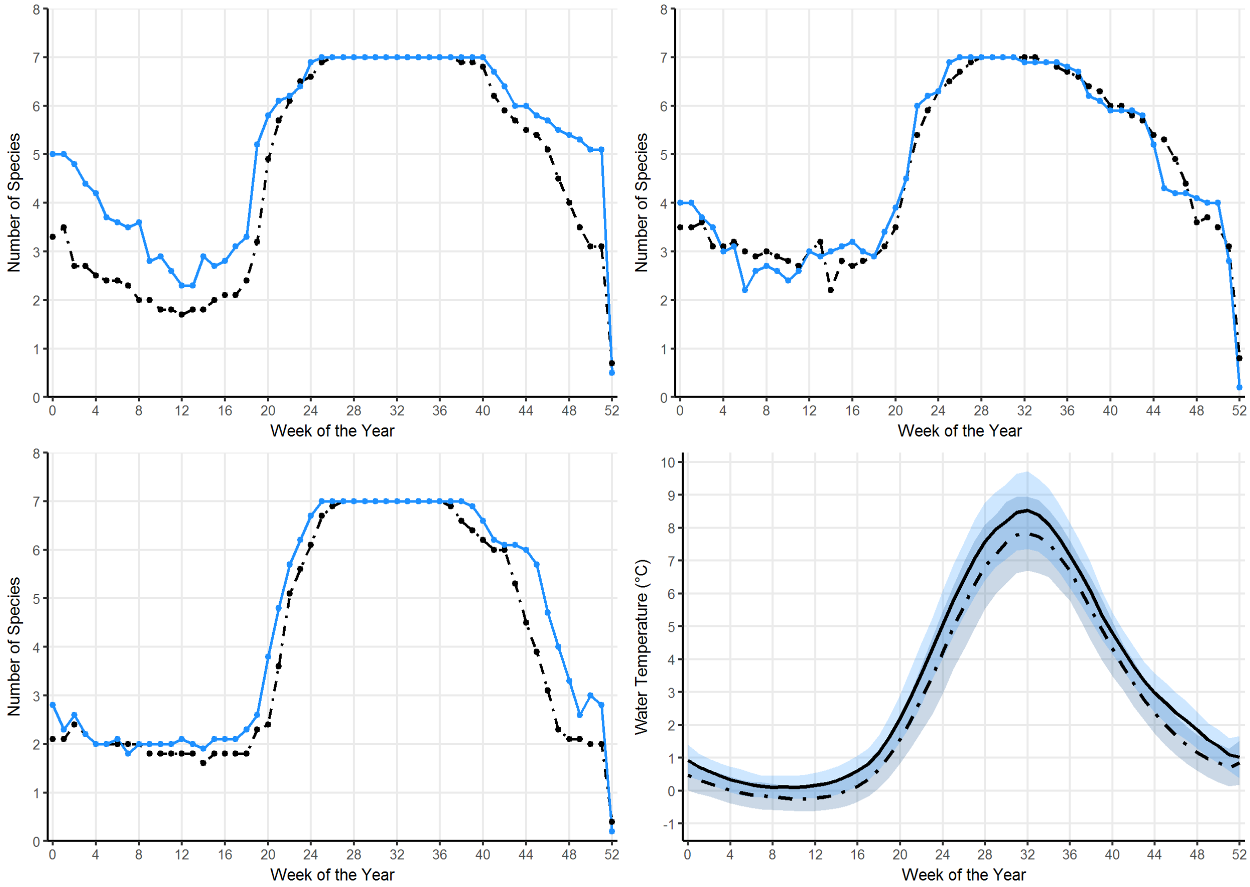


Figure 9. Availability of suitable habitat for seven non-native species that do not have year-round habitat in the Bering Sea during the current study period. The first three panels show projections under current (2003-2012; black line) and future (2030-2039; blue line) conditions for three different ROMS: a) CGCM3-t47 (top left), b) ECHO-G (top right), and MIROC3.2 (bottom left). The fourth panel shows mean water temperature averaged over all three ROMS in our study area under current (dashed line) and future (solid line) conditions.

When comparing our yearly and weekly habitat suitability models, we identified a discrepancy between the number of species projected to have suitable year-round habitat and the number of species projected to have suitable habitat for every week of the year. Two species (*Hediste diadroma* and *Molgula manhattensis*) were identified during the year-round habitat analysis as not having suitable habitat, but during the weekly habitat analysis, were classified as having suitable habitat for every week of the year. Given our definitions of year-round and weekly suitability, this discrepancy suggests that suitable habitat for these species depends on their ability to move to suitable environments, because no single pixel was found to provide suitable conditions year-round.

Reproduction

Suitable habitat for reproduction was identified for 20 to 24 species (out of 29) in the Bering Sea, under three different ROMS models, and for current (2003-2012) and mid-century (2030-2039) time periods (Table E-1). Under current conditions, most species have suitable reproductive habitat for approximately six to nine consecutive weeks; by mid-century, the number of suitable weeks is expected to increase slightly (Table 4; Table E-1). CGCM3-t47 and MIROC 3.2 models estimate that by mid-century, habitat will become suitable for an additional two and four species (*Crassostrea gigas*, *Ilyanassa obsolete*, *Eriocheir sinensis,* and *Venerupis philippinarum*), respectively (Table 4; Table E-1).

Under current conditions, two species (*Caprella mutica* and *Mya arenaria*) had suitable habitat nearly year-round. In contrast, several species had less than one week of suitable habitat, and an average of six species had no suitable reproductive habitat identified in the Bering Sea (Table E-1). However, two of these (*Alosa sapidissima, Salmo salar*) require freshwater conditions for spawning, and one of these (*Hediste diadroma*) requires brackish conditions (≤ 20 ppt) for at least part of its development, suggesting that regardless of current and future climate projections, these species will not be capable of reproduction in the marine environment. The other three species lacking suitable reproductive habitat, require temperatures of at least 16°C for reproduction. Current maximum water temperatures (projected by the ROMS) never exceed 17°C (Table 4). Mid-century water temperatures maximums are expected to increase by 0.2°C to 2.3°C, with maximum temperatures in the Bering Sea projected to exceed 18°C.

Table 4. Average number of weeks of consecutive reproductive habitat for the three ROMS models and two study periods. We assessed suitable habitat for 29 species using species-specific, published temperature and salinity thresholds required for growth and reproduction. Prior to calculations, we excluded species that could not reproduce in our study area (number of weeks = 0) and two "outliers" that were able to reproduce nearly year-round (number of weeks ≥ 49). Maximum projected temperature values for the Bering Sea, up to 40m depth, are listed.

Study Period	**Model**	**Consecutive weeks** (mean ± SD)	**Number of species**	**Maximum temperature** (°C)
Current (2003-2013)	CGCM3-t47	9.19 ± 8.19	21	16.26
	ECHO-G	5.60 ± 6.90	22	16.95
	MIROC3.2	6.72 ± 6.36	20	16.28
Future (2030-2039)	CGCM3-t47	9.40 ± 9.31	23	16.64
	ECHO-G	6.21 ± 7.02	22	17.15
	MIROC3.2	8.53 ± 6.94	24	18.62

All species-specific habitat models are presented in the Habitat Suitability Atlas, Appendix F.

Discussion

Habitat suitability analyses provide insight on which non-native taxa may be a threat (i.e. considered invasive), and in which areas of the Bering Sea they may be of greatest concern. Of the 42 non-native marine taxa that we assessed, we found that most species (>78%) had suitable year-round habitat in the Bering Sea, and temperature values drove majority of the variation in habitat suitability among species and across the study area. Our analysis predicts that species unable to tolerate temperatures ≤ 0°C and salinities ≥ 35 ppt have very little suitable area for year-round survival. These limitations preclude some highly ranked invaders (e.g. *Mytilus galloprovincialis*, *Molgula manhattensis*) from surviving under current conditions, suggesting that while these species are invasive in nearby regions, they may not be invasive in the Bering Sea. Of the species we evaluated that did not have year-round survival habitat, all could survive for at least six weeks of the year, when water temperatures were warmest (from early July to mid-August). However, these species were unable to survive during the coldest months of the year (from December to April), even under projected mid-century conditions (2030-2039). Examination of weekly survival habitat emphasizes the role of cold-water (i.e. < 0°C) tolerance as a determining factor in the invasion success of non-native species in the Bering Sea.

Reproduction requirements appear to be more limiting for colonization success than survival requirements. Although most of the evaluated species had at least one week of suitable reproductive habitat, the Bering Sea's short summer season is likely insufficient for many taxa to reproduce and undergo early development (e.g. the European green crab *Carcinus maenas*; de Rivera et al. 2007), especially given the common interplay between temperature and larval development. For example, species that require temperatures > 12°C have less than two consecutive weeks of suitable habitat under current conditions. Thus, some taxa that were ranked high by our ranking system (e.g. *Crassostrea gigas, Venerupis philippinarum*) or that are already established elsewhere in the state (e.g. *Botrylloides violaceus*, *Didemnum vexillum*), appear to have limited opportunities for reproduction under current conditions in the Bering Sea, despite having the capacity to live year-round across moderately large areas of the shelf. As conditions change in the future, these limitations may be relaxed.

Areas that were suitable for the highest number of species included the coastlines of the Aleutian Islands and the region near the northwestern Alaska Peninsula. Suitability patterns had a strong latitudinal gradient, and there was a sharp decline in habitat suitability above ~58°N, which roughly corresponded to the 0°C isotherm (Figure 6; Figure 7). Areas currently unsuitable to non-native species, such as Norton Sound, are characterized by seasonal sub-zero water temperatures and/or sea ice cover during the winter months (Grebmeier et al. 2006); however, these oceanographic conditions, which are thought to prevent the survival of non-native species in the Bering Sea, are rapidly changing. Sea ice cover has decreased substantially since the 1950s, and surface water temperatures have increased by 0.23°C per decade over the same time period (Mueter and Litzow 2008). Both global and regional ocean models project continued warming and loss of sea ice throughout the coming century (Wang et al. 2012; Hermann et al. 2016). Over the next twenty years, habitat suitability models predict that 40 to 60% of the Bering Sea shelf will shift from unsuitable to suitable habitat for the year-round survival of non-native species. Habitat suitability is expected to expand northeastward from the Alaska Peninsula, and to areas along the Aleutian Islands (Figure 7). Our models suggest that while the number of species with suitable habitat will remain relatively constant under mid-century conditions (Table 3), warming conditions will favor species that are currently able to survive in the Bering Sea, by increasing the amount of suitable habitat available to them. In addition, some species that currently have conditions suitable for survival only (e.g. *Crassostrea gigas*), may see an increase in habitat suitability for reproduction, promoting the establishment of populations, and an increase in invasive threat in the future.

IV. SHIPPING TRAFFIC AS A TRANSPORTATION VECTOR

Methods

We assessed the use of anthropogenic transportation vectors for each non-native species considered during the ranking procedure through a literature review. The vectors we considered were: ballast water, fouling, hitchhiking, and intentional introductions. A species could employ none, one, or several of these vectors. The fouling category included not only hull foulers, but also species that were transported in sea chests, anchors, fishing gear, or other wetted surfaces.

We analyzed current vessel traffic and ballast water movement patterns into the Bering Sea using two databases: vessel monitoring system (VMS) data and the National Ballast Information Clearinghouse (NBIC). These data allowed us to explore patterns of shipping traffic from commercial and fishing vessels, and patterns of ballast water discharge for vessels larger than 24 meters. Previous studies indicate that shipping traffic is correlated to non-native species richness (e.g. Lord et al. 2015), and we assume that high-traffic ports in Alaska are more susceptible to receiving non-native species that are transported by fouling and/or ballast water.

NBIC data are publicly available (https://invasions.si.edu/nbic/search.html) reports of vessel landings and their ballast water activities. The majority of large vessels (> 24 m) are required to report their ballast water exchanges when entering any port in the United States (USCG, 33 CFR Part 151). Because regulations have changed in the last decade, especially with respect to mandatory reporting by crude oil tankers (Verna et al. 2016), we only considered the three most recent, complete years (2014 - 2016). For vessel landings, we queried Ship Arrival Records from the NBIC data portal for any vessel arriving in Alaska from 01 January 2014 to 31 December 2016. Records without a port name were removed (*N* = 13), and spellings for each port were standardized. Ports in Alaska were binned into the following regions (see Supplementary R code for port specific groupings): Arctic, Bering Sea / Aleutian Islands (BSAI), Gulf of Alaska (GOA), or Southeast Alaska (SEAK). For ballast water volumes and their sources, we queried Ballast Tank Records from the NBIC data portal with the same locale and date parameters as described above. Source ports with fewer than five trips reported were binned in a group labeled “Other”. Port connections were examined using the circlize package (Gu 2014) for R Statistical Software version 3.3.2 (R Core Team 2016).

For the past two decades, the National Marine Fisheries Service (NMFS) has monitored fishing vessel locations from certain fishing vessels in the BSAI and GOA (Spalding 2016). These locations are transmitted at 30-minute intervals. Currently, NMFS regulations require VMS reporting by all fishing vessels that target walleye Pollock (*Gadus chalcogrammus*), Pacific cod (*Gadus macrocephalus*), Atka mackerel (*Pleurogrammus monopterygius*), and crab (various species). For consistency with the NBIC data, we examined all trips by vessels with VMS from 2014 – 2016 using methods from Watson and Haynie (2016) for trip identification. We analyzed a total of 4133 trips by 566 vessels during this time. Port connections with fewer than 3 different vessels were omitted according to confidentiality rules.

While the NBIC database includes a vessel type category, “fishing” is not included as one of the vessel types. However, as some U.S. fishing vessels appeared in both the VMS database and the

NBIC database, we used their co-occurrence to create a “fishing” vessel type (removing these vessels from the ‘Other’ category). These vessels were identified by linking NMFS fishing permit and U.S. Coast Guard numbers to the International Maritime Organization (IMO) vessel identifiers in the NBIC data via a NMFS vessel database (st.nmfs.noaa.gov/coast-guard-vessel-search/index).

Results

All non-native marine species considered in this study have been observed using some form of anthropogenic transportation vector, and many have been observed using more than one type of vector. The highest reported vector for the 46 species considered was fouling, followed by ballast water (Table 5).

Table 5. Anthropogenic transportation vectors used by non-native marine species occurring in the Bering Sea or neighboring regions. 46 species were considered for this analysis.

Transportation vector	**% Species**
Fouling	70
Ballast water	55
Hitchhikers	45
Intentional (e.g. aquaculture)	17

The NBIC data reported a total of 816 arrival records for Bering Sea ports from trips originating outside of the Bering Sea; 675 of which originated from ports outside Alaska (Figure 10a). Dutch Harbor received the greatest amount of traffic for both NBIC and VMS reported boats. Nome received the second highest amount of traffic for NBIC reported vessels, and Akutan received the second highest amount of traffic for VMS reported vessels. California (*N* = 175), Washington (*N* = 142), and South Korea (*N* = 127) accounted for greater portions of NBIC reported vessel traffic coming into the Bering Sea than the more proximate Gulf of Alaska ports (*N* = 120). However, from VMS data, an overwhelming majority of trips, predominantly made by smaller fishing vessels that do not report to the NBIC, originated from Gulf of Alaska ports (*N* = 657; Figure 10b). Ports reported as “Other” in tables and figures are those with ≤ 5 trips.

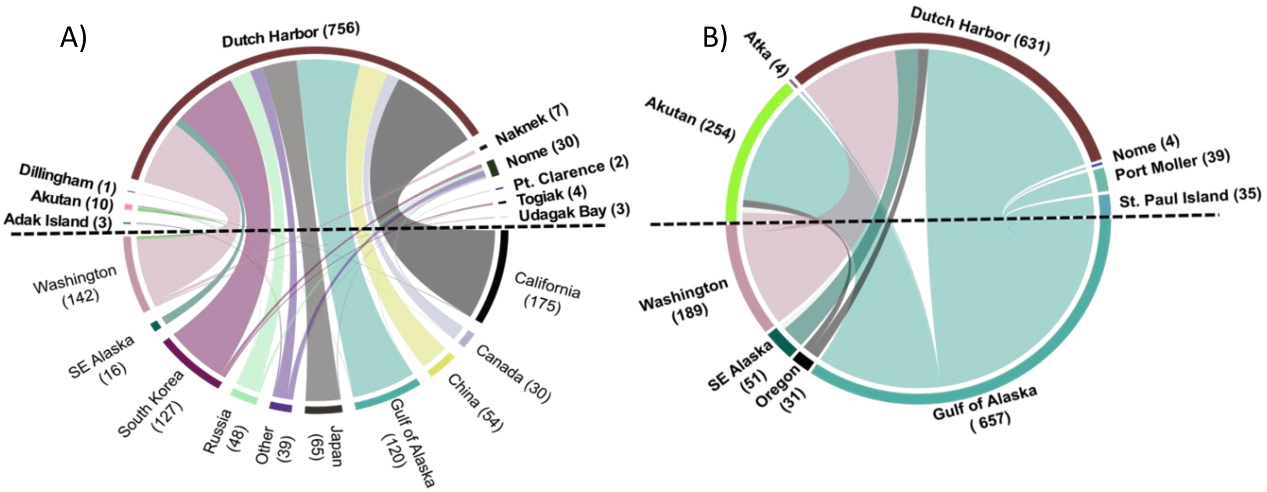


Figure 10. Illustration of vessel transit origins (below dashed line) outside of the Bering Sea and their Bering Sea destination (bold text, above dashed line), 2014 - 2016. Numbers in parentheses indicate numbers of records for a given port. (A) Data from arrival records in the National Ballast Information Clearinghouse. “Other” includes ports with ≤ 5 transits. (B) Fishing vessel data from vessel monitoring systems. Connections with fewer than three vessels have been excluded to retain confidentiality.

The NBIC dataset included 15,837 ballast water discharge reports in Alaska from 2014 – 2016[7]. These records were distributed across 9 vessel types: Bulker (*N* = 2755), Container (*N* = 295), General Cargo (*N* = 114), Other (*N* = 396), Passenger (*N* = 774), Refrigerated Cargo (*N* = 418), Roll-on/Roll-off Cargo (*N* = 10), Tanker (*N* = 9935), and Fishing (*N* = 1140). The majority of reported discharge occurred in Dutch Harbor, with Nome having the second largest discharge volume (Figure 11).

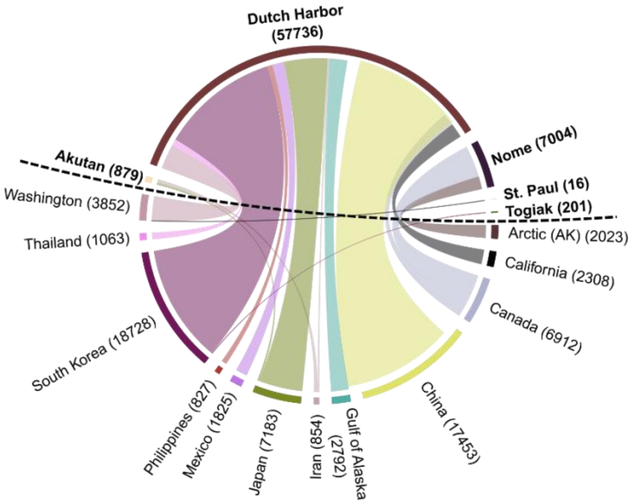


Figure 11. Volume of ballast water (metric tons) discharged to Alaska ports in the Bering Sea (bolded ports, above dashed line) and their regions of origin (unbolded text, below dashed line). Ballast water exchanges not reported by a specific port / country (e.g., open ocean exchanges) account for approximately 20% of reported ballast water exchange and were excluded from the analysis. Data from the National Ballast Information Clearinghouse.

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[7] Discharge reports that did not include valid source locations were omitted from the analyses.

Ballast water exchange data revealed a different pattern than the ship arrival records. While ports in the eastern Pacific Ocean accounted for more trips, the majority of ballast water released in the Bering Sea originated from Asian ports (Figure 12). South Korea and China each accounted for an order of magnitude more ballast water (18,728 and 17,453 mt, respectively) than the next greatest sources, Japan (7183 mt), Canada (6912 mt), and Washington (3852 mt). Approximately 20% of the 15,837 ballast water exchange records (10.6% of the discharged volume) identified the source of their ballast water using coordinates (typically from offshore waters) instead of port names. Among these non-port ballast water sources, 25% of water originated from locations in the northeast Pacific Ocean (defined here as latitudes > 23.5° N, longitudes between 179.9° W and 110°W) and 15% originated from locations in the northwest Pacific Ocean (defined here as latitudes > 23.5° N, longitudes between 100° E and 180° E).

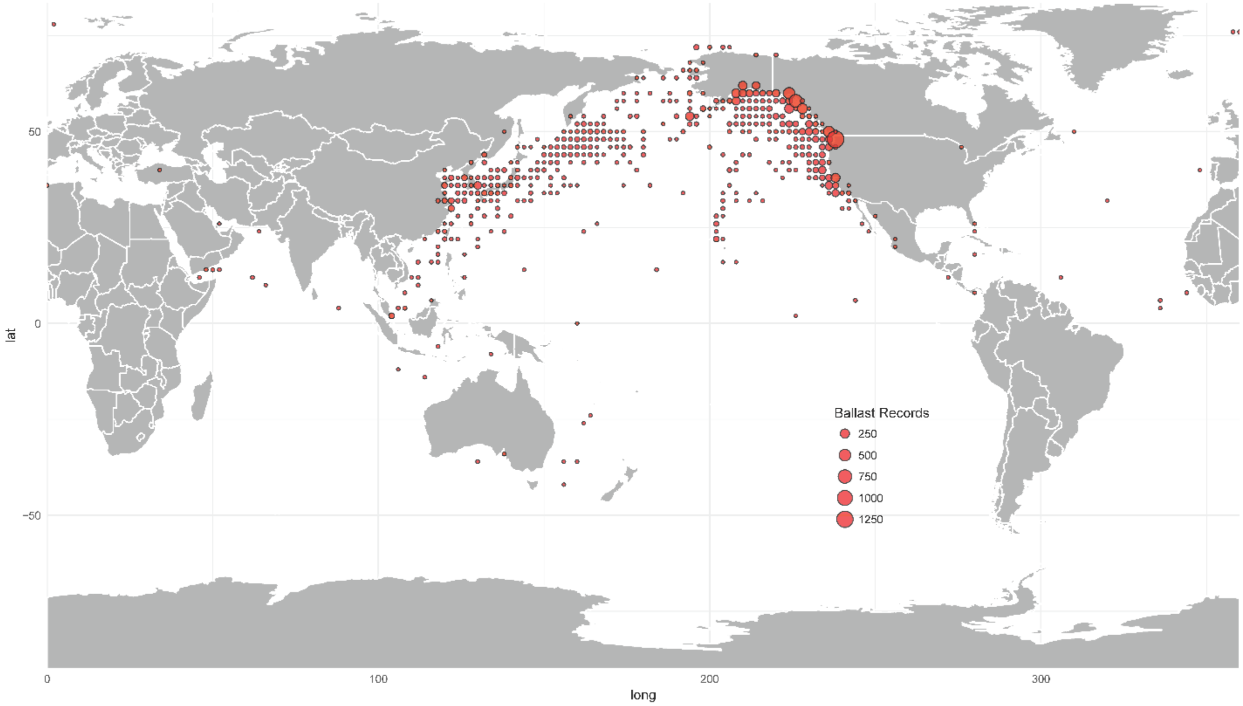

Figure 12. Points of origin for ballast water transported to the Bering Sea. Symbol size is relative to the number of ballast water exchange records from that location.

Discussion

For invasive species in neighboring regions to the Bering Sea, our research suggests that the most common vectors of transportation are ballast water and fouling. These results are similar to the most common pathways observed for invasive marine species on a global scale (Molnar et al. 2008), and are important to consider since anthropogenic dispersal is a major factor in the arrival of marine invasive species to new areas (Ruiz et al. 1997).

Among Bering Sea ports in Alaska, Dutch Harbor accounted for the vast majority of both fishing and commercial vessel transits reported by the VMS and NBIC data. In addition, Dutch Harbor received the majority of ballast water discharged in the Bering Sea from 2014 to 2016. These vessel traffic patterns indicate a high degree of connectivity between Dutch Harbor and ports from both the eastern and western Pacific Ocean. This global connectivity and the high number of transits from both fishing vessels and shipping vessels, increase Dutch Harbor's susceptibility to invasive species arriving through multiple sources, pathways, and vectors (e.g. fouling and ballast water). Dutch Harbor may therefore be a prime location to monitor for the arrival of invasive species into the Bering Sea. Furthermore, the connectivity of Dutch Harbor to other Bering Sea ports, like those of the Pribilof Islands, Bristol Bay, and Akutan further underscore the potential impacts of invasive species in Dutch Harbor.

It is important to note that invasive species transportation and survival is more nuanced than the simple metrics we describe here. The likelihood of survival for an organism during a sea voyage may be influenced by several factors including the voyage duration, the organism's physiological condition, and environmental differences between donor and recipient ports (Verling et al. 2005; Verna et al. 2016). For example, ports connected by the shortest geographic distance are more likely to pose the greatest threat due to shorter transit times (e.g. less time in ballast tanks; Verna et al. 2016) and a similarity of environmental conditions between ports. Verna et al. (2016) quantified ballast water risk of Alaskan ports and found that while Dutch Harbor was at medium risk in terms of discharged water volumes, the relatively long residence time of the ballast water that was discharged there was likely to reduce the probability of establishment.

Factors like ballast water age may mitigate propagule risks at specific ports but vessel traffic between ports throughout the Gulf of Alaska and both Dutch Harbor and Akutan emphasizes the scale of connectivity among many Alaskan communities. Thus, to examine risk factors (e.g., ballast water) in isolation may underestimate the risks posed from the network of ports and the vessels that join them. Without a road system to provide access to Alaska's port communities, vessels of all types form a marine highway system that is traveled by ferries, tugs, barges, and as demonstrated here, fishing vessels. Many of these vessels are not required to report ballast water activities because of their size or because they remain within State waters. Given this, future analyses of vessel traffic in the context of invasive species transport may benefit from analysis of Automatic Identification System (AIS) data, which are available for a greater portion of vessels traveling through Alaskan waters.

When anticipating the future risk of invasive species' arrival in the Bering Sea, it is important to consider how patterns in global shipping are projected to change in the coming years. Within the arctic region, the Bering Sea is currently a major hub for vessel traffic and fisheries, receiving almost 50% of all traffic in the region (Ellis and Brigham 2009), and it is the only water body that is used by both northeast and northwest shipping routes. By 2025, an additional 600 to 900 vessels are expected to navigate the Bering Sea, and by 2020, 2% to 8% of vessels currently transiting through the Panama and Suez canals are expected to start using Arctic routes instead (Ellis and Brigham 2009). Our analysis identified a relatively low number of vessel transits to Nome, but future expansions of the Arctic for shipping and oil and gas exploration may lead to continued development of nascent plans for establishing industrial scale port facilities there. Meanwhile, ports like Kivalina, which is adjacent to Red Dog Mine and is slightly north of the Bering Sea region, account for many vessel transits between South Korea and the Alaskan Arctic that transit through the Bering Sea. Such transits still represent potential risks from hull fouling organisms and offshore ballast water exchanges. As the Arctic becomes an increasingly popular shortcut between the Pacific and Atlantic, the risk of non-native species introductions into the Bering will likely increase.

V. CONCLUSION

This project provides a foundation for monitoring efforts by demonstrating a) which non-native species should be monitored (highly ranked species), b) where monitoring efforts should take place (ports of highest traffic and greatest habitat suitability), and c) potential impacts of climate change on habitat suitability for non-native species survival and reproduction.

Our ranking system provides managers with a simple, transparent method to evaluate the risk of non-native marine species to the Bering Sea. It considers the potential for a species to establish in the Bering Sea, its biological traits (including reproductive and dispersal abilities), and its potential ecological and socioeconomic impacts. The information we gathered during the ranking process also allowed us to analytically explore questions pertaining to habitat suitability, and the spatial and temporal components of risk of non-native arrival and colonization. Taken together, our analyses of habitat suitability and vessel traffic point to the southeastern Bering Sea, and the port of Dutch Harbor in particular, as high risk areas for biological introductions. Situated at 53.9°N, this port is one of the most southerly ports in the Bering Sea, is ice-free year-round, and experiences relatively warm water temperatures compared to the rest of the Bering Sea. Dutch Harbor is also the most likely entry point for non-native species because it receives the majority of commercial and fishing vessel traffic, as well as the highest volume of ballast water discharge. Moreover, Dutch Harbor is the most internationally-connected port in the Bering Sea, with trips ending in Dutch Harbor that originated from more than ten countries.

The Bering Sea is a valuable ecological and economic system that currently supports relatively few invasive species compared to other regions within U.S. marine systems. At the same time, the oceanographic and socioeconomic conditions of this system are changing quickly, and in a direction that is likely to increase the rate of non-native species introductions and subsequent risk of establishment. By ranking species, exploring suitable habitat, and describing current shipping patterns, our study offers a better understanding of the spatial and temporal risk of non-native species colonization into the Bering Sea. Furthermore, it can serve to inform monitoring and research efforts, and identify knowledge gaps that need to be filled to better protect this marine system.

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