Discussion Paper on Advancing Essential Fish Habitat Descriptions and Maps for the 2022 5-year Review

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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 10 components for the EFH contents of FMPs. **This Discussion Paper presents the new information that NMFS is developing under EFH component 1, the description and identification of EFH (50 CFR 600.815(a)(1)), for the upcoming 2022 5-year Review.** For component 1, the EFH regulations require FMPs 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 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)).

The North Pacific Fishery Management (Council) completed the last EFH 5-year Review in 2017 (2017 5-year Review, Simpson et al. 2017). For that 5-year Review, a new approach to EFH component 1 was developed that used species distribution models (SDM) to map the distribution and relative-abundance across different habitats for individual life stages of species in Alaska FMPs, including the FMP for Groundfish of the Bering Sea and Aleutian Islands (BSAI) Management Area, FMP for Groundfish of the Gulf of Alaska (GOA), and FMP for Bering Sea/Aleutian Islands King and Tanner Crabs. New information was also reviewed for the FMP for Salmon Fisheries in the EEZ off Alaska that included quantitative model-based maps (Echave et al. 2012) and for the FMP for Fish Resources of the Arctic Management Area that included maps of species distribution from surveys. The new SDM approach to EFH was a significant advancement, with new EFH Level 1 (distribution) and Level 2 (habitat-related density or abundance) information for groundfish and crabs and a substantial improvement to the EFH maps. The new and revised EFH descriptions and maps were integrated with advancements in understanding the impacts of fishing and non-fishing activities on EFH and other new information in the 2017 5-year Review (Simpson et al. 2017). Accordingly, the Council and NMFS revised the EFH sections of these FMPs to incorporate the results of 2017 5-year Review and the EFH Omnibus Amendment package was approved on May 31, 2018 (83 FR 31340, July 5, 2018).

Under component 1, the EFH regulations provide an approach to organize the information necessary to describe and identify EFH (50 CFR 600.815(a)(1)(iii))—

- Level 1: Distribution data are available for some or all portions of the geographic 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.

Further, the EFH regulations state that Councils should strive to describe habitat based on the highest level of detail. **The studies presented in this Discussion Paper use this approach to explain the SDM information and maps in terms of EFH Levels 1 and 2, and for the first time, Level 3.**

New EFH Information from Studies In-Progress

The Alaska EFH Research Plan that guides research to meet EFH mandates in Alaska was revised following the progress of the 2017 5-year Review (Sigler et al. 2017). This revision incorporated additional research and information needs along with the five long-term EFH research goals that have guided EFH research in Alaska since 2005 (Sigler et al. 2017, Appendix 2). The revised plan provided two-specific research objectives to advance EFH information for Alaska in the intervening 5 years leading up to the 2022 5-year Review:

1. Develop EFH Level 1 (distribution) or Level 2 (habitat-related densities or abundance) for life stages and areas where missing.
2. Raise EFH information from Level 1 or Level 2 to Level 3 (habitat-related growth, reproduction, or survival rates (i.e., vital rates)).

NMFS Alaska Region (AKR) and Alaska Fisheries Science Center (AFSC) funded several studies to accomplish Alaska EFH Research Plan research objectives. **This Discussion Paper presents new research from four in-progress studies that will be available to the Council and NMFS for the 2022 5-year Review—**

- Two studies are developing new SDM EFH information and maps for groundfish species life stages in the GOA and BSAI (Laman et al. FY19/20) and fish resources of the Arctic (Marsh et al. FY19/20), using a modernized SDM approach building on that of the 2017 5-year Review and presenting Arctic SDM EFH maps for the first time (*EFH Levels 2 and 3*).
- A third is a multi-year, integrated study with field, lab, and modeling components that is measuring and mapping habitat-related vital rates for groundfish in the GOA (*EFH Level 3*) (Laurel et al. FY17/18/19).
- A fourth study is a novel application of biophysical individual-based models to develop EFH information and maps for groundfish early life stages (*EFH Levels 1, 2, and 3*) (Shotwell et al. FY18/19).

The new or revised *EFH Level 1, 2, and 3* information from these studies will be used to assess whether amending EFH text or maps in the groundfish FMPs is warranted based on available information. These stand-alone studies function as a package to provide new information for the 2022 EFH 5-year Review— where Laman et al. is leading the revised SDM EFH approach, Marsh et al. co-develops this new approach for Arctic species, and Laurel et al. and Shotwell et al. combine new techniques with SDM to advance EFH information for Alaska. All four studies are summarized here and described in this Discussion Paper with sections specific to each.

This body of work is innovative and inclusive of many contributors. In addition to supporting our EFH mandates, this new species-specific habitat information can be extended to stock assessment and other ecosystem-based fisheries management (EBFM) efforts for our region. **As an opportunity to strengthen this work, we seek input from the Council's Scientific and Statistical Committee (SSC) regarding study methods, progress to date, and planned products for the 2022 5-year Review.** We look forward to sharing the complete body of work that is described in this Discussion Paper with the Council and NMFS at a later stage of the 2022 5-year Review.

1. *Advancing Model-Based Essential Fish Habitat Descriptions for North Pacific Species*

Ned Laman (Groundfish Assessment Program (GAP), AFSC), Jodi Pirtle (Habitat Conservation Division (HCD), NMFS Alaska Region), Jeremy Harris (GAP, AFSC), Chris Rooper (Department of Fisheries and Oceans (DFO), Canada), Tom Hurst (Fisheries Behavioral Ecology Program (FBEP), AFSC), Christina Conrath (GAP, AFSC), funded by the Alaska EFH Research Plan in FY19 and FY20 (Laman et al. FY19/20).

NMFS funded this study under the Alaska EFH Research Plan in FY19 and FY20. Using data and methods that are current with the best available science, this study will develop SDMs for life stages of nearly 30 species in the GOA and BSAI groundfish FMPs. **This Discussion Paper demonstrates with case studies of three groundfish species how the revised SDM EFH approach by Laman et al. can meet four key objectives to describe and map EFH in Alaska.**

The cases studies focus on the following groundfish species life stages:

1. Sablefish (*Anoplopoma fimbria*) subadult and adult life stages in the Bering Sea;
2. Pacific cod (*Gadus macrocephalus*) early juvenile, subadult, and adult life stages in the GOA;
3. Pacific ocean perch (*Sebastes alutus*) (POP) subadult life stage in the GOA.

The case studies address the following objectives:

1. Validate the 2017 SDM EFH approach by assessing the forecasting accuracy of the 2017 models with new data.
2. Develop and describe how this new and revised set of SDM EFH information and maps supports the 2022 5-year Review.
3. Evaluate how the data updates and model refinements of the revised approach affect SDM performance and EFH map area.
4. Demonstrate one method to advance EFH information to Level 3, through combining the SDM EFH for subadult POP with maps of temperature-dependent growth potential.

This Discussion Paper includes an overview of data updates and model refinements used in this study and compares a summary of the 2017 SDM EFH approach with the revised approach (Table 1.1). The complete methods of the revised SDM-based approach to describe and map EFH is then detailed and differences from the 2017 approach are highlighted. **Importantly, the three types of SDM used in 2017 were retained in the revised approach, including a generalized additive model (GAM), hurdle GAM (hGAM), and MaxEnt model.** A fourth SDM, a presence-absence GAM (paGAM), has been added, along with other important updates with respect to modeling methods, such as switching from CPUE to count data in the SDM and selecting the best performing model by skill testing.

New data incorporated into the SDMs include—

- 5 years of groundfish summer bottom trawl survey data from the Bering Sea (2015-2019) and 3 years from the GOA (2015, 2017, and 2019).
- Updates to maturity schedules and the addition of an early juvenile life stage, which redefined the life stage breaks for several species.

- Early juvenile life stage SDMs use a combination of nearshore and offshore survey data from the GOA.
- Bathymetry and bathymetry-derived seafloor terrain covariates updated for the GOA and a measure of bathymetric position added for all regions.
- Regional bottom temperature covariates updated from 5 years of new environmental data collected during the summer bottom trawl surveys (2015-2019).

Together, these updates to the 2017 SDM EFH approach have resulted in new and revised information from the case studies presented in this Discussion Paper to advance EFH for Alaska.

To validate the 2017 EFH SDM approach, Laman et al. assesses the forecasting accuracy of the 2017 SDM with new summer bottom-trawl survey data. In this exercise, the predicted distribution and abundance of GOA Pacific cod and POP fitted to data from 1993-2013 was compared with observations from subsequent survey years 2015, 2017, and 2019 (i.e., out years). Agreement between model predictions and subsequent out year observations in the external validation exercise was similar to the internal model validation, indicating that the 2017 SDM performed as well predicting distribution and abundance in out years as they did internally validating the model fits in the 2017 5-year Review.

This study meets the current objectives of the Alaska EFH Research Plan (Sigler et al. 2017), to develop new EFH information for species life stages where not described and advance EFH levels where possible (e.g., from Level 1 distribution to Level 2 relative abundance) with progress towards EFH Level 3 vital rates.

New and revised EFH information from the case studies include—

- New Level 2 EFH for previously undescribed Bering Sea subadult sablefish and GOA early juvenile Pacific cod;
- Advanced EFH levels from Level 1 to Level 2 for Bering Sea adult sablefish;
- New method to describe and map EFH Level 3 for GOA subadult POP.

The areal extent of North Pacific groundfish EFH maps from these case studies changed compared to the EFH maps from the 2017 5-year Review. Bering Sea adult sablefish and GOA subadult Pacific cod EFH area was reduced, GOA adult Pacific cod EFH area remained about the same, and GOA subadult Pacific ocean perch EFH area more than doubled. Redefining life stages and updating modeling methods were the biggest influences on changing EFH area in the case studies (e.g., Bering Sea adult sablefish, Fig. S.9). Updates to modeling methods also made skill testing among SDM possible (i.e., 2017 SDM were assigned *a priori* based on sample size), which is a robust approach when more than one SDM are considered. **The combined updates to the 2017 SDM EFH approach have resulted in new and refined EFH information for groundfish species life stages in all case studies, including new EFH Level 2 for undescribed life stages, advances from Level 1 to Level 2, and for the first time, from Level 2 to Level 3.**

As in the 2017 5-year Review, this study provides maps of the SDM output (e.g., Fig. S.2) and percentiles of SDM EFH area (e.g., Fig. 1.5), where the upper 95% of the predicted area is the current definition of EFH maps for Alaska (i.e., upper 25% is “hot spots”, upper 50% is “core habitat”, and 25-95% is EFH). Importantly, presenting this set of maps demonstrates that the SDM can identify more nuanced spatial stock structure than is communicated in the upper 95% SDM EFH maps, which lends to utility of these SDM beyond current EFH applications and provides a basis for discussions on how EFH is mapped for Alaska.

The progress of these case studies will be extended as this study continues to develop new SDM EFH for North Pacific groundfish species. This work has the potential to advance EFH information levels for nearly 30 groundfish species from Level 1 to Level 2, including previously undescribed species life stages. The methods to combine SDM EFH for subadult POP with growth potential to advance EFH from Level 2 to Level 3 can be further developed and applied to other species where vital rates have been measured (Table 1.6). **Next, this study will complete SDM EFH for the remaining groundfish species in the GOA and BSAI FMPs.** These SDMs will be developed for the adult, subadult, and early juvenile life stages, where possible (Table 1.7). This complete package will be provided to the Council and NMFS at a later stage of the 2022 5-year Review.

2. *Model-Based Essential Fish Habitat Descriptions for Fish Resources of the Arctic Management Area*

Jen Marsh (University of Alaska Fairbanks (UAF), HCD, NMFS Alaska Region), Jodi Pirtle (HCD, NMFS AKR), and Franz Mueter (UAF), funded by the Bureau of Ocean Energy Management (BOEM) and supported by UAF and NMFS in FY19 and FY20 (Marsh et al. FY19/20).

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. **Arctic EFH maps are not currently based on SDM, but rather survey presence-absence data presented as qualitative maps of distribution (EFH Level 1).** This study will ultimately develop SDM EFH for life stages of Arctic cod (*Boreogadus saida*), saffron cod (*Eleginus gracilis*) and snow crab (*Chionoecetes opilio*), including Level 2 and 3 descriptions and maps, concurrently with Laman et al., to modernize Arctic species EFH descriptions and maps current with the state of science for the region.

The Arctic Management Area is comprised of the Beaufort and Chukchi 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 will be developed for the summer season. Survey data of Arctic cod, saffron cod and snow crab have been separated by life stage, including larval, early juvenile, late juvenile, and mature (Fig. 2.1). A variety of ecologically meaningful habitat covariates have been assembled, including depth, seafloor terrain, sediment types, currents, temperature, salinity, and productivity. Two types of SDM are used, including MaxEnt models and GAMs, which were used to describe and map EFH for groundfish and crabs in the 2017 5-year Review and concurrently by Laman et al. FY19/20 for the 2022 5-year Review. MaxEnt models and GAM will be developed for all life stages of all species, where possible (EFH Level 2). This study will also integrate SDM with vital rates (temperature-dependent growth and body condition) for juvenile Arctic and saffron cods from published studies (Laurel et al. 2016, Copemen et al. 2017) (EFH Level 3).

This Discussion Paper presents preliminary SDMs that have been developed by this study for age-0, late juvenile, and mature Arctic and saffron cods. These SDM use presence-only data from offshore and nearshore surveys of various gear-types (e.g., MaxEnt, Arctic cod, Level 1, Fig. 2.3). Summer bottom temperature had high percent contribution in the models, where Arctic cod habitat suitability decreased with increasing temperature and saffron cod habitat suitability increased with increasing temperature. Model predictions indicate that mature Arctic cod are more likely to occur in areas with higher bottom current speeds, which was a covariate with high percent contribution in the models.

Next steps by this study include—

- Acquire additional species sampling data if available;
- Develop habitat covariates for the pelagic early life stage SDMs (e.g., surface temperature and currents);
- Refine modeling methods (i.e., modernized MaxEnt, GAM, and skill testing among models, resulting in EFH Level 2 information);
- Complete SDM EFH for all species life stages (EFH Level 2);
- Integrate SDM EFH with vital rates of temperature-dependent growth (EFH Level 3).

This study in-progress will be completed and shared with the Council and NMFS as part of the full package of new EFH information available for the 2022 5-year Review.

3. Optimal Thermal Habitat of Juvenile Walleye Pollock (Gadus chalcogrammus) in the Gulf of Alaska

Ben Laurel (FBEP, AFSC), Louise Copeman (FBEP, AFSC; Oregon State University), Tom Hurst (FBEP, AFSC), Jodi Pirtle (HCD, NMFS Alaska Region), and Georgina Gibson (UAF), funded by the Alaska EFH Research Plan in FY17, FY18, and FY19 (Laurel et al. FY17/18/19).

Understanding mechanisms through which environmental conditions influence survival, growth, and condition of juvenile life stages can help inform stock productivity estimates for commercially and ecologically important species such as walleye pollock (*Gadus chalcogrammus*). In addition, the ability to link habitat information such as temperature to rate-dependent functions of survival, growth, and condition can help describe and map EFH Level 3 information (habitat-linked vital rates). This was the first multi-year, integrated study funded by the revised Alaska EFH Research Plan (Sigler et al. 2017). **In an integrated approach, this study combines field sampling, laboratory experiments, and SDM to describe and map EFH Level 3 for North Pacific species.**

This study is developing EFH Level 3 information, from temperature-dependent growth and energy (lipid) loss rates for juvenile pollock under winter conditions (laboratory component of the present study), and temperature-dependent growth and lipid accumulation rates that were developed from laboratory studies of juvenile pollock under summer conditions and previously published (Laurel et al. 2016, Copeman et al. 2017). EFH for North Pacific species is not currently described at Level 3 (habitat-linked vital rates). This study will combine measured vital rates from laboratory experiments with SDM to develop EFH Level 3 descriptions and maps for North Pacific species.

This Discussion Paper presents preliminary work by Laurel et al. that demonstrates one approach to describe and map EFH Level 3 information, using juvenile pollock summer vital rates developed for the GOA. Laboratory experiments have been conducted with pollock collected in the GOA to develop temperature and size-dependent vital rate functions under summer conditions, including growth (Laurel et al. 2016) and lipid accumulation, a metric of body condition (Copeman et al. 2017). The vital rates have been applied to regional temperature data from the Regional Ocean Modeling System (ROMS) for the GOA (3 km^2), including model years 1997-2011. A juvenile pollock (40-120 mm) SDM was previously developed, using MaxEnt with presence-only species data assembled from multiple surveys and gear types and regional habitat covariates (Pirtle et al. 2019). Habitat covariates with the greatest percent contribution to the model were depth (40.4%, 25-300 m), bathymetric position index (6.5 km^2) (34.0%, low-lying and edge terrain), substrate rockiness (15.2%, not rocky), and seafloor slope

(3.8%, flat and edge terrain) (Fig. 3.4). The vital-rates have been integrated with the SDM to produce preliminary maps of temperature-dependent vital rates in areas of suitable habitat for juvenile pollock in a co-mapping approach (Fig. 3.5).

Next steps by this study include—

- Complete juvenile pollock laboratory experiments of vital rates (applied in the summer example) for winter conditions;
- Update juvenile pollock SDM, including species data, habitat covariates, and revised modeling methods;
- Explore other SDM-integrated Level 3 mapping approaches (e.g., temperature-dependent vital rates as a covariate in the SDM);
- Develop Level 3 maps, using annual depth-integrated temperature data for summer and winter seasons in the GOA from the updated ROMS (e.g., through 2018 or 2019).

This study will continue this work in-progress. New EFH information from this work will become part of the full package available to the Council and NMFS for the 2022 5-year Review.

4. *Developing a Novel Approach to Estimate Habitat-Related Survival Rates for Early Life History Stages using Individual-Based Models*

S. Kalei Shotwell (REFM, AFSC), William Stockhausen (REFM, AFSC), Georgina Gibson (UAF), Jodi Pirtle (HCD, NMFS Alaska Region), Chris Rooper (DFO), Alison Deary (RPP, AFSC), funded by the Alaska EFH Research Plan in FY18 and FY19 (Shotwell et al. FY18/19).

The Alaska EFH Research Plan describes two pathways to advance to EFH Level 3 including, 1) using pre-existing vital rates, or 2) conducting additional laboratory and/or field studies to develop the required information (Sigler et al. 2017). Because the first option only currently exists for certain species and the second option can be very time-consuming and expensive, it is reasonable to consider alternative methods to describe and map EFH Level 3. This is particularly true for the early life history stages (ELHS: eggs, larvae, pelagic juveniles, and settled early juveniles), where limited survey data are available for most species to develop SDM EFH information and maps. IBM trajectory analysis can also identify pathways of connectivity between offshore pelagic ELHS and nursery habitats on the continental shelf, including locations where settlement may be more likely to occur and where it may not, which can refine EFH maps for settled early juvenile life stages of species with this life history strategy (e.g., Goldstein et al. in review).

SDM EFH Level 1 information was developed for the pelagic ELHS of North Pacific groundfish and crab species for the 2017 5-year Review (e.g., Laman et al. 2018). Shotwell et al. has developed a novel application of biophysical life-stage integrated individual-based models (IBM) to advance EFH information for ELHS from Level 1 to Level 2 and Level 3, through case studies of sablefish and Pacific cod in the GOA. **This Discussion Paper presents preliminary EFH Level 1 maps developed by Shotwell et al., using an IBM for Pacific cod that is informed by spawning locations and a settled early juvenile stage SDM.**

IBMs were developed for sablefish and Pacific cod ELHS as part of the North Pacific Research Board's Gulf of Alaska Integrated Ecosystem Research Program (GOAIERP). Results from these models were used to estimate variability in annual connectivity due to changes in the oceanic environment over

1996-2011 (Gibson et al. 2019, Hinckley et al. 2019). This study will ultimately provide survival rate EFH maps for the ELHS of these two species to demonstrate that IBM output can be used within the context of EFH. Once established, this new methodology may be explicitly applied to other groundfish and crab species in Alaska where IBMs have been developed (e.g., walleye pollock, POP, snow crab), including as a starting reference for other co-occurring species with similar early life history strategies.

Observed spawning locations set the origin of the egg life stage in the IBM at the start of the model run (i.e., winter fishery, S. Barbeaux, AFSC, pers. comm.). Early juvenile stage SDM were developed for Pacific cod and sablefish as part of the GOAIERP (Pirtle et al. 2019). The IBMs now use these maps to trigger settlement success once an individual reaches suitable benthic habitat during the early juvenile life stage at the end of the model run (e.g., Fig. 4.1) (i.e., whereas, settlement was triggered by an individual reaching a certain depth in the IBM for the GOAIERP). EFH maps from this study are based on presence-absence of successful individuals in the IBM trajectory analysis. The corresponding life stage maps are spatial histograms of the number of unique, successful individuals that occupied each grid cell of the ROMS domain at some time during that life stage and also where that life stage was absent. Preliminary examples of Pacific cod EFH Level 1 maps are abundance (presence-absence) of successful individuals by life stage averaged across all model years (Figs. 4.2 – 4.7).

Next steps by this study include developing the following EFH information for sablefish and Pacific cod early life stages in the GOA:

1. EFH Level 1 maps developed for sablefish, similar to the Pacific cod maps presented here;
2. EFH Level 2 maps developed by weighting the abundance results from individual years by an estimate of annual spawning stock biomass;
3. EFH Level 3 maps developed by post-processing the model trajectories to calculate temperature-dependent survival and growth rates by life stage in the model domain.

New EFH information and maps developed by this study will be provided to the Council and NMFS for consideration in the 2022 5-year Review as part of the complete package of new information described by this Discussion Paper.

Importance of the Alaska Species Distribution Models

In addition to supporting our EFH mandates, the new species-specific habitat information presented by this Discussion Paper can be extended to stock assessment and other EBFM efforts for our region. The Ecosystem and Socioeconomic Profiles (ESP) in the Stock Assessment and Fishery Evaluation (SAFE) Reports for Alaska Sablefish (Shotwell et al. 2017, 2018, 2019a) and GOA Pollock (Shotwell et al. 2019b) include SDMs from the 2017 5-year Review (Rooney et al. 2018) and the GOAIERP (Pirtle et al. 2019). Recent studies have also applied these SDMs to test hypotheses about spatial and temporal stock structure in the Bering Sea under future climate scenarios (Rooper et al. in review) and groundfish recruitment processes in the GOA (Goldstein et al. in review). Several milestones of the Alaska EBFM Roadmap Implementation Plan (NMFS 2018) reference actions related to habitat science and EFH. In these examples, information and SDM developed for EFH are extended in a meaningful context to support fishery and ecosystem management in our region in an effort to *model once and use many times*.

The four studies presented in this Discussion Paper modernize the SDM EFH approach of the 2017 5-year Review and offer new information and techniques for the 2022 5-year Review. This body of work is innovative and inclusive of many contributors that are developing new habitat-linked distribution, abundance, and vital rate information for North Pacific and Arctic species. This Discussion Paper demonstrates that these approaches can validate extant SDM EFH information and advance EFH descriptions and maps for species in Alaska FMPs, including new and revised EFH Level 1 and 2, and for the first time, Level 3. **At this stage, we welcome input from the SSC on the methods, progress-to-date, and planned products presented by this Discussion Paper.** We look forward to sharing this completed body of work with the Council and NMFS at a later stage of the 2022 5-year Review.

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INTRODUCTION

Essential fish habitat (EFH) is defined as those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity (50 CFR 600.10). The EFH Final Rule requires that the National Marine Fisheries Service (NMFS) and Fishery Management Councils (Councils) describe and identify EFH for managed species, minimize to the extent practicable the adverse effects of fishing and other anthropogenic activities on EFH, and identify actions to encourage the conservation and enhancement of EFH. Federal agencies that authorize, fund, or undertake actions that may adversely affect EFH must consult with NMFS, and NMFS must provide conservation recommendations to federal and state agencies regarding these actions. As part of this mandate, EFH text descriptions and maps are necessary for each life stage of species in a Fishery Management Plan (FMP) (EFH component 1, descriptions and identification) (50 CFR 600.815) with an overarching consideration that the science related to this effort meets the standards of best available science (NMFS National Standard 2 – Scientific Information 50 CFR 600.315).

Councils and NMFS are also required to review the EFH components of FMPs and revise or amend these components based on available information at least every 5 years (50 CFR 600.815(a)(10)). In 2017, NMFS and the North Pacific Fishery Management Council (Council) conducted an EFH 5-year Review (2017 5-year Review, Simpson et al. 2017). A new approach to develop stock-specific habitat information for EFH component 1 was presented that used species distribution models (SDM) to map the distribution and relative-abundance across different habitats for individual life stages of species in Alaska FMPs, including the FMP for Groundfish of the Bering Sea and Aleutian Islands (BSAI) Management Area, FMP for Groundfish of the Gulf of Alaska (GOA), and FMP for Bering Sea/Aleutian Islands King and Tanner Crabs. New information was also reviewed for the FMP for Salmon Fisheries in the EEZ off Alaska that included quantitative model-based maps (Echave et al. 2012) and for the FMP for Fish Resources of the Arctic Management Area that included maps of species distribution from surveys. With regard to EFH component 1, the 2017 5-year Review determined that the EFH descriptions and maps for individual species life stages warranted FMP revisions to reflect the new information on their life history, biological and habitat associations, and fisheries (i.e., distributions determined from fishery-dependent data). In particular, the new SDM approach to EFH was a significant advancement, including new EFH Level 1 and Level 2 information for groundfish and crabs and a substantial improvement to the EFH maps (Fisheries Leadership and Sustainability Forum 2016, Simpson et al. 2017). Accordingly, the Council and NMFS revised the EFH sections of the FMPs and the EFH Omnibus Amendment package was approved in May, 2018 (83 FR 31340, July 5, 2018).

The Alaska EFH Research Plan has guided research to meet EFH mandates in Alaska since 2005 (AFSC 2006, Sigler et al. 2012). Revisions of this plan accompany the EFH 5-year reviews that summarize the status of EFH research (EFH component 9 – research and information needs), which provides a basis to determine future research directions. Building on the progress of the 2017 5-year Review, the Alaska EFH Research Plan was revised (Sigler et al. 2017), incorporating additional research and information needs along with the five long-term EFH research goals (Sigler et al. 2017, Appendix 2). The revised plan provided two-specific research objectives to advance EFH information for Alaska in the intervening 5 years leading up to the 2022 5-year Review:

1. Develop EFH Level 1 (distribution) or Level 2 (habitat-related densities or abundance) for life stages and areas where missing; and
2. Raise EFH information from Level 1 or Level 2 to Level 3 (habitat-related growth, reproduction, or survival rates (i.e., vital rates)).

Several studies were funded by NMFS Alaska Region (AKR) and Alaska Fisheries Science Center (AFSC) with respect to these research objectives. These include new multi-year, integrated studies with lab and/or field and modeling components intended to develop SDM approaches that incorporate vital rates (Level 3). This Discussion Paper presents new research from these studies that will be available to the Council and NMFS for the 2022 5-year Review. These studies are listed here and described in the document with sections specific to each.

1. **Advancing Model-Based Essential Fish Habitat Descriptions for North Pacific Species:** Ned Laman (Groundfish Assessment Program (GAP), AFSC), Jodi Pirtle (Habitat Conservation Division (HCD), NMFS Alaska Region), Jeremy Harris (GAP, AFSC), Chris Rooper (Department of Fisheries and Oceans (DFO), Canada), Tom Hurst (Fisheries Behavioral Ecology Program (FBEP), AFSC), and Christina Conrath (GAP, AFSC), funded by the Alaska EFH Research Plan in FY19 and FY20 (Laman et al. FY19/20).

    - SDM from this study will compose the bulk of new information available for the 2022 5-year Review to advance EFH for BSAI and GOA groundfish from none or Level 1 to Level 2. In addition, this project will apply vital rates from published studies to SDM to describe and map EFH Level 3. This Discussion Paper presents three case studies by Laman et al. that demonstrate a revised SDM EFH approach for the 2022 5-year Review current with the best available science.

2. **Model-Based Essential Fish Habitat Descriptions for Fish Resources of the Arctic Management Area**: Jen Marsh (University of Alaska Fairbanks (UAF), HCD, NMFS Alaska Region), Jodi Pirtle (HCD, NMFS Alaska Region), Franz Mueter (UAF), funded by BOEM FY19/20 (Marsh et al. FY19/20).

    - Arctic EFH maps are not currently based on SDM. This study will develop SDM for life stages of Arctic cod (*Boreogadus saida*), saffron cod (*Eleginus gracilis*) and snow crab (*Chionoecetes opilio*), including EFH Level 2 and 3 descriptions and maps, concurrently with Laman et al., to modernize Arctic species EFH information.

3. **Optimal Thermal Habitat of Juvenile Walleye Pollock (*Gadus chalcogrammus*) in the Gulf of Alaska:** Ben Laurel (FBEP, AFSC), Louise Copeman (FBEP, AFSC, Oregon State University (OSU)), Tom Hurst (FBEP, AFSC), Jodi Pirtle (HCD, Alaska Region), and Georgina Gibson (UAF), funded by Alaska EFH Research Plan FY17/18/19 (Laurel et al. FY17/18/19).

    - This was the first integrated study funded by the EFH Research Plan in FY17, where field sampling, laboratory experiments of new temperature-dependent vital rates, and SDM are incorporated to develop EFH Level 3 descriptions and maps. This study will develop EFH Level 3 information, including summer and winter temperature-dependent growth and condition for juvenile walleye pollock (and potentially Pacific cod; *Gadus macrocephalus*) in the GOA.

4. **Developing a Novel Approach to Estimate Habitat-Related Survival Rates for Early Life History Stages using Individual-Based Models:** Kalei Shotwell (Resource Ecology and Fisheries Management (REFM), AFSC), Buck Stockhausen (REFM, AFSC), Georgina Gibson (UAF), Jodi Pirtle (HCD, NMFS Alaska Region), Chris Rooper (DFO), Alison Deary (Recruitment Processes Program, AFSC), funded by Alaska EFH Research Plan FY18/19 (Shotwell et al. FY18/19).

    - This integrated modeling study applies biophysical individual-based models (IBM), SDM, spawning locations and biomass, and vital rates to develop EFH Level 1, 2, and 3 information for sablefish (*Anoplopoma fimbria*) and Pacific cod early life history stages in the GOA. Building on the IBM and SDM developed for the

GOAIERP (North Pacific Research Board), this study presents a novel alternative to develop EFH information for early life history stages that are difficult to comprehensively sample by field surveys alone.

In addition to supporting our EFH mandates, the new species-specific habitat information presented by this Discussion Paper can be extended to stock assessment and other ecosystem-based fisheries management (EBFM) efforts for our region. The Ecosystem and Socioeconomic Profiles (ESP) in the Stock Assessment and Fishery Evaluation (SAFE) Reports for Alaska Sablefish (Shotwell et al. 2017, 2018, 2019a) and GOA Pollock (Shotwell et al. 2019b) include SDMs from the 2017 5-year Review (Rooney et al. 2018) and the GOAIERP (Pirtle et al. 2019). Recent studies have also applied these SDMs to test hypotheses about spatial and temporal stock structure in the Bering Sea under future climate scenarios (Rooper et al. in review) and groundfish recruitment processes in the GOA (Goldstein et al. in review). Several milestones of the Alaska EBFM Roadmap Implementation Plan (NMFS 2018) reference actions related to habitat science and EFH. In these examples, information and SDMs developed for EFH are extended in a meaningful context to support fishery and ecosystem management in our region in an effort to *model once and use many times*.

The four studies presented in this Discussion Paper modernize the SDM EFH approach of the 2017 5-year Review and offer new information and techniques for the 2022 5-year Review. This body of work is innovative and inclusive of many contributors that are developing new habitat-linked distribution, abundance, and vital rate information for North Pacific species. This Discussion Paper demonstrates that these approaches can validate extant SDM EFH information and advance EFH descriptions and maps for species in Alaska FMPs, including new and revised EFH Level 1 and 2, and for the first time, Level 3. At this stage, we welcome input from the SSC on the methods, progress-to-date, and planned products presented by this Discussion Paper. We look forward to sharing this completed body of work with the Council and NMFS at a later stage of the 2022 5-year Review.

1 Advancing Model-Based Essential Fish Habitat Descriptions for North Pacific Species

Ned Laman [15], Jodi Pirtle [16], Jeremy Harris [15], Chris Rooper [17], Tom Hurst [18], Christina Conrath [19]

Essential fish habitat (EFH) is a key component of ecosystem-based fisheries management (EBFM) (NMFS EBFM Policy 2016, Peters et al. 2018). In fishery management plans (FMPs), EFH is described for species life history stages with text descriptions and maps at four information levels (EFH Final Rule: 50 CFR 600.815). The first EFH maps for Alaska were limited to qualitative delineations of species observations (Sigler et al. 2012). Echave et al. (2012) later developed quantitative EFH maps by using cumulative distribution frequencies of species observations with habitat covariates for Pacific salmon life stages in the Exclusive Economic Zone (EEZ) off Alaska. In the work presented here, and in our previous studies supporting the 2017 EFH Review (2017 5-year Review) (e.g., Laman et al. 2017, Rooney et al. 2018), we use SDMs to combine species observations of distribution and abundance with habitat covariates to describe and map habitat-linked EFH for species in Alaska FMPs.

Extending SDM to the concept of EFH relies on establishing relationships between a species' spatial population structure and the habitat attributes of their environment (e.g., depth, bottom temperature, current speed, or presence of biogenic structures). Our approach for describing and mapping EFH in the 2017 5-year Review used SDMs to predict habitat-related distribution (EFH Level 1 information) and density (EFH Level 2 information) from field observations of groundfish and crab life stages. We used presence or density from trawl catches as dependent variables with static and dynamic habitat covariates as predictor variables for the three Alaska regions sampled by fishery-independent surveys (eastern Bering Sea, Laman et al. 2017; Aleutian Islands, Turner et al. 2017; and Gulf of Alaska (GOA) Rooney et al. 2018). The SDM-based EFH descriptions and maps from these studies represented substantial refinements that advanced Alaska FMP groundfish and crab EFH from no information to Level 1 for previously undescribed species, life stages, and seasons and from Level 1 to Level 2 for the first time (Fisheries Leadership and Sustainability Forum 2016, Simpson et al. 2017). The North Pacific Fishery Management Council (Council) accepted these new SDM-based EFH descriptions and maps and revised or amended the FMPs for GOA groundfishes and Bering Sea and Aleutian Islands (BSAI) groundfishes and king and tanner crabs (83 FR 31340; May, 2018).

The work that we present here is intended to support the 2022 5-year Review with new EFH information. The information developed in the present studies is current with the best available science for our region and modeling approaches (National Standard 2: 50 CFR 600.315). For the 2022 5-year Review, we will utilize new species catch data, updated life history information, new and updated habitat covariates, and refined modeling techniques to modernize the SDM approach of the 2017 5-year Review. This body of work will re-describe, or describe for the first time in some cases, EFH for life stages of nearly 30 federally managed North Pacific species in the GOA and BSAI groundfish FMPs. The SDMs developed here will also extend to other EBFM information needs (e.g., 2017 SDM have contributed to stock assessments in Ecosystem and Socioeconomic Profiles for Alaska Sablefish (Shotwell et al. 2017, 2018, 2019a) and GOA Walleye Pollock (Shotwell et al. 2019b)), ecosystem processes research to support fisheries management (e.g., Goldstein et al. in review, Rooper et al. in review).

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In the present work we will demonstrate, with case studies of three groundfish species, how our revised SDM EFH approach for the 2022 5-year Review can meet four key objectives for describing EFH in Alaska. The cases studies focus on developing new and revised EFH Level 2 information for these groundfish species life stages:

1. Sablefish (*Anoplopoma fimbria*) subadult and adult life stages in the Bering Sea;
2. Pacific cod (*Gadus macrocephalus*) early juvenile, subadult, and adult life stages in the GOA;
3. Pacific ocean perch (*Sebastes alutus*) (POP) subadult life stage in the GOA.

Using these case studies, we first validate the 2017 SDM EFH approach by assessing the forecasting accuracy of the 2017 models with new data. Second, we develop a revised set of SDM EFH and describe the new information available to update the EFH text descriptions and maps for the 2022 5-year Review. Third, we evaluate how the data updates and model refinements of our revised approach affect SDM performance and EFH map area. To address a fourth objective, we combine the SDM EFH for subadult POP with spatially explicit maps of growth potential to demonstrate one approach to advance EFH information from Level 2 (habitat-related density or abundance) to Level 3 (habitat-related vital rates). This approach has the potential to be extended to other species life stages where vital rates are available from laboratory or field studies.

1.1 WHAT'S NEW?

Overview of Data Updates and Model Refinements

Since the 2017 5-year Review, we have updated our SDM inputs (dependent and independent variables) and refined our modeling methods (Table 1.1). In the following sections of this document we will highlight what is different about the updated data and modeling approaches. The complete methods for our SDM-based approach for describing EFH (both old and updated) are included below in the Methods section, where *italicized* subheadings indicate loci where data or modeling techniques have been updated since the 2017 5-year Review.

1.1.1 Response Variables

The dependent response variables used in our SDM are species occurrence (i.e., distribution) and abundance. Fundamental differences between the response variables presented in the 2017 5-year Review SDM are that we now use the complementary log-log (cloglog) link to approximate abundance (Fithian et al. 2015, Golding et al. in prep) from presence-only and presence-absence models (formerly reported as probability of suitable habitat or probability of presence, respectively) and we use count data with a Poisson distribution and area swept (fishing effort) as an offset instead of 4^{th}-root transformed catch-per-unit-effort (CPUE) and a Gaussian distribution. In the present models, we have incorporated an additional 5 years of NMFS Alaska Fisheries Science Center (AFSC) Resource Assessment and Conservation Engineering Groundfish Assessment Program (RACE-GAP) summer bottom trawl survey data (Table1. 2), extending the terminal year of the dataset from 2014 to 2019. We have also included new sources of data for a newly described life stage with respect to EFH (Table 1.3).

1.1.2 Life History Information

Demography and length-based life stage definitions have been updated since the 2017 5-year Review (Tables 1.4 and 1.5). Updated maturity schedules can be used to re-define subadult and adult life stage breaks for several species. Additionally, we include for the first time the ecologically important early juvenile life stage and describe their EFH. Inshore survey data from the recent update to the AFSC

Nearshore Fish Atlas of Alaska, GOA Integrated Ecosystem Research Program (GOAIERP) Mid-Trophic Level (MTL) studies, and the Alaska Department of Fish and Game (ADFG) small-mesh bottom trawl survey, are combined with AFSC RACE GAP offshore bottom trawl survey data to support modeling early juvenile life stages of some groundfishes in GOA (Pirtle et al. 2019) (Table 1.3).

An example of the nexus of newly available early life stage definitions and maturity schedules is presented here in the Bering Sea sablefish case study, where the upper length limit of the early juvenile sablefish life stage corresponds to length at first maturity of GOA sablefish, which was used in the 2017 5-year Review to define the upper limit of subadults (formerly late juveniles). In the present study, we set the lower length limit of subadults at the length at first maturity and the upper limit at the length at 50% maturity from the GOA (Rodgveller et al. 2016, 2018). This change in life stage definitions resulted in substantial impacts to Bering Sea sablefish EFH areal extent.

1.1.3 Independent Variables

Several independent variables have been updated or added to the suite of habitat covariates for the SDMs (Table 1.1). The bathymetry compilation for the GOA has been extended west and updated (Zimmermann and Prescott 2015, Zimmermann et al 2019). Consequently, we revised the bathymetry-derived seafloor slope covariate for the GOA. We also added a measure of bathymetric position as a new covariate for all regions. Five additional years of environmental data collection during the RACE-GAP summer bottom trawl surveys (2015-2019) have resulted in updates to the regional bottom temperature dynamic covariates as well.

1.1.4 Modeling Refinements

In the 2017 5-year Review, SDM methods were assigned to a species and life stage *a priori* based on their prevalence in trawl survey catch. In the case studies presented here, we use a new approach for assigning SDMs. We apply 4 SDMs (MaxEnt = maximum entropy model, GAM = generalized additive model, paGAM = presence-absence GAM, and hGAM = hurdle GAM) to each species life stage and then use skill-testing to identify the best-performing model. By selecting the model with the lowest root mean-square error (RMSE) we are able to objectively tailor the modeling approach to a species life stage within an Alaska region. Analyses are conducted in R (R Core Development Team 2019) using the *maxnet*[20] and *mgcv*[21] packages (Phillips 2017, Wood 2011).

1.1.5 Introducing Essential Fish Habitat (EFH) Level 3

For the 2022 5-year Review, we integrate field and laboratory studies describing spatially explicit subadult POP growth potential in the GOA with habitat-linked SDM EFH descriptions to demonstrate a method for evaluating Level 3 EFH information (habitat-related vital rates). In this case study, the upper length limit for subadult POP is the length at first maturity (≤ 250 mm FL; Paraketsov 1963, Chikuni 1975), which research suggests corresponds to an ontogenetic shift in habitat use (Chris Rooper, DFO pers. comm., e.g., Pirtle et al. 2019). The work presented here demonstrates an approach to integrating Level 3 information with EFH descriptions and should be considered one potential option for achieving this EFH Research Plan objective. Existing and ongoing studies focused on vital rates (Table 1.6) have the potential to advance EFH information to Level 3 for several more North Pacific groundfish species.

1.1.6 Advancing EFH Information Levels

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[20] R v3.6.1; Fitting 'MaxEnt' species distribution models with 'glmnet'; *maxnet*: R package version 0.1.2.
[21] R v3.6.1; Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models; *mgcv*: R package version 1.8-29

The many updates and additions to survey data described above, along with advances in demographic information and refinements to modeling techniques, help us to meet the EFH Research Plan objectives and address EFH mandates for Alaska. The EFH Final Rule[22] requires that the periodic reviews of EFH take into account available information such as published scientific literature, unpublished scientific reports, and previously inaccessible or unavailable data sources, as we have done here. Modeling refinements to our SDM approach have improved our methodology and will advance EFH information levels for many FMP species in Alaska (Table 1.7). Integrating new data with the modeling refinements has modernized our SDM EFH approach and helped us to meet the two specific research objectives in the revised EFH Research Plan for Alaska (Sigler et al. 2017), to develop Level 1 (distribution) or Level 2 (habitat-related densities or abundance) EFH information where missing, and raise EFH information to Level 3.

1.2 METHODS

1.2.1 Study Areas

Our study applies SDM to federally managed groundfish species found in the 4 large marine ecosystems (LME) off Alaska. The NMFS AFSC RACE-GAP conducts summer bottom trawl surveys in all 4 Alaska LME (Table 1.2). There are two bottom trawl surveys in the Bering Sea LME (eastern Bering Sea shelf (EBS) and eastern Bering Sea shelf and upper continental slope (EBS slope)) and one each in the Arctic LME (the Northern Bering Sea (NBS) survey), Aleutian Islands (AI) LME, and Gulf of Alaska (GOA) LME. In the case studies presented here, 3 of the 4 LME are represented.

Distribution and abundance data from the three surveys in the Bering Sea and Arctic LMEs (EBS shelf, EBS slope, and NBS) are combined in our analyses and hereafter will be collectively referred to as the Bering Sea (BS) data set. This combined BS region, where our modeling studies took place, is bounded by the continental slope in the west (maximum depth of 1200 m), the U.S.-Russia Convention Line and the Bering Strait in the north, Norton Sound and the mainland to the east, and the Alaska Peninsula and Aleutians Islands to the south (Fig. 1.1). The Bering Sea eastern continental shelf is shallow, flat, and comprised mostly of soft, unconsolidated sediments (Smith and McConnaughey 1999) with the majority of the seafloor shallower than 100 m. The upper continental slope (~200-1200 m depth) is steep and encompasses five major submarine canyon zones (Zimmermann and Prescott 2018). The seafloor mosaic of the slope is more diverse than the shelf, with areas of rocky substrate (e.g., Pribilof Canyon) interspersed throughout an area otherwise dominated by soft unconsolidated sediments. The NBS bottom trawl survey area, on average, is half as deep as the eastern Bering Sea continental shelf survey area and is comprised of a relatively low relief mosaic of harder bottom and soft, unconsolidated sediments (Rooper et al. 2016).

The GOA LME is sampled during the RACE-GAP GOA summer bottom trawl survey (GOA survey). The geographic boundaries of the GOA survey study area are Dixon Entrance (133°W) at the US Exclusive Economic Zone (EEZ) border in the east to Unimak Pass (165°W) in the Aleutian Islands in the west (Fig. 1.2). This study area extends from near shore (~20 m depth) to 1000 m depth over a continental shelf and slope that range from 20 km up to > 200 km wide (Rooney et al. 2018). The GOA continental shelf is incised by glacial troughs and valleys that were formed by erosional glacial processes during the Pleistocene ice ages, forming deep channels from inshore areas to the shelf break and slope (Carlson et al. 1982, Zimmermann and Prescott 2015, Zimmermann et al. 2019). The GOA seafloor is diverse, forming a mosaic of rocky substrate and soft, unconsolidated sediments. Areas of extensive rocky substrate that

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[22] 50 CFR 600.815

have been uplifted by tectonic activity are interspersed with areas of unconsolidated substrate (rocky and soft) deposited during glacial retreat.

1.2.2 Survey Design

The RACE-GAP summer bottom trawl surveys have been conducted annually on the EBS shelf (1982-2019), semi-annually on the EBS slope (2002-2016) and NBS surveys (2010-2019), and periodically on the AI and GOA surveys (triennially 1990-1999, biennially 1999-2019). All RACE-GAP trawl surveys follow national trawling protocols (Stauffer 2004). Since 1982, the EBS shelf survey area has been sampled systematically on a regular 25 nautical mile square (nm^2) grid (Conner et al. 2017) that was extended in 2010 to include the northern Bering Sea and Norton Sound (Lauth 2011); this extension was repeated in 2017 and 2019. The EBS slope survey began in 2002, is quasi-biennial (no survey took place in 2006, 2014, or 2018), and has been conducted on the EBS upper continental shelf and slope at depths from 200 to 1200 m (Hoff 2016). The slope survey randomly samples existing stations within depth and area strata and prospects for new stations each survey year. The AI summer bottom trawl survey which began in 1980 became standardized for trawl net, trawling procedure, and trawl duration in 1996. We do not present case studies from the AI survey in this document. In the GOA, summer bottom trawl surveys have been conducted since 1984, but, like the AI survey, trawl nets and trawling procedures have been more consistent and reproducible since the early to mid-1990s (von Szalay and Raring 2018). Survey trawling stations in GOA are allocated using a stratified random sampling design, consistent with previous GOA surveys (von Szalay and Raring 2018), that assigns both previously sampled and previously unsampled stations to the fishing vessels using a modified Neyman optimal allocation strategy (Cochran 1977). The GOA survey is conducted on a 5 km^2 grid superimposed over the region.

All fishes and invertebrates collected on RACE-GAP bottom trawl surveys are identified to the lowest possible taxonomic classification, weighed, and enumerated when possible. Since names and identifications have changed over the survey time series, the data available for certain species and taxonomic groups are limited to certain stanzas of time. For example, arrowtooth and Kamchatka flounder were not confidently distinguished from each other on EBS shelf surveys until around 1992 (Stevenson and Hoff 2009) so only data since and including 1993 surveys were used to parameterize separate models for these two species.

1.2.3 Response Variables: Groundfish Distribution and Abundance

Updated Demographic Information

During the 5 years since the 2017 5-year Review, there have been updates to the life history information available to describe North Pacific groundfish species. Differentiation of early juvenile life stages by length based on ontogenetic habitat associations for several groundfish species (Table 1.4) have refined subadult and adult life stage definitions. We combine survey data (Table 1.3) from inshore areas, where the early juvenile stage of some species are prevalent, with offshore survey data to describe EFH for this ecologically distinct and critical life stage for the first time. Maturity schedules for a variety of North Pacific species have also been updated since the 2017 EFH Review (Table 1.5) leading to additional refinement among the length-based definitions of subadult and adult life stages.

New Data Sources

Guidance from the EFH Final Rule indicates that new and previously unavailable data be considered in the periodic EFH 5-year reviews. Here we include new surveys (Table 1.3) with respect to describing EFH for Alaska with SDM, including data for the ecologically important early juvenile life stages of North Pacific groundfishes. These data collections focus on inshore areas that are typically under-sampled by the RACE-GAP summer bottom trawl surveys. Recent updates to the Nearshore Fish Atlas for Alaska (Lindeberg and Pirtle in prep, Johnson et al. 2012) that is curated by AFSC Auke Bay

Labs, provided samples collected by beach and purse seine (3.2-32 mm mesh) and small-mesh bottom trawls (3.2 cm mesh) from many different sampling efforts in nearshore areas throughout the GOA and other regions. ADFG conducts a small-mesh (3.2 cm) bottom trawl survey for shrimp and fish resources in the central and western GOA that overlaps spatially and temporally with the RACE-GAP summer bottom trawl survey (Jackson and Ruccio 2003, NOAA AFSC 2008) and also includes stations inshore of the RACE-GAP study area. Although the early juveniles of some species also occur in offshore areas (e.g., arrowtooth flounder and walleye pollock; Pirtle et al. 2019), these inshore and small-mesh surveys collect demersal early juvenile life stages from presumed nursery areas that are not well represented in the RACE-GAP GOA bottom trawl study area.

To create a comprehensive dataset for early juvenile GOA Pacific cod in the case study presented here, we combined early juvenile presence data from the inshore surveys described above with early juvenile occurrences in RACE-GAP bottom trawl survey (Fig. S.10). A paucity of occurrence data is a common issue when developing SDMs for early juvenile groundfish life stages and combining data from a variety of surveys with differing sampling designs, gear types, and catchability introduces an issue of comparability across data sources (Laman et al. 2018, Pirtle et al. 2019). To address this issue, we apply a maximum entropy (MaxEnt) model using presence-only data to develop the SDM presented here (e.g. Pirtle et al. 2019). MaxEnt was designed to combine presence-only data from multiple sources in cases of limited species response data (Phillips et al 2006, Guisan et al. 2007, Elith et al. 2011). Although this presence-only method is known to confound sampling intensity with species habitat predictions and a presence-absence approach is preferred when data are available (Fithian et al. 2015), the MaxEnt model provides a valuable starting point to include this ecologically important groundfish life stage that has not been previously described and mapped with respect to EFH for Alaska.

Since the Council and NMFS completed the 2017 5-year Review, an additional 5 years of RACE-GAP summer bottom trawl survey catch data have been collected extending the time series used in 2017 (1982-2014) through 2019. On the EBS shelf, bottom trawl surveys were conducted in each of the 5 years following the last EFH review, extending the time series there from 33 to 38 total years of fishery-independent bottom trawl data. Recalling that the BS data set presented in the sablefish case study here incorporates the EBS slope and NBS bottom trawl surveys, note that 1 more year of EBS slope data and 2 more years of NBS data were added, bringing their totals from 5 to 6 years on the slope and from 1 to 3 years in the NBS. During the same time period (2015-2019), 3 additional years of GOA bottom trawl data were collected (raising the total data years for analyses from 10 to 13) and 5 more years of AI data were added (increasing the number of data years in this region from 20 to 25).

1.2.4 Independent Variables: Habitat Covariates

The full suite of independent variables (habitat covariates) used to predict distribution and abundance from the best-fitting SDM are comprised of static (e.g., bottom depth) and dynamic (e.g., bottom temperature) habitat covariates (Table 1.8, Fig. 1.3). Some of these variables are measured during the bottom trawl survey and others are derived from bottom trawl survey observations or derived or modeled independently of the survey data. Several of these covariates have been updated or newly incorporated since the 2017 5-year Review. All of the habitat covariates included when formulating the SDM for North Pacific groundfish and crab life stages for the 2017 5-year Review were assessed for their potential to influence distribution and abundance of the animals in the LMEs where they were sampled.

Habitat covariates were interpolated on regular spatial grids (rasters) with scales ranging from 100 m^2 to 1 km^2 using natural neighbor interpolation (Sibson 1981), inverse distance weighting (Watson and Philip 1985), ordinary kriging (Venables and Ripley 2002) with an exponential semi-variogram, or empirical Bayesian kriging (Diggle and Ribeiro 2002) with a semi-variogram estimated using restricted maximum likelihood (REML). Much of this was accomplished using ArcGIS mapping software[23], but some was completed on the R computing platform[24] (R Core Development Team 2019). Rasters for our analyses were re-gridded to a resolution of 1 km^2 when the original resolution was on a finer scale. Covariates used in early juvenile stage SDM are a spatial resolution of 100 m^2. All rasters were projected using Alaska Albers Equal Area Conic (EAC) projection (standard parallels = 55° and 65° N and center longitude = 154° W). We assessed multi-collinearity among habitat covariates by examining variance inflation factors (VIF; Zuur et al. 2009). Values of VIF < 5.0 were acceptable for inclusion in the SDMs and calculated VIFs ranged from 1.02 for presence-absence of sea pens and whips in the GOA to 4.07 for maximum tidal current in the BS.

Spatial modeling exercises such as those presented here commonly use a location variable to represent geographical position and to incorporate potential spatial autocorrelation in the residuals (Ciannelli et al. 2008, Politou et al. 2008, Boldt et al. 2012). We chose to combine latitude and longitude into a bivariate position term to delineate spatial trends in our data. Start and end positions for the vessel during the on-bottom portion of the trawl haul were collected for each trawl event using a digital global positioning system (dGPS) receiver mounted on the vessel. Vessel position was corrected to represent the position of the bottom trawl by triangulating how far the net was behind the vessel (based on the seafloor depth and the wire out) and subtracting this distance from the vessel position in the direction of travel of the bottom trawl haul. We assumed that the bottom trawl was directly behind the vessel during the tow and that all bottom trawl hauls were conducted in a straight line from the beginning to the end point. The mid-point of the net’s trawl path between the start and end positions was used as the location variable in the models. The longitude and latitude data for each tow (and all other geographical data including the raster layers described here) were projected into EAC and degrees of latitude and longitude were transformed into eastings and northings for modeling. The location variable was used to identify spatial trends in the bottom trawl survey catches in the regions surveyed.

Updated Gulf of Alaska Bathymetry

Bathymetry rasters for the BS and GOA were developed from several sources. The GOA bathymetry has been updated since the 2017 5-year Review; the BS bathymetry has not. Depth soundings from digitized NOAA National Ocean Service (NOS) smooth sheets and surveys (hydrographic and non-hydrographic) that used single-beam or multibeam acoustic echosounders were compiled for all of the regions represented in this study. Details on the preparation and processing of the bathymetry datasets are documented elsewhere (Zimmermann and Benson, 2013; Zimmermann and Prescott 2014, 2015, 2018, 2019; Zimmermann unpublished data; Lewis unpublished data, additional data[25]). We gridded the point data from these bathymetry datasets at 100 m^2 resolution into regional bathymetry rasters for our study areas, using natural neighbor interpolation (Sibson 1981) in ArcGIS[26]. The resolution of these data rasters was subsequently reduced to 1 km^2 for analysis of the subadult and adult life stages. Data gaps between bathymetry compilations were filled using modeled bathymetry point data estimates from the Regional Ocean Modeling System (ROMS) adapted for the GOA with 3 km resolution (Dobbins et al., 2009; Hermann et al., 2016). Areas of land were removed from the bathymetry rasters using a mask (Alaska DNR coastline 1:63,360).

Updated Seafloor Slope

Seafloor terrain metrics can be derived from gridded bathymetry data using neighborhood-based analysis methods that describe attributes of seafloor morphology. Seafloor slope was recomputed from the

[23] ESRI 2018, version 10.7
[24] R version 3.6.1 “Action of the Toes”
[25] https://www.afsc.noaa.gov/RACE/groundfish/Bathymetry/default.htm
[26] ESRI: version 10.7, Redlands, CA

updated GOA bathymetry. Seafloor slope is the rate of change in bathymetry over a defined area. Slope was derived as degrees of incline from 3x3 neighborhood of grid cells over the 100 m^2 bathymetry rasters using Horn's (1981) method (ArcGIS[27]); higher numbers indicating steeper slopes. This resolution of seafloor slope was reduced to 1 km^2 for analysis of the subadult and adult life stages. Average seafloor slope values were extracted from the slope raster along the trawl path at each trawl haul site to use when training the models and identifying the best-fitting SDM. When model selection retained the seafloor slope term, the complete slope raster was input into the best-fitting SDM when predicting species distribution or abundance.

New Seafloor Terrain Covariate

Bathymetric position index (BPI) describes the elevation of one location relative to the mean of neighboring locations, using an annulus-shaped neighborhood around a central cell or cells (Guisan et al. 1999). This habitat covariate is being included for the first time in the case studies presented here demonstrating our SDM-based EFH approach. BPI emphasizes features that are shallower or deeper than the surrounding area, such as ridges, valleys, and places with abrupt changes in slope; larger absolute BPI values indicate greater differences of a point from its surroundings. Broad-scale measures of BPI (> 1 km) have been useful to distinguish between areas of trawlable and untrawlable seafloor encountered by the RACE-GAP bottom trawl surveys (Pirtle et al. 2015) and as covariates in SDM to describe groundfish habitat in the GOA (Pirtle et al. 2019) and other regions (Wilson et al. 2007, Howell et al., 2011). We derived BPI from EBS bathymetry using a 33-cell radius neighborhood and from updated GOA bathymetry using a 65-cell radius neighborhood; each had an inner radius of 3-cells. This is equivalent to horizontal scales of 3.3 and 6.5 km which represent relatively broad-scale terrain features in our study areas (Pirtle et al. 2019). The BPI rasters were derived from these bathymetry datasets at 100 m^2 resolution and then reduced to 1 km^2 for analysis of the subadult and adult life stages. Average BPI values were extracted from the BPI raster along the trawl path at each trawl haul site to use when training the models and identifying the best-fitting SDM. When model selection retained the BPI term, the complete BPI raster was input into the best-fitting SDM when predicting species distribution or abundance.

Bottom depth and temperature were routinely collected at each trawl haul site, but different instruments were used to measure these values over the survey years (Buckley et al. 2009). From 1982 to 1992, depth and temperature were recorded using expendable bathythermographs (XBTs). In 1993, the XBTs were replaced by the Brancker XL200 digital bathythermographic data logger (Richard Brancker Research, Ltd., Kanata, Ontario, Canada) which was mounted on the headrope of the trawl net. With the advent of continuous temperature and depth recording at the trawl net, the survey began reporting on-bottom depth and temperature averaged over the trawl haul duration. Starting in 2004, the Brancker data logger was replaced by the SeaBird SBE-39 microbathythermograph (Sea-Bird Electronics, Inc., Bellevue, WA). In 1993-1995, mean gear depth measured at the headrope was equated with bottom depth. Since 1996, mean gear depth has been added to mean net height during the on-bottom period of the trawl to estimate mean bottom depth. Since 1996, average net heights for successful RACE-GAP trawls in the EBS were ~2 m and were ~6.5 m in the GOA. Average bottom depth measured during the trawl haul was input when training the models and identifying the best-fitting SDM. When model selection retained the bottom depth term, the complete bathymetry raster was input into the best-fitting SDM when predicting species distribution or abundance.

Updated Bottom Temperature Covariate

Bottom temperature measured at the trawl haul site was used to parameterize and train the SDM when selecting the best-fitting models. Mean bottom temperatures from each trawl haul, incorporating

[27] Benthic Terrain Modeler extension (Walbridge et al. 2018)

data collected since the last EFH review (2015-2019), were interpolated to a 1 km^2 grid in the EBS and GOA regions using empirical Bayesian kriging (Diggle and Ribeiro 2002) with a semi-variogram estimated using restricted maximum likelihood (REML) in ArcGIS. This resulted in distinct temperature raster layers for the EBS and the GOA that represent the average temperature conditions across bottom trawl surveys conducted in these regions throughout the time series (EBS: 1982-2019, GOA: 1993-2019). When the best-fitting SDM retained the bottom temperature term, this temperature raster layer was input into the model to predict distribution and abundance.

Two measures of water movement and its potential interaction with the seafloor were used as habitat covariates in modeling and prediction; maximum tidal speed and bottom current speed. Maximum tidal speed at each bottom trawl haul site was estimated over a lunar year (369 consecutive days between January 1, 2009 and January 4, 2010) for spring and neap cycles using Oregon State University's tidal inversion program parameterized on a 1 km^2 grid (Egbert and Erofeeva 2002). The lunar year maxima of predicted tidal current (tmax) were extracted at each bottom trawl survey haul position and used when selecting the best-fitting SDM. For prediction from the best-fitting SDM, a raster of tmax was kriged over the survey area using an exponential semi-variogram (Venables and Ripley 2002) to interpolate values on a 1 km^2 grid. The second water movement covariate was bottom water layer current speed predicted from ROMS runs 1969-2005 (in Danielson et al. 2011). Long-term current speed and direction were available as points on a 10 km^2 grid. ROMS values were based on a three-dimensional grid with 60 depth tiers for each grid cell. For example, a point at 60 m water depth would have 60 depth bins at 1 m intervals while a point at 120 m depth would have 60 depth bins at 2 m depth intervals. The value from the deepest depth bin at the point closest to the seafloor was used in the analyses. The regularly spaced ROMS data, interpolated by inverse distance weighting to a 100 m^2 grid and further aggregated to a 1 km^2 grid, were used for prediction from the best-fitting SDM when retained in the model. Values from this bottom current raster were extracted at each bottom trawl haul site and the mean value over the trawl path was used when selecting the best-fitting SDM. When one or both of these covariates were retained in the best-fitting SDM, model predictions of distribution and abundance were made using the kriged rasters at 1 km2 resolution.

Sediment grain size from the National Geophysical Data Center Seafloor Sediment Grain Size database EBSSED[28] (Smith and McConnaughey 1999) was incorporated as a predictor variable in the EBS SDMs. Mean grain size (mm) is expressed as *phi* which is the negative $\log_2$-transform of grain size (i.e., a large *phi* indicates fine grains). The sampling tools for this sediment information were bottom grabs and corers, which do not distinguish boulder or bedrock habitat and, as a result, we did not consider these habitat types. The grain size and sorting values from the sediment data (n = 803) were kriged using an exponential model (Venables and Ripley 2002) representing the best fit to the semi-variogram of both grain size and sorting values. Average *phi* values were extracted from the *phi* raster along the trawl path at each trawl haul site to use when training the models and identifying the best-fitting SDM. When model selection retained the *phi* term, the complete *phi* raster was input into the best-fitting SDM when predicting species distribution or abundance.

There is not an equivalent sediment or substrate data set for the whole GOA management area with data lacking in particular west of Shelikof Strait. Sediment data are available for the GOA from Dixon Entrance to Shelikof Strait (Golden et al. 2016) – a surface developed from this data set and others to represent seafloor rockiness increased model fit when applied to groundfish models for the GOA (Pirtle et al. 2019). We will explore utility of a recent surface developed for the GOA representing areas of trawlable and untrawlable seafloor (Dave Bryan, AFSC, pers. comm.), which can be used as a covariate in SDM as a proxy for rocky and not rocky categorical seafloor substrate types, similar to Pirtle et al. (2019).

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[28] URL: http://ngdc.noaa.gov/geosamples/ [accessed 15 November 2016]

Previous studies have indicated that structure forming invertebrates (SFI) such as sponges, corals, and Pennatulaceans (i.e., sea whips) can form important habitat (Heifetz et al. 2005, Malecha et al. 2005, Stone et al. 2011) for temperate marine fishes (Marliave and Challenger 2009, Rooper et al. 2010, Laman et al. 2015) by providing additional structure to the surrounding physical substrate. Presence and absence of SFI can also be indicative of substratum type (Du Preez and Tunnicliffe 2011) since these animals attach to rocks or other hard substrates or anchor in soft substrate to remain in place. Therefore, we included the presence and absence from our trawl catches of grouped sponge, coral, and Pennatulacean taxa as binomial factors in the suite of habitat covariates used when identifying the best-fitting SDM. Rasters of SFI presence-absence were derived from distribution models for each group of animals (Rooper et al. 2014, 2016, 2017) and, when retained in the best-fitting SDM, were used as input to the models when predicting distribution and abundance.

1.2.5 Species Distribution Models (SDM): Maximum Entropy Models

Updated modeling approach: R package updated, cloglog link used to approximate abundance

Maximum entropy models (MaxEnt) is a probabilistic approach to describe species distribution from environmental data at locations where presence has been recorded. MaxEnt was developed to model probability of suitable habitat or species occurrence with presence-only data (*dismo*[29] package in R; Phillips et al. 2006) in cases of rare species and when presence-only data are available from multiple surveys with varied sampling designs or gear types (Guisan et al. 2007, Elith et al. 2011). Subsequent statistical research has shown that MaxEnt models (and other presence-only modeling approaches) are mathematically equivalent to assuming a known distribution of absence data (Warton and Shepherd 2010), and then fitting a presence-absence model to the observed presence data and the assumed distribution of pseudo-absence records. In this way, presence-only models confound sampling intensity and population density such that they result in biased distribution estimates whenever the sampling distribution is not uniform (Fithian et al. 2015). Although a presence-absence model (paGAM) or standard GAM would be theoretically preferred over this approach, the availability of response data is not always adequate to accomplish these SDM with a high level of skill (i.e., our case studies and MaxEnt SDM developed for the 2017 5-year Review). MaxEnt models provide an alternate method that may be advantageous in some circumstances to develop habitat-linked distribution and abundance information to describe EFH for North Pacific groundfish species (Laman et al. 2018, Pirtle et al. 2019).

Recently, Phillips et al. (2017) updated the MaxEnt model (*maxnet*[30] package in R). One advantage of this new formulation is the relative ease of including observed absence locations to inform the background locations in the MaxEnt. However, it is important to note that the MaxEnt model does not fit absences as does a paGAM, which models presence and absence together. Another key advantage of this new implementation for our present work is that the updated model utilizes the cloglog transform in place of the logistic transform of the previous version (Fithian et al. 2015, Golding et al. in prep.). Access to the cloglog link provides an advantage in interpretation and comparability by translating the probability of occurrence generated from the MaxEnt into an approximation of numerical abundance. In addition, the *maxnet* package automatically estimates the regularization parameters that had to be manually tuned in the *dismo* package previously used to run MaxEnt. Features that define the relationship of the covariates with the response data are now also auto-tuned under this new procedure.

MaxEnt models were applied to all life stages of the North Pacific groundfish species treated in these cases studies but the data sources among the life stages differed. The early juvenile life stage distributions come from multiple sampling programs and survey designs and are modeled using the

[29] R v3.6.1; Species Distribution Modeling. Hijmans, R.J., S. Phillips, J. Leathwick, J. Elith. 2017. *dismo*: R package version 1.1-4

[30] Steven Phillips (2017). maxnet: Fitting 'Maxent' Species Distribution Models with 'glmnet'. R package version 0.1.2.

maxnet MaxEnt package from presence-only data. Model results are transformed through the cloglog link into approximations of abundance and validation statistics based on the presence output are provided. The subadult and adult life stage MaxEnt models, also run from the *maxnet* package, incorporate both presence and absence observations from RACE-GAP bottom trawl surveys only, and again, the cloglog transform is used to approximate relative abundance from these modelled probabilities.

Habitat covariates included in the formulation of MaxEnt models were selected *a priori* following the example set in the 2017 5-year Review. For subadult and adult MaxEnt models, all covariates except geographic position and SFI presence-absence factors were included. Early juvenile MaxEnt models were parameterized similarly, but included the SFI presence-absence and bottom temperature factors. Here, bottom temperature is derived as an annual mean climatology from the GOA 3 km ROMS (e.g., Pirtle et al. 2019), rather than bottom temperature from the RACE-GAP surveys, due to improved resolution of this covariate inshore with ROMS. Relative importance of habitat covariates included in the MaxEnt model was estimated using a jackknife procedure, where each covariate was dropped from the model in turn, and the deviance explained by the reduced model was compared to the deviance explained by the full model. Values reported for these covariate effects were scaled to the total deviance explained in the full model.

1.2.6 SDM: Generalized Additive Models

Updated modeling approach: count data, area swept offset, Poisson distribution, cloglog link

We used 3 forms of the GAM in the case studies presented here. The 3 forms were a presence-absence GAM (paGAM), a hurdle GAM (hGAM; Barry and Welsh 2002, Potts and Elith 2006), and a standard GAM (Hastie and Tibshirani 1990). The paGAM is new to the 2022 SDM EFH approach and predicts the probability of species presence utilizing presence-absence data with a binomial distribution and a cloglog link (Wood 2017); we invoke the cloglog link to approximate numerical abundance from the paGAM probability of occurrence (Golding et al. in preparation). The hGAMs model presence-absence and abundance in 3 stages and are advantageous because they account for the over-dispersion and zero-inflation common to field-collected abundance data (McCullagh and Nelder 1989). In the first stage of the hGAM, the probability of presence is predicted from presence-absence data using a paGAM and binomial distribution. For the second stage, an optimal threshold probability for presence is determined by balancing the false positive and false negative predictions of species' presence-absence using the *PresenceAbsence*[31] package in R. In the final stage of the hGAM, a second GAM is constructed for the positive catch counts, using a Poisson distribution and a log link with fishing effort as an offset, to predict numerical abundance from environmental covariates where present (Manel et al. 2001, Barry and Welsh 2002, Wilson et al. 2005). The standard GAM for numerical abundance was also fitted using a Poisson distribution, log link, and fishing effort as an offset.

For each form of GAM applied, model formulation began with the same initial suite of predictor variables within a region and the model was fit to a randomly selected training data set (80% of the total data set) containing the catch count and the corresponding environmental covariates at that sampling location. The remaining 20% of the data were considered the "test" set and were used to provide an independent measure of model fit and prediction accuracy. The basis degrees of freedom used in the smoothing function for each habitat covariate used as predictor variables in the GAMs were constrained following the methods in Weinberg and Kotwicki (2008) to reduce the possibility of overfitting and we used iterative backward stepwise term elimination to remove insignificant terms (based on *p*-values), minimizing the information criterion (the unbiased risk estimator (UBRE) for presence-absence data and the GCV for abundance data) to identify the best-fitting models (Chambers and Hastie 1992; Wood

[31] R v3.6.1; Freeman, E. A. and Moisen, G. (2008). *PresenceAbsence*: An R Package for Presence-Absence Model Analysis. Journal of Statistical Software, 23(11):1-31.

2006). For a species, life-stage combination, and model iteration, the reduced model with the lowest UBRE or GCV was deemed the best-fitting.

1.2.7 Validating SDM

For internal validation of SDMs from the previous and present work, distinct training (80%) and testing (20%) data sets were randomly selected. The training and testing data sets were selected before modeling began and were held constant during analyses of each data class. The larger (80%) segment of data was used to train the SDM (e.g., stepwise term-selection to identify the best-fitting model) while the remaining 20% was used to test and validate the model fit. The habitat covariates in the test data set were used to predict the response using the best-fitting model and a linear coefficient of determination (r^2) from a plot of observed vs. predicted values was used to assess how well the model performed at unsampled locations,

$$r^2 = \left(\frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{(n\sum x^2 - (\sum x)^2)(n\sum y^2 - (\sum y)^2)}} \right)^2$$

where *n* is the number of records, *x* is the observed value, and *y* is the predicted value.

Validating SDM Approach

Another objective of present work was to validate the SDM approach accepted in the 2017 5-year Review. To do this, we compared model predictions generated from the 2017 SDM formulations (data through survey year 2014 in the BS and 2013 in the GOA) with observations from the recently added 5 years of bottom trawl survey data (2015-2019) in the BS (3 survey years of data in GOA: 2015, 2017 & 2019). Subadult BS sablefish and early juvenile GOA Pacific cod were not modeled in the 2017 studies so are not compared here. To assess the level of agreement between predicted and observed point values, we computed an r^2 of the linear relationship between the two sets of values.

1.2.8 Model Selection: Skill Testing

New Approach to SDM Selection

In the case studies presented, we demonstrate skill testing among up to 4 predictive models to identify the best performing, best-fitting SDM. When skill testing, we identified the best-performing model as the one with the least overall error; indicated by the lowest affiliated RMSE value (Hastie et al. 2009) where,

$$\boldsymbol{RMSE} = \sqrt{\frac{\sum(\boldsymbol{y}-\boldsymbol{x})^2}{\boldsymbol{n}}}$$

and *n* is the number of records, *x* is the observed value, and *y* is the predicted value. The RMSE provides a general purpose estimate of the ability of a model to accurately predict abundance at a series of locations. We chose to use the RMSE statistic from the testing data set (the 20% held back) since it was independent of the model fit and potentially provides a more conservative assessment of overall model performance at unsampled locations.

1.2.9 SDM EFH Maps

Maps of abundance predicted for each species and life stage from the habitat-linked SDM are currently used to delineate EFH for North Pacific groundfishes and crabs in Alaska. In the present work, EFH maps for federally managed species were produced as population percentiles of the ordered distribution of positive abundance predictions. For each map of model predictions, 600,000 points were randomly sampled from the prediction raster surface. These were ordered in ascending order with absences (locations with numeric abundance < 0.01 on average) removed and divided into percentiles. Four population percentiles were applied to these abundance predictions (25%, 50%, 75%, and 95%) and were used as break points to translate the model predictions (maps of abundance) into maps of EFH percentiles. The top 95% of abundance predictions for a species and life stage correspond to the standing definition for EFH in Alaska (as reported in Sigler et al. 2017). The top 50% of predictions were termed "core habitat" in the fishing effects analysis for the 2017 5-year Review (Simpson et al. 2017) and we term the top 25% of abundance predictions "hot spots" and consider those areas to represent important habitat for a species life stage.

1.2.10 EFH Level 3: SDM EFH and Vital Rates

We integrated field and laboratory studies describing spatially explicit subadult POP growth potential in the GOA with habitat-linked SDM EFH descriptions to demonstrate a method for elevating EFH information to Level 3 that is new since the 2017 5-year Review. For this case study, subadult POP are defined by length at first maturity (≤ 250 mm FL; Paraketsov, 1963; Chikuni, 1975), which research suggests corresponds to an ontogenetic shift in habitat usage (Chris Rooper, DFO, pers. comm.) that is demonstrated in SDM that apply this life stage break for POP in the GOA (Pirtle et al. 2019). The work presented here demonstrates an approach to incorporating Level 3 information with EFH descriptions and should be considered one potential option for achieving the Research Plan objectives. Existing and ongoing studies focused on vital rates (Table 1.6) have the potential to advance EFH information to Level 3 for several more North Pacific groundfish species.

Rooper et al. (2012), using field and laboratory data collections (Rooper et al. 2007, Boldt and Rooper 2009), parameterized a Wisconsin bioenergetics model (Hewett and Johnson 1992, Harvey 2005) to predict growth rate (g) of subadult POP in the GOA given an estimated level of food consumption. Daily consumption was estimated independent of the bioenergetics model as the weight of prey consumed per gram of fish weight per day using the Elliot-Persson model (Elliott and Persson 1978, Rooper and Haldorson 2000),

$$C_t = \frac{(S_t - S_0 e^{-Rt}) * Rt}{1 - e^{-Rt}}$$

where C_t is food consumption during daylight hours, R is the gut clearance rate, t is the number of daylight hours, S_0 is the stomach contents (weight per gram of body weight) at time 0, and S_t is the average stomach contents (weight per gram of body weight) at time t. Estimates of stomach contents were assumed to be constant over daylight hours. The bioenergetics model also incorporated diet, energetics, and growth data from field and laboratory analyses in a series of EFH-funded studies in the eastern Aleutian Islands from 2003 to 2008 (Rooper et al. 2007, Boldt and Rooper 2009) and was dependent upon zooplankton bloom timing and monthly mean temperatures derived from relationships between satellite-derived sea-surface temperature (SST) and bottom temperature data collected on the RACE-GAP summer bottom trawl survey.

The relationship between SST and observed bottom temperatures was established as a second order polynomial relationship between surface temperature (≤ 1 m depth) and the bottom temperature from data collected on the Gulf of Alaska bottom trawl survey (Rooper et al. 2012). A monthly mean of the optimally interpolated sea surface temperature is available on a 1° latitudinal and longitudinal grid for the entire globe (Reynolds et al., 2002). During the bottom trawl survey, surface and bottom temperatures are collected with a SeaBird SBE microbathythermograph attached to the net headrope at each location where a bottom trawl haul is conducted. The bottom temperature (BT) was predicted as,

$$BT = -0.020ST^2 + 0.596ST + 1.655$$

where ST is the optimally interpolated mean surface temperature for the month in which the bottom trawl haul was conducted. The relationship explained ~40% of the variability ($r^2 = 0.393$, $P < 0.001$) in bottom temperature and was applied to optimally interpolated monthly mean sea surface temperature to calculate bottom temperatures on a 1° grid for the start and end of the growing season. The calculated bottom temperature was then interpolated in daily time steps from the beginning to the end of the growing season and used to predict the daily consumption and the resulting daily growth increment.

The bioenergetics model also incorporated the duration of the growing season inferred from continuous plankton recorder data from the central Gulf of Alaska (Batten and Mackas 2009). Predicted growth from the model run for 1982-2013 accurately reflected growth measured in the field during the 2003-2008 Aleutian Islands EFH projects and generated a spatially explicit calculation of growth potential across the GOA for subadult POP. In combination with EFH descriptions, models like these could be used to estimate the growth potential for other species as well as for subadult POP (Table 1.6).

1.2.11 Tables

Table 1.1. Comparison of species distribution model (SDM) data and methods in the present work with that of the 2017 EFH Review (e.g., Laman et al. 2017): RACE-GAP = NMFS Resource Assessment and Conservation Engineering Groundfish Assessment Program summer bottom trawl surveys; ADFG = Alaska Department of Fish and Game; MaxEnt = maximum entropy model, GAM = generalized additive model, hGAM = hurdle GAM, paGAM = presence-absence GAM.

2017 EFH Review	**2022 EFH Review**
Data: Dependent variables	Data: Dependent variables
RACE-GAP bottom trawl surveys through 2014	+ RACE-GAP bottom trawl surveys 2015-2019 added
	+ Updated Nearshore Fish Atlas beach and purse seines, small-mesh bottom trawls, hook-and-line
	+ ADFG small-mesh bottom trawl surveys
	+ Nursery-affiliated early juvenile life stage (GOA only)
	Length-based life stages
	Maturity-based life stages
Data: Independent variables	Data: Independent variables
Static and Dynamic covariates through 2014	Updated GOA bathymetry
	Updated GOA slope
	+ bathymetric position index (BPI)
	Updated bottom temperature through 2019
SDM methods	SDM methods
MaxEnt (*dismo* package[1])*	MaxEnt (*maxnet* package[2]) †
-	+ paGAM †
hGAM*	hGAM †
GAM*	GAM †
4th root transformed CPUE, Gaussian distribution	Count data with effort offset, Poisson distribution

+ New since 2017 EFH Review

[1] - R v3.6.1; Species Distribution Modeling. Hijmans, R.J., S. Phillips, J. Leathwick, J. Elith. 2017. *dismo*: R package version 1.1-4

[2] - Steven Phillips (2017). maxnet: Fitting 'MaxEnt' Species Distribution Models with 'glmnet'. R package version 0.1.2.

*- An *a priori* model assignment based on species life stage prevalence in RACE-GAP trawl surveys

†- Models count data, using fishing effort as an offset, with a Poisson distribution; using a complementary log-log (cloglog) transformation to convert results to numeric abundance

Table 1.2. National Marine Fisheries Service (NMFS) Resource Assessment and Conservation Engineering Groundfish Assessment Program (RACE-GAP) summer bottom trawl surveys, large marine ecosystems (LME) represented by each, and the data years included in the species distribution models for the 2017 EFH Review (*italics*) and in the present study for the 2022 EFH Review (**bold**).

Survey Name	Large Marine Ecosystem	Data Years Included	Periodicity
Aleutian Islands*	Aleutian Island LME	*1991-2014* **2015-2019**	Triennial (1991-2000), Biennial (2000-present)
Eastern Bering Sea Shelf	Eastern Bering Sea LME	*1982-2014* **2015-2019**	Annual
Eastern Bering Sea Slope	Eastern Bering Sea LME	*2002,'04,'08,'10,'12* **2016**	Periodic
Gulf of Alaska	Gulf of Alaska LME	*1993-2013* **2015, 2017, 2019**	Triennial (1993-2001), Biennial (2001-present)
Northern Bering Sea	Arctic LME	*2010* **2017 & 2019**	Periodic

*For our analyses, we appended the western Gulf of Alaska portions of RACE-GAP summer bottom trawl surveys on to the Aleutian Islands data set in interposing survey years to support the geographic split between the two LMEs at Unimak Pass.

Table 1.3. Catch data sources available to develop SDM of groundfish early juvenile life stages in the Gulf of Alaska (GOA), including location with GOA subregion indicated (western = w, central = c, eastern = e, and all = a), gear type, and years included; ADFG = Alaska Department of Fish and Game, AFSC = NMFS Alaska Fisheries Science Center, RACE-GAP = AFSC Resource Assessment and Conservation Engineering Division Groundfish Assessment Program.

Survey/ Source	Location	Gear Type	Years
RACE-GAP Summer Bottom Trawl Survey (von Szalay and Raring 2018)	GOAa, continental shelf	RACE Poly Nor'Eastern Bottom Trawl	1993-2019
ADFG and ADFG/AFSC Small-mesh Bottom Trawl Survey (Jackson and Ruccio 2003; NOAA AFSC 2008)	GOAce, nearshore, continental shelf	Small-mesh bottom trawl (3.2 cm mesh)	1989-2019
AFSC Nearshore Fish Atlas of Alaska (Johnson et al. 2012; Lindeberg and Pirtle in prep.)	GOAa, coastal, nearshore	Beach seine, purse seine, small-mesh bottom trawl (3.2-32 mm mesh), hook-and-line	1998-2019
GOA Integrated Ecosystem Research Program (GOAIERP) Mid-Trophic Level (MTL) (Ormseth et al. 2016)	GOAa, coastal, nearshore	Beach and purse seine, bottom trawl (3.2-32 mm mesh), hook-and-line	2011
AFSC Sablefish Tagging Program (Rutecki and Varosi 1997; Courtney and Rutecki 2011)	GOAa, nearshore	Hook-and-line	1985-2019

Table 1.4. Length-based life stage breaks (length units = mm) for groundfish species in Alaska FMPs, where a new life stage definition is available for the 2022 EFH Review, including early juveniles (*In* Pirtle et al. 2019), and subadults and adults (i.e., from AFSC maturity schedules; Table 5), with survey region indicated when necessary (AI = Aleutian Islands, BSAI = Bering Sea/Aleutian Islands combined, EBS = eastern Bering Sea, GOA = Gulf of Alaska). Breaks between the subadult and adult life stages for the 2017 EFH Review are indicated parenthetically in *italics*.

Species Common Name	Early Juvenile	Subadult	Adult
Sablefish	150–399	400–585 (≤ *400*)	> 585 (> *400*)
Pacific cod	40–150	BSAI: 151–460; GOA: 151–420	BSAI: > 460; GOA: > 420
Walleye pollock	30–140	AI: 141–290; EBS: 141–250; GOA: 141–370	AI: > 190; EBS: > 250; GOA: > 370
Alaska plaice	40–140	BSAI: ≤ 319; GOA: 141–319 (≤ *280*)	> 319 (> *280*)
Arrowtooth flounder	40–160	161–350	> 350
Flathead sole	40–140	AI: 141–290; EBS: 141–342 (≤ *250*); GOA: 141–290	AI: > 290; EBS: > 342 (> *250*); GOA: > 290
Greenland turbot	–	≤ 571 (≤ *650*)	> 571 (> *650*)
Northern rock sole	80–140	AI: 141–300; EBS: 141–240; GOA: 141–300	AI: > 300; EBS: > 240; GOA: > 300
Yellowfin sole	40–140	141–296 (≤ *250*)	> 296 (> *250*)
Blackspotted rockfish	–	≤ 453 (≤ *430*)	> 453 (> *430*)
Harlequin rockfish	–	≤ 188 (≤ *230*)	> 188 (> *230*)
Northern rockfish	–	BSAI: ≤ 277 (≤ *250*) GOA: ≤ 260	BSAI: > 277 (> *250*) GOA: > 260
Pacific ocean perch	50–200	201–250 (≤ *250*)	> 250
Rougheye rockfish	–	≤ 450 (≤ *430*)	> 450 (> *430*)
Shortraker rockfish	–	≤ 499 (≤ *440*)	> 499 (> *440*)

Table 1.5. Alaska Fisheries Science Center groundfish maturity schedules that have been updated since the 2017 EFH Review (length units = mm) to redefine the length-based life stage breaks applied in the present study for the subadult and adult life stages presented in **Table 1.4**.

Species Common Name	Region	Length@50% Maturity	Life Stage	Source
Pacific ocean perch (POP)	GOA	334	Late Juvenile Adult	Conrath and Knoth, 2013
Blackspotted rockfish (RF)	GOA	453	Late Juvenile Adult	Conrath, 2017
Rougheye RF	GOA	450	Late Juvenile Adult	Conrath, 2017
Shortraker RF	GOA	499	Late Juvenile Adult	Conrath, 2017
Harlequin RF	GOA	188	Late Juvenile Adult	Tenbrink and Helser (unpubl. data)
Sablefish	GOA	515 (2011) 585 (2015)	Late Juvenile Adult	Rodgveller et al. 2016, 2018
POP	AI	324	Late Juvenile Adult	Tenbrink and Spencer, 2013
Northern RF	AI	277	Late Juvenile Adult	Tenbrink and Spencer, 2013
Greenland turbot	EBS	571	Late Juvenile Adult	Helser et al. (NPRB #1605)
Yellowfin sole	EBS	296	Late Juvenile Adult	Tenbrink and Wilderbuer 2015
Alaska plaice	EBS	319	Late Juvenile Adult	Tenbrink and Wilderbuer 2015
Flathead sole	EBS	342	Late Juvenile Adult	Tenbrink and Wilderbuer 2015

Table 1.6. Alaska groundfish species ongoing and existing studies focused on vital rates (e.g., temperature-dependent growth rate) with the potential to advance EFH information to Level 3.

Species	Life Stage	Region	Vital Rate
Arctic cod *	juvenile	Arctic	temperature (temp.)-dependent growth [a], lipids [m]
Walleye pollock	age-0, juvenile	AI, EBS, GOA †	temp.-dependent growth [a, n], prey consumption [b], lipids [m, n], condition [i, k]
Saffron cod *	juvenile	Arctic	temp.-dependent growth [a], lipids [m]
Pacific cod	age-0, juvenile	EBS, GOA †	temp.-dependent growth [a], prey consumption [b], temp.-dependent bioenergetics [c], lipids [m], condition [j, k]
Yellowfin sole	juvenile	EBS, GOA	temp.-dependent growth [d, f, l]
Northern rock sole	juvenile	EBS, GOA	temp.-dependent growth [d ,l]
Alaska plaice	juvenile	EBS, GOA	temp.-dependent growth [d, l]
Arrowtooth flounder	juvenile and adult	AI, EBS, GOA	temp.-dependent prey consumption [b]
POP	juvenile	EBS, GOA	temp.-dependent bioenergetics [g], temp.-dependent growth [h]

[a] Laurel et al. 2016, [b] Holsman and Aydin 2015, [c] Hurst et al. 2018, [d] Matta et al. 2010, [f] Matta and Helser 2016, [g] Rooper et al. 2012, [h] Van der Sleen et al. 2016, [i] Heintz et al. 2013, [j] Farley et al. 2016, [k] Moss et al. 2016, [l] Hurst and Copeman FY18 EFH-funded project, [m] Copeman et al. 2017, [n] Laurel et al. FY17/18/19 EFH-funded project.
* Addressed by Marsh et al. FY19/20 (in prep) for the 2022 EFH Review.
† Addressed by Laurel et al. FY17/18/19 (in prep) for the 2022 EFH Review.

Table 1.7. New and updated information available to advance EFH Levels through SDM for groundfish species in Alaska FMPs in the 2022 EFH Review, including survey data (Bottom Trawl Surveys = RACE-GAP summer bottom trawl surveys; Nearshore Surveys = ADFG small-mesh bottom trawl surveys, Nearshore Fish Atlas beach and purse seines, small-mesh trawls, and hook-and-line sampling) and life history information (Updated Maturity Schedules; Separating Juvenile Life Stages = new distinction between the early juvenile and subadult life stages), and expected SDM advances in EFH Levels from none or Level 1 to Level 2 (L2 EFH Info.) and from Level 1 or Level 2 to Level 3 (L3 EFH Info.).

Group	Common Name	Region	Bottom Trawl Surveys	Nearshore Surveys	Updated Maturity Schedules	Separating Juvenile Life Phases	L2 EFH Info.	L3 EFH Info.
Flatfishes	*Alaska plaice	EBS	updated data	new data, new demographic information	new data, new demographic information		Advancing EFH Information Levels	Advancing EFH Information Levels
	Arrowtooth flounder	AI, EBS, GOA	updated data	new data, new demographic information		new data, new demographic information	Advancing EFH Information Levels	Advancing EFH Information Levels
	Dover sole	GOA	updated data	new data, new demographic information			Advancing EFH Information Levels	
	Flathead sole	EBS, GOA	updated data	new data, new demographic information		new data, new demographic information	Advancing EFH Information Levels	
	Greenland turbot	EBS	updated data	new data, new demographic information	new data, new demographic information		Advancing EFH Information Levels	
	*Northern rock sole	GOA	updated data	new data, new demographic information		new data, new demographic information	Advancing EFH Information Levels	Advancing EFH Information Levels
	*Rex sole	AI, EBS, GOA	updated data	new data, new demographic information		new data, new demographic information	Advancing EFH Information Levels	
	*Yellowfin sole	EBS, GOA	updated data	new data, new demographic information	new data, new demographic information	new data, new demographic information	Advancing EFH Information Levels	Advancing EFH Information Levels
Roundfishes	*Great sculpin	GOA	updated data	new data, new demographic information			Advancing EFH Information Levels	
	*Pacific cod	AI, EBS, GOA	updated data	new data, new demographic information		new data, new demographic information	Advancing EFH Information Levels	Advancing EFH Information Levels
	*Sablefish	EBS, GOA	updated data	new data, new demographic information	new data, new demographic information	new data, new demographic information	Advancing EFH Information Levels	
	*Walleye pollock	AI, EBS, GOA	updated data	new data, new demographic information		new data, new demographic information	Advancing EFH Information Levels	Advancing EFH Information Levels
Rockfishes	*Black rockfish	GOA	updated data	new data, new demographic information			Advancing EFH Information Levels	
	*Blackspotted rockfish	GOA	updated data		new data, new demographic information		Advancing EFH Information Levels	
	*Dark rockfish	GOA	updated data	new data, new demographic information			Advancing EFH Information Levels	
	*Dusky rockfish	AI, EBS, GOA	updated data	new data, new demographic information			Advancing EFH Information Levels	
	*Harlequin rockfish	GOA	updated data		new data, new demographic information		Advancing EFH Information Levels	
	*Northern rockfish	AI, GOA	updated data	new data, new demographic information	new data, new demographic information		Advancing EFH Information Levels	
	*Pacific ocean perch	AI, EBS, GOA	updated data	new data, new demographic information	new data, new demographic information	new data, new demographic information	Advancing EFH Information Levels	Advancing EFH Information Levels
	*Quillback rockfish	GOA	updated data	new data, new demographic information			Advancing EFH Information Levels	
	*Rougheye rockfish	GOA	updated data		new data, new demographic information		Advancing EFH Information Levels	
	*Sharpchin rockfish	GOA	updated data				Advancing EFH Information Levels	
	*Shortspine thornyhead	AI, EBS, GOA	updated data	new data, new demographic information			Advancing EFH Information Levels	
	*Shortraker rockfish	GOA	updated data		new data, new demographic information		Advancing EFH Information Levels	
Skates	*Bering skate	AI, EBS, GOA	updated data	new data, new demographic information			Advancing EFH Information Levels	
	*Big skate	GOA	updated data	new data, new demographic information			Advancing EFH Information Levels	
	*Longnose skate	GOA	updated data	new data, new demographic information			Advancing EFH Information Levels	

* EFH information level advanced to Level 2 for at least one life stage or region sampled

- updated data
- new data, new demographic information
- Advancing EFH Information Levels
- no change

Table 1.8. Static and dynamic habitat covariates used to fit and train species distribution models (SDM) for predicting the distribution and abundance of North Pacific groundfish species in Alaska to describe essential fish habitat (EFH).

Variable	Unit	Definition	Interpolation method	Source
Position	eastings, northings	Midpoint of bottom trawl hauls corrected for position of the trawl net relative to the vessel and project in Alaska Albers Equal Area conic projection	--	DGPS collected at bottom trawl hauls
Depth	meters (m)	Bathymetry of the seafloor based on acoustic seafloor mapping data and digitized and position corrected NOS charts	Natural neighbor	Bathymetry data compilations and unpublished data [a]
Slope	degrees	Maximum gradient in depth between adjacent cells, derived from bathymetry	--	Horn (1981) applied in ArcGIS with Benthic Terrain Modeler (BTM) in ArcGIS (Walbridge et al. 2018)
Bathymetric Position Index (BPI)	--	Relative difference of elevation among neighboring locations, illustrating bathymetric highs and lows across the landscape, derived from bathymetry	--	Guisan et al. (1999) applied with BTM in ArcGIS (Walbridge et al. 2018)
Maximum tidal current	$cm \cdot sec^{-1}$	Predicted tidal current maximum at each bottom trawl location over a lunar year cycle	Ordinary kriging	Egbert and Erofeeva 2002
* Sediment grain size (phi)	--	Sediment grain size derived from sampling in the eastern Bering Sea and curated in the EBSSED database	Ordinary kriging	Smith and McConnaughey 1999
Coral presence or absence	--	Coral presence-absence in bottom trawl catches / raster of predicted coral presence-absence	--	Catch data from bottom trawl hauls with generalized additive model (GAM) (Rooper et al. 2016)
Sponge presence or absence	--	Sponge presence-absence in bottom trawl catches / raster of predicted sponge presence-absence	--	Catch data from bottom trawl hauls with GAM (Rooper et al. 2016)
Whip presence or absence	--	Pennatulacean presence-absence in bottom trawl catches / raster of predicted Pennatulacean presence-absence	--	Catch data from bottom trawl hauls with GAM (Rooper et al. 2016)
Bottom temperature (btemp)	°C	Raster of bottom temperatures measured on bottom trawls during RACE-GAP summer trawl surveys (EBS: 1982-2019, GOA: 1993-2019)	Empirical Bayesian kriging	Temperature data collected at bottom trawl hauls (Diggle and Ribeiro 2002)
Mean bottom ocean current	$m \cdot sec^{-1}$	Seafloor ocean current speed predicted from the ROMS 10 km^2 grid and averaged among years (EBS 1970-2004 and GOA (1996-2011)	Inverse distance weighting	Danielson et al. 2011

a – Zimmermann and Prescott 2014, 2015, 2018; Zimmermann et al. 2019; Steve Lewis (AKRO) unpublished data
* - eastern Bering Sea

1.2.12 Figures

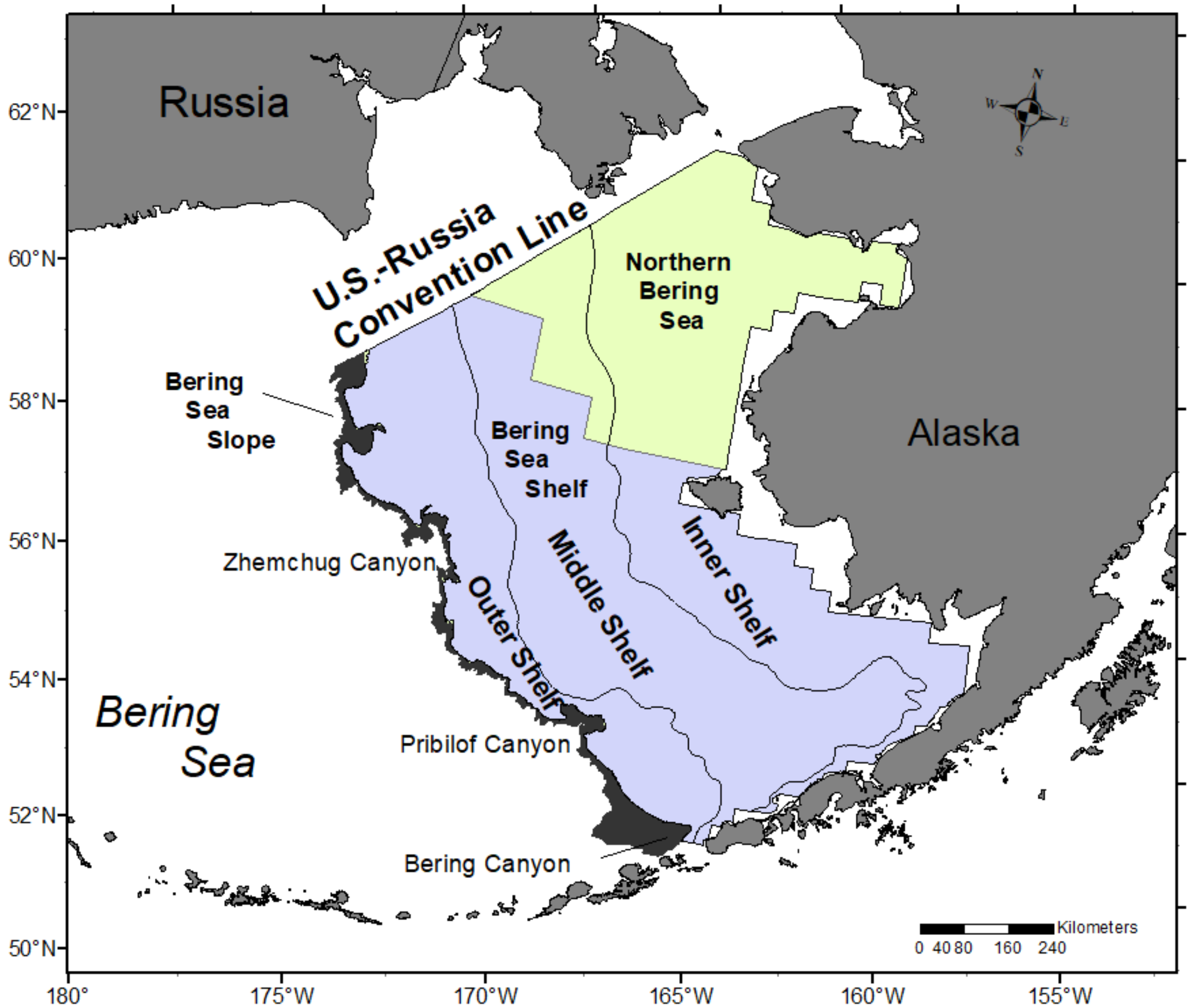


Fig. 1.1. Eastern Bering Sea from the Alaska Peninsula to the northern Bering Sea and U.S.-Russia Convention Line where this modeling study was carried out.

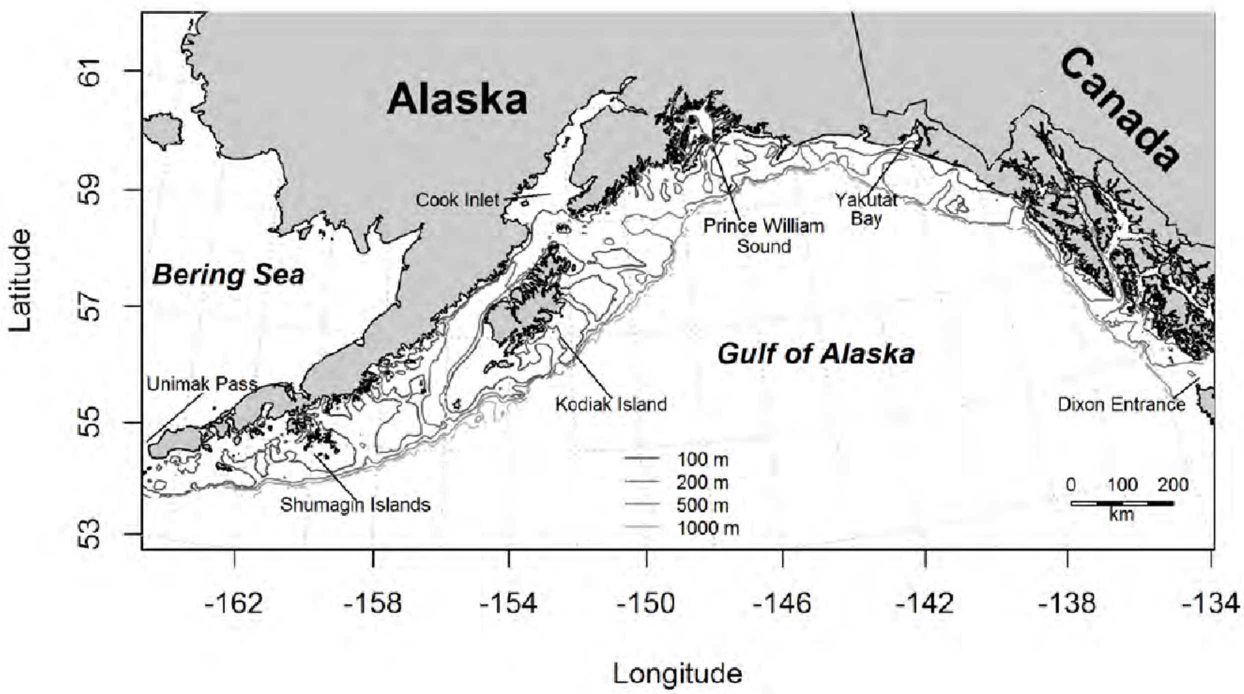
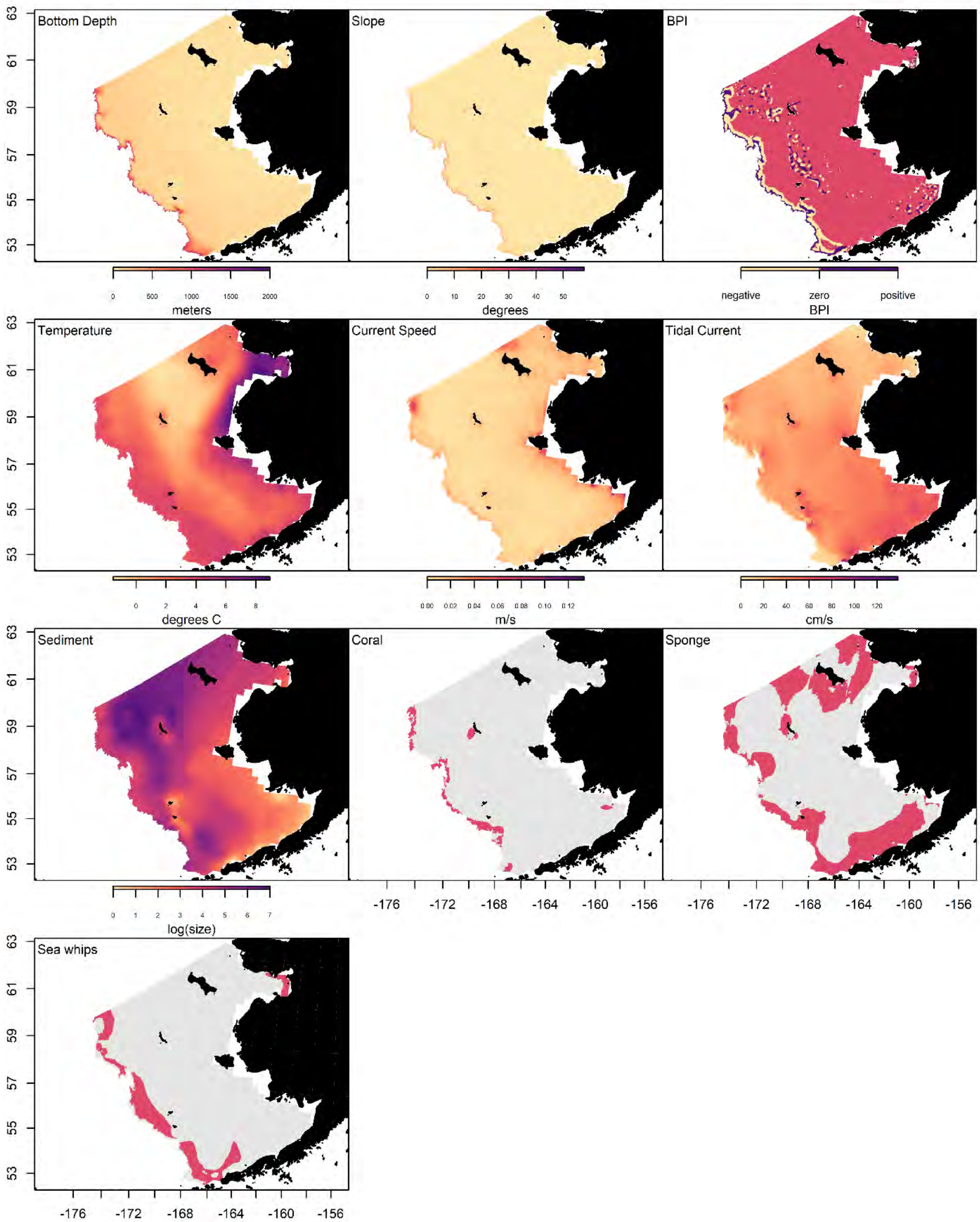


Fig. 1.2. Gulf of Alaska survey area, where this modeling study was carried out, from Dixon Entrance to Unimak Pass.

Fig. 1.3a.


Bottom Depth
Slope
BPI
meters
degrees
negative
zero
positive
BPI
Temperature
Current Speed
Tidal Current
degrees C
m/s
cm/s
Sediment
Coral
Sponge
log(size)
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-168
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-156

Fig. 1.3b.

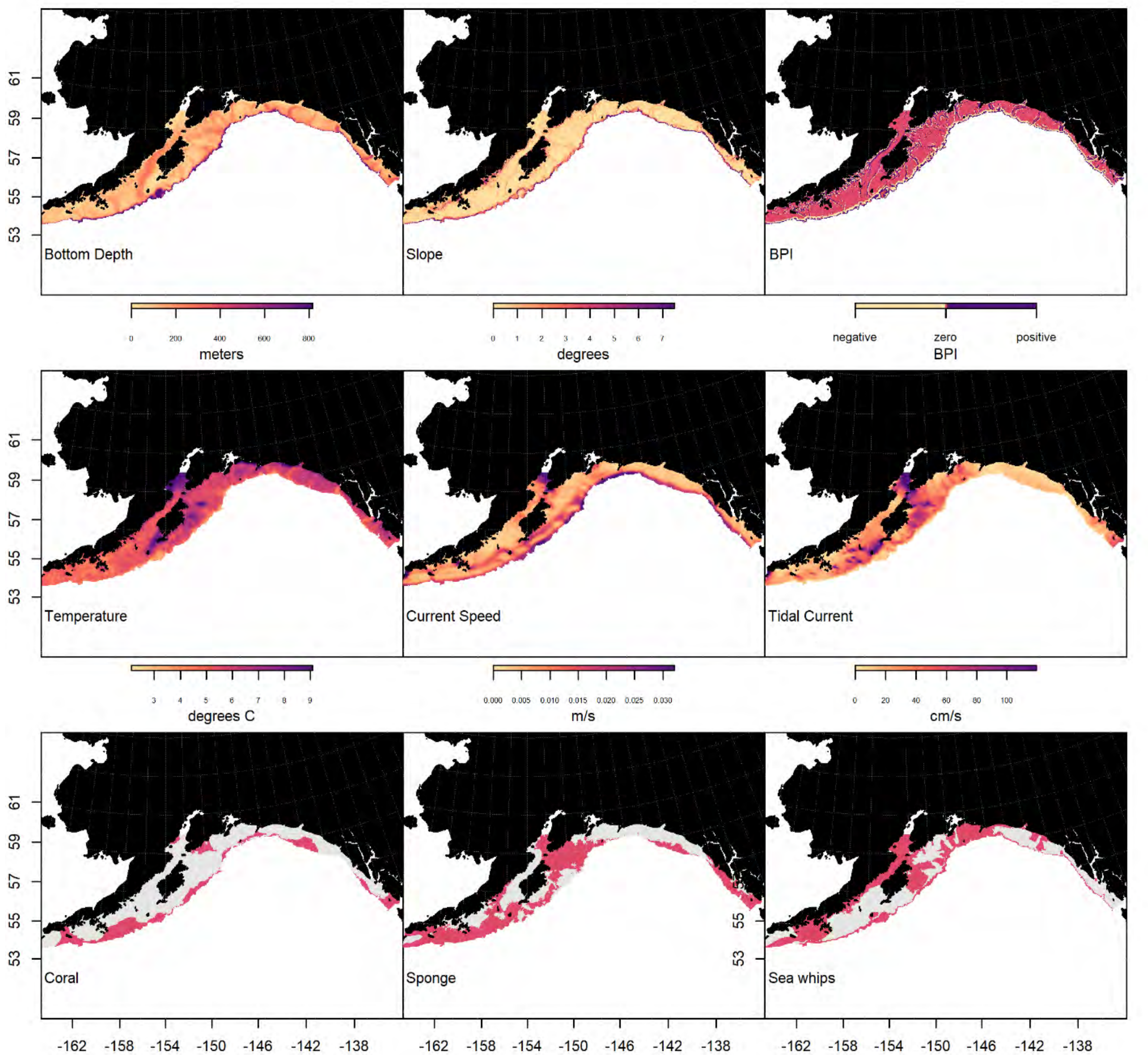

Fig. 1.3. Habitat covariate rasters used in species distribution models for groundfish species life stages in the eastern and northern Bering Sea **(a)** and Gulf of Alaska **(b)**: BPI = bathymetric position index, Temperature = bottom temperature, Current speed = bottom current speed derived from ROMS, Tidal current = tidal maxima, Sediment = *phi* or grain size; Coral, Sponge, and Sea Whips are modeled presence-absence factors.

1.3 RESULTS

1.3.1 Comparing 2017 SDM EFH with EFH from Present Case Studies

In the case studies presented here, we demonstrate a variety of refinements and updates to our SDM EFH approach as it was presented in the 2017 5-year Review:

1. Refined SDM methods,
2. Updated groundfish life stage definitions,
3. Continued collection of RACE-GAP survey data,
4. Addition of new data sources, and
5. Inclusion of vital rates.

We compare the 2017 SDM EFH maps with those generated from our revised SDM EFH approach and indicate where our modeling refinements lead to recommended advances in EFH information levels for each species and life stage (i.e., from none or Level 1 distribution information to Level 2 habitat-related abundance information). An important update to our EFH approach is that we now assign models to species life stages by identifying the best performing SDM through skill testing among 4 separate models. As in the 2017 5-year Review, the selected SDM provides insight into mechanisms of habitat association and is translated into an EFH map that informs the EFH text descriptions.

Comparing the 2017 SDM EFH maps to those based on our refined and updated SDM approach reveals that the areal extent of EFH declined for 3 out of the 4 species life stages presented here (Table 1.9). The two biggest influences on predicted EFH area from our revised SDM approach are updated life stage definitions and switching response variables from 4^{th} root transformed CPUE to count data with a fishing effort offset. These differences in modeling techniques, along with continued data collections and the addition of new data sources, follow the requirements for maintaining standards of best available science (MSA National Standard 2) and incorporating new data when available in EFH 5-year Reviews (EFH Final Rule). Extended results summaries, including maps showing the effect of each update to our modeling approach on the resulting EFH area (e.g., Fig. S.9) are presented in the attached material (Supplement I).

Table 1.9. Case study summaries of the differences among selected species distribution models (SDM) for groundfish life stages in the Gulf of Alaska (GOA) and Bering Sea (BS), comparing the 2017 SDM EFH selection and best performing new SDM (input dependent variable units), 2017 and new EFH map area (km^2), area reduced and added by the new EFH map, and percent difference in EFH area (% ±).

Case Study	2017 SDM	New SDM	2017 EFH (km^2)	New EFH (km^2)	Area Reduced (km^2)	Area Added (km^2)	% EFH Difference
GOA subadult Pacific cod	GAM (CPUE)	hGAM (count)	572,300	271,200	252,300	4,600	-53
GOA adult Pacific cod	GAM (CPUE)	GAM (count)	651,900	578,900	30,700	14,200	-11
GOA subadult Pacific ocean perch	hGAM (CPUE)	MaxEnt (presence/ absence *)	190,700	515,200	600	328,400	+270
BS adult sablefish	MaxEnt (presence)	paGAM (presence/ absence)	190,000	119,400	81,100	11,300	-37

* Presence and absence locations can be utilized in the *maxnet* MaxEnt models (Phillips et al. 2017), as opposed to the presence-only *dismo* MaxEnt models of the 2017 5-year Review (Phillips et al. 2006, R Core Development Team 2019).

1.3.2 Bering Sea Sablefish (*Anoplopoma fimbria*)

We describe subadult sablefish EFH in the BS for the first time in this case study and do so at EFH information Level 2. Subadult sablefish SDM EFH was not developed for the Bering Sea in the 2017 5-year Review because of their low prevalence in survey samples, but, in this case study, refinements to our approach, the addition of more data from continued surveys, and the redefinition of life stages allowed us to describe SDM-based subadult sablefish EFH for the first time. Skill testing identified a standard abundance GAM as the best performing model for this species life stage (Supplement I) and the model explained 55% of the deviance in the abundance data. The most significant covariate terms retained in the best-fitting GAM were geographic position, bottom depth, and sediment size. Model effects indicate that subadult sablefish abundance increases between 300-700 m depth moving offshore and with decreasing sediment size (Fig. 1.4). Subadult sablefish hot spots (locations with the top 25% of predicted abundance) extended from the outer shelf, across the shelf break, and on to the upper continental slope. Overall, subadult sablefish EFH areal extent extends from the BS continental shelf offshore beyond the shelf break and from Unimak Pass northwest to the U.S.-Russia Convention Line (Fig. 1.5). Since SDM EFH was not developed for BS subadult sablefish in the 2017 5-year Review, there is no SDM-based EFH information to compare with the present description.

For adult sablefish in the BS, our revised SDM approach predicted a 37% reduction in the spatial extent of their EFH. This reduction of EFH can be traced primarily to length-based life stage redefinition and to SDM method refinements (Fig. 1.6, Supplement I). The description of a length-based early juvenile sablefish life stage (Hanselman et al., AFSC, pers. comm.) changed the definition of subadults used in the 2017 5-year Review (Table 1.4) so that we shifted the maximum subadult length to correspond to the current definition of maximum sablefish length at 50% maturity (Rodgeveller et al. 2018). This, in turn, reduced the range of lengths categorizing adult sablefish, which contributed to the reduction in sablefish EFH area in the present study.

Skill testing identified the paGAM as the best performing model for adult sablefish, shifting from the presence-only MaxEnt model of the 2017 5-year Review (Table 1.9). The paGAM explained 75% of the deviance in the abundance data. Bottom depth and geographic position were among the most statistically significant terms retained in the SDM describing adult sablefish abundance and model effects (Fig. 1.7) indicated that their abundance was maximized between 700 and 800 m depth moving offshore on to the upper continental slope. Adult sablefish habitat hot spots (top 25% of predictions) were more spatially stable in the face of model refinements and data updates than the area circumscribing EFH (top 95%) in the BS. In the present case, we advanced the BS adult sablefish EFH description from a presence-only distribution model (EFH Level 1) to Level 2, habitat-linked abundance EFH using the cloglog link to approximate abundance from the paGAM-predicted probability of presence.

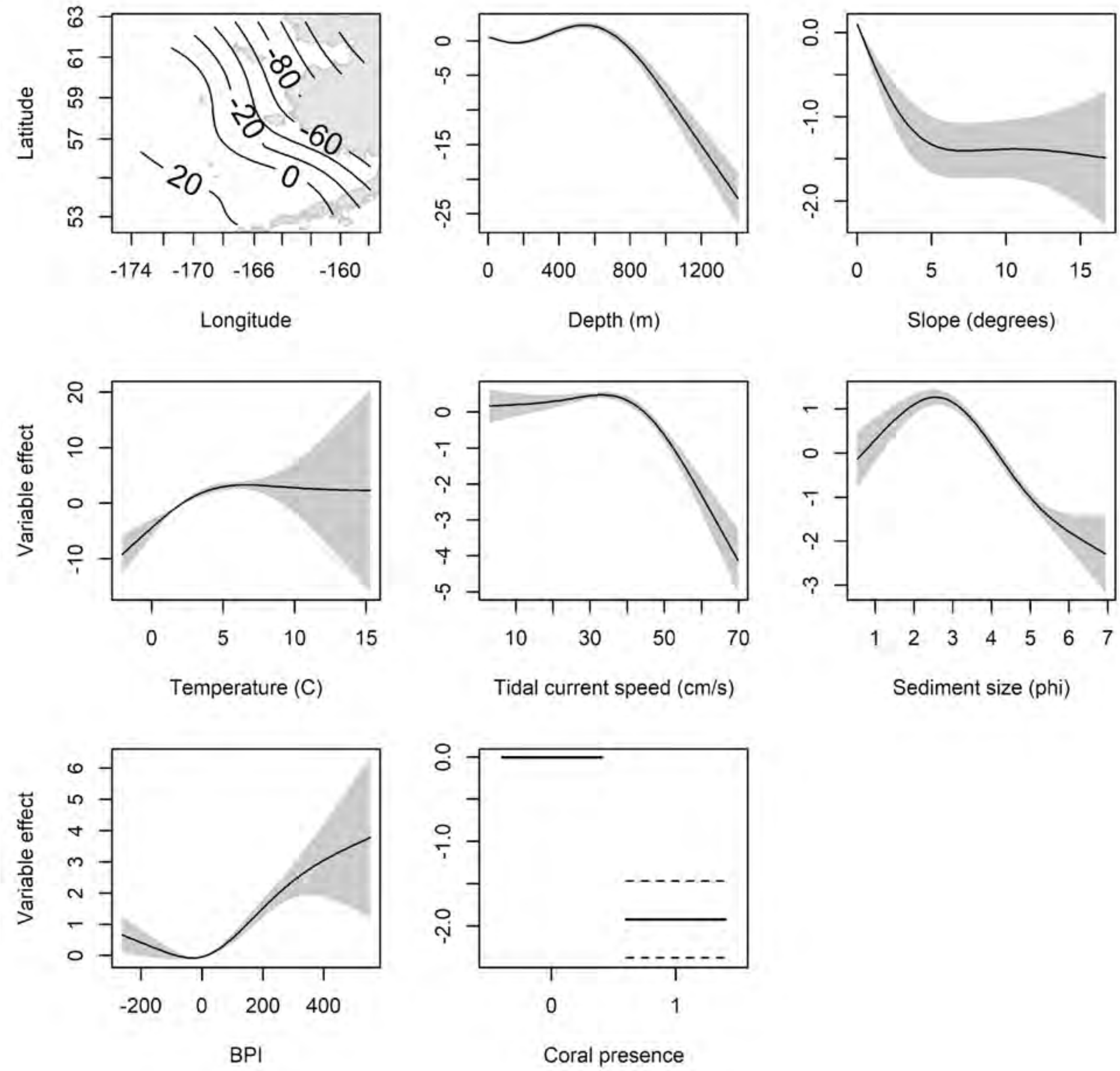

Fig. 1.4. Habitat covariate effects in the standard GAM predicting Bering Sea subadult sablefish abundance for the first time from RACE-GAP summer bottom trawl surveys (1982-2019).

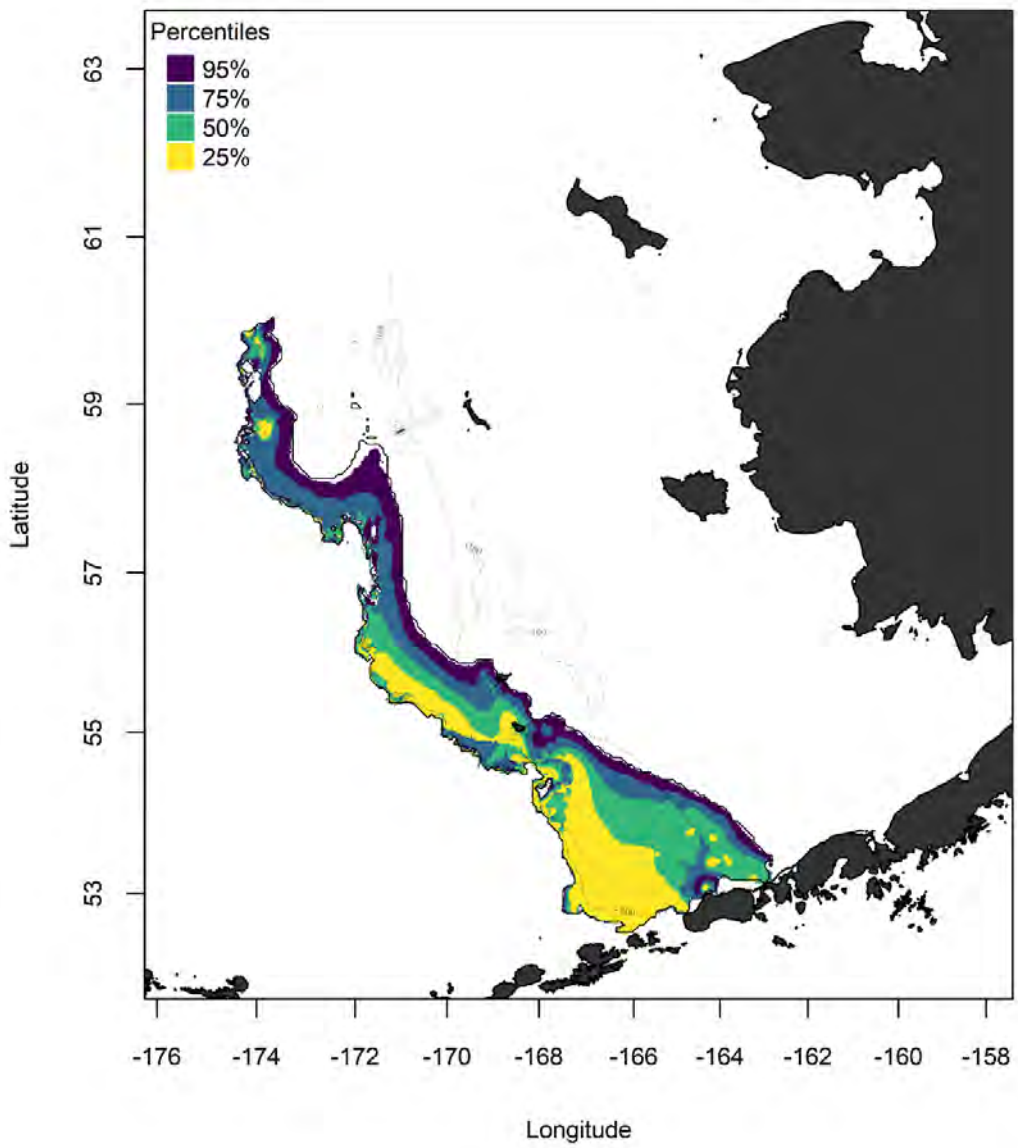

Fig. 1.5. Composite of Bering Sea subadult sablefish EFH percentiles (25% = "hot spots", 50% = "core habitat", all colored areas (25-95%) = EFH) constructed from species distribution model (SDM) predicted, habitat-linked abundance using RACE-GAP summer bottom trawl surveys (1982-2019); contours are 100, 200, and 500 m isobaths.

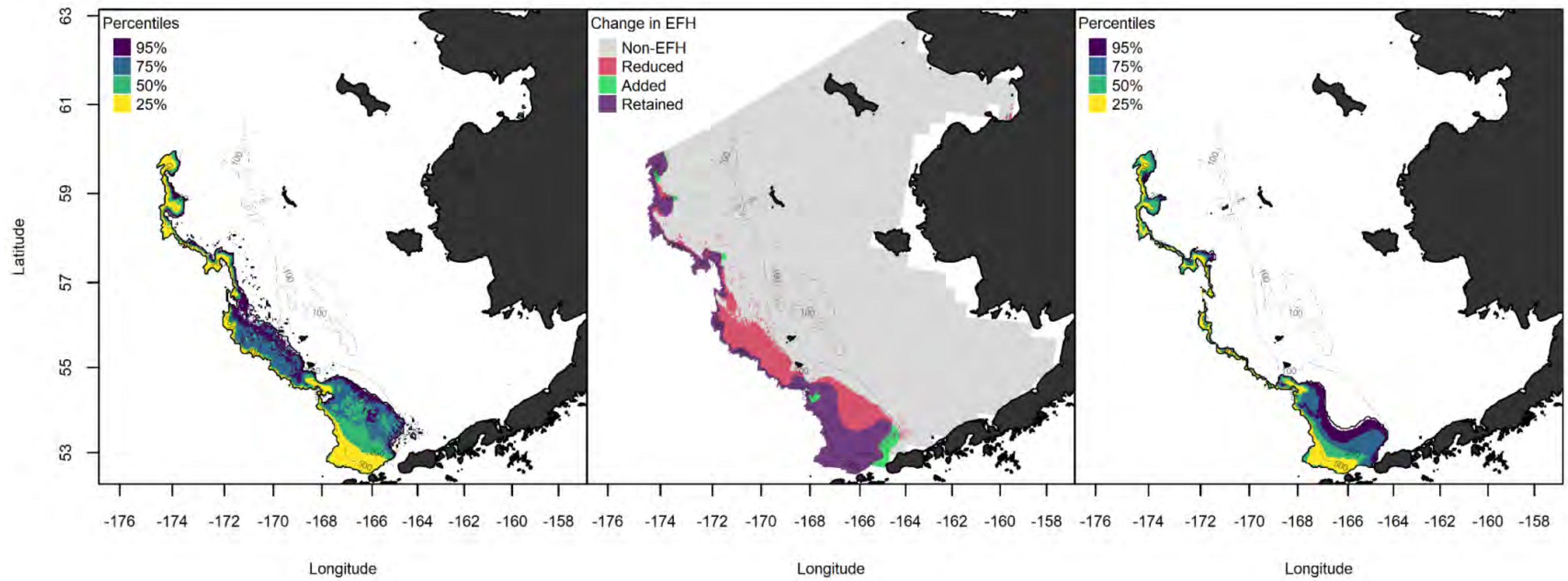

Fig. 1.6. Bering Sea adult sablefish 2017 EFH percentiles **(left)** from RACE-GAP summer bottom trawl surveys (1982-2014; Laman et al. 2017), changes in EFH area between the 2017 EFH map and the new EFH map **(center)**, and new EFH percentiles **(right)** (1982-2019), where 25% = “hot spots”, 50% = “core habitat”, and all colored areas (25-95%) = EFH); contours are the 100, 200, and 500 m isobaths.

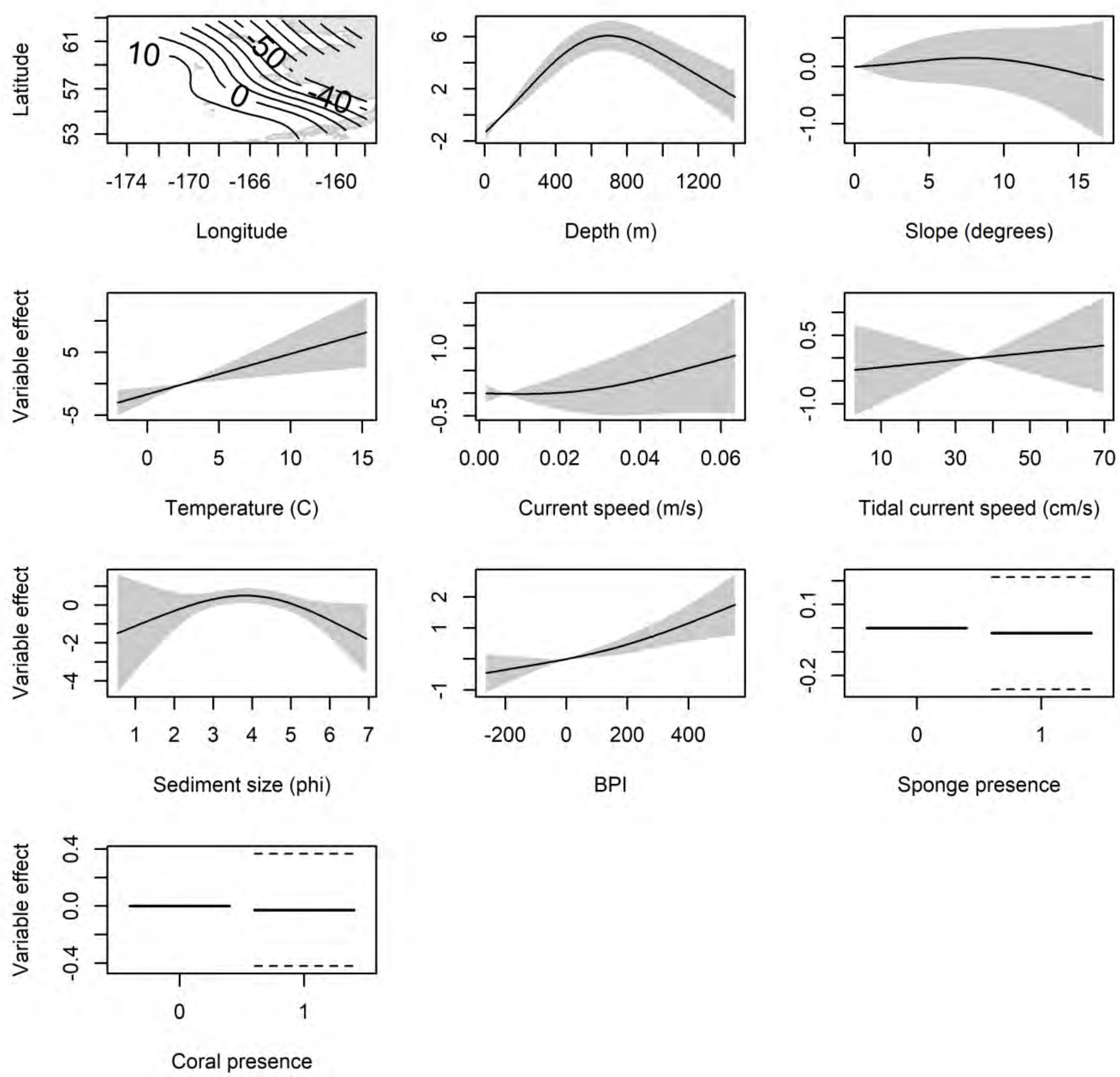

Fig. 1.7. Habitat covariate effects of the paGAM predicting Bering Sea adult sablefish abundance from RACE-GAP summer bottom trawl surveys (1982-2019).

1.3.3 Gulf of Alaska Pacific Cod (*Gadus macrocephalus*)

We now distinguish Pacific cod early juveniles from subadults in the GOA (e.g., Pirtle et al. 2019) and so describe their EFH in the GOA for the first time here. To model their distribution and abundance, we used presence-only data in a MaxEnt model (*maxnet*; Phillips et al. 2017) to combine a variety of surveys (nearshore and offshore) and gear types (Table 1.3) and used the cloglog link to approximate abundance from the model results. The total deviance in the response data explained by this SDM was ~28%. Bottom depth and local slope were among the terms with the highest leverage in the model and, combined, accounted for ~73% of the total model deviance explained. The abundance of early juvenile Pacific cod was highest at shallow depths on the continental shelf and in nearshore areas, increased with increasing BPI and bottom current speed, and increased slightly with increasing bottom temperature up to a maximum of 10°C (Fig. 1.8). Early juvenile Pacific cod EFH occurred across the GOA continental shelf primarily in waters shallower than 200 m (Fig. 1.9). Habitat hot spots for this species life stage (top 25% of predictions) were spread throughout the region typically in coastal areas and in shallower waters (< 100 m depth). The EFH description for early juvenile Pacific cod is based on habitat-linked abundance and is, therefore, EFH Level 2.

A revised SDM modeling approach, combined with updates to dynamic covariates (e.g., bottom temperature), adjustments to the length ranges defining GOA Pacific cod life stages, and the addition of 3 more survey years of bottom trawl survey data were all incorporated into predictions of the distribution and abundance of subadult and adult Pacific cod in the GOA, which were used to describe their EFH. Results from these revised models yielded reductions to the spatial extent of subadult (53%) and adult (11%) Pacific cod EFH in the GOA (Table 1.9). The updated quantitative approach in the best-performing SDM appears to be the largest contributor to the reductions in EFH area for both life stages when comparing studies (Supplement I). In the present work, the best performing model for each life stage was identified by skill testing among SDM and selecting the model with the lowest RMSE. The best performing subadult Pacific cod model was the hGAM (explained 21% of the deviance in the abundance data) and the best performing adult model remained a GAM (now explaining 23% of the deviance in the abundance data). Static habitat covariates geographic position, bottom depth, and slope were among the most significant terms retained in the best-fitting hGAM predicting subadult Pacific cod abundance and the model effects indicate that their abundance was higher in the western and central Gulf in shallower waters (< 200 m) over moderate slopes (Fig. 1.10). Both static and dynamic habitat covariates were retained in the best-fitting GAM predicting adult Pacific cod abundance. Model effects on adult Pacific cod indicate that abundance was higher in the western GOA and southeastern Alaska at bottom temperatures around 5°C, bottom depths shallower than 300 m, and tidal maxima around 100 $cm \cdot s^{-1}$ where SFIs were absent (Fig. 1.11). Pacific cod EFH is primarily distributed over the GOA continental shelf in waters < 200 m depth with subadult EFH largely restricted to the western GOA while adult EFH is more widely dispersed throughout the region (Fig. 1.12). Habitat hot spots for both of these Pacific cod life stages are focused in the central and western GOA. Pacific cod subadult and adult EFH in the GOA are both described at EFH Level 2, which is unchanged since the 2017 5-year Review.

2017 SDM EFH Method Validation

One of our objectives in the present study was to validate the 2017 SDM EFH approach for modeling groundfish distribution and abundance and translating those predictions into EFH maps. We used the 2017 SDM formulations (based on 1993-2013 survey data) to make predictions that were compared with observed distribution and abundance from the 3 additional years of GOA surveys (2015, 2017, 2019). Results of this validation exercise indicated that agreement between observed and predicted distribution and abundance was fair (r^2 = 0.17 subadults; r^2 = 0.16 adults; Table 1.10). For further comparison, the 2017 SDM performed slightly better in internal cross validation than the present model with r^2 values ranging from 21-27% across training and testing data sets.

Table 1.10. Summarizing the performance of the 2017 SDM EFH for subadult and adult GOA Pacific cod (Gaussian catch-per-unit-effort (CPUE; 1993-2013) GAM; Rooney et al. 2018) to forecast abundance of these life stages in three subsequent RACE-GAP summer bottom trawl survey years (2015, 2017, 2019); r^2 = coefficient of determination and RMSE = root mean square error.

	r^2		RMSE	
Data Set	**Subadult**	**Adult**	**Subadult**	**Adult**
Training	0.27	0.24	0.56	0.71
Test	0.23	0.21	0.59	0.76
Forecast	0.17	0.16	0.54	0.68

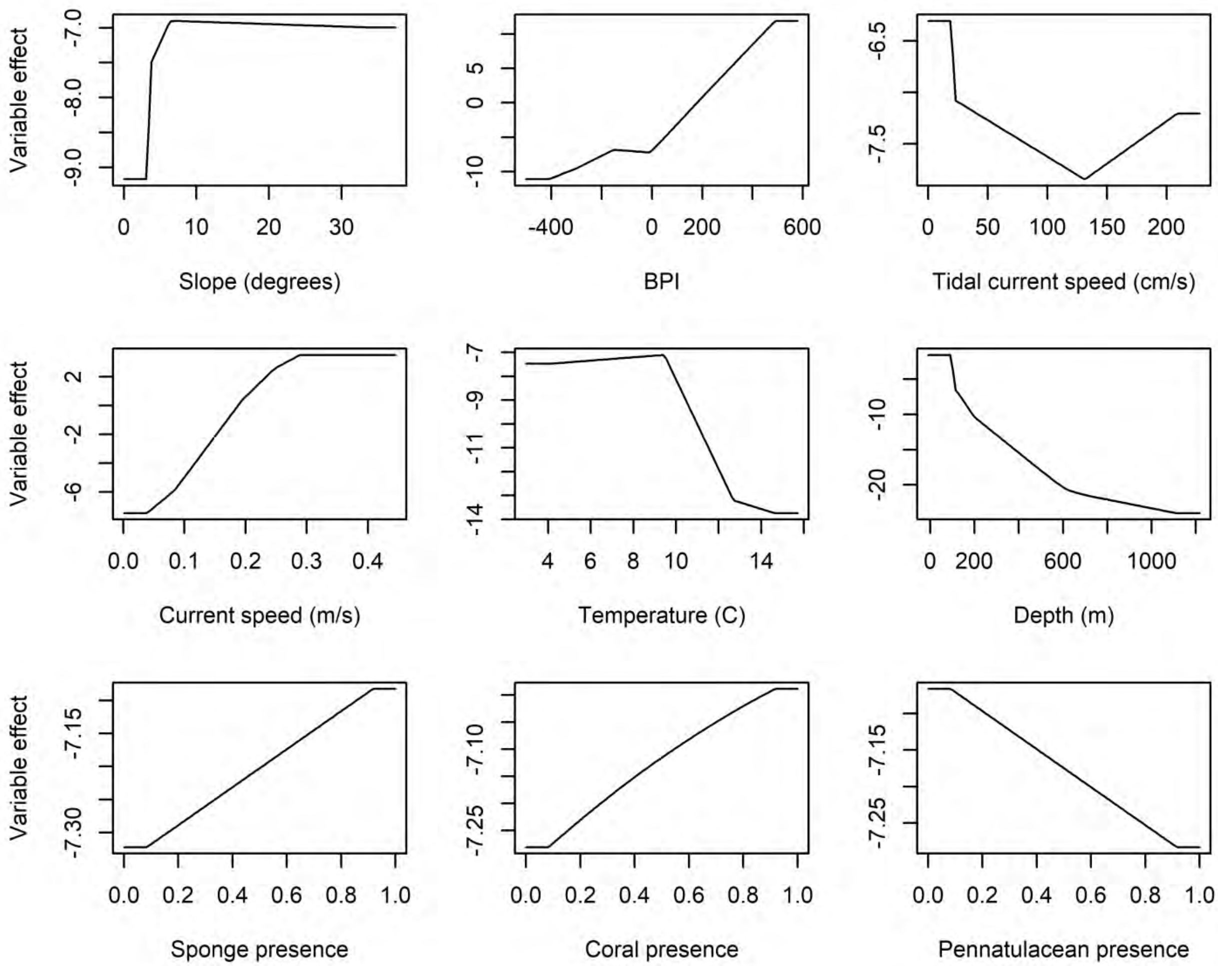

Fig. 1.8. Habitat covariate effects in the MaxEnt model (presence-only) predicting early juvenile Pacific cod abundance (cloglog) from a combination of survey data sources (e.g., beach seines, hook-and-line, small-mesh bottom trawls, and RACE-GAP Poly Nor'Eastern bottom trawl; 1993-2019).

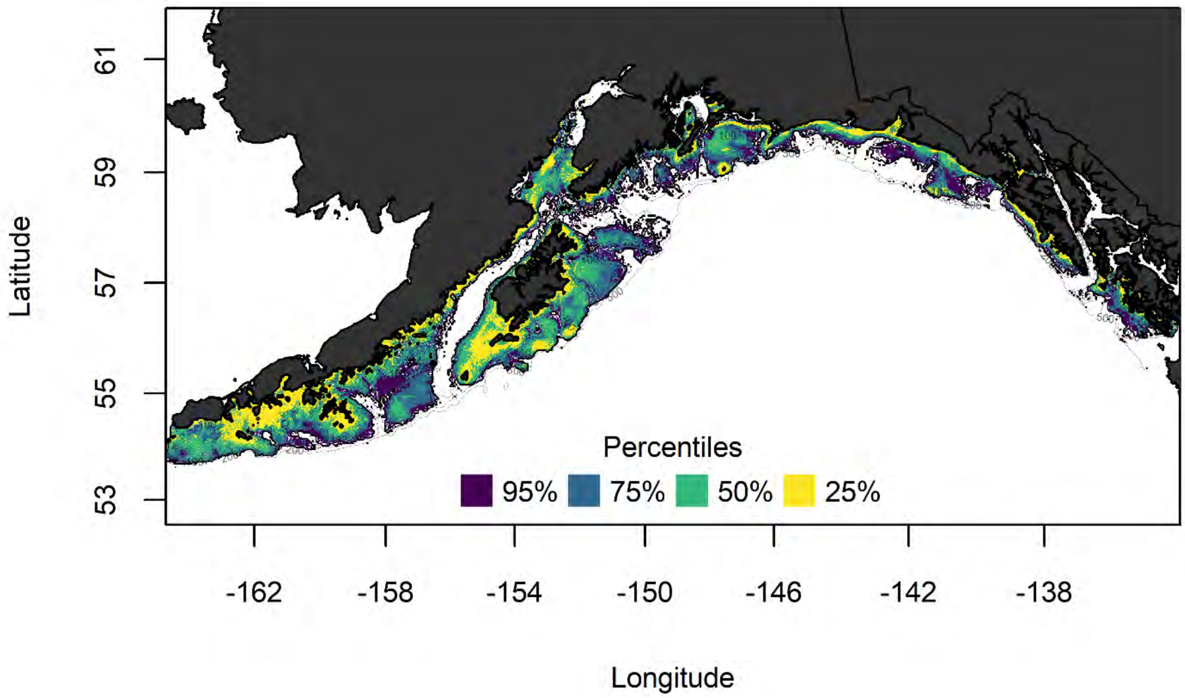

Fig. 1.9. Composite of Gulf of Alaska early juvenile Pacific cod EFH percentiles (25% = "hot spots", 50% = "core habitat", all colored areas (25-95%) = EFH) constructed from MaxEnt model cloglog approximated abundance from a combination of survey data sources (1993-2019); contours are 100, 200, and 500 m isobaths.

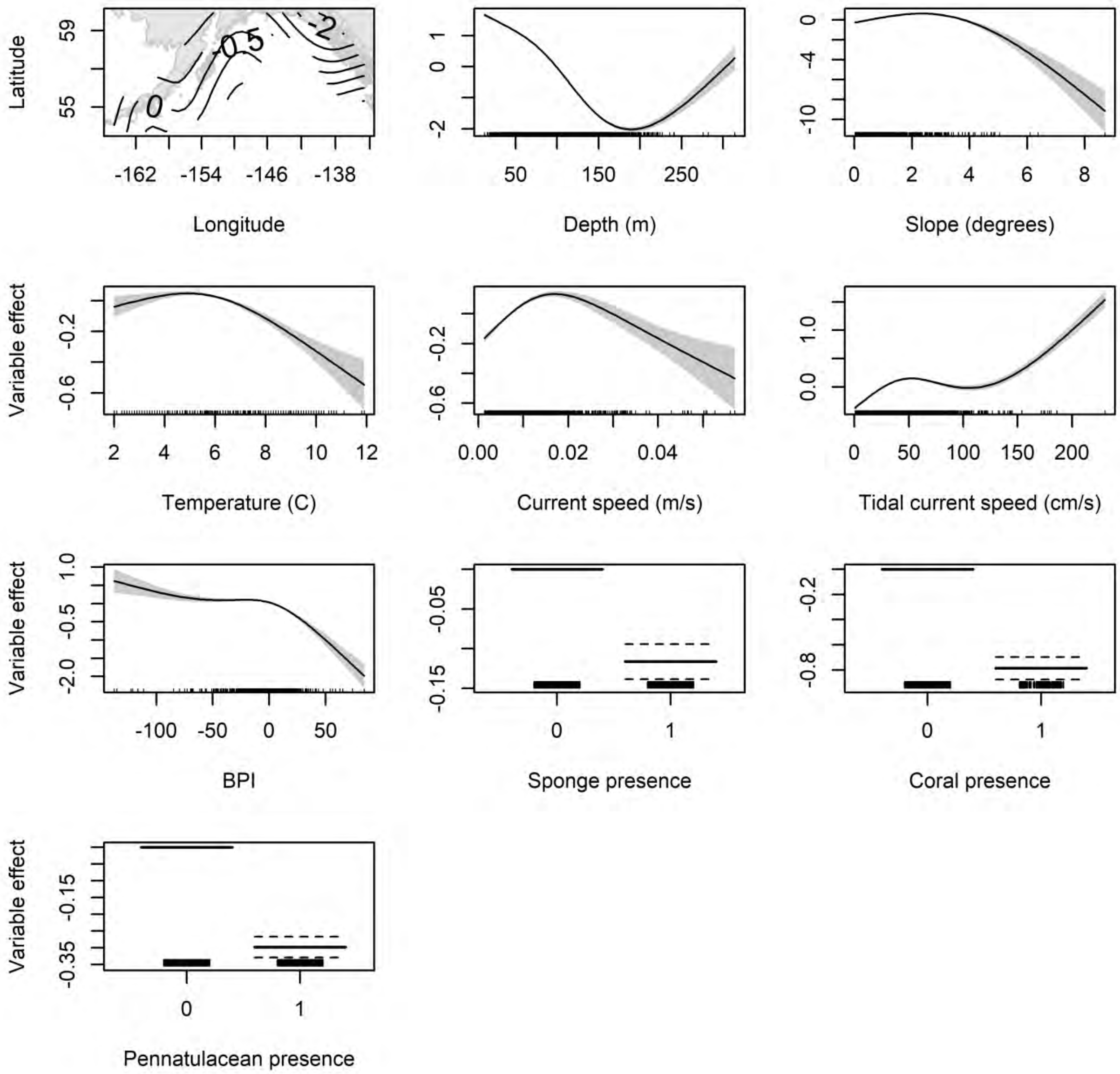

Fig. 1.10. Habitat covariate effects in the hGAM predicting subadult Pacific cod abundance from RACE-GAP summer bottom trawl surveys of the Gulf of Alaska (1993-2019).

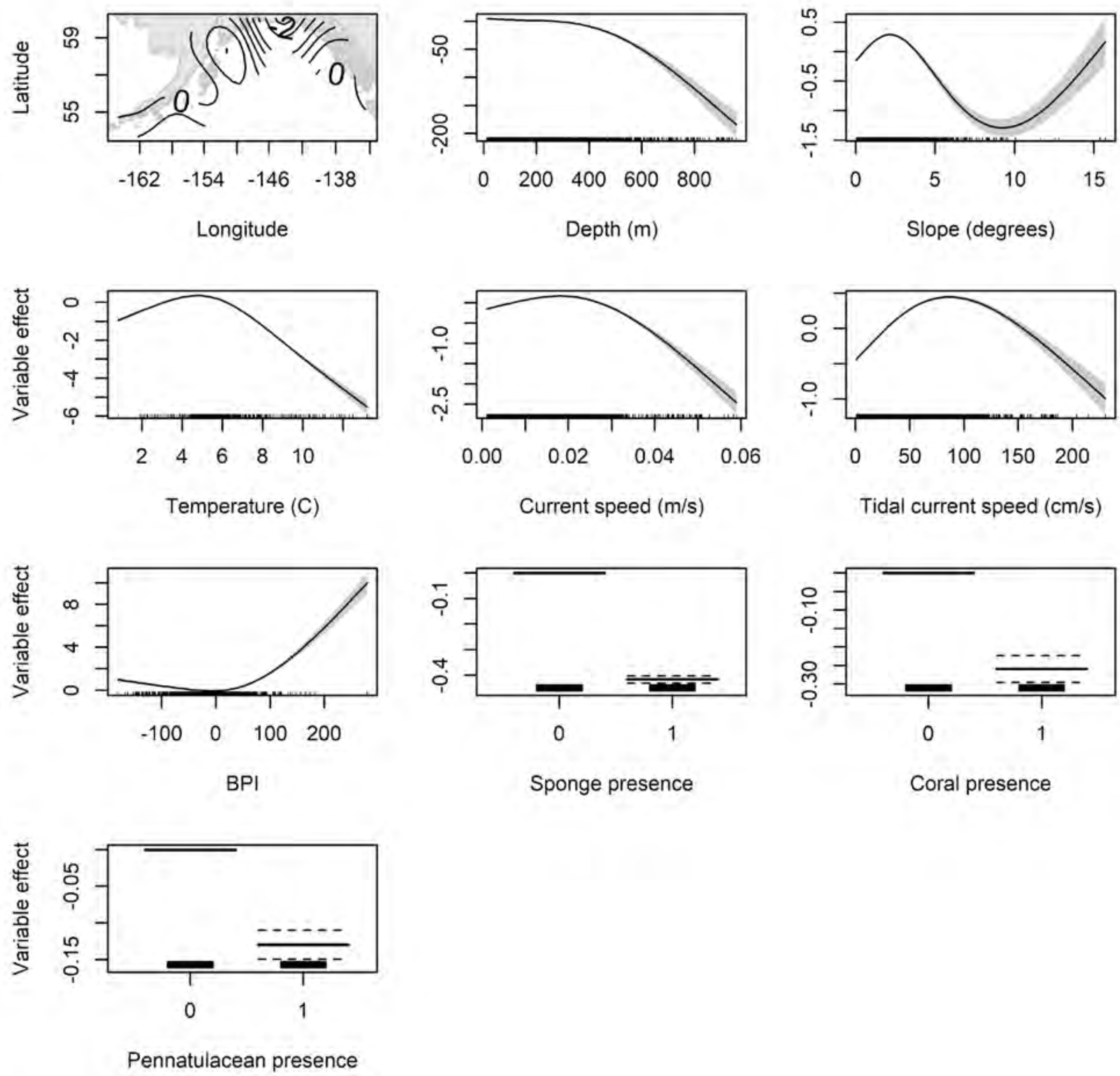

Fig. 1.11. Habitat covariate effects in the GAM predicting adult Pacific cod abundance from RACE-GAP summer bottom trawl surveys of the Gulf of Alaska (1993-2019).

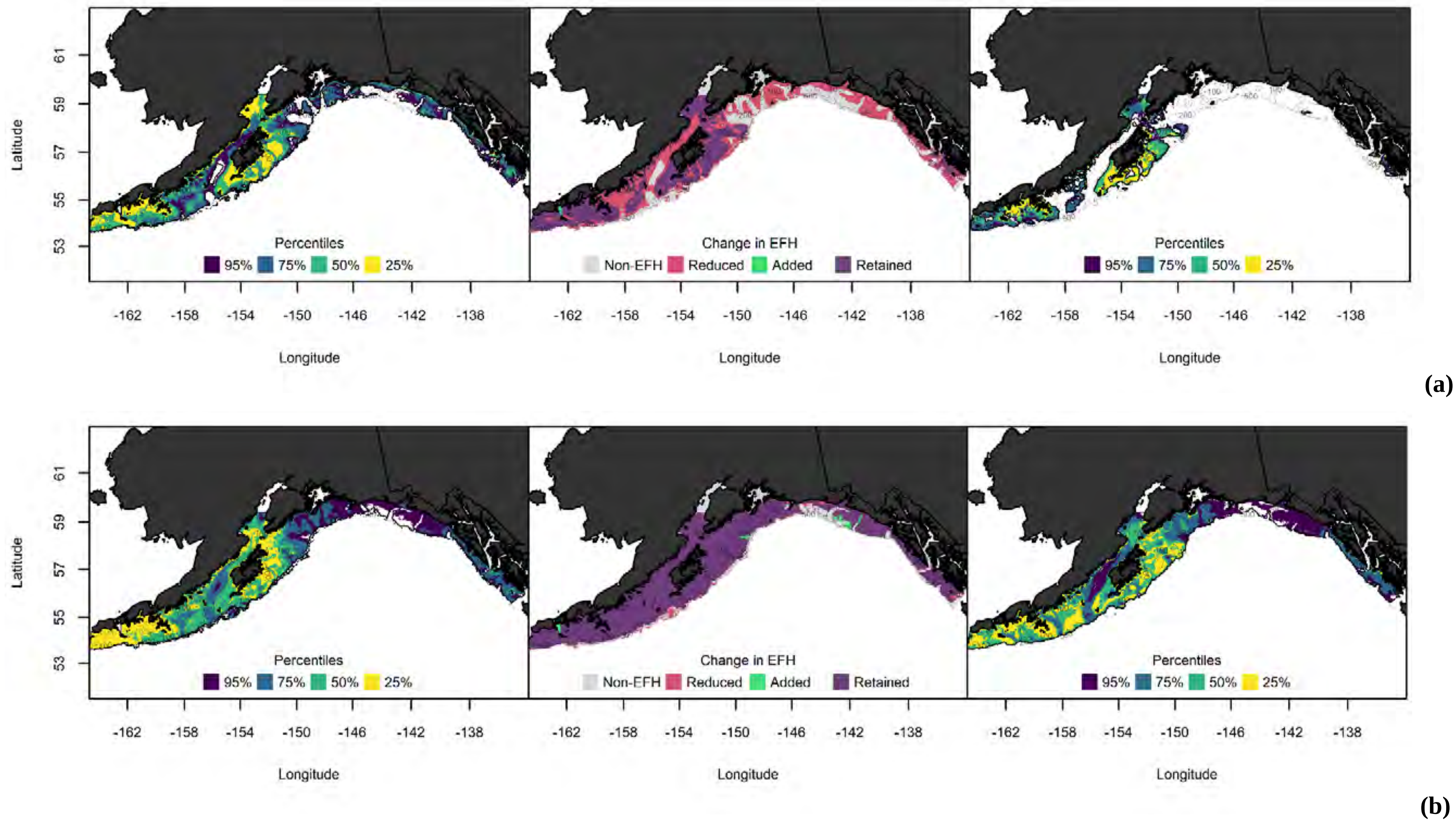

Fig. 1.12. Gulf of Alaska Pacific cod 2017 EFH percentiles **(left)** from RACE-GAP summer bottom trawl surveys (1993-2013; Rooney et al. 2018), changes in EFH area between the 2017 EFH map and the new EFH map **(center)**, and new EFH percentiles **(right)** (1993-2019), where 25% = "hot spots", 50% = "core habitat", and all colored areas (25-95%) = EFH for subadults **(a)** and adults **(b)**; contours are the 100, 200, and 500 m isobaths.

1.3.4 Gulf of Alaska Pacific Ocean Perch (*Sebastes alutus*)

Refinements to the SDM approach used to describe subadult GOA Pacific ocean perch (POP) EFH, updates to dynamic covariates (e.g., bottom temperature), redefinition of GOA POP life stages, and the addition of 5 more years of bottom trawl survey data resulted in changes to EFH area (Fig. 1.13). Updates to the SDM approach and selection of the MaxEnt model through skill testing (compared with the hGAM using 4^{th} root transformed CPUE in 2017) had the greatest influence on changes to subadult POP EFH area (Supplement I). Model effects indicate that predicted subadult POP abundance was maximized at depths ~250 m, bottom temperatures ~6°C, bottom current speeds ~0.25 $m \cdot s^{-1}$, and decreased with increasing BPI (Fig. 1.14).

By recognizing an early juvenile POP life stage (FL ≤ 200 mm), and consequently redefining the lower limit of subadult POP, we will generate the first description of EFH for early juvenile POP in the GOA (e.g., Pirtle et al. 2019), advancing the EFH information level for this life stage from none to Level 2 meeting a key objective of the Alaska EFH Research Plan (Sigler et al. 2017). GOA POP subadult EFH area more than doubled in the present study (Table 1.9) compared with the description from Rooney et al. (2018). In practice, the MaxEnt model is one of the most inclusive SDM we have applied and hGAM is the most restrictive, which helps to explain the large increase in predicted EFH area. We advanced EFH for subadult POP in the GOA from Level 1 (hGAM) to Level 2 (MaxEnt with cloglog transform of presence-absence to an approximation of relative abundance).

2017 SDM EFH Method Validation

For the model validation exercise, we compared predictions from the 2017 GOA POP subadult SDM (1993-2013) with observations from the 3 additional years of GOA surveys (2015, 2017, 2019), which indicated that agreement between observed and predicted distribution and abundance was fair (r^2 = 0.21; Table 1.11). For further comparison, the forecast from the new subadult SDM EFH performed slightly better than the 2017 model (hGAM) in internal cross validation where r^2 values ranged from 17-25% across training and test data sets.

EFH Level 3: SDM EFH and Vital Rates

Combining spatially-explicit growth potential for subadult POP with EFH maps is one approach to address the Research Plan objective to advance EFH information to Level 3 (Sigler et al. 2017). In this case study, we provide an example of integrating previously published field and laboratory studies to determine vital rates (in this case growth potential) with distribution models and EFH maps to meet this objective. This approach highlights habitat areas with greater somatic growth potential for early juvenile POP. Regions of higher growth potential that coincide with habitat hot spots (areas encompassing the top 25% of habitat predictions within EFH) are likely areas of particular importance to subadult POP in the GOA.

Averaged across all years (1981-2013), growth potential for subadult POP was higher in the eastern GOA (where water temperatures were generally higher in the summer) and lower west of Kodiak. This pattern was consistent across years (Fig. 1.15), but the temporal pattern was variable. The observed interannual variability is a combination of the interplay between the duration of the spring and summer zooplankton bloom and the water temperature during that bloom. For example, in 2005, there was an extremely short duration for the zooplankton bloom, yet water temperatures in the spring were the highest in the time series (Rooper et al. 2012), which resulted in about average growth potential for the year. In contrast, 2008 had one of the longest zooplankton blooms and cooler water temperatures, but resulted in high growth potential extending from the eastern into the central GOA.

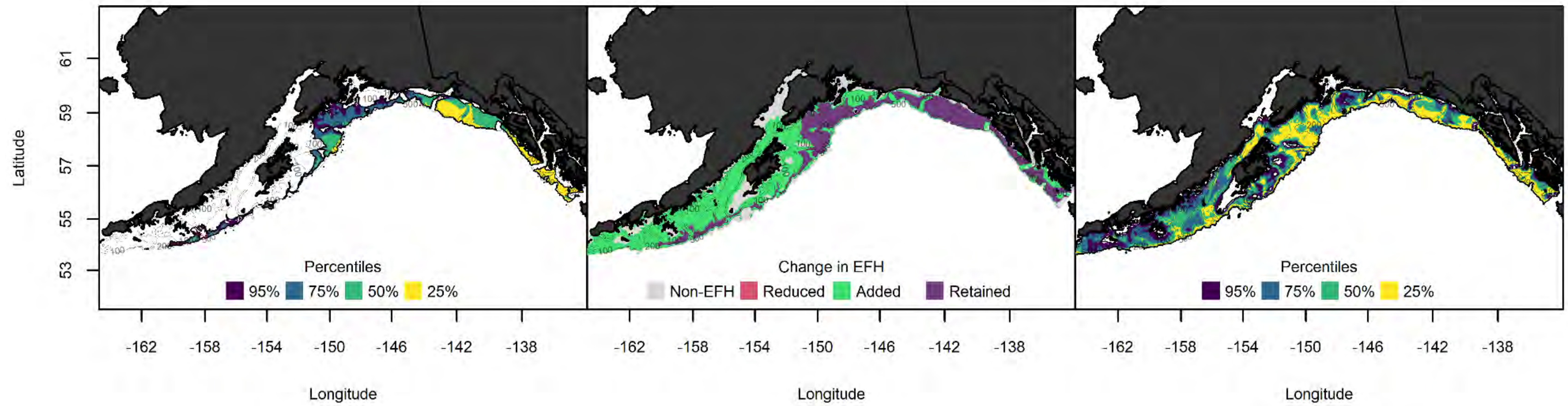

Fig. 1.13. Gulf of Alaska subadult POP 2017 EFH percentiles **(left)** from RACE-GAP summer bottom trawl surveys (1993-2013; Rooney et al. 2018), changes in EFH area between the 2017 EFH map and the new EFH map **(center)**, and new EFH percentiles **(right)** (1993-2019), where 25% = "hot spots", 50% = "core habitat", and all colored areas (25-95%) = EFH for a) subadults and b) adults; contours are the 100, 200, and 500 m isobaths.

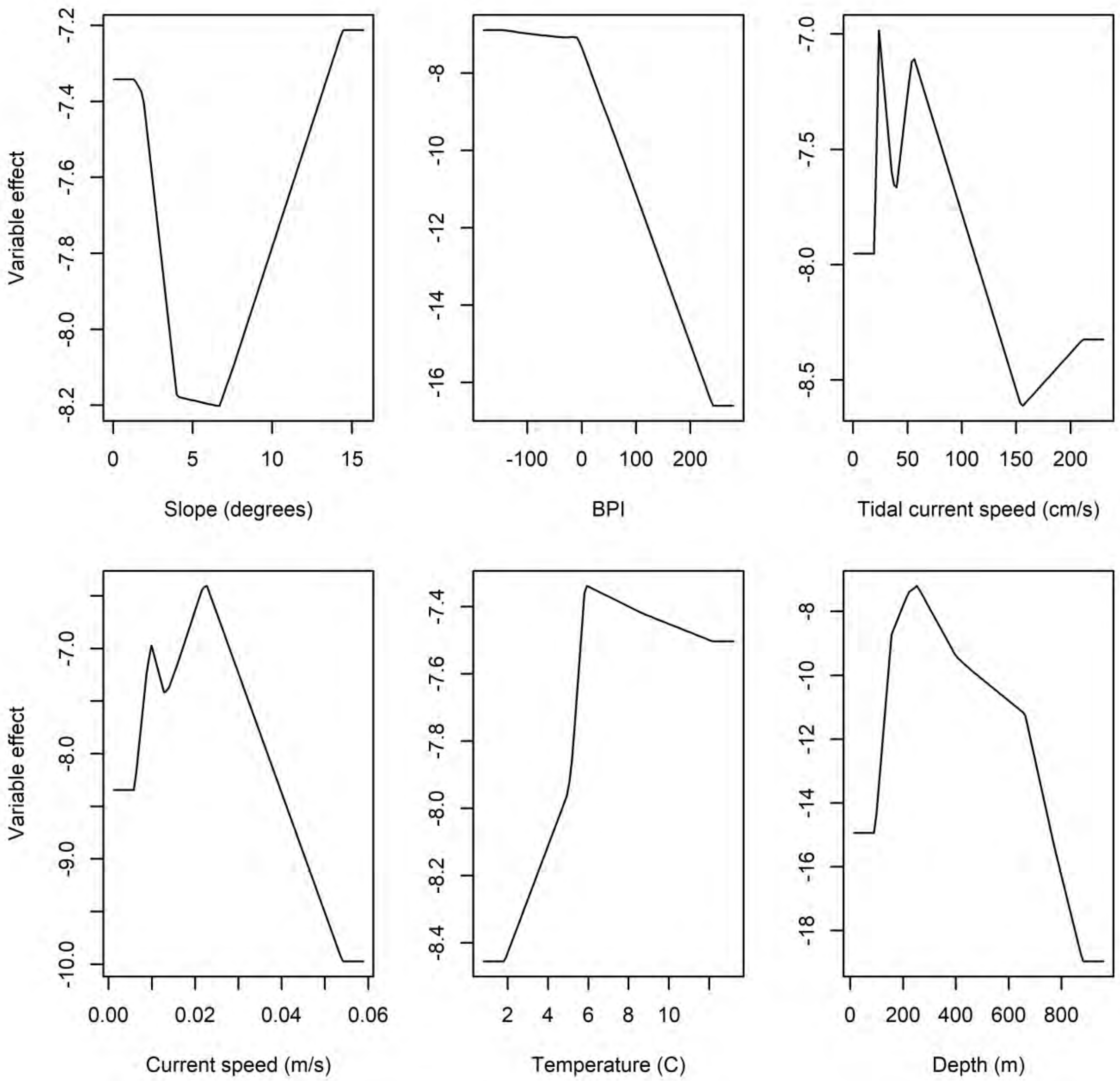

Fig. 1.14. Habitat covariate effects in the MaxEnt model (presence-absence) predicting subadult POP abundance (cloglog) from RACE-GAP summer bottom trawl surveys of the Gulf of Alaska (1993-2019).

Table 1.11. Summarizing the performance of the 2017 SDM EFH for GOA subadult POP (Gaussian catch-per-unit-effort (CPUE; 1993-2013) hGAM; Rooney et al. 2018) to forecast abundance of this life stage in three subsequent RACE-GAP summer bottom trawl survey years (2015, 2017, 2019); r^2 = coefficient of determination and RMSE = root mean square error.

Data Set	r^2	**RMSE**
Training	0.17	0.66
Test	0.25	0.71
Forecast	0.21	0.74

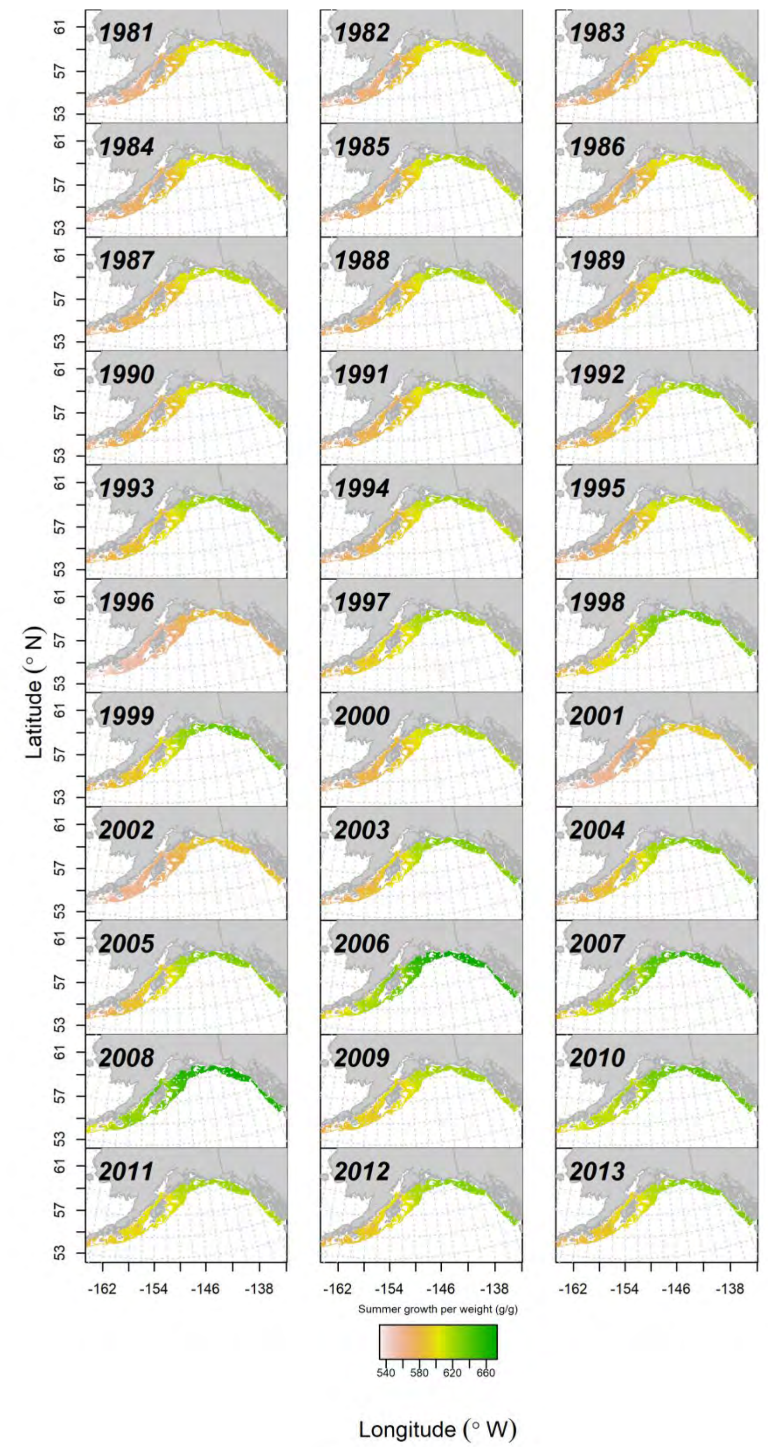

Fig. 1.15. Map of summer predicted growth potential for subadult Pacific ocean perch (< 250 mm) in the Gulf of Alaska within the boundaries of EFH defined in the present study (1993-2019); growth potential (grams per gram of body weight per day) was estimated using a bioenergetics model (Rooper et al. 2012) for 1987-2013.

1.4 PRELIMINARY CONCLUSIONS AND NEXT STEPS

We have demonstrated an updated approach for mapping EFH from SDM with the case studies presented here. To provide new information for the 2022 5-year Review that is current with the best available science, we have refined our SDM techniques, revised our methods for assigning SDM to species life stages, updated life stage definitions and existing data sets, and introduced new data sources. Enhancements to our modeling approach include using count data as the SDM response variable (we previously used 4th root transformed CPUE) coupled with a Poisson distribution and fishing effort as an offset in the models. Another modeling enhancement is to assign SDM to species life stages by skill testing among multiple models to select the best performing SDM in each case (e.g., Table 1.9, Table S.1). The fishery-independent RACE-GAP bottom trawl surveys have continued since SDM were developed for the 2017 5-year Review, adding 5 years of survey data from the BS (2015-2019) and 3 years from the GOA (2015, 2017, and 2019) to the SDM. In addition, new research conducted in the intervening years has distinguished early juvenile life stages from subadults for several species and we now include SDM for this life stage developed with inshore and offshore survey data.

This work meets the objectives of the Alaska EFH Research Plan, revised following the 2017 5-year Review (Sigler et al. 2017), to develop new EFH information for species life stages where not described and advance EFH levels where possible with progress towards EFH Level 3. Through our case studies we have provided Level 2 EFH maps for previously undescribed BS subadult sablefish and GOA early juvenile Pacific cod, advanced EFH information from Level 1 to Level 2 for BS adult sablefish, and developed new EFH Level 3 information by co-mapping GOA subadult POP SDM EFH with temperature-dependent growth potential. Further progress will be made as we complete new SDM for additional groundfish species life stages. For example, the method we are now using to transform results in units of probability (e.g., from MaxEnt or paGAM) into approximations of abundance using the cloglog link has the potential to advance EFH information levels for nearly all North Pacific groundfish species from Level 1 to Level 2 (Table 1.7).

We have also validated the accepted SDM approach from the 2017 5-year Review by comparing predicted distribution and abundance of GOA Pacific cod (subadult and adult life stages) and Pacific ocean perch (subadults) (fitted to 1993-2013 RACE-GAP bottom trawl survey data) with observations from subsequent survey years (2015, 2017, and 2019). The 2017 SDMs explained from 17-27% of the deviance in the response data and r^2 ranged from 0.16 to 0.27 for training and testing data in the internal model validation exercise. Agreement between model predictions and subsequent survey ("out year") observations for the external validation exercise was similar to the internal model validation (r^2 range of 0.16-0.21), indicating that the 2017 SDM performed as well predicting distribution and abundance in "out years" as they did internally validating the model fits in the 2017 5-year Review.

The areal extent of North Pacific groundfish EFH maps from our case studies changed compared to the EFH maps from the 2017 5-year Review.

- Adult sablefish (BS) and subadult Pacific cod (GOA) EFH area was reduced ~37 and ~53%, respectively;
- Adult Pacific cod (GOA) EFH area remained about the same (~11% reduction); and
- Subadult Pacific ocean perch (GOA) EFH area more than doubled.

Redefining life stages (e.g., increasing the maximum length of subadult sablefish in the BS) and switching from CPUE and a Gaussian distribution in the 2017 SDM to count data and a Poisson distribution in the present study were the biggest influences on changing EFH area for BS adult sablefish (Fig. S.9) and GOA subadult Pacific cod (Fig. S.18). This shift, along with the using the cloglog link to transform probabilities (from MaxEnt or paGAM models) into relative abundance, not only made skill testing among SDM possible, but advanced EFH information to Level 2 for what had previously been classified as Level 1 (habitat-linked distribution). Introducing skill testing to select the best performing model (i.e., shifting from the 2017 hGAM for subadult GOA POP to a MaxEnt in the present study) appears largely responsible for the expansion of EFH for this species life stage (Fig. S.28).

As in the 2017 5-year Review, we have provided maps of the SDM output (e.g., Fig. S.2) and percentiles of SDM EFH area (e.g., Fig. 1.5), where the upper 95% of the predicted area is the current definition of EFH maps for Alaska (i.e., upper 25% is “hot spots”, upper 50% is “core habitat”, and 25-95% is EFH). Importantly, presenting this set of maps for each species life stage demonstrates that these SDM can identify more nuanced spatial stock structure than is communicated in the upper 95% SDM EFH maps, which lends to utility of these SDM beyond current EFH applications and provides a basis for discussions on how EFH is mapped for Alaska.

Our next step is to complete the full SDM EFH package for the 2022 5-year Review. In addition to providing new EFH information, these SDM can be extended to support stock assessment and other EBFM information needs. Our 2017 SDM have contributed to stock assessments in the Ecosystem and Socioeconomic Profiles (e.g., Alaska Sablefish, Shotwell et al. 2017, 2018, 2019a; GOA Walleye Pollock, Shotwell et al. 2019b) and ecosystem process research to support fisheries management (e.g., recruitment processes, Goldstein et al. in review; distribution shifts under climate scenarios, Rooper et al. in review). Additionally, knowledge of SDM habitat covariate effects that improve understanding of mechanisms underlying species habitat associations (i.e., to refine EFH text descriptions) has the potential to inform habitat-based post-stratification and next generation sampling designs for existing stock assessment surveys. Once the 2022 5-year Review is completed the new SDM results, EFH descriptions and maps, SDM framework (source code), and data sources will be made available to other fishery researchers.

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1.6 SUPPLEMENT I

This section presents **extended case study results** with comparisons between the 2017 SDM EFH maps and those from our revised SDM EFH approach. We also include maps illustrating the stepwise effect of each substantive refinement to our modeling approach or update to model variables on the resulting EFH area (e.g., Fig. S.9).

1.6.1 Extended Results: Bering Sea Sablefish (*Anoplopoma fimbria*)

Subadult Sablefish

Distribution and Abundance

Subadult sablefish were not common across the RACE-GAP Bering Sea (BS) survey areas (Fig. S.1) and weren't modeled in the 2017 EFH Review. Around 2,500 individuals of this life stage were collected on RACE-GAP BS summer bottom trawl surveys between 1982 and 2019 where they occurred at ~3% of stations sampled per survey on average. Catches from the bottom trawl surveys were made primarily at the shelf break in the southwestern portion of the BS, and ranged from 0 to > 170 individuals per trawl catch. The standard abundance GAM with a log link, a Poisson distribution, and using fishing effort as an offset had the lowest test data set RMSE, indicating that this was the best model to describe distribution and abundance of this species and life stage (Table S.1). The general form of the best-fitting GAM was

$$A \sim s(lat, lon) + s(bottom\ depth) + s(sediment\ size) + s(bottom\ temp) + s(tidal\ maxima) + s(BPI) + F(corals) + s(slope) + offset(area\ swept) + E,$$

where A = numerical abundance, s indicates a smoother, F indicates a factor term, E is an error term and the variables retained (e.g., *(lat,lon)* is a bivariate term describing geographic position and BPI = bathymetric position index) are listed in order of statistical significance. Among the variables retained in the model, the terms with the highest significance (lowest *p*-value) were geographic position, bottom depth, and sediment size. The habitat-linked SDM for subadult BS sablefish explained 55% of the deviance in abundance data and predicted their highest abundance around the head of the Bering Canyon extending northwestward along the shelf break (Fig. S.2). Model effects indicate that subadult sablefish abundance increases between 300-700 m depth moving offshore with decreasing sediment size (Fig. S.3). Comparing the r^2 values from the cross-validation exercise indicates that the training data were not well-described by the best-fitting model (r^2 = 10%) which did a better job of predicting abundance at the unsampled locations in the testing data set (r^2 = 24%).

Essential Fish Habitat Maps

The SDM-predicted subadult sablefish abundance was translated into a spatially-explicit description of EFH (Fig. S.4). Sub-adult sablefish EFH extends in patches from the southern Bering Sea above Unimak Pass over the Bering Canyon northwestward along the shelf break to the U.S.-Russia Convention Line. Much of subadult sablefish EFH is in close proximity to submarine canyons along the eastern Bering Sea continental shelf-break and slope. Habitat hot spots for this species and life stage (top 25% of abundance predictions) are focused around the head of Bering Canyon and north along the outer continental shelf and upper slope.

Table S.1. Bering Sea subadult sablefish (1982-2019) multiple model skill testing: MaxEnt = maximum entropy model, GAM = generalized additive model, paGAM = presence-absence GAM, hGAM = hurdle GAM, r^2 = coefficient of determination, RMSE = root mean square error, EFH = essential fish habitat.

	Training data		**Test data**		
Model	r^2	**RMSE**	r^2	**RMSE**	**Area of EFH (km^2)**
MaxEnt	0.05	2.29	0.05	2.80	254,570
paGAM	0.08	2.29	0.18	2.82	141,016
hGAM	0.04	3.61	0.07	3.71	78,998
*GAM	0.10	2.20	0.24	2.63	275,507

*best-performing model

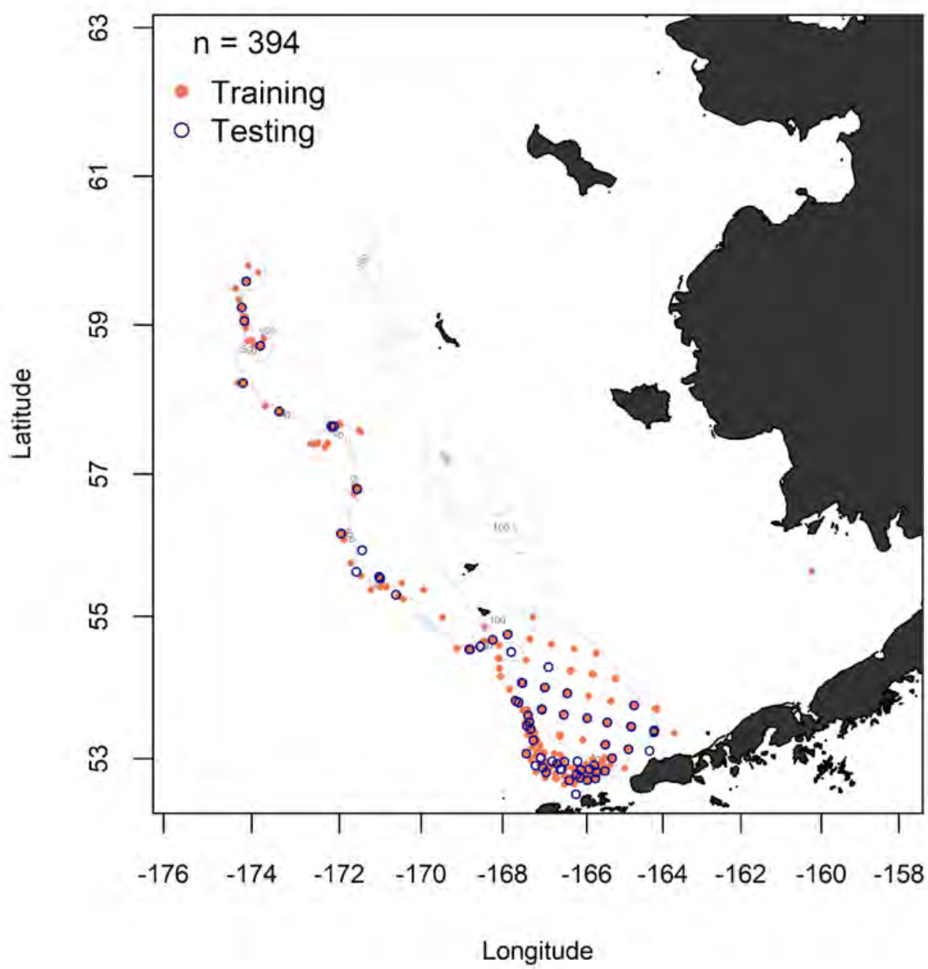

Fig. S.1. Presence of subadult sablefish on RACE-GAP summer bottom trawl surveys of the Bering Sea (1982-2019) with training (orange dots) and testing (blue circles) data sets indicated; contours are 100, 200, and 500 m isobaths.

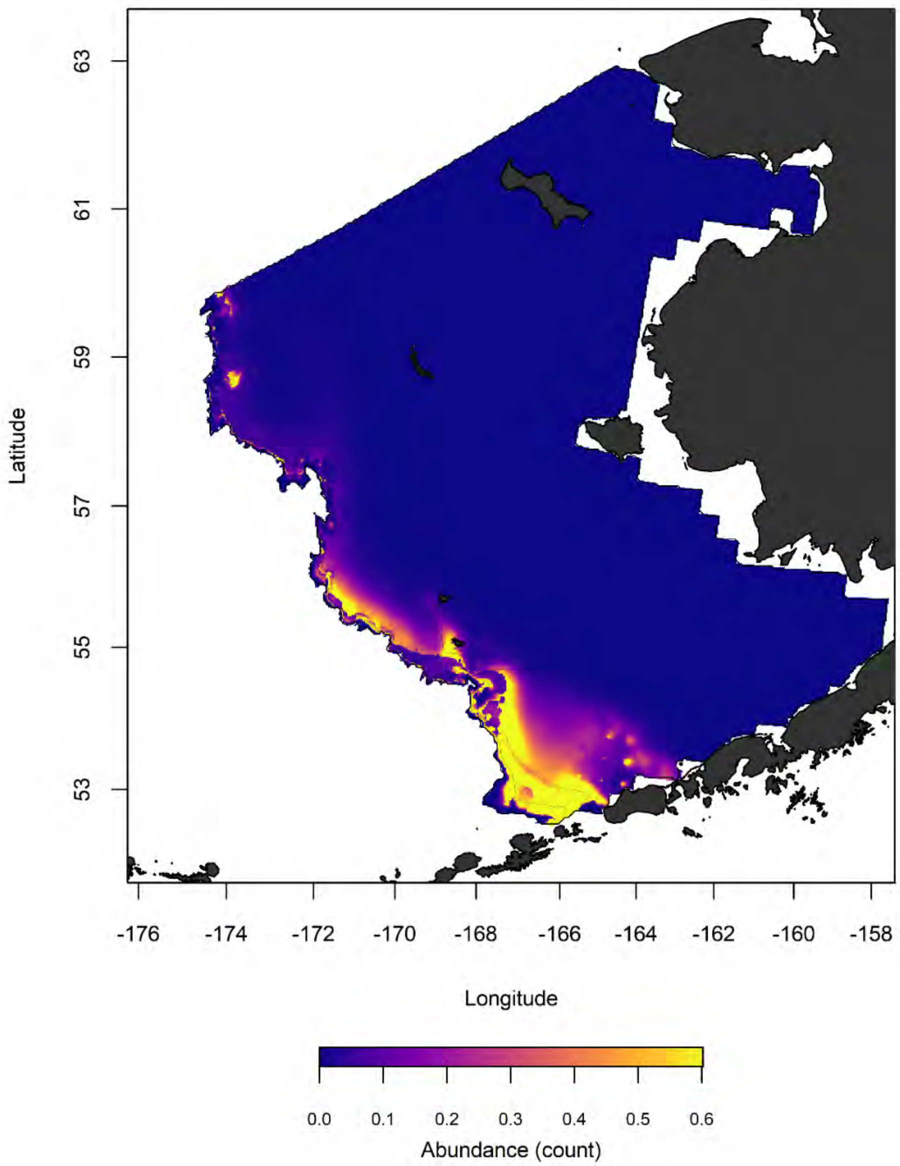

Fig. S.2. Species distribution model (GAM) predicted abundance (average number of animals) of Bering Sea subadult sablefish from RACE-GAP summer bottom trawl surveys (1982-2019); contours are 100, 200, and 500 m isobaths.

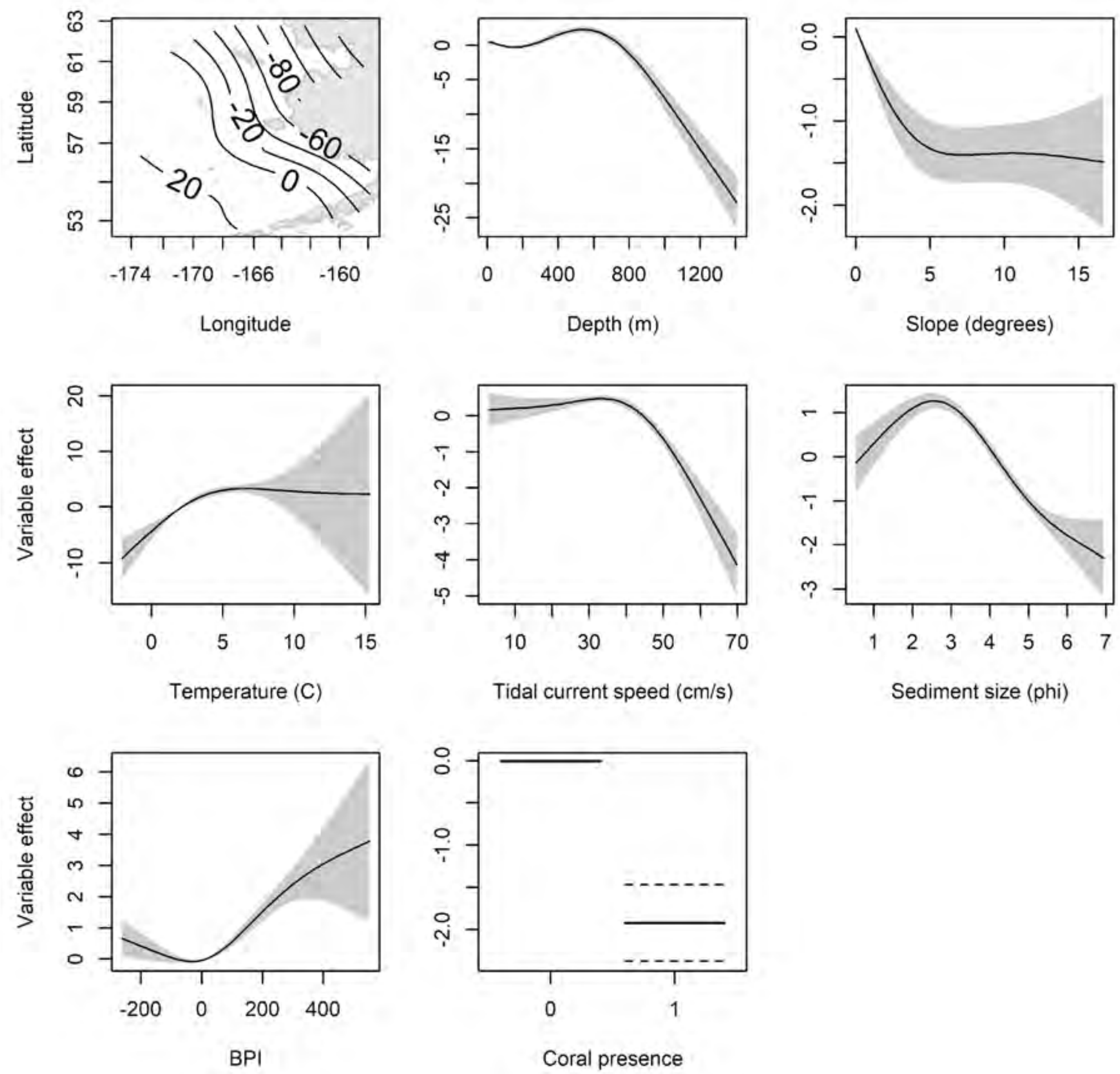

Fig. S.3. Habitat covariate effects on the species distribution model (GAM) predicting Bering Sea subadult sablefish abundance from RACE-GAP summer bottom trawl surveys (1982-2019).

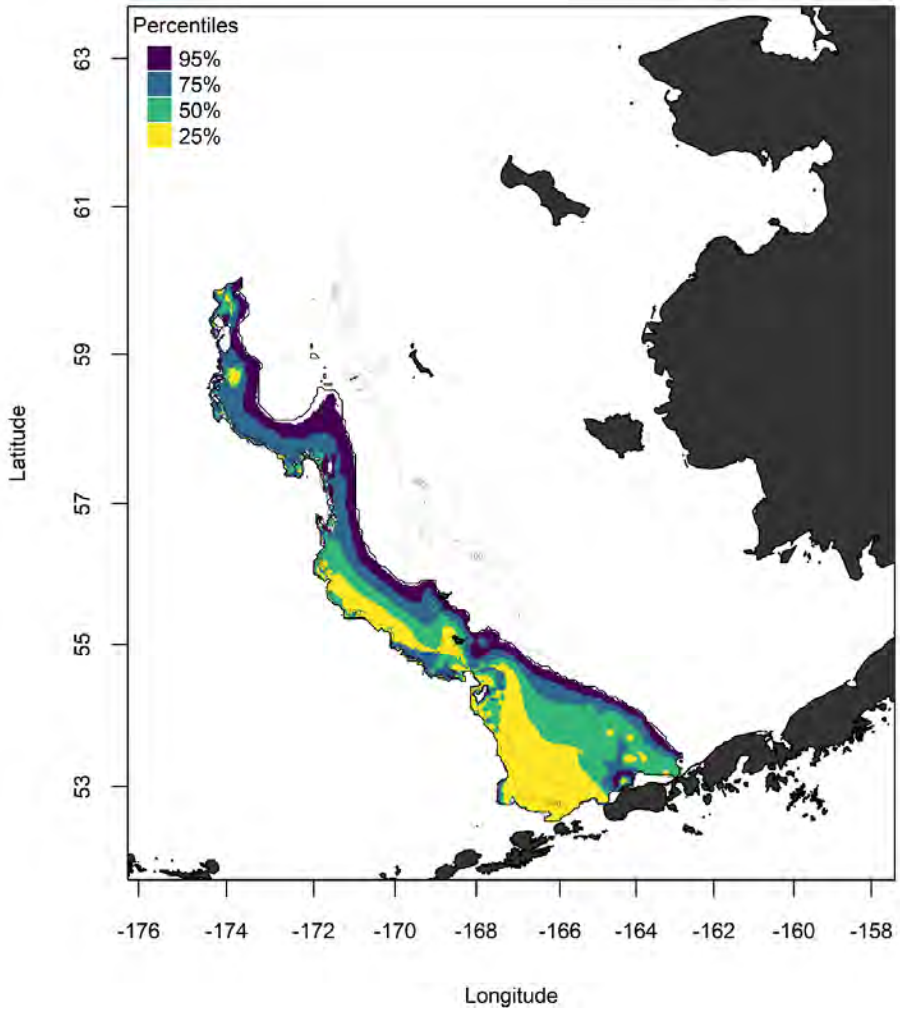

Fig. S.4. Composite of Bering Sea subadult sablefish EFH percentiles (25% = “hot spots”, 50% = “core habitat”, all colored areas (25-95%) = EFH) constructed from species distribution model (SDM) predicted, habitat-linked abundance using RACE-GAP summer bottom trawl surveys (1982-2019); contours are 100, 200, and 500 m isobaths.

Adult Sablefish

Distribution and Abundance

Adult sablefish were present in 19 of the 38 BS summer bottom trawl surveys between 1982 and 2019 (Fig. S.5), but had relatively low overall prevalence, occurring at ~3% of stations sampled per survey on average. Catches from the BS summer bottom trawl surveys occurred primarily at the shelf break and ranged from 0 to ~90 individuals. A paGAM with a Poisson distribution using fishing effort as an offset was identified as the best performing model (lowest RMSE; Table S.2). The general form of the best-fitting paGAM was

$$A \sim s(bottom\ depth) + s(lat, lon) + s(BPI) + s(bottom\ temp) + s(sediment\ size) + s(current\ speed) + s(tidal\ maxima) + s(slope) + F(sponges) + F(corals) + offset(area\ swept) + E,$$

where *A* = numerical abundance, *s* indicates a smoother, *F* indicates a factor term, *E* is an error term and the variables retained (e.g., *(lat,lon)* is a bivariate term describing geographic position and BPI = bathymetric position index) are listed in order of statistical significance. This habitat-linked SDM explained 75% of the deviance in the data and predicted their highest abundances near the heads of submarine canyons (e.g., Bering and Pribilof Canyons) and along the 500 m isobath throughout the region (Fig. S.6). Among the variables retained in the model, the terms with the highest statistical significance (lowest *p*-values) were bottom depth, geographic position, BPI, and bottom temperature. Adult sablefish abundance increased with increasing depth (up to ~700 m) moving offshore as well as with increasing BPI and bottom temperature (Fig. S.7). Comparing r^2 values from the validation exercise indicates that the training data were well-described by the best-fitting model (r^2 = 34%) which also did a good job of predicting abundance at the unsampled locations in the testing data set (r^2 = 37%).

Essential Fish Habitat Maps

The cloglog approximation of adult sablefish abundance calculated from the paGAM results was translated into a spatially explicit description of EFH (Fig. S.8). EFH for adult sablefish extends from the along the shelf break and slope from the Bering Canyon in the south to the U.S.-Russia Convention Line at the northwestern boundary of the BS survey area. Abundance hot spots for adult sablefish (top 25% of predictions) are focused on the Bering and Pribilof Canyons in the southwestern BS, but core habitat (top 50% of predictions) is scattered throughout the region along the eastern Bering Sea continental shelf and upper continental slope around the 500 m isobath. The areal extent of adult sablefish EFH from this case study (119,400 km^2) represents a 37% reduction of EFH area compared to the 2017 description. The reduction of EFH area produced from the present SDM is primarily the result of redefining length-based sablefish life stages (Fig. S.9) by accommodating an early juvenile sablefish life stage that conflicted with our 2017 definition of the subadult stage and subsequently equating the maximum length of subadult sablefish with maximum length at 50% maturity.

Table S.2. Bering Sea adult sablefish (1982-2019) multiple model skill testing: MaxEnt = maximum entropy model, GAM = generalized additive model, paGAM = presence-absence GAM, hGAM = hurdle GAM, r^2 = coefficient of determination, RMSE = root mean square error, EFH = essential fish habitat.

	Training data		**Test data**		
Model	r^2	**RMSE**	r^2	**RMSE**	**Area of EFH (km^2)**
MaxEnt	0.01	20.3	0.01	16.2	86,323
*paGAM	0.34	2.23	0.37	1.5	119,398
hGAM	0.08	3.8	0.05	4.25	64,515
GAM	0.37	1.93	0.28	1.63	261,148

*best-performing model

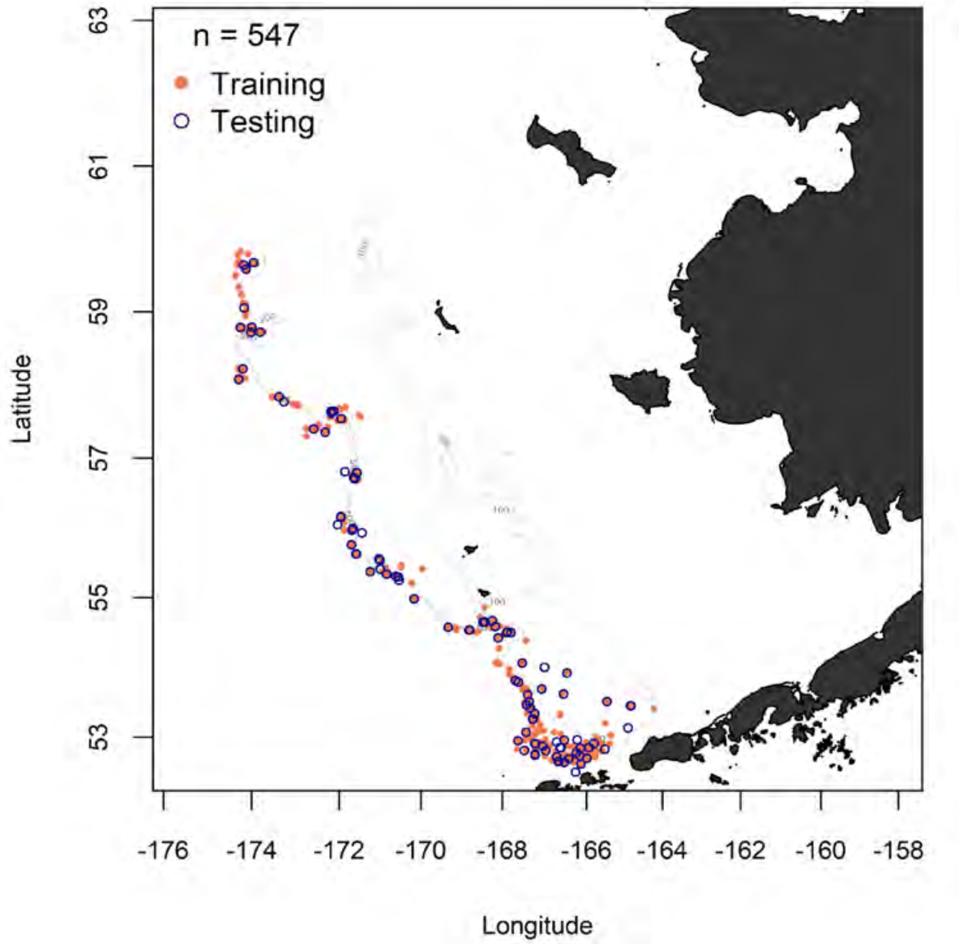

Fig. S.5. Presence of Bering Sea adult sablefish in RACE-GAP summer bottom trawl surveys (1982-2019) with training (orange dots) and testing (blue circles) data sets indicated; contours are the 100, 200, and 500 m isobaths.

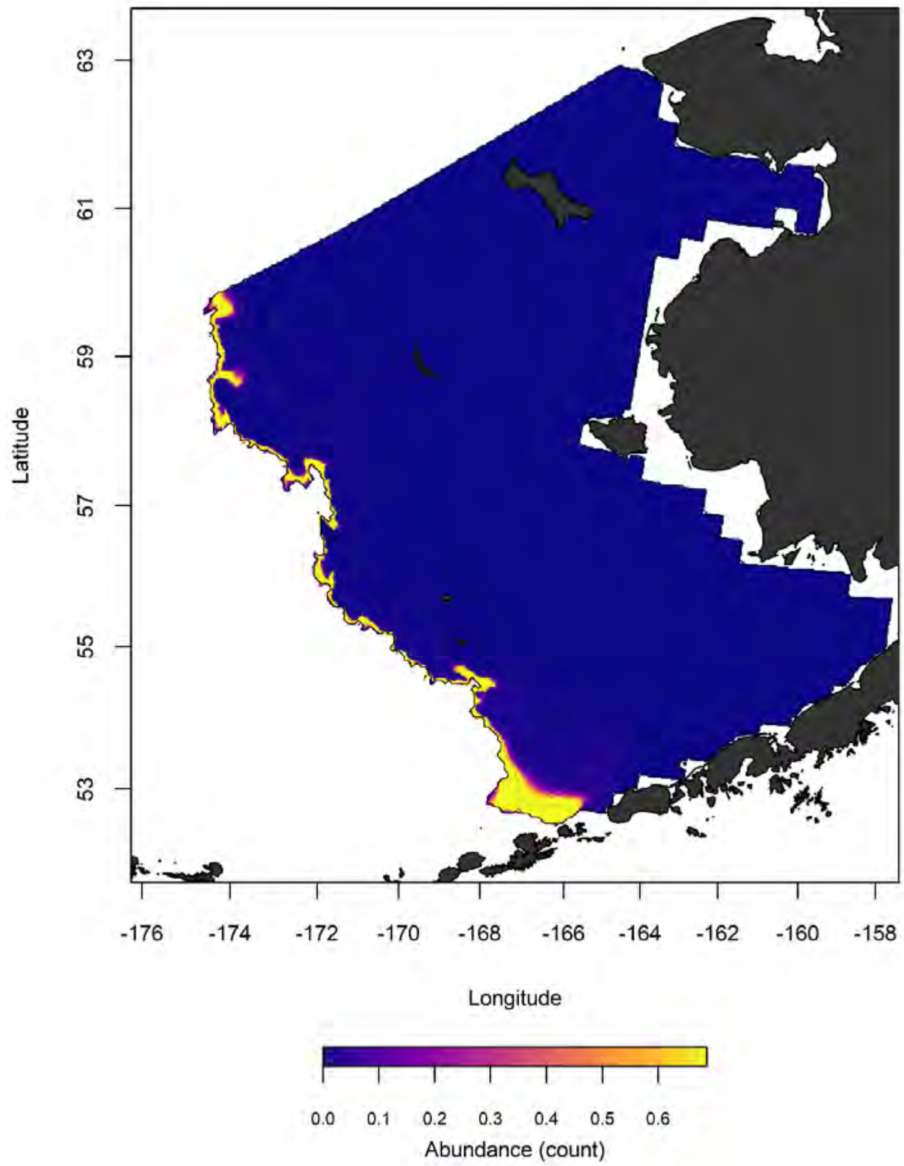

Fig. S.6. Species distribution model (paGAM) predicted abundance (average number of animals) of Bering Sea adult sablefish from RACE-GAP summer bottom trawl surveys (1982-2019); contours are the 100, 200, and 500 m isobaths.

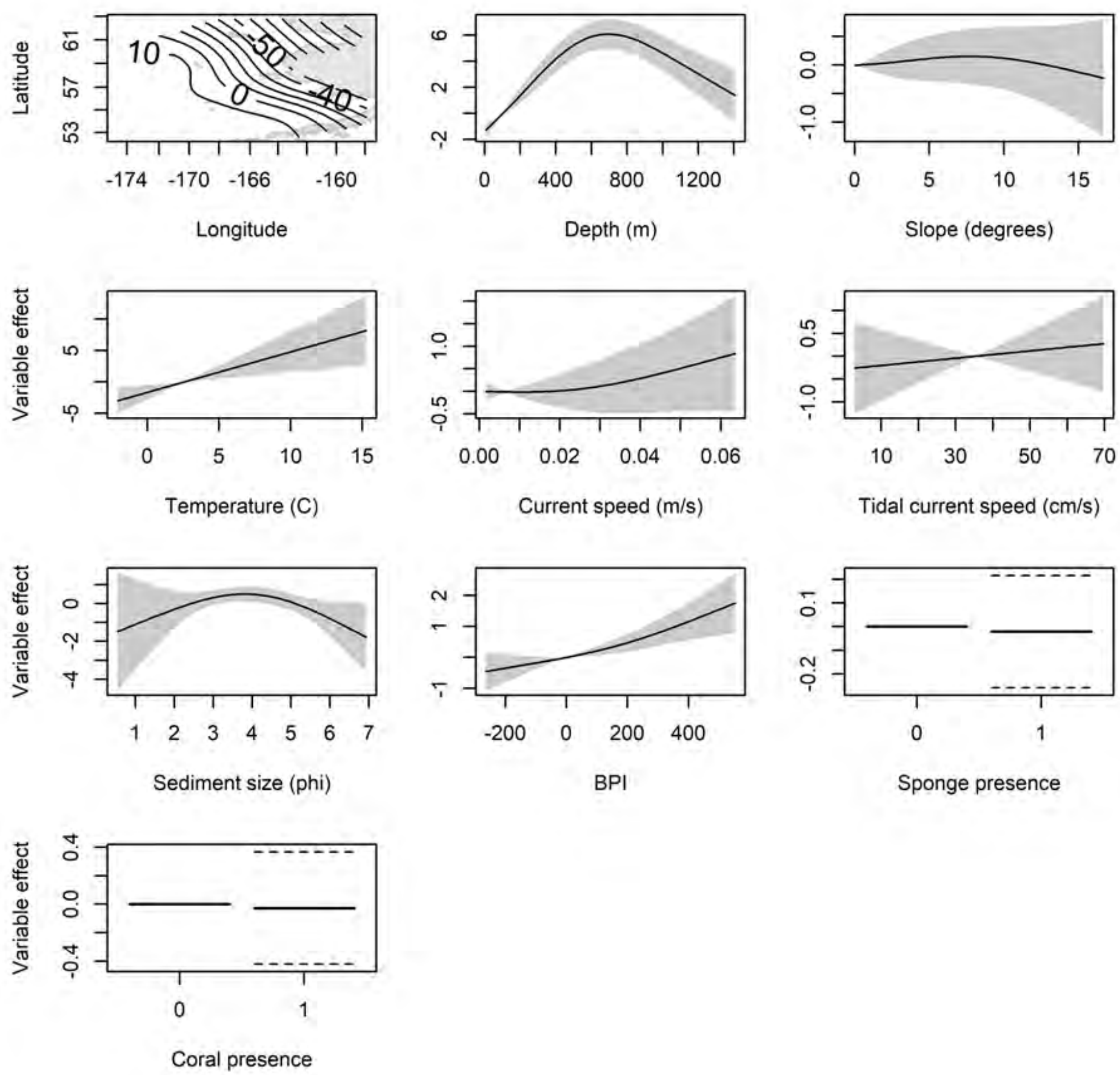

Fig. S.7. Habitat covariate effects on the species distribution model (paGAM) predicting Bering Sea adult sablefish abundance from RACE-GAP summer bottom trawl surveys (1982-2019).

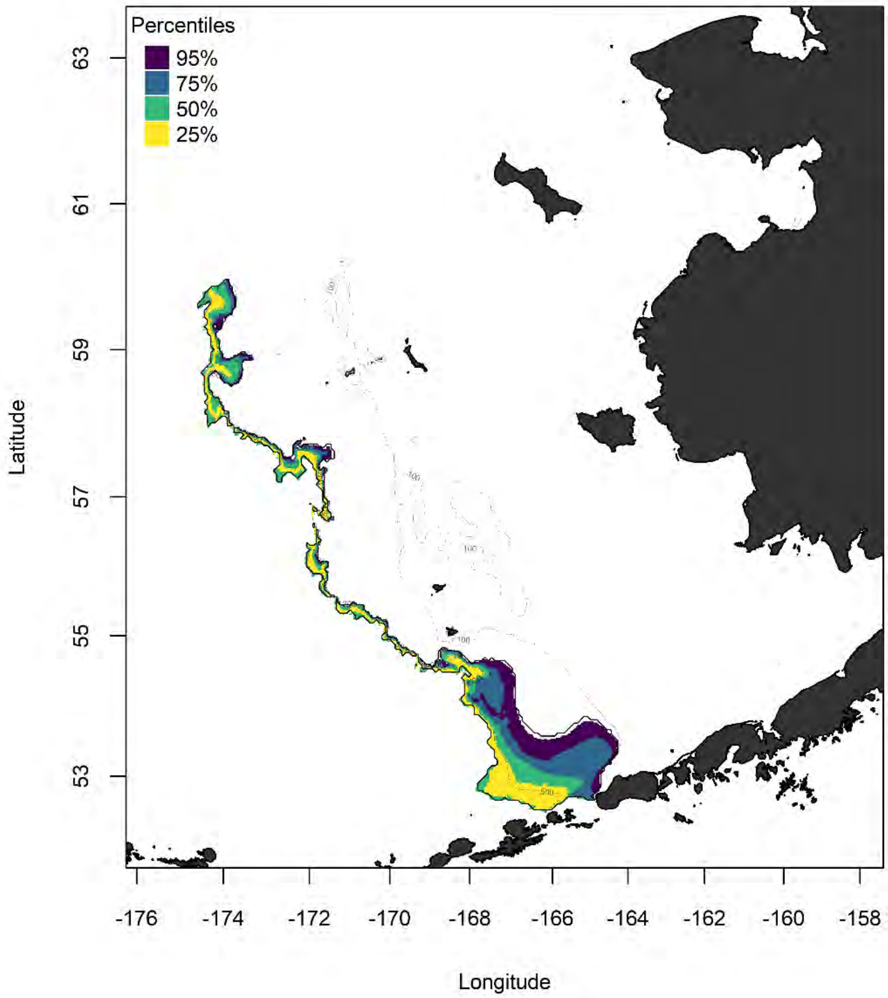

Fig. S.8. Composite of Bering Sea adult sablefish EFH percentiles (25% = "hot spots", 50% = "core habitat", all colored areas (25-95%) = EFH) constructed from species distribution model (paGAM) predicted, habitat-linked abundance using RACE-GAP summer bottom trawl surveys (1982-2019); contours are 100, 200, and 500 m isobaths.

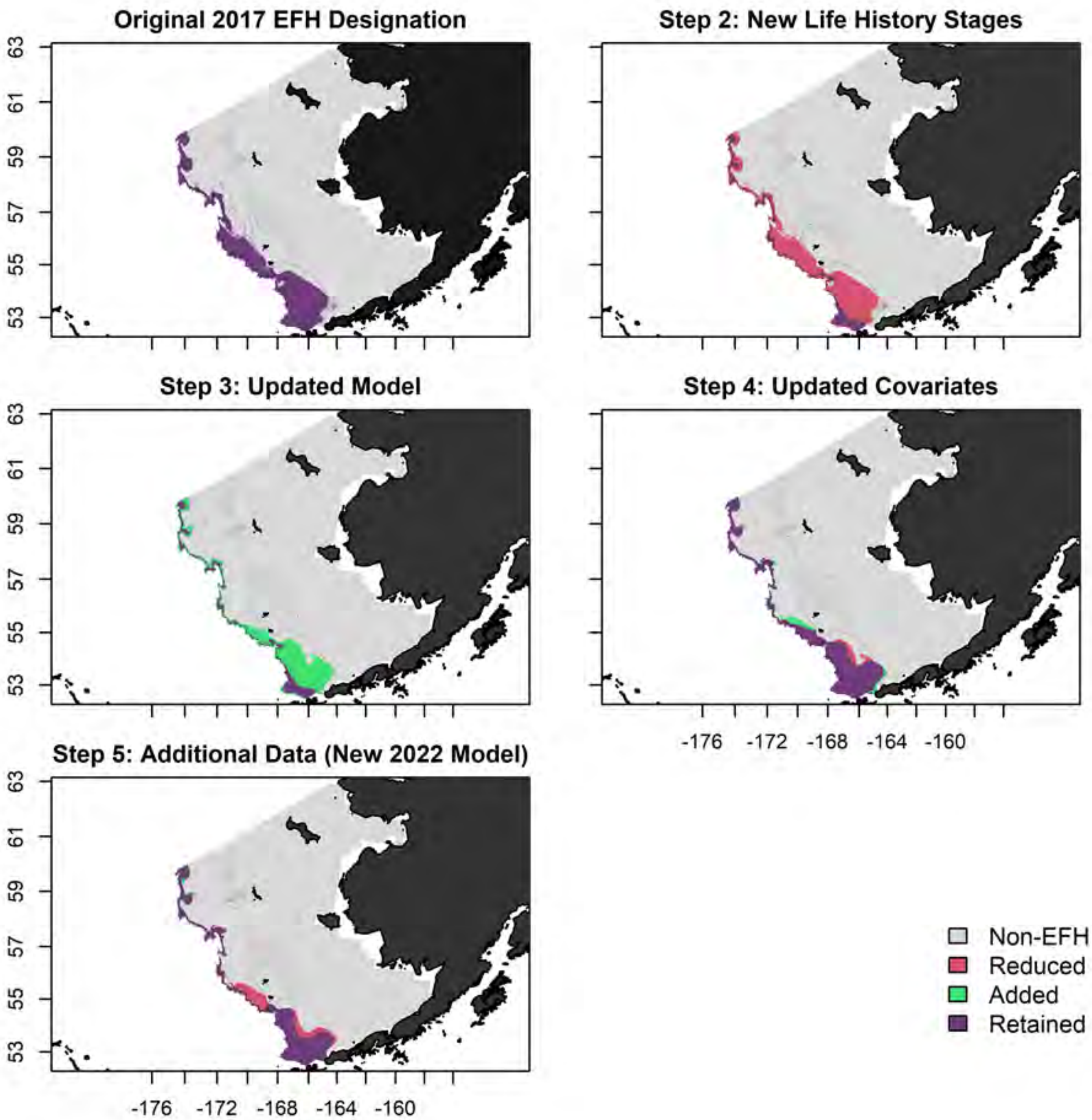

Fig. S.9. Iterative comparison of cumulative Bering Sea adult sablefish EFH area changes in the refined SDM EFH approach, relative to the 2017 EFH map (Bering Sea surveys 1982-2014, MaxEnt model; Laman et al. 2017), including the effects of life stage redefinition **(Step 2)**, refinements to modeling approach **(Step 3)**, updates to habitat covariates **(Step 4)**, and inclusion of additional years of bottom trawl survey data (2015-2019) **(Step 5)**.

1.6.2 Extended Results: Gulf of Alaska Pacific Cod (*Gadus macrocephalus*)

Early Juvenile Pacific Cod

Distribution and Abundance

Sample locations (*n* = 438) from various data sources were available to parameterize an early juvenile Pacific cod SDM. Early juvenile Pacific cod were mainly captured at coastal inshore stations and over the continental shelf by beach seines and bottom trawls of various mesh sizes, but were also collected on RACE-GAP summer bottom trawl surveys well offshore (Fig. S.10). Assigning a presence-only MaxEnt model to this particular data set *a priori* facilitated the combination of early juvenile Pacific cod distribution data from disparate surveys and gear types. The fully parameterized MaxEnt model included 9 covariate terms (bottom depth, slope, bottom temperature, bottom current speed, tidal maxima, BPI, and 3 SFI presence-absence terms) and accounted for ~28% of the total deviance in the presence-only response data (Table S.3). The terms with the greatest leverage in the model were bottom depth and slope which explained a combined ~73% of the total deviance explained by the model. MaxEnt model output and the cloglog link were used to approximate abundance from this SDM. The abundance of early juvenile Pacific cod was highest in shallow waters (≤ 100 m) and was maximized over moderate slopes (~7°; Fig. S.11). The highest abundances were predicted in nearshore and coastal zones throughout the GOA and around offshore islands (Fig. S.12).

Essential Fish Habitat Maps

For the first time, we described EFH (top 95% of abundance predictions) of early juvenile Pacific cod in the GOA. Their EFH is spread across the continental shelf primarily in waters shallower than 200 m (Fig. S.13). Habitat hot spots for this species life stage (top 25% of predictions) were also found throughout the GOA, but primarily in coastal areas and in shallower water (< 100 m depth). Using the cloglog link to approximate abundance from the MaxEnt model output (probability of suitable habitat) yields a Level 2 description (habitat-linked abundance) of their EFH.

Table S.3. Relative importance of covariate terms (jackknifed % deviance explained) in the GOA early juvenile Pacific cod MaxEnt model, including total deviance explained, prediction accuracy, and approximate area under the receiver operating curve (AUC) for training and test data sets.

Covariate Term	% Deviance Explained	% Total Deviance Explained	Training Data		Testing Data	
			Accuracy	AUC	Accuracy	AUC
Bottom Depth	57.6	28.1	69.7	0.87	68.0	0.85
Slope	15.0					
Bottom Temp	8.5					
BPI	8.2					
Tidal Current	3.8					
Current Speed	2.8					
Sponges	2.1					
Corals	1.2					
Pennatulacean	0.8					

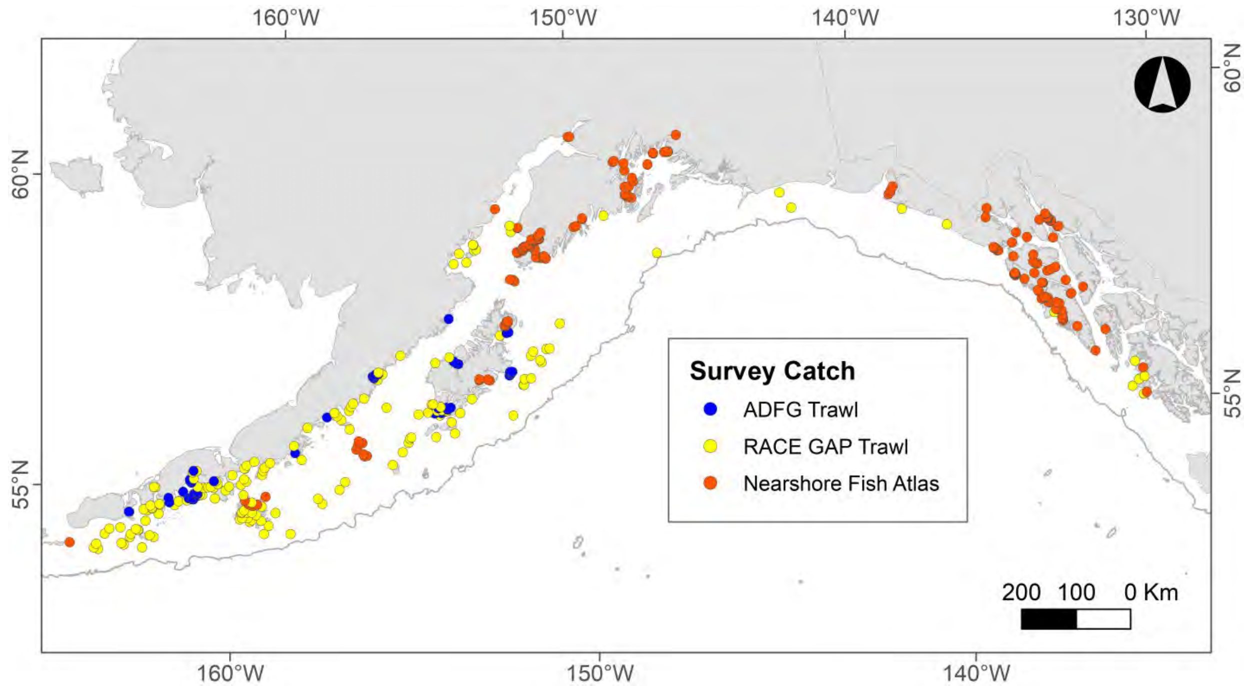

Fig. S.10. Presence of early juvenile Pacific cod from surveys in the Gulf of Alaska (1989-2019), including ADFG small-mesh bottom trawl survey **(blue)**, RACE-GAP bottom trawl survey **(yellow)**, and multiple surveys standardized and compiled by the updated Nearshore Fish Atlas for Alaska **(orange)**. Contour is the 1000 m isobath.

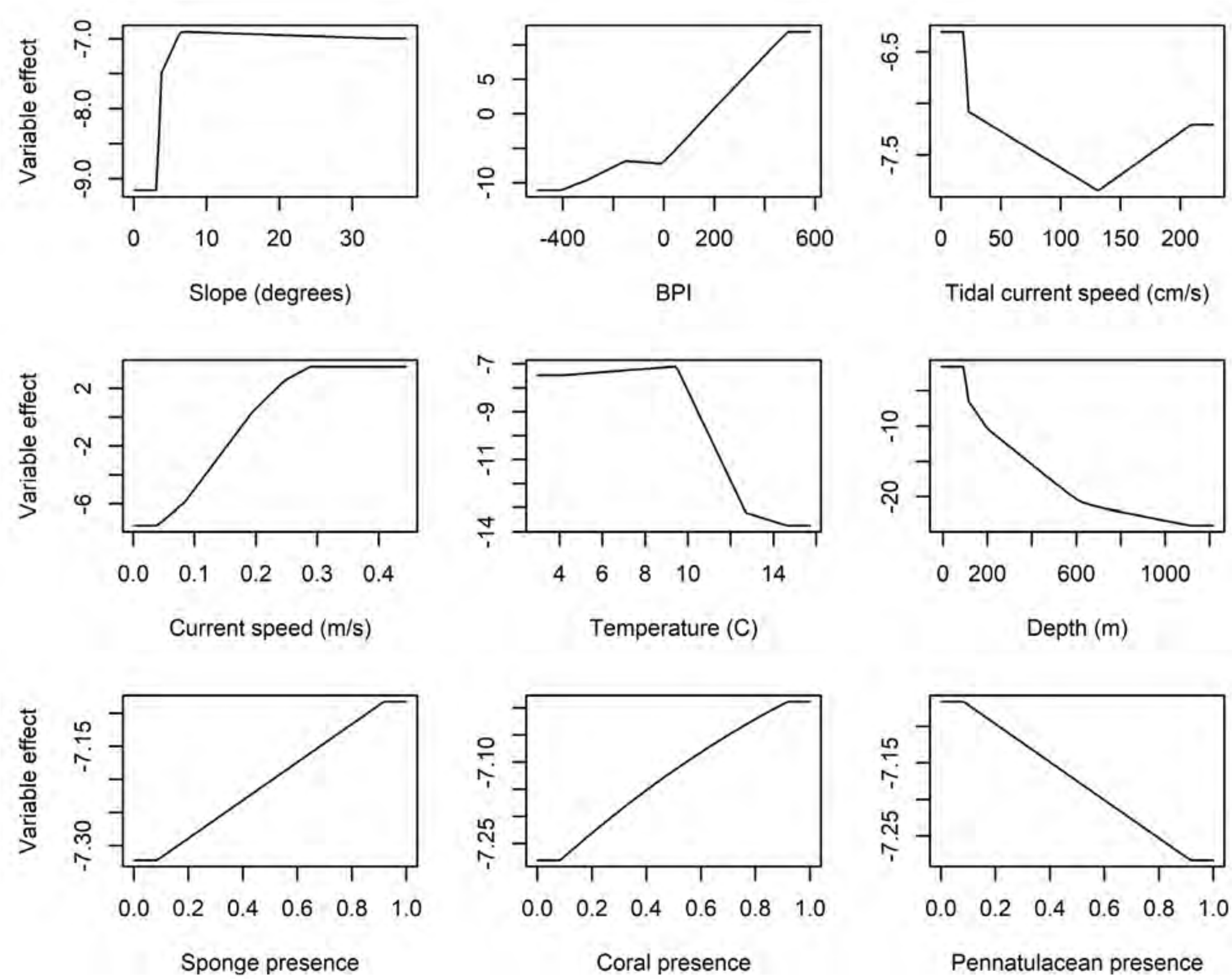

Fig. S.11. Effects of habitat covariates on the species distribution model (MaxEnt) for early juvenile Pacific cod in the Gulf of Alaska from a combination of survey data sources (i.e., beach and purse seines, hook-and-line, bottom trawls with various mesh sizes).

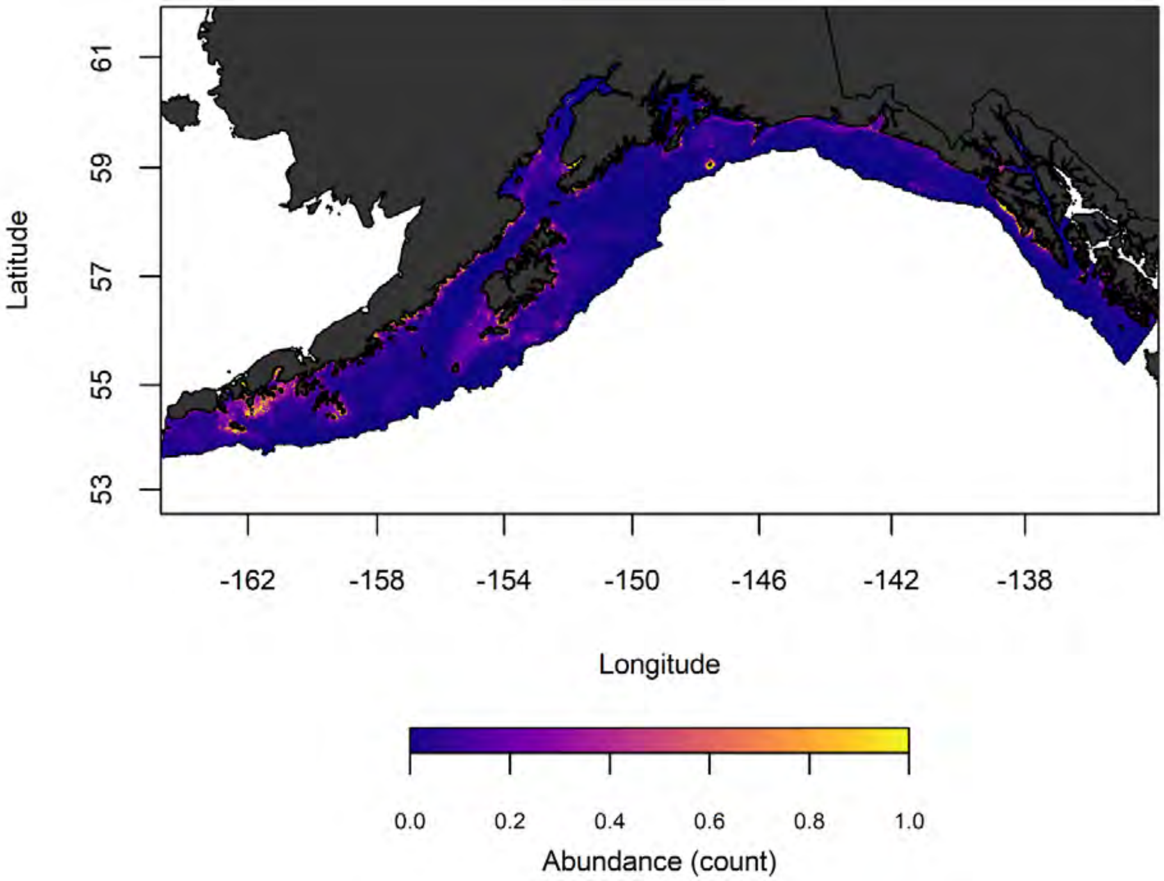

Fig. S.12. Species distribution model (MaxEnt) map of the cloglog approximated abundance of early juvenile Pacific cod in the Gulf of Alaska.

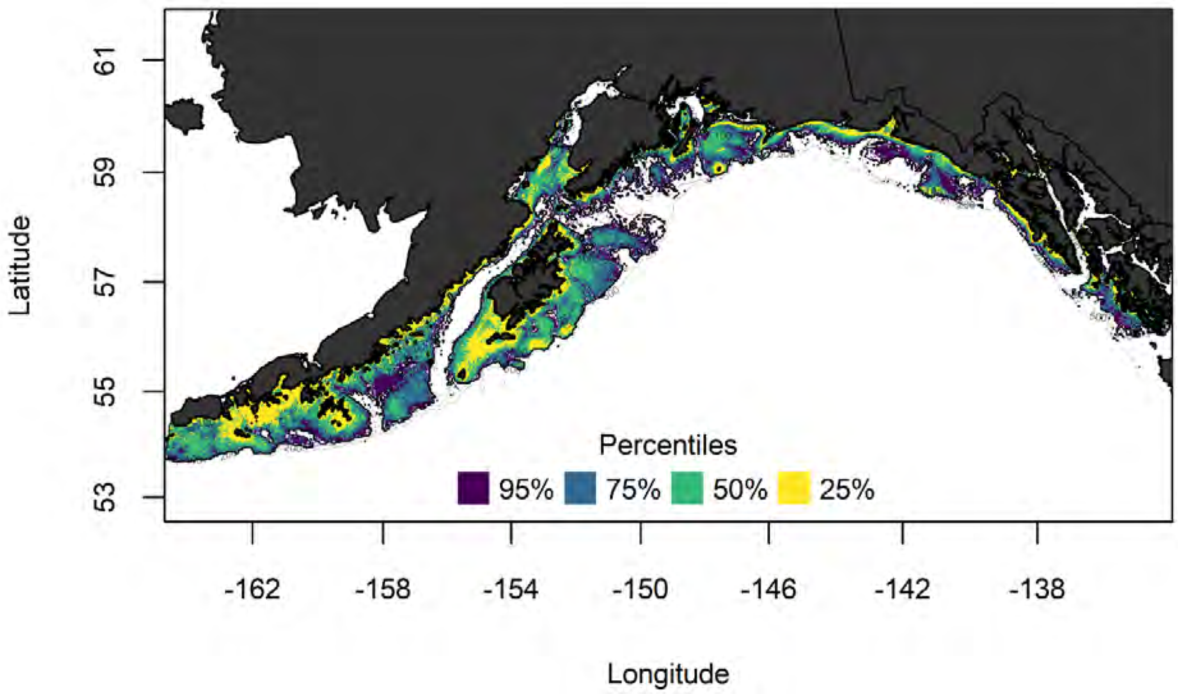

Fig. S.13. Composite of Gulf of Alaska early juvenile Pacific cod EFH percentiles (25% = "hot spots", 50% = "core habitat", all colored areas (25-95%) = EFH) constructed from species distribution model (MaxEnt) predicted, habitat-linked cloglog approximated abundance using RACE-GAP summer bottom trawl surveys (1993-2019); contours are 100, 200, and 500 m isobaths.

Subadult Pacific Cod

Distribution and Abundance

Subadult Pacific cod were collected on 13 GOA summer bottom trawl surveys conducted between 1993 and 2019 (Fig. S.14). Trawl catches ranged from 0 to > 4,000 individuals per trawl haul and were encountered across the middle and outer shelf in the western and central Gulf. Skill testing of the 4 SDMs used to predict subadult Pacific cod distribution across the GOA survey area identified the best performing model by the lowest RMSE for the test data (Table S.4) as the hGAM. The general form of the best-fitting hGAM was

$$A \sim s(lat, lon) + s(bottom\ depth) + s(slope) + s(tidal\ maxima) + F(sea\ whips) + F(corals) + s(BPI) + s(current\ speed) + F(sponges) + s(bottom\ temp) + offset(area\ swept) + E,$$

where A = numerical abundance, s indicates a smoother, F indicates a factor term, E is an error term and the variables retained (e.g., *(lat,lon)* is a bivariate term describing geographic position and BPI = bathymetric position index) are listed in order of statistical significance. This model explained 21% of the deviance in the training response data. Static habitat covariates geographic position, bottom depth, and slope were among the most significant terms retained in the best-fitting hGAM and the model effects indicate that subadult Pacific cod abundance was higher in the western and central Gulf in shallower waters (< 200 m) over moderate slopes (Fig. S.15). This habitat-linked SDM predicted the highest abundances of subadult Pacific cod in the western GOA along the Alaska Peninsula, around the southeastern margins of Kodiak Island, and on Albatross Bank in the central Gulf (Fig. S.16). The r^2 from the internal validation exercise comparing observed and predicted abundance were low for the training (4%) and testing (3%) data.

Essential Fish Habitat Maps

The SDM-predicted subadult Pacific cod abundance was translated into a map of EFH (Fig. S.17). The majority of their EFH is mapped to the central and western GOA with very little EFH predicted east of the Yakutat region. Most of the hot spots for subadult Pacific cod habitat (top 25% of predictions) in the GOA were located over the continental shelf in the western Gulf around Sanak Island and the Shumagins and in the central Gulf south and west of Kodiak. The reduction of EFH area produced from the present SDM (~53%) is primarily the result of refinements in our modeling approach (Fig. S.18). For subadult Pacific cod the quantitative approach shifted from using 4th root transformed CPUE as the response variable to using count data and skill testing among models identified the hGAM as the best performing model in contrast to the MaxEnt model assigned to this life stage in 2017.

Table S.4. Gulf of Alaska subadult Pacific cod (1993-2019) multiple model skill testing: MaxEnt = maximum entropy model, GAM = generalized additive, paGAM = presence-absence GAM, hGAM = hurdle GAM, r^2 = coefficient of determination, RMSE = root mean square error, EFH = essential fish habitat.

	Training data		**Test data**		
Model	r^2	**RMSE**	r^2	**RMSE**	**Area of EFH (km^2)**
MaxEnt	0.02	44.0	0.01	123	570,072
paGAM	0.03	44.1	0.01	123	546,797
*hGAM	0.04	43.3	0.03	121	271,233
GAM	0.04	43.0	0.03	122	533,328

*best-performing model

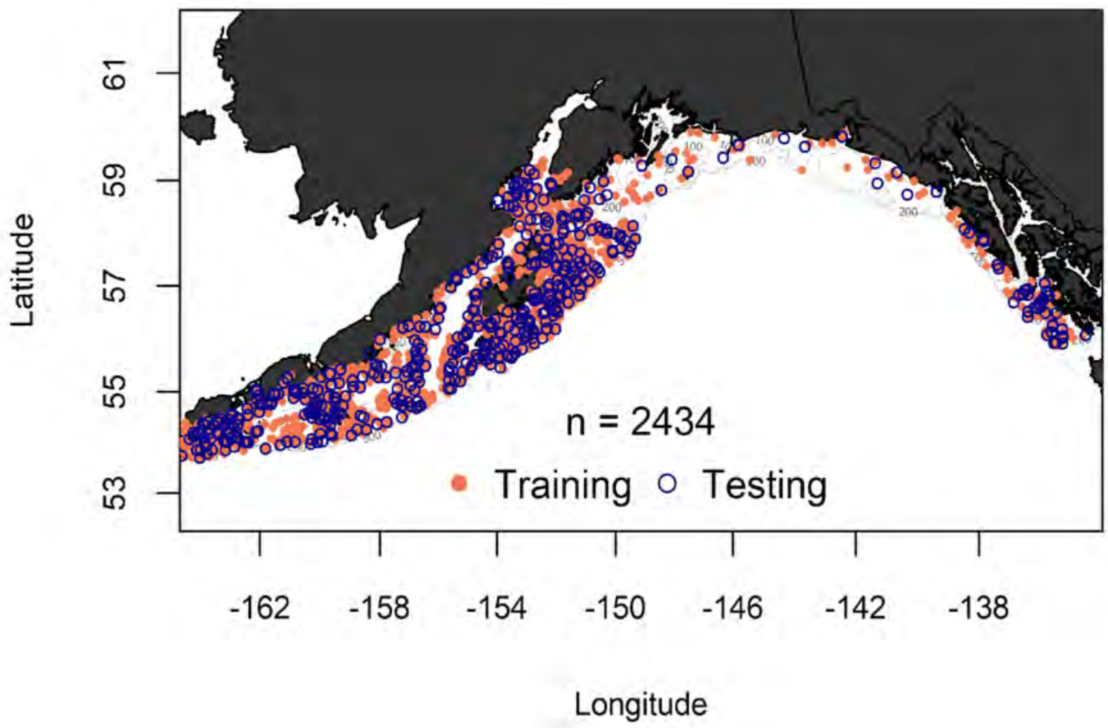

Fig. S.14. Presence of subadult Pacific cod in RACE-GAP summer bottom trawl surveys of the Gulf of Alaska (1993-2019) with training (orange dots) and testing (blue circles) data sets indicated; contours are the 100, 200, and 500 m isobaths.

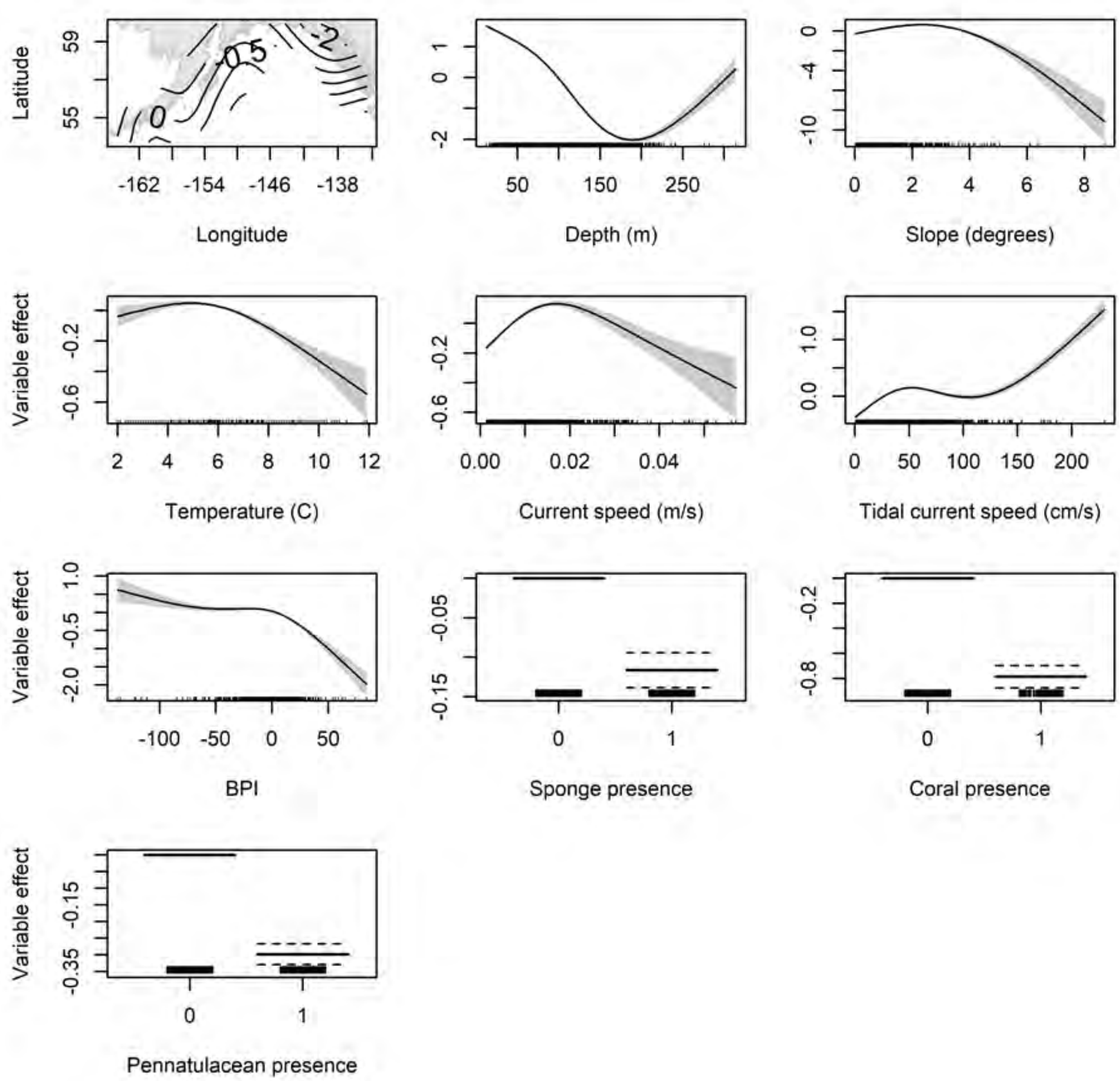

Fig. S.15. Effects of habitat covariates on the species distribution model (hGAM) predicting subadult Pacific cod abundance from RACE-GAP summer bottom trawl surveys of the Gulf of Alaska (1993-2019).

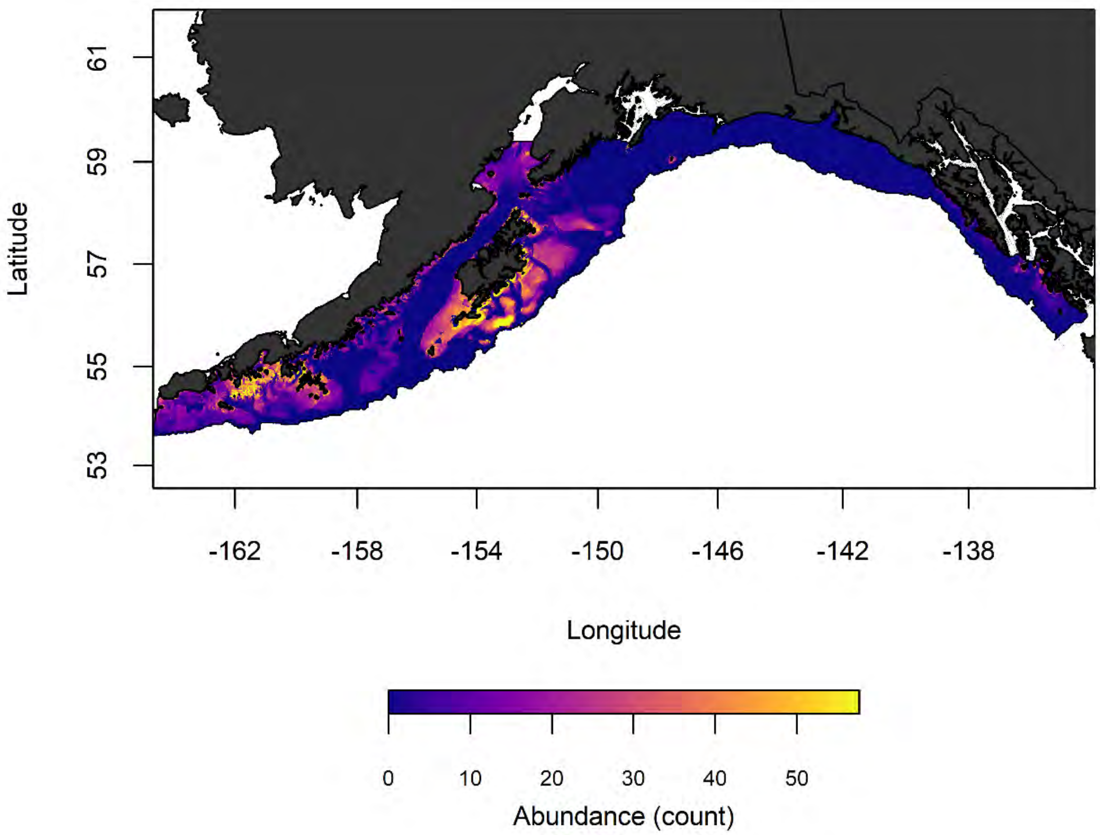

Fig. S.16. Species distribution model (hGAM) abundance (average number of animals) of subadult Pacific cod predicted from RACE-GAP summer bottom trawl surveys of the Gulf of Alaska (1993-2019); contours are the 100, 200, and 500 m isobaths.

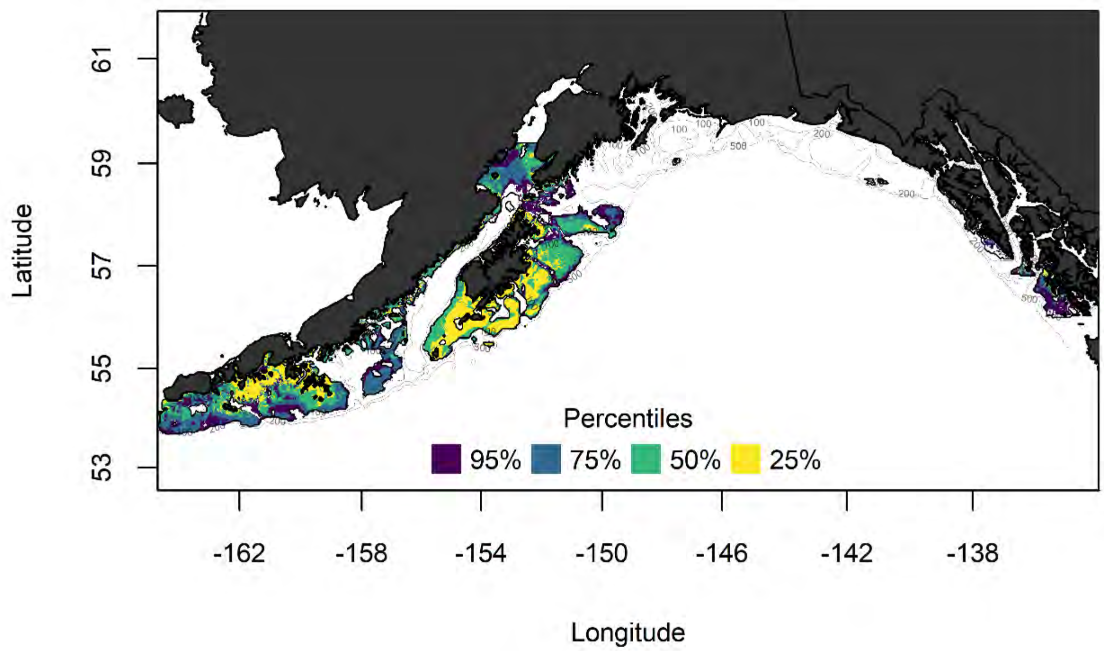

Fig. S.17. Composite of Gulf of Alaska subadult Pacific cod EFH percentiles (25% = "hot spots", 50% = "core habitat", all colored areas (25-95%) = EFH) constructed from species distribution model (SDM) predicted, habitat-linked abundance using RACE-GAP summer bottom trawl surveys (1993-2019); contours are 100, 200, and 500 m isobaths.

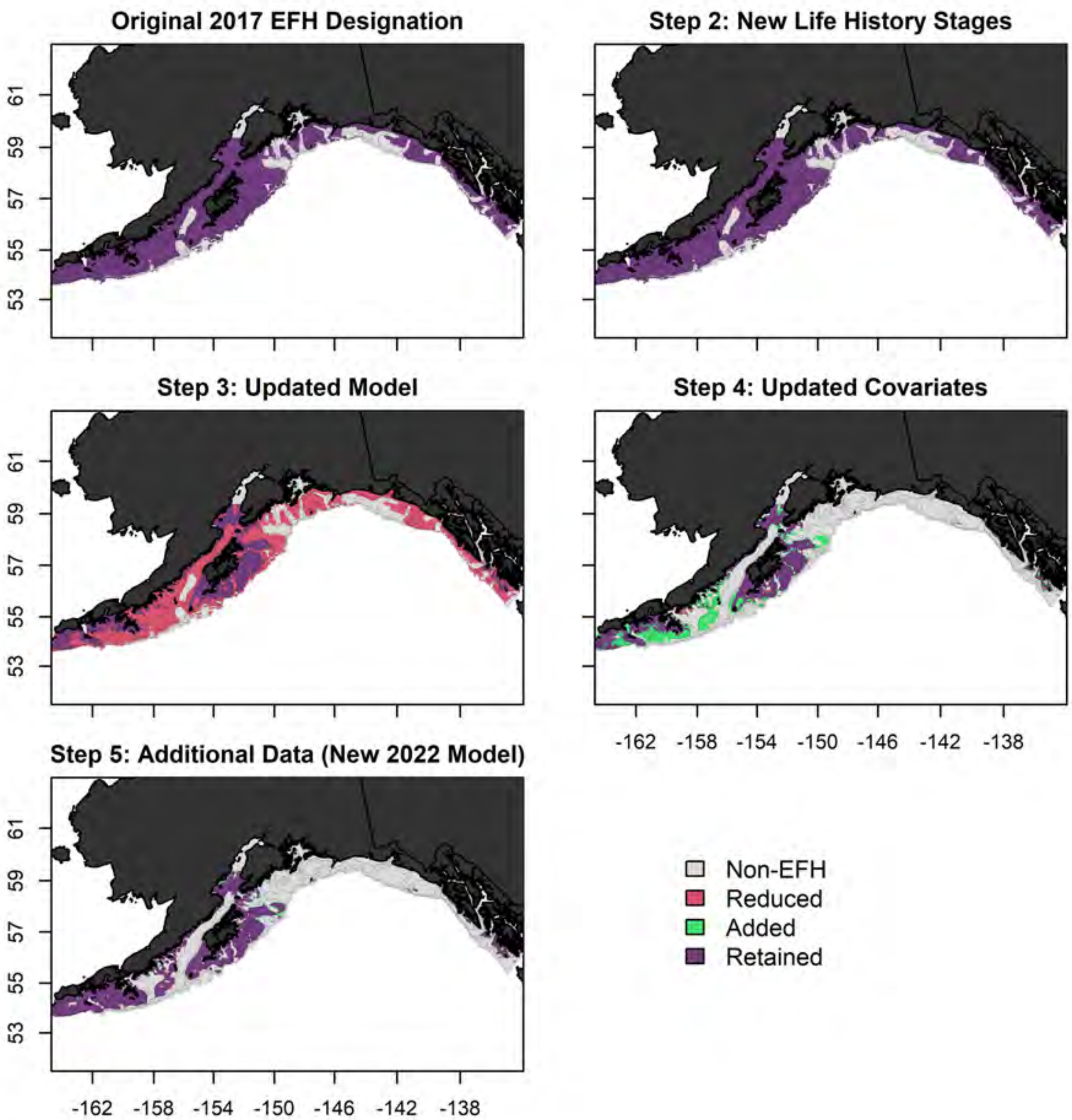

Fig. S.18. Iterative comparison of cumulative Gulf of Alaska (GOA) subadult Pacific cod EFH area changes in the refined SDM EFH approach, relative to the 2017 EFH map (GOA surveys 1993-2013, GAM; Rooney et al. 2018), including the effects of life stage redefinition **(Step 2)**, refinements to modeling approach **(Step 3)**, updates to habitat covariates **(Step 4)**, and inclusion of additional years of bottom trawl survey data (2015, 2017, 2019) **(Step 5)**.

Adult Pacific Cod

Distribution and Abundance

Adult Pacific cod were collected on 13 GOA summer bottom trawl surveys conducted between 1993 and 2019 (Fig. S.19). Trawl catches ranged from 0 to > 5,000 individuals per trawl haul and were most prevalent across the middle and outer shelf in the western and central Gulf. Skill testing of the 4 SDM parameterized from the GOA adult Pacific cod summer bottom trawl survey catches identified the best performing model with the lowest RMSE for the test data set (Table S.5) as a standard abundance GAM. The general form of this best-fitting GAM was

$$A \sim s(lat, lon) + s(bottom\ depth) + s(bottom\ temp) + s(tidal\ maxima) + F(sponges) + s(slope) + s(current\ speed) + s(BPI) + F(corals) + F(sea\ whips) + offset(area\ swept) + E,$$

where A = numerical abundance, s indicates a smoother, F indicates a factor term, E is an error term and the variables retained (e.g., *(lat,lon)* is a bivariate term describing geographic position and BPI = bathymetric position index) are listed in order of statistical significance. This habitat-linked SDM predicted the highest abundance of adult Pacific cod in the central and western GOA (Fig. S.20) and explained 23% of the deviance in the training data. Static and dynamic habitat covariates geographic position, bottom depth and temperature, tidal maxima, and presence of sponges were among the most significant terms retained in the best-fitting GAM. Model effects indicate that adult Pacific cod abundance was predicted to be higher in the western GOA and southeastern Alaska at bottom temperatures around 5°C, bottom depths shallower than 300 m, and tidal maxima around 100 $cm \cdot s^{-1}$ where SFIs were absent (Fig. S.21). The r^2 comparing observed and predicted abundance were low and ranged from 4% for the training data to 3% for the test data.

Essential Fish Habitat Maps

The SDM-predicted adult Pacific cod abundance was translated into a map of EFH, which is dispersed across the GOA study area (Fig. S.22). Adult GOA Pacific cod habitat hot spots (top 25% of predictions) are focused over the continental shelf of the central and western Gulf at depths shallower than 200 m and bottom temperatures around 5°C. Much of the EFH east of Yakutat is incorporated by the more inclusive 75 and 95% percentiles. The relatively small reduction of EFH area produced from the present SDM (~11%) is primarily the result of refinements in our modeling approach (Fig. S.23). For adult Pacific cod, the SDM in 2017 and in the present study is a standard GAM, but the quantitative approach shifted from using 4th root transformed CPUE as the response variable to using count data.

Table S.5. Adult Pacific cod multiple model skill testing: MaxEnt = maximum entropy model, GAM = generalized additive model with Poisson distribution, paGAM = presence-absence GAM with binomial distribution and cloglog link, hGAM = hurdle GAM (binomial and Poisson distributions), r^2 = coefficient of determination comparing observed versus predicted abundance, RMSE = root mean square error, EFH = essential fish habitat.

	Training data		**Test data**		
Model	r^2	**RMSE**	r^2	**RMSE**	**Area of EFH (km^2)**
MaxEnt	<0.01	95.4	0.01	45.4	584,511
paGAM	0.01	95.4	0.02	45.5	582,146
hGAM	0.02	94.1	0.04	44.5	296,244
*GAM	0.02	93.6	0.05	43.0	578,854

*best-performing model

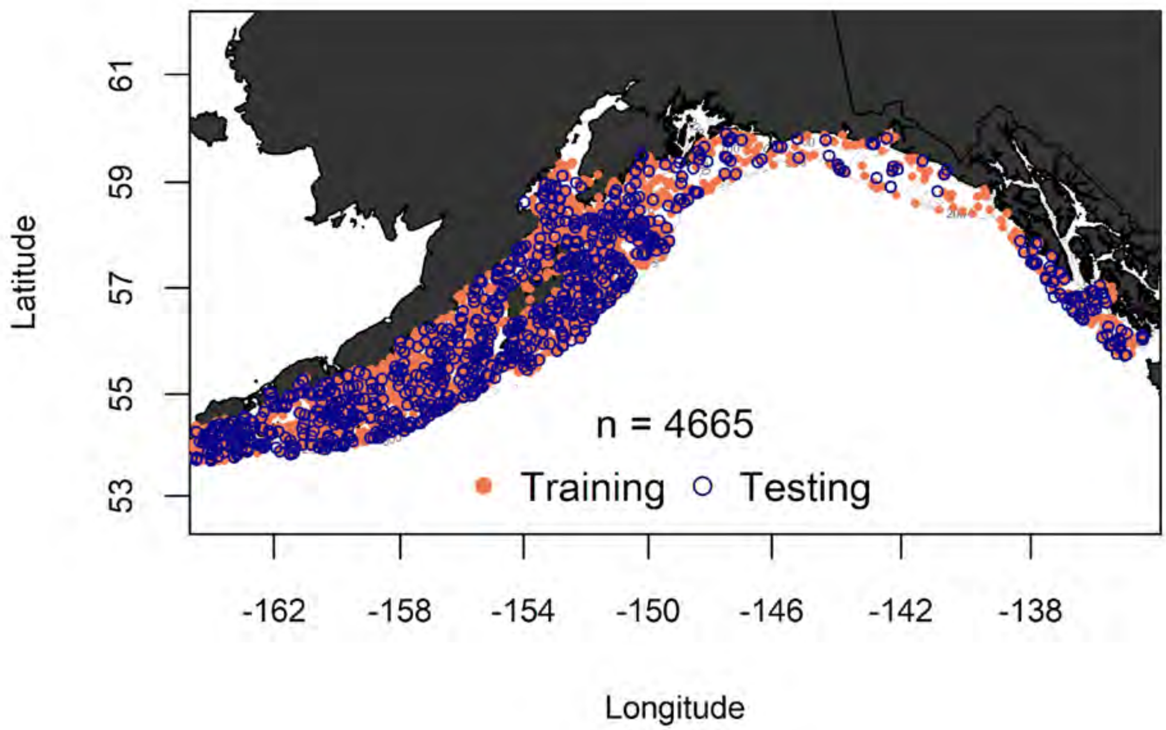

Fig. S.19. Presence of adult Pacific cod in RACE-GAP summer bottom trawl surveys of the Gulf of Alaska (1993-2019) with training (orange dots) and testing (blue circles) data sets indicated; contours are the 100, 200, and 500 m isobaths.

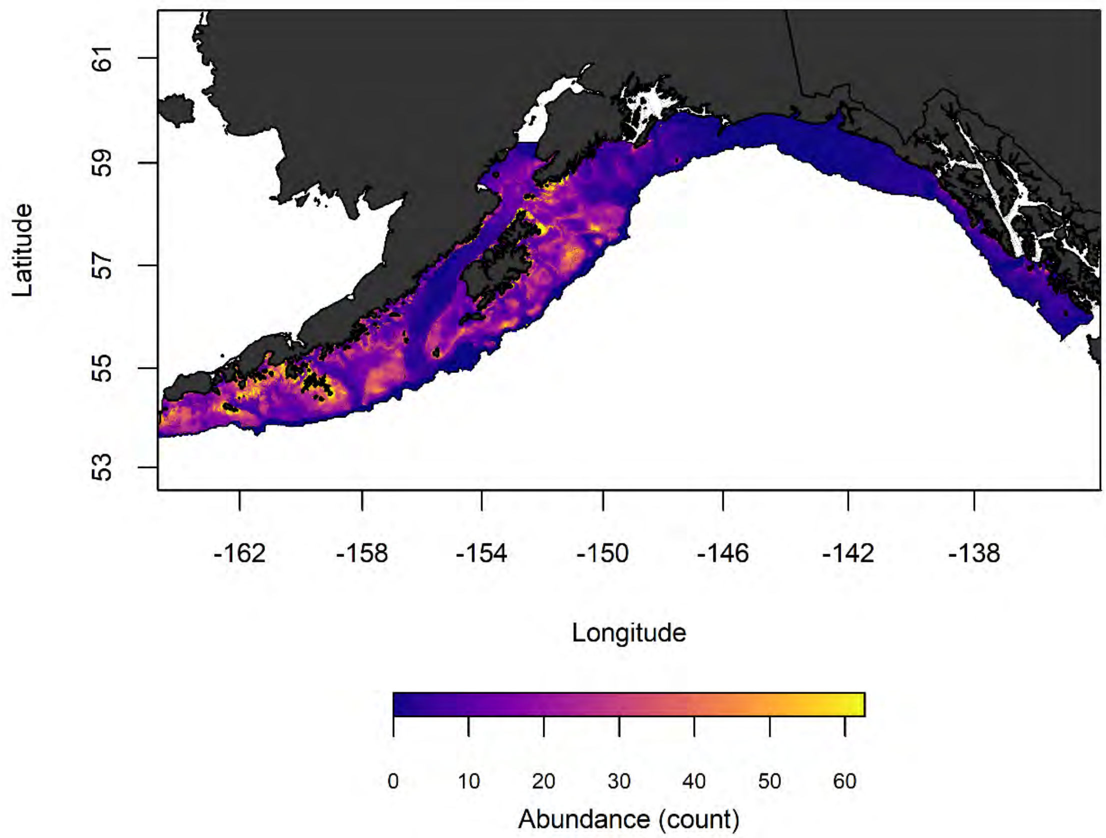

Fig. S.20. Species distribution model (standard GAM) predicted abundance (average number of animals) of adult Pacific cod from RACE-GAP summer bottom trawl surveys of the Gulf of Alaska (1993-2019); contours are the 100, 200, and 500 m isobaths.

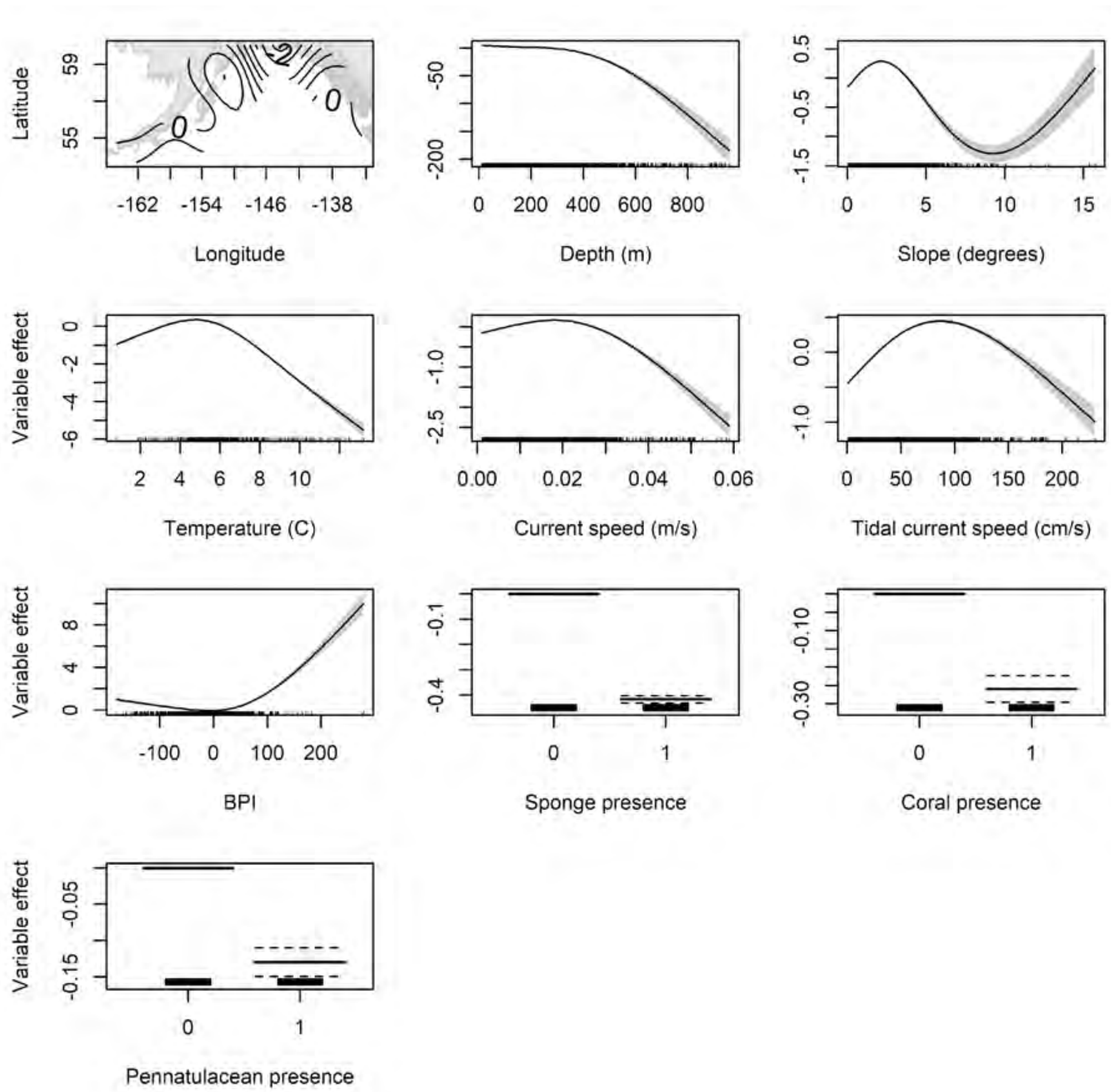

Fig. S.21. Effects of habitat covariates on the species distribution model (standard GAM) predicting adult Pacific cod abundance from RACE-GAP summer bottom trawl surveys of the Gulf of Alaska (1993-2019).

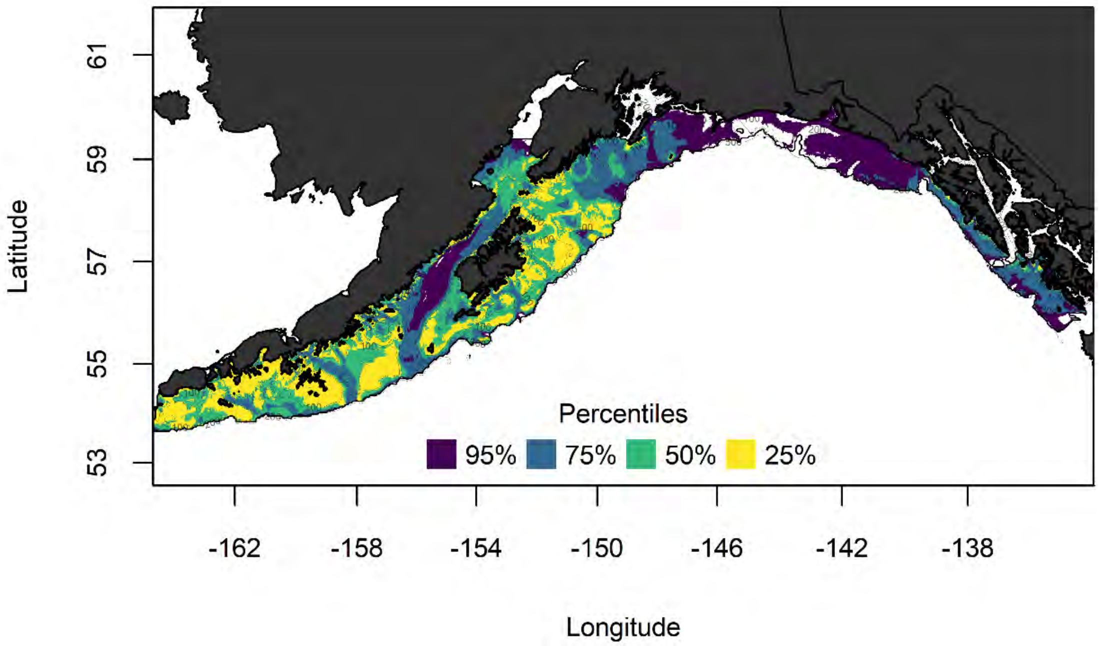

Fig. S.22. Composite of Gulf of Alaska adult Pacific cod EFH percentiles (25% = “hot spots”, 50% = “core habitat”, all colored areas (25-95%) = EFH) constructed from species distribution model (SDM) predicted, habitat-linked abundance using RACE-GAP summer bottom trawl surveys (1993-2019); contours are 100, 200, and 500 m isobaths.

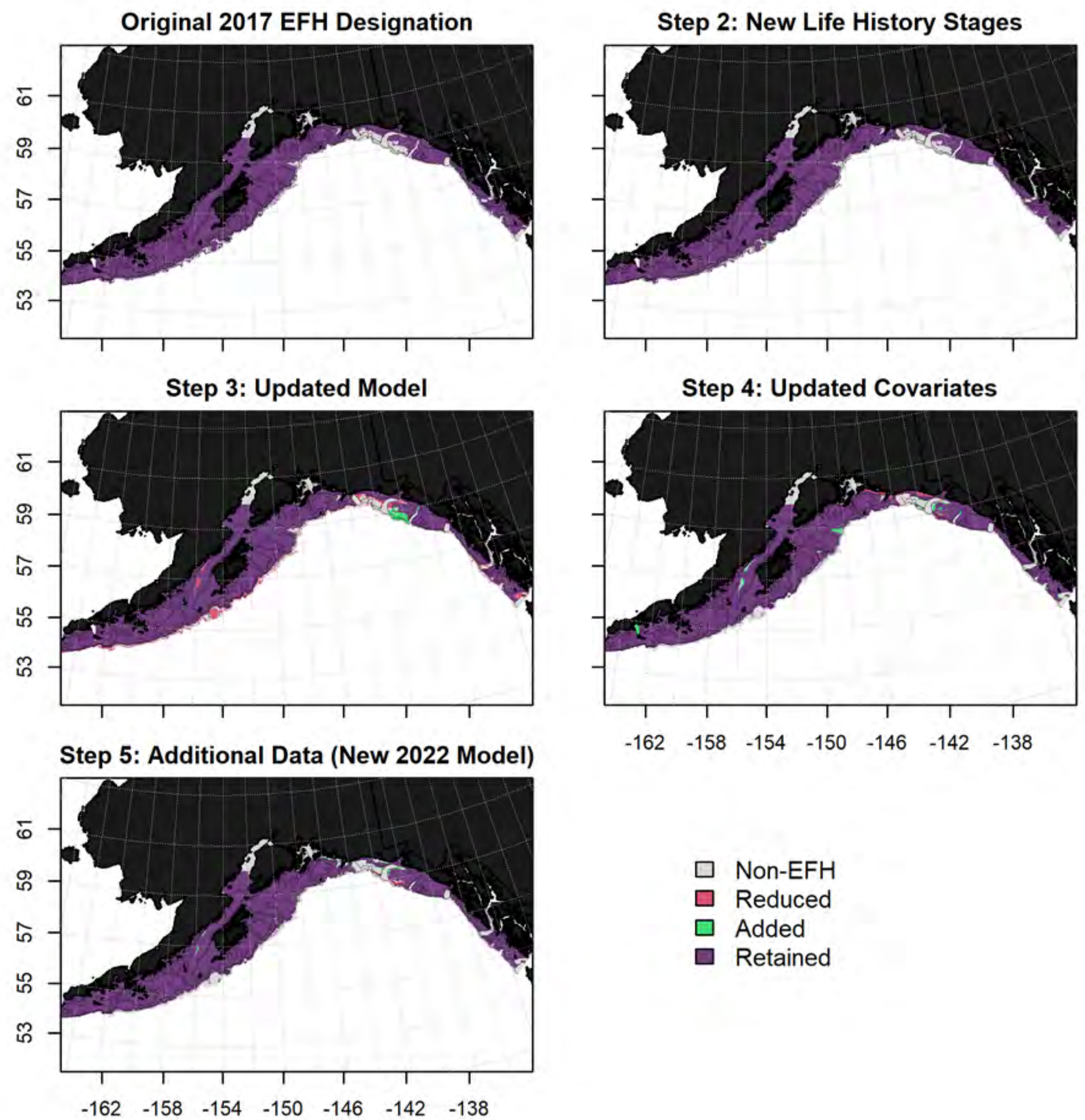

Fig. S.23. Iterative comparison of cumulative Gulf of Alaska (GOA) adult Pacific cod EFH area changes in the refined SDM EFH approach, relative to the 2017 EFH map (GOA surveys 1993-2013, Rooney et al. 2018), including the effects of life stage redefinition **(Step 2)**, refinements to modeling approach **(Step 3)**, updates to habitat covariates **(Step 4)**, and inclusion of additional years of bottom trawl survey data (2015, 2017, 2019) **(Step 5)**.

1.6.3 Extended Results: Gulf of Alaska Pacific Ocean Perch (*Sebastes alutus*)

Subadult Pacific Ocean Perch

Distribution and Abundance

Subadult POP were collected on 13 GOA summer bottom trawl surveys conducted between 1993 and 2019 and occurred throughout the study area (Fig. S.24). Trawl catches ranged from 0 to > 6,000 individuals per trawl haul and were encountered across the middle and outer shelf and along the shelf break. Skill testing of the 4 SDMs parameterized from the GOA subadult POP summer bottom trawl survey catches identified the best performing model with the lowest RMSE for the test data set (Table S.6) as the MaxEnt model. Model fits to training and test data sets were uniformly low for all SDM applied to this species life stage (r^2 ranging from 0.02 to 0.11). The MaxEnt SDM is formulated from a fixed set of covariates and includes the following independent predictor terms: slope, BPI, tidal maxima, bottom current speed, bottom temperature, and bottom depth. The model explains ~12% of the deviance in the underlying response data (Table S.7). Most of the deviance explained in the model (~54% of the total deviance explained) was attributable to a single covariate term - bottom depth. The covariate terms explaining the next greatest proportion of the total deviance in the MaxEnt model were bottom temperature and bottom current speed (~13% deviance explained each), and BPI (~10% deviance explained). Model effects indicate that predicted subadult POP abundance was maximized under particular conditions (at depths ~250 m, bottom temperatures ~6°C, and bottom current speeds ~0.25 m/s) and decreased with increasing BPI (Fig. S.25). The highest predicted abundances were over the continental shelf from the central GOA into southeast Alaska (Fig. S.26).

Essential Fish Habitat Maps

The MaxEnt-predicted subadult POP abundance was translated into a map of EFH that extends from Dixon Entrance in the southeast to the western GOA across the middle and outer shelf (Fig. S.27). Habitat hot spots for GOA subadult POP (top 25% of habitat-linked abundance predictions) were predicted along the shelf break in western and central GOA and extensively throughout southeast Alaska. In Yakutat and southeastern Alaska, where the continental shelf is narrower, important subadult POP habitat extends nearly to shore from the shelf break. The present SDM for subadult POP more than doubled the areal extent of EFH compared with the 2017 description. This is primarily the result of refinements in our modeling approach which led to the skill tested selection of MaxEnt as the best performing SDM in the present study compared with the application of an hGAM in the 2017 EFH Review (Fig. S.28).

SDM EFH and Vital Rate Co-mapping

Combining spatially-explicit growth potential for subadult POP with EFH maps is one approach to achieving the Research Plan objective to advance EFH information to Level 3 (Sigler et al. 2017). In this case study, we provide integrate previously published field and laboratory studies designed to describe vital rates (in this case growth potential) with distribution models and EFH maps to meet this objective. The approach presented here highlights habitat areas with greater somatic growth potential for subadult POP. Regions of higher growth potential that coincide with abundance hot spots are likely to represent areas of particular importance for subadult POP growth in the GOA.

Averaged across all years (1987-2013), growth potential for subadult POP was highest in the eastern GOA (where water temperatures were generally higher in the summer) and lowest west of Kodiak. The spatial pattern was consistent across most years (Fig. S.29), but the temporal pattern across years was variable. The observed interannual variability is a combination of the interplay between the duration of the spring and summer zooplankton bloom and the water temperature during that bloom. For example, in 2005, the zooplankton bloom duration was extremely brief and water temperatures in the spring were the highest in the time series (Rooper et al. 2012). This resulted in near average growth potential for 2005. In contrast, 2003 had one of the longest zooplankton blooms with near average water temperatures, but resulted in high growth potential extending from the eastern into the central GOA.

Table S.6. Subadult Pacific ocean perch multiple model skill testing: MaxEnt = maximum entropy model, GAM = generalized additive model with Poisson distribution, paGAM = presence-absence GAM with binomial distribution and cloglog link, hGAM = hurdle GAM (binomial and Poisson distributions), r^2 = coefficient of determination comparing observed versus predicted abundance, RMSE = root mean square error, EFH = essential fish habitat.

	Training data		**Test data**		
Model	r^2	**RMSE**	r^2	**RMSE**	**Area of EFH (km^2)**
*MaxEnt	0.05	54.5	0.02	52.1	515,164
paGAM	0.06	54.7	0.03	52.2	541,692
hGAM	0.06	59.6	0.04	58.9	236,476
GAM	0.11	52.7	0.03	54.7	552,838

*best-performing model

Table S.7. Relative importance of covariate terms (jackknifed % deviance explained) in Gulf of Alaska subadult Pacific ocean perch MaxEnt model including total deviance explained and coefficient of determination (r^2) of the training and test data.

Covariate Term	% Explained Deviance	% Total Deviance Explained	Training Data r^2	Test Data r^2
Bottom Depth	54.1	11.7	0.048	0.017
Current Speed	13.4			
Bottom Temp	12.5			
BPI	10.3			
Tidal Current	7.6			
Slope	2.1			

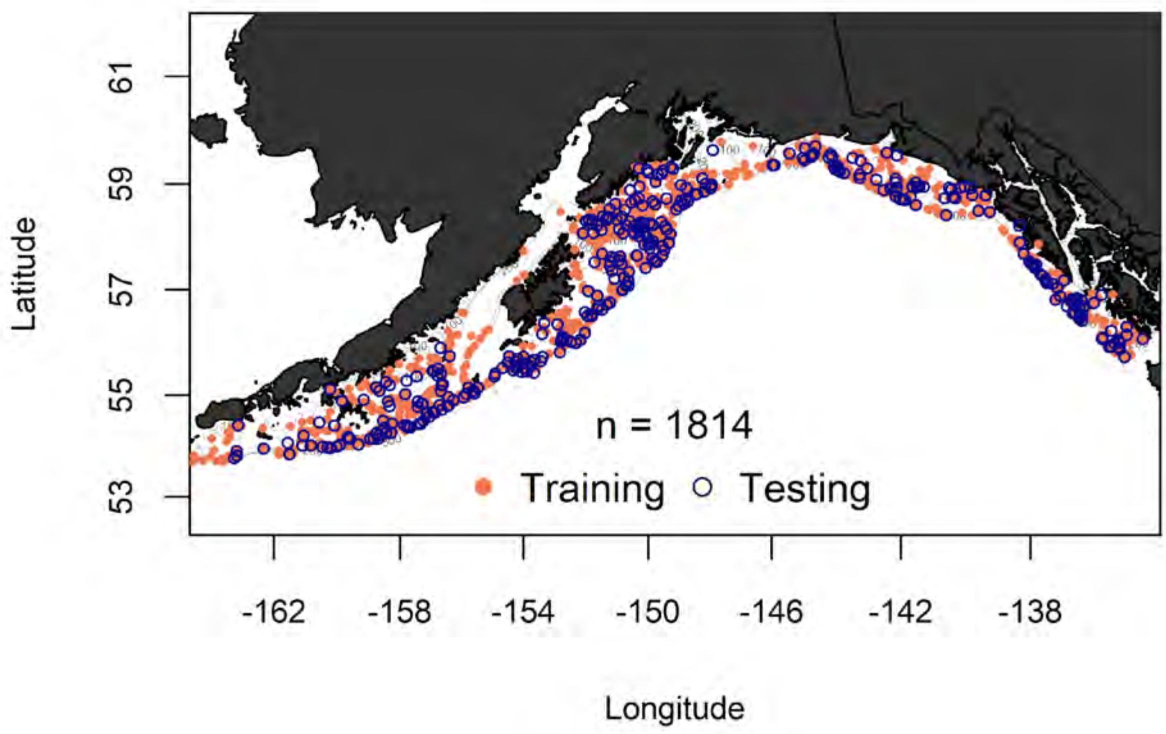

Fig. S.24. Presence of subadult Pacific ocean perch in RACE-GAP summer bottom trawl surveys of the Gulf of Alaska (1993-2019) with training (orange dots) and testing (blue circles) data sets indicated.

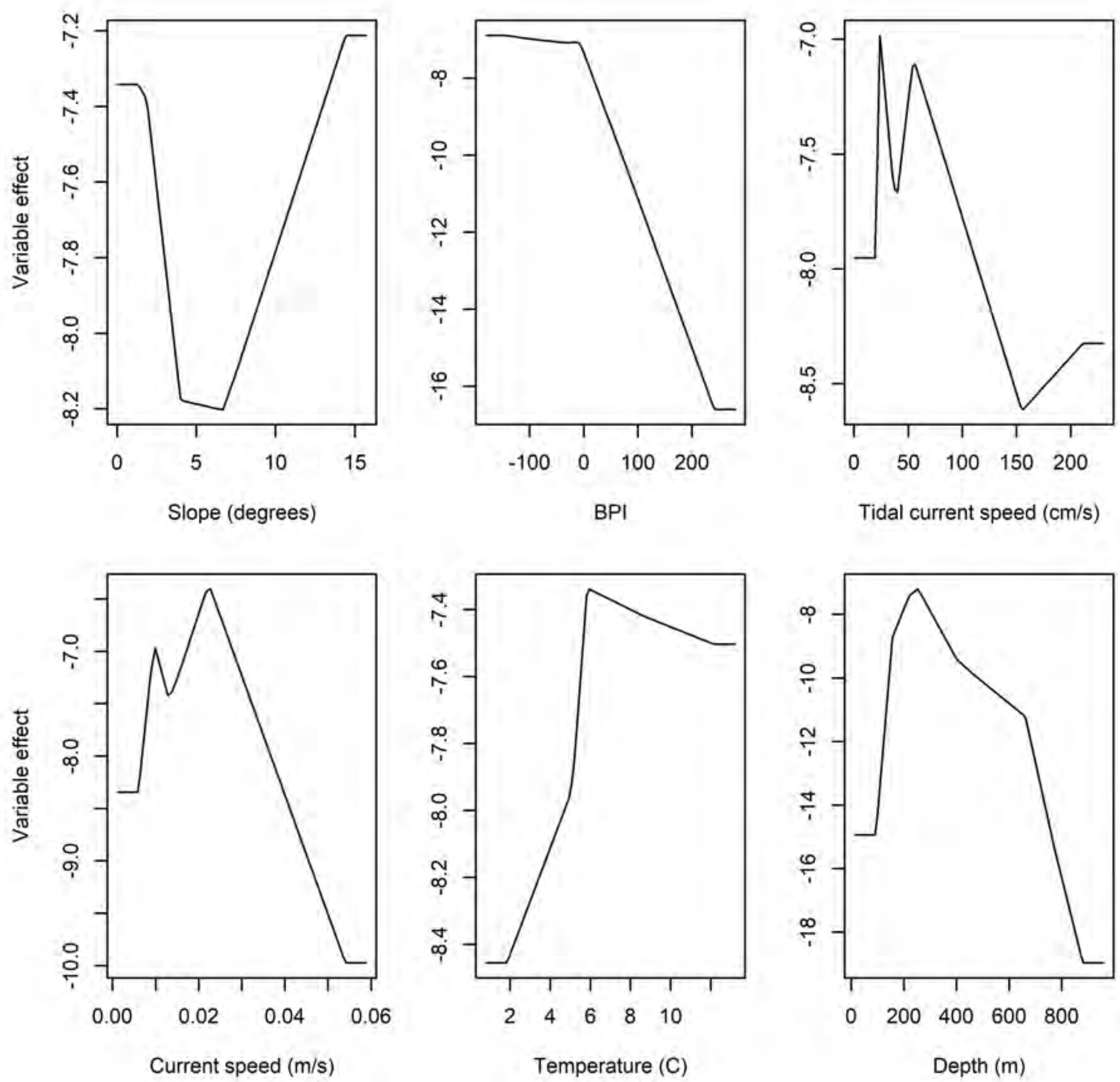

Fig. S.25. Effects of habitat covariates on the species distribution model (MaxEnt) predicting subadult Pacific ocean perch abundance from RACE-GAP summer bottom trawl surveys of the Gulf of Alaska (1993-2019).

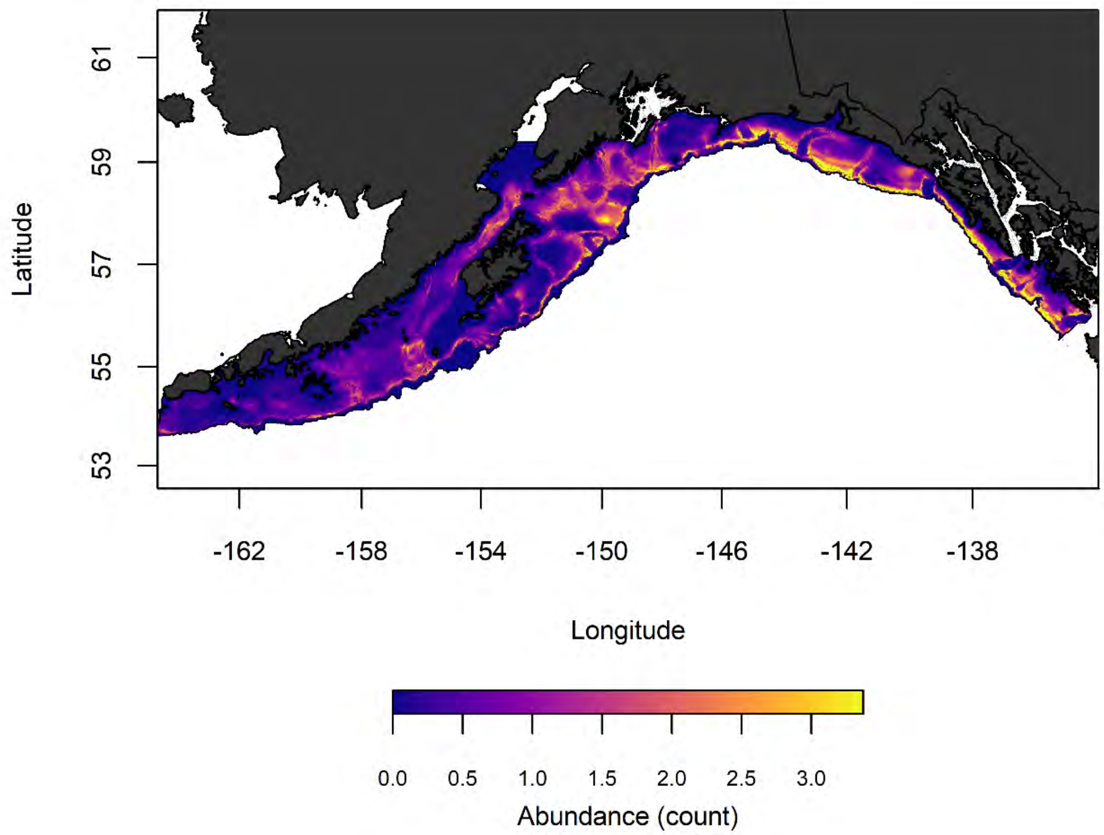

Fig. S.26. Species distribution model (MaxEnt) predicted abundance (average number of animals of subadult Pacific ocean perch from RACE-GAP summer bottom trawl surveys of the Gulf of Alaska (1993-2019).

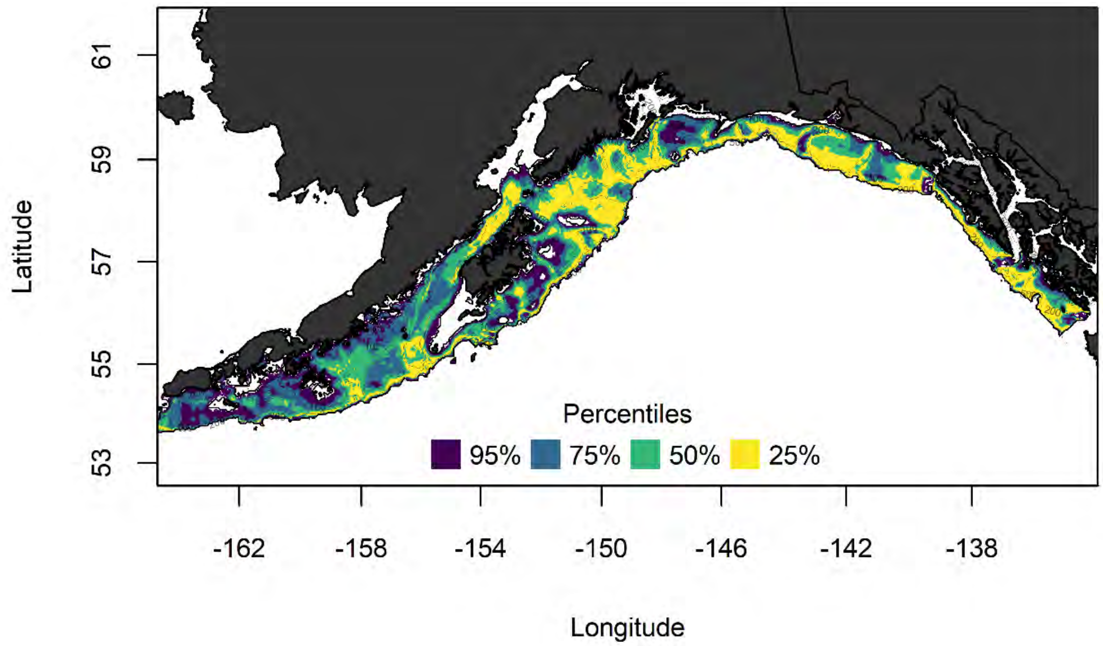

Fig. S.27. Composite of Gulf of Alaska subadult Pacific ocean perch EFH percentiles (25% = “hot spots”, 50% = “core habitat”, all colored areas (25-95%) = EFH) constructed from species distribution model (SDM) predicted, habitat-linked abundance using RACE-GAP summer bottom trawl surveys (1993-2019); contours are 100, 200, and 500 m isobaths.

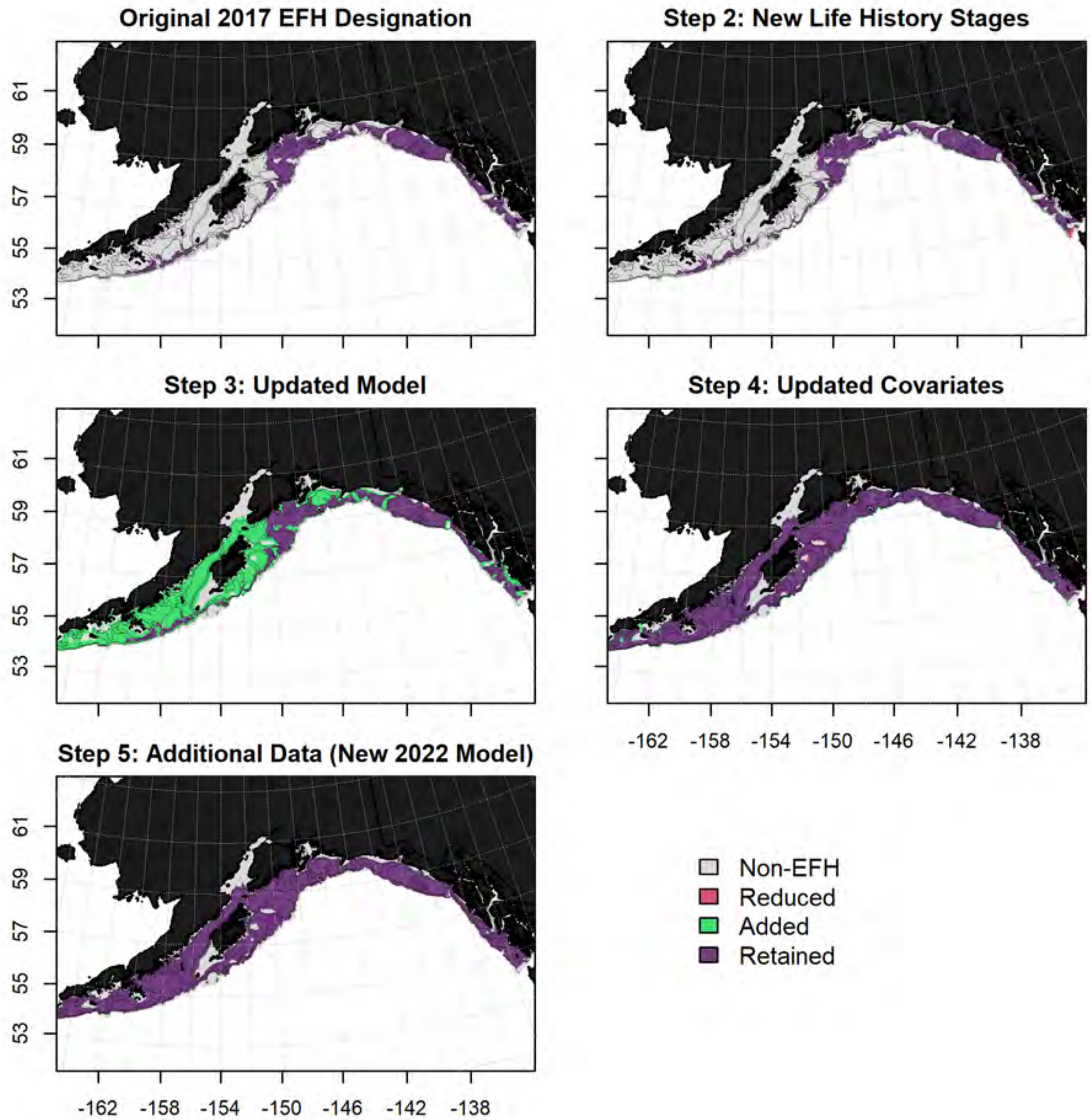

Fig. S.28. Iterative comparison of cumulative Gulf of Alaska (GOA) subadult POP EFH area changes in the refined SDM EFH approach, relative to the 2017 EFH map (GOA surveys 1993-2013, CPUE hGAM; Rooney et al. 2018), including the effects of life stage redefinition **(Step 2)**, refinements to modeling approach **(Step 3)**, updates to habitat covariates **(Step 4)**, and inclusion of additional years of bottom trawl survey data (2015, 2017, 2019) **(Step 5)**.

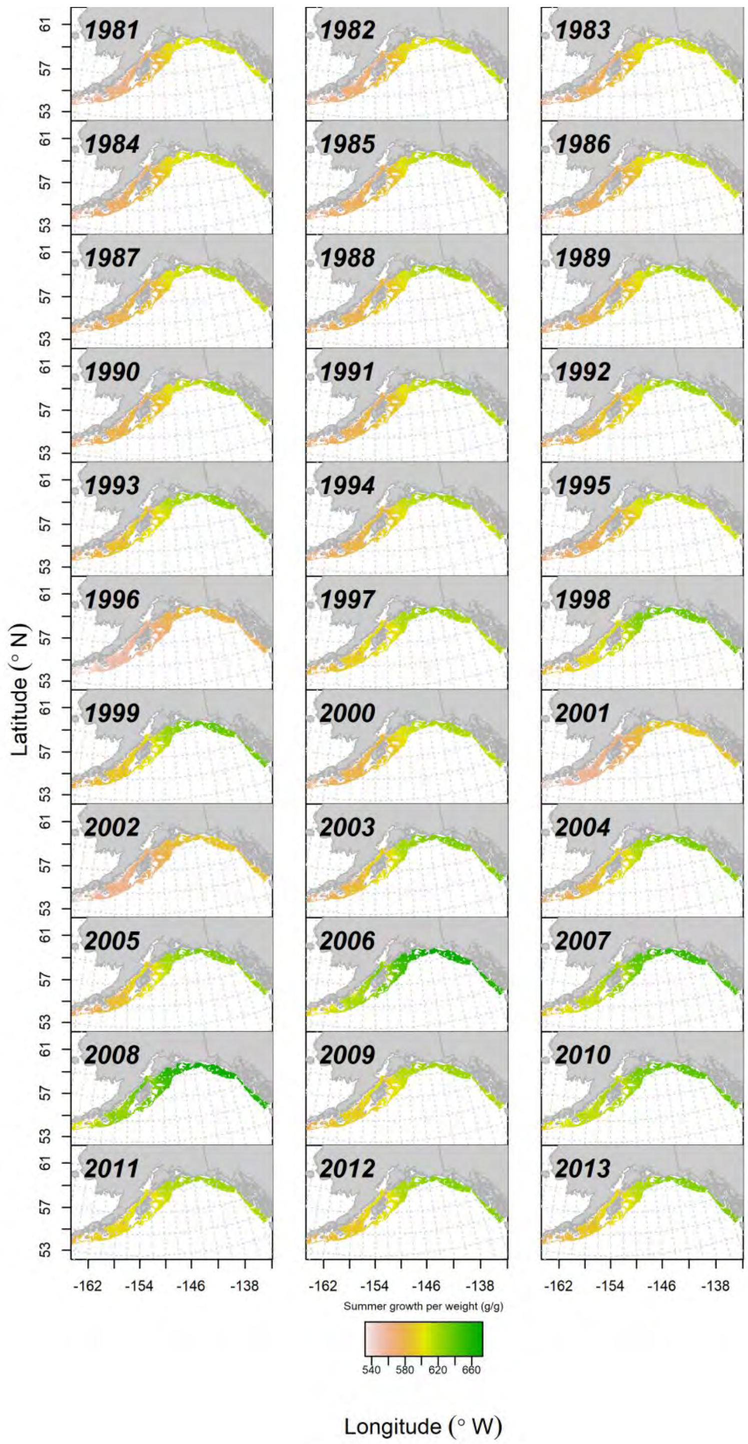

Fig. S.29. Map of summer predicted growth potential for subadult Pacific ocean perch (< 250 mm) in the Gulf of Alaska within the boundaries of defined EFH; growth potential (g/g body weight/day) was estimated using a bioenergetics model (Rooper et al. 2012) for 1987-2013.

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

Jennifer Marsh [32, 33], Jodi Pirtle [33], Franz Mueter [32]

In 2009, three species were identified as potential target species for future commercial fisheries in the Arctic Fisheries Management Plan (FMP): Arctic cod (*Boreogadus saida*), saffron cod (*Eleginus gracilis*) and snow crab (*Chionoecetes opilio*). These species are key components of the Arctic food web, as well as important subsistence resources. Within the FMP, preliminary stock assessments were completed for each species and it was concluded that current stock sizes could not support a fishery. Currently, commercial fishing is prohibited in the Arctic Management Area until there are data to support the creation of a sustainable fishery and ensure the sustainability of other ecosystem components (North Pacific Fishery Management Council (NPFMC) 2009). The habitats of these three ecologically important species may be subjected to non-fishing effects, such as oil and gas activity, necessitating increased understanding of their current habitat distributions.

As the climate continues to warm and the open water season is extended, there will be increases in vessel traffic, oil exploration and extraction in Alaskan Arctic waters, as well as infrastructure to support the increased activity. The warming climate, along with increased use and potential modification of the Arctic region, may have adverse effects on these three species. Therefore, it is crucial to have an understanding of their current EFH and how it may expand and contract with changes in climate and human activity.

Currently, EFH definitions for Arctic species are qualitative based on presence-absence data. We propose to refine EFH for Arctic cod, saffron cod and snow crab in the Beaufort and Chukchi Seas using the most recent and best available science (National Standard 2). Specifically, we will use species distribution models (SDM) to link habitat characteristics to species occurrence and catch per unit effort (CPUE) data from surveys. 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. We intend to refine the EFH text and maps for larval, juvenile, and adult life stages of Arctic cod, saffron cod and snow crab. These refined EFH designations can be used to inform resource managers and mitigate the risk of anthropogenic activities on these ecologically important species.

2.1 METHODS

2.1.1 Study Area

The Beaufort and Chukchi seas comprise the Arctic Management Area (AMA). 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 with an average depth 1,004 m. Ocean currents, wind, and the timing of ice melt largely influence the productivity within each region. Generally, during the open water season currents flow in through the Bering Strait northward toward the Arctic Ocean. Along the coast, the relatively warmer and fresher Alaska coastal current flows northward and then eastward along the Beaufort coastline. Farther offshore in the Beaufort Sea, areas of upwelling occur along the slope in the

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Beaufort Sea and Barrow Canyon leading to an increase in productivity in the water column (Hill and Cota 2005).

2.1.2 Survey Data

As most biological surveys have occurred during the ice-free season (i.e., the summer) in the Arctic Management Area, our proposed models will describe EFH during the summer season only. While there have been no long-term systematic surveys within the region, a number of surveys have been conducted since at least 1959 (Norcross et al. 2013) with more occurring within the past 15 years. We have compiled survey Arctic cod, saffron cod and snow crab. This includes recent survey data from the Beaufort Sea, nearshore regions in the Chukchi and Beaufort Seas, including the productive Barrow Canyon (Fig. 2.1). The survey catches were divided by life stage based on literature (Helser et al. 2017, Divine et al. 2019, Vestfals et al. 2019; Table 2.1). Body length measurements were used for Arctic and saffron cods, and carapace widths for snow crab. Additional survey data will be included in analysis, if available.

2.1.3 Habitat Covariates

For the species distribution models, habitat covariates considered include depth, seafloor terrain, sediment types, currents, temperature, salinity, and productivity. Current, temperature, and salinity data from the Pacific Arctic Regional Ocean Modeling System (Curchitser et al. 2013) and have been provided by S. Danielson, UAF (pers. comm.). Specifically, a daily average from each year (1980-2018) 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 was provided. We further averaged the values over the summer months (July – September) to match the month when most surveys took place. Sediment 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). Modis ocean color data during July – September (2002 – 2018) was used as a proxy for primary productivity ($gC/m^2 \cdot day$) (Behrenfeld and Falkowski 1997). In addition, bathymetry data was provided by S. Lewis, AKR (pers. comm.), slope and bathymetric position index (BPI) were derived using the benthic terrain modeler extension in ArcGIS version 10.7 (ESRI). All habitat data has be interpolated and converted to 1 km^2 raster grids for each habitat covariate for the AMA (Fig. 2.2). Other habitat covariates will be considered, such as additional bathymetry-derived seafloor terrain metrics, biogenic habitat features, and occurrence of prey. A pre-selection of covariates was done based on variance inflation factors (< 5) and correlations with other variables (< 0.7). Model selection procedures will be used to identify the most important habitat characteristics to be used in the best-fit models.

2.1.4 Species Distribution Models

Species distribution models (SDM) can be used to link habitat characteristics to occurrence data from biological surveys. These models can be used to predict habitat suitability or the probability of presence or abundance depending on the type of data available and form of model used. We are considering two main types of SDM that have been used to define EFH for groundfish in the Gulf of Alaska, Bering Sea and Aleutian Islands (Laman et al. 2017, Turner et al. 2017), including maximum entropy (MaxEnt) models (Phillips et al. 2017) and generalized additive models (GAM) (Wood 2006) to predict habitat-related abundance (EFH level 2). We intend to run MaxEnt models on all life stages of Arctic cod, saffron cod and snow crab. GAM will be run on at least late juvenile and mature Arctic cod and explored for other species life stages. Further, maps of models linking vital rates (growth and body condition) to habitat will be conducted for juvenile Arctic cod using laboratory studies on temperature-dependent growth (Laurel et al. 2016) and body condition (Copemen et al. 2017). The most appropriate model will be based on model performance.

2.2 PRELIMINARY RESULTS

Preliminary MaxEnt models have been run for age-0, late juveniles and mature Arctic cod (e.g., Fig. 2.3) and saffron cod using presence-only data from offshore bottom trawl surveys and nearshore surveys of various gear-types (e.g., EFH Level 1). Of the considered habitat covariates, mean summer bottom temperature was included in all models and had high percent contribution to determining habitat suitability. Arctic cod habitat suitability decreased with increasing temperatures and the importance was higher for early life stages. Saffron cod habitat suitability increased with increasing temperatures. Model predictions indicate that mature Arctic are more likely to occur in areas with higher bottom current speeds and it was the covariate with the highest percent contribution, followed by bottom temperature.

2.3 NEXT STEPS

Next steps include—

- Acquire additional species sampling data if available;
- Develop habitat covariates for the pelagic early life stage SDMs (e.g., surface temperature and currents);
- Refine modeling methods (i.e., modernized MaxEnt, GAM, and skill testing among models, resulting in EFH Level 2 information);
- Complete SDM EFH for all species life stages (EFH Level 2);
- Integrate SDM EFH with vital rates of temperature-dependent growth (EFH Level 3).

We will complete this study in-progress and share this work with the Council and NMFS as part of the full package of new EFH information available for the 2022 5-year Review.

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2.5 TABLES

Table 2.1. Proposed life stage for Arctic SDM EFH and maps. All units are in millimeters.

Species	**Larvae**	**Early Juvenile (Age-0)**	**Late Juvenile**	**Mature**
Arctic cod (Length)	< 30	31 – 70	71 – 120 [GAM *]	> 120 [GAM *]
Saffron cod (Length)	< 27	28 – 70	71 – 190	> 190
Snow crab (Carapace width)	< ?	Males: ? – 34 Females: ? – 34	Males: 35 – 61 Females: 35 – 46	Males: > 62 Harvestable Males: > 100 Females: > 46

[*] EFH Level 3: Vital rates using temperature dependent-growth (Laurel et al. 2016) and body condition (Copeman et al. 2017)

[*] GAM: Generalized additive model of habitat linked density or abundance to accomplish EFH Level 2.

2.6 FIGURES

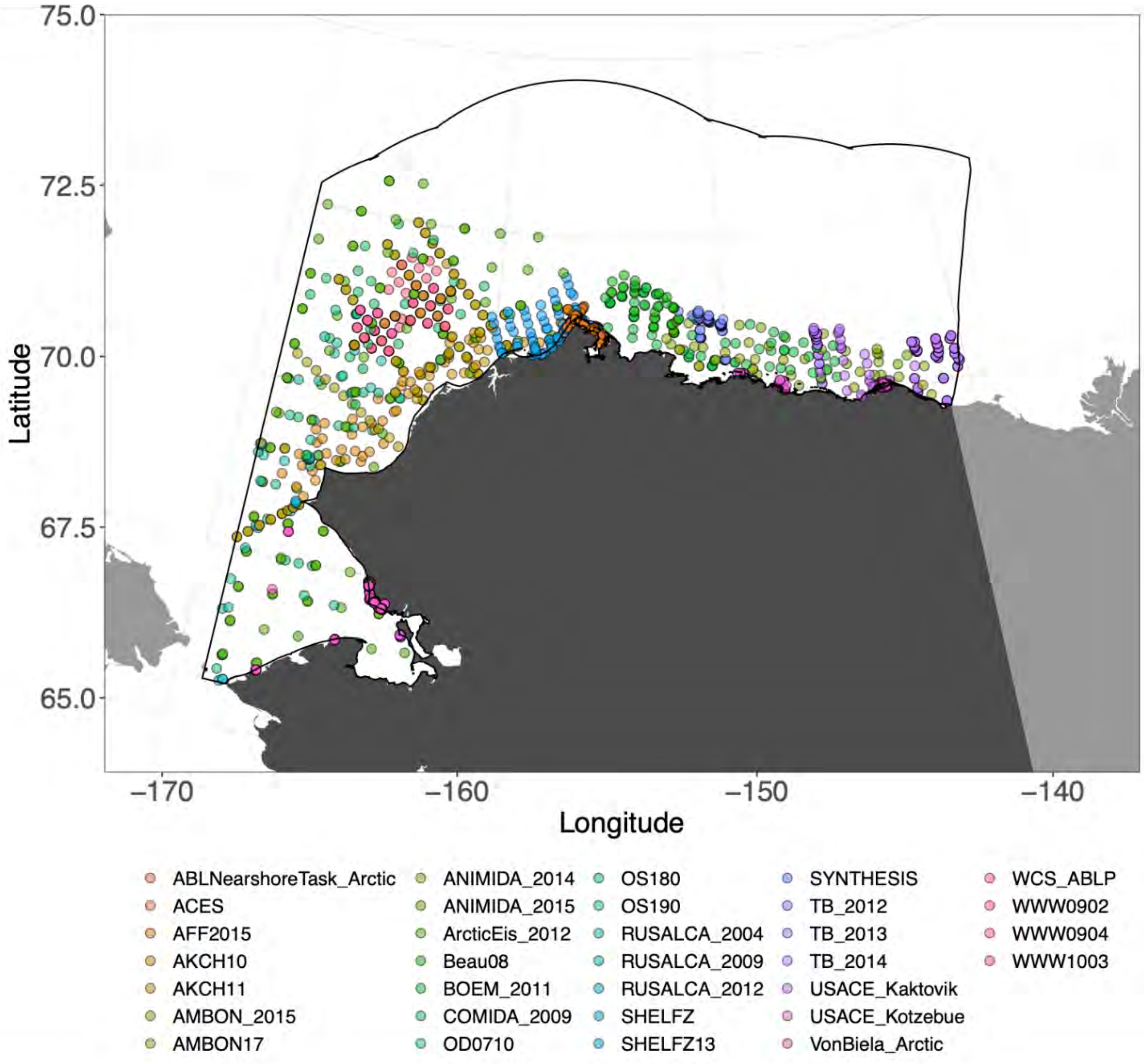

Fig. 2.1. Nearshore (various gear types) and offshore (bottom trawl) survey stations from various research projects in Chukchi and Beaufort seas during 2004 through 2018. The black outline denotes the Arctic Management Area.

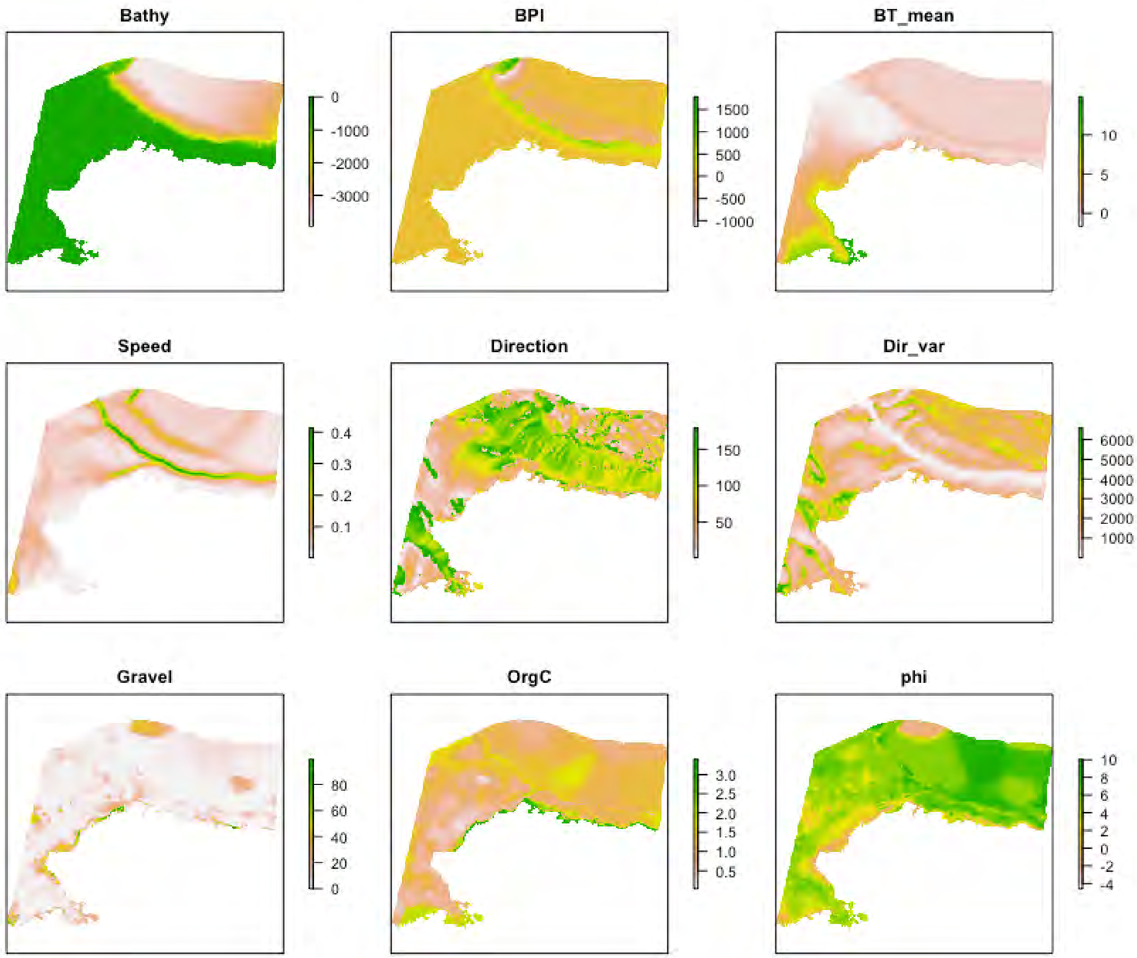

Fig. 2.2. Selected habitat covariates to be considered in the species distribution models for the demersal life stages of Arctic cod, saffron cod, and snow crab: bathymetry (m), bathymetric position index (bpi), mean summer bottom temperature (C), mean bottom current speed (m/s), mean bottom current direction (angle), mean bottom current direction variability, % gravel, % Organic Carbon and sediment size (phi).

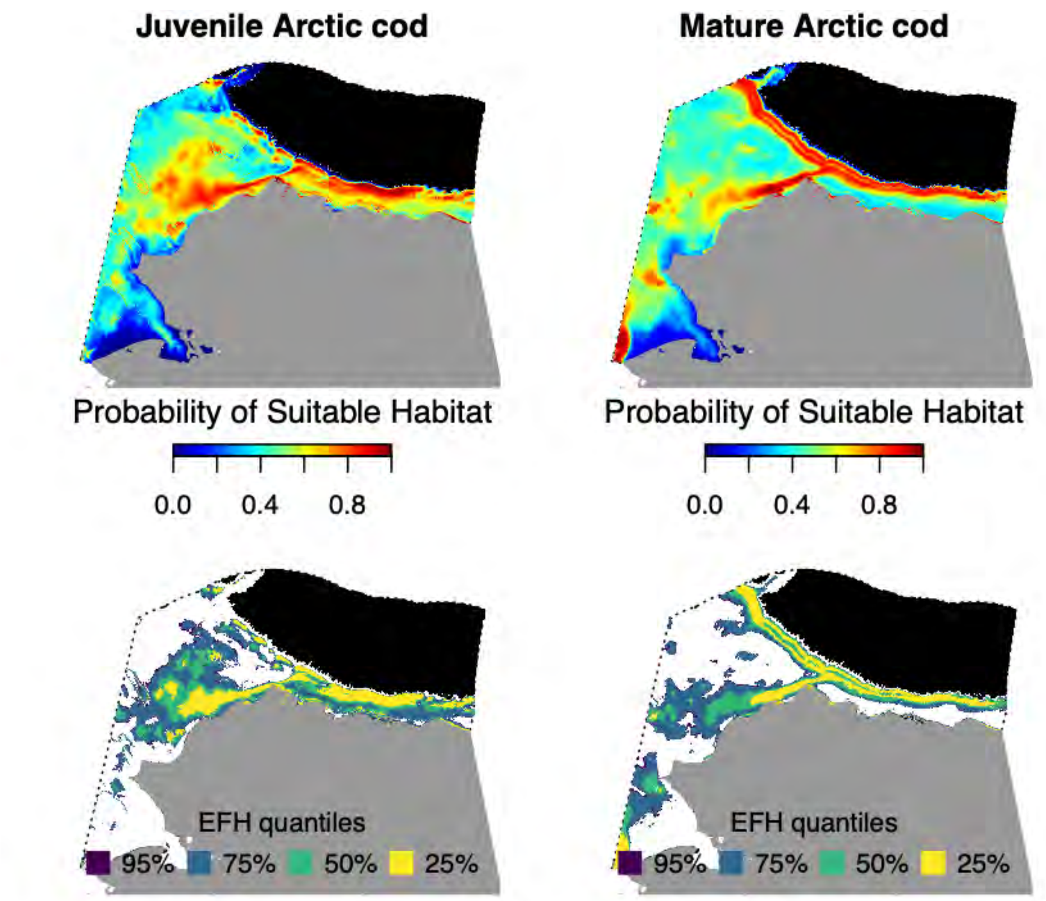

Fig. 2.3. Predictions of probability of suitable habitat for juvenile Arctic cod **(left)** and mature Arctic cod **(right)** based on preliminary best-fit MaxEnt models. The bottom two maps show the preliminary EFH delineations of the top 95% of model predictions for juvenile Arctic cod **(left)** and mature Arctic cod **(right)**. The blacked out area has bottom depths > 1250 m and was not included in models or predictions, as there is currently no survey data available.

3 Optimal Thermal Habitat of Juvenile Walleye Pollock (*Gadus chalcogrammus*) in the Gulf of Alaska

Ben Laurel [34], Louise Copeman [34, 35], Tom Hurst [34], Jodi Pirtle [36], Georgina Gibson [37]

Understanding mechanisms through which environmental conditions influence survival, growth, and condition of juvenile life history stages can help inform stock productivity estimates for commercially and ecologically important species such as walleye pollock (*Gadus chalcogrammus*). In addition, the ability to link habitat information such as temperature to rate-dependent functions of survival, growth, and condition can help describe and map essential fish habitat (EFH) Level 3 information (habitat-linked vital rates). This research is designed to characterize the optimal thermal overwintering habitat of walleye pollock (hereafter referred to as pollock) in the Gulf of Alaska (GOA). These investigations will provide: 1) metrics of regional habitat quality for early juvenile stage pollock in their first winter following transition from a pelagic early juvenile to a “settled” early juvenile in nursery habitats, 2) a regional survival likelihood estimate for age-0 fish emerging from overwintering habitats into their second year of life, and 3) regional maps of these habitat quality and habitat-linked survival metrics related to estimates of the spatial distribution of habitat for this life stage. We will also develop regional habitat-linked vital rate maps for summer conditions based on previously published studies.

Water temperature in the marine environment regulates physiological processes that manifest in terms of growth, condition (lipids and energy), and survival. The thermal habitat in which fish can efficiently grow (Laurel et al. 2016) and store lipids (Copeman et al. 2017) is highly species-dependent. However, optimal thermal habitats for fish are dependent on feeding conditions. In the summer, when food production is high, optimal habitat is defined by temperatures that promote highest growth and energy storage for individual species. In contrast, in the winter when food production is low, optimal habitats are more broadly understood as the range of cooler temperatures that balance energetic loss with predation exposure. Therefore, optimal overwintering habitat is a complex interplay between intrinsic factors of the fish (size and energy storage), extrinsic habitat conditions (temperature, food availability, winter duration) and ecological processes such as predation rate (Sogard 1997, Hurst 2007).

Optimal overwintering habitat for pollock is believed to be dependent on the interactive effects of body size, co-varying autumn energy stores and overwintering thermal habitats (Sogard and Olla 2000, Siddon et al. 2013). Increased recruitment of gadids has been observed in cold-years when increased fish condition during the late larval and juvenile phases is positively correlated with matches in the abundance and distribution of large cold-water high-fat zooplankton species (Beaugrand and Kirby 2010, Sigler et al. 2012, Heintz et al. 2013, Siddon et al. 2013). Thus late summer has been proposed as a critical period for pollock as they must store enough energy or face high overwintering mortality. Despite the recognition that overwintering habitat is critical to the survival of age-0 pollock and likely regulates population dynamics, very little is known about what constitutes essential overwintering habitat in juvenile gadids. The ‘winter knowledge gap’ is arguably the most significant factor limiting our understanding of observed spatial shifts in the adult population as the result of climate change.

This study will develop EFH Level 3 information, from temperature-dependent growth and energy (lipid) loss rates for juvenile pollock under winter conditions (laboratory component of the present

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study), and temperature-dependent growth and lipid accumulation rates that were developed from laboratory studies of juvenile pollock under summer conditions and previously published (Laurel et al. 2016, Copeman et al. 2017). EFH for North Pacific species is not currently described at Level 3 (habitat-linked vital rates). This study will combine measured vital rates from laboratory experiments with a species distribution model (SDM) to demonstrate one approach to develop EFH Level 3 descriptions and maps for North Pacific species. Preliminary methods and results are presented here in brief with an example where the summer vital rates for juvenile pollock have been applied for the GOA.

3.1 EFH LEVEL 3 MAPS EXAMPLE

Laboratory experiments were conducted with pollock collected in the GOA to develop temperature and size-dependent vital rate functions under summer conditions, including growth (Laurel et al. 2016) (Fig. 3.1a) and lipid accumulation, a metric of body condition (Copeman et al. 2017) (Fig. 3.1b). The vital rates were then applied to regional temperature data from the GOA ROMS (3 km^2) for model years 1997-2011 (Dobbins et al. 2009, Coyle et al. 2012, Hermann et al. 2016) (Figs. 3.2 and 3.3). A juvenile pollock (40-120 mm) SDM was developed, using maximum entropy modeling (MaxEnt) of available presence-only species response data assembled from multiple sources and regional habitat covariates (Pirtle et al. 2019). Habitat covariates with the greatest percent contribution to the model were depth (40.4%, 25-300 m), bathymetric position index (6.5 km^2) (34.0%, low-lying and edge terrain), substrate rockiness (15.2%, not rocky), and seafloor slope (3.8%, flat and edge terrain) (Fig. 3.4). The vital-rates were integrated with the SDM to produce preliminary maps of temperature-dependent vital rates in areas of suitable habitat for juvenile pollock in a co-mapping approach (Fig. 3.5).

3.2 PRELIMINARY CONCLUSIONS AND NEXT STEPS

We demonstrate an approach to quantify and map EFH Level 3 information for juvenile pollock in the GOA Fishery Management Area, where temperature-dependent vital rate functions are applied to a regional habitat model for this life history stage. There is potential to extend this mechanistic approach to other species, where vital rates have been previously developed that are linked to dynamic environmental habitat covariates, such as temperature.

Next steps by this study include—

- Complete juvenile pollock laboratory experiments of vital rates (applied in the summer example) for winter conditions;
- Update juvenile pollock SDM, including species data, habitat covariates, and revised modeling methods;
- Explore other SDM-integrated Level 3 mapping approaches (e.g., temperature-dependent vital rates as a covariate in the SDM);
- Develop Level 3 maps, using annual depth-integrated temperature data for summer and winter seasons in the GOA from the updated ROMS (e.g., through 2018 or 2019).

This study will continue this work in-progress. New EFH information from this work will become part of the full package available to the Council and NMFS for the 2022 5-year Review.

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3.4 FIGURES

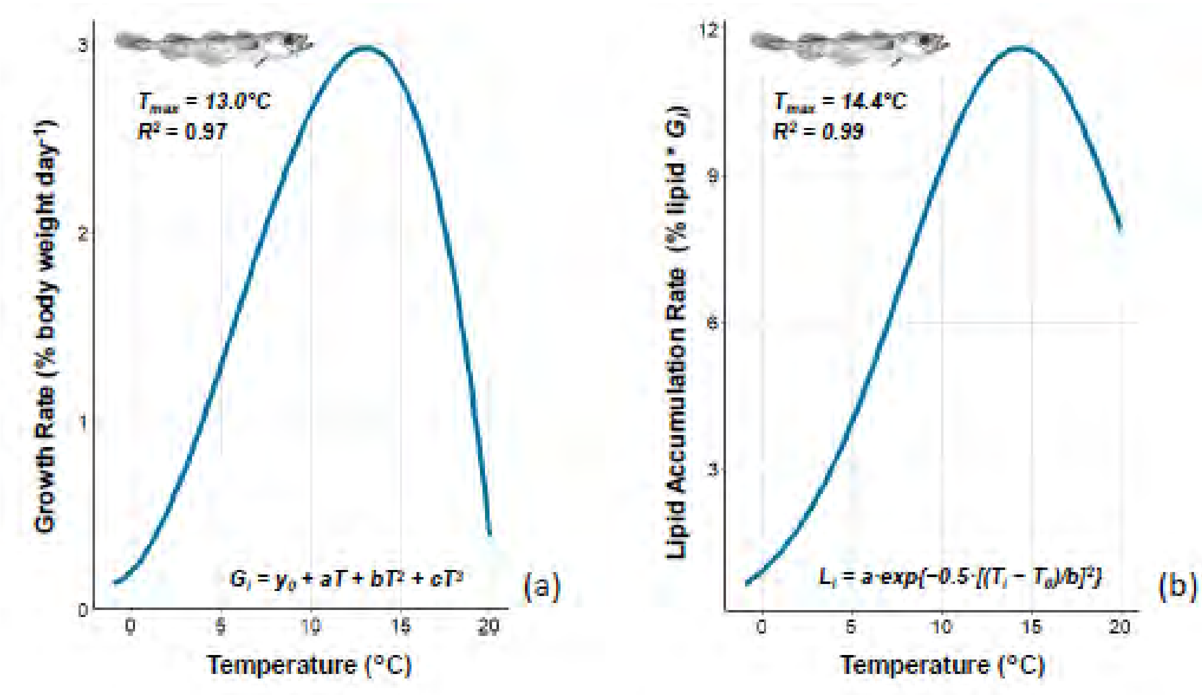


Fig. 3.1. Temperature-dependent vital rate functions for juvenile walleye pollock (40-120 mm) developed in the laboratory under summer conditions, including a) growth rate (G_i), where T_{max} = 13.0°C (Laurel et al. 2016) and b) lipid accumulation rate (condition) (L_i), where T_{max} = 14.4°C (Copeman et al. 2017).

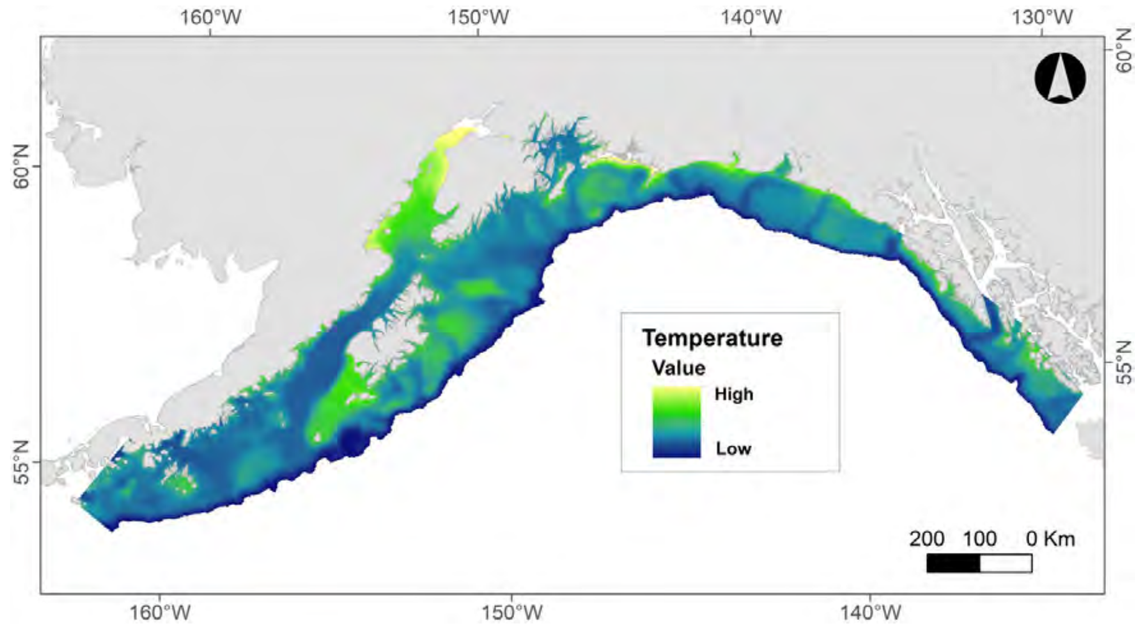
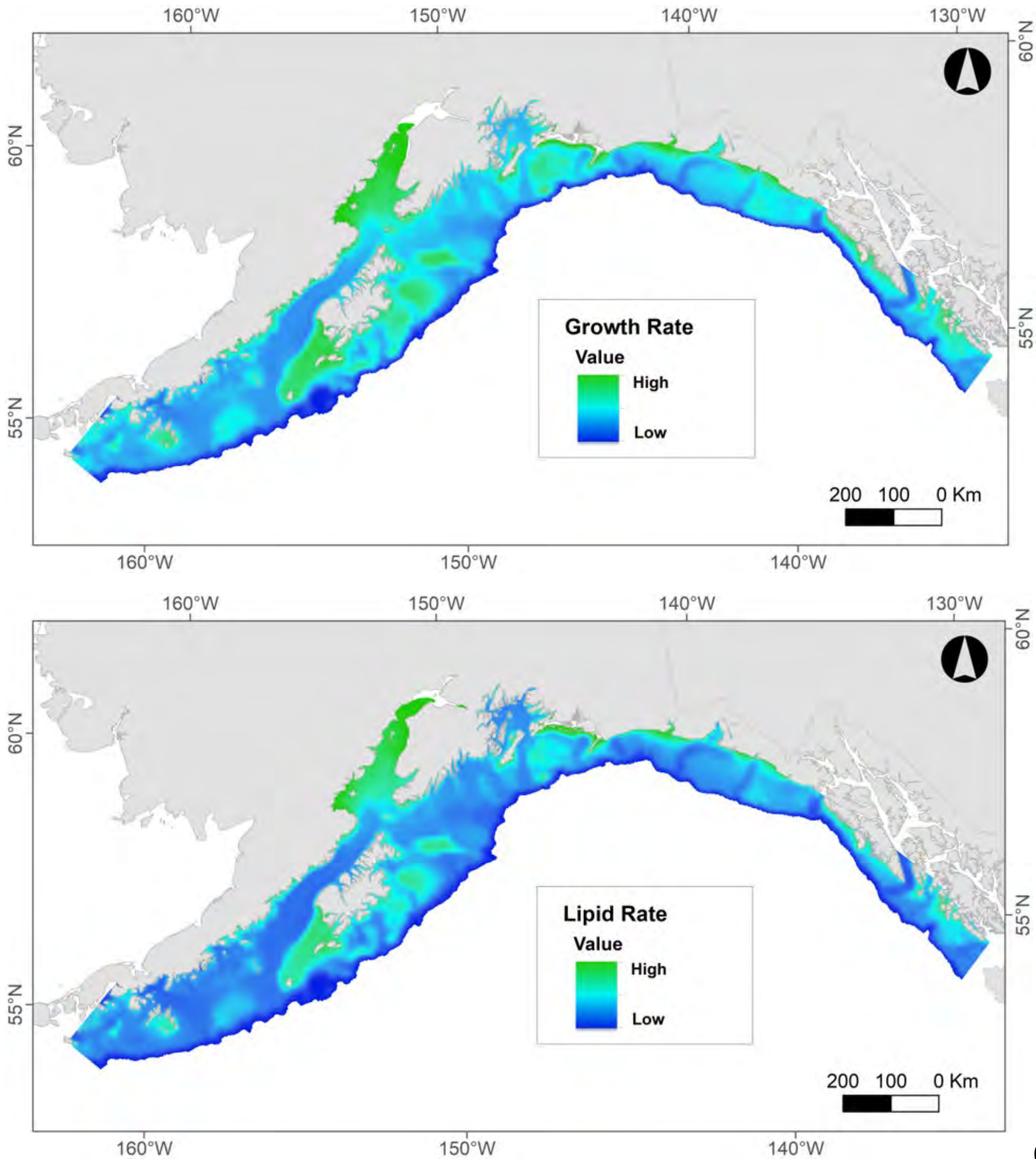


Fig. 3.2. Gulf of Alaska bottom temperature (2.8-14.4 °C) derived from the depth-integrated Regional Ocean Modeling System (ROMS) (3 km^2) for the months of May-September and years 1997-2011, as a mean climatology of regional temperature conditions. An update to the Gulf of Alaska ROMS is currently underway to include additional years, through 2018 (or 2019).



(a)

(b)

Fig. 3.3. Juvenile walleye pollock (40-120 mm) vital rates mapped as a function of temperature in the Gulf of Alaska marine environment, including **a)** growth rate (G_i) (0.7 - 2.9 % body weight·day^{-1}), where T_{max} = 13.0°C (Laurel et al. 2016) and **b)** lipid accumulation rate (condition) (L_i) (2.3 -11.6 % lipid·G_i), where T_{max} = 14.4°C (Copeman et al. 2017).

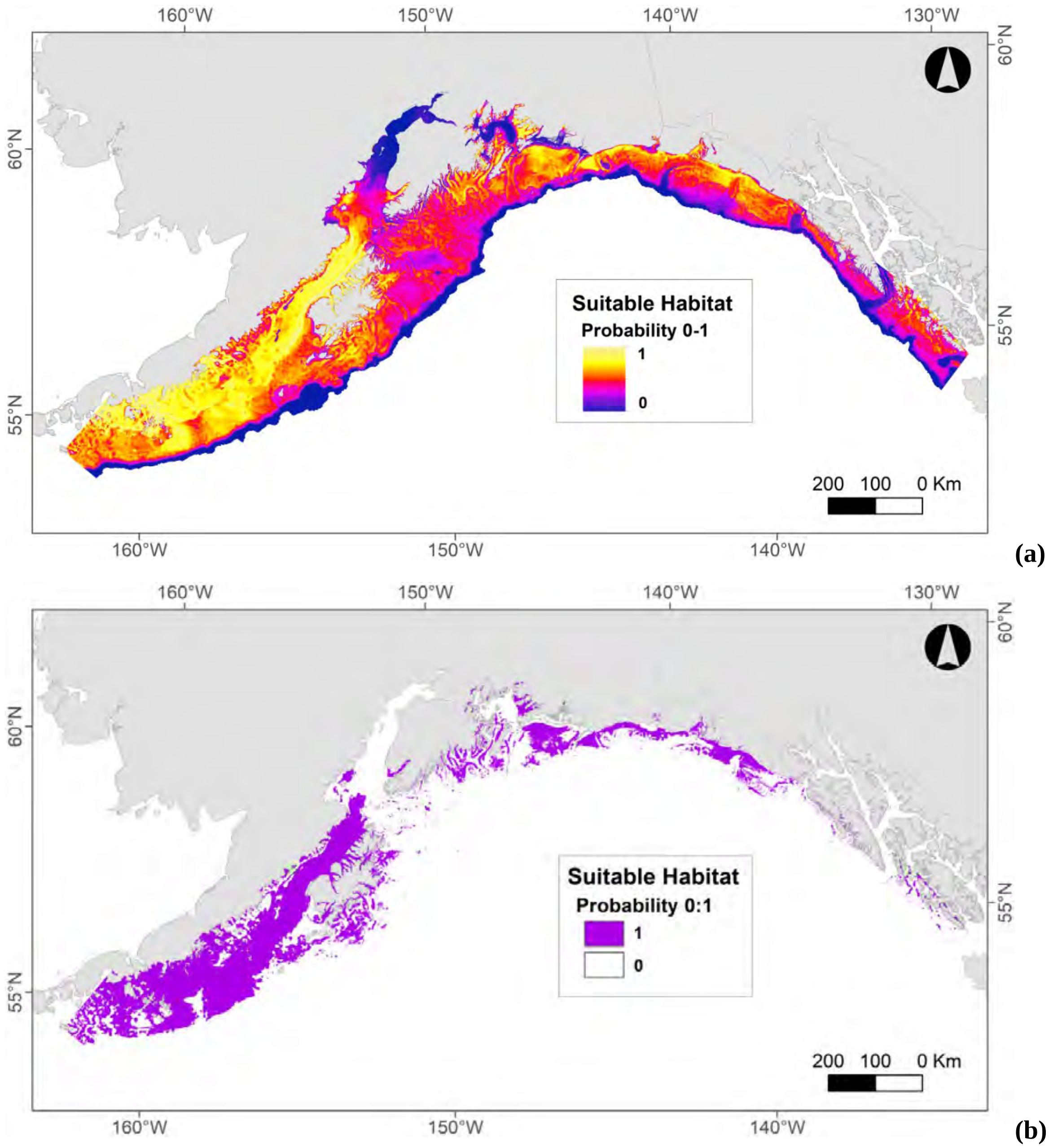
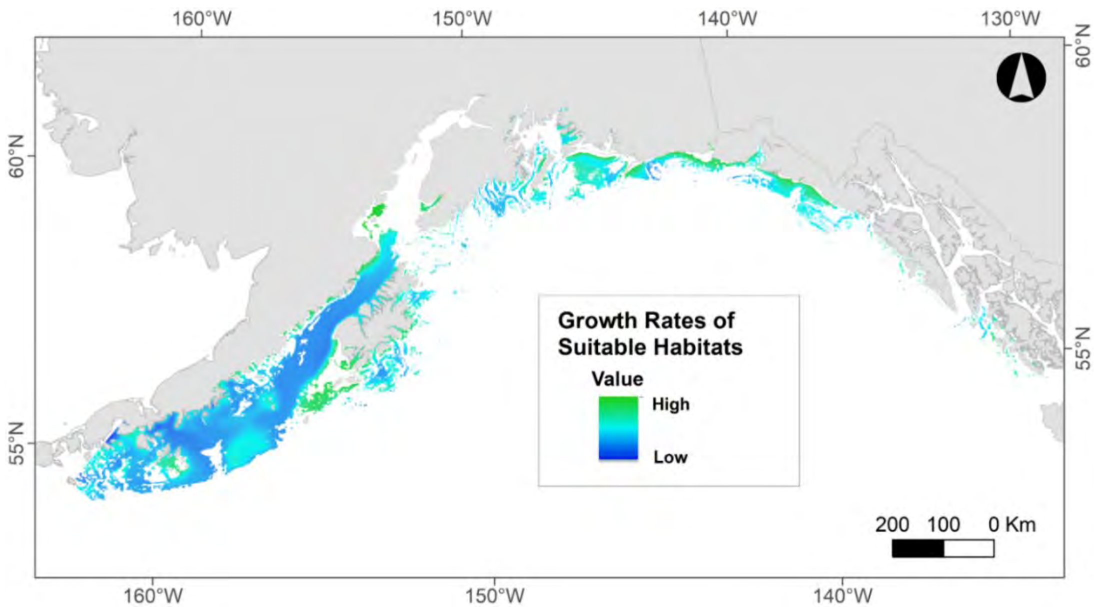
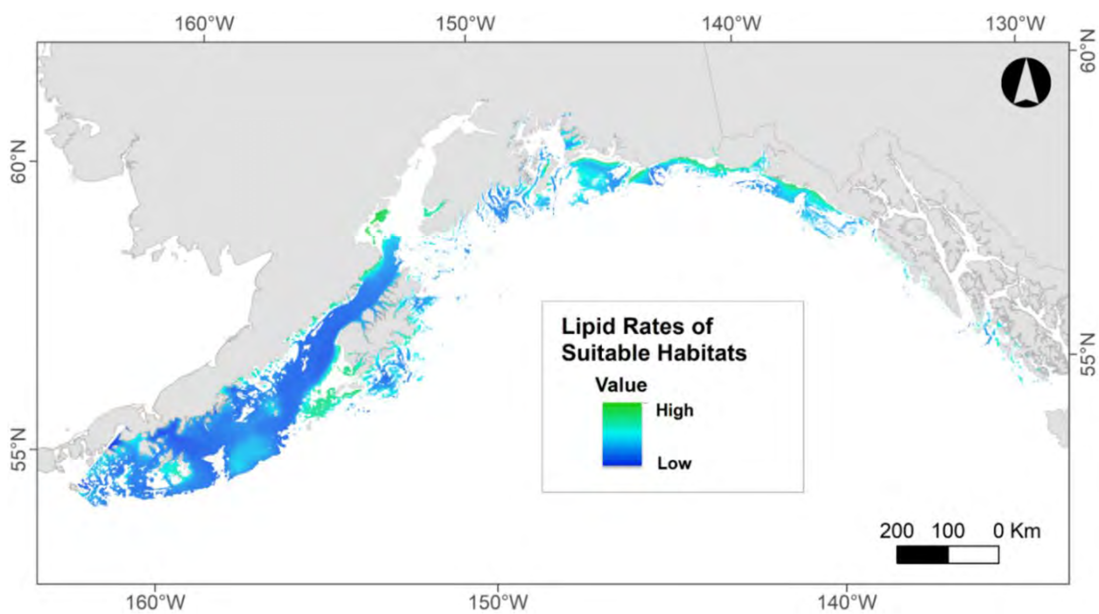


Fig. 3.4. Juvenile walleye pollock (40-120 mm) SDM (MaxEnt) developed for the Gulf of Alaska from 0-1000 m depth (*n* = 812, AUC = 0.73 ± 0.02), including **a)** probability of suitable habitat and **b)** suitable habitat (threshold value of equal training sensitivity and specificity = 0.45) (Pirtle et al. 2019).



(a)



(b)

Fig. 3.5. Juvenile walleye pollock (40-120 mm) vital rates in areas of suitable habitat in the Gulf of Alaska, including **a)** growth rate (*Gi*) (1.0 - 2.7 % body weight·day^{-1}) and **b)** lipid accumulation rate (condition) (*Li*) (3.2 - 10.6 % lipid·*Gi*).

4 Developing a Novel Approach to Estimate Habitat Linked Survival Rates for Early Life History Stages using Individual-Based Models

S. Kalei Shotwell [38], William Stockhausen [39], Georgina Gibson [40], Jodi Pirtle [41], Chris Rooper [42], Alison Deary [43]

In the present study we address Research Priority 1 of the Alaska EFH Research Plan: Characterize habitat utilization and productivity; increase the level of information available to describe and identify EFH; and apply information from EFH studies at regional scales (Sigler et al. 2017). The plan describes two pathways to elevate to Level 3 including 1) using pre-existing growth, survival or reproductive rates or 2) conduct additional laboratory and/or field studies to gather the required information. Because the first option only currently exists for certain species and the second option can be very time-consuming and expensive, it is reasonable to consider alternative methods for elevating EFH information to Level 3. This is particularly true for the early life history stages (ELHS), where very little information exists for non-target species from historic survey data and the available data were collected with variable sampling design, gear type, mesh size, timing, and survey objectives (e.g., pelagic ELHS *In* Laman et al. 2017). We will demonstrate the utility of a novel approach to raise the current EFH level from habitat distribution (Level 1) to habitat-related density (Level 2) and vital rates (Level 3) for ELHS of groundfish (eggs, larvae, pelagic juveniles, and settled early juveniles), using biophysical life-stage integrated individual-based models (IBM) (e.g., Gibson et al. 2016, 2019) that will be post-processed to identify the spatial domain for the ELHS survivor trajectories.

We provide two case studies on Alaska sablefish (*Anoplopoma fimbria*) and Gulf of Alaska (GOA) Pacific cod (*Gadus macrocephalus*) as examples of this new application. Recruitment estimates from the age-structured assessment models for these stocks are highly variable and do not conform to standard stock-recruit relationships, suggesting that environmental variability is the primary driver of recruitment to these stocks, although the mechanisms are not well-understood (Hanselman et al. 2016, Barbeaux et al. 2016, Thompson 2016). Determining these mechanisms is a key research priority identified in the stock assessments. Additionally, research on sablefish recruitment processes has been identified as a key priority in the Alaska Fisheries Science Center's (AFSC) Annual Guidance Memo for 2017 and 2018 (AFSC, 2016; 2017) and for both sablefish and Pacific cod for 2019 (AFSC, 2018). One potential mechanism driving recruitment variability is changes in physical transport and "connectivity" between adult spawning (natal) areas and juvenile nursery habitats. As part of the North Pacific Research Board's Gulf of Alaska Integrated Ecosystem Research Program (GOAIERP; Dickson and Baker 2016), early-life IBMs were developed for sablefish and Pacific cod in the GOA. Results from these models were used to estimate variability in annual connectivity due to changes in the oceanic environment over 1996-2011 (Gibson et al. 2019, Hinckley et al. 2019). We will ultimately provide survival rate EFH maps for the ELHS stages of these two species as a demonstration that IBM output can be used within the context of EFH and provide this information to support the 2022 EFH Review by the National Marine Fisheries Service (NMFS) and the North Pacific Fishery Management Council (Council). Once established, our new methodology may be explicitly applied to other groundfish and crab species in

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Alaska where IBMs have been developed (e.g., walleye pollock, Pacific ocean perch, snow crab) and used as a starting reference for other co-occurring species during the early life stages to develop IBM-based EFH information for pelagic ELHS of additional species. In addition, because IBM trajectory analysis can identify pathways of connectivity between offshore pelagic ELHS and nursery habitats on the continental shelf, including locations where settlement may be more likely to occur and where it may not, this information can be used to refine EFH maps for settled early juvenile life stages of species with this life history strategy (e.g., Goldstein et al. in review).

4.1 METHODS

4.1.1 Individual-Based Models

We use the IBM for Pacific cod and sablefish early-life stages to demonstrate the utility of the IBM trajectories for defining the spatial domain of the survival rates for the ELHS and for identifying habitat metrics that relate to survival. The two fish species provide contrasting life history strategies in regard to dispersion during early life stages. Sablefish spawn from January through May in deep water off the continental shelf, with a majority of spawning females observed at depths greater than 800 m (Hunter et al., 1989). Their eggs are pelagic and descend into deeper water prior to hatching. Larvae are incapable of active swimming until approximately 20 days after hatching (Alderdice et al. 1988), at which point they swim to the surface and join the neuston (Kendall and Matarese 1987, Deary et al. 2019). Young sablefish have been observed as far offshore as 160 km in southeast Alaska (Wing 1997), but by the end of the summer the young-of-the-year are found inshore in coastal bays and inlets, where they spend at least the next year in early juvenile nurseries (Maloney and Sigler 2008, Mason et al. 1983, Rutecki and Varosi 1997). In contrast to sablefish, Pacific cod spawn from February through July in the GOA and lay semi-adhesive, demersal eggs on the continental shelf (Laurel et al. 2008; IIS 2019), which is thought to limit dispersion during subsequent pelagic larval stages prior to settlement. Newly-hatched larvae show a strong orientation to the surface, and are primarily found in the upper 45 m of the water column (Hurst et al. 2010). However, like sablefish, Pacific cod juvenile nursery areas are primarily shallow coastal embayments, although with structured habitat features and higher salinity water (Abookire et al. 2007, Laurel et al. 2007).

The sablefish and Pacific cod IBMs incorporate temperature-dependent, bioenergetically-determined development, feeding, and growth rates where available (Hinckley et al. 2019). For sablefish, this represents an updated model from the original IBM produced for the GOAIERP (Gibson et al. 2019). In the original model Gibson et al. (2019) individual sablefish were considered successful if they reached shallow water in which they were able to settle. In the updated model, we now consider the water column through which individuals move as essential habitat to their survival. Also, recent rearing experiments (A. Deary, AFSC, pers. comm.) have found that the sablefish yolk sack stage is temperature sensitive, with individuals failing at temperature of 9^{o}C. Following this stage, they are fairly resilient. For each species, we will use output from an updated 3-km Regional Ocean Modeling System (ROMS NEP-3k) model and Nutrient Phytoplankton Zooplankton (NPZ) model (Coyle et al. 2012, Hermann et al. 2016) to provide the simulated oceanic environment for the years 1997-2013.

We use the ROMS-NPZ model to track “food experience” (e.g., biomass of small copepods) that the individual particles experience as they move from their spawning location to their settlement ground. This will enable us to determine if there are areas in the Gulf of Alaska shelf that are critical to ensuring individuals experience sufficient food to thrive. For example, exploration into the gape width of individuals (A. Deary, AFSC, pers. comm.) provided a suggested prey size that sablefish and Pacific cod of different lengths could realistically consume. We use this information to develop a “prey food consumption algorithm” that enables us to determine the likely success of individuals that settled based on the prey field through which they were transported. As an example, for sablefish, we initially assume that eggs and yolk-sac larvae require no exterior prey source, individuals 7-17mm can feed on small copepods, and individuals larger than 17mm can feed on large copepods. This same information is available for Pacific cod.

Natal zones were originally defined at alongshore scales of ~ 150 km width (e.g., Gibson et al. 2019). However, this approach did not match the spatial zones of fisheries management for these two species and can be more clearly aligned with management goals. Here, natal zones will be developed by approximating the scales of the management zones used in the stock assessments (Hanselman et al. 2019, Barbeaux et al. 2019). This will allow for a clean translation of results to management for these two stocks. Simulated individuals are spawned within a defined natal area, and will be followed from egg stage through subsequent early-life stages until they reach the YOY stage and the end of the annual simulation (December 31st).

Individuals will be post-processed into survivors and non-survivors by using the probability of suitable habitat assigned to the underlying model grid from the previously developed habitat suitability model of the early juvenile settlement stages (Pirtle et al. 2019). The relative contribution of individuals from each natal area to each settlement area will also be computed using the population biomass within each natal zone as estimated from the stock assessment model or the primary assessment surveys. The trajectories determined to represent individual survivors will then be separated by ELHS and recorded positions along the trajectory will be treated as "observations".

4.1.2 EFH Information Levels

Our EFH Level 1 through 3 maps are based on the presence-absence of successful individuals in the IBM trajectory analysis. The corresponding life stage maps are spatial histograms of the number of unique, successful individuals that occupied each grid cell of the ROMS domain at some time during that life stage and also where that life stage was absent. Early juvenile stage benthic habitat maps were developed using SDM (MaxEnt) for both Pacific cod and sablefish as part of the GOAIERP (Pirtle et al. 2019). The IBMs now use these maps to trigger settlement success once an individual reaches suitable benthic habitat during the early juvenile life stage at the end of the model run (e.g., Fig. 4.1) (i.e., whereas, settlement was triggered by an individual reaching a certain depth in the IBM for the GOAIERP). Suitable benthic habitat is species-specific and based on the threshold probability value where model sensitivity and specificity are equal along the continuous probability prediction from 0-1. Sensitivity is the proportion of presences correctly predicted and specificity is the proportion of absences correctly predicted (Phillips et al. 2006). The model threshold for Pacific cod is 0.29 and for sablefish is 0.41 (mean threshold value among k-folds for the final model with an AUC test value of 0.86 and 0.81 for Pacific cod and sablefish, respectively) (Pirtle et al. 2019). A juvenile is considered successfully settled when they encounter benthic habitat where the suitability value is at or above the species-specific threshold by the end of the IBM model simulation.

The successful trajectories are used to define the presence locations by life stage (e.g., egg, yolk sac larvae, feeding larvae (pre-post flexion), epipelagic juveniles, and juvenile) for the Level 1 EFH product (e.g., Figs. 4.2 – 4.6). The Level 2 products (*In prep*) are then based on these same successful trajectories and then weighted by area-specific spawning biomass estimates from the stock assessment reports for each species. These can be estimated from the bottom trawl survey for Pacific cod and the longline survey for sablefish. The Level 3 products (*In prep*) will be based on the entire ROMS domain in which the IBM is run. For the Level 3 survival rate map, all trajectories in the IBM are weighted by spawning biomass and the survival rate is calculated for each grid cell as the number of total successful trajectories divided by total trajectories for each life stage. The survival rate map can be calculated for both Pacific cod and sablefish. For the Level 3 growth rate map, again all trajectories in the IBM are weighted by spawning biomass and the growth rate is the average of the temperature-dependent growth rate (Hurst et al., 2010) for all trajectories within a cell for a given life stage. The growth rate map can be calculated for several ELHS stages of Pacific cod and potentially some stages of sablefish.

4.2 RESULTS

4.2.1 Gulf of Alaska Pacific Cod (*Gadus macrocephalus*)

Preliminary life stage-specific maps for 1997 through 2013 for “successful individuals” have been produced for Pacific cod. These maps were generated using a threshold value of 0.29 to define suitable nursery habitat for the Pacific cod settled early juvenile life stage (Pirtle et al. 2019) and observed spawning locations from the winter fishery maturity scans (S. Barbeaux, AFSC, pers. comm.). Here, the observed spawning locations set the origin of the egg life stage at the start of the model run and the grid cells designated as suitable habitat for the settled early juvenile life stage determine settlement success at the end of the model run. Settlement success was determined by an individual reaching suitable settlement habitat upon transitioning to the settled early juvenile life stage prior to the end of the model. Preliminary examples of EFH Level 1 maps for Pacific cod are presented (Figs. 4.2 – 4.7), including maps of presence-absence and abundance of successful individuals by life stage averaged across all model years.

It is clear that the spawning locations set at the start of the IBM run have a large effect on the resulting distribution of successful individual presence-absence and abundance for each life stage. For example, we demonstrate two spawning scenarios for Pacific cod, where 1) spawning is assumed to be shelf-wide (as an earlier stage of the Pacific cod IBM development for the GOA IERP; Hinckley et al. 2019), and 2) based on observed spawning locations, as applied to the present study (Figs. 4.8 – 4.9).

4.3 NEXT STEPS AND EXTENSIONS

Next steps will include, developing 1) EFH Level 1 maps for sablefish, similar to our approach for the Pacific cod preliminary maps presented here, 2) Level 2 maps for Pacific cod and sablefish by weighting the abundance results from individual years by an estimate of annual spawning biomass, and 3) EFH Level 3 maps for Pacific cod and sablefish by post-processing the model trajectories to calculate a) survival rate by life stage for each grid cell, and b) growth rate by applying the temperature-dependent rate to each grid cell in the model domain (see above methods). In preparation for the Level 3 growth rate maps, we will review the literature to determine if the food biomass/starvation period data are available that can be used to develop a food related survival algorithm. This new information and map products will be available to NMFS and the Council for consideration in the 2022 EFH Review.

4.3.1 Ecosystem-Based Fisheries Management Coordination

This information from the Level 1-3 products may be useful for developing spatially-explicit indicators that could be useful for the stock assessment or the ecosystem and socioeconomic profile (ESP) for the two species. As an example, a “prey experience” indicator specifically tuned to a particular life stage for sablefish or Pacific cod could be developed from the output of the IBM model. Additional coordinated efforts are also underway. A workshop occurred in Juneau during the week of July 29, 2019 regarding the development of a spatially integrated life cycle (SILC) model for sablefish (Goethel et al. 2018). K. Shotwell is a co-PI for the SILC project and coordinated several discussion meetings between the PIs of the SILC workshop and the EFH-IBM project presented here. Additionally, at the start of the SILC meeting, PIs Gibson and Stockhausen provided a presentation to the SILC group regarding IBM mechanics. The SILC project seeks to use the results of the updated and enhanced sablefish IBM from the

EFH-IBM project to initiate a newly developed spatially-explicit stock assessment model. PI Gibson provided sample IBM code for initial exploration throughout the SILC meeting to aid with discussion on how to use the sablefish IBM results. The connectivity matrices of the original sablefish model (1997-2011) were provided to the SILC team at the close of the workshop. Future collaboration will include updating the connectivity matrices based on the new sablefish model and the updated years.

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4.5 FIGURES

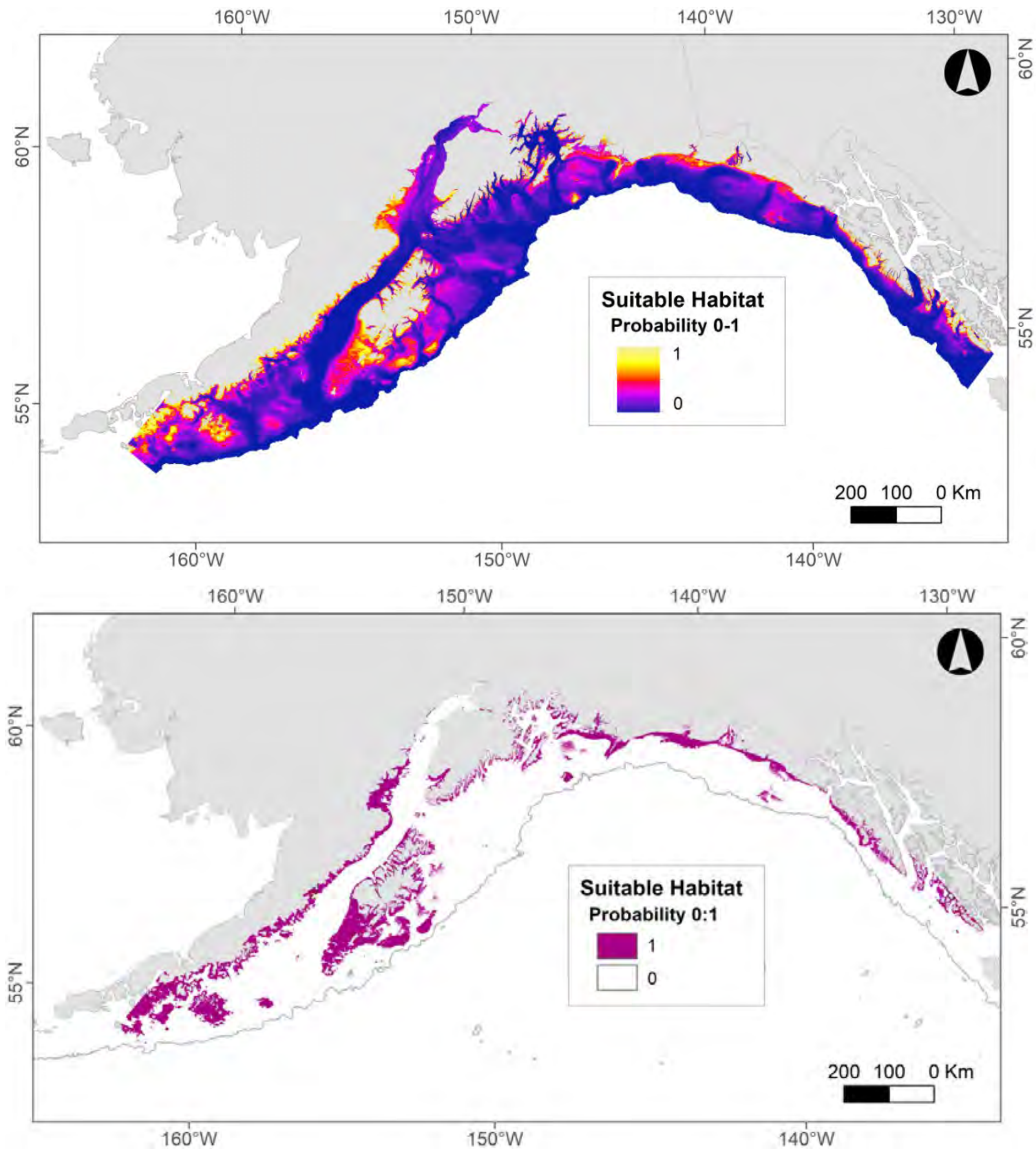


Fig. 4.1. Pacific cod probability of suitable habitat for the settled early juvenile life stage from a species distribution model (MaxEnt), including the continuous probability prediction (1-0) **(top)** and the binary prediction (1:0) **(bottom)**, based on a threshold value of (0.29) and applied to the IBM to determine areas where a settlement stage individual was successful (reached suitable settlement habitat) or not successful (did not reach suitable settlement habitat) at the end of the IBM run.

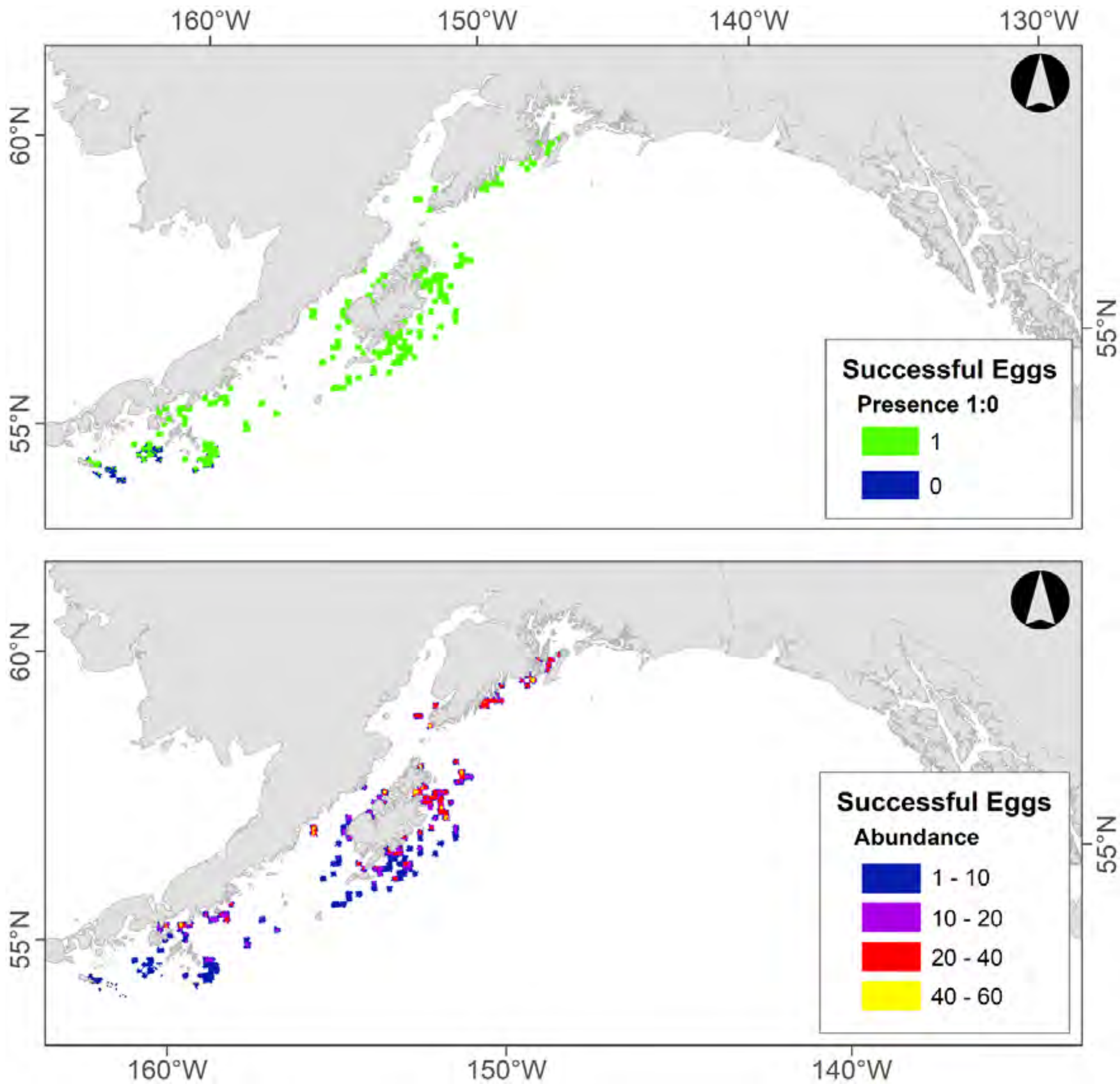


Fig. 4.2. Maps of successful individuals for the **egg stage** by grid cell over all model years (1997-2013) within the Gulf of Alaska 3 km ROMS grid domain, including presence and absence **(top)** and average abundance **(bottom)**.

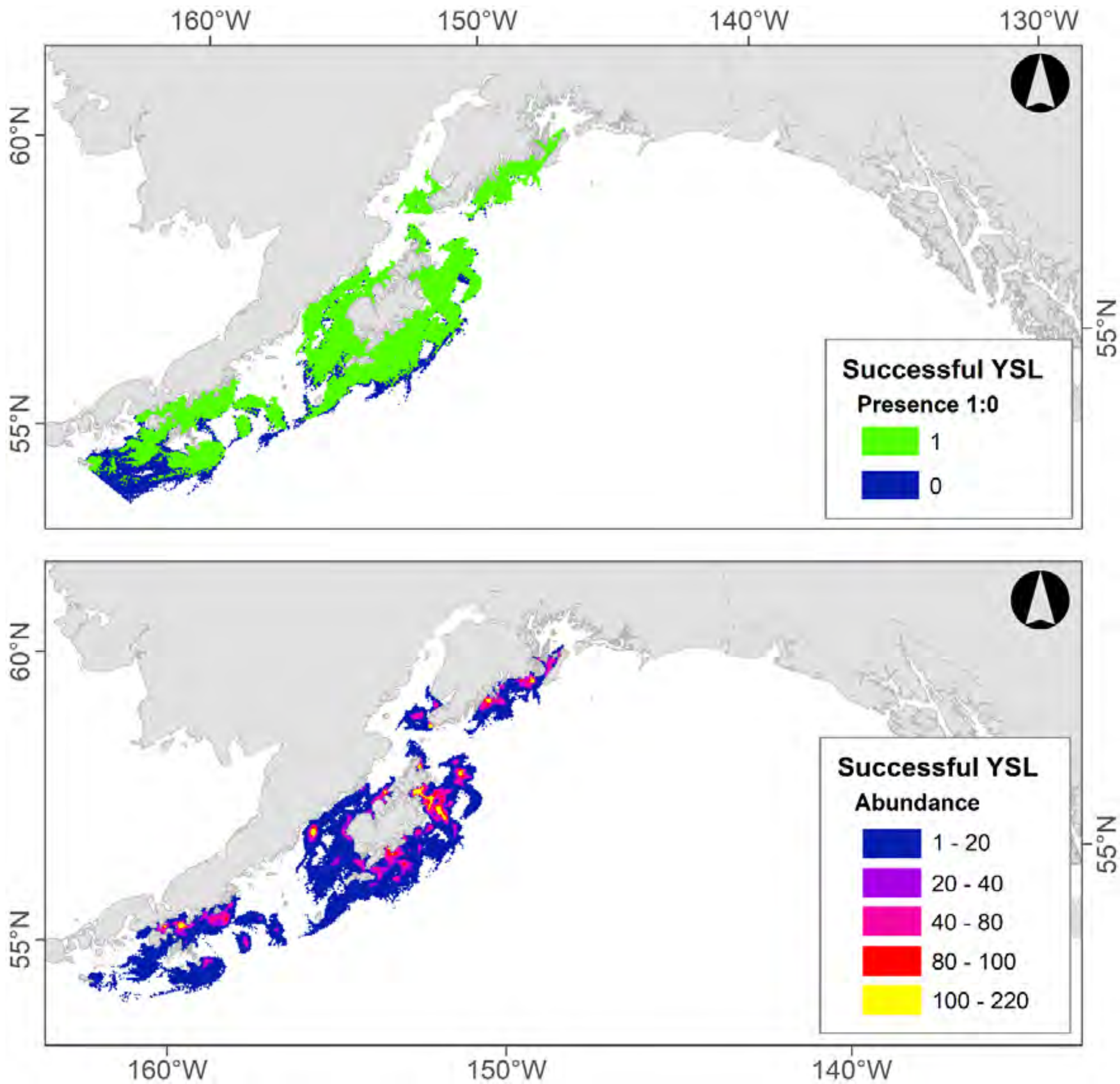


Fig. 4.3. Maps of successful individuals for the **yolk-sac larvae stage** by grid cell over all model years (1997-2013) within the Gulf of Alaska 3 km ROMS grid domain, including presence and absence **(top)** and average abundance **(bottom)**.

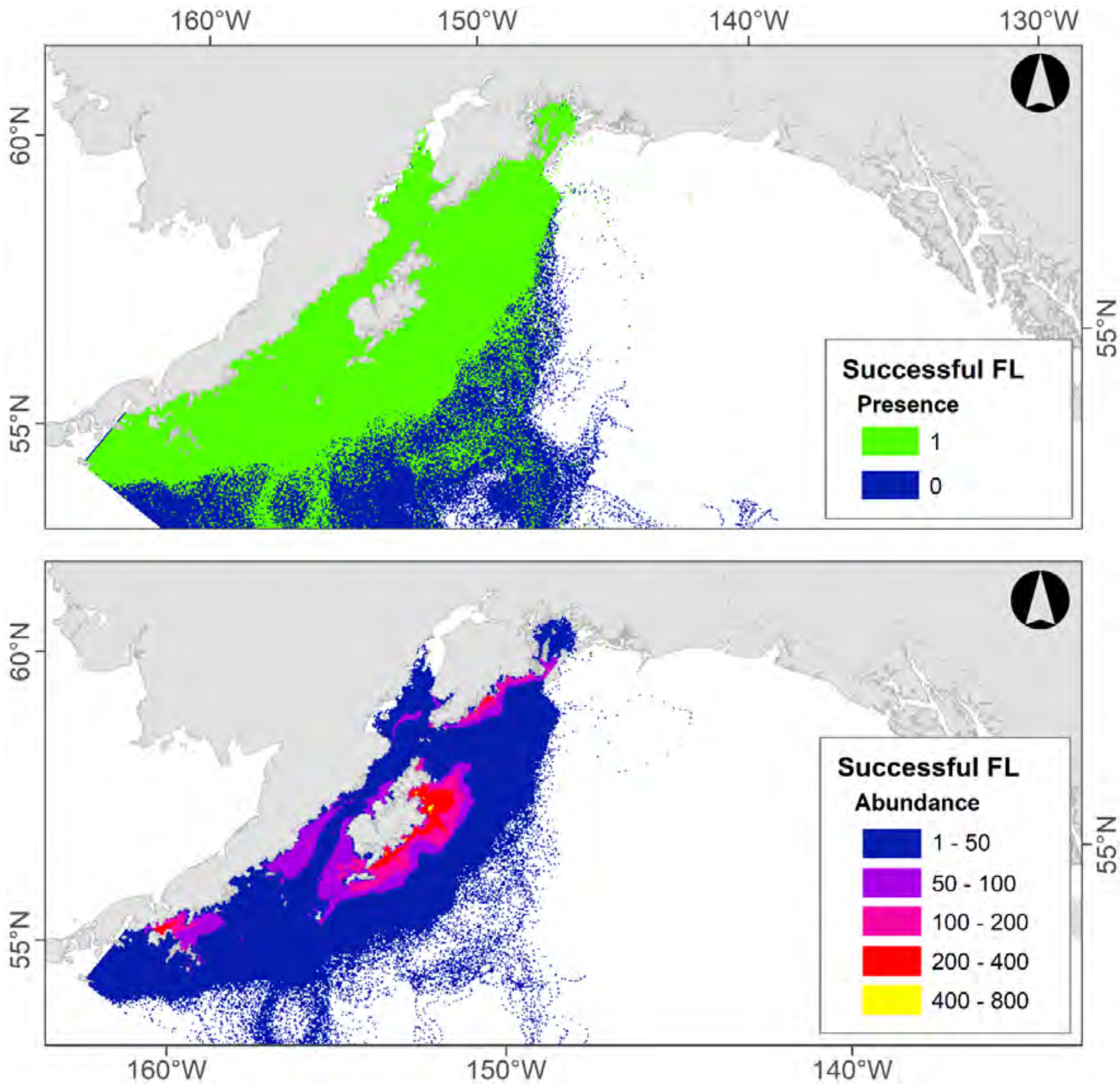


Fig. 4.4. Maps of successful individuals for the **feeding larvae pre-flexion stage** by grid cell over all model years (1997-2013) within the Gulf of Alaska 3 km ROMS grid domain, including presence and absence **(top)** and average abundance **(bottom)**.

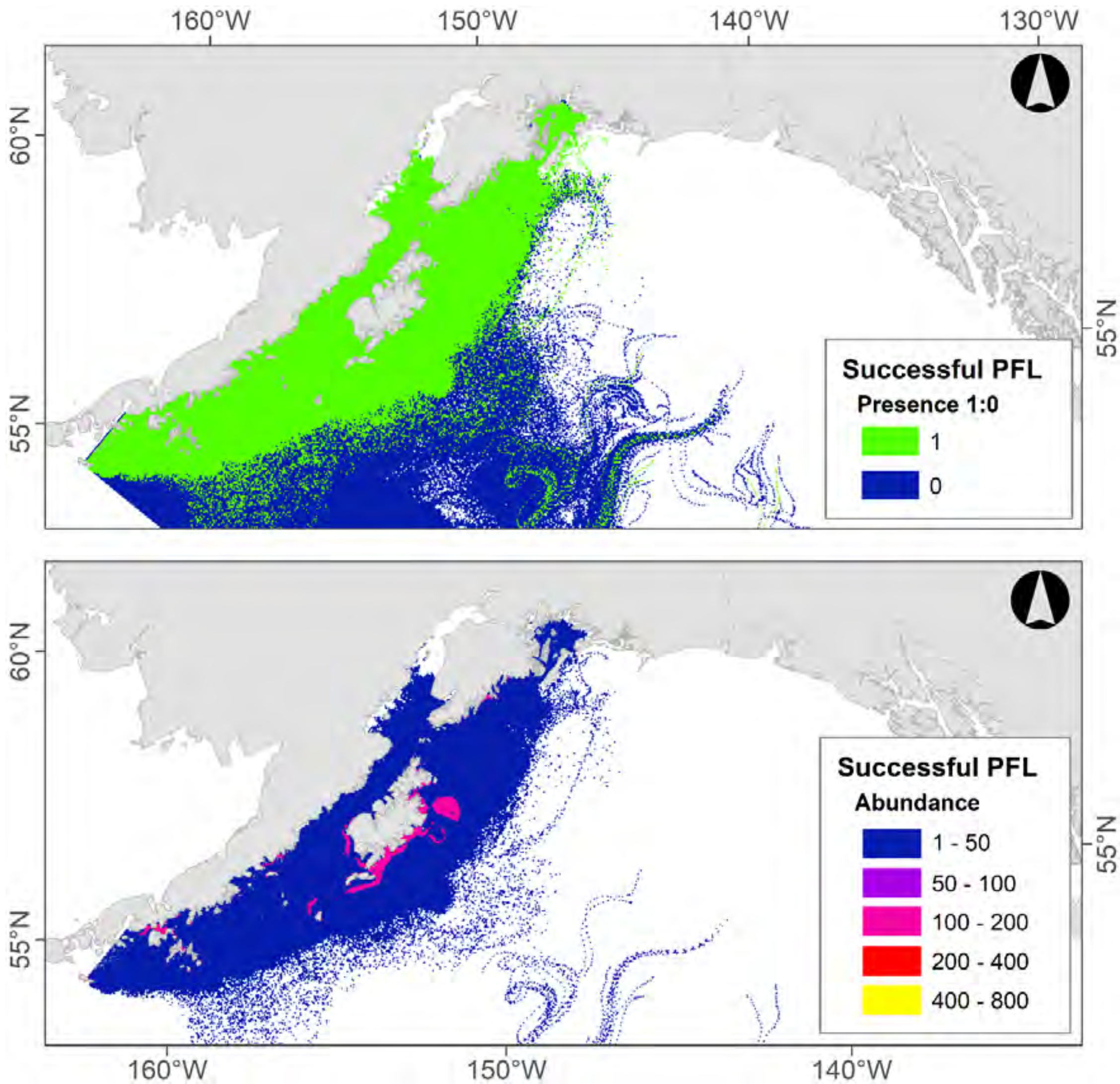


Fig. 4.5. Maps of successful individuals for the **feeding larvae post-flexion stage** by grid cell over all model years (1997-2013) within the Gulf of Alaska 3 km ROMS grid domain, including presence and absence **(top)** and average abundance **(bottom)**.

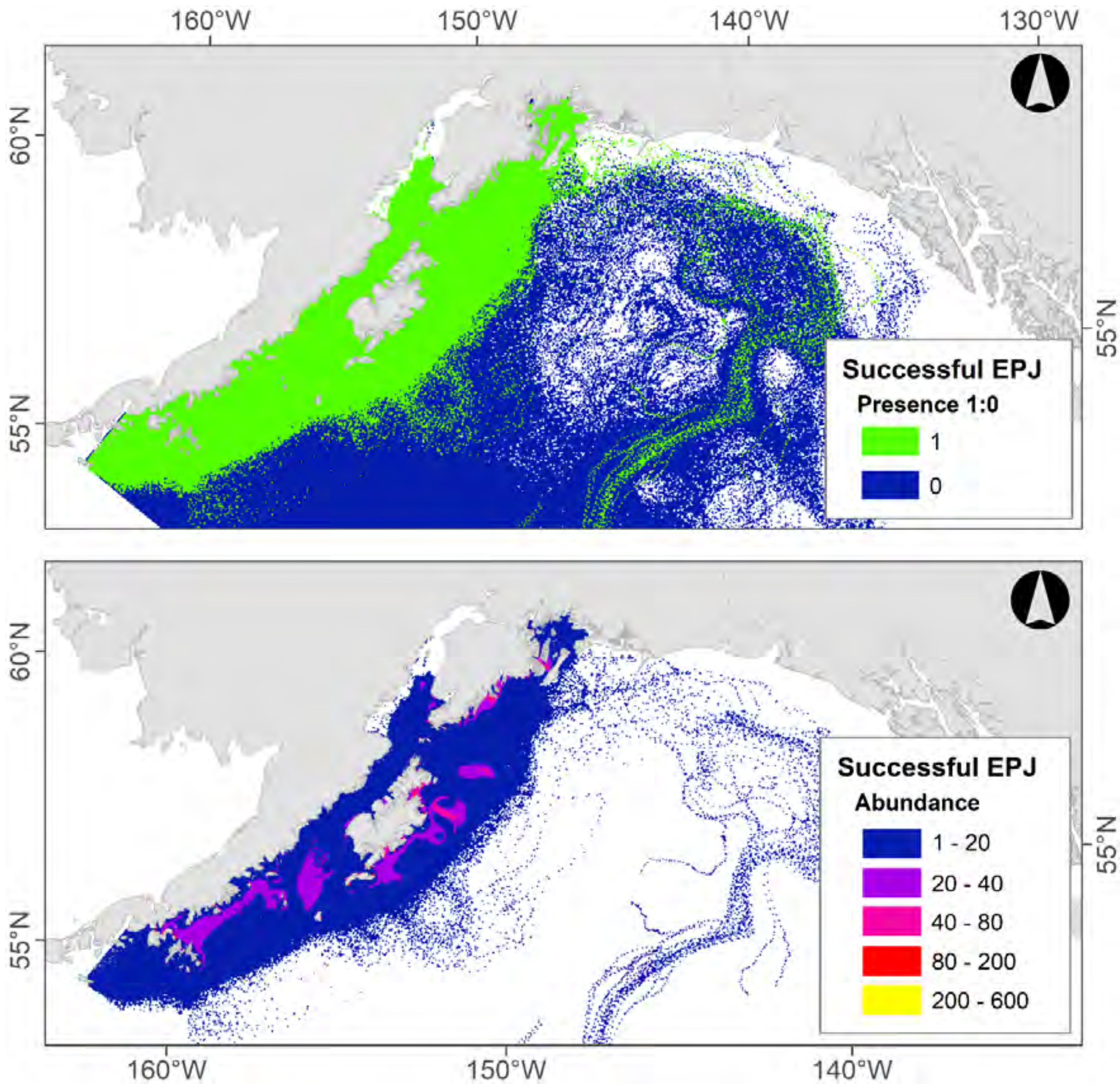


Fig. 4.6. Maps of successful individuals for the **epipelagic juvenile stage** by grid cell over all model years (1997-2013) within the Gulf of Alaska 3 km ROMS grid domain, including presence and absence **(top)** and average abundance **(bottom)**.

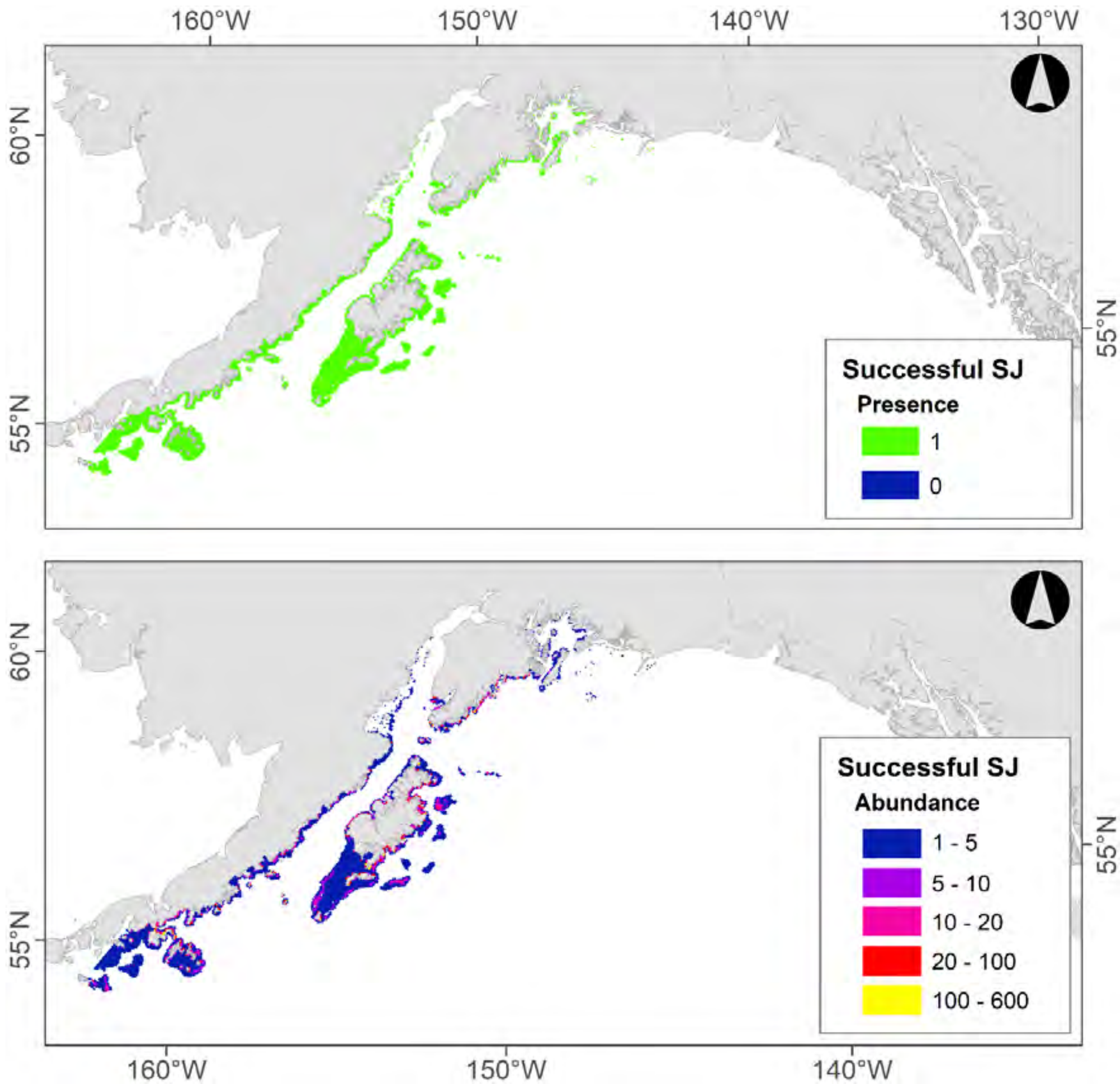
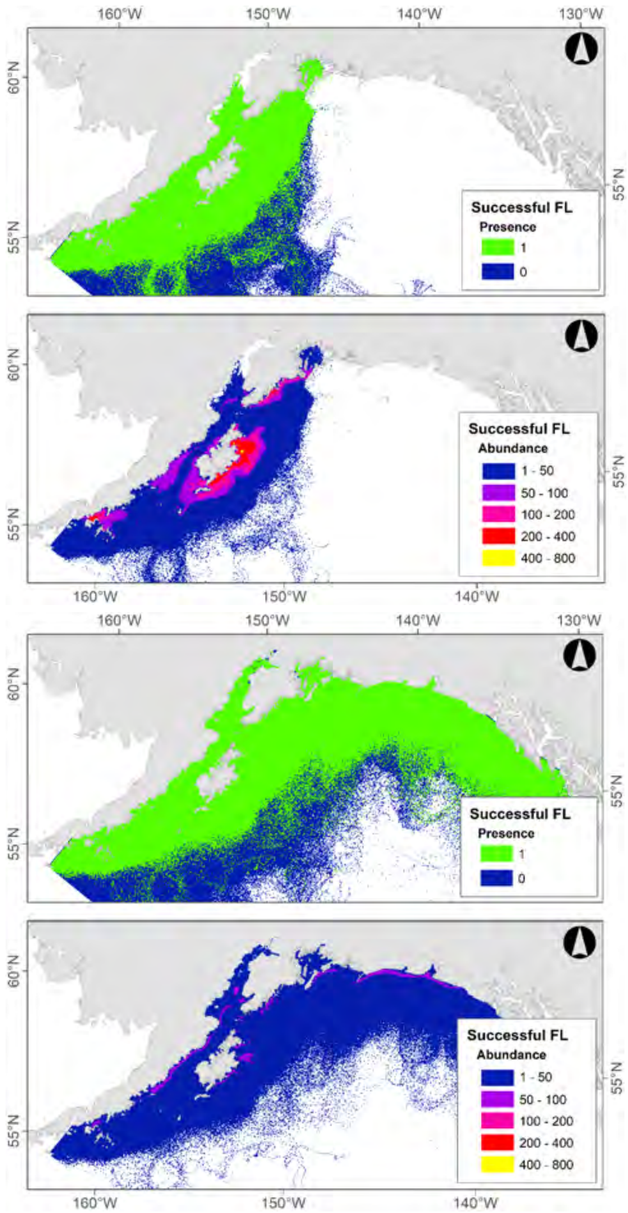


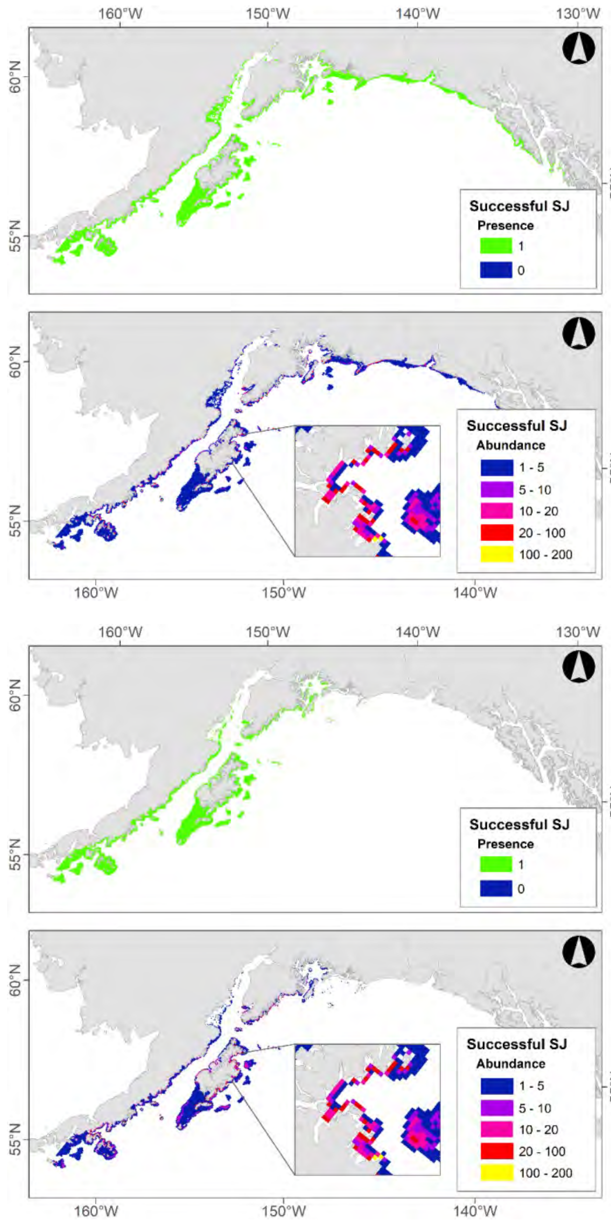
Fig. 4.7. Maps of successful individuals for the **settled juvenile stage** by grid cell over all model years (1997-2013) within the Gulf of Alaska 3 km ROMS grid domain, including presence and absence **(top)** and average abundance **(bottom)**.



(a)

(b)

Fig. 4.8. Maps of successful individuals for the feeding larvae pre-flexion stage by grid cell over all model years (1997-2013) within the Gulf of Alaska 3 km ROMS grid domain, including the scenario of observed spawning locations at the start of the model **(a)** presence and absence **(top)** and average abundance **(bottom)** and the scenario of all shelf spawning at the start of the model **(b)** presence and absence **(top)** and average abundance **(bottom)**.



(a)

(b)

Fig. 4.9. Maps of successful individuals for the settled juvenile stage by grid cell over all model years (1997-2013) within the Gulf of Alaska 3 km ROMS grid domain, including the scenario of all shelf spawning at the start of the model **(a)** presence and absence **(top)** and average abundance **(bottom)** and the scenario of observed spawning locations only at the start of the model **(b)** presence and absence **(top)** and average abundance **(bottom)**.