# Model-Based Essential Fish Habitat Descriptions for Fish Resources of the Arctic Management Area

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**Abstract:** The Arctic Fishery Management Plan (FMP) includes three target species, Arctic cod (*Boreogadus saida*), saffron cod (*Eleginus gracilis*) and snow crab (*Chionoecetes opilio*), for consideration of potential future commercial fishing activities in the Arctic Management Area that encompasses the U.S. Chukchi and Beaufort Seas. Arctic species EFH descriptions and maps are not currently informed by species distribution models (SDMs) as has been the approach for the groundfish and crab FMPs in the 2017 and 2023 EFH 5-year Reviews. Our study uses environmental and biological survey data from 2000–2018 and SDMs to advance EFH descriptions and maps for Arctic species' life stages current with the state of science for the region. A total of 13 EFH Level 1 maps (distribution) and three EFH Level 3 maps (habitat-related vital rates) are available for these three species and up to four life stages for the Arctic FMP in the 2023 Review. The Arctic climate and oceans are rapidly warming and will likely have far reaching impacts on marine ecosystems, including fish and crabs. We also compare the probability of suitable habitat distribution and area occupied in warm and cold years as a first step to consider climate change effects on EFH for Arctic species.



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# EXECUTIVE SUMMARY

The objective of an essential fish habitat (EFH) 5-year Review is to review the ten EFH components of Fishery Management Plans (FMPs) and revise or amend EFH components as warranted based on available information (50 CFR 600.815(a)(10)). The EFH regulations outline ten components for the EFH contents of FMPs. For component 1, FMPs are required to describe and identify EFH in text that clearly states the habitats or habitat types determined to be EFH for each life stage of the managed species and to include maps that display the geographic locations of EFH or the geographic boundaries within which EFH for each species and life stage is found. Additionally, FMPs must demonstrate that the best scientific information available was used in the description and identification of EFH, consistent with national standard 2 (50 CFR 600.815(a)(1)(i)(B)).

This report presents the new information available under EFH component 1, the description and identification of EFH, for the Arctic FMP in the 2023 5-year Review. The requirements for EFH component 1 are that some or all portions of the geographic range of the species are mapped (50 CFR 600.815(a)(1)(iii)(1)). **These mapping requirements have been comprehensively met for the new Arctic species SDM EFH maps. The Arctic species EFH maps do not support the EFH component 2 fishing effects evaluation.**

**Component 1 EFH Descriptions and Identification**

Component 1 descriptions and identification of EFH (50 CFR 600.815(a)(1)) consist of written summaries, tables, and maps in the FMPs or their appendices. The EFH regulations provide an approach to organize the information necessary to describe and identify EFH (50 CFR 600.815(a)(1)(iii)). When designating EFH, the Council should strive to describe and identify EFH information in the FMPs at the highest level possible (50 CFR 600.815(a)(1)(iii)(B))—

*Level 1:* Distribution data are available for some or all portions of the geogra*phi*c range of the species.

*Level 2:* Habitat-related densities or relative abundance of the species are available.

*Level 3:* Growth, reproduction, or survival rates within habitats are available.

*Level 4:* Production rates by habitat are available. [Not available at this time.]

Further, the EFH regulations state that Councils should strive to describe habitat based on the highest level of detail. **The study presented uses this approach to explain the SDM information and maps in terms of EFH Level 1 and for the first time, Level 3.**

Arctic FMP EFH descriptions consist of text descriptions and maps for the three target species, Arctic cod, saffron cod, and snow crab. Arctic FMP EFH maps from the 2017 Review are not based on SDMs, but rather survey presence-absence data presented as qualitative maps of distribution for several life stages combined. Due to the accelerated rate of climate change in the Arctic, there have been increased efforts to understand this dynamic region with many surveys occurring in recent years. This study developed SDM EFH maps for Arctic FMP species life stages, including Level 1 and Level 3 descriptions and maps, concurrently with the Laman et al. study[5], to advance Arctic species EFH descriptions and maps current with the state of science for the region. In addition, this work compares the area of occupied habitat and habitat-related vital rates for species life stages in warm and cold years as a first step to consider climate change effects on EFH for Arctic species.

[5] EFH Component 1 Descriptions and Maps (updated January 2023) available on the Council agenda for this meeting.

The Arctic Management Area includes the Chukchi and Beaufort Seas off Alaska, where ocean currents, wind, and the timing of ice melt largely influence productivity. As most biological surveys have occurred during the ice-free summers, SDM EFH was developed for the summer season. The study acquired several survey data sets where life stages of Arctic cod, saffron cod, and snow crab were included and separated by life stage, including larval, early juvenile (age-0 or immature), subadult (juvenile or adolescent females and males), and mature (adult or mature females and males). They also assembled and developed a variety of ecologically meaningful habitat covariates (e.g., depth, seafloor terrain, sediment, currents, and temperature). MaxEnt SDMs were developed for all life stages of all species where possible in a similar approach by the Laman et al. study in the 2023 Review. This study also integrated SDMs with vital rates (temperature-dependent growth rate) for juvenile Arctic and saffron cods from published studies (Laurel et al. 2016; 2017) to map EFH Level 3 for these species and life stages.

NMFS reviewed the current Arctic FMP EFH text descriptions and maps. A total of 13 new EFH Level 1 maps (distribution) and three new EFH Level 3 maps (habitat-related vital rates) are available for the three Arctic species and up to four life stages for the 2023 EFH 5-year Review. **Changes and updates to the Arctic FMP EFH text descriptions, maps, and information levels are recommended, as new information is available for several life stages of each species, using methods and data that were not available for the 2017 Review.** There is currently no commercial fishing in the Arctic, so fishing effects on EFH were not evaluated. The EFH 5-year Review Summary Report[6] provides an overall summary of the proposed updates to the Arctic FMP EFH sections.

[6] 2023 EFH 5-year Review Summary Report; available on Council agenda for this meeting.

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# 1 INTRODUCTION

In 2009, the North Pacific Fishery Management Council (NPFMC) developed the Arctic Fishery Management Plan (FMP) that identifies three species as potential targets for future commercial fisheries within the U.S. Arctic Management Area (AMA, Figure 1): Arctic cod (*Boreogadus saida*), saffron cod (*Eleginus gracilis*) and snow crab (*Chionoecetes opilio*) (NPFMC 2009). These species are key components of the Arctic marine food web, and both Arctic cod and saffron cod are important subsistence resources for coastal communities. The FMP describes preliminary stock assessments for each species and concludes that their low abundances, small size and life history characteristics at that time could not support a fishery and states "All Federal waters of the U.S. Arctic will be closed to commercial fishing for any species of finfish, mollusks, crustaceans, and all other forms of marine animal and plant life; however, harvest of marine mammals and birds is not regulated by the Arctic FMP." Therefore, commercial fishing is prohibited in the Arctic Management Area until sufficient data are available that may support the authorization of a sustainable fishery, while also ensuring the sustainability of other ecosystem components (NPFMC 2009). As the habitats of these three ecologically important species may be subjected to non-fishing effects, such as oil and gas activity, a better understanding of their current habitat distributions is required for managing living marine resources in the region.

A required component of the Arctic FMP is the identification of Essential Fish Habitat (EFH) that describes the distribution of key life stages of each potential target species to identify areas where a species may be impacted by anthropogenic activity. Essential fish habitat is defined as those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity (50 CFR 600.10). Current EFH definitions for Arctic species within the AMA are qualitative and are based on limited occurrence data available at the time. The description of EFH for each species in the Arctic FMP consists of polygons drawn around maps of survey distributions irrespective of life-stage.

In 2017, EFH revisions were completed for the Gulf of Alaska (GOA), Eastern Bering Sea (EBS) and Aleutian Islands using species distribution models (SDMs) (Rooney et al. 2018, Laman et al. 2017, Turner et al. 2017). Those management areas have regular biological surveys and support many commercial fisheries. To improve upon Arctic EFH descriptions, preliminary maximum entropy (MaxEnt) models (*Phi*llips et al. 2006) were developed by the lead author with support from Alaska Sea Grant and NOAA's Habitat Conservation Division. These models were applied to combined juvenile and adult life stages to produce maps of potentially suitable habitat for each species. In this report, we provide the first quantitative species distribution model-based EFH maps for the Arctic Federal Management Area.

We refine EFH for Arctic cod, saffron cod, and snow crab in the Chukchi and Beaufort Seas using the most recent and best available biological and environmental data for the region with modern SDM methods. In particular, we incorporated new survey data from the Beaufort Sea, Barrow Canyon, and several nearshore surveys, and survey catch data were partitioned by life stage to develop life stage-specific models of habitat suitability. The resulting habitat maps and species distribution descriptions strengthen the ability of natural resource managers to minimize potential impacts from development activities in the AMA. In addition, this project provides data needed to strengthen the impact assessment process during EFH consultations and National Environmental Policy Act (NEPA) analyses. With these models, we can identify habitat characteristics most important to the distribution and habitat suitability of larval (where data are available), juvenile, and adult Arctic cod, saffron cod, and snow crab.

We go beyond static habitat descriptions by including a temporal component that accounts for dynamic changes in suitable habitat linked to environmental variability and climate change. As the climate continues to warm and the open water season is extended, increased vessel traffic, oil exploration and extraction, and the development of infrastructure to support these activities may have adverse effects on the three target species in Alaskan Arctic waters. Therefore, it is crucial to understand their current habitat use and how suitable habitat may expand and contract with changes in climate and human activity.

Rapid warming in the Arctic challenges the very concept of static, long-term representations of EFH. As a result of these challenges we recommend that EFH descriptions also account for climate change in a temporally dynamic approach. Therefore, we divided the biological survey and environmental data into shorter warm and cold time periods to examine potential shifts in the distribution of Arctic cod, saffron cod, and snow crab life stages over time.

A final extension and enhancement of EFH descriptions was explored here by linking vital rates (growth potential) to habitat characteristics (specifically temperature) for age-0 and juvenile Arctic cod and juvenile saffron cod, using recent laboratory studies on temperature-dependent growth (Laurel et al. 2016; 2017). Combining maps of vital rates with species distribution maps over warm and cold periods will increase our understanding of how species respond to climate shifts, consistent with the idea of developing dynamic EFH descriptions where possible.

To support the development of life-stage specific SDMs and EFH maps, temporally dynamic SDMs comparting warm and cold periods, and habitat descriptions that account for the temperature dependence of fish growth, our specific objectives were to—

1. Develop EFH Level 1 information (distribution) for life stages of Arctic cod, saffron cod, and snow crabs.
2. Develop EFH Level 3 maps (habitat-related growth potential) for life stages of Arctic cod and saffron cod.
3. Develop maps of habitat-related distribution and growth potential for life stages of Arctic cod, saffron cod, and snow crabs during warm and cold periods and explore possible distribution shifts between warm and cold periods.

# 2 METHODS

## 2.1 Study Area

The portions of the Chukchi and Beaufort Seas within the U.S. Exclusive Economic Zone (EEZ, up to 200 miles offshore) comprise the Arctic Management Area (AMA; **Figure 1**). The Chukchi Sea has a broad, shallow shelf with an average depth of 52 m, while the Beaufort Sea has a relatively narrow shelf that extends 50 to 100 km offshore and an average depth of 1,004 m. We constrained the study area to encompass all waters from the coastline to depths less than 1,250 m and latitudes less than 73.1° N, as biological survey data was not collected deeper than 1,250 m or north of 73.1° N.

Ocean currents, wind, and the timing of ice melt largely influence the productivity within each region. Generally, during the open water season (summer months) currents flow northward through the Bering Strait and are comprised of three main water masses: Alaska Coastal Water (ACW), Bering Shelf Water (BSW) and Anadyr Water (AW) (Weingartner 1997; Danielson et al. 2017). Along the coast, the relatively warmer and fresher Alaska Coastal Current (ACC) flows northeastward through Barrow Canyon (Weingartner et al. 2005). A large portion of the ACC empties into the Canada Basin (Gong and Pickart 2015), while some water continues eastward along the edge of the Beaufort Shelf where it becomes known as the Beaufort shelf break jet. In addition to water flowing in from the Chukchi Sea, the Beaufort Sea receives input from the Mackenzie River (Carmack et al. 2015), Arctic, and Atlantic Oceans. Farther offshore in the Beaufort Sea, areas of upwelling occur along the slope in the Beaufort Sea and Barrow Canyon leading to an increase in productivity in the water column (Hill and Cota 2005).

## 2.2 Survey Data

As there are no longstanding, systemic surveys in the AMA, we compiled biological survey data from numerous ecological research studies conducted between 2000 and 2018 (**Figure 2**; **Table 1**) in the U.S. Chukchi and Beaufort Seas. Fish were collected nearshore and offshore, on the seafloor and throughout the water column using a variety of gear types. The most common bottom trawl gear type was the plumb-staff beam trawl with a 4.1 m headrope, 5.1 m footrope, and a 4 mm mesh cod-end liner in two configurations (PSBT and PSBT-A). Regardless of configuration, the catchability remains similar (Norcross et al. 2018). In addition, a much larger 83-112 Eastern Bottom Trawl (EBT) was used during several surveys. The EBT has 25.3 m (83 ft) headropes, 34.1 m (112 ft) footropes and cod-ends with a stretched mesh size of 8.9 cm with and without 3.2 cm mesh liners. In addition to the larval occurrence data from the surveys listed in **Table 1**, data on larval saffron cod and Arctic cod caught in bongo nets were provided by the NOAA EcoFOCI group from the ECODAAT database.

Catch data were divided into life stages based on body length measurements for Arctic and saffron cods (Helser et al. 2017; Vestfals et al. 2020) and carapace width for snow crab (Conan et al. 1992; Divine et al. 2019; **Table 2**). Life stage divisions for Arctic and saffron cods included larvae, age-0, late juvenile (1-2 year olds) and mature. Snow crab have sexually dimorphic growth after the immature stage (Conan et al. 1992), so older life stages were divided by sex. Snow crab data were divided into groups of immature individuals, adolescent males, adolescent females, mature males and mature females. Occurrence data (presence/absence) by species and life stage was compiled at each survey location within the AMA.

We combined survey datasets to maximize spatial coverage within the study area for the species' life stages modeled. Occurrence data were used in the species distribution models (SDMs) due to the tradeoff of combining surveys and gear types. Prior to statistical modeling, we extracted presence locations by life stage for each species and then eliminated duplicate data within each 1 $km^2$ grid cell. For warm and cold periods, we partitioned the raw data into warm and cold years and then eliminated duplicates by grid cell.

## 2.3 Habitat Covariates

Several ecologically meaningful static and dynamic habitat covariates were considered for inclusion in the SDMs. These potential explanatory variables were selected based on known ecological associations (Dawe and Colbourne 2002, Norcross et al. 2013, Marsh et al. 2019), past species distribution models for EFH (Laman et al. 2018) and availability.

The bulk of the dynamic habitat covariates were extracted from daily outputs (netcdf files) of the Pacific Arctic Regional Ocean Modeling System (PAROMS; Curchitser et al. 2013) run16 hindcast of Arctic4, provided by S. Danielson, UAF (pers. comm.). Specifically, each file contained a daily average of near surface and near bottom zonal and meridional current velocities, temperature and salinity for each 0.1° latitude and 0.2° longitude grid cell for the entire Arctic from 1980-2018. We extracted daily values from the summer months (July – September) during 2000–2018 by grid cell for each oceanographic variable (salinity, temperature, and velocities from the surface or near bottom). We then computed the long-term average by grid cell as well as the minimum, maximum and standard deviation. We chose only the summer months to align with the season when most surveys took place.

Sediment composition data for percent rock, gravel, sand, mud, and organic carbon and sediment size (*phi* = negative $\log_2$-transform of grain size (mm)) was provided by C. Jenkins using dbSEABED protocols (Jenkins 1997). The larger the *phi* value the finer the grain size. Further, we downloaded ocean color data from the Moderate Resolution Imaging Spectroradiometer (MODIS) collected during July – September 2002-2018, which can be used as a proxy for primary productivity ($gC/m^2 \cdot day$) (Behrenfeld and Falkowski 1997). In addition, bathymetry data were provided by S. Lewis and J. Pirtle (Alaska Regional Office, Juneau, AK, pers. comm), slope and bathymetric position index (BPI) were derived using the benthic terrain modeler extension in ArcGIS version 10.7 (Wright et al. 2012).

Each habitat covariate was interpolated and converted to 1 $km^2$ raster grids in R (R core team 2020) using packages gstat (Pebesma 2004) and raster (Hijmans 2020). We used inverse distance interpolation with an inverse distance power set to 2.5 and the number of nearest observations set to 7 for the dynamic PAROMS covariates. Point data of bathymetric and associated terrain covariates were interpolated to a 100 $m^2$ grid to create a raster surface using natural neighbor interpolation (Sibson 1981) in ArcMap. Rasters of sediment related variables created with ordinary kriging with exponential variograms for the sediment related covariates (see methods in Jenkins 1997) and provided by Chris Jenkins. The longitude and latitude data for each tow (and all other geographical data for this study) were projected into the Alaska Albers Equal Area Conic projection (standard parallels = 65° and 75° N and center longitude = 154° W) and degrees of latitude and longitude were transformed into eastings and northings for modeling. We cropped the extent of each raster from the Alaskan coast to the outer edge of the AMA. The covariate rasters were further cropped to exclude areas in which we had no survey data (depths > 1,250 m and latitudes > 73.1° N).

A pre-selection of covariates was done based on variance inflation factors (< 5.0) (Zuur et al. 2009) and Pearson's correlations with other variables (< 0.7). Several potential covariates were eliminated during the pre-selection procedure. The independent predictor variables used in the models are described in **Table 3**. These independent rasters were combined into two separate raster stacks for near surface (**Figure 3**) and near bottom (**Figure 4**) sets of explanatory variables.

## 2.4 Species Distribution Models

To link habitat covariates to species occurrence data, we explored the use of a number of state-of-the-art SDMs. Due to the limited sampling with disparate gear types in the Alaskan Arctic and to maximize the use of available data, we focused on Maximum Entropy (MaxEnt) models (Phillips et al.

2006, Elith et al. 2011)[7]. MaxEnt models estimate the probability of suitable habitat based on species prevalence (point data) and the co-occurring habitat covariates (explanatory variables, as raster grids) relative to random background points. For each life stage/species combination we extracted predictor values from the habitat covariate raster stacks for each point presence data and for 10,000 random background points within the study area. These data sets were used to train the MaxEnt models and test model performance.

As larval Arctic cod and saffron cod primarily occur in the surface waters, we modeled their distribution using surface habitat variables (**Table 3**; **Figure 3**). Age-0 Arctic and saffron cods were modeled with both the bottom and surface covariates and we selected the model with the highest area under the receiver operating curve statistic (AUC, see below for details) for the remaining analysis. The models for the remaining species life stage combinations were run with the bottom habitat covariates as the explanatory variables.

We modeled the probability of suitable habitat for all species and life stage combinations (**Table 2**) using presence only data from all gear types and the habitat covariates listed in Table 3 using *maxnet* v.0.1.2 package (Phillips et al. 2017) with a cloglog link run in R (R Core Team 2020).

#### *2.4.1 Model Optimization*

We tuned the MaxEnt models to optimize model parameters using K-fold cross validation. We randomly partitioned our presence data (from each species life combination) and background data into 5 approximately equal subsets (K-folds). The models were trained on data from four K-folds, while model performance was tested on the K-fold that was left out. This process was repeated four more times, so each K-fold was used in turn as test data. The model performance as measured by two performance criteria (AUC and AICc, as described below) was then averaged over the five sets of test data. The parameters that we optimized were the regularization multiplier (beta), which influences model complexity (the lower beta, the more complex the model), and feature classes, which define the relationship between predictor and dependent variables. Model performance was evaluated for a range of beta values (0.5 – 3.0 in increments of 0.5) and feature class combinations (linear, hinge, quadratic and product) using the ENMeval package (Muscarella et al. 2014) in R. We selected the optimized parameter combinations from the model with the lowest Akaike's Information Criterion corrected for small sample sizes (AICc; Burnham and Anderson 2004, Warren and Seifert 2011). When the difference in AIC values was < 2.0, the more parsimonious model (fewer parameters) was selected (Burnham and Anderson 2002).

In addition to the AICc for the data set, average values for the area under the receiver operator curve (AUC) for the test data were computed in ENMeval as a diagnostic measure. The AUC approximates the probability that a randomly chosen presence observation would have a higher probability of presence than a randomly chosen absence observation: values > 0.5 are better than chance, > 0.7 are considered acceptable, > 0.8 are good, and > 0.9 excellent (Hosmer and Lemeshow 2005). Using the optimized models and the raster habitat covariates we mapped the predicted probabilities of suitable habitat for each species and life stage and plotted the estimated effect of each covariate on habitat suitability. Additionally, we mapped the standard deviation calculated from a set of five k-fold models (20:80 testing:training) with the "best" selected parameters (standard deviation maps are provided in Appendix 1).

### 2.5 Essential Fish Habitat Mapping

For each species and life stage, EFH Level 1 maps were created based on the predicted probability of suitable habitat from the best model. The definition of EFH area in Alaska is the area containing 95% of the occupied habitat (NMFS 2005). Occupied habitat was defined as all locations

[7] Section 3.2.4.2 in EFH component 1 Descriptions and Maps (updated January 2023); available on the Council agenda for this meeting.

where a species' life stage had probability of suitable habitat greater than 5%. Within the occupied habitat, four sub-areas were identified containing 95%, 75%, 50%, and 25% of the total occupied habitat. Each of the lower percentiles describes a more focused partition of the total EFH area. The area containing 75% of the occupied habitat based on SDM predictions is referred to as the principal EFH area, the area containing 50% of the occupied habitat is termed the core EFH area, and the area containing the top 25% of the occupied habitat is referred to as "EFH hot spots". Mapping habitat percentiles for EFH subareas like these helps demonstrate the heterogeneity of fish and crab distributions over available habitat within the larger area identified as EFH and aligns our mapping methods with those of other studies contributing to the 2023 EFH 5-year Review[8].

## 2.6 Habitat Related Vital Rates

In addition to mapping suitable habitat (EFH Level 1), we created maps depicting estimated habitat-related growth potential (EFH Level 3). Regions that are favorable to growth were identified and mapped by linking growth rates to habitat temperature for age-0 and juvenile Arctic cod and juvenile saffron cod. Potential growth rates were estimated and mapped based on laboratory studies of temperature-dependent growth (Laurel et al. 2016; 2017) by using temperature raster data as input to the temperature terms of the growth rate equations. To highlight areas of high potential productivity, we took the product of the probability of suitable habitat and potential growth rate in each grid cell to map habitat-related growth potential and highlight physiologically important areas that may support higher Arctic cod and saffron cod population productivity. Our approach to mapping EFH Level 3 information corresponds to the approach of other studies in the 2023 Review[9].

## 2.7 Warm and Cold Conditions

Warm and cold years (2000 – 2018) were determined by calculating the annual summer (July, August, and September) mean of bottom temperatures within the AMA at depths < 1,250 m. Years in which the mean summer bottom temperatures were higher than the overall summer mean from 2000 – 2018 were considered warm while those below the mean were considered cold (**Figure 5**). Separate habitat covariate sets were created for warm and cold years, respectively. For each species and life stage combination, species distribution was predicted on the warm and the cold covariate sets using the best-fit model for all the data combined. We looked for potential shifts in distribution between warm and cold years by comparing the area occupied during each period and comparing differences between the habitat suitability for each period.

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[8] Section 3.2.8 in EFH component 1 Descriptions and Maps (updated January 2023); available on the Council agenda for this meeting.

[9] Section 3.2.8.6 in EFH component 1 Descriptions and Maps (updated January 2023); available on the Council agenda for this meeting.

**Table 1.** Survey data used in species distribution models of species and life history stages in the Arctic Management Area, including survey year (2004 – 2019), cruise code, location (Nearshore, Chukchi Sea, and Beaufort Sea), gear types available (bongo, beach seine, purse seine, otter trawl (OT), tucker trawl, plumb-staff beam trawl (PSBT and PSBT-A), 83-112 eastern bottom trawl (EBT), Canadian Bottom Trawl (CBT), and Isaacs Kidd Midwater Trawl (IKMT), fyke net, gillnet, ring net, minnow trap, and jig), available hauls, and survey months.

| Years | Survey | Cruise Codes | Location | Gear | Hauls | Months |
|---|---|---|---|---|---|---|
| 2004, 2005, 2006, 2007, 2009 | Synthesis | SYNTH04, SYNTH05, SYNTH06, SYNTH07, SYNTH09 | Nearshore | beach seine | 46 | Aug, Sept |
| 2007, 2008, 2009 | ABL_Arctic | ABL_Arctic07, ABL_Arctic08, ABL_Arctic09 | Nearshore | OT | 42 | Aug, Sept |
| 2012 | USACE_Kaktovik | USACE12 | Nearshore | beach seine, OT | 18 | Aug |
| 2013, 2014, | ACES | ACES13, ACES14 | Nearshore | beach seine, ring net, tucker trawl, OT | 65 | July, Aug |
| 2015 | AFF | AFF15 | Nearshore | beach seine, PSBT | 83 | July, Aug, Sept |
| 2015, 2016, 2017, 2018 | ABL_WCS | ABL_WCS15, ABL_WCS16, ABL_WCS17, ABL_WCS18 | Nearshore | fyke net, beach seine, gillnet, minnow trap, jig | 380 | Jun, Jul, Aug, Sept |
| 2016 | USACE_Kotzebue | USACE16 | Nearshore | beach seine, OT | 11 | Aug |
| 2017, 2018 | USGS | USGS17, USGS18 | Nearshore | fyke net, PSBT, beach seine | 77 | Jul, Aug |
| 2004, 2009, 2012 | RUSALCA | RUSALCA04, RUSALCA09, RUSALCA12 | Chukchi | PSBT | 13 | Aug, Sept |
| 2007 | OD0710 | OD07 | Chukchi | PSBT | 21 | Sept |
| 2007 | OS180 | OSM07 | Chukchi | PSBT | 9 | Aug |

| Years | Survey | Cruise Codes | Location | Gear | Hauls | Months |
|---|---|---|---|---|---|---|
| 2008 | OS190 | OSM08 | Chukchi | PSBT | 15 | Jul |
| 2008 | Beaufort Pilot | Beau08 | Beaufort | 83-112 EBT | 24 | Aug |
| 2009 | COMIDA | COMIDA09 | Chukchi | PSBT | 30 | Jul, Aug |
| 2009, 2010 | CSESP WWW | WWW809, WWW909, WWW10 | Chukchi | PSBT, IKMT | 91 | Aug, Sept, Oct |
| 2010, 2011 | AKCH, AKMAP | AKCH10, AKCH11 | Chukchi | PSBT | 58 | Aug, Sept |
| 2011 | BeauFish | BOEM_11 | Beaufort | PSBT, IKMT, bongo | 81 | Aug, Sept |
| 2012 | Transboundary | TB12 | Beaufort | CBT, OT, PSBT-A | 57 | Sept |
| 2012 | Arctic Eis | ArcEIS12 | Chukchi | PSBT, 83-112 EBT | 111 | Aug, Sept |
| 2013 | SHELFZ | SHELFZ13 | Chukchi | beach seine, pelagic trawl, 83-112 EBT | 63 | Aug, Sept |
| 2013 | Transboundary | TB13 | Beaufort | CBT, PSBT-A | 63 | Aug |
| 2014 | Transboundary | TB14 | Beaufort | PSBT-A | 68 | Aug, Sept |
| 2014, 2015 | ANIMIDA | ANIMIDA14, ANIMIDA15 | Beaufort | PSBT-A | 47 | July, Aug |
| 2015, 2017 | AMBON | AMBON15, AMBON17 | Chukchi | PSBT-A | 143 | Aug, Sept |
| 2017, 2019 | Arctic IES II | ArcticIES17 | Chukchi | PSBT-A | 58 | Aug |

**Table 2.** Species and life history stages where a species distribution model-based essential fish habitat map was developed for the Arctic FMP.

| Species | Larvae | Early Juvenile | Late Juvenile | Adult |
|---|---|---|---|---|
| Arctic cod (Length, mm) | < 30 | 31 – 70 (age-0) | 71 – 120 | > 120 |
| Saffron cod (Length, mm) | < 27 | 28 – 70 (age-0) | 71 – 190 | > 190 |
| Snow crab (Carapace width, mm) | -- | < 34 (immature) | 35 – 61 (adolescent male)<br>35 – 46 (adolescent female) | > 62 (mature male)<br>> 46 (mature female) |

**Table 3.** Habitat covariates used in species distribution models to describe and map essential fish habitat of Arctic species.

| Variable | Unit | Description of Prediction Raster | Interpolation Method |
|---|---|---|---|
| Depth | meters (m) | Bathymetry of the seafloor based on acoustic seafloor mapping data and digitized, position corrected NOS charts (Lewis and Pirtle unpublished) | Natural neighbor |
| Bottom temperature | °C | Seafloor ocean temperature predicted from the Pacific Arctic ROMS (Danielson and Hedstrom) averaged for the bottom 5m across years (2000-2018) during summer months (Jul-Sep) | Inverse distance weighting |
| Minimum bottom temperature | °C | Seafloor ocean temperature predicted from the Pacific Arctic ROMS (Danielson and Hedstrom) averaged for the bottom 5m across summer months and years (2000-2018) | Inverse distance weighting |
| Bottom current Eastward velocity | $m \cdot sec^{-1}$ | Seafloor ocean current components predicted from the Pacific Arctic ROMS (Danielson and Hedstrom) averaged for the bottom 5m across summer months and years (2000-2018) | Inverse distance weighting |
| Bottom current Northward velocity | $m \cdot sec^{-1}$ | Seafloor ocean current components predicted from the Pacific Arctic ROMS (Danielson and Hedstrom) averaged for the bottom 5m across summer months and years (2000-2018) | Inverse distance weighting |
| Bottom current Eastward velocity variability | $m \cdot sec^{-1}$ | Pooled standard deviation of seafloor ocean current velocities ROMS (Danielson and Hedstrom) from the bottom 5m across summer months and years (2000-2018) | Inverse distance weighting |
| Bottom current Northward velocity variability | $m \cdot sec^{-1}$ | Pooled standard deviation of seafloor ocean current velocities ROMS (Danielson and Hedstrom) from the bottom 5m across summer months and years (2000-2018) | Inverse distance weighting |
| Sediment grain size | *phi* | Sediment grain size derived from sampling in the Alaskan Arctic and curated in the dbSEABED database (Jenkins) | Ordinary kriging |
| Organic Carbon | -- | Percent organic carbon from sampling sediment in the Alaskan Arctic and curated in the dbSEABED database (Jenkins) | Ordinary kriging |

| Variable | Unit | Description of Prediction Raster | Interpolation Method |
|---|---|---|---|
| Longitude | m | Grid points spaced every 1 $km^2$ within the Arctic Management Area in Alaska Albers Equal Area conic projection | -- |
| Sea Surface temperature | °C | Seafloor ocean temperature predicted from the Pacific Arctic ROMS (Danielson and Hedstrom) averaged for the bottom 5m across years (2000-2018) during summer months (Jul-Sep) | Inverse distance weighting |
| Minimum bottom temperature | °C | Seafloor ocean temperature predicted from the Pacific Arctic ROMS (Danielson and Hedstrom) averaged for the bottom 5m across summer months and years (2000-2018) | Inverse distance weighting |
| Surface current Eastward velocity | $m\cdot sec^{-1}$ | Seafloor ocean current components predicted from the Pacific Arctic ROMS (Danielson and Hedstrom) averaged for the bottom 5m across summer months and years (2000-2018) | Inverse distance weighting |
| Surface current Northward velocity | $m\cdot sec^{-1}$ | Seafloor ocean current components predicted from the Pacific Arctic ROMS (Danielson and Hedstrom) averaged for the bottom 5m across summer months and years (2000-2018 | Inverse distance weighting |
| Surface current Eastward velocity variability | $m\cdot sec^{-1}$ | Pooled standard deviation of seafloor ocean current velocities ROMS (Danielson and Hedstrom) from the bottom 5m across summer months and years (2000-2018) | Inverse distance weighting |
| Surface current Northward velocity variability | $m\cdot sec^{-1}$ | Pooled standard deviation of seafloor ocean current velocities ROMS (Danielson and Hedstrom) from the bottom 5m across summer months and years (2000-2018) | Inverse distance weighting |

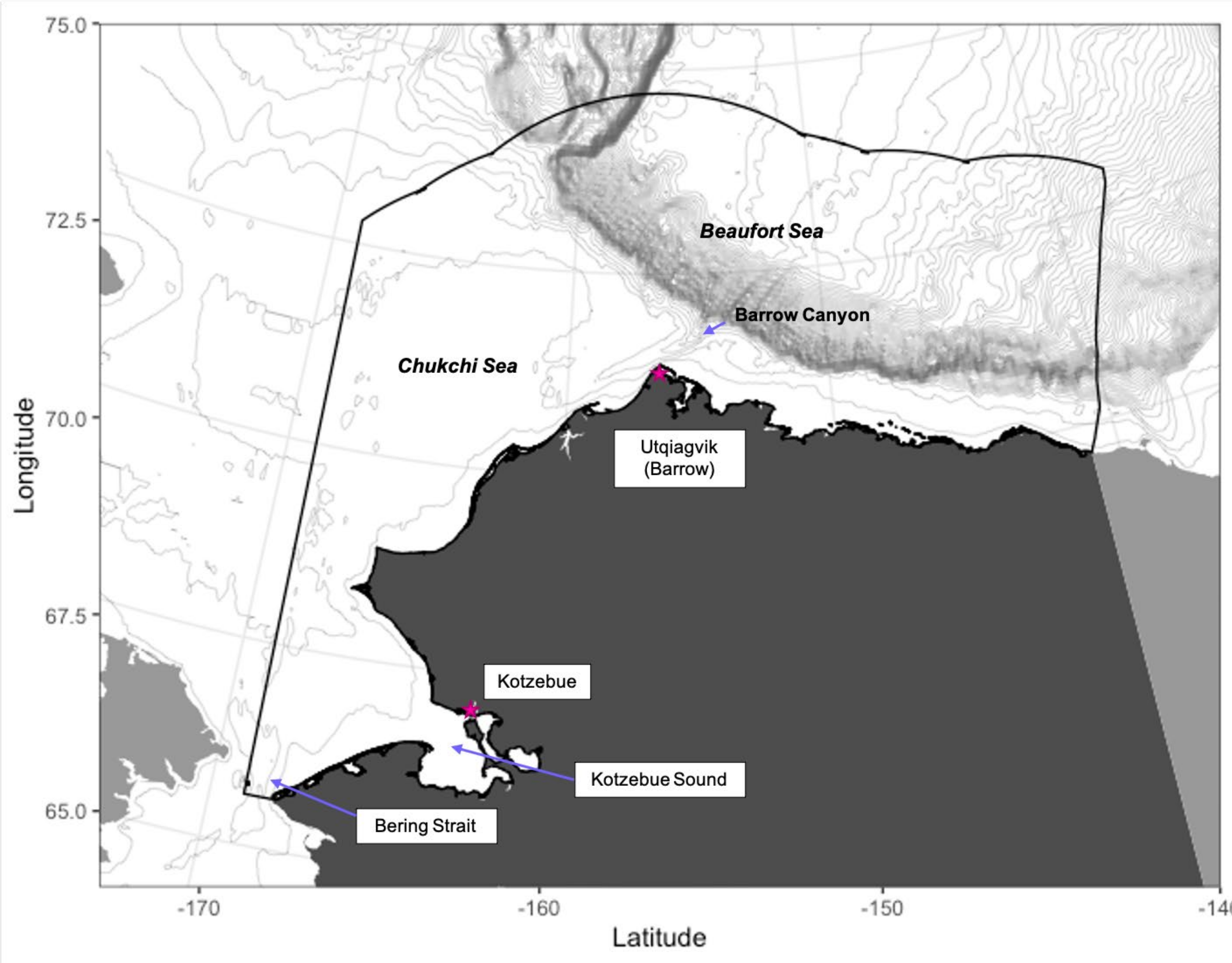



**Figure 1**. U.S. Arctic Management Area (AMA). The AMA is outlined in black. Isobaths displaying depths of 25 m and from 50 m – 4000 m spaced every 50 m are in grey. Blue arrows are pointing to labeled bodies of water and labeled communities are marked with magenta stars.

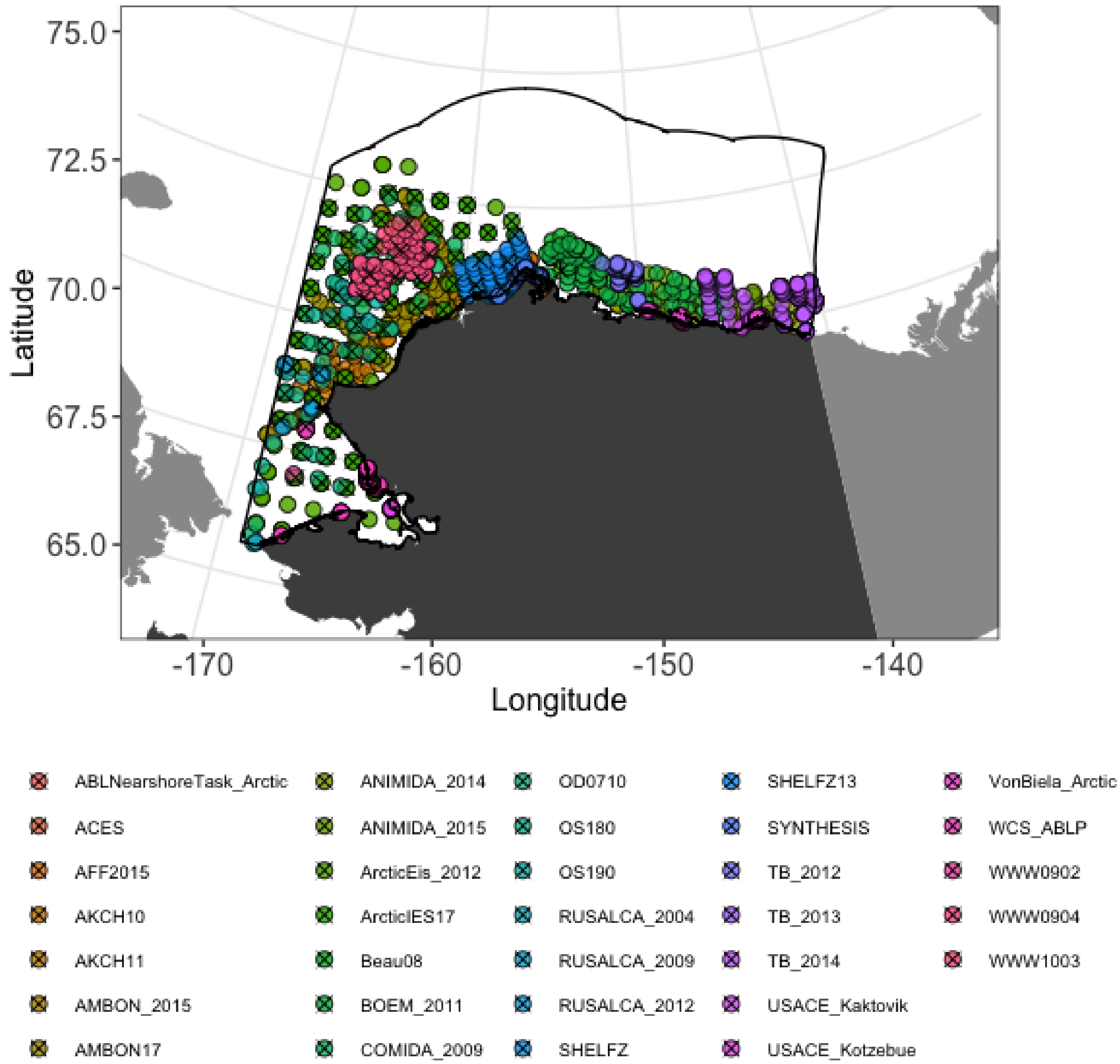



**Figure 2.** Survey locations within the Arctic Management Area (AMA). The AMA is outlined in black. Species distribution models were based on available occurrence data at these sites where the survey cruise code corresponds to the above symbols. Cruise codes and additional survey information is provided in **Table 1**.

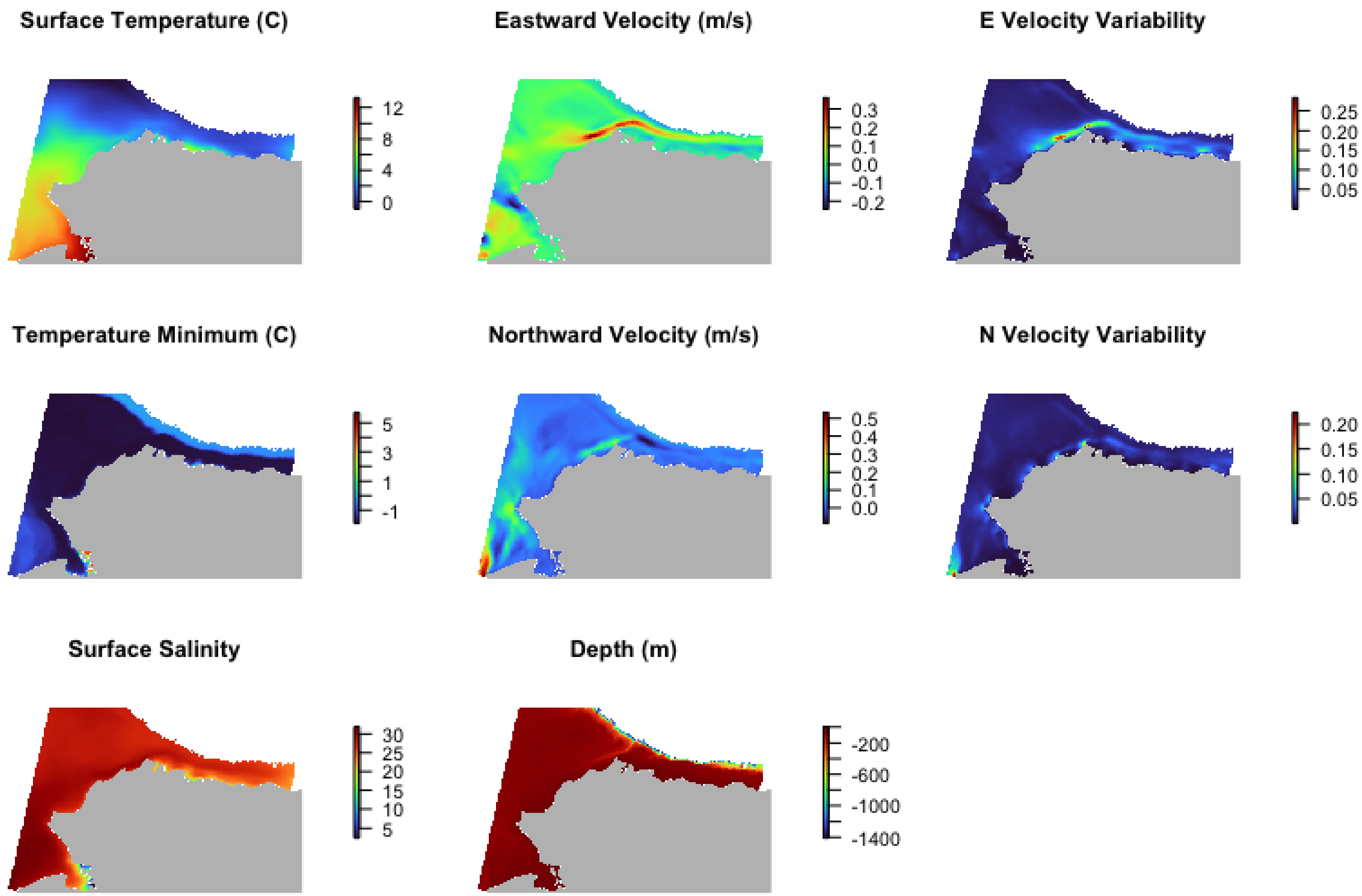



**Figure 3.** Near surface habitat covariate rasters used in the species distribution models for life stages of Arctic Fishery Management Plan species (see **Table 3** for additional information).

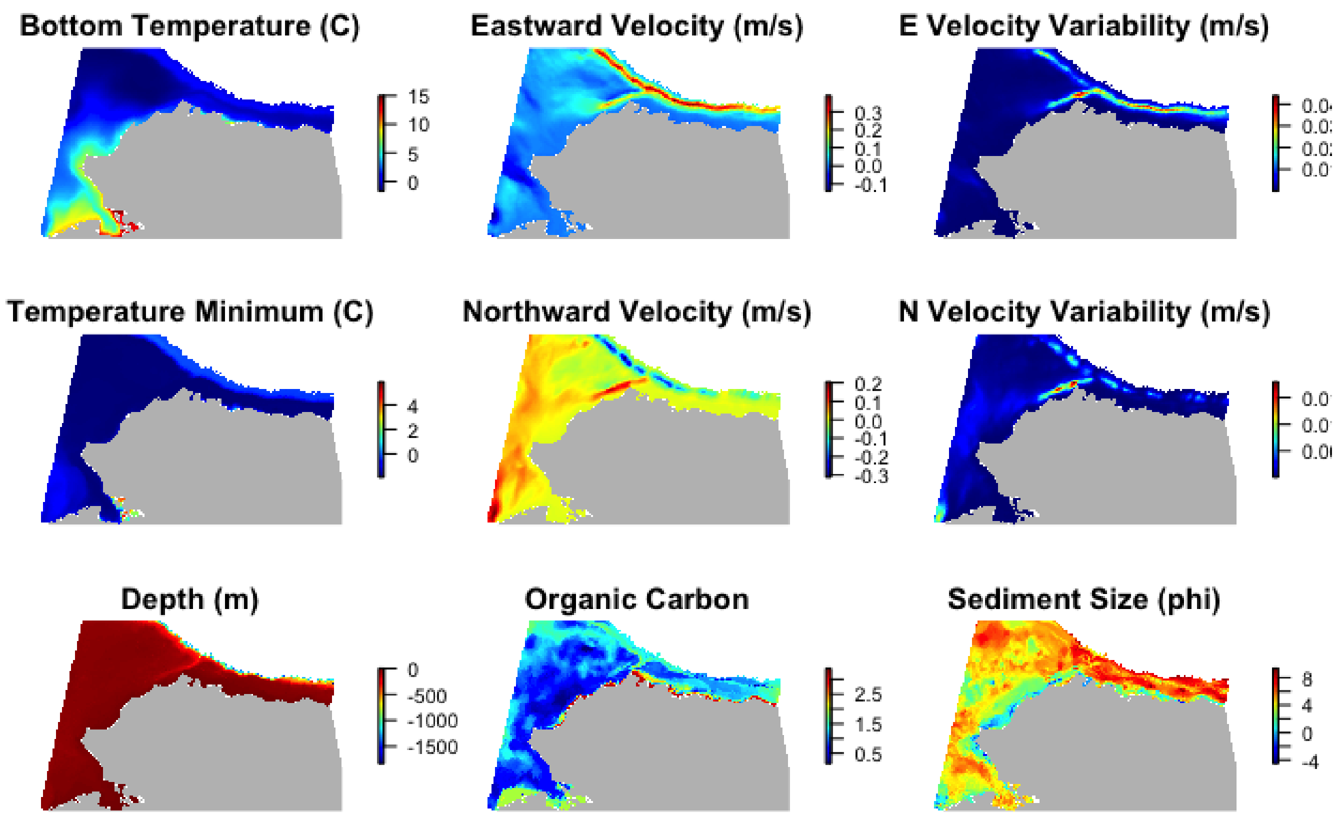



**Figure 4.** Near bottom habitat covariate rasters used in the species distribution models for life stages of Arctic Fishery Management Plan species (see **Table 3** for additional information).

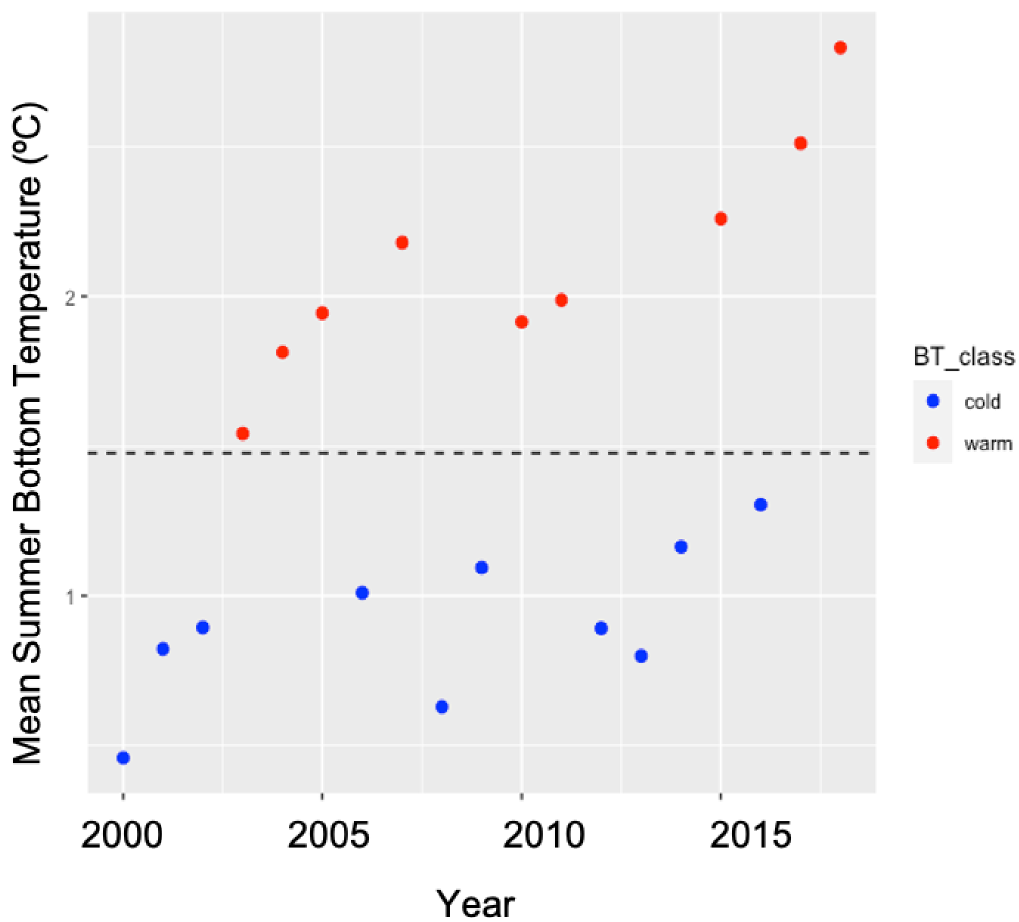



**Figure 5.** Warm and cold years based on annual mean summer bottom temperature. The annual and overall (dashed line) mean summer bottoms temperatures were computed from the Pacific Arctic ROMs output within the Arctic Management Area.

# 3 RESULTS

## 3.1 Arctic Cod Distribution and Habitat Associations

Arctic cod are the most abundant and widely distributed forage fish in the Alaskan Arctic (Lowry and Frost 1981; Barber et al. 1997; Logerwell et al. 2018) and provide an integral part of the Arctic food web (Welch et al. 1992; Loseto et al. 2009; Matley et al. 2012). They occurred throughout the sampling area in the Chukchi and Beaufort Seas (**Figure 6** top row). They are adapted for polar conditions (low light and cold temperatures) with large eyes and the ability to synthesize antifreeze glycoproteins in order to withstand subzero temperatures. Past fisheries have found commercial uses for Arctic cod (Gjøsæter 1995), but due to their integral role in the ecosystem, there are concerns over commercial removals. Currently, commercial fishing is prohibited in the US Arctic due to insufficient data to assess the sustainability of a potential fishery (NPFMC 2009).

Arctic cod have slow growth rates, early maturation, and a short life-span, usually less than seven years (Bradstreet 1986). They typically spawn under the ice in the middle of winter from December to March with peak spawn time occurring from January to February in Svalbard waters, Barents Sea and the U.S. Arctic (Craig et al. 1982, Lowry and Frost 1983, Korshunova 2012, Vestfals et al. 2021). First maturity can occur as early as one year of age for males and two years of age for females in the coastal water of the Beaufort Sea (Craig et al. 1982). On average, females reach maturity at three (Barents Sea and Alaskan Arctic) years of age, while males tend to mature earlier at two years of age (Craig et al. 1982).

### *3.1.1 Larval Arctic Cod*

MaxEnt model predictions of suitable larval Arctic cod habitat was high in the northeast Chukchi Sea, especially along the coast, in coastal areas of the Beaufort Sea, and along the Beaufort shelf break (**Figure 7**; model standard deviation **Figure A1**). There is limited suitable habitat in the southern Chukchi Sea. Surface temperature and depth were the two most important habitat covariates determining the distribution of suitable larval Arctic cod habitat with a relative importance of 36% and 29%, respectively (**Table 4**). The probability of suitable habitat was highest over a narrow range of temperatures, around 2 – 5 °C. Salinity and eastward velocity were the third and fourth most important habitat variables, with relative importance of 13% and 11%, respectively. The probability of habitat suitability declined rapidly at salinities below 28. The model fits were considered good (avg. $AUC_{testing}$ = 0.82).

### *3.1.2 Age-0 Arctic Cod*

MaxEnt model predictions of suitable age-0 Arctic cod habitat were high in the northeast Chukchi Sea, especially along the coast, around Barrow, and along the Beaufort shelf break (**Figure 8**; model standard deviation **Figure A2**). Similar to larval Arctic cod, there is limited suitable habitat in the southern Chukchi Sea. Surface temperature was the most important (45%) habitat covariate determining the distribution of suitable Age-0 cod habitat (**Table 4**). The probability of suitable habitat was highest at lower temperatures (1.5 – 4 °C,) though the overall range was wider than for larval Arctic cod. Depth, eastward velocity variability and salinity were the second, third, and fourth most important habitat variables with relative importance of around 23%, 11% and 9%, respectively. The probability of habitat suitability increased to a peak at salinities below 29 then declined rapidly. The model fits were considered acceptable ($AUC_{testing}$ = 0.77). We reported predictions from the model fit to surface covariates as it resulted in a higher AUC.

### *3.1.3 Juvenile Arctic Cod*

MaxEnt model predictions of suitable juvenile Arctic cod habitat were high in the northeast Chukchi Sea, in Barrow Canyon, and along the Beaufort shelf break (**Figure 9**; model standard deviation **Figure A3**). The probability of suitable habitat is lower along the coast than for the earlier life stages. Depth and bottom temperature were the most important habitat covariates determining the distribution of suitable juvenile Arctic cod habitat, with a relative importance of 21% and 20% (**Table 4**). Habitat suitability was high at intermediate depths. The probability of suitable habitat was higher over a larger range of temperatures when compared with earlier life stages. Northward velocity and percent organic carbon and were the third and fourth most important habitat variables with relative importance of 18% and 15%, respectively. The model fits were considered acceptable (avg. $AUC_{testing}$ = 0.73).

### *3.1.4 Mature Arctic Cod*

MaxEnt model predictions of suitable mature Arctic cod habitat were relatively high over a broader area of the Chukchi Sea compared to those for other life stages with the highest habitat suitability in the Bering Strait, Barrow Canyon, and along the Beaufort shelf break (**Figure 10**; model standard deviation **Figure A4**). The probability of suitable habitat is lower along the coast than for the earlier life stages (including juvenile Arctic cod). Depth, organic carbon, northward velocity variability and northward velocity were the 4 most important habitat covariates determining the distribution of suitable mature Arctic cod habitat (**Table 4**). Habitat suitability was highest at intermediate depths from 200 – 500 m. Northward velocity variability and northward velocity were the third and fourth most important habitat variables with relative importance of 17% and 13%, respectively. Though not in the top four, bottom temperature was the fifth most important habitat covariate with an importance of 9%. The probability of suitable habitat was higher over a larger range of temperatures when compared with earlier life stages. The model fits were considered acceptable (avg. $AUC_{testing}$ = 0.72).

### *3.1.5 Essential Fish Habitat*

The EFH area increases with ontogeny for Arctic cod, as the probability of suitable habitat becomes less dependent on lower temperatures, particularly in the southern Chukchi Sea (**Figure 11**; **Table 5**). The area upstream of Barrow Canyon, Barrow Canyon, and the Beaufort shelf break are EFH hotspots for all life stages. It should be noted the that the life stages are vertically stratified as larval and age-0 Arctic cod occur near the surface, while juvenile and mature Arctic cod tend to occur deeper in the water column or on the bottom. Larval and age-0 Arctic cod habitat hotspots are mainly concentrated in the northeast Chukchi Sea to the coast and in in the western Beaufort Sea from the shelf break to the coast. Arctic cod seem to move offshore with maturity in the Beaufort Sea.

**Table 4.** Optimized MaxEnt model parameter Beta (regularization multiplier) and the top four contributing habitat covariates (% deviance explained) in species distribution models developed for life stages of Arctic cod in the Arctic Management Area. FC is the best feature class combination (l=linear, h=hinge, q=quadratic and p=product) and the AUC is the average of the testing data over the 5 k-folds with the corresponding standard deviation (SD).

| Species – Life stage | Presences | Beta | FC | AUC (± SD) | Variable 1 (%) | Variable 2 (%) | Variable 3 (%) | Variable 4 (%) |
|---|---|---|---|---|---|---|---|---|
| Arctic cod – Larval | 127 | 1 | lpq | 0.82 (0.02) | Surface Temperature (36) | Depth (29) | Salinity (13) | Eastward velocity (11) |
| Arctic cod – Age-0 | 427 | 1 | lpqh | 0.77 (0.01) | Surface Temperature (45) | Depth (23) | Eastward velocity variability (11) | Salinity (9) |
| Arctic cod – Juvenile | 507 | 0.5 | lpq | 0.73 (0.01) | Depth (21) | Bottom Temperature (20) | Northward Velocity (18) | Organic Carbon (15) |
| Arctic cod – Mature | 254 | 1.5 | lpqh | 0.72 (0.02) | Depth (27) | Organic Carbon (22) | Northward Velocity Variability (17) | Northward Velocity (13) |

**Table 5.** Model-based estimates of EFH area ($km^2$) and the percent of the study area that can be designated EFH for species life stages.

| Species - Life stage | EFH area ($km^2$) | Percent of study area |
|---|---|---|
| Arctic cod - Larvae | 220,089 | 76% |
| Arctic cod – Age-0 | 241,623 | 83% |
| Arctic cod - Juvenile | 265,835 | 91% |
| Arctic cod - Mature | 270,827 | 93% |
| Saffron cod - Larvae | 193,821 | 67% |
| Saffron cod – Age-0 | 187,146 | 64% |
| Saffron cod - Juvenile | 169,851 | 58% |
| Saffron cod - Mature | 155,601 | 53% |
| Snow crab - Immature | 226,325 | 78% |
| Snow crab – Adolescent Female | 237,661 | 82% |
| Snow crab – Adolescent Male | 239,400 | 82% |
| Snow crab – Mature Female | 239,259 | 82% |
| Snow crab – Mature Male | 241,498 | 83% |

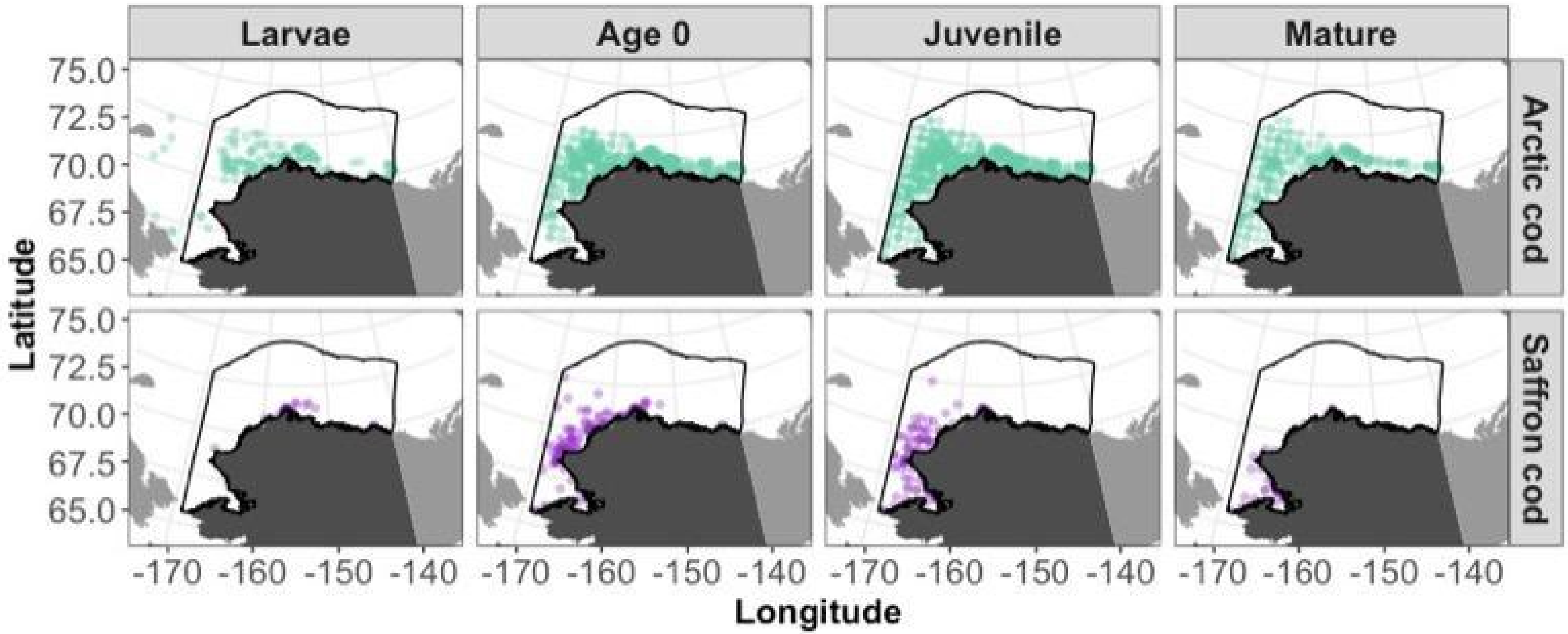



**Figure 6.** Presence only data by life stage (columns) for Arctic cod (top row) and saffron cod (bottom row) within the Arctic Management Area

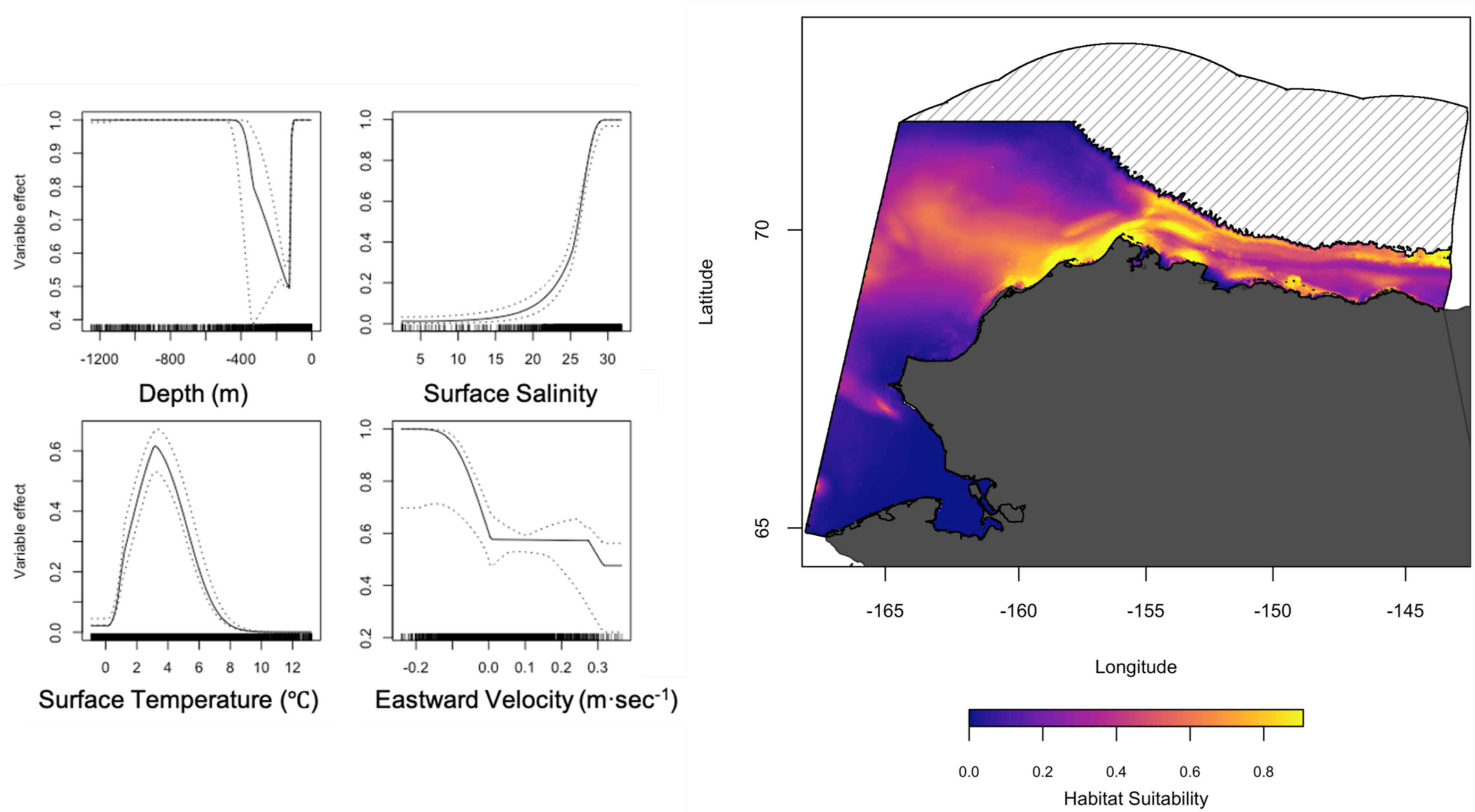



**Figure 7.** Response curves for the top four most influential habitat covariates in the MaxEnt model predicting probability of suitable habitat (left panel) and predicted distribution of probability of suitable habitat for larval Arctic cod (right panel).

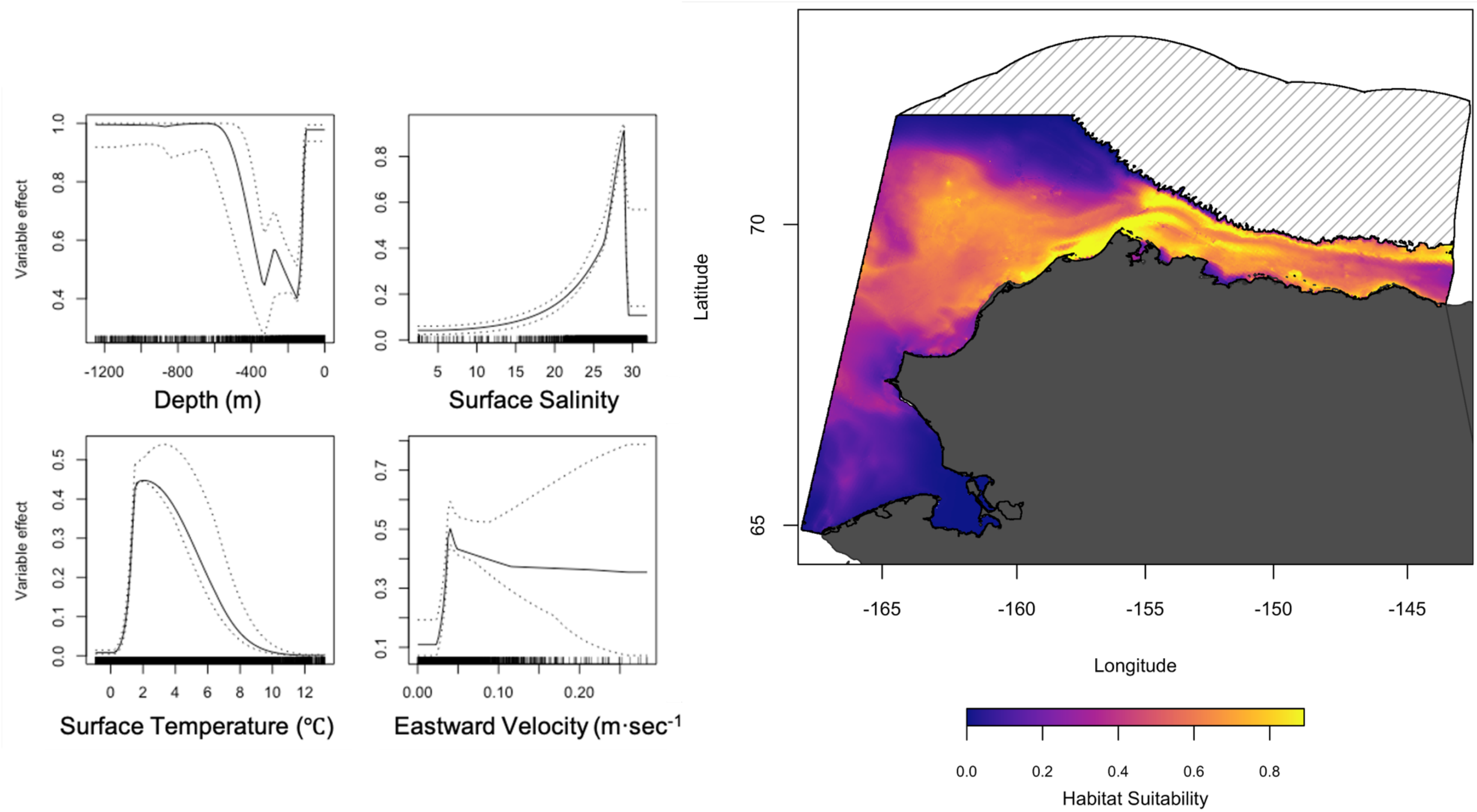



**Figure 8.** Response curves for the top four most influential habitat covariates in the MaxEnt model predicting probability of suitable habitat (left panel) and predicted distribution of probability of suitable habitat for age-0 Arctic cod (right panel).

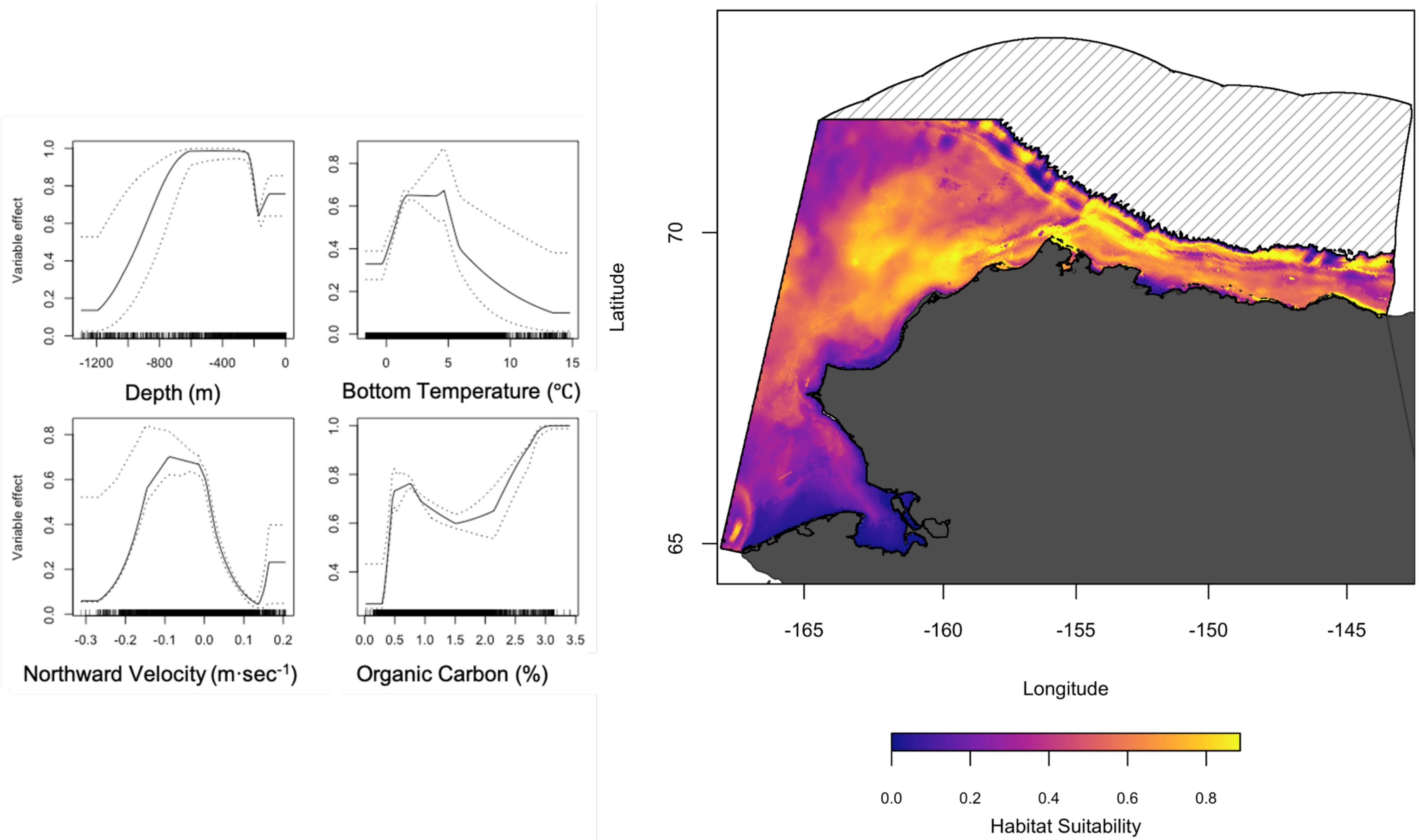



**Figure 9.** Response curves for the top four most influential habitat covariates in the MaxEnt model predicting probability of suitable habitat (left panel) and predicted distribution of probability of suitable habitat for juvenile Arctic cod (right panel).

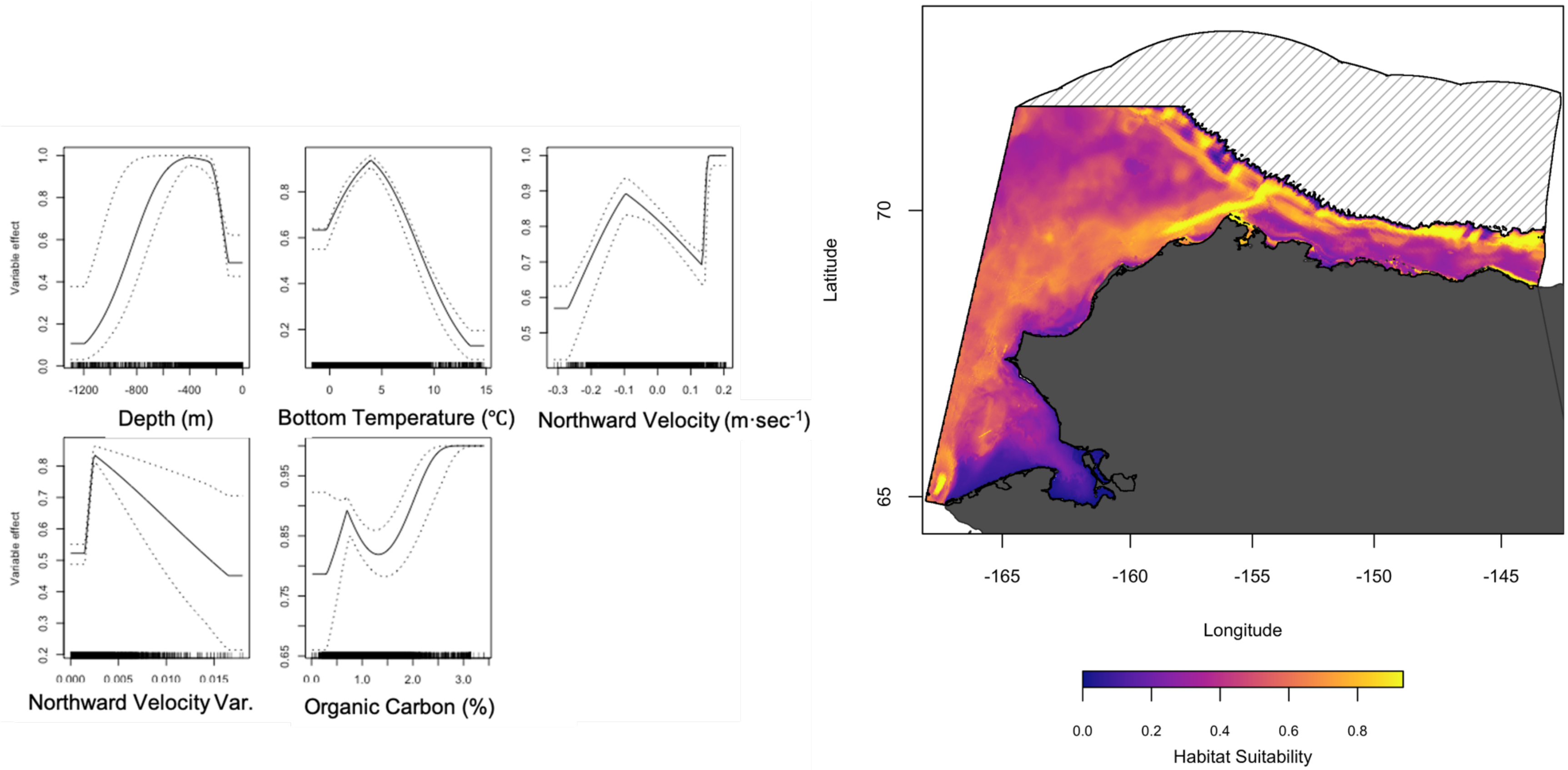



**Figure 10.** Response curves for the top five most influential habitat covariates in the MaxEnt model predicting probability of suitable habitat (left panel) and predicted distribution of probability of suitable habitat for mature Arctic cod (right panel).

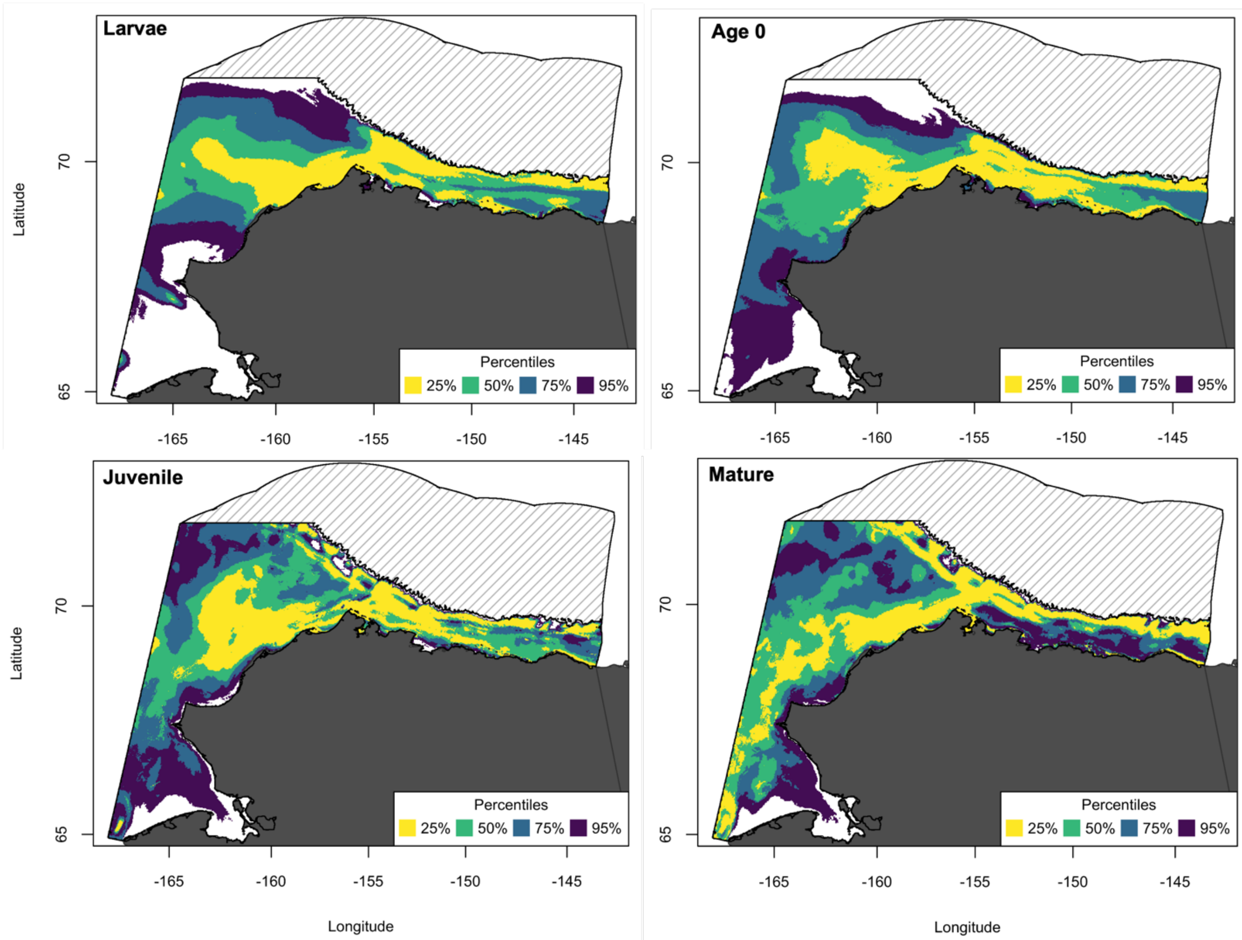



**Figure 11.** Essential fish habitat for larval, age-0, juvenile and mature Arctic cod.

## 3.2 Saffron Cod Distribution and Habitat Associations

Saffron cod are abundant in coastal waters of the North Pacific Ocean and into the Arctic, typically occurring at depths from 0 – 50 m (Allen and Smith 1988) with a maximum depth of 300 m (Cohen et al. 1990). This is consistent with the survey prevalence data (**Figure 6**). The growth rate of juvenile saffron cod exceeds that of Arctic cod at temperatures above about 10 °C and their growth continues to increase at higher temperature (Laurel et al. 2016). Similarly, saffron cod adults have a faster growth rate and larger maximum length compared to Arctic cod (Helser et al. 2017). They have a maximum length of 60 cm, and typically mature at 2 - 3 years. Like Arctic cod, saffron cod have the ability to synthesize antifreeze glycoproteins and can withstand temperatures as low as -1.8 C (Hargens 1972). Although less energy-dense than Arctic cod, they are an important component of the food web and are often found in the diets of ringed seals (*Phoca hispida*) in the Chukchi Sea (Lowry et al. 1980).

### *3.2.1 Larval Saffron Cod*

MaxEnt model predictions of suitable larval saffron cod habitat were highest along the coast in the northeast Chukchi Sea and into the Beaufort Sea (**Figure 12**; standard deviation **Figure A5**). There is limited suitable habitat offshore. Depth was by far the most important habitat covariate determining the distribution of suitable larval saffron cod habitat with a relative importance of 72% (**Table 6**). The probability of suitable habitat was highest at the shallowest depths and decreased rapidly below about 100 m. Surface temperature, northward velocity and eastward velocity, were the second, third, and fourth most important habitat variables, with relative importance of around 14%, 8% and 3%, respectively. The probability of habitat suitability was highest in waters with a strong northward component, probably reflecting a high prevalence in the coastal current over Barrow Canyon, and decreased with increasing surface temperatures above around 2 °C. The model fits were considered good (avg. $AUC_{testing}$ = 0.89).

### *3.2.2 Age-0 Saffron Cod*

MaxEnt model predictions of suitable age-0 saffron cod habitat was highest along the Chukchi Sea coast (excluding Kotzebue Sound) to Barrow (**Figure 13**; standard deviation **Figure A6**). A high probability of suitable habitat extended offshore in the Chukchi Sea and in Bering Strait. Bottom temperature was the most important (35%) habitat covariate determining the distribution of suitable age-0 saffron cod habitat (**Table 6**). The probability of suitable habitat increased with increasing temperatures and was highest above 8 °C. Sediment size, northward velocity variability and organic carbon were the second, third, and fourth most important habitat variables with relative importance of around 19%, 16% and 13%, respectively. The probability of habitat suitability decreased with finer sediment size (larger *phi*), increased with the sediment organic carbon content, and was higher at moderate levels of northward current variability. The model fits were considered good (avg. $AUC_{testing}$ = 0.88). We reported predictions from the model fit to the bottom covariates, as it resulted in a higher AUC.

### *3.2.3 Juvenile Saffron Cod*

MaxEnt model predictions of suitable age-0 saffron cod habitat was highest along the Chukchi Sea coast (excluding Kotzebue Sound) to Barrow (**Figure 14**; standard deviation **Figure A7**). A high probability of suitable habitat extended offshore in the central Chukchi Sea and from the Bering Strait north. Bottom temperature and organic carbon were the most important (45% and 30%, respectively) habitat covariates determining the distribution of suitable juvenile saffron cod habitat (**Table 6**). Similar to age-0 saffron cod, the probability of suitable habitat increased with increasing temperatures and was highest above 8 °C. The model fits were considered good (avg. $AUC_{testing}$ = 0.87).

### *3.2.4 Mature Saffron Cod*

MaxEnt model predictions of suitable mature saffron cod habitat was highest along the Chukchi Sea coast (including Kotzebue Sound) to the central Beaufort Sea (**Figure 15**; standard deviation **Figure A8**). Bottom temperature was the most important (38%) habitat covariate determining the distribution of suitable mature saffron cod habitat (**Table 6**). Similar to age-0 and juvenile life stages, the probability of suitable habitat increased with increasing temperatures and was highest above 8 °C (Figure 15). Organic carbon, minimum bottom temperature and sediment grain size were the 2$^{nd}$, 3$^{rd}$ and 4$^{th}$ most important habitat variables with relative importance of 24%, 21% and 7%, respectively (Table 6). Although probability of habitat suitability increased with temperature, it was highest when minimum bottom temperatures were relatively low (< 2 °C). Habitat suitability peaked at intermediate sediment grain sizes (*phi*=0 to *phi*=1) and decreased with finer sediment size (larger *phi*). The model fits were considered excellent (avg. $AUC_{testing}$ = 0.91).

### *3.2.5 Essential Fish Habitat*

With the exception of larval saffron cod, whose suitable habitat occurred mostly in the Beaufort Sea and northern Chukchi Sea, EFH hotspots for older life stages occurred along the Chukchi Sea coast extending to various distances offshore and along the Beaufort Sea coast in nearshore waters (**Figure 16**). Kotzebue Sound was a habitat hotspot for mature saffron cod. Bottom temperature was likely an important factor driving the distribution of saffron cod, as age-0, juvenile and mature saffron cod have habitat hotspots in the warmer waters along the coast. Saffron cod seem to be moving southward and coastward with ontogeny. In contrast to Arctic cod, EFH area decreases with ontogeny (**Table 5**; **Figure 11** and **Figure 16**).

**Table 6.** Optimized MaxEnt model parameter Beta (regularization multiplier) and the top four contributing habitat covariates (% deviance explained) in species distribution models developed for life stages of saffron cod in the Arctic Management Area. FC is the best feature class combination (l=linear, h=hinge, q=quadratic and p=product) and the AUC is the average of the testing data over the 5 k-folds with the corresponding standard deviation (SD).

| Species - Life stage | Presences | Beta | FC | AUC (± SD) | Variable 1 (%) | Variable 2 (%) | Variable 3 (%) | Variable 4 (%) |
|---|---|---|---|---|---|---|---|---|
| Saffron cod – Larvae | 22 | 2.5 | lqh | 0.89 (0.04) | Depth (72) | Surface Temperature (14) | Northward Velocity (8) | Eastward Velocity Variability (3) |
| Saffron cod – Age-0 | 128 | 2 | lpqh | 0.88 (0.01) | Bottom Temperature (35) | Sediment Size (19) | Northward Velocity Variability (16) | Organic Carbon (13) |
| Saffron cod – Juvenile | 80 | 1.5 | lpqh | 0.87 (0.02) | Bottom Temperature (45) | Organic Carbon (30) | Min. Bottom Temperature (12) | Sediment Size (3) |
| Saffron cod – Mature | 26 | 2 | l | 0.91 (0.01) | Bottom temperature (38) | Organic Carbon (24) | Min. Bottom Temperature (21) | Sediment Size (7) |

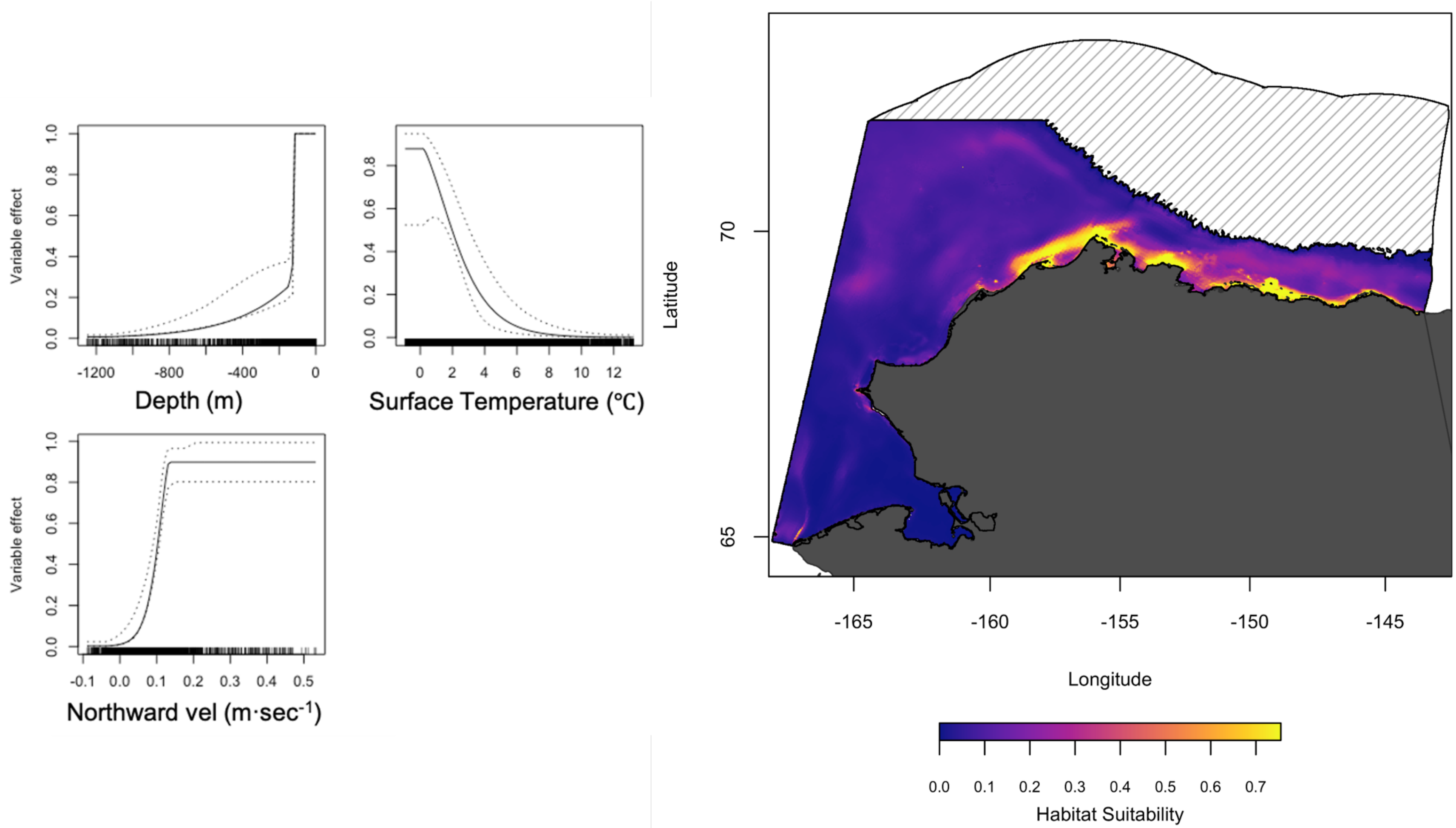



**Figure 12.** Response curves for the top four most influential habitat covariates in the MaxEnt model predicting probability of suitable habitat (left panel) and predicted distribution of probability of suitable habitat for larval saffron cod (right panel).

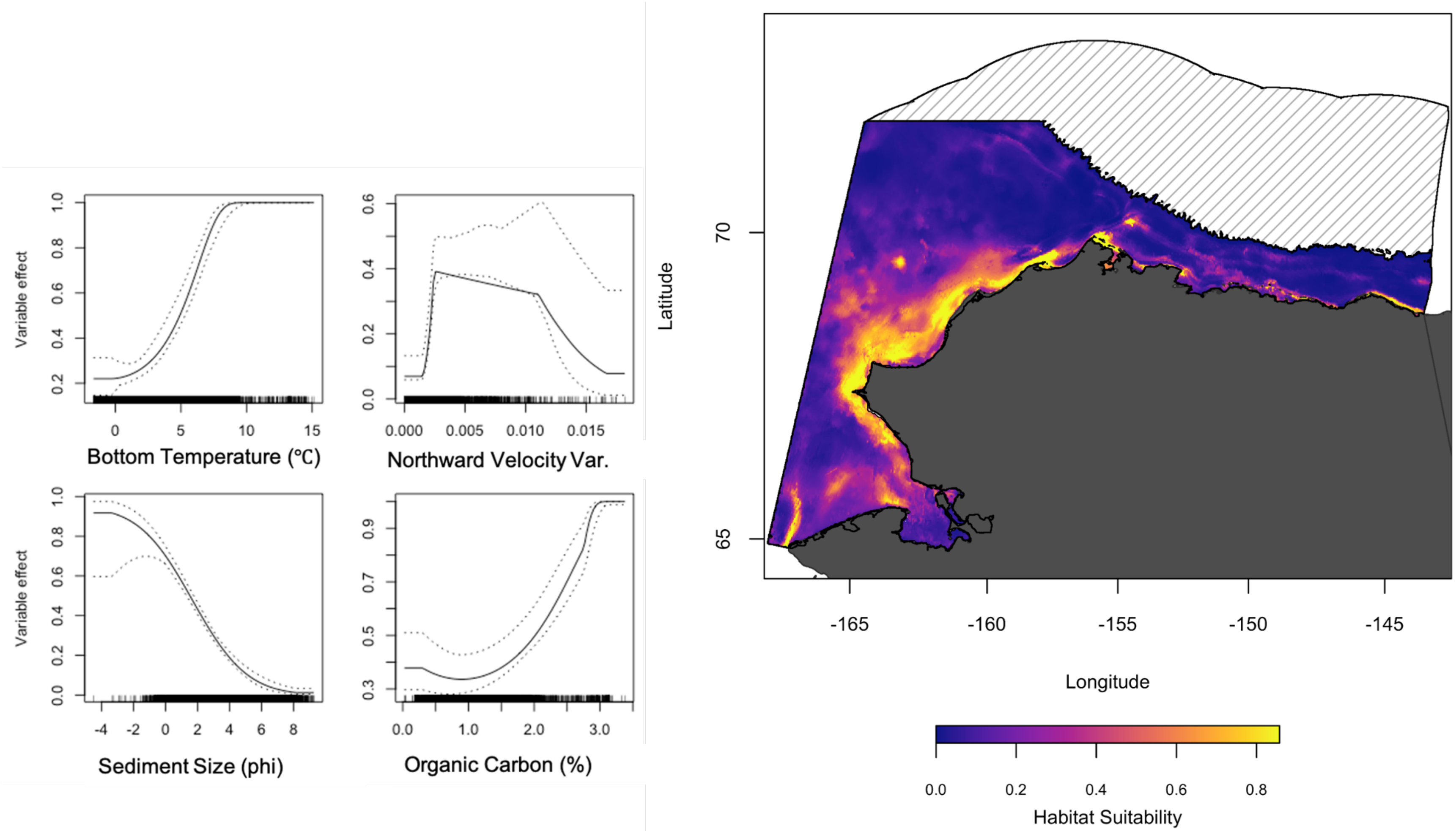



**Figure 13.** Response curves for the top four most influential habitat covariates in the MaxEnt model predicting probability of suitable habitat (left panel) and predicted distribution of probability of suitable habitat for age-0 saffron cod (right panel).

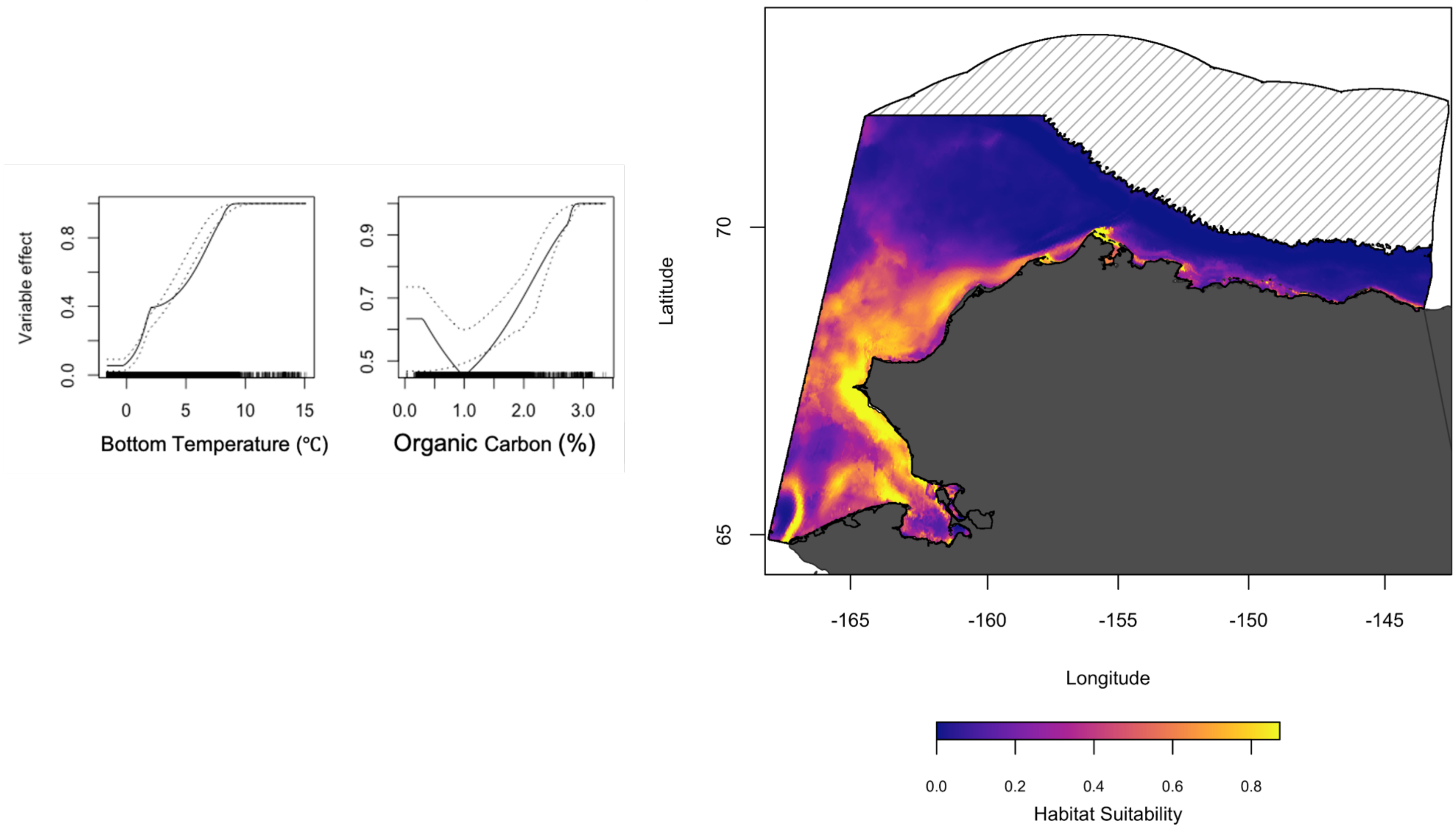



**Figure 14.** Response curves for the two most influential habitat covariates in the MaxEnt model predicting probability of suitable habitat (left panel) and predicted distribution of probability of suitable habitat for juvenile saffron cod (right panel).

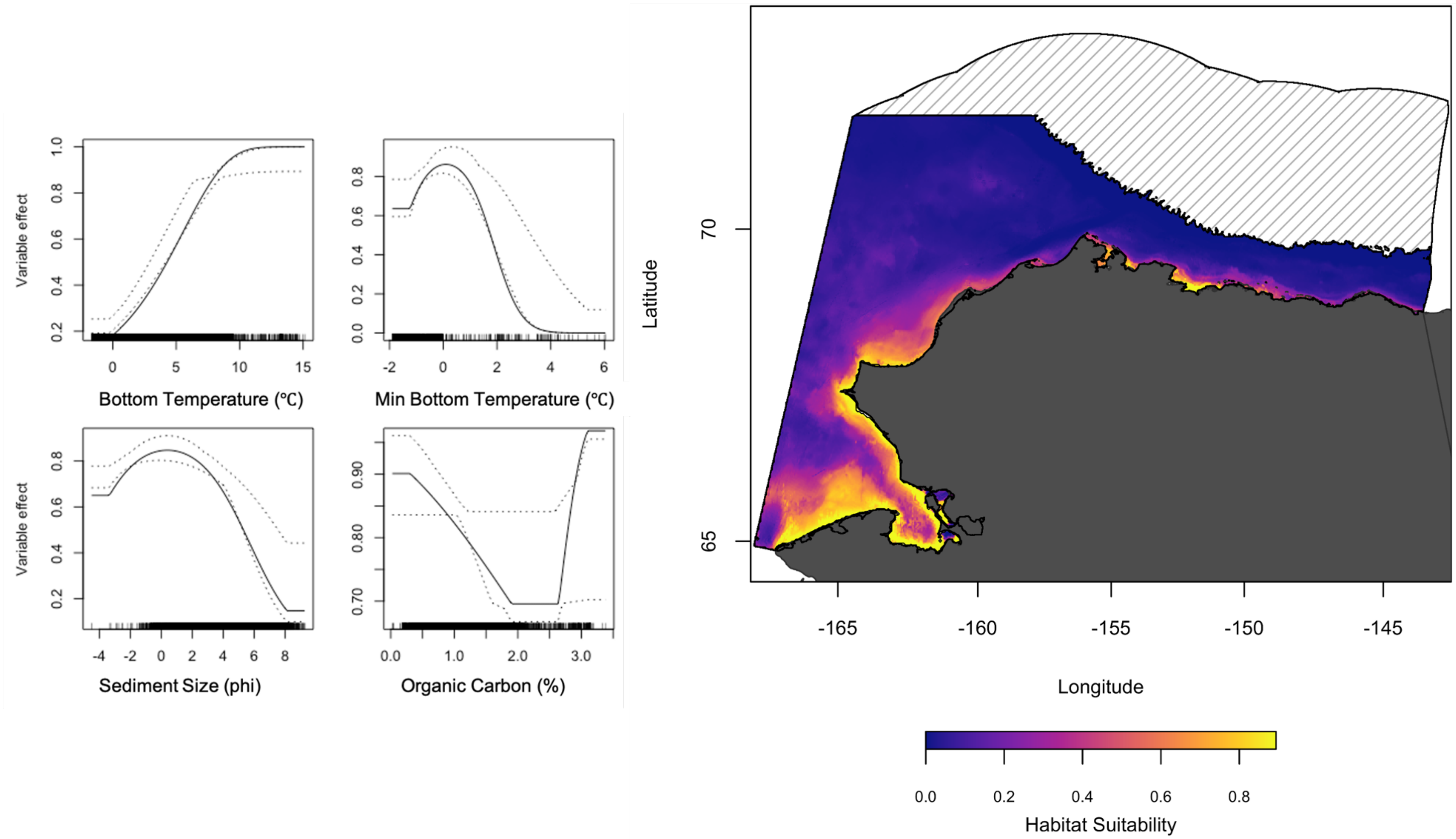



**Figure 15.** Response curves for the four most influential habitat covariates in the MaxEnt model predicting probability of suitable habitat (left panel) and predicted distribution of probability of suitable habitat for mature saffron cod (right panel).

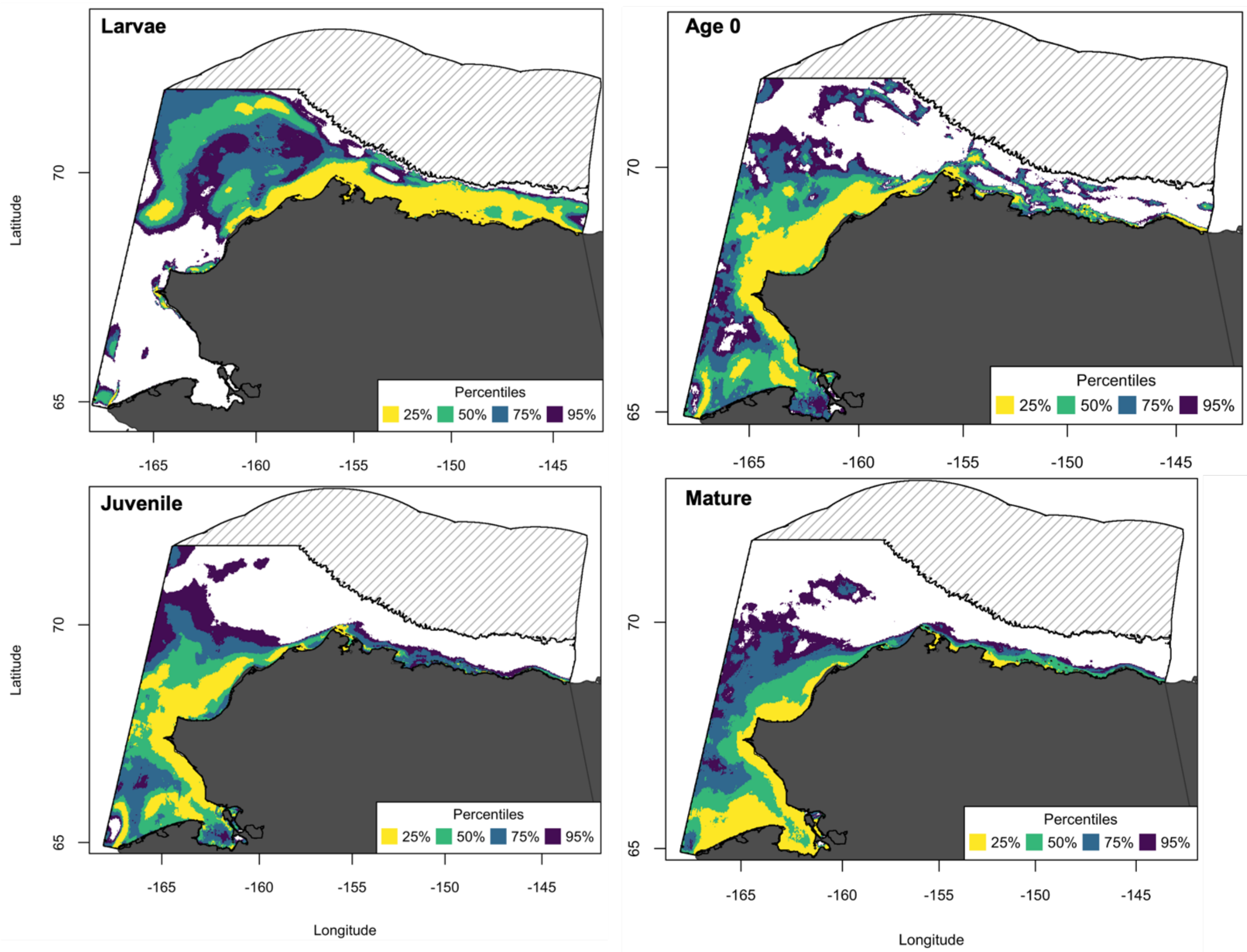



**Figure 16.** Essential fish habitat map for larval, age-0, juvenile and mature saffron cod.

## 3.3 Snow Crab Distribution and Habitat Associations

Snow crab of various sizes occurred throughout the Chukchi Sea (**Figure 17**). Some snow crab occurred at intermediate depths in the western Beaufort Sea. Few snow crab were sampled in the eastern Beaufort Sea, hence we included a longitude raster as a covariate in our MaxEnt models to account for the east-west gradient.

Snow crab have sexually dimorphic growth after the immature stages. Males grow faster and larger compared to females (Divine et al. 2019). Mature male snow crab are commercially harvested in the Bering Sea. A few males of harvestable size (carapace width > 100 mm) were caught in the Beaufort Sea, but none in the Chukchi Sea (**Figure 17**).

### *3.3.1 Immature Snow Crab*

MaxEnt model predictions of immature snow crab habitat were highest at intermediate depths in the Chukchi Sea and western Beaufort Sea (**Figure 18**; standard deviation **Figure A9**). Depth and bottom temperature were the most important habitat covariates determining the distribution of suitable immature snow crab habitat with a relative importance of 17% and 15%, respectively (**Table 7**). The probability of suitable habitat decreased with increasing bottom temperature and was highest over a narrow depth range peaking at approximately 100 m. Longitude and minimum bottom temperature were the third and fourth most important habitat variables with relative importance of 13% and 10%, respectively. The probability of habitat suitability decreased with increasing longitude to the east. The model fits were considered good (avg. $AUC_{testing} = 0.80$).

### *3.3.2 Adolescent Female Snow Crab*

MaxEnt model predictions of adolescent female snow crab habitat were highest at intermediate depths in the Chukchi Sea (**Figure 19**; standard deviation **Figure A10**). Longitude was the most important habitat covariate (31%) determining the distribution of suitable adolescent female snow crab (**Table 7**). The probability of suitable habitat decreased with increasing longitude. Organic carbon, bottom temperature, northward velocity variability, and depth were the second through fifth most important habitat variables with relative importance of 16%, 14%, 14% and 12%, respectively. Habitat suitability decreased with increasing organic carbon content and was consistently high at bottom temperatures below 8 °C before decreasing at higher temperatures. The model fits were considered acceptable (avg. $AUC_{testing} = 0.75$).

### *3.3.3 Adolescent Male Snow Crab*

MaxEnt model predictions of adolescent male snow crab habitat were highest offshore in the Chukchi Sea and along the slope in the Beaufort Sea (**Figure 20**; standard deviation **Figure A11**). Predicted probability of suitable habitat was low in Barrow Canyon and at similar depths along the slope, although this is not evident in the depth response curve. Longitude and eastward velocity variability were the most important habitat covariates 17% and 14% determining the distribution of suitable adolescent male snow crab (**Table 7**). The probability of suitable habitat decreased to the east with increasing longitude and remained intermediate until increasing at the highest eastward velocity values, as evident in high habitat suitability along the Beaufort slope current. Organic carbon, eastward velocity variability, bottom temperature, and depth were the third through sixth most important habitat variables with relative importance of 13%, 11%, 11% and 10%, respectively. The probability of habitat suitability decreased with increasing organic carbon content and was high at temperatures below 8 °C before decreasing at higher temperatures similar to the relationships for adolescent female snow crab. The model fits were considered acceptable (avg. $AUC_{testing} = 0.76$).

### *3.3.4 Mature Female Snow Crab*

MaxEnt model predictions of mature female snow crab habitat were highest offshore in the southern and central Chukchi Sea, near Barrow Canyon and along the slope in the Beaufort Sea (**Figure 21**; standard deviation **Figure A12**). Longitude and depth were the most important habitat covariates (21% and 19%, respectively) determining the distribution of suitable mature female snow crab (**Table 7**). The probability of suitable habitat decreased to the east with increasing longitude and was highest at depths form 150 – 800 m. Northward velocity, eastward velocity, and bottom temperature were the third through fifth most important habitat variables with relative importance of around 16%, 12%, and 9%, respectively. The probability of habitat suitability decreased with increasing eastward velocity and had a dome-shaped relationship with bottom temperature, peaking at 5.5 °C. The model fits were considered acceptable (avg. $AUC_{testing}$ = 0.77).

### *3.3.5 Mature Male Snow Crab*

MaxEnt model predictions of mature male snow crab habitat suitability was highest offshore in the southern, central and northwestern Chukchi Sea, in Barrow Canyon and along the slope in the Beaufort Sea (**Figure 22**; standard deviation **Figure A13**). Longitude was the most important habitat covariate (26%) determining the distribution of suitable mature male snow crab (**Table 7**). The probability of suitable habitat was high at lower and intermediate longitudes and then rapidly decreased to the east. Northward velocity, bottom temperature, eastward velocity, and depth were the second through fifth most important habitat variables with relative importance of 14%, 13%, 9%, and 9%, respectively. The probability of habitat suitability increased with northward velocity, decreased with increasing eastward velocity, was highest at bottom temperatures from 0 to 4 °C and highest at depths of 250 – 600 m. The model fits were considered good (avg. $AUC_{testing}$ = 0.81).

### *3.3.6 Essential Fish Habitat*

For all life stages of snow crab, EFH hotspots occur offshore throughout the Chukchi Sea (**Figure 23**). For adolescent males, mature females and mature males, additional hotspots occur along the Beaufort slope. Barrow Canyon is a habitat hotspot for mature male and female snow crab. Snow crab tend to move to deeper water with ontogeny, though the total EFH area remains fairly consistent.

**Table 7.** Optimized MaxEnt model parameter Beta (regularization multiplier) and the top four contributing habitat covariates (% deviance explained) in species distribution models developed for life stages of snow crabs in the Arctic Management Area. FC is the best feature class combination (l=linear, h=hinge, q=quadratic and p=product) and the AUC is the average of the testing data over the 5 k-folds with the corresponding standard deviation (SD).

| Species – Life stage | Presences | Beta | FC | AUC (± SD) | Variable 1 (%) | Variable 2 (%) | Variable 3 (%) | Variable 4 (%) |
|---|---|---|---|---|---|---|---|---|
| Snow crab – Immature | 164 | 1.5 | lp | 0.80 (0.01) | Depth (17) | Bottom Temperature (15) | Longitude (13) | Min. Bottom Temperature (10) |
| Snow crab – Adolescent Female | 142 | 2 | l | 0.75 (0.02) | Longitude (31) | Organic Carbon (16) | Bottom Temperature (14) | Northward Velocity Var. (14) |
| Snow crab – Adolescent Male | 178 | 1.5 | lqh | 0.76 (0.02) | Longitude (17) | Eastward Velocity Var. (14) | Organic Carbon (13) | Bottom Temperature (11) |
| Snow crab – Mature Female | 122 | 1.5 | lqh | 0.77 (0.02) | Longitude (21) | Depth (19) | Northward Velocity (16) | Eastward Velocity (12) |
| Snow crab – Mature Male | 90 | 1.5 | lqh | 0.81 (0.03) | Longitude (26) | Northward Velocity (14) | Bottom Temperature (13) | Eastward Velocity (9) |

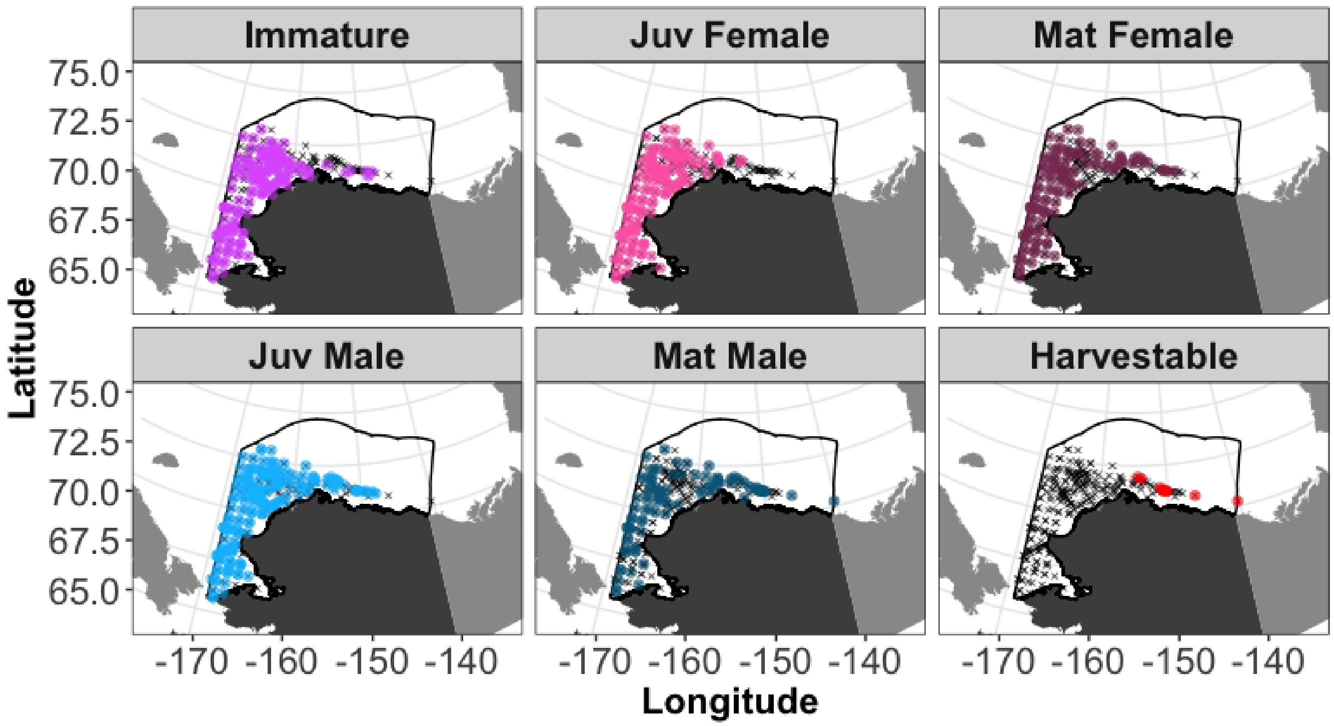



**Figure 17.** Snow crab presence (colored dots) and absence data (black x's) by life stage.

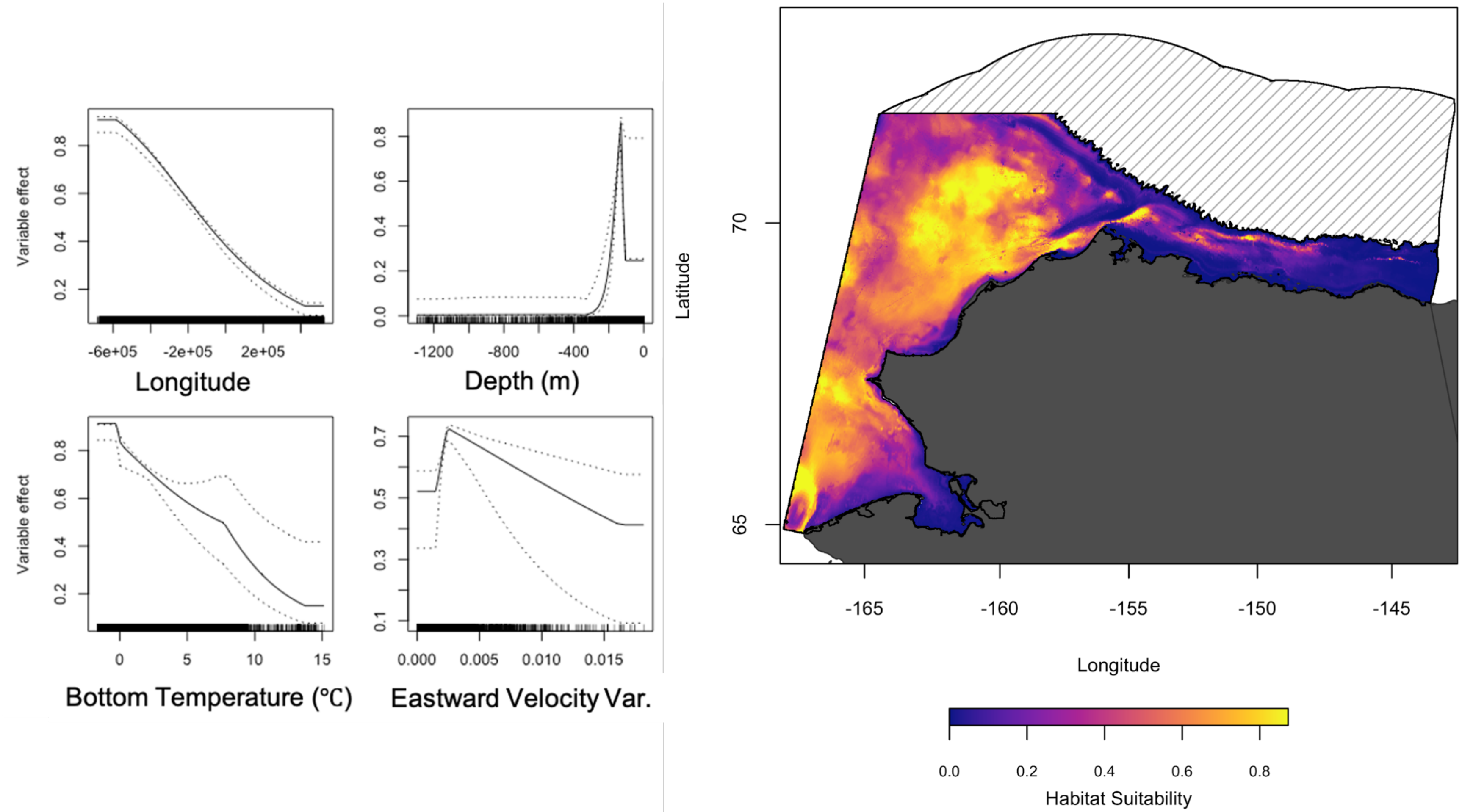



**Figure 18.** Response curves for the four most influential habitat covariates in the MaxEnt model predicting probability of suitable habitat (left panel) and predicted distribution of probability of suitable habitat for immature snow crab (right panel).

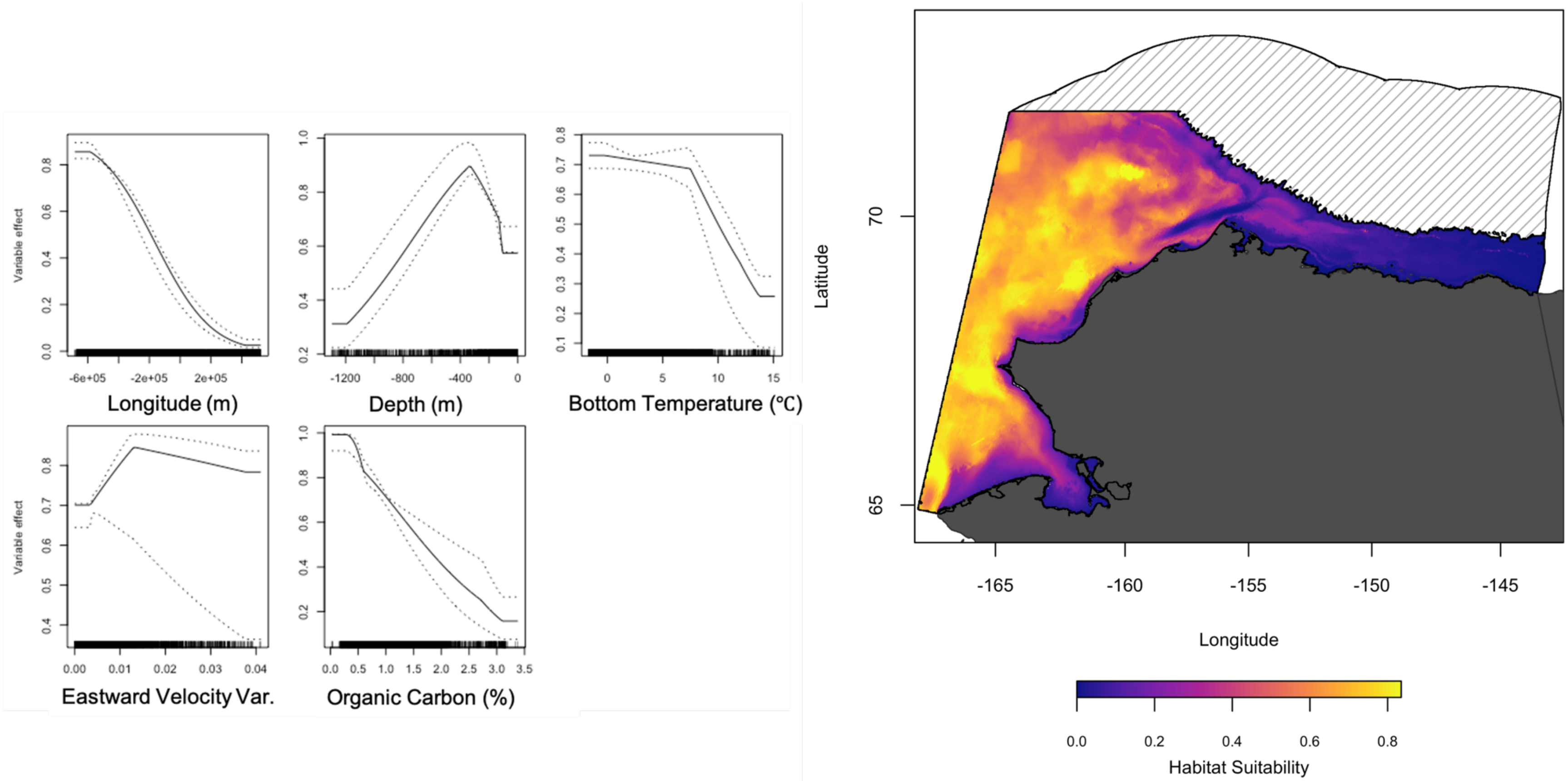
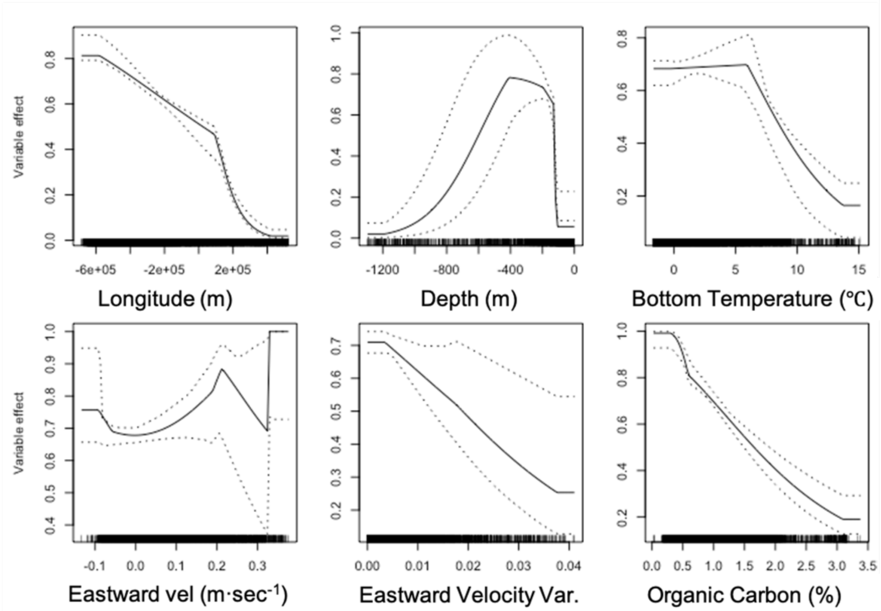



**Figure 19.** Response curves for the four most influential habitat covariates in the MaxEnt model predicting probability of suitable habitat (left panel) and predicted distribution of probability of suitable habitat for adolescent female snow crab (right panel).



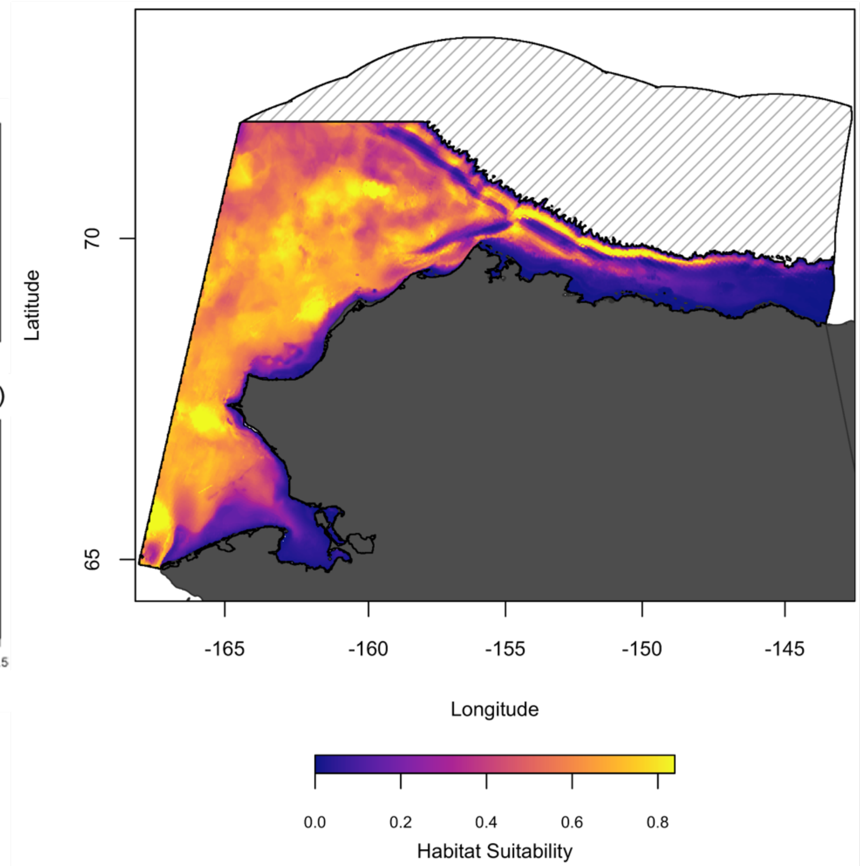




**Figure 20.** Response curves for the four most influential habitat covariates in the MaxEnt model predicting probability of suitable habitat (left panel) and predicted distribution of probability of suitable habitat for adolescent male snow crab (right panel).

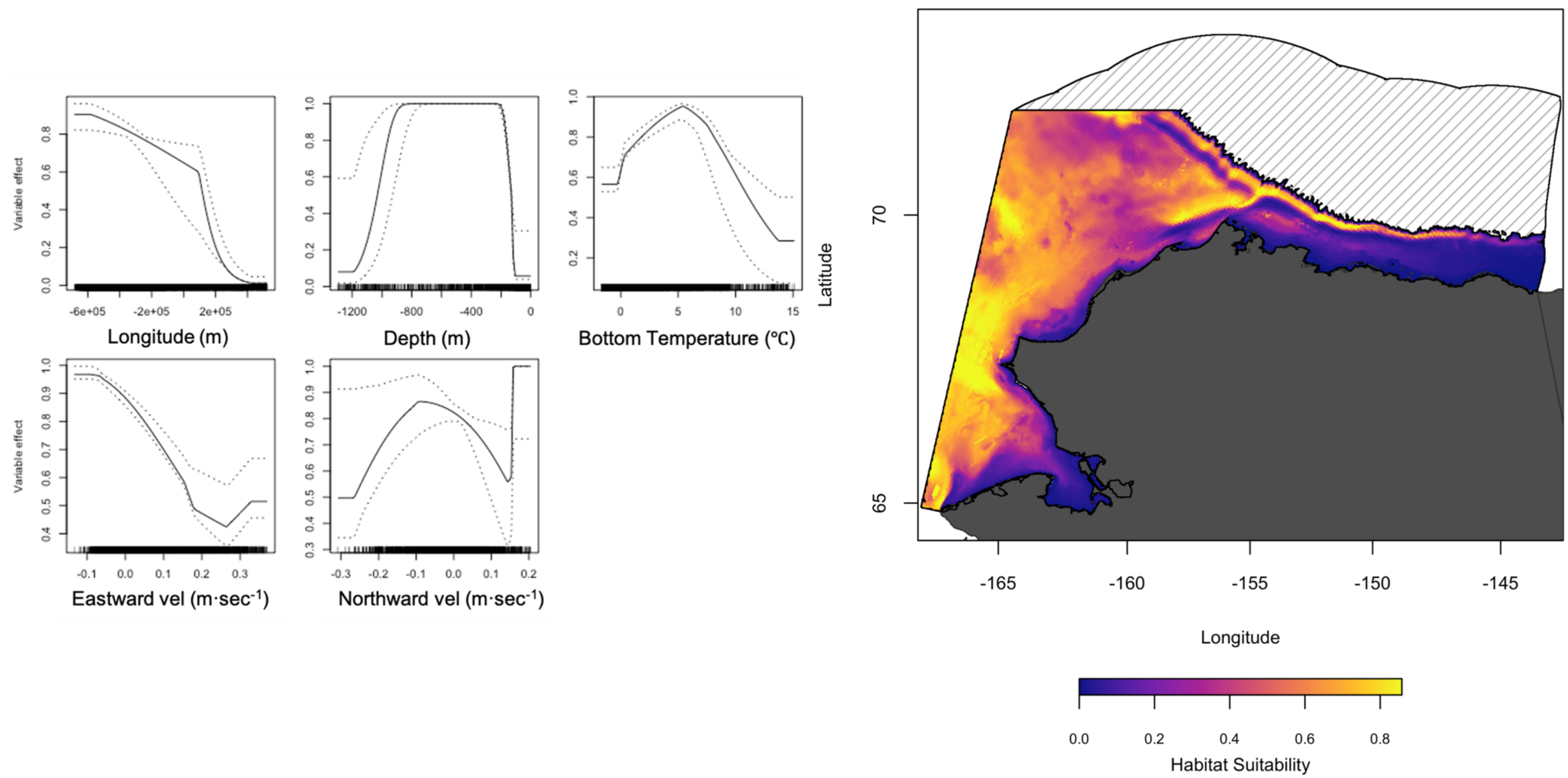



**Figure 21.** Response curves for the four most influential habitat covariates in the MaxEnt model predicting probability of suitable habitat (left panel) and predicted distribution of probability of suitable habitat for mature female snow crab (right panel).

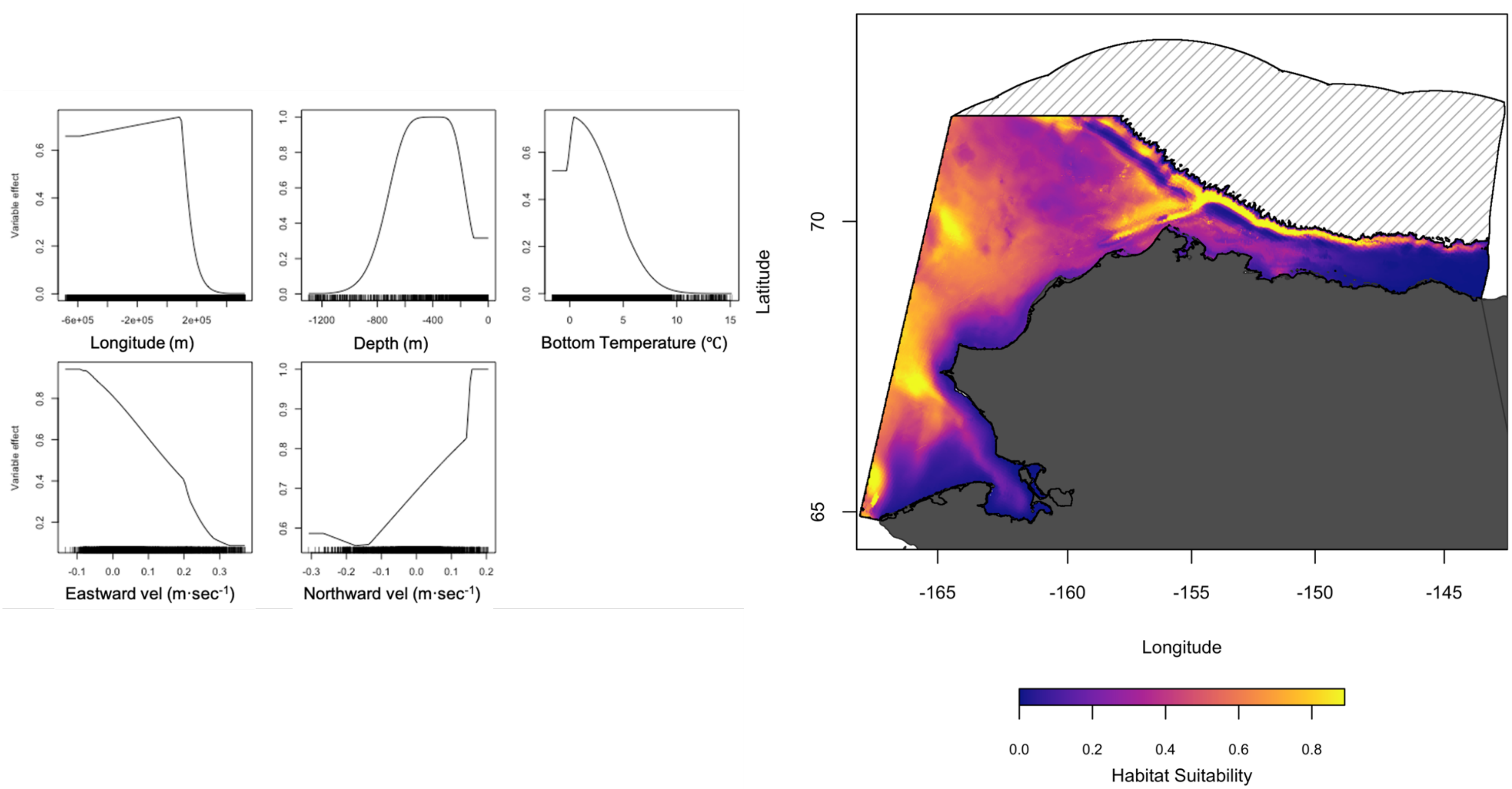



**Figure 22.** Response curves for the four most influential habitat covariates in the MaxEnt model predicting probability of suitable habitat (left panel) and predicted distribution of probability of suitable habitat for mature male snow crab (right panel).

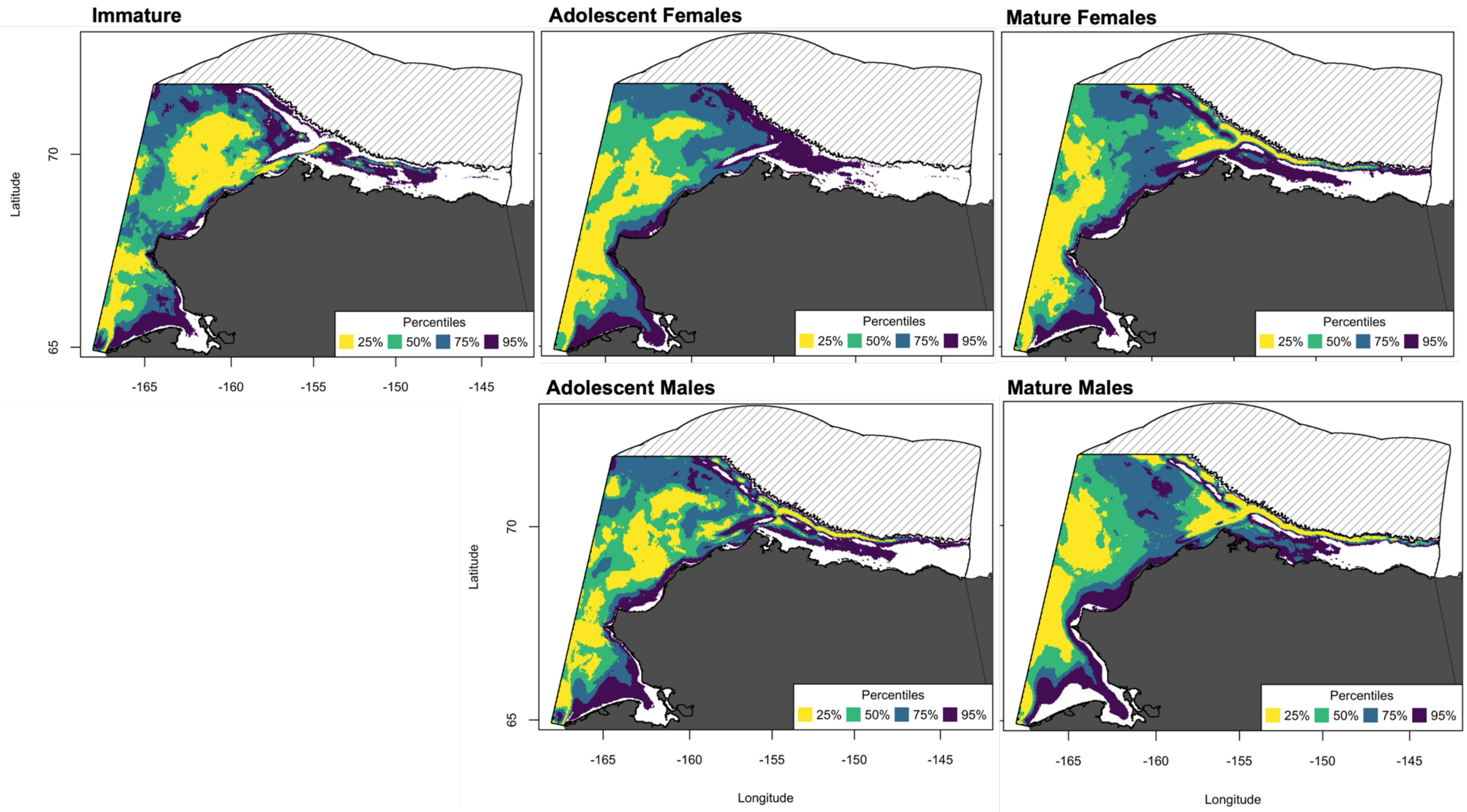



**Figure 23.** Essential fish habitat for immature, adolescent, and mature snow crab.

### 3.4 Habitat Related Vital Rates

We used temperature dependent growth rate equations obtained from Laurel et al. (2016; 2017) to convert temperature rasters (all years, warm years, and cold years) to potential growth rate maps for age-0 and juvenile Arctic cod and for juvenile saffron cod (**Figure 24** column 1). For juvenile saffron cod, potential growth rate was highest in the southern Chukchi Sea, primarily along the coast, where the water was warmest. Potential growth rates were low in the northern Chukchi Sea and Beaufort Sea. Juvenile Arctic cod had higher potential growth rates than saffron cod over much of the Chukchi Sea and Beaufort Sea with the highest rates in the southern Chukchi Sea and in coastal waters. We multiplied probability of suitable habitat (**Figure 8**, **Figure 9**, and **Figure 14**) by the potential growth rate in each grid cell to highlight potential areas of high production (**Figure 24** column 2). High productivity primarily reflects the high estimated probability of suitable habitat for Arctic cod as the areas with high growth potential in the southern Chukchi Sea have low probability of suitable habitat. In contrast, areas of high growth potential for saffron cod coincide with areas of high suitable habitat, resulting in a similar pattern of high productivity along the coast of the southern Chukchi Sea.

We compared potential growth rates during warm and cold conditions and mapped the difference between warm and cold years for age-0 Arctic cod, juvenile Arctic cod, and juvenile saffron cod (**Figure 25**). Warm years were associated with higher potential growth rates of age-0 and juvenile Arctic cod on the northern Chukchi Shelf and over much of the Beaufort Sea, particularly for age-0 Arctic cod (**Figure 25** rows 1 and 2). Only some nearshore areas in Kotzebue Sound were associated with a higher growth potential for Arctic cod in cold years. The growth potential of juvenile saffron cod was higher in warm years over much of the Chukchi Sea, particularly in nearshore areas, but remained unchanged in the northern Chukchi Sea and Beaufort Sea (**Figure 25** row 3). There were no areas of higher growth for juvenile saffron cod in cold years.

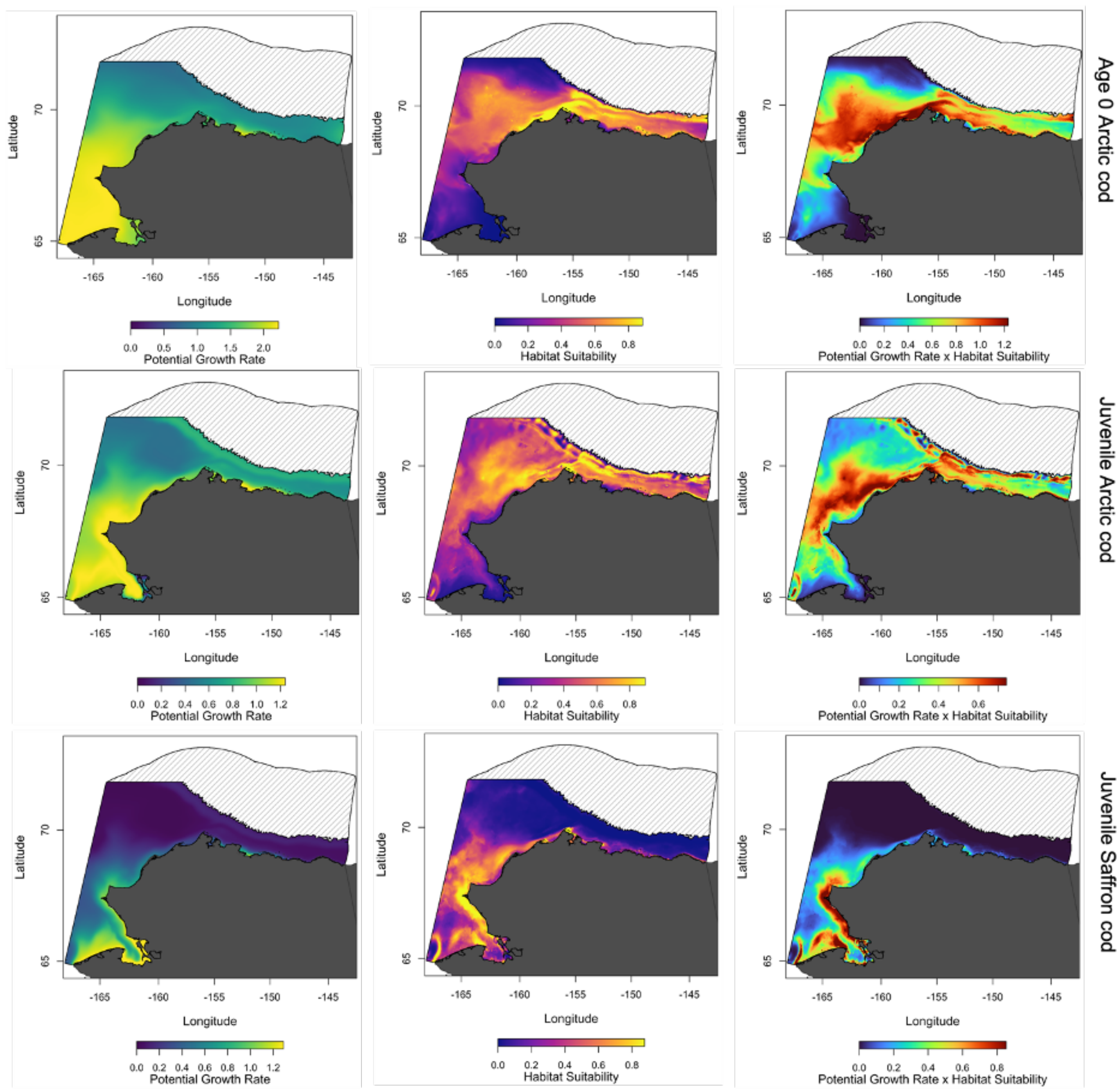



**Figure 24.** Potential growth rates, habitat suitability and areas of potential high productivity for age-0 and juvenile Arctic cod and juvenile saffron cod.

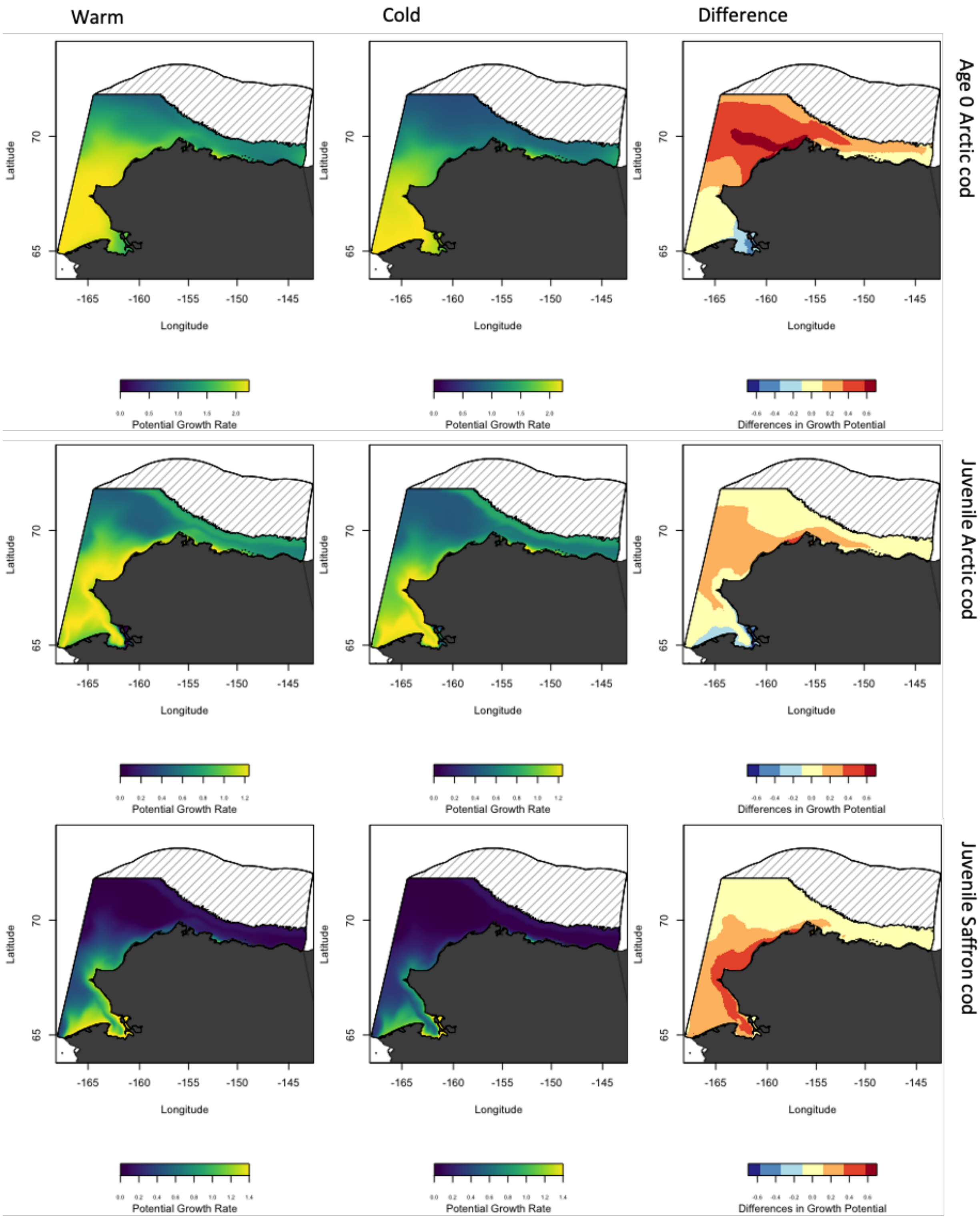



**Figure 25.** Potential growth rates for age-0 Arctic cod (top), juvenile Arctic cod (middle) and juvenile saffron cod (bottom) during warm periods (left), cold periods (center) and the difference (right).

## 3.5 Temporal Shifts under Warm and Cold Conditions

In warm years, surface and bottom temperatures along the coast and surface temperatures over much of the northern Chukchi Sea continental shelf were 2 – 3 °C warmer than in cold years due to atmospheric warming and advection of warmer water from the Pacific (**Figure 26** and **Figure 27**). This also resulted in higher minimum temperatures north of the Bering Strait. Warmer years were associated with stronger northward and eastward velocities of surface waters over much of the Chukchi Sea shelf and through Barrow Canyon, as well as stronger eastward and northward flow at the bottom throughout the region, suggesting a higher inflow of Pacific waters into the Arctic. One exception was the enhanced southward and westward flow of bottom waters in Barrow Canyon during warm years, suggesting enhanced upwelling of Arctic waters through Barrow Canyon.

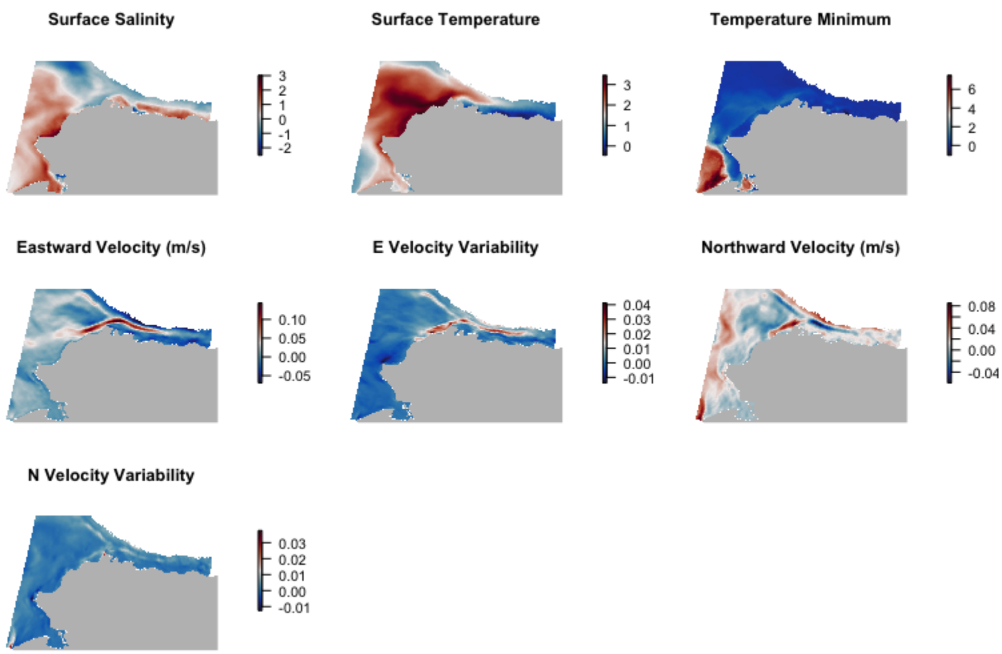



**Figure 26.** Differences between warm and cold periods for near surface habitat covariates.

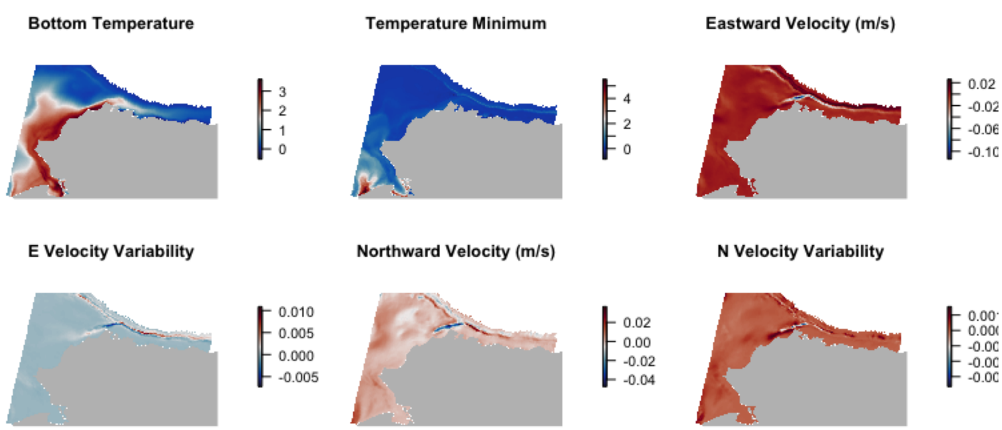



**Figure 27.** Differences between warm and cold periods for near bottom habitat covariates.

### *3.5.1 Arctic Cod*

In warm years Arctic cod appear to be pushed offshore, particularly in the northeast Chukchi Sea, possibly because nearshore waters are too warm (**Figure 28**). Habitat suitability of larval and age-0 stages increases in warm years on the northern portion of the Chukchi Sea shelf and along the outer Beaufort Sea shelf, consistent with enhanced transport of early life stages from the south in warm years (**Table 8**). Early life stages of Arctic cod are more sensitive to temperature changes and had larger fluctuations in the area of suitable habitat between warm and cold years. There was a minimal difference in the probability of suitable habitat for mature Arctic cod between warm and cold years. EFH maps of Arctic cod life stages in warm and cold years also illustrate these spatial differences in suitable habitat area (**Figure A14 – Figure A17**).

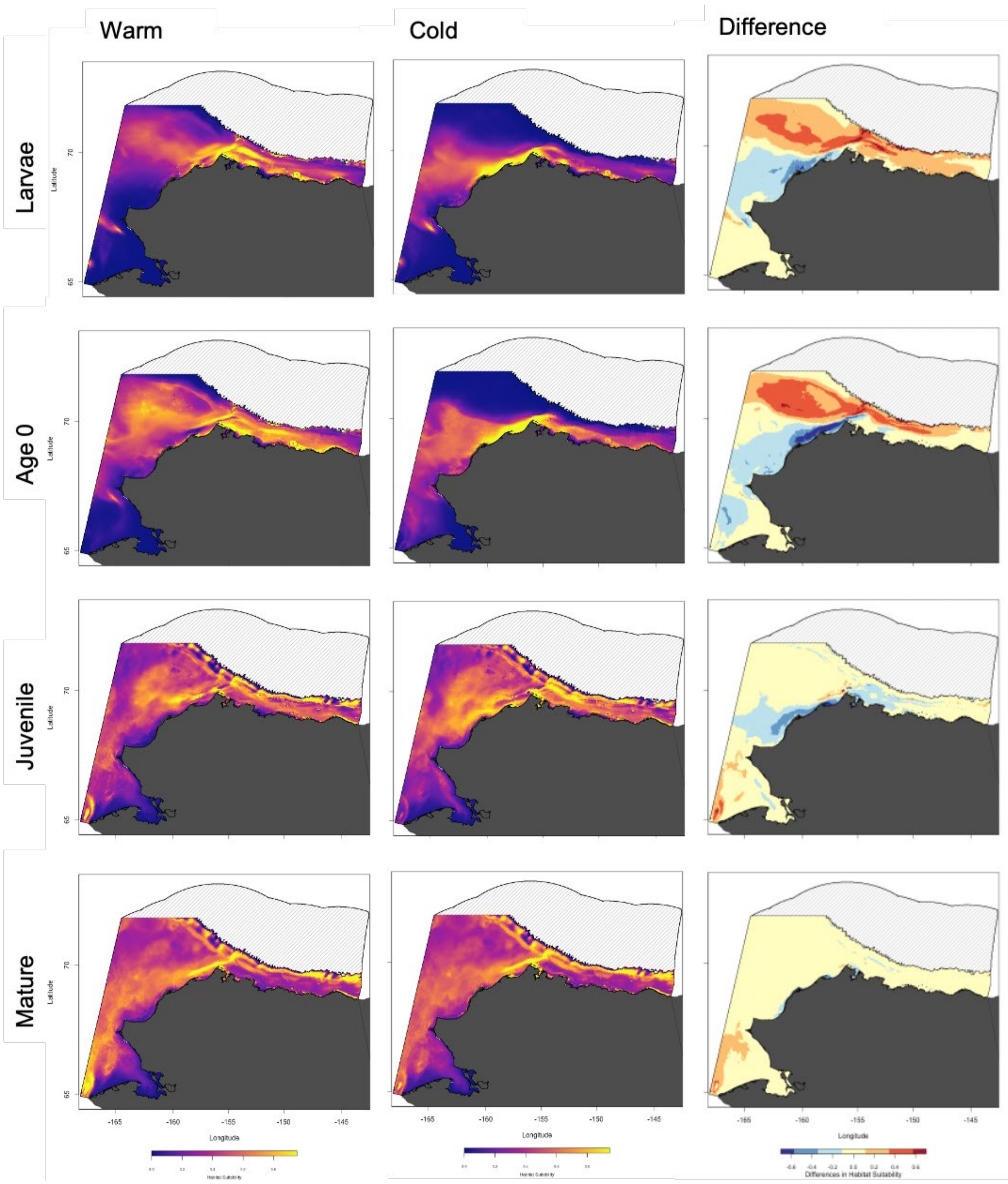



**Figure 28.** Arctic cod habitat suitability during warm and cold periods and the difference. In right panel, red (blue) denotes higher probability of suitable habitat in warm (cold) years.

### 3.5.2 *Saffron Cod*

In warm years, older life stages of saffron cod spread out further from the coast in the southern and central Chukchi Sea and the area of suitable habitat increases (**Figure 29**). In cold years, there was an increase in habitat for larval and age-0 saffron cod along northern Chukchi Sea coast (**Table 8**). In contrast to Arctic cod, mature saffron area of suitable habitat appears to be more sensitive to differences in temperature. EFH maps of saffron cod life stages in warm and cold years also illustrate these spatial differences in suitable habitat area (**Figure A18 – Figure A21**).

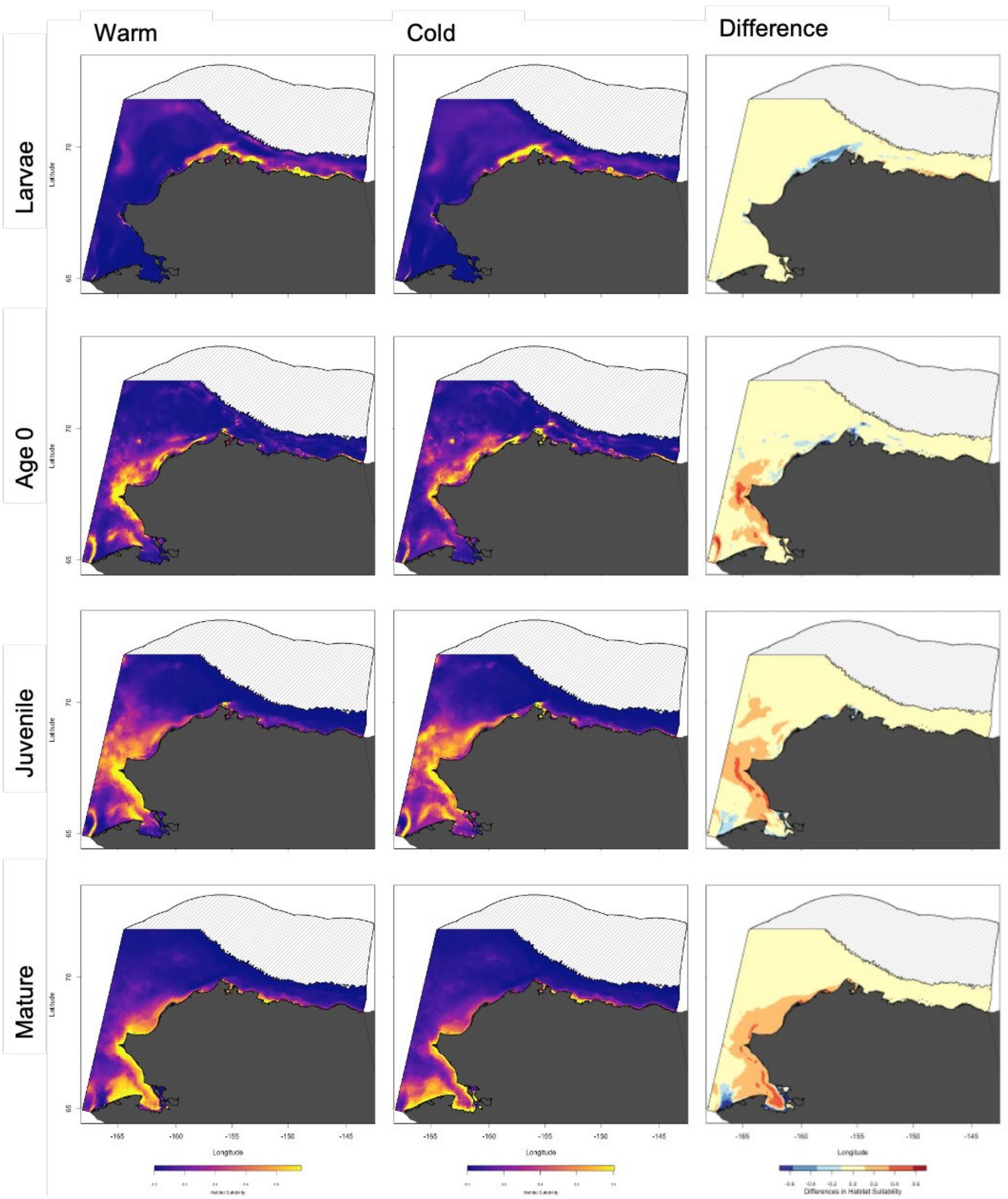



**Figure 29.** Saffron cod habitat suitability during warm and cold period and the difference. In right panel, red (blue) denotes higher probability of suitable habitat in warm (cold) years.

### *3.5.3 Snow Crab*

Differences in habitat suitability for snow crab between warm and cold years were moderate compared to the two cod species. For immature and adolescent snow crab there was an increase in suitable habitat in cold years along the Chukchi Sea coast (**Figure 30**, **Table 8**). Habitat suitability of immature crab increased during warm conditions from Bering Strait north to Point Hope. For mature male snow crab, temperature was an influential predictor of habitat suitability and the highest suitability occurred over a narrow range of cooler temperatures (**Figure 22**). As a consequence, they showed the largest changes in the probability of suitable habitat, which increased on the northern shelf during warm years and increased along the central Chukchi Sea coast during cold years. EFH maps of snow crab life stages in warm and cold years also illustrate these spatial differences in suitable habitat area (**Figure A22** – **Figure A26**).

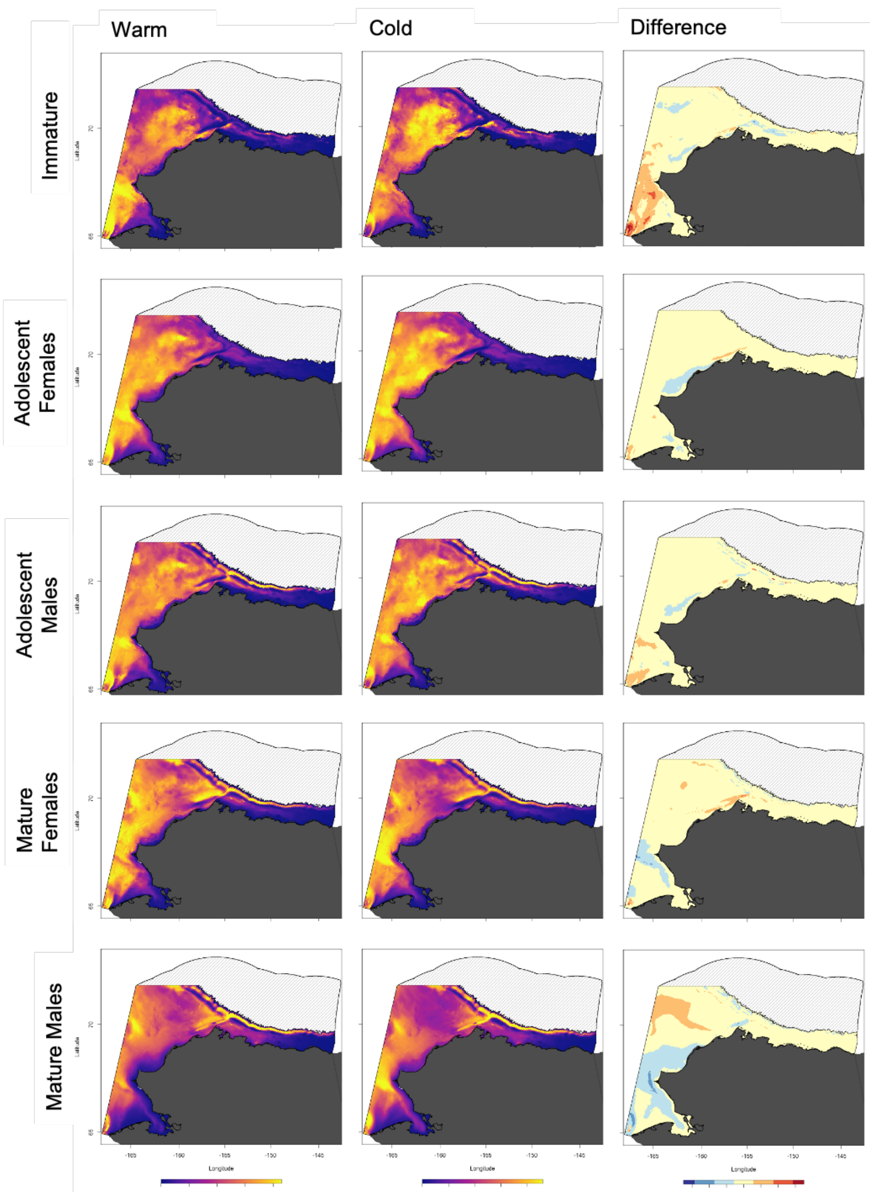



**Figure 30.** Snow crab habitat suitability during warm and cold periods and the difference. In right panel, red (blue) denotes higher probability of suitable habitat in warm (cold) years.

**Table 8.** Model-based estimates of EFH area ($km^2$) during warm and cold years and the difference in area (parentheses indicate an increase in area).

| Species - Life stage | Warm Years EFH Area ($km^2$) | Cold Years EFH Area ($km^2$) | Difference EFH Area ($km^2$) |
|---|---|---|---|
| Arctic cod – Larvae | 215,284 | 185,208 | 30,076 |
| Arctic cod – Age-0 | 232,133 | 197,371 | 34,762 |
| Arctic cod – Juvenile | 262,200 | 265,769 | (3,569) |
| Arctic cod – Mature | 269,458 | 271,955 | (2,497) |
| Saffron cod – Larvae | 167,872 | 208,107 | (40,235) |
| Saffron cod – Age-0 | 160,931 | 175,222 | (14,291) |
| Saffron cod – Juvenile | 162,924 | 161,206 | 1,718 |
| Saffron cod – Mature | 163,412 | 148,162 | 15,250 |
| Snow crab – Immature | 226,955 | 226,325 | (1,425) |
| Snow crab – Adolescent Female | 237,200 | 238,227 | (1,027) |
| Snow crab – Adolescent Male | 240,032 | 241,253 | (1,221) |
| Snow crab – Mature Female | 238,068 | 241,142 | (3,074) |
| Snow crab – Mature Male | 233,088 | 248,007 | (14,919) |

# 4 CONCLUSIONS AND FUTURE RECOMMENDATIONS

Increases in data availability from numerous surveys conducted since 2009 and advances in species distribution modeling allowed us to update and substantially refine EFH descriptions and maps for three species by life stage in the Alaskan Chukchi Sea and Beaufort Sea. Model performance was acceptable or good in all cases, suggesting that our models provide an adequate basis for updated EFH descriptions for the target species. Moreover, the available data support the development of separate SDMs for warm and cold conditions as a first step towards more temporally dynamic EFH descriptions. Finally, we showed that estimates of growth potential based on temperature-dependent growth rates from laboratory studies, where available, can be combined with SDMs to further improve habitat descriptions by estimating areas of relatively higher or lower habitat-related growth potential. In total our study developed 13 new EFH Level 1 SDM-based maps and three new EFH Level 3 maps with additional new information for the EFH sections of the Arctic FMP.

Temperature was an important habitat covariate for predicting the probability of suitable habitat for many of the life-stage species combinations. Early life stages of Arctic cod were more sensitive to temperature changes and had larger fluctuations in suitable habitat between warm and cold years. The area of suitable habitat decreased for Arctic cod in warm years and increased in cold years indicating climate warming may limit their distribution in the Chukchi Sea. Like early life stages of Arctic cod, larval saffron cod were limited to cooler temperatures. For all older life stages of saffron cod, habitat suitability increased with temperature and were consistent with laboratory growth studies from Laurel et al. (2016). Suitable habitat was greatest during warm periods for age-0 saffron cod, but was similar for older life stages. For adolescent snow crab, temperature fluctuations had limited influence on changes in habitat suitability. Mature males snow crabs were the most sensitive to changes in temperatures. Overall, these results support the idea that saffron cod may have a competitive advantage over Arctic cod in the Chukchi Sea in warmer years. Arctic cod my shift their distribution northward as well as mature snow crab. These results support the importance of adding a temporal component to the EFH descriptions and maps, especially in a region experiencing rapid climate change.

As more surveys are conducted and more data becomes available future studies could include prey, predator or competitor species occurrence as potential explanatory variables. Predation pressure, prey availability and competition likely impact the distribution of these three ecologically important species (e.g., Marsh and Mueter 2019), especially if boreal gadids continue to shift northward (Hollowed et al. 2013, Fossheim et al. 2015, Thorsen et al. 2019). Pacific cod (*Gadus macrocephalus*) and walleye pollock (*G. chalcogrammus*) have been moving into the Alaskan Arctic (Stevenson and Lauth 2019, Marsh et al. 2020). The ecosystem in the Alaskan Arctic is changing, and this study demonstrates that future species distribution models for EFH should apply temporally dynamic mapping approaches.

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# APPENDIX 1 STANDARD DEVIATION OF THE PROBABILITY OF SUITABLE HABITAT FOR ARCTIC SPECIES LIFE STAGES

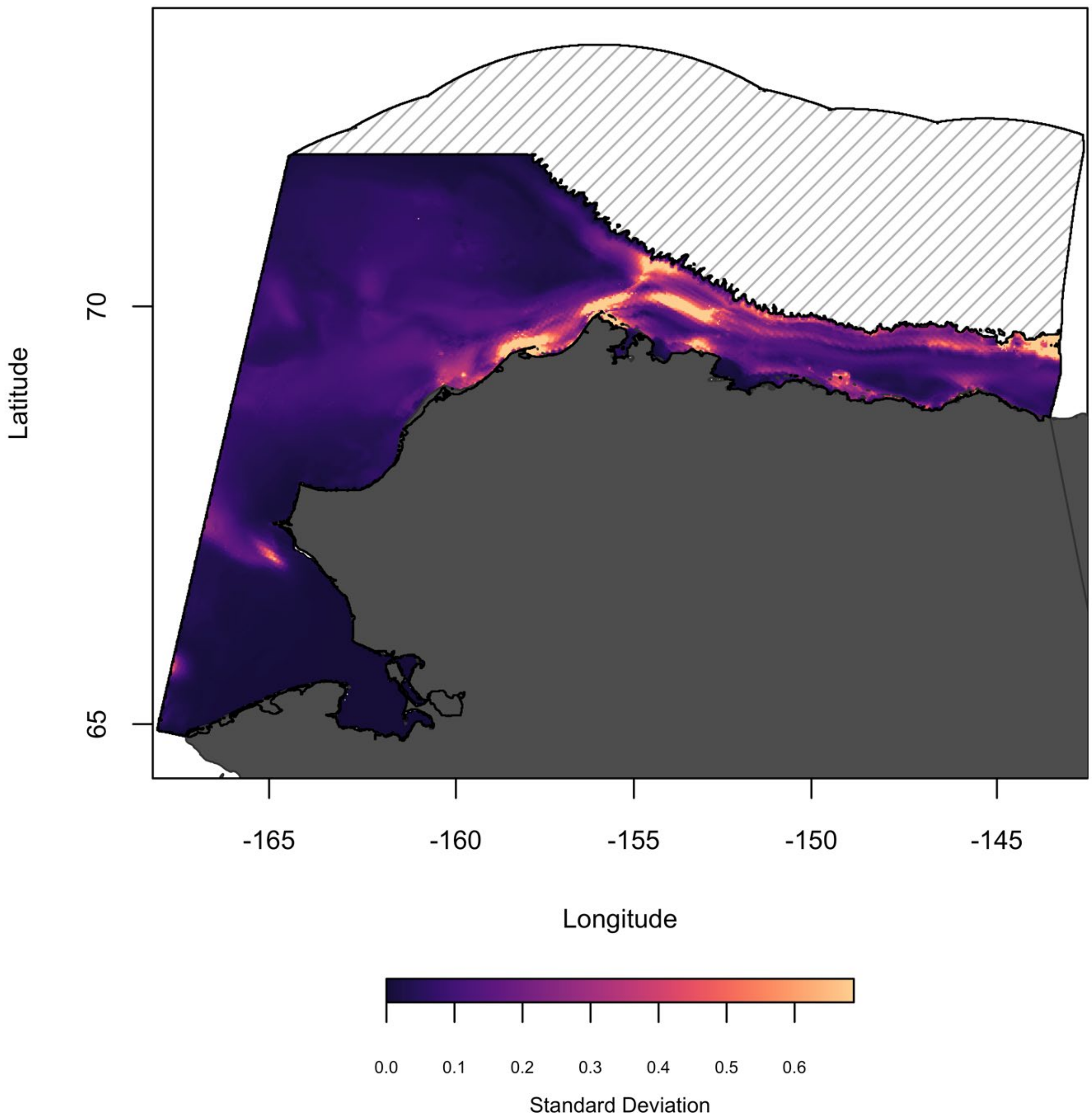


**Figure A1**. Standard deviation of the probability of suitable habitat for larval Arctic cod.

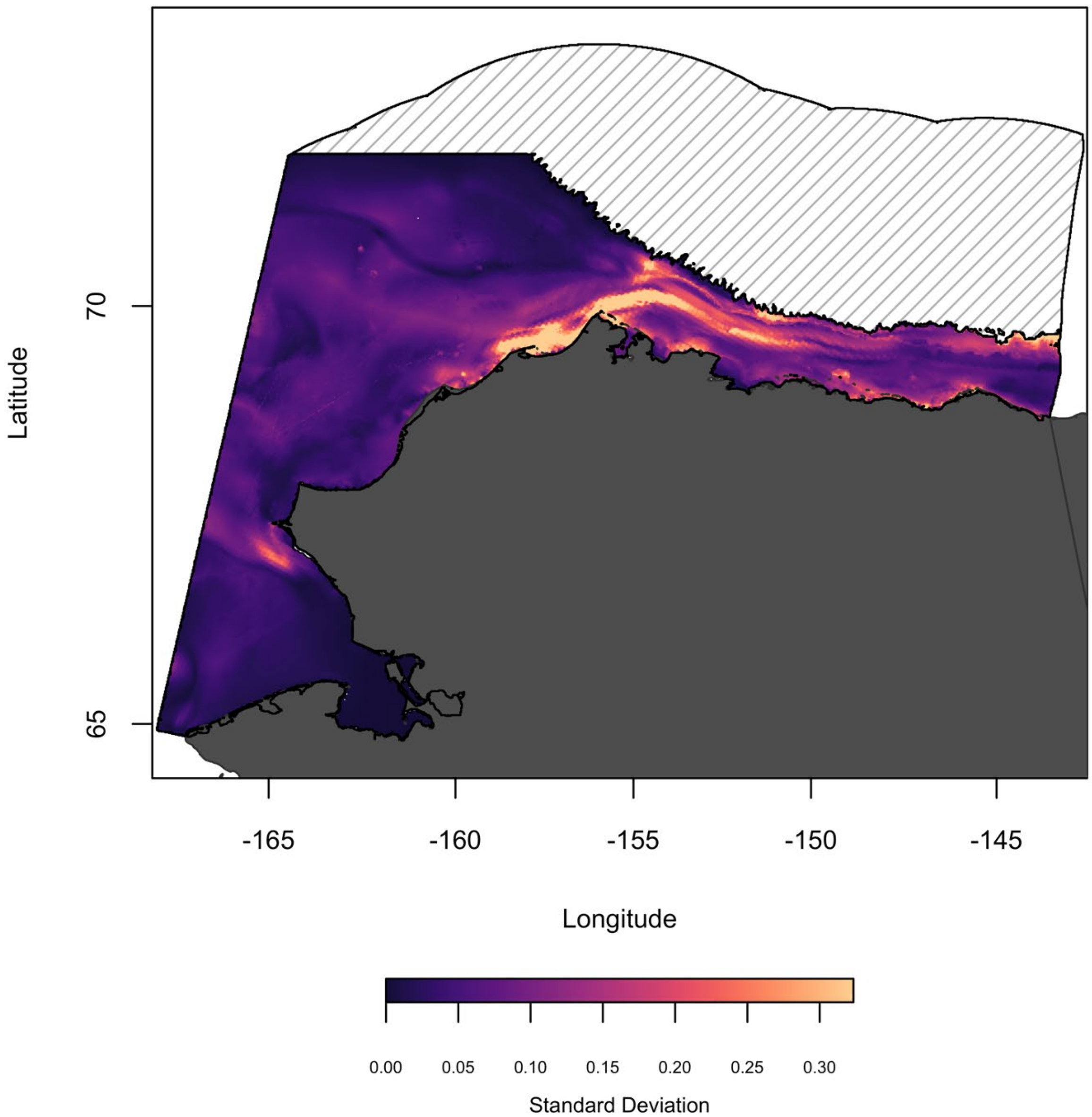


**Figure A2**. Standard deviation of the probability of suitable habitat for age-0 Arctic cod.

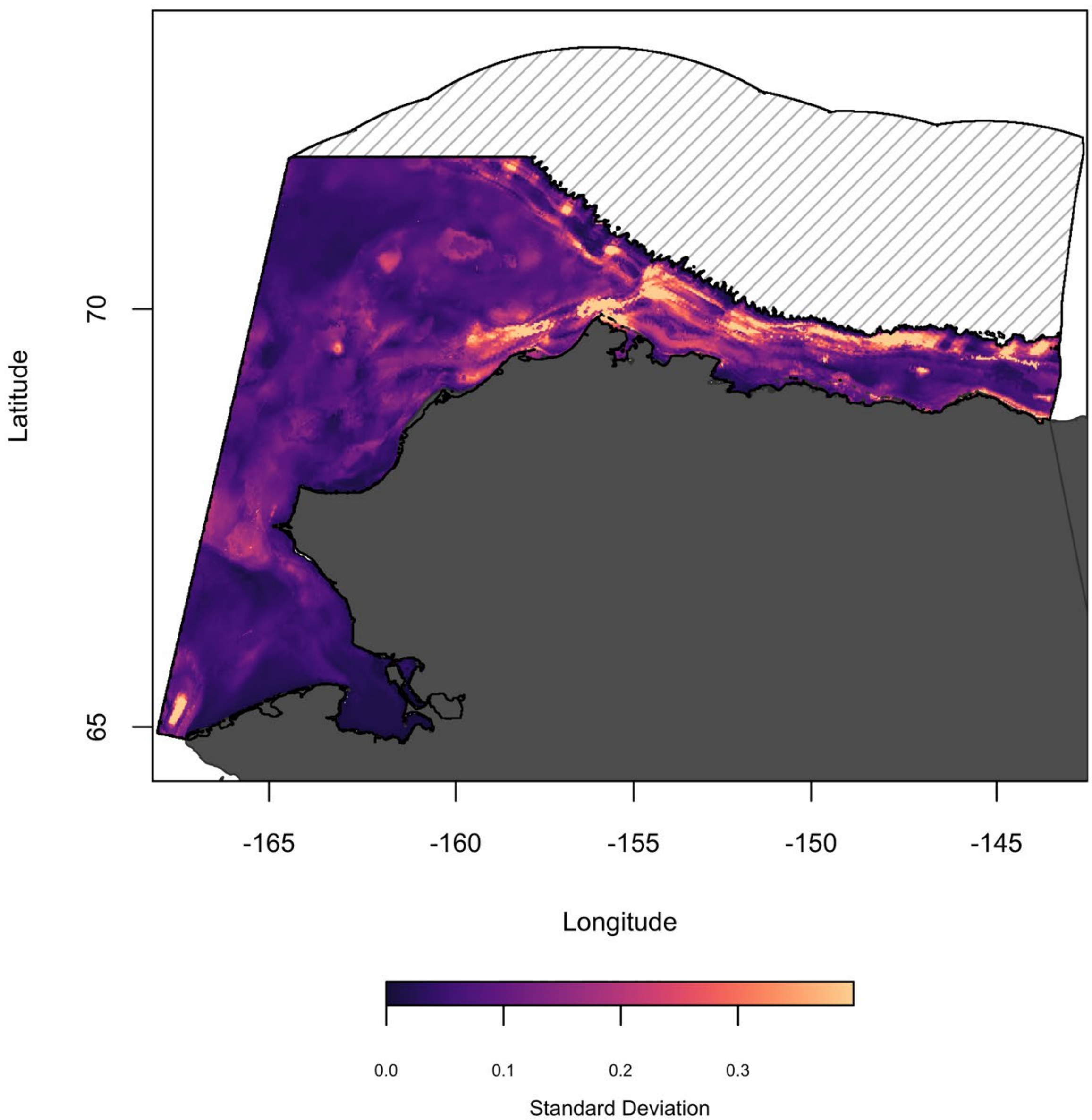


**Figure A3**. Standard deviation of the probability of suitable habitat for juvenile Arctic cod.

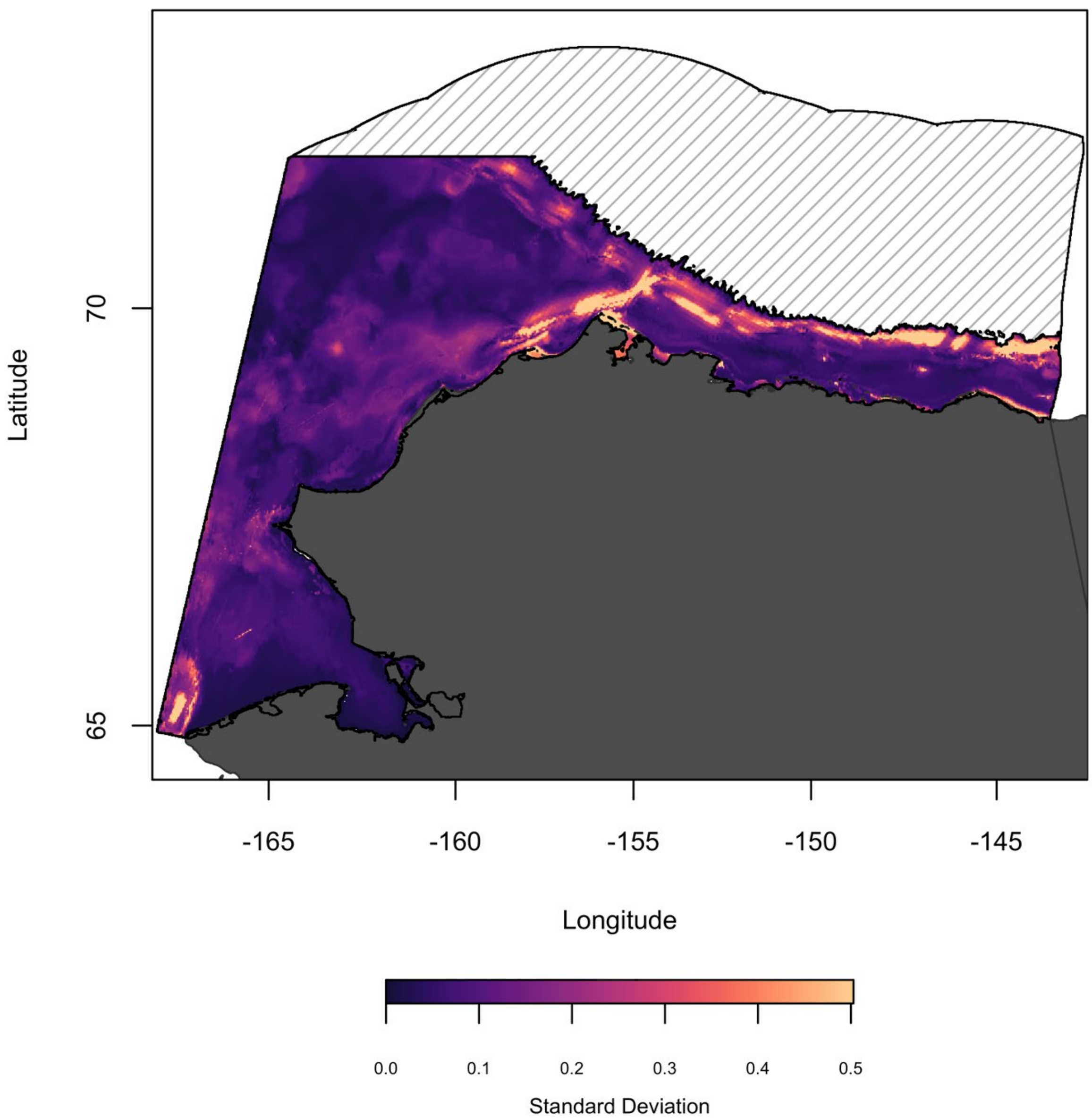


**Figure A4**. Standard deviation of the probability of suitable habitat for mature Arctic cod.

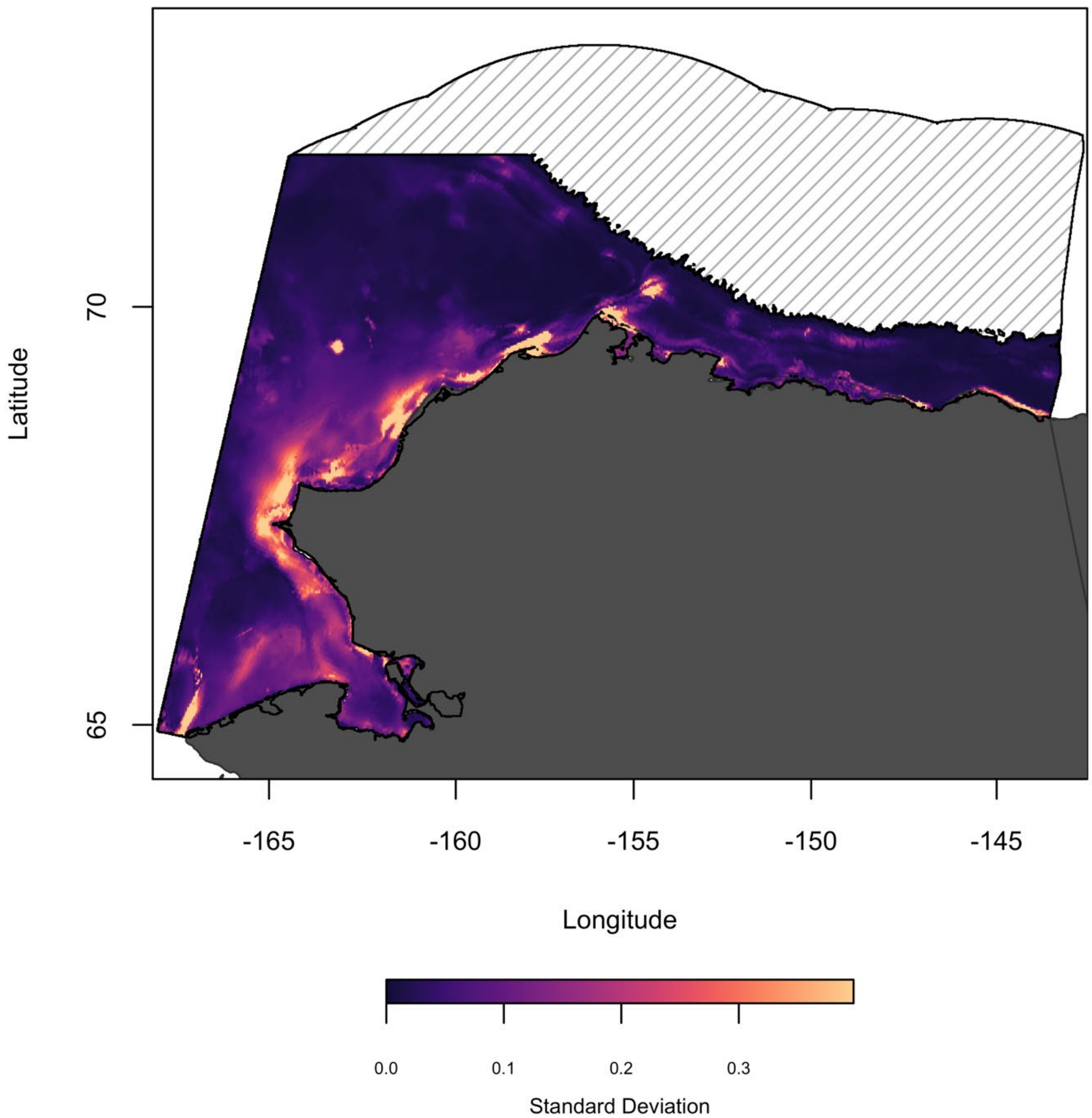


**Figure A5**. Standard deviation of the probability of suitable habitat for larval saffron cod.

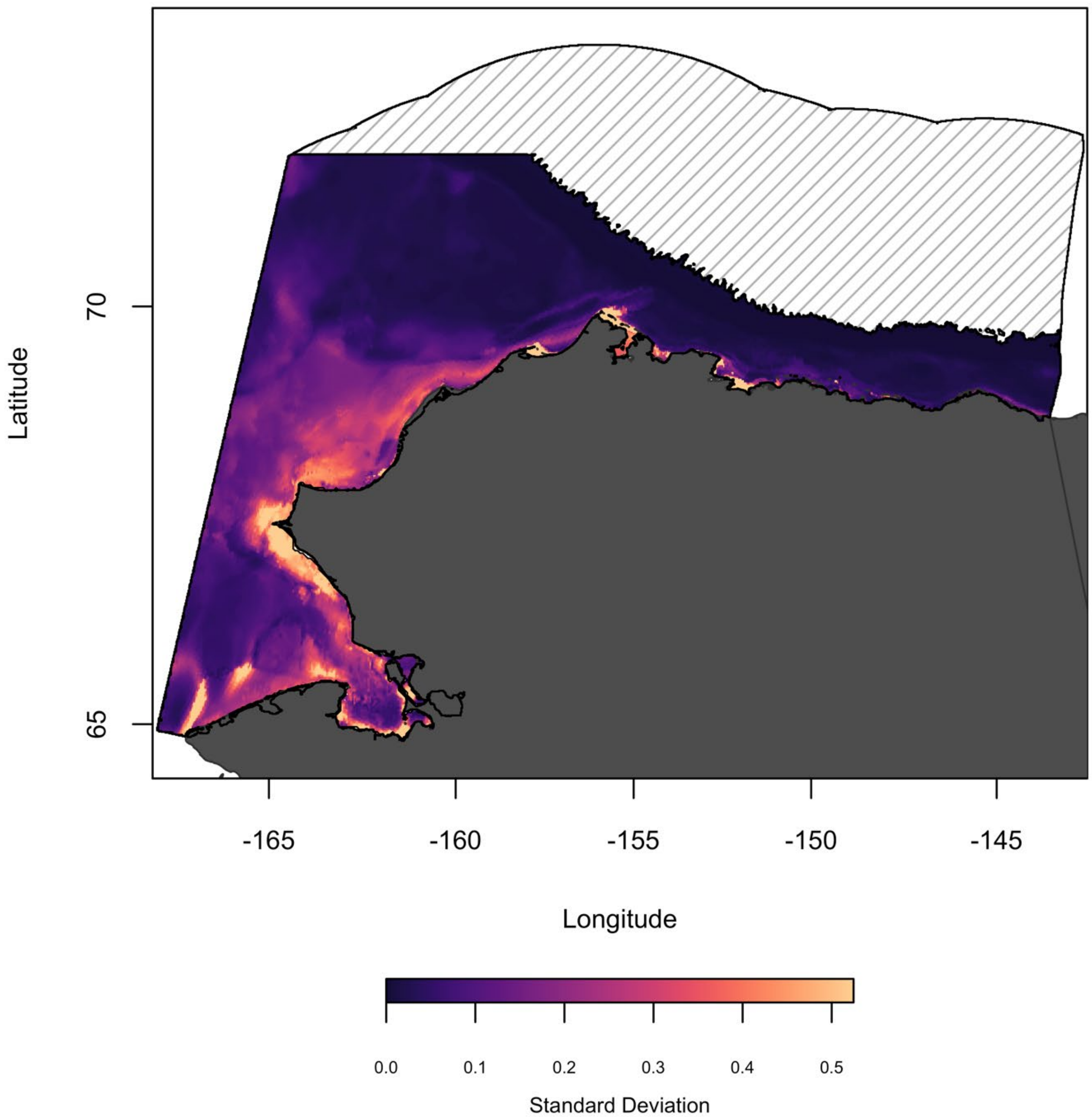


**Figure A6**. Standard deviation of the probability of suitable habitat for age-0 saffron cod.

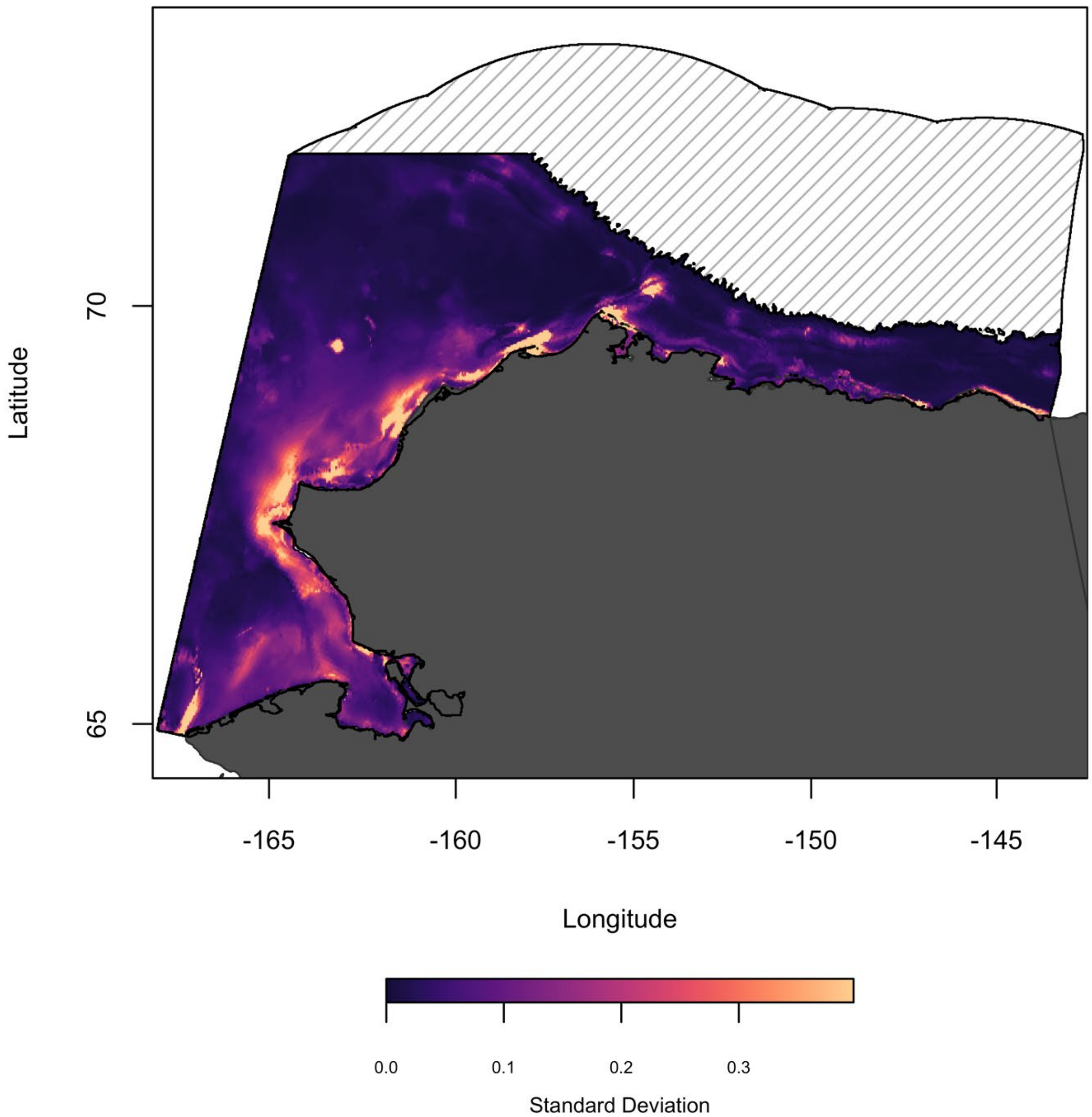


**Figure A7**. Standard deviation of the probability of suitable habitat for juvenile saffron cod.

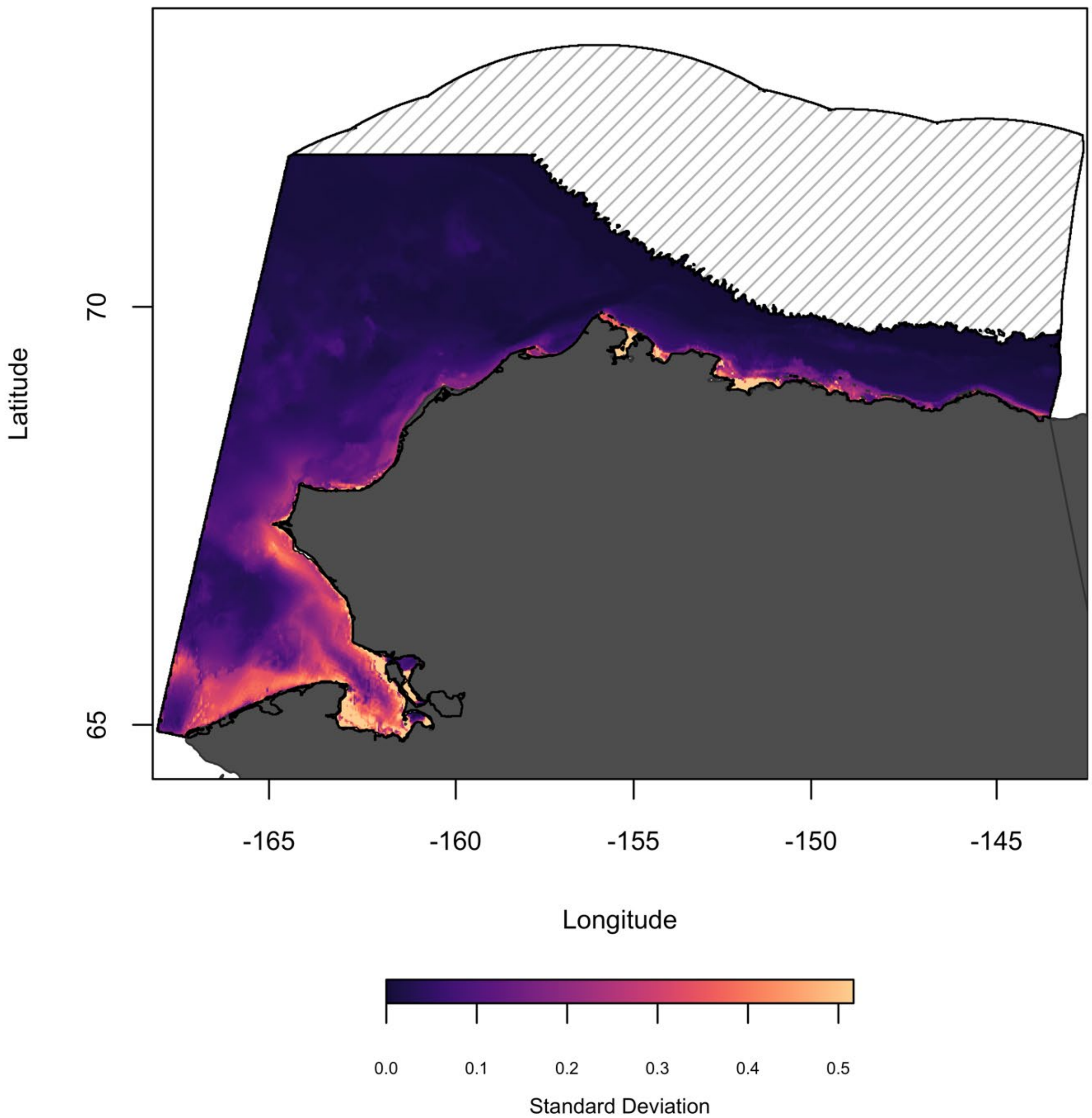


**Figure A8**. Standard deviation of the probability of suitable habitat for mature saffron cod.

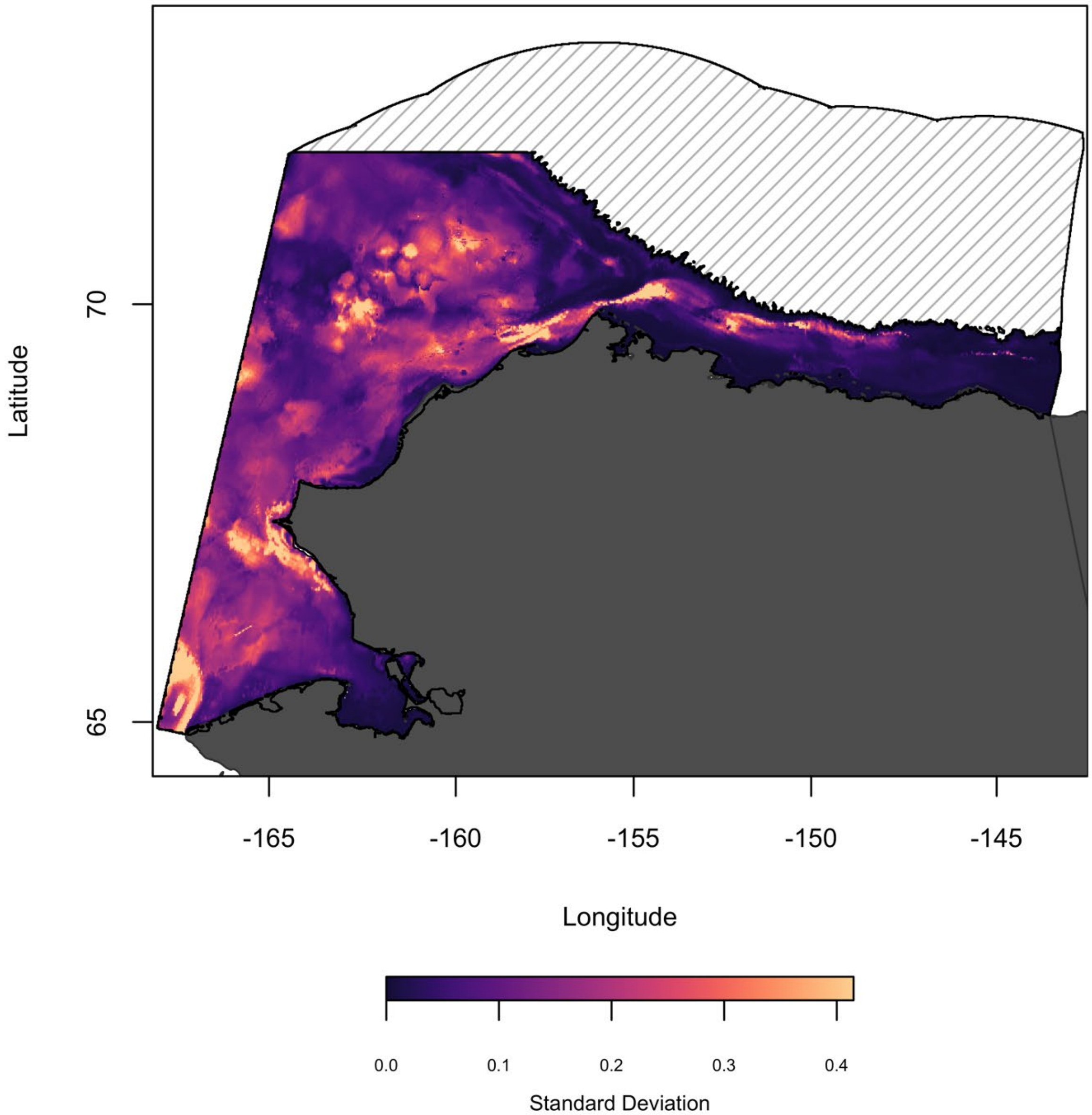


**Figure A9**. Standard deviation of the probability of suitable habitat for immature snow crab.

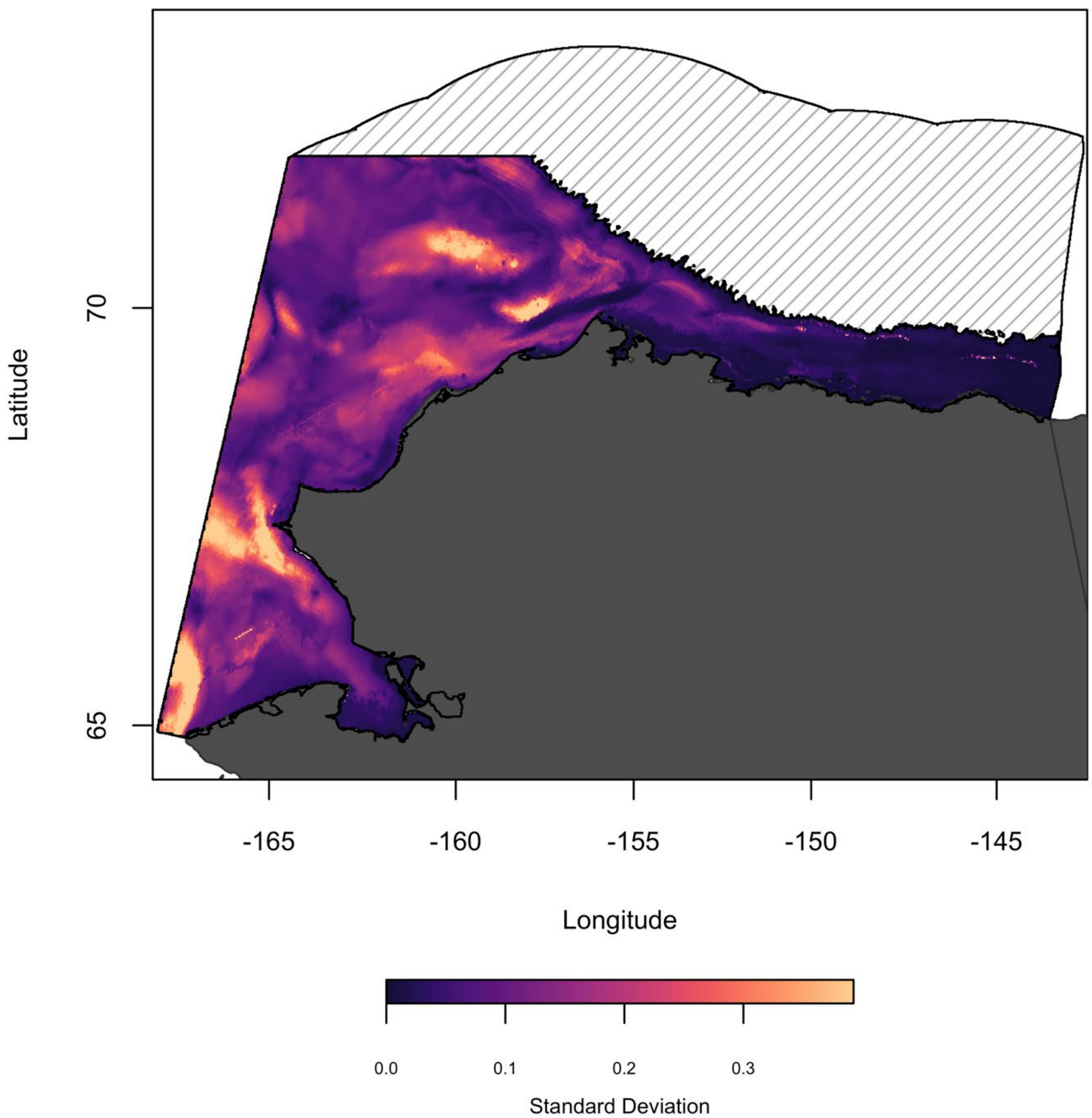


**Figure A10**. Standard deviation of the probability of suitable habitat for adolescent female snow crab.

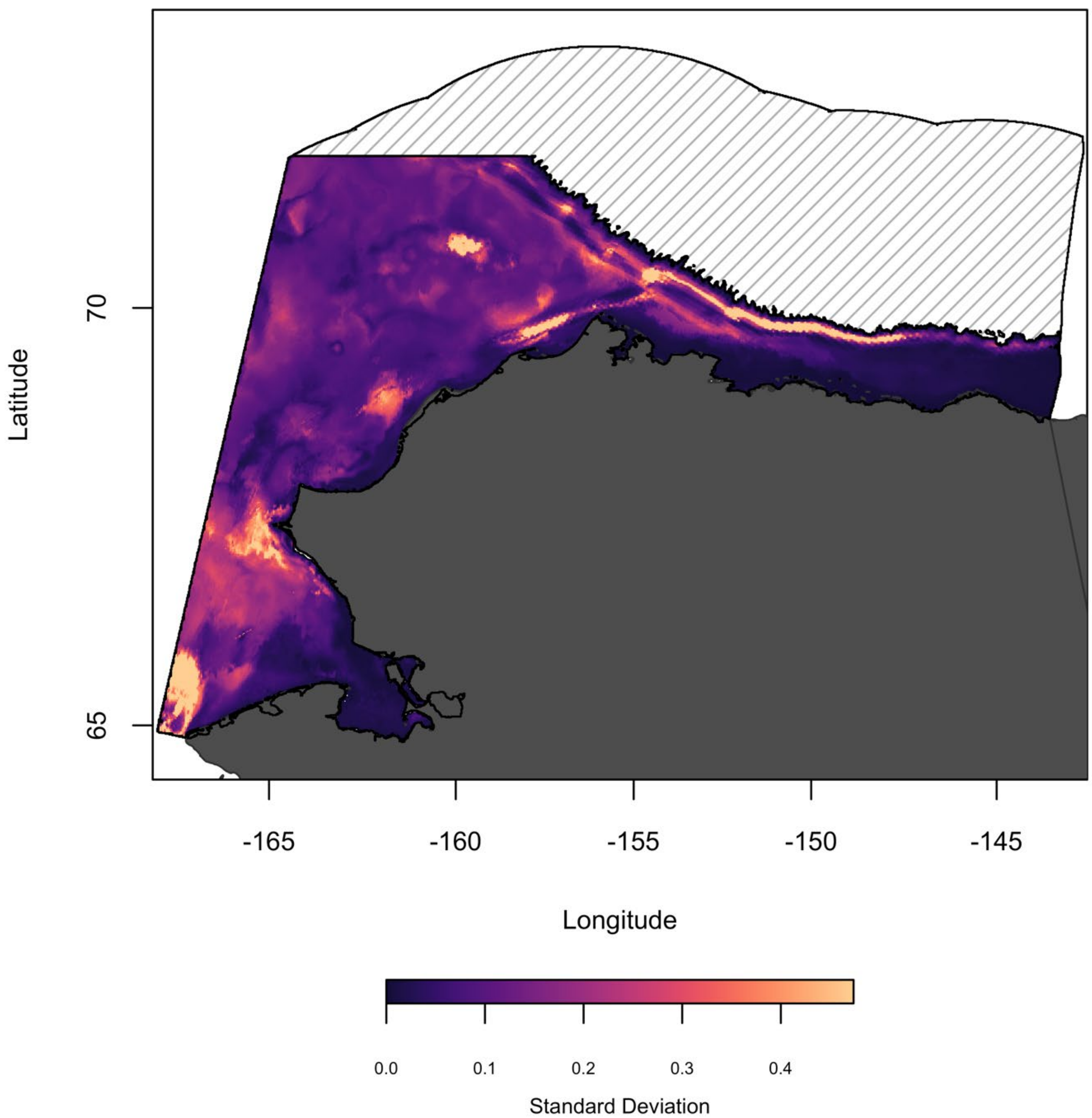


**Figure A11**. Standard deviation of the probability of suitable habitat for adolescent male snow crab.

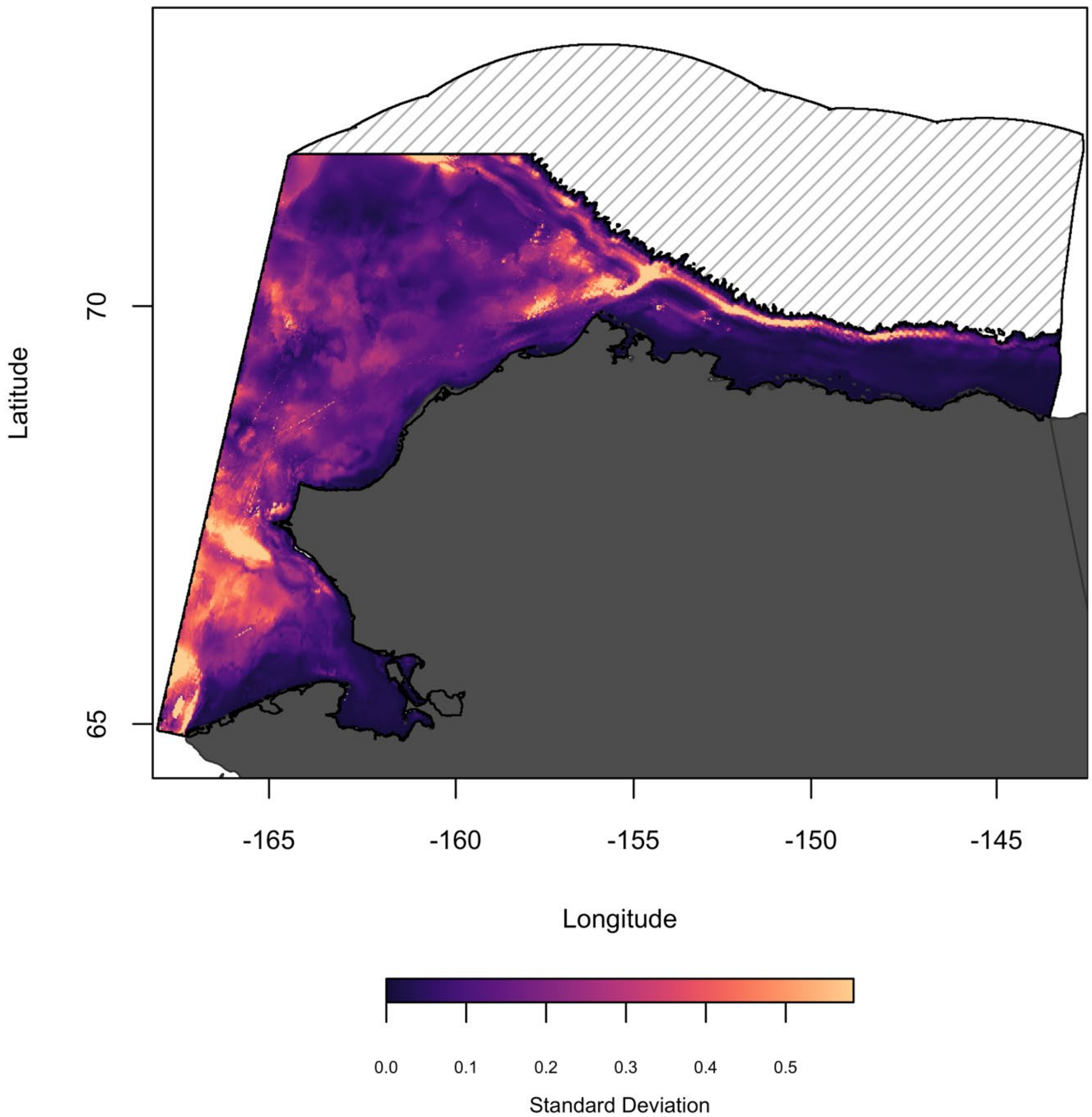


**Figure A12**. Standard deviation of the probability of suitable habitat for mature female snow crab.

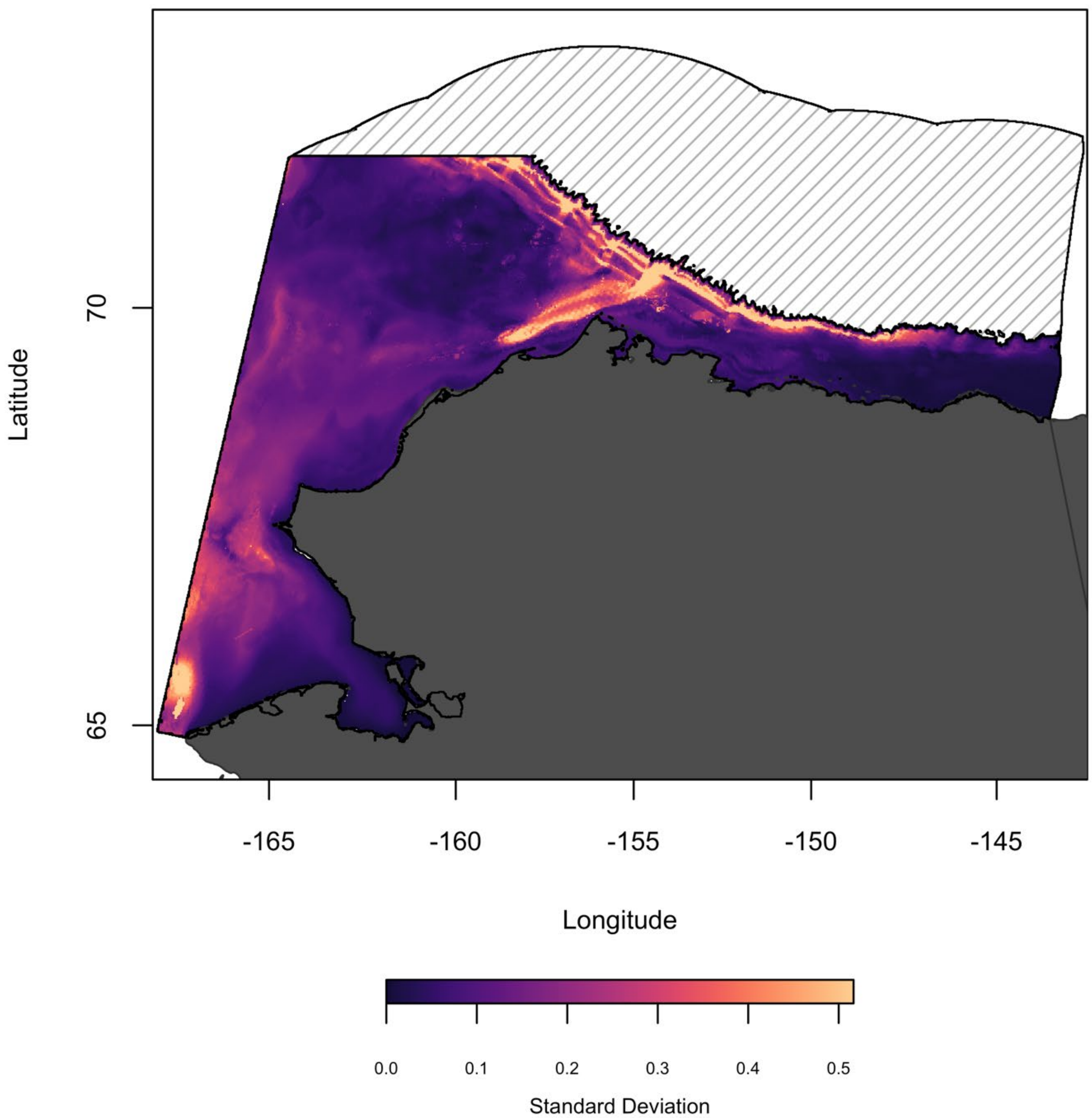


**Figure A13**. Standard deviation of the probability of suitable habitat for mature male snow crab.

# APPENDIX 2 EFH MAPS FOR WARM AND COLD PERIODS IN THE ARCTIC MANAGEMENT AREA

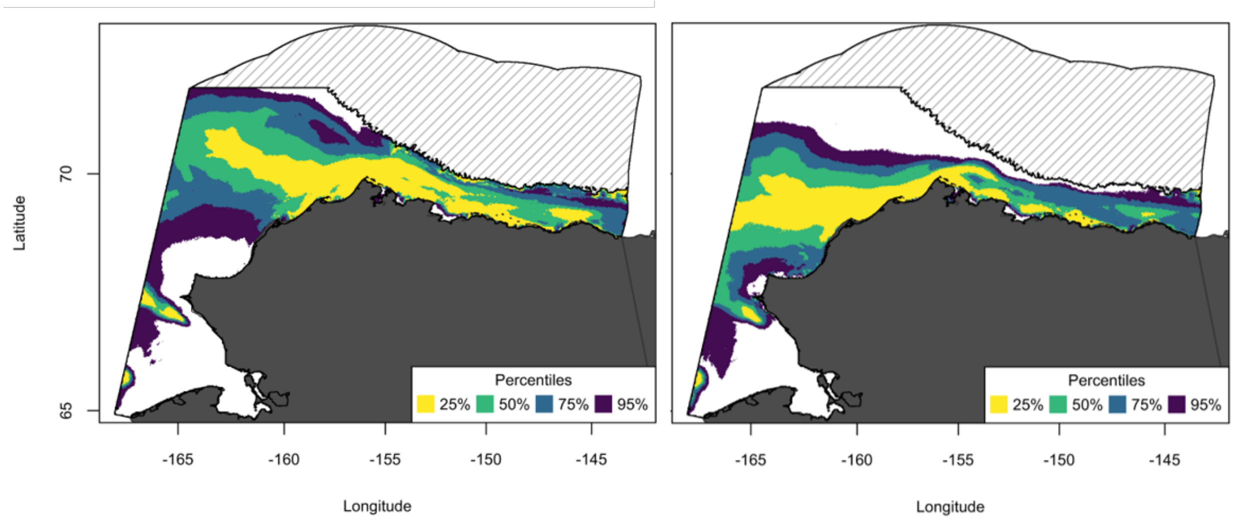


**Figure A14.** Essential fish habitat of larval Arctic cod in warm (left panel) and cold (right panel) years.

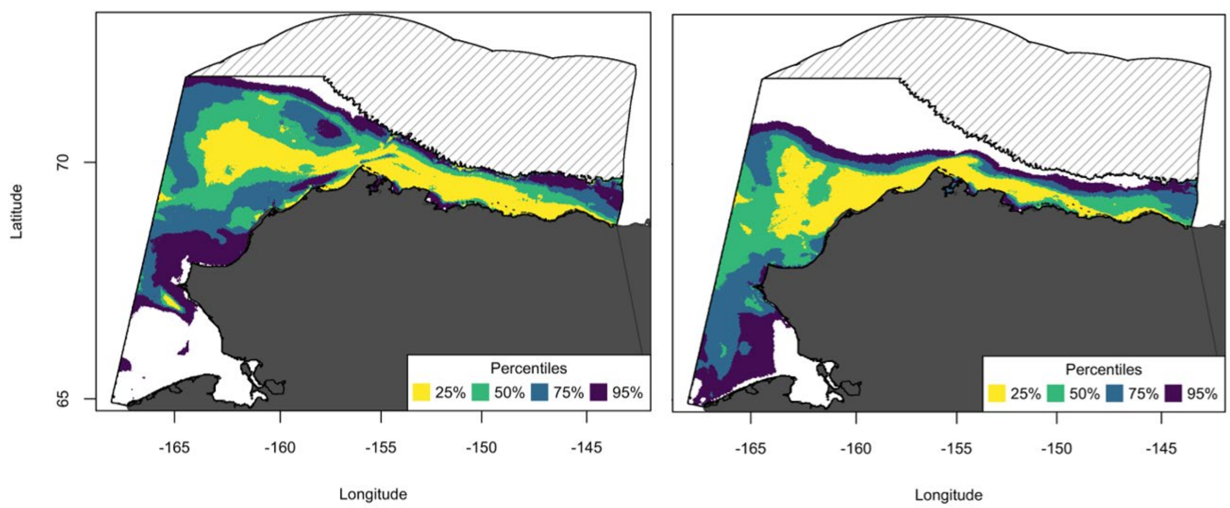


**Figure A15.** Essential fish habitat of age-0 Arctic cod in warm (left panel) and cold (right panel) years.

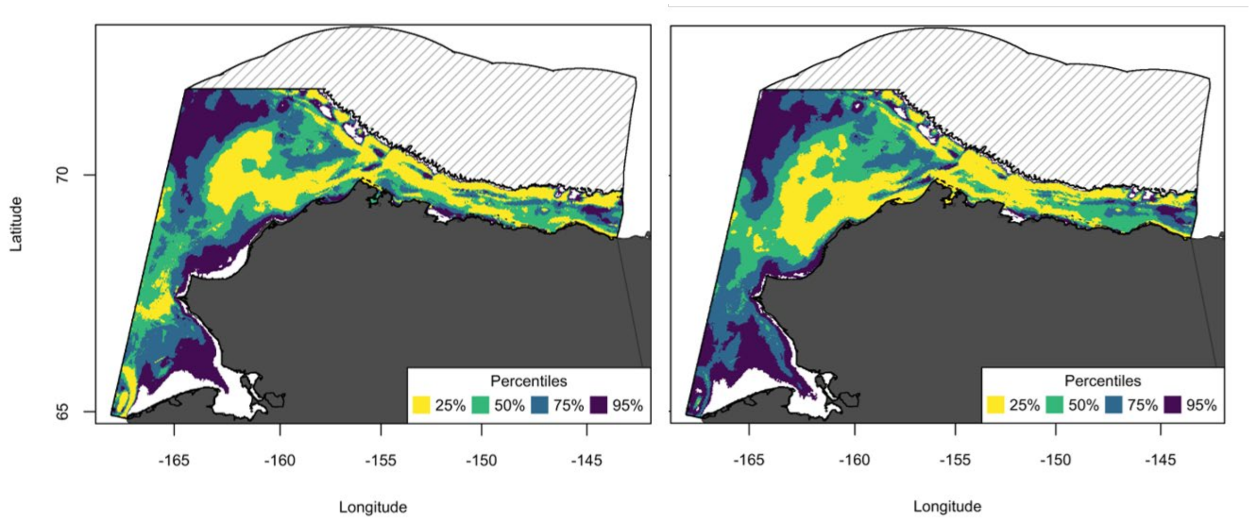


**Figure A16.** Essential fish habitat of juvenile Arctic cod in warm (left panel) and cold (right panel) years.

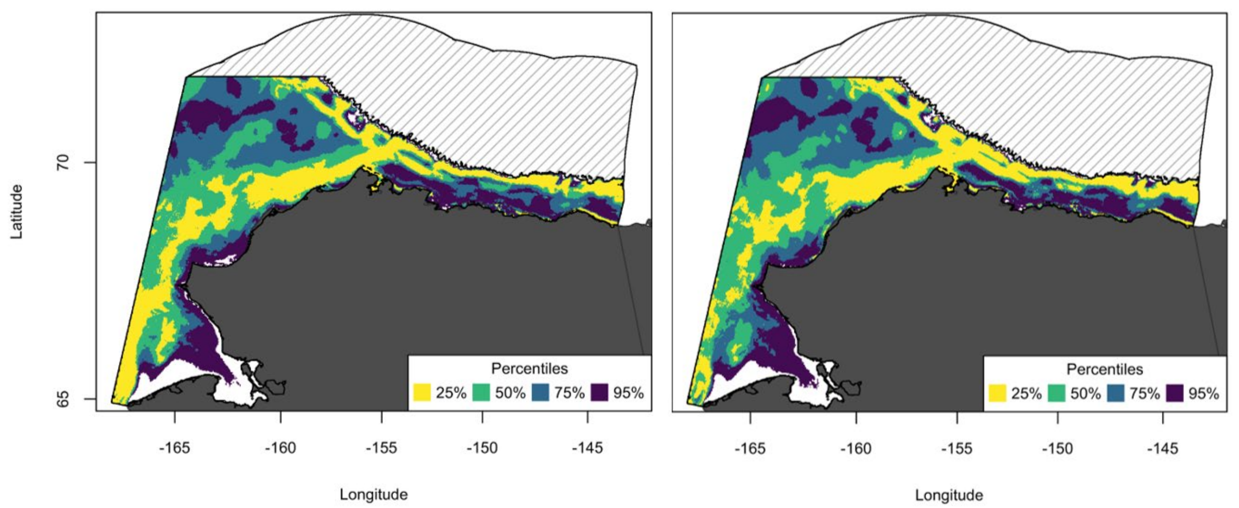


**Figure A17.** Essential fish habitat of mature Arctic cod in warm (left panel) and cold (right panel) years.

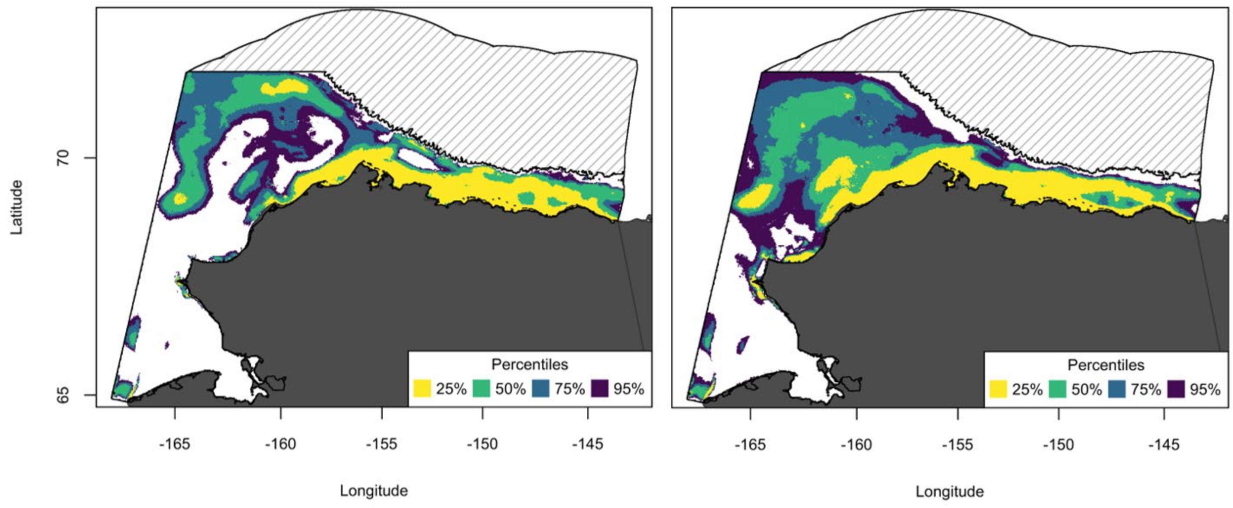


**Figure A18.** Essential fish habitat of larval saffron cod in warm (left panel) and cold (right panel) years.

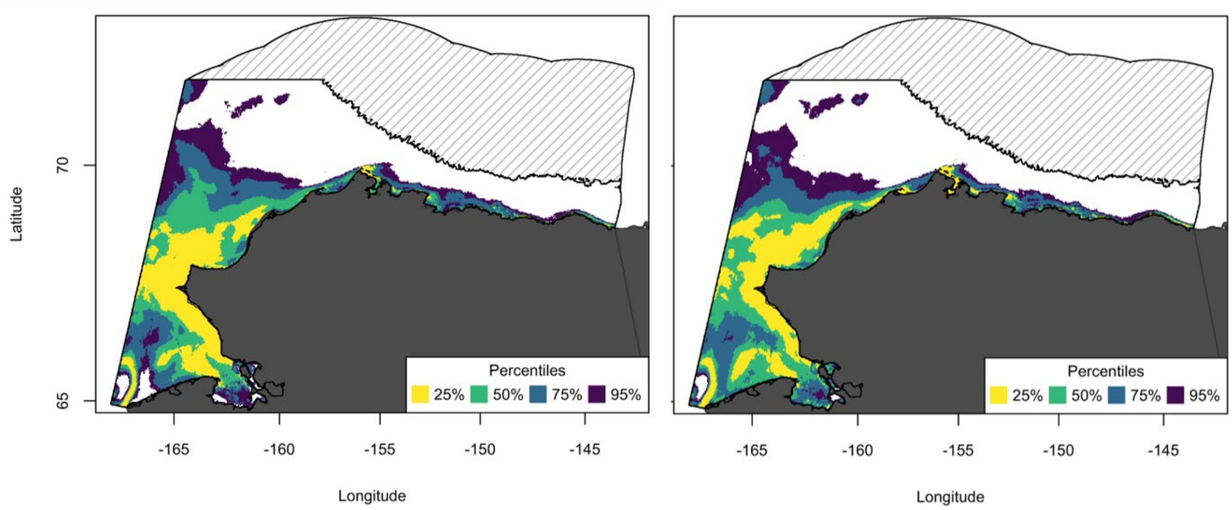


**Figure A19.** Essential fish habitat of age-0 saffron cod in warm (left panel) and cold (right panel) years.

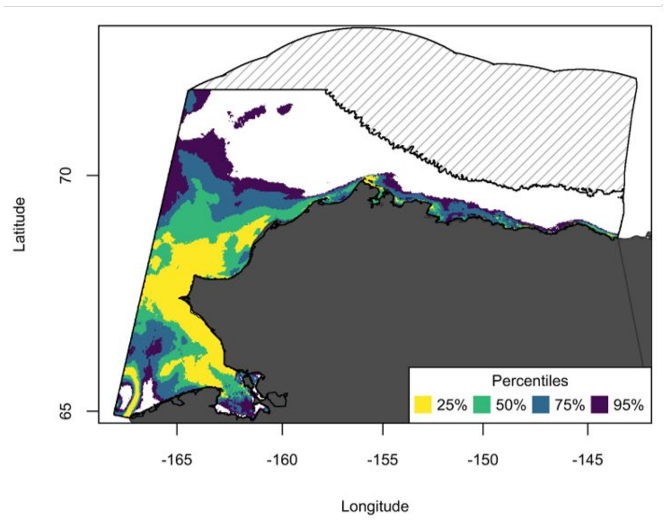


**Figure A20.** Essential fish habitat of juvenile saffron cod in warm (left panel) and cold (right panel) years.

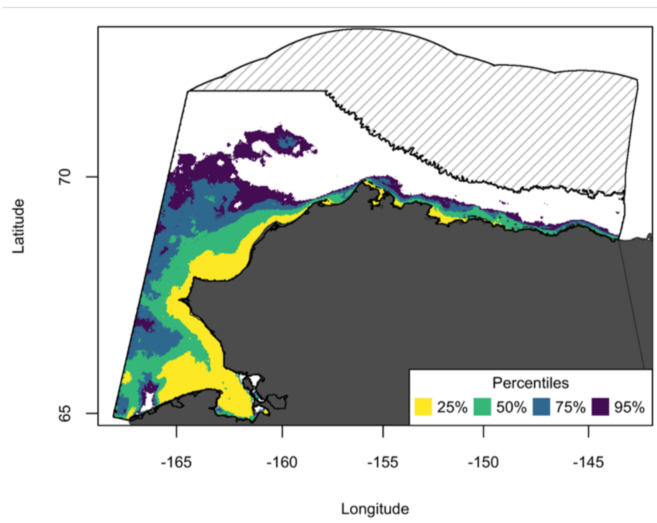


**Figure A21.** Essential fish habitat of mature saffron cod in warm (left panel) and cold (right panel) years.

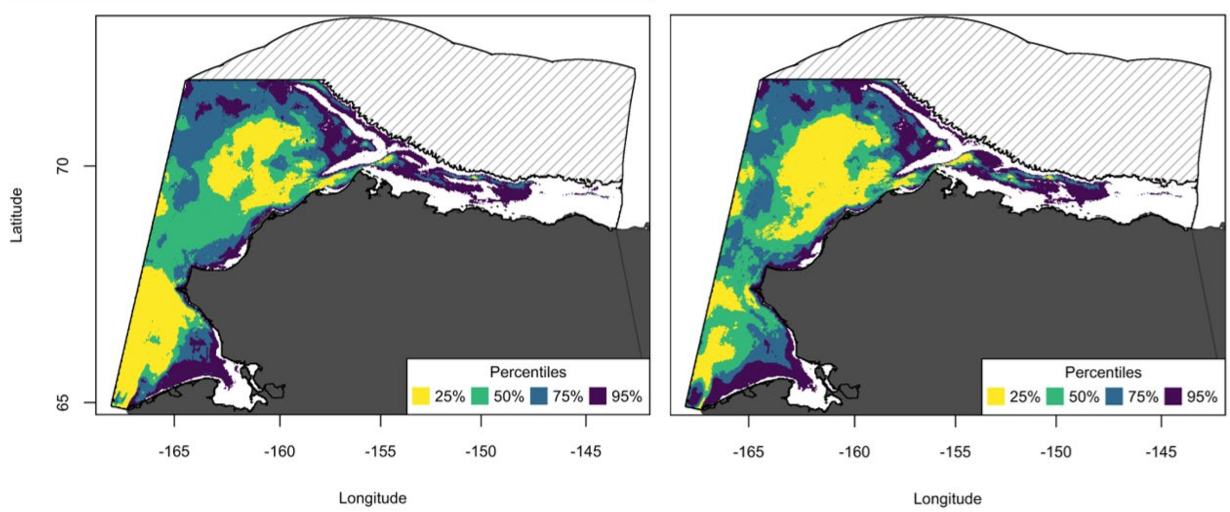


**Figure A22.** Essential fish habitat of immature snow crab in warm (left panel) and cold (right panel) years.

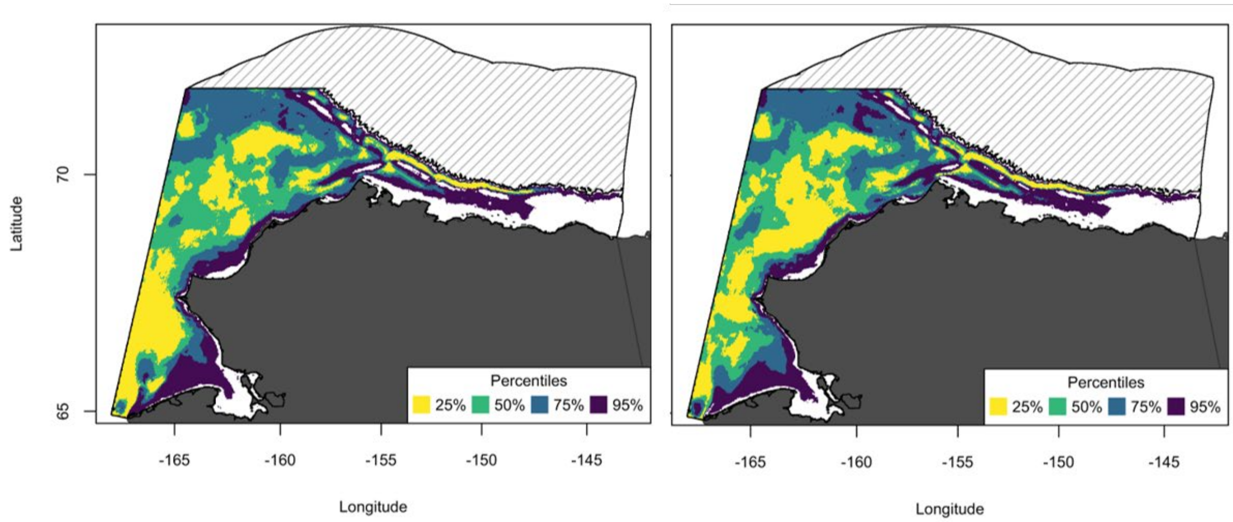


**Figure A23.** Essential fish habitat of adolescent male snow crab in warm (left panel) and cold (right panel) years.

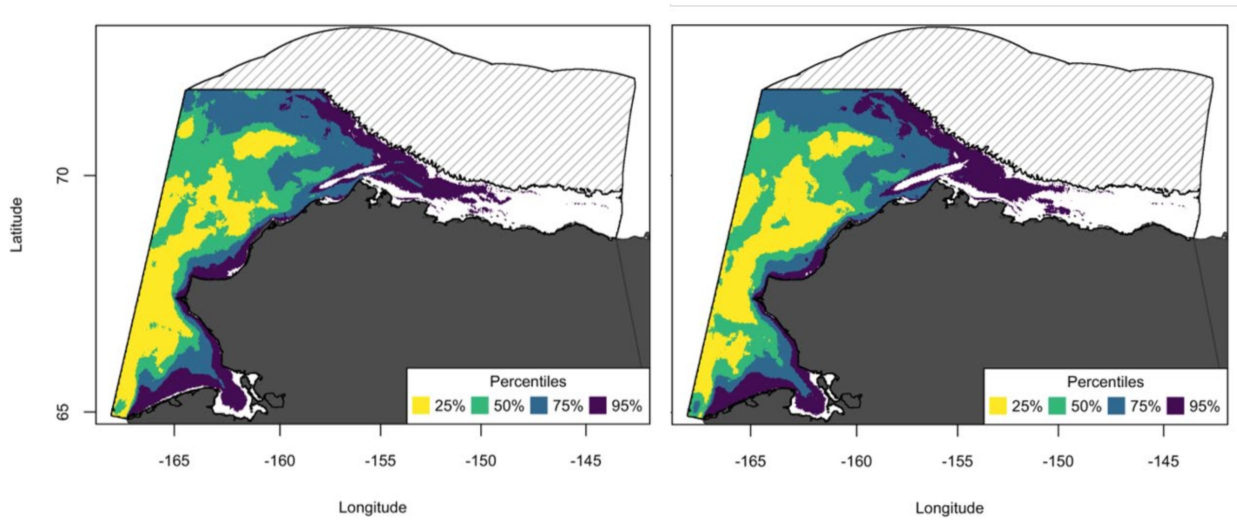


**Figure A24.** Essential fish habitat of adolescent female snow crab in warm (left panel) and cold (right panel) years.

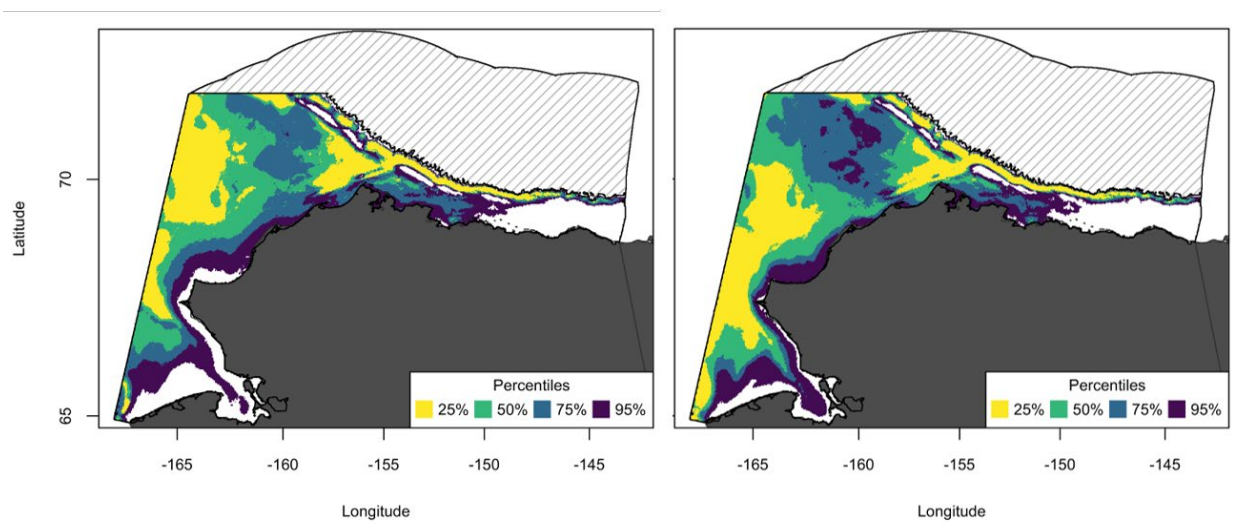


**Figure A25.** Essential fish habitat of mature male snow crab in warm (left panel) and cold (right panel) years.

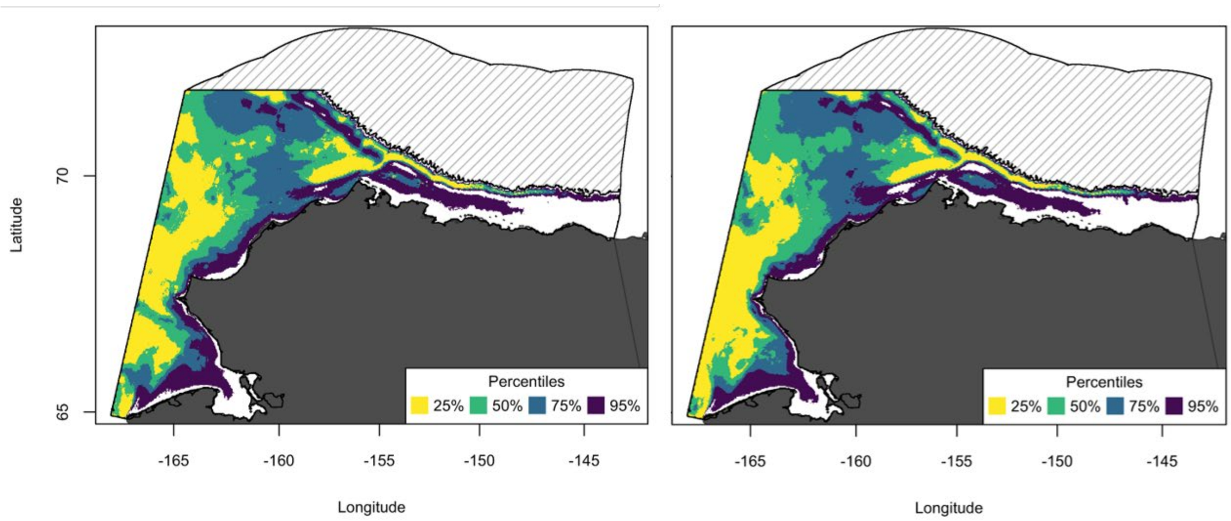


**Figure A26.** Essential fish habitat of mature female snow crab in warm (left panel) and cold (right panel) years.