Methods for Advancing Essential Fish Habitat Descriptions and Maps for the 2028 5-year Review

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Abstract

The objective of an essential fish habitat (EFH) 5-year review is to evaluate and synthesize new information for the ten EFH components of Fishery Management Plans (FMPs) and revise or amend the EFH components as warranted based on available information (50 CFR 600.815(a)(10)). For Component 1, FMPs are required to describe and identify EFH in text that clearly states the habitats or habitat types determined to be EFH for each life stage of the managed species and to include maps that display the geographic locations of EFH or the geographic boundaries within which EFH for each species and life stage is found. This discussion paper presents the new information that NMFS is developing under EFH Component 1, the description and identification of EFH, for the 2028 EFH 5-year Review. The 2028 EFH Review will advance EFH information for a subset of FMP species by incorporating new and updated data and methods. We will apply the ensemble species distribution model (SDM) from the 2023 EFH 5-year Review and introduce a new spatiotemporal modeling approach for EFH. In this discussion paper, we provide an overview of the regulatory background, scope of the 2028 EFH Review prioritization, and summary of proposed updates by FMP. We describe data updates, analytical methods advancements, and present examples of work in progress for the ensemble SDMs and new spatiotemporal models (STMs). At this meeting, we are seeking SSC input on the overall scope of planned Component 1 updates for the 2028 EFH Review; proposed updates to the ensemble SDM EFH maps, including new species and environmental covariate data and methods; and new STM EFH maps, including data, methods, and application.

Executive Summary

The objective of an essential fish habitat (EFH) 5-year review is to evaluate and synthesize new information for the ten EFH components of Fishery Management Plans (FMPs) and revise or amend the EFH components as warranted based on available information (50 CFR 600.815(a)(10)). The regulations outline ten 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 2028 EFH 5-year Review. For EFH Component 1, FMPs are required to describe and identify EFH in text that clearly states the habitats or habitat types determined to be EFH for each life stage of the managed species and to include maps that display the geographic locations of EFH or the geographic boundaries within which EFH for each species and life stage is found. Additionally, FMPs must demonstrate that the best scientific information available was used to describe and identify EFH, consistent with national standard 2 (50 CFR 600.815(a)(1)(i)(B)).

2023 EFH 5-year Review

The North Pacific Fishery Management (Council) and NMFS completed the last EFH 5-year review in 2023 (Pirtle et al. 2025a). For the 2023 EFH Review, a new approach to Component 1 was developed that used ensemble 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 (BSAI FMP), FMP for Groundfish of the Gulf of Alaska (GOA) (GOA FMP), and FMP for Bering Sea/Aleutian Islands King and Tanner Crabs (Crab FMP). New information was also reviewed and developed for the FMP for Fish Resources of the Arctic Management Area (Arctic FMP) that included SDM-based EFH maps for the first time. The new ensemble SDM approach to EFH was a significant advancement, with new Level 1 (distribution) and Level 2 (habitat-related density or abundance) information for groundfish and crabs and a substantial improvement to the underlying SDMs and EFH maps. The 2023 EFH Review also introduced Level 3 maps (habitat-related vital rates) for the first time for the BSAI, GOA, and Arctic FMPs. 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 available since 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 2023 Review and the EFH Omnibus Amendments were approved in July 2024 (89 FR 58632, 7/19/24) (Pirtle et al. 2025a).

2028 EFH 5-year Review

For the 2028 EFH 5-year Review, we will advance EFH information for FMP species' life stages for a subset of FMP species in light of capacity constraints for both the Council and NMFS. The subset includes sablefish, pollock, Pacific cod, Pacific ocean perch, and arrowtooth flounder in the BSAI and GOA FMPs, and all five species in the Crab FMP. This discussion paper describes the scope, organization, and methodology for the 2028 EFH 5-year Review, Component 1 (EFH description and identification).

EFH Component 1 - Proposed Updates

In this review, we plan to improve model inputs and performance for the subset of targeted species by—

- refining and updating environmental covariates,
- updating ensemble SDMs for Level 2 and 3 EFH with new species survey data,
- advancing life-history specific mapping for crabs, and
- building spatiotemporal models (STMs) to describe dynamic groundfish and crab distributions.

Covariate Updates

We are updating the environmental covariates that are applied with species survey data in the ensemble SDMs to map EFH, including, bathymetry, all bathymetry-derived terrain variables (slope, aspect, curvature, and bathymetric position index), substrate rockiness, and sediment grainsize (*phi*). We are developing new structure-forming invertebrate (SFI) covariates with new methods combining data from underwater image analysis from the Alaska Coral and Sponge Initiative (AKCSI) with AFSC Resource Assessment and Conservation Engineering Division (RACE-GAP) bottom-trawl survey data in SDMs of coral, sponge, and Pennatulacean presence-absence. We are also updating oceanographic covariates, such as bottom temperature and currents, using recently available Modular Ocean Model (MOM6) data from NOAA CEFI.

Level 2 EFH

We will update the Level 2 EFH descriptions and maps for the above subset of species using our ensemble SDMs from the 2023 EFH 5-year Review with five additional years of survey data from the AFSC RACE-GAP summer bottom-trawl surveys of the Bering Sea, Aleutian Islands, Gulf of Alaska. Additionally, for the Crab FMP, we will model crab species by sex and maturity stage for the first time.

Level 3 EFH

We will construct EFH Level 3 maps using the combined vital rates and SDM approach from the 2023 EFH 5-year Review (Pirtle et al. 2025b). A key update will apply the published temperature-dependent vital rates across the FMP regions, using the MOM6 NEP bottom temperature covariate raster as the temperature value in the rate equations.

EFH Across Temporal Scales

During the 2023 EFH Review, the SSC recommended that the next EFH review consider EFH under both long-term average and temporally contrasting conditions (Pirtle et al. 2025a). Spatiotemporal models (STMs) will be developed to provide supplemental EFH maps of groundfish and crab habitat-related distribution and abundance through time, to improve understanding of EFH for these species under varying environmental conditions. The STMs will additionally provide more accurate forecasting of EFH to near-term conditions or to explore possible future scenarios. We will implement the STMs using a GAMM within sdmTMB (Anderson et al. 2022; Kristensen et al. 2016).

Summary

The 2028 EFH 5-year Review will advance EFH Component 1 information for FMP species, following recommendations from the 2023 EFH 5-year Review and the current priorities of the Council and NMFS (Table 1). This document provides an overview of the regulatory background, scope of the 2028 EFH Review prioritization, and summary of proposed Component 1 updates by FMP (Chapter 1); describes the proposed data updates and analytical methods advancements for the ensemble SDMs to map EFH and introduces new EFH STMs (Chapter 2); and presents examples and draft results of updates using BSAI adult Pacific cod as a case study to demonstrate the impact of these data and methodological improvements (Chapter 3). **At this meeting staff are seeking SSC input on—**

- Overall scope of planned Component 1 updates for the 2028 EFH 5-year Review;
- Proposed updates to the ensemble SDM EFH maps, including new data and updated methods; and
- New STM EFH maps, including data, methods, and application.

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1 Introduction

This discussion paper describes the scope, organization, and methodology for the 2028 Essential Fish Habitat (EFH) 5-year Review, Component 1 (EFH description and identification). The document is organized into three chapters. Chapter 1 provides an overview of the regulatory background, scope of the 2028 Review prioritization, and summary of proposed updates by FMP. Chapter 2 describes the proposed data updates and analytical methods advancements for the ensemble species distribution models (SDMs), including study area and design, species data, environmental covariates, and EFH maps, and introduces new spatiotemporal models (STMs) for EFH. Chapter 3 presents examples and draft results of updates using BSAI adult Pacific cod as a case study to demonstrate the impact of these data and methodological improvements.

This discussion paper does not encompass additional studies developing new information for Component 1 and Component 7, which are noted in the 2028 EFH 5-year Review Plan. Component 1 BSAI crab studies are developing condition indices and EFH Level 3 maps for *Chionocetes* spp. juvenile life stages (Copeman et al. *in prep*) and supplemental maps for Bristol Bay red king crab (Ryznar and Litzow *in review*).[1] Component 7 studies are developing habitat maps for prey of EFH species, using SDMs of prey species in the GOA (Gerson et al. *in prep*) and eastern Bering Sea (Siple et al. *in prep*)).[2] New information from these studies will be available and presented to the SSC for review and recommendations at the February/March 2027 Council meeting (tentatively).

At this meeting staff are seeking SSC input on—

- Overall scope of planned EFH Component 1 updates for the 2028 Review,
- Proposed updates to the ensemble SDM EFH maps, including new data and updated methods; and
- New STM EFH maps, including data, methods, and application

1.1 Overview of EFH 5-year Reviews

The Magnuson-Stevens Fishery Conservation and Management Act (Magnuson-Stevens Act) requires NMFS and regional Fishery Management Councils (Councils) to describe and identify essential fish habitat (EFH) for all fisheries (section 303(a)(7)). The Magnuson-Stevens Act (MSA) defines EFH as “those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity”. 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 actions that would adversely affect EFH. Councils also have the authority to comment on Federal or state agency actions that would adversely affect the habitat, including EFH, of managed species.

Additionally, section 303(a)(7) of the MSA requires that Fishery Management Plans (FMPs) describe and identify EFH based on the guidelines established by the Secretary under section

[1] D3 EFH 5-year Review Plan, Section 2.1.2.4, available with the Council Agenda for this meeting https://meetings.npfmc.org/Meeting/Details/3117

[2] D3 EFH 5-year Review Plan, Section 2.7.2, available with the Council Agenda for this meeting https://meetings.npfmc.org/Meeting/Details/3117

305(b)(1)(A) of the MSA, minimize to the extent practicable adverse effects on such habitat caused by fishing, and identify other actions to encourage the conservation and enhancement of such habitat.

NMFS published guidelines to implement the MSA's EFH provisions in Federal regulations at 50 CFR 600 Subpart J - Essential Fish Habitat and Subpart K - EFH Coordination, Consultations, and Recommendations. Federal regulations require that each FMP contains the following ten EFH components:

1. Description and identification of EFH
2. Fishing activities that may adversely affect EFH
3. Non-Magnuson-Stevens Act fishing activities that may adversely affect EFH
4. Non-fishing activities that may adversely affect EFH
5. Cumulative impacts analysis
6. Conservation and enhancement
7. Prey species
8. Identification of habitat areas of particular concern (HAPC)
9. Research and information needs
10. Review and revision of EFH components of FMPs

To guide the review of EFH every 5 years, Federal regulations at 50 CFR 600.815(a)(10) state:

> *Councils and NMFS should periodically review the EFH provisions of FMPs and revise or amend EFH provisions as warranted based on available information. FMPs should outline the procedures the Council will follow to review and update EFH information. The review of information should include, but not be limited to, evaluating published scientific literature and unpublished scientific reports; soliciting information from interested parties; and searching for previously unavailable or inaccessible data. Council should report on their review of EFH information as part of the Annual Stock Assessment and Fishery Evaluation (SAFE) report prepared pursuant to §600.315(e). A complete review of all EFH information should be conducted as recommended by the Secretary, but at least once every 5 years.*

1.1.1 2028 EFH 5-year Review Prioritization

For the 2028 EFH 5-year Review, review of certain EFH components in the Council's FMPs is prioritized, as new information is available for these components and to focus on top priorities in light of capacity constraints for both the Council and NMFS. In December 2025, the Council supported the scope and plan for the 2028 EFH 5-year Review as presented[3,4]. The Council and NMFS have prioritized the EFH components in bold for review:

1. **Description and identification of EFH**
2. **Fishing activities that may adversely affect EFH**
3. Non-Magnuson-Stevens Act fishing activities that may adversely affect EFH
4. Non-fishing activities that may adversely affect EFH
5. Cumulative impacts analysis

[3] Discussion Paper, D2 EFH 5-year Review Plan, December 2025 https://meetings.npfmc.org/Meeting/Details/3116
[4] Council Motion, D2 EFH 5-year Review Plan, December 2025 https://meetings.npfmc.org/Meeting/Details/3108

6. **Conservation and enhancement**
7. **Prey species**
8. Identification of habitat areas of particular concern (HAPC)
9. Research and information needs
10. **Review and revision of EFH components of FMPs**

The Council may choose to open a call for HAPC nominations coinciding with an EFH 5-year review, or at any time during their regular process, if information and need are available (EFH C&E section 2.6, HAPC section 2.8)[3]. Analysis and potential FMP amendments resulting from proposals will occur as a separate process (e.g., NMFS 2012). For this discussion paper we focus on EFH Component 1.

1.2 Component 1: EFH Description and Identification

An EFH provision in an FMP must include all fish species in the fishery management unit (FMU) (50 CFR 600.805). EFH Component 1, description and identification of EFH, consists of written summaries, tables, and maps for species in the FMP or appendices. The EFH regulations provide an approach to organize the information necessary to describe and identify EFH (50 CFR 600.815(a)(1)). When designating EFH, the Council should strive to describe and identify EFH information at the highest level possible (50 CFR 600.815(a)(1)(iii)(B))—

Level 1: Distribution data are available for some or all portions of the 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 [not available at this time].

1.2.1 2023 EFH 5-year Review

An update to the Alaska EFH Research Plan (Sigler et al. 2017) was published following the 2017 EFH 5-year Review (Simpson et al. 2017). Under this plan, research topics prioritized and funded by NMFS to advance Component 1 information for the 2023 EFH 5-year Review, included several studies: a new ensemble SDM method to map EFH (*ensemble study)*, new Arctic species SDMs, new methods to apply vital rates from laboratory studies to map EFH Level 3 (habitat-related vital rates) for the first time, and a new method to map pelagic early life history stage EFH using biophysical individual-based models (IBMs) and SDMs. An example of the new and revised EFH maps in the FMPs is included in (Figure 1).

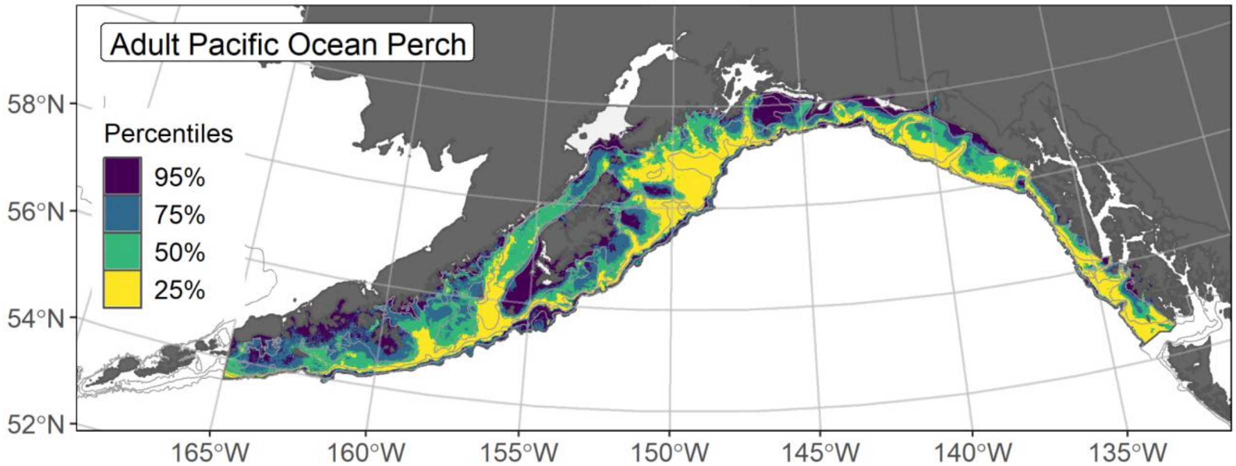

Figure 1. Essential fish habitat (EFH) map for adult Pacific ocean perch in the Gulf of Alaska. EFH is the area containing the top 95% of occupied habitat (defined as model estimated encounter probabilities greater than 5%) from an SDM ensemble fitted to adult Pacific ocean perch distribution and abundance in AFSC RACE-GAP summer bottom trawl surveys (1993–2019) with 50 m, 100 m, and 200 m isobaths indicated. Within the EFH map are the subareas of the top 25% (EFH hot spots), top 50% (core EFH area), and top 75% (principal EFH area) of habitat-related, ensemble-predicted numerical abundance.

For the 2023 Review, new EFH Component 1information provided new and revised EFH maps for the BSAI, GOA, Crab, and Arctic FMPs that included—

- New EFH Level 1, 2, and 3 descriptions and maps for life stages of groundfish in the Gulf of Alaska, Bering Sea, and Aleutian Islands, including settled early juveniles, subadults, and adults, for the GOA and BSAI FMPs.
- New EFH Level 2 and 3 descriptions and maps for up to five pelagic early life history stages of Pacific cod and sablefish in the Gulf of Alaska, including eggs, yolk-sac larvae, feeding larvae, pelagic early juveniles, and settling early juveniles for the GOA FMP.
- New EFH Level 2 descriptions and maps for life stages of crabs in the Bering Sea and Aleutian Islands, including subadults and adults combined for the Crab FMP.
- New EFH Level 1 and 3 descriptions and maps for Arctic cod, saffron cod, and snow crab life history stages, including larvae, settled early juveniles, juveniles, and adults for the Arctic FMP.

The research funded to complete this extensive update is described in the EFH Component 1 Synthesis Report (Pirtle et al. 2025b) and 2023 EFH 5-year Review Final Summary Report (Pirtle et al. 2025a).[5]

As a highlight, the *ensemble study* produced three NOAA Technical Memoranda detailing the regional methods, results, and future research and process recommendations (Harris et al. 2022,

[5] 2023 EFH 5-year Review Final Summary Report (chapter 2), D3 EFH 5-year Review Workplan, February 2026 https://meetings.npfmc.org/Meeting/Details/3117

Laman et al. 2022, Pirtle et al. 2023). A manuscript, *Ensemble models mitigate bias in area occupied from commonly used species distribution models* (Harris et al. 2024), is a helpful contribution to the rapidly developing field of SDMs with applications to EFH and EBFM. In addition, and so that our methods are transparent, repeatable, and available, we published a repository of the ensemble SDM EFH code used to develop the new summer distribution EFH maps in the 2023 Review.[6] Regular updates to this repository keep the R code (R Core Team 2020) and documentation current, as staff have subsequently developed SDMs using these methods as decision support for other Council actions.[7]

This work plan directly addresses Council recommendations from the previous review (Pirtle et al. 2024)[4] to prioritize and improve EFH for selected species, increase the scope and applicability of EFH research, and improve process and communication. Specifically, we plan to improve model inputs and performance for targeted species by: (1) updating ensemble SDMs with new species survey data, (2) refining and updating environmental covariates, and (3) advancing life-history specific mapping for crab fisheries. Additionally, to increase the scope and applicability of EFH research, particularly regarding responsiveness to ecosystem change, we are for the first time (4) building Spatiotemporal Models (STMs) to describe dynamic groundfish and crab distributions and bridging these outputs to inform stock assessment via ESPs and other decision support needs. By focusing on a prioritized subset of species and adhering to the emphasis areas of the Alaska EFH Research Plan, this review streamlines the analytical process to maximize the quality and utility of the products within current capacity constraints.

1.2.2 New in 2028 EFH 5-year Review

The proposed scope of review and updates for EFH Component 1 includes a subset of FMP species. The subset includes—

- Sablefish, pollock, Pacific cod, Pacific ocean perch, and arrowtooth flounder in the BSAI and GOA FMPs, and
- All five species of crab in the Crab FMP.

With this proposed scope, Component 1 will maintain *status quo* in the Arctic, Salmon, and Scallop FMPs.

The Alaska EFH Research Plan (Pirtle et al. 2024), updated following the 2023 EFH 5-year Review, provides a research objective with three emphasis areas to advance Component 1 information for North Pacific species in the 2028 EFH 5-year Review:

Objective 1: Improve EFH information for targeted species and life stages

- *1.1 Additional field data and alternative data sources*,
- *1.2 Demographic processes driving variation over time, and*
- *1.3 Improved methods to integrate both monitoring and process research.*

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[6] https://github.com/alaska-groundfish-efh

[7] SDMs developed for e.g., C2 Bristol Bay red king crab closure areas analysis (appendix 3), February 2024 https://meetings.npfmc.org/Meeting/Details/3029

The emphasis areas were informed from input by Council bodies, reviewing stock assessment scientists, EFH analysts, and the public. For the 2028 EFH 5-year Review, we will advance EFH information for FMP species' life stages under this objective and three emphasis areas with studies described in the following sections.

1.2.2.1 Level 2 EFH Ensemble Species Distribution Models

EFH is mapped for species in the fishery management unit of the FMP. We will update all current Level 2 EFH descriptions and maps for the subset of species in the BSAI and GOA FMPs, and all five species in the Crab FMP, using our ensemble SDM with five years of new species survey data from the AFSC RACE-GAP summer bottom-trawl surveys of the Bering Sea, Aleutian Islands, Gulf of Alaska. We are also developing new SDM methods to combine RACE-GAP bottom-trawl survey data with AFSC Auke Bay Laboratories (ABL) longline survey data to demonstrate a combined data approach to map EFH Level 2 for Alaska sablefish; however, given current NMFS capacity constraints, this work is paused.

For the Crab FMP, we will model crab species by sex and maturity stage for the first time. SDMs by sex and maturity stage were presented for Bristol Bay red king crab (BBRKC) during other Council analysis[8], which demonstrated a preliminary approach to mapping EFH with greater life history resolution for crabs. We are also exploring an approach to develop what may be considered supplemental EFH maps for BBRKC by stock area in other seasons (fall, winter, spring) to update seasonal EFH information in the Crab FMP.

We are updating the environmental covariates that are applied with species survey data in the ensemble SDMs, including bathymetry, all bathymetry-derived terrain variables (slope, aspect, curvature, and bathymetric position index), substrate rockiness, sediment grainsize (*phi*), and structure-forming invertebrates (SFI) that will be used in model fitting. We are developing new SDM methods to update the SFI covariates of coral, sponge, and sea whip presence-absence by combining new data from underwater image analysis from the Alaska Coral and Sponge Initiative (AKCSI)[9] with RACE-GAP bottom-trawl survey data. We are updating oceanographic covariates, such as bottom temperature and currents, using recently available Modular Ocean Model (MOM6) data from NOAA CEFI.[10]

Updating Level 2 EFH descriptions and maps using our ensemble SDM with the most recent species survey and environmental data will directly inform Alaska EFH Research Plan *objectives 1.1 (additional field data and alternative data sources)* and *1.3 (improved methods to integrate both monitoring and process research)*. This work plan is also responsive to EFH methods development requests received during the 2023 5-year Review.[11]

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[8] C2 Bristol Bay red king crab closure areas analysis (appendix 3), February 2024 https://meetings.npfmc.org/Meeting/Details/3029

[9] NMFS Deep Sea Coral Research and Technology Program https://deepseacoraldata.noaa.gov/

[10] NOAA Changing Ecosystems and Fisheries Initiative https://www.fisheries.noaa.gov/science-data/changing-ecosystems-and-fisheries-initiative-regional-activities#alaska

[11] 2023 EFH 5-year Review Final Summary Report (chapter 10), D2 EFH 5-year Review Plan, available on the Council Agenda for this meeting https://meetings.npfmc.org/Meeting/Details/3108

1.2.2.2 Level 3 EFH Ensemble Species Distribution Models

We propose to update the subset of BSAI and GOA FMP species with an existing EFH Level 3 map from the 2023 5-year Review, including settled early juvenile life stages of sablefish, pollock, Pacific cod, and Pacific ocean perch, using new Level 2 maps and updated temperature data from MOM6 with vital rates from published laboratory studies. In addition, new Level 3 EFH maps for juvenile snow and Tanner crabs will be developed by a contributing study (Copeman et al. *in prep*). The results of this work will directly inform Alaska EFH Research Plan *objectives 1.1* and *1.3*.

1.2.2.3 EFH Species Distribution Models Across Temporal Scales

We are developing methods to apply SDMs at dynamic temporal scales to map EFH for North Pacific species. Current SDM EFH mapping purposefully uses the long-term time series of species survey and environmental data. However, temporal resolution affects mapping species distributions under varying environmental conditions (Smith et al. *in review*). We will apply this spatial-temporal SDM (STM) method for the subset of species in the BSAI and GOA FMPs and the Crab FMP to demonstrate supplemental EFH Level 2 maps at annual (and other) time steps. We are finding this approach is helpful to understand how species and their EFH can shift in space and time with varying environmental conditions, such as cold pool variation in the eastern Bering Sea and the presence of marine heat waves in Alaska ecosystems. In addition, we are working with AFSC stock assessment scientists to apply the STMs to develop annual stock-specific indicators for the ecosystem and socioeconomic profiles (ESPs). ESP indicators are a meaningful extension of the EFH SDMs to inform stock assessment (Shotwell et al. 2022, Yeager et al. *in prep*). The EFH STMs support Alaska EFH Research Plan *objective 1.2* (*demographic processes driving variation over time*). The ensemble SDMs and STMs will be available as an analytical tool for a variety of other Council actions.

1.2.2.4 Additional BSAI Crab Studies

We are working with AFSC staff at the Kodiak and Newport laboratories and other crab experts to incorporate the results from new crab studies funded by the Alaska EFH Research Plan and others during 2021-2025. These studies support progress under Alaska EFH Research Plan *objectives 1.1*, *1.2*, and *1.3*.

- *Supplemental EFH Level 2 maps for Bristol Bay red king crab (BBRKC) and other BSAI crabs in the fall/winter/spring seasons.* A completed study developed SDMs of mature male BBRKC, using data from the directed fishery collected in the fall and winter seasons (Ryznar and Litzow *in review*). Additional studies are underway, to develop SDMs for crabs, using fishery dependent data such as from cooperative pot surveys, in collaboration with AFSC Kodiak Laboratory, Alaska Department of Fish and Game (ADFG), and Bering Sea Fisheries Research Foundation (BSFRF).
- *EFH Level 2 and Level 3 maps for Chionocetes spp. juvenile life history stages.* A study is investigating juvenile snow and Tanner crab energetics and survival to develop EFH Level 2 and 3 information and maps for juvenile life stages in the Bering Sea (Copeman et al. *in prep*). This study is developing condition indices and physiology-based SDMs

using temperature-dependent laboratory vital rates, field-based energetic condition metrics, and existing SDMs.

1.2.2.5 Summary of New EFH Component 1 Information by FMP

A summary of the proposed review and updates to this EFH review cycle can be found in Table 1. Under this plan, EFH Component 1 will maintain *status quo* for the Arctic, Salmon, and Scallop FMPs.

Table 1. Summary of proposed updates to EFH descriptions and maps by FMP for the 2028 EFH 5-year Review.

FMP	**Update Level 2 EFH**	**Update Level 3 EFH**	**Analytical Method** (unless specified, developed for all species and life stages)
BSAI Groundfish	sablefish, walleye pollock, Pacific cod, Pacific ocean perch, and arrowtooth flounder settled early juvenile, subadult, and adult life stages	walleye pollock and Pacific cod settled early juvenile life stages	1. ensemble SDMs 2. STMs
GOA Groundfish	sablefish, walleye pollock, Pacific cod, Pacific ocean perch, and arrowtooth flounder settled early juvenile, subadult, and adult life stages	sablefish, walleye pollock, Pacific cod, and Pacific ocean perch early juvenile life stages	1. ensemble SDMs 2. STMs 3. IBMs/STMs (sablefish and Pacific cod pelagic early life stages)
BSAI Crab	all five species of crab by sex and maturity stage	snow crab, and Tanner crab juvenile life stages	1. ensemble SDMs 2. STMs 3. SDMs of the fall/winter/spring distribution of mature male BBRKC (supplemental maps supporting EFH information)

2 Methods

This section details the analytical framework used to map and describe EFH for North Pacific groundfish and crab species. We begin by defining the geographic extent of the three study regions (Section 2.1), the data preparation process, distinguishing between the biological species data selected as dependent variables (Section 2.2) and the suite of habitat covariates selected as independent predictors (Section 2.3). When an independent predictor was updated, a bridging analysis was conducted to compare covariate surfaces between those applied to the 2023 EFH Review and those that are new for the 2028 EFH Review (Section 2.3). We then present modeling protocols, including the construction and validation of the ensemble species distribution models (SDMs) used for static EFH mapping (Section 2.4), and the development of spatiotemporal models (STMs) to characterize temporally dynamic species distributions (Section 2.5).

In the following sections describing the ensemble SDM EFH methods, we "incorporate by reference" the published ensemble SDM EFH methods from the 2023 EFH 5-year Review, available in the EFH Component 1 Synthesis Report (Pirtle et al. 2025b), and three regional NOAA Technical Memoranda for the Bering Sea (BS) (Laman et al. 2022), Aleutian Islands (AI) (Harris et al. 2022), and Gulf of Alaska (GOA) (Pirtle et al. 2023).

2.1 Study Area

In the present work, three marine regions of Alaska are the focus of the SDMs to map EFH for North Pacific groundfish and crab species. These regions extend from Dixon Entrance in southeast Alaska, through the GOA and along the AI archipelago to Stalemate Bank, and north across the eastern Bering Sea (EBS) shelf and slope into the Northern Bering Sea (NBS).

2.1.1 Bering Sea

The BS study area includes the EBS continental shelf (15 to 200 m), EBS upper continental slope (~200 m to 1200 m), and the NBS. Throughout this report, we refer to the shelf, slope, and NBS collectively as the EBS, which represents a total area of approximately 725,000 km^2. The EBS encompasses a diverse mosaic of benthic habitats. Much of the continental shelf, which extends more than 200 km from shore, is shallow, flat, and composed of soft unconsolidated sediments (Smith and McConnaughey 1999, Rooper et al. 2016). The shelf region is commonly divided into three domains: the inner shelf (0 to 50 m), middle shelf (50 to 100 m), and outer shelf (100 to 200 m; Coachman 1986). The shelf-slope break is located between 180 and 200 m depth, except at the northern edge of Bering Canyon, where the shelf-slope break is around 200 m (Sigler et al. 2015). The EBS upper continental slope (~200 m to 1200 m) is steep and includes five major canyon systems along its north-south axis. The seafloor of the upper continental slope is interspersed with areas of rocky substrata, especially in Pribilof Canyon, but is mainly dominated by soft unconsolidated sediments (Rooper et al. 2016). The NBS is considered a distinct region and is not as well described as the more frequently sampled EBS shelf and slope. Grebmeier et al. (1988) indicated that the seafloor in the NBS near Norton Sound is shallow, with average water depths < 50 m, and is composed of unconsolidated sediments similar to those found on the EBS continental shelf, although there is substantial variation in grain size that affects infaunal prey composition.

2.1.2 Aleutian Islands

The AI are a chain of volcanic islands stretching from southwest Alaska across the North Pacific, separating the western GOA from the BS. The continental shelf and upper continental slope of the AI represent a diverse mosaic of benthic habitats from Unimak Pass (165°W) in the east to Stalemate Bank in the west (170.5°E). The Alaskan Stream flows westward on the Pacific side of the Aleutians, while on the Bering Sea side, the Aleutian North Slope Current flows eastward (Stabeno et al. 1999, Stabeno et al. 2002, Ladd et al. 2005). There is extensive transport to the north through passes in the island chain from the Pacific side to the BS. In the Aleutians, there is a very narrow continental shelf that ranges in width from 20 km to greater than 200 km. The continental slope is steep and features multiple passes incising the continental shelf. The seafloor of the AI is diverse, with extensive rocky substrate resulting from volcanic activity dominating the continental shelf (Zimmermann et al. 2013).

2.1.3 Gulf of Alaska

The GOA study area extends from Dixon Entrance (131°W longitude) in southeastern Alaska to Unimak Pass (165°W° longitude) at the western edge of the Alaska Peninsula (Figure 3). The GOA coastline in this region forms an intricate complex of many bays and islands with diverse terrestrial and marine habitats (Johnson et al. 2012, Zimmermann 2019). The GOA continental shelf and upper continental slope encompass a mosaic of benthic habitats with extensive rocky substrate that has been uplifted due to tectonic activity and deposited by glacial retreat (Carlson et al. 1982, Zimmermann et al. 2019). Much of the continental shelf is dominated by soft unconsolidated sediments (Golden et al. 2016). The shelf is narrow in southeastern Alaska and in western GOA, but relatively broad in the central GOA with numerous glacial troughs (Carlson et al. 1982, Goldstein et al. 2020). The shelf break occurs at about 200 m throughout the GOA and the shelf itself is deeply incised by numerous gullies and troughs. Oceanic currents in the GOA ecosystem are the Alaska Coastal Stream and Alaska Coastal Current which both flow westward (counterclockwise) around the GOA from Dixon Entrance to the Aleutian Island chain (Stabeno et al. 2004). These currents result in downwelling of surface water at the coast while seasonal freshwater discharge results in a highly stratified system in the summer (Stabeno et al. 2004, 2016).

2.2 Dependent Variables: Species Data

2.2.1 RACE-GAP bottom-trawl survey

The Alaska Fisheries Science Center (AFSC) Resource Assessment and Conservation Engineering Division's Groundfish Assessment Program (RACE-GAP) summer bottom trawl surveys document the distribution and abundance of federally managed fish and invertebrate species across the eastern Bering Sea (EBS), Aleutian Islands (AI), and the Gulf of Alaska (GOA). These surveys adhere to standardized trawling protocols and provide species data for the species distribution models applied to EFH management. The EBS shelf bottom trawl survey has been conducted annually since 1982—except in 2020 due to the COVID-19 pandemic—using a systematic design with stations arranged on a regularly-spaced 20 × 20 nautical mile grid. This grid was extended to include the Northern Bering Sea (NBS) in 2010, 2017, 2019–2023, and 2025. The EBS slope survey was conducted biennially between 2002 and 2016 (except 2006 and 2014), sampling depths from 200 to 1,200 meters using a stratified random sampling design.

Surveys in the AI and GOA have followed a periodic schedule, with methodology becoming standardized and consistent in 1990 for the GOA and 1991 for the AI. The AI survey was conducted triennially from 1991 to 1997 and biennially from 2000 to present. Similarly, the GOA survey ran triennially from 1990 to 1999 before switching to a biennial schedule. Both surveys have a stratified random design on a 5×5 km grid. For EFH analyses, the AI dataset combines AI and GOA data collected west of Unimak Pass.

All fishes and invertebrates collected during these surveys are identified to the lowest practicable taxonomic classification, weighed, and enumerated. However, species and demographic composition data are sometimes limited to certain time periods due to historical changes in species identification confidence and size-frequency sampling; for example, arrowtooth and Kamchatka flounder were not confidently distinguished on EBS shelf surveys until 1992 and the northern and southern rock sole were considered the same species until around 1996 (Orr and Matarese, 2000). To support detailed assessments, researchers collect length, sex, and maturity information that allow partitioning of life stages (settled early juveniles, subadults, and adults) using species-specific size cut-offs derived from the literature and the NMFS Nearshore Fish Atlas of Alaska. In cases where catches cannot be differentiated by life stage, species distribution models are fitted to combined data from all life stages.

2.2.2 Bering Sea Large-Mesh Bottom Trawl Survey

The primary data source for fish and crab distribution and abundance in the EBS is the fishery-independent AFSC RACE-GAP summer bottom trawl survey of the EBS continental shelf that has been conducted annually using a standardized survey design since 1982. Additional data included in our analyses were obtained from the AFSC RACE-GAP EBS upper continental slope survey (Hoff 2016) occurring in years 2002, 2004, 2008, 2010, 2012, and 2016 and AFSC RACE-GAP NBS surveys (Lauth 2011) in 2010, 2017, 2019, 2021–2023, and 2025.

Three standardized AFSC RACE-GAP summer bottom trawl surveys are conducted in U.S. waters of the Bering Sea. The EBS shelf summer bottom trawl survey is conducted annually on a regularly-spaced 20×20 nautical mile (nm) grid using an 83-112 eastern otter trawl (112 ft footrope and 83 ft headrope). The survey grid and sampling methodology have been extended to include the NBS and Norton Sound since 2010 (Lauth 2011). The bottom trawl survey of the Bering Sea upper continental shelf and slope was conducted from 2002 to 2016 at depths from 200 to 1200 m using a Poly Nor'eastern high opening trawl net with a mudsweep footrope and a stratified sampling design (Hoff and Britt 2011). We plan to use catch and effort data from EBS shelf, NBS, EBS slope survey hauls that met standardized survey performance standards to estimate numerical abundance, length composition, and area swept (Alverson and Pereyra 1969) as inputs for the SDMs. Trawl data include observations of geographic location, distance fished, and bottom temperature.

2.2.3 Gulf of Alaska and Aleutian Islands Large-Mesh Bottom Trawl Survey

Until 2025, GOA and AI surveys were stratified based on longitude, depth and habitat type and by statistical districts delineated by the International North Pacific Fisheries Commission (INPFC). Assignment of sampling effort within strata for both GOA (through 2023) and AI surveys was determined using a Neyman optimal allocation sampling strategy (Cochran 1977) which considers relative abundance and variance of commercially important groundfish species from previous surveys of the area as well as stratum area and the previous year's ex-vessel price for select species. Starting in 2025, the GOA survey stratification was based on longitude, depth, and NMFS statistical sampling districts, and allocation used a Bethel algorithm, designed to minimize survey sample size while achieving index precision constraints for a specific set of commercially and ecologically important species (Oyafuso et al. 2022). It is worth noting that the shift from the historic INPFC districts to the NMFS districts changed the overall GOA survey area footprint. The fishing gear used on the RACE-GAP AI and GOA bottom trawl surveys consists of a Poly Nor'Eastern high-opening bottom trawl detailed in Stauffer (2004). Trawl width is measured with acoustic mensuration gear during every trawl haul to support calculating catch-per-unit-effort (CPUE) for each trawl catch using the swept area method of Wakabayashi et al. (1985).

2.2.4 Groundfish Species

For species where length-based definitions of life stages were available, length ranges for settled early juveniles, subadults, and adults were used to partition the catch based on proportionality estimated from the random length subsample taken from each catch (Table 2). These length-based definitions of ontogenetic life stages came from the extant scientific literature, web resources (e.g., the Ichthyoplankton Information System, AFSC RACE: https://access.afsc.noaa.gov/ichthyo/speciesdict.php), or length data recorded in the updated Nearshore Fish Atlas and collected in beach seines, purse seines, and small-mesh bottom-trawls (as described in Grüss et al. 2021).

Groundfish analysis will be updated for sablefish, walleye pollock, Pacific cod, Pacific ocean perch, and arrowtooth flounder, that will be split into life history groups using length-based life stage breaks, similar to the 2023 EFH 5-year Review (Table 2) (Pirtle et al. 2025b). We plan to evaluate the stage breaks from the 2023 EFH 5-year Review and update as needed based on new life history information.

Table 2. North Pacific groundfish species length-based life stage breaks (length units = mm) used in the 2023 EFH 5-year Review (Pirtle et al. 2025b). When different, the survey region is indicated (Eastern Bering Sea = EBS, Gulf of Alaska = GOA, Aleutian Islands = AI).

Species	Settled Early Juvenile	Subadult	Adult
Arrowtooth flounder	35-160	161-480	>480
Pacific cod	40-150	BSAI: 151–580; GOA: 151–503	BSAI: > 580; GOA: > 503
Pacific ocean perch	25–200	201–250 (≤ 250)	> 250
Sablefish	150–399	400–585 (≤ 400)	> 585 (> 400)
Walleye pollock	40–140	AI: 141–381; EBS: 141–381; GOA: 141–410	AI: > 381; EBS: > 381; GOA: > 410

2.2.5 Crab Species

All five species in the Crab FMP (red king crab, blue king crab, golden king crab, Tanner crab, and snow crab) will be modeled and mapped by sex and maturity stage for the first time in an EFH review. The maturity of female crabs is determined by researchers onboard the bottom trawl surveys using morphological characteristics, such as the shape and size of the abdominal flap or presence of clutch (Donaldson and Byersdorfer 2005). The maturity of male crabs is determined based on established size cutoffs used in the most recent bottom trawl survey reports and/or stock assessments (Table 3). We will work with crab species experts to determine the final sex and maturity life stage breaks appropriate for our analysis.

Table 3. Carapace length (CL) and carapace width (CW) (draft) delineations define the size-at-maturity of male golden king crab, red king crab, blue king crab, Tanner crab, and snow crab by region. EFH analysts will work with crab species experts to determine the final sex and maturity life stage breaks appropriate for analysis.

Species	Region	Maturity (Male) Delineation	Reference
Golden King Crab	Aleutian Islands	> 116 mm CL	Sideek et al. (2022)
Red King Crab	Bristol Bay/Pribilof	> 120 mm CL	Zacher et al. (2024)
	Norton Sound	> 94 mm CL	
Blue King Crab	Pribilof	> 120 mm CL	
	Saint Matthew	> 105 mm CL	
	Northern Bering Sea	> 94 mm CL	
Tanner Crab	East of 166° W	> 113 mm CW	
	West of 166° W	> 103 mm CW	
Snow Crab	Eastern Bering Sea	> 95 mm CW	
	Northern Bering Sea	> 68 mm CW	

2.3 Independent Variables: Habitat Covariates

To characterize species abundance and EFH within the SDM framework, we selected a suite of environmental covariates representing geographic, physical, biological, and oceanographic conditions, some temporally static while others dynamic. For the 2028 EFH 5-year Review, most of the covariates have been or are in the process of being updated to incorporate the most recent data sources and refined interpolation and modeling methods (**Table 4Error! Reference source not found.**). Updated or new covariates include bathymetry-derived bottom depth and seafloor terrain variables (slope, aspect, curvature, bathymetric position index (BPI)), sediment grainsize (*phi*), substrate rockiness, structure-forming invertebrates (SFI), and MOM6-derived oceanographic variables (bottom temperature, bottom currents, and cold pool extent). Geographic location and tidal speed are the only covariates retained without changes from the 2023 EFH 5-year Review.

Table 4. Covariates for the ensemble SDMs and/or STMs for the 2028 EFH 5-year Review. The covariates will be used as the prediction rasters to predict North Pacific groundfish and crab species habitat-related abundance and build EFH maps. Covariate unit, region, temporal availability (annually dynamic, static, or both), and whether the variable has been updated, and its status.

Covariate	**Unit**	**AI**	**GOA**	**EBS**	**Temporally Dynamic or Static**	**Update**: (New Covariate, Data Update, or No Update)	**Status**: (Complete, or In progress)
Geographic location	Latitude, Longitude	X	X	X	Static	No Update	Complete
Bottom depth	meters (m)	X	X	X	Static	New Data Update	Complete
Slope	degrees	X	X	X	Static	New Data Update	Complete
Aspect, northings and eastings	-	X	X	X	Static	New Data Update	Complete
Curvature, mean	m^{-1}	X	X	X	Static	New Data Update	Complete
Bathymetric position index (BPI)	-	X	X	X	Static	New Data Update	Complete
Summer mean bottom temperature	℃	X	X	X	Static (Ensemble) and Dynamic (STMs)	New Data Update	Complete
Summer mean bottom currents, northings and eastings	m·sec-1	X	X	X	Static (Ensemble) and Dynamic (STMs)	New Data Update	In Progress
Summer variability of bottom currents, northings and eastings	m·sec-1	X	X	X	Static (Ensemble) and Dynamic (STMs)	New Data Update	In Progress

Covariate	**Unit**	**AI**	**GOA**	**EBS**	**Temporally Dynamic or Static**	**Update**: (New Covariate, Data Update, or No Update)	**Status**: (Complete, or In progress)
Maximum tidal current	cm·sec-1	X	X	X	Static	No Update	Complete
Sediment grain size	*phi*	X	X	X	Static	New Data Update (EBS), New Covariate (GOA/AI)	Complete
Rockiness	-	X	X	-	Static	New Data Update	Complete
Sponge presence or absence	probability	X	X	X	Static	New Data Update	Complete
Coral presence or absence	probability	X	X	X	Static	New Data Update	Complete
Pennatulacean presence or absence	probability	X	X	X	Static	New Data Update	Complete
Cold pool extent	km^2	-	-	X	Dynamic (STMs)	New Covariate (only for STMs)	Complete

2.3.1 Geographic Location

Spatial modeling, such as the SDMs presented here, often include a location variable to represent geographic location and account for spatial autocorrelation (Ciannelli et al. 2008, Politou et al. 2008, Boldt et al. 2012). To reduce the effects of spatial autocorrelation on the results, we chose to combine latitude and longitude into a smoothed bivariate geographic location term included as an independent predictor in SDM formulations. Rooper et al. (2021) demonstrated that this approach can reduce spatial autocorrelation in the model residuals. Geographic location was collected during each haul using a variety of positioning systems through time (e.g., manual charting, long range navigation (LORAN-C), and digital global positioning system [dGPS]). Since 2005 (EBS) and 2006 (GOA and AI), start and end positions for the vessel during the on-bottom portion of the trawl haul were collected from a dGPS receiver mounted on the vessel. We corrected vessel position to represent the position of the bottom trawl by triangulating how far the trawl net was behind the vessel (based on the seafloor depth and the length of wire out) and subtracting this distance from the vessel position. 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

SDMs. The Equal Area Conic projected longitude and latitude data for each haul (and all other geographical data for this study) were projected to eastings and northings prior to modeling.

2.3.2 Bottom Depth

Bathymetry-derived bottom depth was generated with a 100 x 100 m resolution grid for the Bering Sea, Aleutian Islands, and Gulf of Alaska by combining data from gridded digital terrain models (DTMs) for the eastern Bering Sea (GEBCO Bathymetric Compilation Group 2024, 2024; Zimmermann and Prescott 2018), Norton Sound (Prescott and Zimmermann 2015), Gulf of Alaska (Zimmermann et al. 2019), and Aleutian Islands (Zimmermann et al. 2013; Zimmermann and Prescott 2021). Individual DTMs had overlapping spatial coverage but differences in data quality. Therefore, the bottom depth value for each grid cell was assigned from the DTM raster that was considered to be the most accurate for that location based on correspondence to depth observations from AFSC bottom trawl surveys and qualitative visual inspection of terrain features. A 1 x 1 km resolution predictor grid for bottom depth was created from the 100 x 100 m grid by calculating the mean depth among aggregated blocks of 100 grid cells. Bottom depth grids for each EFH region were obtained by masking the 1 x 1 km grid to the extent of individual survey areas and removing any remaining land area by inverse masking with the Alaska Department of Natural Resources' 1:63,360 scale Alaska Coastline Shapefile (2017 version). The rasters were combined using the R package terra v1.7-83 (Hijmans 2024) and the 'Raster Mosaic' tool in ArcGIS Pro (v3.4.0) via the R-ArcGIS bridge (ESRI 2024).

2.3.2.1 Bottom Depth Bridging Analysis

To examine differences between the 2023 EFH 5-year Review and 2028 EFH 5-year Review bottom depth rasters, we first calculated the Mean Relative Error (MRE) for each varying depth bins across the three regions (Table 5). We also took the difference of depth from the 2028 EFH Review and 2023 EFH Review rasters to identify spatial discrepancies (Figure 2). The accuracy of the new bathymetry is validated against ground-truth data in the scatter plots (center and right panels). These plots regress the modeled depth against observed tow midpoint depths collected during AFSC bottom trawl surveys from 2000–2023. The middle plot represents the comparison of the 2023 EFH Review bathymetry with trawl survey depths, and the right plot is the updated 2028 EFH Review bathymetry with trawl survey depths. As the resulting terrain variables are calculated based on bathymetry, we simply show bridging for depth.

Table 5. A table comparing the Mean Relative Error (MRE) of the 2023 EFH 5-year Review versus the 2028 EFH 5-year Review bathymetry at varying depth strata across the three regions: eastern Bering Sea (EBS), Gulf of Alaska (GOA), and Aleutian Islands (AI). The bold numbers highlight the MRE value is best by that depth bin/region.

	EBS		**GOA**		**AI**	
Depth Bin	2028 MRE	2023 MRE	2028 MRE	2023 MRE	2028 MRE	2023 MRE
0-50	**0.071**	0.144	**0.100**	0.136	**0.131**	0.131
50-100	**0.017**	0.116	**0.044**	0.084	**0.050**	0.062
100-200	**0.008**	0.020	**0.033**	0.088	**0.044**	0.059
200-300	0.098	**0.047**	**0.032**	0.074	0.292	**0.065**
300-400	0.083	**0.057**	**0.058**	0.100	**0.062**	0.065
400-500	0.058	**0.032**	**0.036**	0.041	0.048	**0.034**
500-600	0.038	**0.025**	**0.044**	0.065	-	-
600-700	0.053	**0.029**	**0.041**	0.076	-	-
700-800	0.048	**0.036**	**0.025**	0.036	-	-
800-900	0.066	**0.049**	**0.026**	0.035	-	-
900-1000	0.091	**0.035**	**0.016**	0.019	-	-
1000-1200	0.066	**0.041**	-	-	-	-

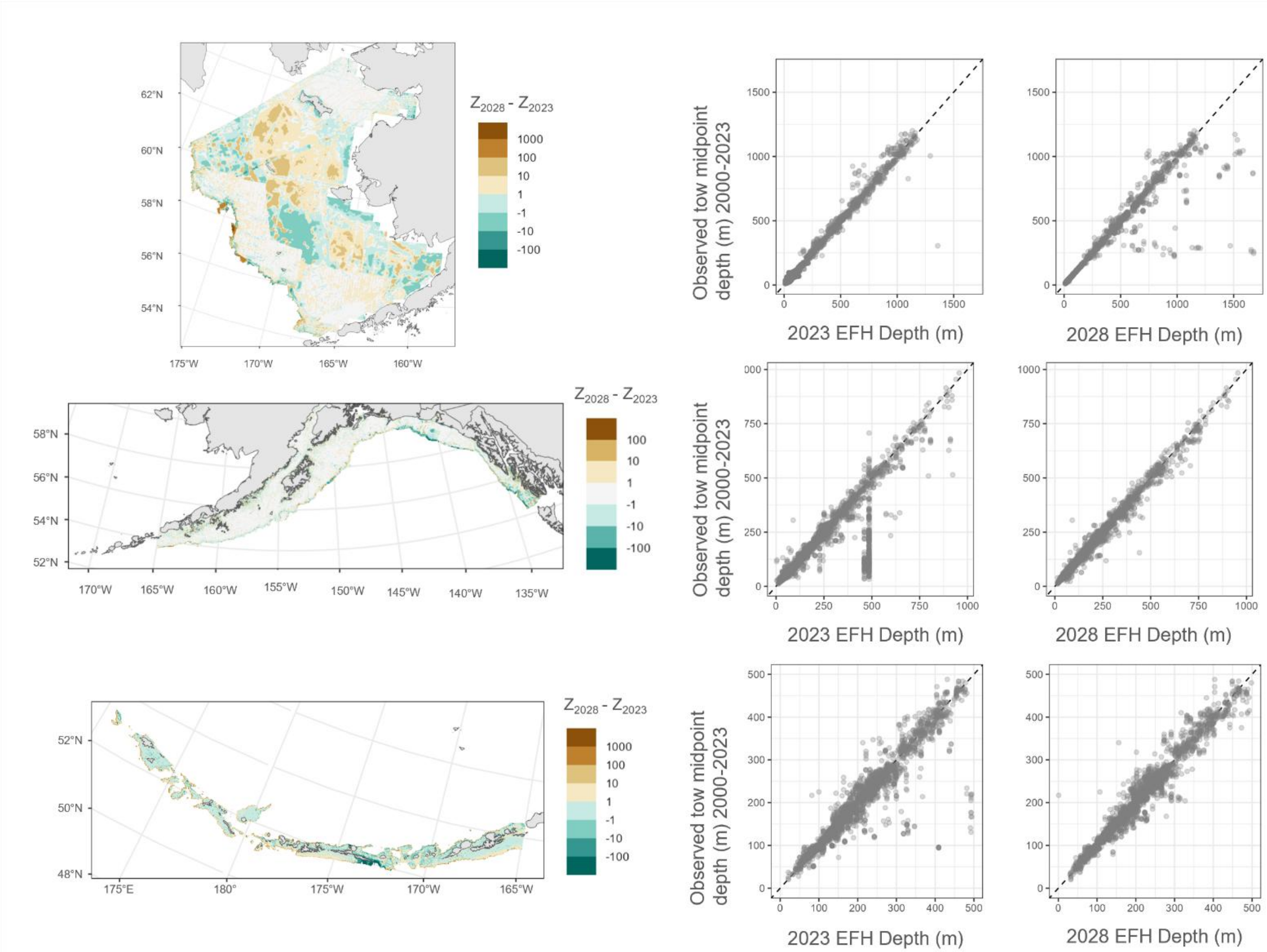

Figure 2. Bridging analysis of bathymetry-derived depth from the 2023 EFH 5-year Review to the 2028 EFH 5-year Review in the Eastern Bering Sea (top), Gulf of Alaska (middle), and Aleutian Islands (bottom). The left panels are maps of depth differences from the 2028 EFH Review and 2023 EFH Review bathymetry, where brown colors indicate the 2028 EFH Review data is deeper and cool colors indicate it is shallower. The scatter plots validate each dataset by comparing bathymetry depths (x-axis) against observed tow midpoint depths from 2000–2023 survey (y-axis); tighter clustering around the dashed 1:1 line indicates higher accuracy.

2.3.3 Seafloor Terrain

The bathymetry-derived terrain variables of slope, aspect (eastness and northness), curvature (mean), and bathymetric position index (BPI), were calculated from the 100 x 100 m resolution bottom depth grid and aggregated to 1 x 1 km resolution by calculating the means for 100 grid cell blocks. All terrain variables were calculated using the MultiscaleDTM R package (Ilich et al. 2023) and the methods for calculating each terrain variable are described below.

Seabed slope is defined as the rate of change in bottom depth at a location in degrees (Horn 1981). Slope can affect groundfish species distribution because the physical habitat (e.g., substrate) and community structure in areas with steeper slopes can differ from areas with flatter slopes (e.g., Pirtle et al. 2019). We calculated slope for each grid cell in the 100 x 100 m resolution bottom depth grid using a 3 x 3 cell focal window.

Aspect eastness and northness, characterize the direction of a slope as the sine and cosine, respectively, of the compass direction of the slope, ranging from -1 to 1. Aspect can indicate the predominant current speed and direction over the seafloor and the 'side' of a terrain feature (e.g., north and south sides of the Aleutian Islands). We calculated eastness and northness for each focal grid cell based on the aspect of a 3 x 3 focal window (Horn 1981). Using this method, a north facing slope has northness = 1 and a south facing slope has northness = -1, whereas east and west facing slopes equal to -1 and 1, respectively.

Mean curvature characterizes the concavity/convexity of a surface and is defined as the average of the minimum and maximum profile curvature (Wilson et al. 2007). The curvature of the seafloor can influence habitat exposure to currents and affect current speed and direction. Positive curvature indicates a slope is convex, which can be associated with currents decelerating or diverging. Zero curvature indicates a flat surface that does not influence current speed and direction. Negative curvature indicates concave slopes where currents may be accelerating or converging. Mean curvature was calculated from the 100 x 100 m resolution bottom depth grid using a 3 x 3 cell focal window.

Bathymetric position index (BPI) characterizes the elevation of a grid cell relative to the surrounding area (Lundblad et al. 2006). Positive values indicate the depth of a cell is shallower than the surrounding area and negative values indicate the elevation is lower than the surrounding area. BPI is useful for characterizing terrain features such as troughs and crests that affect larval/juvenile settlement, cross-shelf transport, and habitat suitability (e.g., Goldstein et al. 2020). We calculated BPI following Lundblad et al. (2006), but without rounding values to the nearest integer. We calculated BPI for each grid cell from the 100 x 100 m resolution bottom depth grid using an inner annulus of 1.5 km and outer annulus of 6.4 km.

2.3.4 MOM6 Covariates: Bottom Temperature and Bottom Current

We derived annual mean summer (June–August) bottom temperature and bottom current velocity (nothings and eastings vectors) for the years 1993–2025 using the Northeast Pacific 10km Modular Ocean Model 6 (MOM6-NEP; Drenkard et al., 2025). The MOM6-NEP domain covers the Gulf of Alaska, Aleutian Islands, and Bering Sea, extending north into the Arctic and continuously south to Baja California. The model uses an orthogonal curvilinear grid (342 x 816 cells) with an average horizontal resolution of 9.7 ± 0.5 km. Vertically, the model employs a z^*

coordinate system with a vertical discretization of 52 layers. To conform to GEBCO-derived bathymetry (GEBCO Bathymetric Compilation Group, 2020), the bottom-most active layer varies continuously in thickness, while layers below the bathymetric interface collapse to zero thickness. Consequently, the index of the bottom layer varies spatially across the domain.

To characterize conditions at the seafloor, we extracted the northeast Pacific monthly hindcasted, raw gridded data for sea water potential temperature on bottom (tob; degrees C) and current velocity vectors (uo and vo; m s^{-1}), alongside the static ocean grid to assign latitude and longitude to each horizontal grid point. For temperature, we used the provided bottom-layer variable constructed in a 2-dimensional horizontal grid. For currents, which are provided in a 3-dimensional grid, we identified the bottom depth layer at every horizontal grid location as the deepest vertical index (k) for which layer thickness remained positive. Northing (v) and easting (u) velocity components were sampled from this spatially varying index to represent currents overlying the seafloor.

To structure the gridded data into spatial files, we first filtered all data to north of latitude 40 degrees, selected summer months (June, July, and August) and averaged summer month temperatures/current velocities across each of the 33 years. Using the R package terra v1.8-80 (Hijmans 2024), we performed an Inverse Distance Weighting (IDW) interpolation to interpolate between spatial points, using a standard power of 2, a neighborhood maximum of 7 and interpolated to a 1 x 1 km resolution raster. We did this each year resulting in a mean summer tob, vo and uo 1 km resolution rasters for 33 years (Figure 3). Lastly the raster was inverse masked by the Alaska Department of Natural Resources' 1:63,360 scale Alaska Coastline Shapefile (2017 version) and masked the rasters to: (1) EEZ with a 100 km buffer and (2) our EFH model extent with a 100 km buffer and each year was stacked into one large raster stack, for each variable. The raster stack of these three variables will be used as covariates in the STMs. Lastly, we took the mean annual summer bottom temperature and current velocities to produce an average across all survey sampling years (1993-2025) to be used in the ensemble SDM.

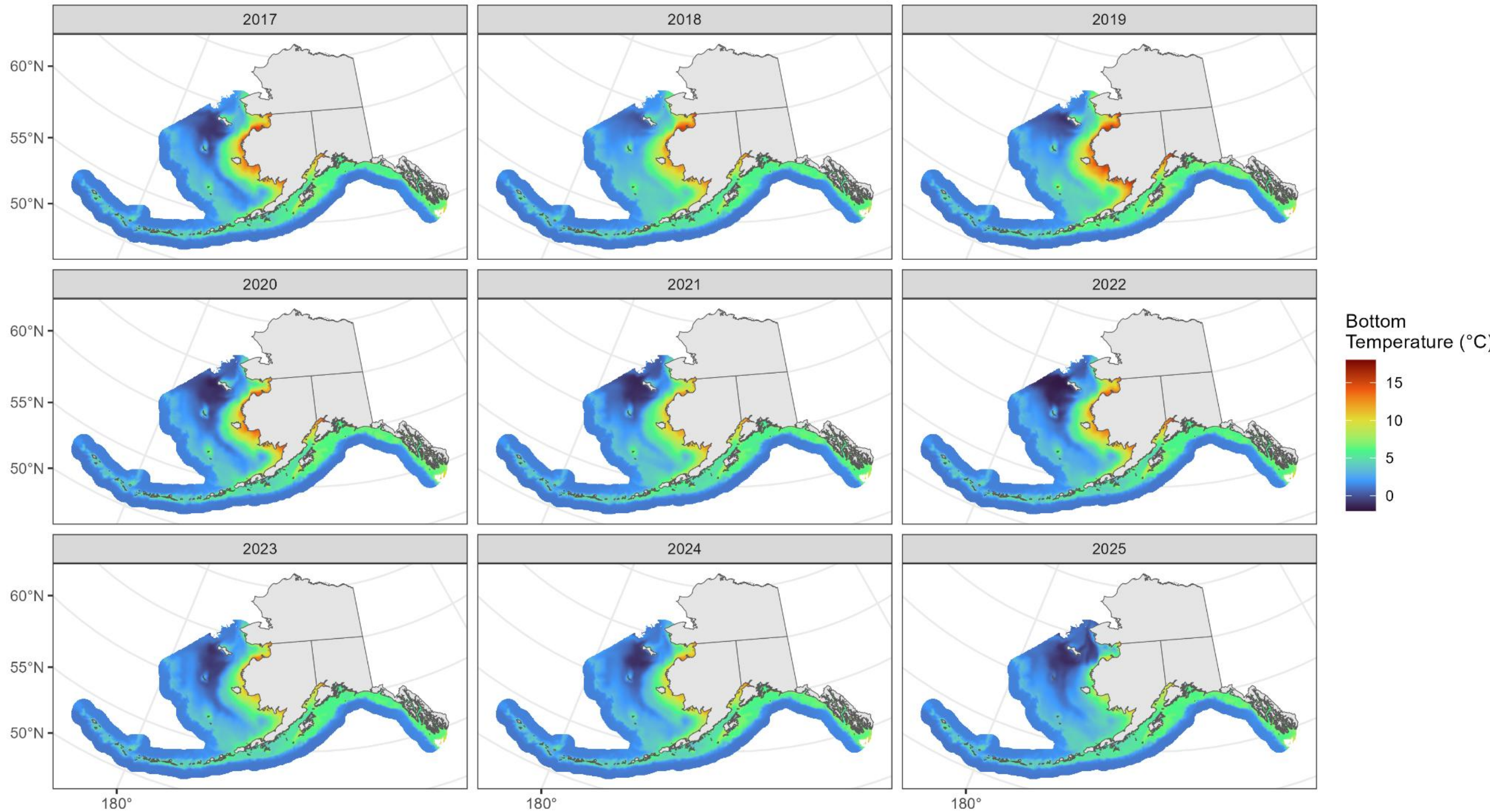

Figure 3. Multiplot of MOM6-NEP derived mean summer bottom temperature from 2017- 2025 (a subset of the 33 years) across the Gulf of Alaska, Aleutian Islands and Bering Sea. Rasters are masked to the EFH boundary plus a 100 km buffer.

2.3.4.1 Bottom Temperature Bridging Analysis

To compare the new MOM6-derived bottom temperature covariate against the 2023 EFH 5-year Review covariate method of interpolating bottom temperature across survey stations, we first standardize years and domain and calculate the spatial temperature differences between the two covariate rasters. The spatial patterns reveal that while both models capture broad temperature gradients—displaying warmer waters (orange/red) in Bristol Bay and cooler waters (blue) in the northern Bering Sea —the MOM6-NEP model (left panel) provides a detailed representation that resolves finer-scale oceanographic features and covers the more temporal resolutions (Figure 4). The temperature difference map (right panel) quantifies these divergences, with brown areas indicating regions where the MOM6 model predicts warmer temperatures than the survey interpolation, most notably along the southern Alaska Peninsula and parts of the inner shelf. Conversely, blue-green areas highlight regions where the MOM6 model predicts cooler temperatures, such as the northern Bering Sea shelf and into Norton Sound. A potential explanation for these cooler temperatures in the northern Bering Sea could be due to the survey stations only sampling this region intermittently (2010, 2017, 2019-2023, 2025), thus the aggregate is unevenly represented throughout years. Additionally, the MOM6 data averages monthly bottom temperatures across June-August each year, while the survey station temperatures are sampled once per year. Through changing our methods of bottom temperature covariate, we will have a larger range of seasonal temporal resolution which may make areas look cooler or warmer depending on when the survey typically samples across the summer months.

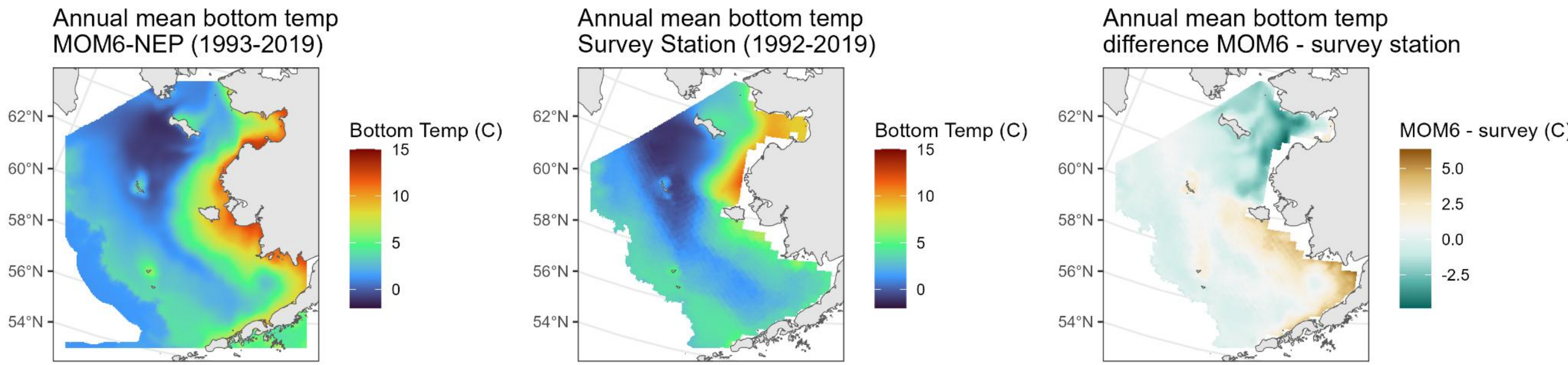

Figure 4. Comparison of annual mean of ocean bottom temperatures in the Bering Sea region from the MOM6-NEP compared to the survey station bottom temp interpolation and their temperature differences. Annual mean bottom temperature (°C) averaged over the period 1993-2019 from the MOM6-NEP model (left). Annual mean bottom temperature (°C) averaged over the period 1992-2019 from the interpolated survey stations (middle). Both left and middle panels use the same color scale, ranging from -2°C (dark blue) to 15°C (dark red). Temperature differences (°C) in the annual mean bottom temperature between the two rasters (MOM6 - interpolated survey stations) (right). The color scale for the difference plot (right) is centered on zero (white), with shades of brown indicating MOM6 predicted warmer than the survey station raster and shades of blue-green indicating MOM6 predicted cooler than the survey station raster.

2.3.5 Maximum Tidal Current

During the 2017 EFH 5-year Review, a raster representing maximum tidal current was developed and applied as a covariate to the SDMs in both the 2017 and 2023 EFH 5-year reviews (Pirtle et al. 2025b). This was done by first estimating maximum tidal current at each survey station over a lunar year (369 consecutive days between January 1, 2009 and January 4, 2010) using a tidal inversion program parameterized for each study region on a 1-km^2 grid (Egbert and Erofeeva 2002). This tidal prediction model was used to produce a series of tidal currents for spring and neap cycles at every bottom trawl survey station. The maximum of the lunar annual series of predicted tidal current was then extracted at each bottom trawl survey haul location. A 1-km^2 raster of maximum tidal current speed was kriged over the study region using an exponential semi-variogram and values were extracted and averaged along individual trawl haul towpaths to use as input to the best fitting SDMs when predicting distribution and abundance. We plan to use the same covariate raster for the 2028 EFH 5-year Review, as more recent, best available tidal current data have not been identified.

2.3.6 Sediment Grain Size

During the 2023 EFH 5-year Review, a raster representing sediment grain size (*phi*) was developed for the EBS (EBSSED; Richwine et al. 2018) and applied as a covariate to the ensemble SDMs (Pirtle et al. 2025b). We have updated sediment grain size data from the last review using the updated database (dbSEABED; Jenkins et al. 2025) which in addition to the EBS, GOA and AI will now be included as a predictor variable in the SDMs. Mean grain size (mm) is expressed as *phi*, the negative log2-transform of average grain size. Thus, large *phi* values indicate fine grains. The sampling tools for this sediment information were bottom grabs and cores, which cannot distinguish boulder or bedrock habitat. Across the three regions of AK, the dbSEABED collated 644 datasets resulting in 1,203,766 samples/observations collected. In the EBS, this includes 48,665 samples, a substantial increase from the 13,874 samples from the Eastern Bering Sea Sediment database (EBSSED; Richwine et al. 2018) used to make the EBS *phi* raster for the 2023 Review (Pirtle et al. 2025b). Sediment grain size point data was 3D Inverse Distance weighted with calculating a weighted mean of the five nearest neighbors, utilizing a specialized distance metric that scales depth to follow bathymetric contours and applies variable power exponents (n=2 for sediment, n=3 for rock) to reflect material mobility, resulting in 1km resolution rasters for each of the three regions (for more details on methods see Jenkins et al., 2025). Sediment grain size at each survey station was spatially extracted and averaged along the towpath to train and test the models.

2.3.6.1 Sediment Grain Size Bridging Analysis

We compared the EBS *phi* used in the 2023 EFH 5-year Review (Pirtle et al. 2025b) and the new, updated surface acquired from Jenkins et al. (2025) (Figure 5). Some of the largest differences between the surfaces are the result of decreased *phi* (darker blue in comparison plot), which would correspond to larger grain sizes, often near island features (Pribilof, St. Matthews, and St. Lawrence islands).

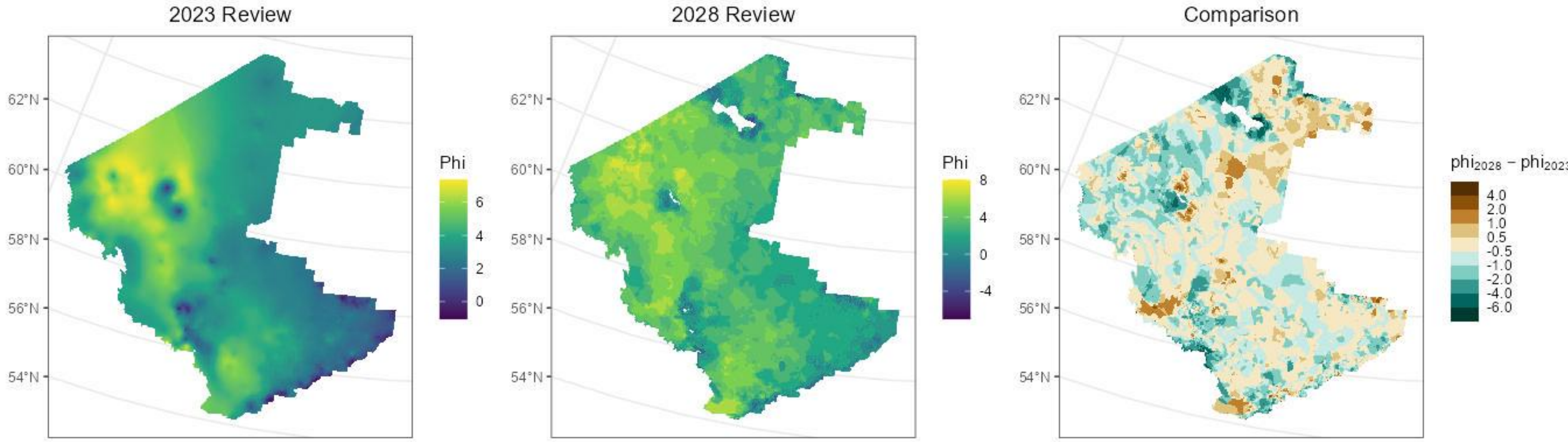

Figure 5. Bridging of the covariate *phi* in the Eastern Bering Sea used in the 2023 EFH 5-year Review compared to the updated 2028 EFH 5-year Review *phi* raster acquired from Jenkins et al. (2025). Both left and middle panels use the same color scale, where dark blue colors indicate small *phi* (or larger sediment grain size) values and green to yellow colors indicate larger *phi* (smaller sediment grain size) values. Lastly a map of differences in *phi* between the two rasters (2028 EFH Review – 2023 EFH Review) (right), where the color scale for the difference plot (right) shows shades of brown indicating 2028 EFH Review raster predicted smaller sediment grain size than the 2023 EFH Review, and shades of blue-green indicating 2028 EFH Review raster predicted larger sediment grain size than the 2023 EFH Review.

2.3.7 Rockiness

During the 2023 EFH 5-year Review, a seafloor rockiness surface was developed for the Aleutian Islands (AI) and Gulf of Alaska (GOA) to represent a continuous gradient of rockiness features, utilizing methods similar to Pirtle et al. (2019). For the AI region, the model incorporated sediment data from digitized smooth sheets (Zimmermann et al. 2013), EBSSED-2 grab and core samples (Richwine et al. 2018), and a prediction surface of seafloor trawlability (based on a generalized linear model of acoustic seafloor backscatter and terrain) as a proxy for seafloor rockiness (Pirtle et al. 2015). This was supplemented by historic RACE-GAP haul data, where gear damage likely indicated presence of rocky features and good haul performance likely indicated non-rocky seafloor. The GOA analysis included these methods and added region-specific digitized smooth sheet data (Zimmermann and Prescott 2014, 2015), dbSEABED sediment features (Golden et al. 2016), and RACE-GAP survey grid centroids coded for specific rocky (e.g., pinnacles, ledges) or non-rocky (e.g., sand waves) attributes. For more detailed information refer to Harris et al. (2022) and Pirtle et al. (2023).

Adding to the compiled point data from the 2023 EFH Review, we updated the seafloor rockiness surface across both regions of AI and GOA with information on net hangs within our RACE-GAP survey and fishery observer databases. We selected locations in the RACE-GAP database from years 1983-2024, where performance was negative and the descriptions included: “Major Hang, stopped forward progress of vessel”, “Hung up”, “Hauled back early due to hang(s)”, “Caught large rock”, and “Snag”. Within the observer database we selected locations from years 1988-2025, where the performance description included: “Hang up”, or “Net Hung (Backed down)”. Each one of those spatial data points was considered a rock and compiled with the point location data from the four datasets in AI and the six datasets in GOA. This new updated spatial point data was interpolated using natural neighbor interpolation to produce a raster surface of 1 km2 resolution (ArcGIS 10.7, ESRI).

2.3.7.1 Rockiness Bridging Analysis

We compared the 2023 EFH 5-year Review rockiness covariate against the updated rockiness surface that we plan to apply to the SDMs for the 2028 EFH 5-year Review by evaluating the impact of adding observer and survey hang-up datasets as new “rock” locations to the dataset (Figure 6). The 2023 EFH Review (top) and the 2028 EFH Review (middle) rasters both display a percent of rockiness where purple represents high rockiness (values near 1.0) and peach represents low rockiness (values near 0.0). The updated model retains the general structure of the 2023 EFH Review raster but shows intensified rockiness in areas where hang-up data provided new evidence of hard substrate. To quantify changes in rockiness, we mapped the difference of rockiness (2028 EFH Review – 2023 EFH Review) to highlight areas of change. Brown areas indicate where the updated model predicts increased rockiness relative to the 2023 EFH Review, suggesting that the previous model may have underestimated substrate complexity in these locations. This comparison demonstrates that the inclusion of hang-up data successfully refined the rockiness covariate, particularly in distinct localized areas across the shelf and slope.

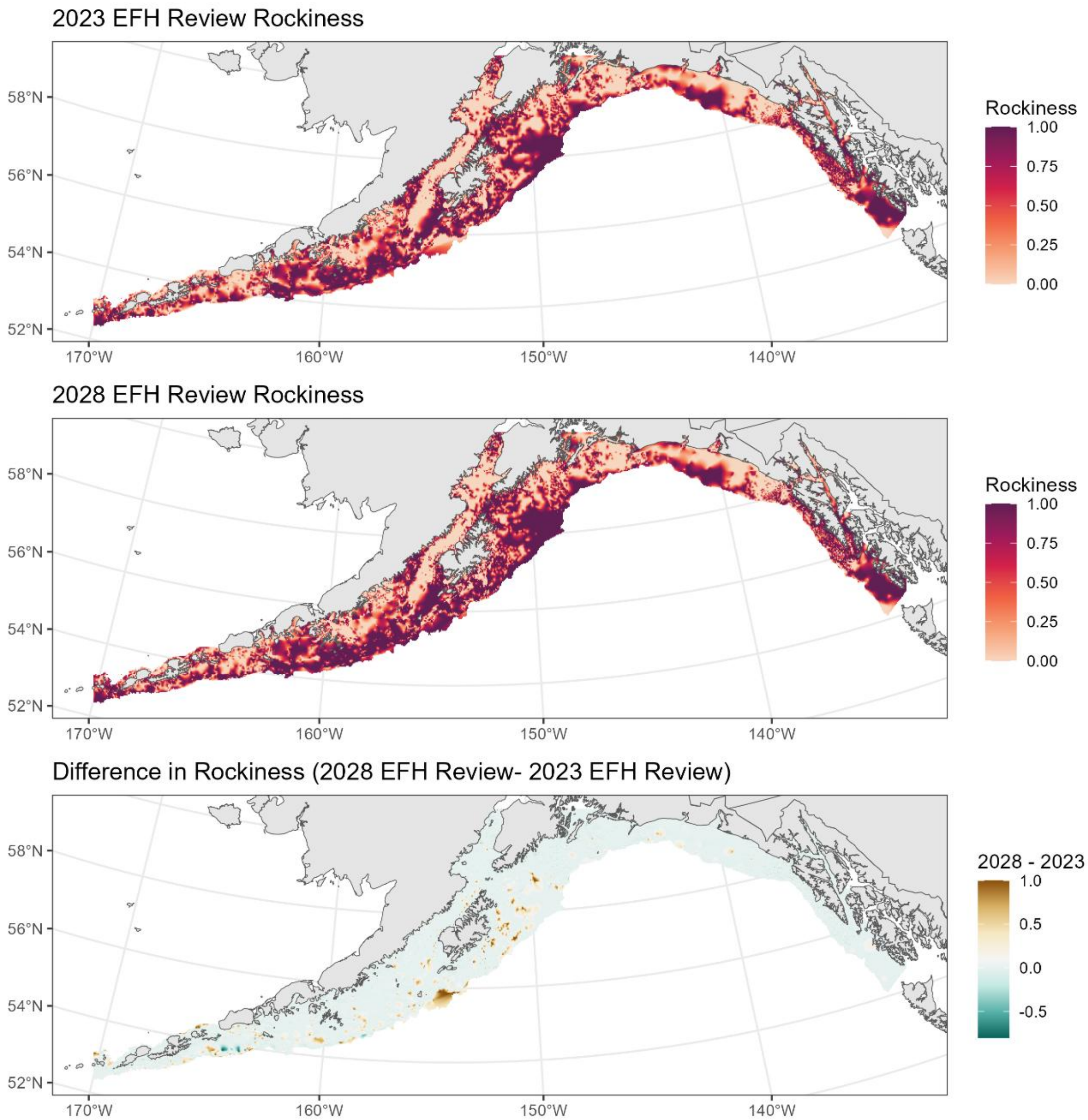

Figure 6. Evaluation of updated rockiness covariates in the Gulf of Alaska and Aleutian Islands, including comparison of the spatial distribution of substrate rockiness for the 2023 EFH baseline (top) against an updated model incorporating Observer and RACE-GAP gear hang-up data (middle). In the first two panels, darker reds to purple indicate higher rockiness (values near 1.0) while lighter reds to peach indicate lower rockiness (values near 0.0). Difference between the two models (2028 EFH Review – 2023 EFH Review) are mapped (bottom), highlighting specific regions where the 2028 EFH Review covariate predicts increased (brown) or decreased (teal) rockiness relative to the 2023 EFH Review covariate.

2.3.8 Structure-forming invertebrates (SFI)

Structure-forming invertebrates (SFI) such as sponges, corals, and Pennatulaceans (sea pens and sea whips) can form important structural habitat for temperate marine fishes (e.g., Heifetz et al. 2005, Laman et al. 2015, Malecha et al. 2005, Marliave and Challenger 2009, Rooper et al. 2010, Stone et al. 2011). The occurrence of SFIs can also be indicative of substratum type (Du Preez and Tunnicliffe 2011), as sponges and corals attach to rocks and hard substrata, whereas sea pens and sea whips (Pennatulaceans) anchor into soft substrata. During the 2023 EFH 5-year Review, a raster representing presence of coral, sponge and Pennatulaceans was developed and applied as a covariate to the ensemble SDMs (Pirtle et al. 2025b). Following the categories of the 2023 EFH 5-year Review, we developed new presence-absence covariates of sponge, coral, and Pennatulaceans to be applied as binomial factors in the suite of habitat covariates, to predict distributions and abundances from best-fit SDMs (Pirtle et al. 2025b).

The new rasters of SFI presence/absence were developed using a new combined gear model to combine new data from underwater image analysis from the Alaska Coral and Sponge Initiative with RACE GAP bottom-trawl survey data to refine covariates of coral, sponge, and Pennatulacean presence-absence. We implemented a version of a generalized additive mixed model (GAMM) using the package sdmTMB (Anderson et al. 2022). We estimated presence with a binomial distribution and logit link at spatial location i as:

$$Logit(p_i) = \beta_0 + \beta_1(Gear) + f_1(depth_i) + f_2(temp_i) + f_3(phi_i) + f_4(rockiness_i) + f_5(mean\ current_i) \quad (1);$$

where Gear is a fixed factor of “trawl” or “camera”, depth is the bottom depth at capture (Section 2.3.2), temp is the bottom temperature at capture, phi is the sediment grain size (Section 2.3.6), rockiness is the degree of rock (GOA and AI only; Section 2.3.7), and mean current is the mean magnitude of easting and northing bottom current vectors (Section 2.3.4), respectively. For each covariate smooth, we used the default thin-plate regression splines and limited the basis dimensions (k) to six, with a first-order penalty (m=1).

2.3.8.1 SFI Bridging Analysis

To compare the new SFI covariates produced using the new combined gear model with the previous SFI maps produced using bottom-trawl survey data, we ran cross-validations to test the models’ skill in classifying presence and absence data using five folds of training and testing splits. For this cross-validation, we used the area under the receiving operator curve (AUC) and true skill statistic (TSS) to test the classifications. The AUC assesses the model's ability to discriminate binary outcomes (presence vs. absence) with a minimum value of 0.5 (i.e., random 50/50 chance) and a maximum of 1. AUC values under 0.7 are generally considered poor, values between 0.7 and 0.9 are good, and values greater than 0.9 suggest excellent discrimination ability (Hosmer and Lemeshow 2005). The TSS combines how many times the models correctly classified presence and absence and combines them into one score (Allouche et al. 2006).

For each region (EBS, GOA, and AI), the combined gear model most often improved model classification skill of presence or absence over the trawl-only approach used in the 2023 EFH 5-year Review (Pirtle et al. 2025b). Overall, classification differences were minor (Table 6, Figure 7).

Table 6. Model skill tests of Area Under the Receiver-Operator-Characteristics Curve (AUC) and the true skill statistic (TSS) for comparing combined gear (trawl + camera; new 2028 EFH 5-year Review method) and trawl only (2023 EFH 5-year Review method) model across the regions of the Eastern Bering Sea (EBS), Gulf of Alaska (GOA) and Aleutian Islands (AI) and the three taxa of sponge, coral and Pennatulaceans using a 5-fold cross-validation.

		AUC		**TSS**	
Region	**Taxon**	**Trawl + Camera**	**Trawl Only**	**Trawl + Camera**	**Trawl Only**
EBS	sponge	0.83	0.84	0.50	0.50
EBS	coral	0.82	0.80	0.48	0.43
EBS	pen	0.94	0.93	0.75	0.73
GOA	sponge	0.80	0.80	0.46	0.46
GOA	coral	0.84	0.74	0.51	0.37
GOA	pen	0.80	0.74	0.44	0.34
AI	sponge	0.67	0.66	0.25	0.24
AI	coral	0.68	0.65	0.25	0.20
AI	pen	0.88	0.82	0.63	0.44

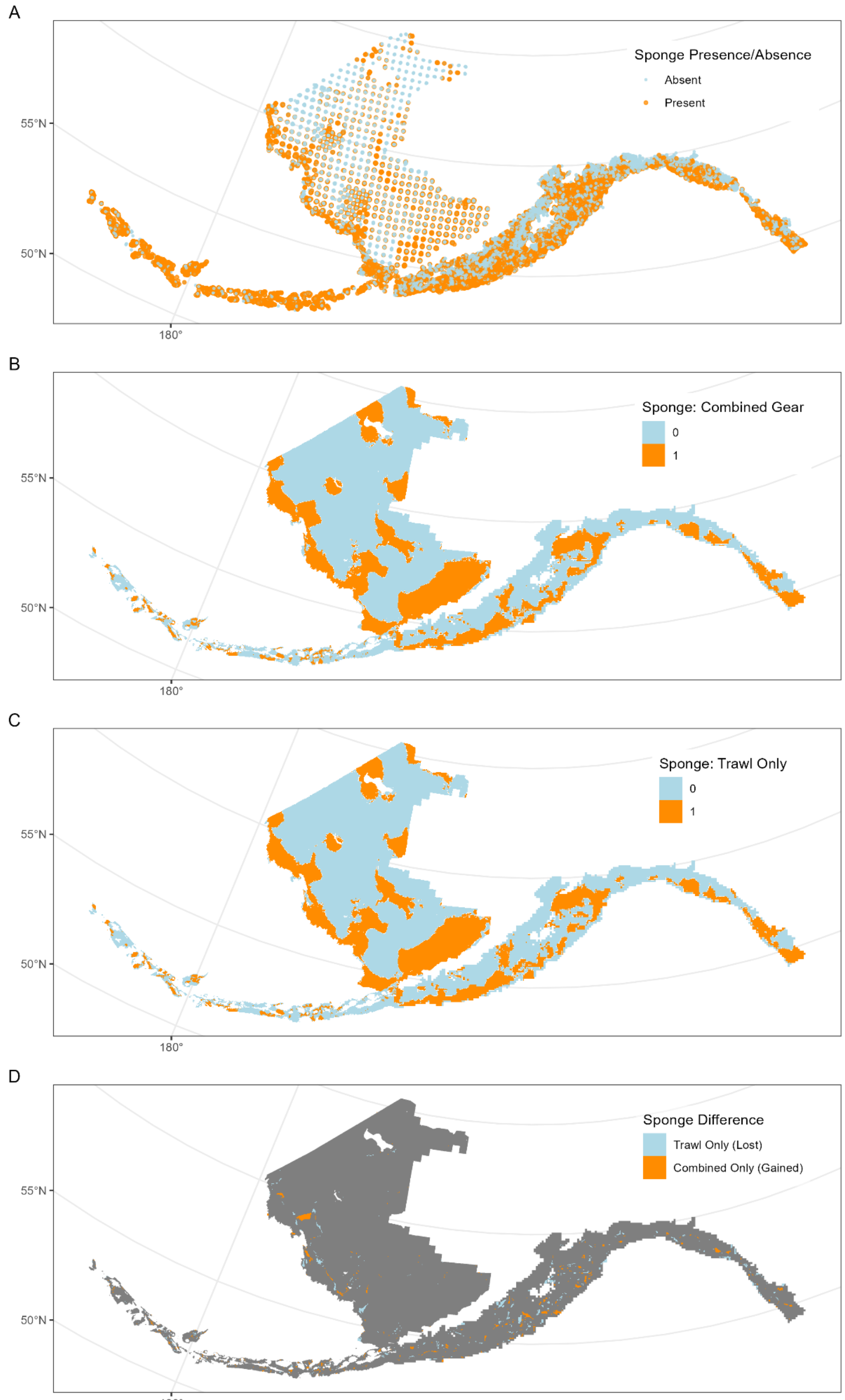

Figure 7. Comparison of predicted presence/absence of sponge in the new combined gear model (B), the trawl-only model used in the 2023 EFH 5-year Review (C) and the difference (D), relative to the actual presence/absence records from all trawl and camera surveys combined (A).

2.3.9 Cold Pool Extent

The 'cold pool' is a distinct benthic pool of water below 2°C in the EBS which forms seasonally following winter sea ice formation and spring ice melt and stratification each year (Clement Kinney et al. 2022). The cold pool acts as a physical barrier to the movement of many species, and its contraction in warmer years allows groundfish and crab distributions to shift northward (e.g., Loher and Armstrong 2005, Meuter and Litzow 2008, Zador et al. 2011, Stevenson and Lauth 2019, Spies et al. 2020, Baker 2021). As this metric is based on annual variability (i.e., Cold Pool Extent area per year), we plan to use this metric as a covariate in the STMs only. We produced this covariate by sub-setting the MOM6 bottom temperature data (described in Section 2.3.4) to include all area at or below 2°C for each year to create the spatially-varying index of the cold pool extent (km^2) in the EBS (Figure 8, Thorson 2019).

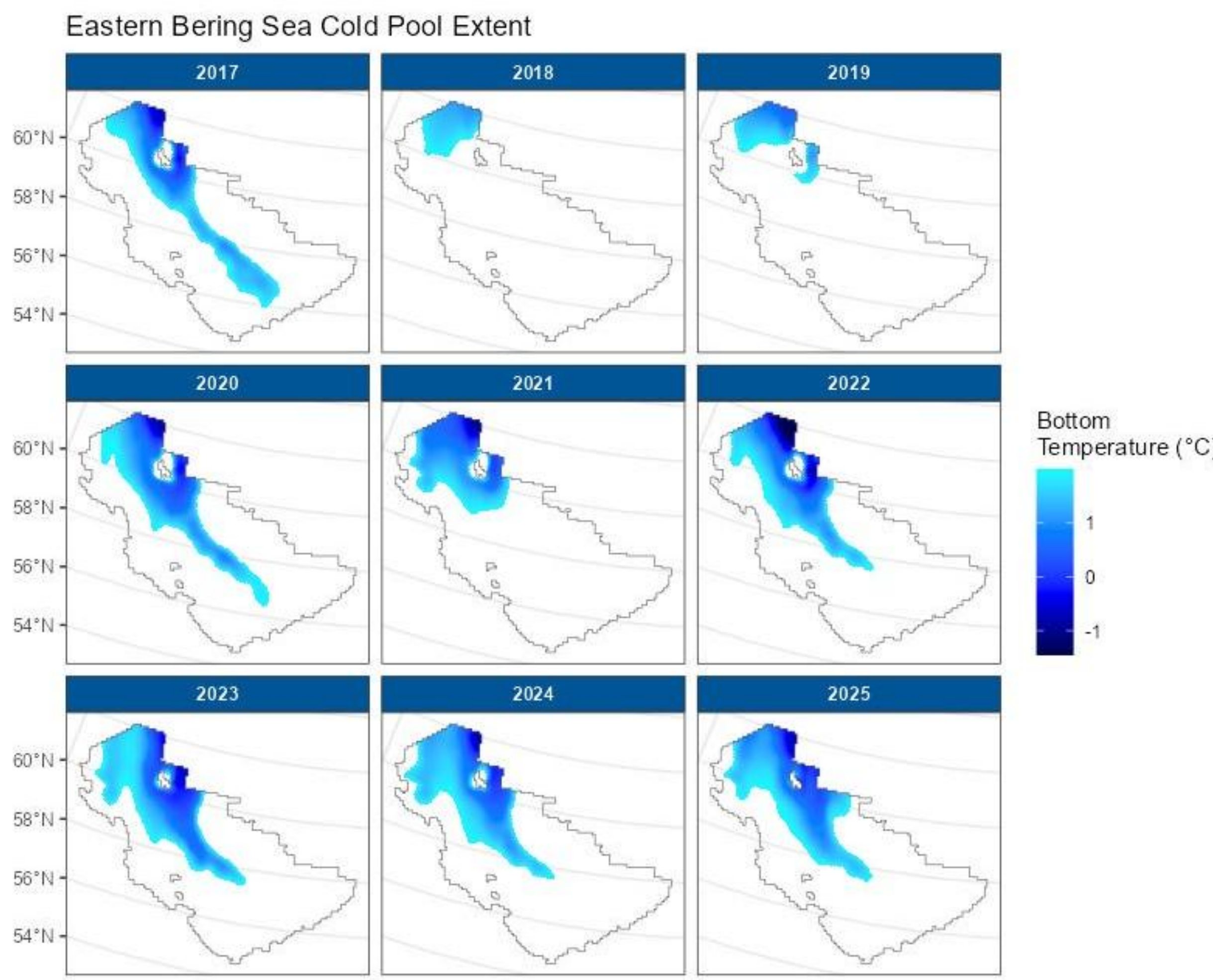

Figure 8. Eastern Bering Sea cold pool (< 2°C) extent in recent years (2017-2025) as derived from MOM6 average summer (Jun-Aug) bottom temperature.

2.4 EFH Ensemble Species Distribution Models

The following methods on EFH ensemble SDM fitting, validation, model selection, performance and uncertainty estimates follow the same methodology as the 2023 EFH 5-year Review. Below, we summarize the process. However, please refer to the 2023 EFH Review Component 1 Synthesis Report (Pirtle et al. 2025b) and regional NOAA Technical Memoranda (Bering Sea- Lamen et al. 2022, Aleutian Islands - Harris et al. 2022, and Gulf of Alaska - Pirtle et al. 2023) for the most comprehensive descriptions.

Following the process of the 2023 EFH 5-year Review (Pirtle et al. 2025b), we will model numerical abundance using five different SDMs: a maximum entropy model (MaxEnt), a presence-absence GAM (paGAM), a hurdle GAM (hGAM), and two forms of standard gam using the Poisson distribution (GAM_P) and the negative binomial distribution (GAM_{nb}) and predict onto raster surfaces of covariates. For a full description of each model used, please refer to the regional NOAA Technical Memoranda (Bering Sea- Laman et al. 2022, Aleutian Islands - Harris et al. 2022, and Gulf of Alaska - Pirtle et al. 2023). Briefly, the hGAM, GAM_P, and GAM_{nb} each use a log-link and effort offset to estimate the abundance directly. The MaxEnt and paGAM use presence or presence-absence data to estimate probabilities of occurrence (Phillips et al. 2006, Wood 2017) and will use the complementary log-log (cloglog) link function allows us to approximate abundance from the estimated probabilities (Fithian et al. 2015). Transforming these native model outputs (probability) into approximate numerical abundance yields predictions in the same units as the response variables from the other three SDMs, which facilitated skill testing and model comparison while meeting the requirements to qualify predictions as EFH Level 2, habitat-related density or abundance. Because some models (notably MaxEnt) produce results on different scales, a scaling factor will also be calculated for each model by dividing the mean of the observed abundance by the mean of the model predictions. This ensures that predictions from all models are directly comparable and can be used to construct a weighted ensemble.

2.4.1 Model validation, model selection/skill/performance and uncertainty estimates

2.4.1.1 Cross validation and skill testing

Based on the method of the 2023 EFH 5-year Review, we will validate each SDM using a 10-fold cross-validation process, partitioning data into 90% training and 10% testing sets to calculate the Root Mean Square Error (RMSE) as a measure of prediction accuracy and is calculated as:

$$RMSE = \sqrt{\frac{\sum_{k=1}^{10}\sum_{i=1}^{n_k}(y_{ki}-x_{ki})^2}{\sum_{k=1}^{10} n_k}}, \quad (2)$$

where y_{ki} is the predicted numerical abundance in cross-validation fold k, x_{ki} is the observed numerical abundance at trawl station i in cross-validation fold k, and n_k is the number of stations sampled in the kth fold. This metric is utilized to construct an ensemble in which constituent models will be weighted based on their inverse squared RMSE following the formula,

$$w_i = \frac{RMSE_i^{-2}}{\sum_{i=l}^{m} RMSE_i^{-2}}, \quad (3)$$

where w_i is the weight for model *i*, $RMSE_i$ is the cross-validated RMSE for model *i*, and *m* is the number of constituent models. To ensure robustness, this methodology will employ strict filtering criteria: models will be discarded if they received less than 10% relative weight or if they predict unrealistic abundances exceeding 10 times the maximum observed survey value, particularly to prevent errors in data-sparse regions. The final retained models will be combined to generate abundance maps for the Essential Fish Habitat (EFH) area. For a more comprehensive description regarding the cross validation and skill please refer to the EFH 2023 synthesis report (Pirtle et al. 2025b).

2.4.1.2 Ensemble model and Uncertainty

We employ ensemble modeling to generate robust habitat-related abundance predictions (Aruajo and New 2007) for settled early juvenile, subadult, and adult life stages, a method selected to minimize bias, better estimate uncertainty, and reduce sensitivity to minor data fluctuations. To build the ensemble, we first optimize individual constituent models—specifically MaxEnt, paGAM, hGAM, and standard GAMs. This optimization involves testing various regularization multipliers for MaxEnt, while GAMs undergo backwards stepwise term elimination; standard GAMs are further refined by comparing Poisson and negative binomial error distributions to select the one that best characterized the data based on RMSE skill testing. These optimized models are then precision-weighted using the inverse of their cross-validated RMSE (normalized to sum to one), and the final ensemble prediction is calculated as the sum of these weighted constituent predictions. The result of this exercise is a final ensemble for each species’ subadult and adult life stage that predicts habitat-related abundance.

To assess uncertainty, we will generate variance estimates across the 10 cross-validation folds for each constituent model at every location. After repeating this process for all constituent models in the ensemble, we adapted the following equation from Burnham and Anderson (2002), substituting our RMSE derived weights for their AIC weights: These individual variances are combined into an overall ensemble variance using a weighted formula adapted from Burnham and Anderson (2002).

$$SD_j(ensemble) = \sum_{i=1}^{m} w_i \, x \, \sqrt{var_{ij} + (y_j^* - y_{ij})^2} \quad (4)$$

where SDj is the standard deviation of the ensemble at location j, wi is the weight for model *i*, m is the number of constituent models, var_{ij} is the variance for model *i* at location *j*, is the ensemble abundance prediction at location *j*, and y_{ij} is the abundance prediction for model *i* at location *j*. Finally, a Coefficient of Variation (CV) is derived from the ensemble standard deviation.

$$CV_j = \frac{SD_j}{y_j^* + c} \quad (5)$$

where CV_j is the coefficient of variation at location *j*, SD_j is the ensemble standard deviation at location *j*, and y_j^* is the ensemble prediction at location *j*. Because the term y_j^* in the denominator can sometimes be close to zero, a small constant c, which was set at 1% of the max predicted abundance for that species and life stage, must be added to all abundance estimates when calculating the CV. We plan to spatially plot CV for each ensemble (example of EBS adult Pacific Cod far right plot in Figure 13) to represent spatial uncertainty.

2.4.1.3 SDM Performance Metrics

To evaluate model performance beyond RMSE, we will compute Spearman's rank correlation coefficient (ρ), the Area Under the Receiver-Operator-Characteristics Curve (AUC), and the Poisson Deviance Explained (PDE). Spearman's ρ measures the rank correlation between predicted and observed densities to distinguish high- from low-density areas and is preferred for non-normal count data (Best and Roberts 1975, Zar 1984, Legendre and Legendre 2012). The AUC assesses the model's ability to discriminate binary outcomes (presence vs. absence) with a minimum value of 0.5 (i.e., random 50/50 chance) and a maximum of 1. AUC values under 0.7 are generally considered poor, values between 0.7 and 0.9 are good, and values greater than 0.9 suggest excellent discrimination ability (Hosmer and Lemeshow 2005). The PDE quantifies the percent reduction in residual deviance compared to a null Poisson model. The deviance (*D*) and null deviance (*D_0*) are calculated using the following equations:

$$D = 2\sum_{i=1}^{n}\left[x_i ln\left(\frac{x_i}{exp(y_i)}\right) - (x_i - exp(y_i))\right], \quad (6)$$

$$D_0 = 2\sum_{i=1}^{n}\left[x_i ln\left(\frac{x_i}{exp(\underline{x})}\right) - \left(x_i - exp(\underline{x})\right)\right], \text{ and} \quad (7)$$

$$PDE = \frac{D}{D_0} \quad (8)$$

where x_i is the observed abundance, y_i is the predicted abundance, and $\underline{x}$ is the mean observed abundance.

Species Distribution Model Performance Metric Rubric:

ρ: < 0.20 (poor), 0.21–0.40 (fair), 0.41–0.60 (good), 0.61–0.99 (excellent)

AUC: < 0.70 (poor), 0.71–0.90 (good), 0.90–0.99 (excellent)

PDE: < 0.20 (poor), 0.21–0.40 (fair), 0.41–0.60 (good), 0.61–0.99 (excellent)

2.4.2 Mapping Species Distributions

2.4.2.1 Habitat-related Abundance

The weighted ensemble predictions of habitat-related abundance will be used as the basis for deriving EFH as described in Sections 2.4.2.2 and 2.4.2.3 below. For each species and life stage, the habitat-related abundance will be reported along with its coefficient of variation (CV) between ensemble models and effects plots (example of EBS adult Pacific cod Figure 13). The effects plots show the relationships used in the models between each covariate and the species abundance while holding all other covariates constant, produced as a weighted sum of the exponentiated effects from all models in the ensemble.

2.4.2.2 Occupied Habitat

Occupied habitat will be calculated as the probability under a Poisson distribution of observing one or more fish given the ensemble-predicted abundance, allowing for a consistent scale across all SDMs used in the ensemble (Pirtle et al. 2025b; example of EBS adult Pacific Cod Figure 14). Under this assumption, the probability of encounter will be equal to one minus the likelihood of zero abundance, given the predicted abundance at that location (Pirtle et al. 2025b).

2.4.2.3 EFH Mapping - Level 2

The EFH maps will follow the methods of the 2023 EFH 5-year Review, producing four subareas at 95%, 75%, 50%, and 25% of the occupied habitat (Pirtle et al. 2025b; example of EBS adult Pacific Cod Figure 15). At 95% of the occupied habitat, this subarea meets the definition of EFH area in Alaska (NMFS 2005). Each of the lower quantiles describes a more focused partition of the total EFH area. The area containing 75% of the occupied habitat based on SDM predictions is referred to as the "principal EFH area." The area containing 50% of the occupied habitat is termed the "core EFH area," and is the area used in the fishing effects analysis (EFH Component 2). Finally, the areas containing the top 25% of the occupied area are referred to as "EFH hot spots". Mapping EFH by subareas helps demonstrate the heterogeneity of fish and crab distributions over available habitat within the larger area identified as EFH.

2.4.2.4 EFH Mapping - Level 3

For EFH information Level 3 (habitat-related vital rates) for our set of groundfish species', we will integrate temperature-dependent vital rates developed from field and laboratory studies with SDM predictions of the probability of suitable habitat. Temperature-dependent vital rates have been published or are in development for groundfish species in Alaska. A representative example that can be applied in this context is from Laurel et al. (2016), who described the temperature-dependent growth rate of early juvenile Pacific Cod as:

$$GR = y0 + a * T + b * T^2 - c * T^3, \quad (9)$$

$$GR = 0.2494 + 0.3216 * T + 0.0069 * T^2 - 0.0004 * T^3, \quad (10)$$

where GR is the growth rate expressed as the % change in body weight per day (% body weight per day), T is temperature in degrees Celsius, and y0, a, b, and c are estimated parameters. Species-specific vital rate formulations are detailed in each Results chapter where EFH Level 3 information will be generated (See example of EBS early juvenile Pacific Cod in Results Figure 16).

We will construct EFH Level 3 maps by first mapping the temperature-dependent vital rates used in the 2023 EFH 5-year Review (Pirtle et al. 2025b) across the survey study area, using the MOM6 NEP bottom temperature covariate raster as the temperature value in the rate equations.

Next, we plan to compute the product of the rate map and the SDM predicted probability of habitat map by multiplying the two rasters. The product map will then be transformed onto a relative scale ranging from zero to one, where zero indicates areas of low probability of suitable habitat and low habitat-related temperature-dependent growth potential, and one indicates areas of high probability of suitable habitat and high habitat-related temperature-dependent growth potential. The Level 3 maps will provide additional context when interpreting EFH Level 1 or Level 2 maps developed from the same SDMs.

2.5 Spatiotemporal Models (STMs)

During the 2023 EFH 5-year Review, the SSC recommended that the next EFH review consider EFH under both long-term average and temporally contrasting conditions (Pirtle et al. 2025a). Spatiotemporal models (STMs) will be developed to provide supplemental EFH maps of groundfish and crab habitat-related distribution and abundance through time, to improve understanding of EFH for these species under varying environmental conditions. The STMs will additionally provide more accurate forecasting of EFH to near-term conditions or exploring possible future scenarios. The STMs are proposed to be implemented using a GAMM within sdmTMB (Anderson et al. 2022, Kristensen et al. 2016). Numerical abundance will be specified with a Tweedie distribution and log link at spatial location s and time t as follows:

$$\log(\mu_{s_t}) = f_1(D_{s_t}) + f_n(X_{s_t}) + offset(\log(k)_{s_t}) + P_t \cdot \gamma_s + \omega_{s\_t} + \epsilon_{s\_t} \qquad (11)$$

$$Y_i \sim Tweedie(\mu_{s_t}, \emptyset, \psi) \qquad (12)$$

where fn represents a different smooth function for each covariate 'X' at spatial location s and time t, k is the bottom trawl effort in area swept (km^2), γs is a spatial varying coefficient for the cold pool extent P, ω is a spatiotemporal random field, and ϵ is the residual error. The models will also include a spatially varying effect to account for shifting species distributions through time, in response to cold pool extent (Thorson et al. 2019).

The sdmTMB framework uses the Stochastic Partial Differential Equation (SPDE) approach, which uses a triangulated spatial mesh, to handle spatial autocorrelation (Anderson et al. 2022). We will construct a single mesh per region (BS, GOA, AI) with a minimum edge length several times smaller than an estimated range for the study area, and an outer boundary at least as long as the estimated range to avoid edge effects (Figure 9). Spatial random effects will be implemented using the SPDE approximation (Lindgren et al. 2011) on the mesh, and spatiotemporal random effects implemented using an autoregressive model at an annual time slice (Thorson et al. 2019). All models will be fit by Restricted Maximum Likelihood (REML) using a thin plate regression basis spline constrained to seven knots.

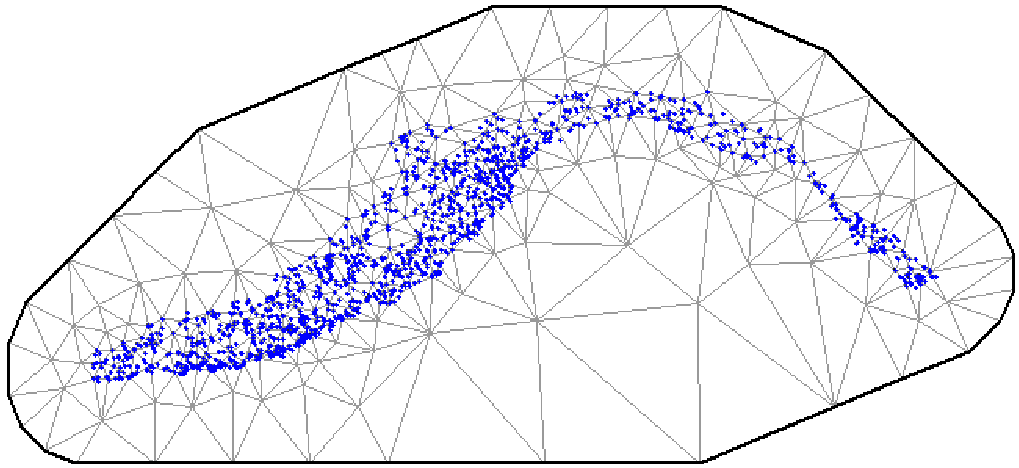

Figure 9. Example of mesh used by SPDE to estimate spatial autocorrelation between vertices for the Gulf of Alaska modeling extent.

For numerical stability, covariates will be scaled and centered (Anderson et al. 2022), and spatial units scaled to 100 km to promote model convergence. Although geostatistical models are recommended to run on equal-distance projections such as UTM (Anderson et al. 2022), each region extends multiple UTM zones, and we will project our data to the Alaska Albers Equal Area Conic projection to provide full coverage of our data points, which has been shown to have likely minimal impact on distance biases (Babcock et al. 2023). Each model will be tested with the sdmTMB “sanity” function to ensure successful convergence (Anderson et al. 2022).

Model validation and skill tests will follow the methods of the ensemble models described in Section 2.5 and in further detail in the 2023 EFH 5-year Review Component 1 Synthesis Report (Pirtle et al. 2025b).

3 Draft Results and Examples

3.1 Habitat Covariates by Region

In this section we display the full suite of covariates used to characterize Essential Fish Habitat (EFH) in our ensemble spatial distribution models (SDMs) across the three regions of Alaska Gulf of Alaska (GOA), Aleutian Islands (AI) and the eastern Bering Sea (EBS). The spatial extent of each region is standardized across the covariates and encompasses the spatial footprint of The Alaska Fisheries Science Center (AFSC) Resource Assessment and Conservation Engineering Division's Groundfish Assessment Program (RACE-GAP) summer bottom trawl survey grid. As the MOM6-NEP-derived bottom current and bottom current variability are still being updated, they are not included in the maps presented here but will be added as soon as they are completed. The remaining physical, biological, and oceanographic covariates are displayed for the GOA (Figure 10), AI (Figure 11), and EBS (Figure 12).

3.1.1 Gulf of Alaska Habitat Covariates

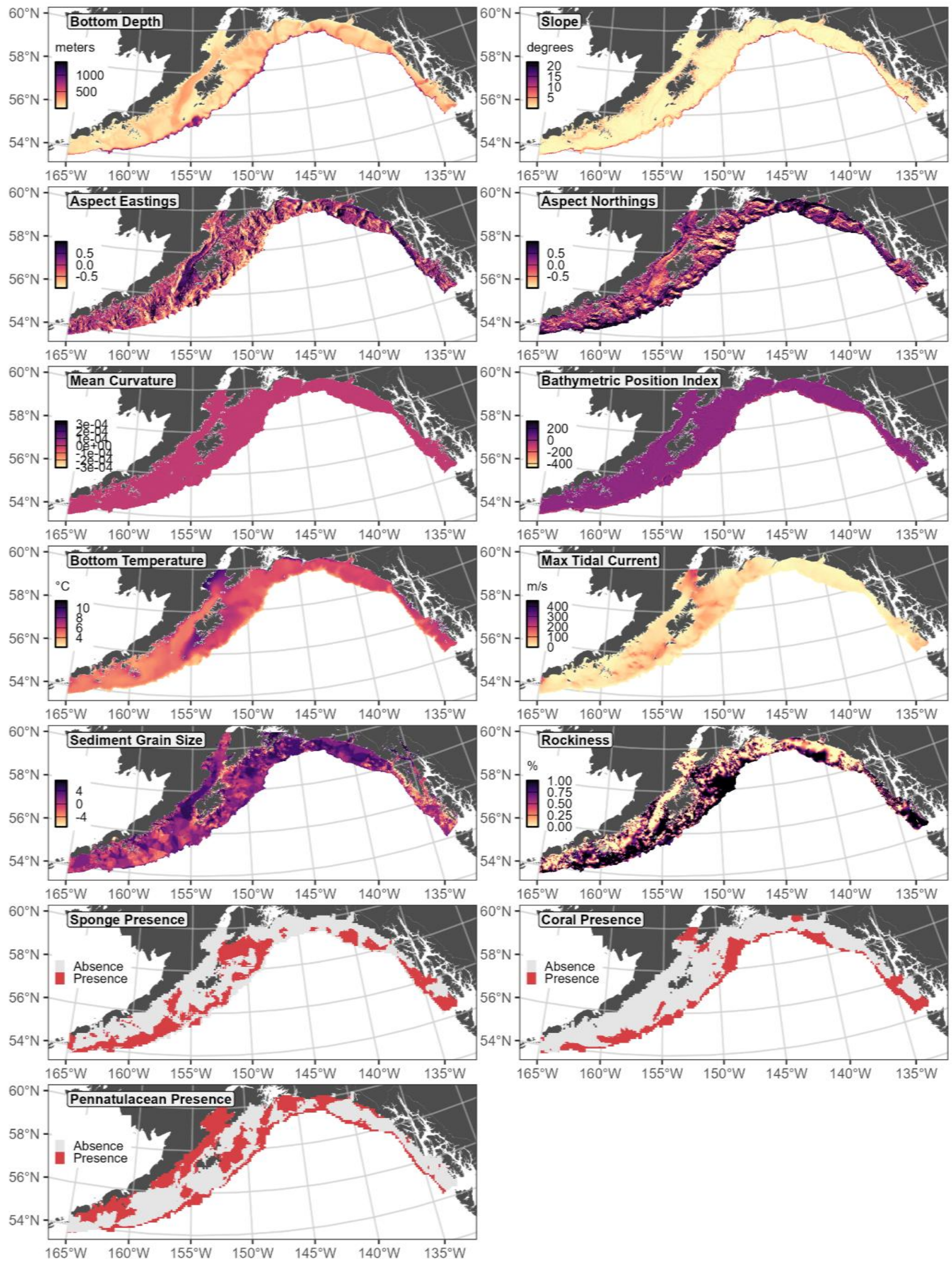

Figure 10. The suite of physical, biological, and oceanographic covariates used in the Gulf of Alaska (GOA) ensemble spatial distribution models (SDMs). Terrain and substrate characteristics include bottom depth (m), slope (degrees), aspect (as eastings and northings), curvature (mean), bathymetric position index (BPI), sediment grain size (*phi*), and rockiness (%). Oceanographic variables are represented by bottom temperature (°C) and maximum tidal current (m/s). The final three panels display the biological covariate as distributions for Sponge, Coral, and Pennatulacean taxa, where red areas indicate recorded presence and grey areas indicate absence.

3.1.2 Aleutian Islands Habitat Covariates

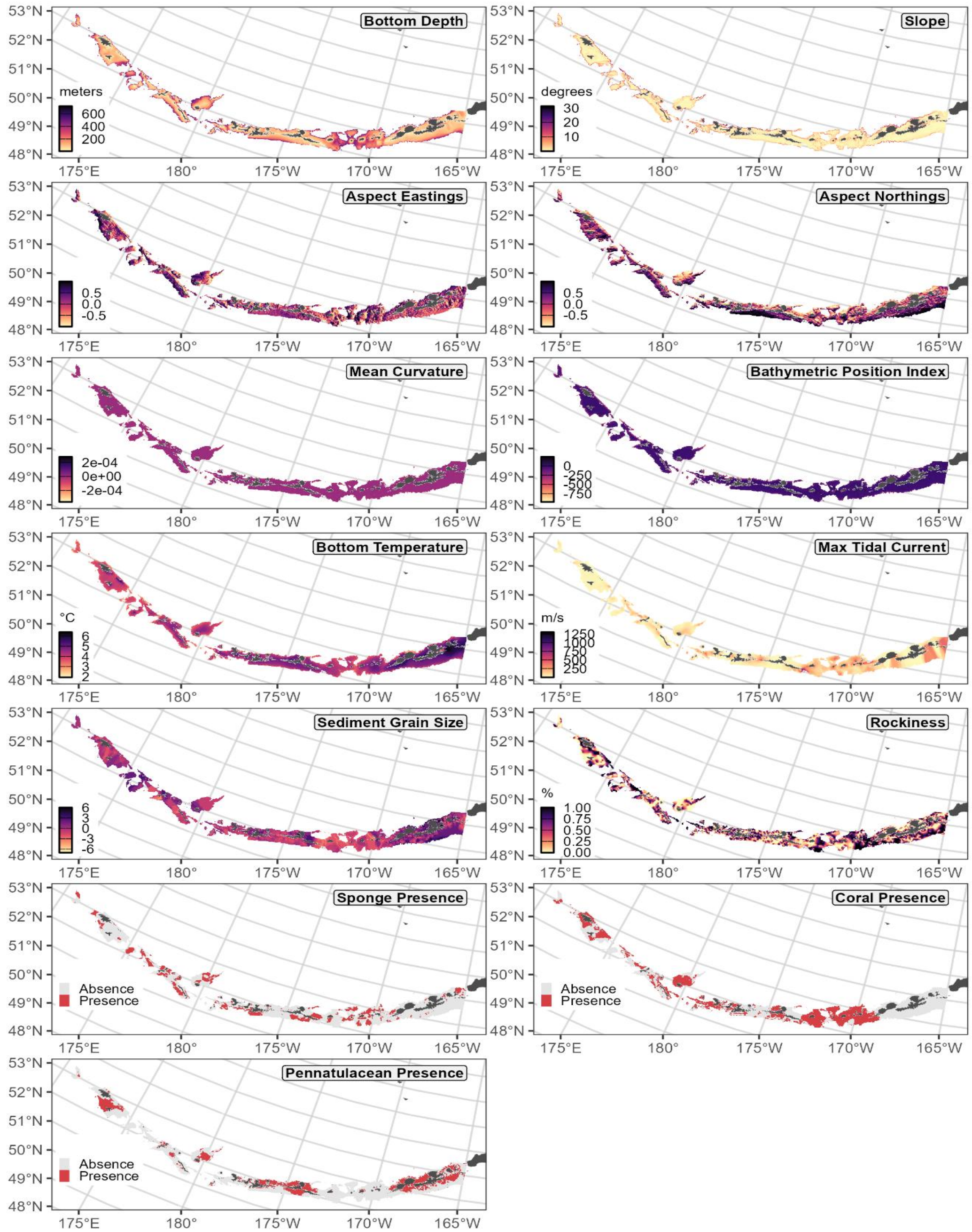

Figure 11. The suite of physical, biological, and oceanographic covariates used in the Aleutian Islands (AI) ensemble spatial distribution models (SDMs). Terrain and substrate characteristics include bottom depth (m), slope (degrees), aspect (as eastings and northings), curvature (mean), bathymetric position index (BPI), sediment grain size (*phi*), and rockiness (%). Oceanographic variables are represented by bottom temperature (℃) and maximum tidal current (m/s). The final three panels display the biological covariate as distributions for Sponge, Coral, and Pennatulacean taxa, where red areas indicate recorded presence and grey areas indicate absence.

3.1.3 Bering Sea Habitat Covariates

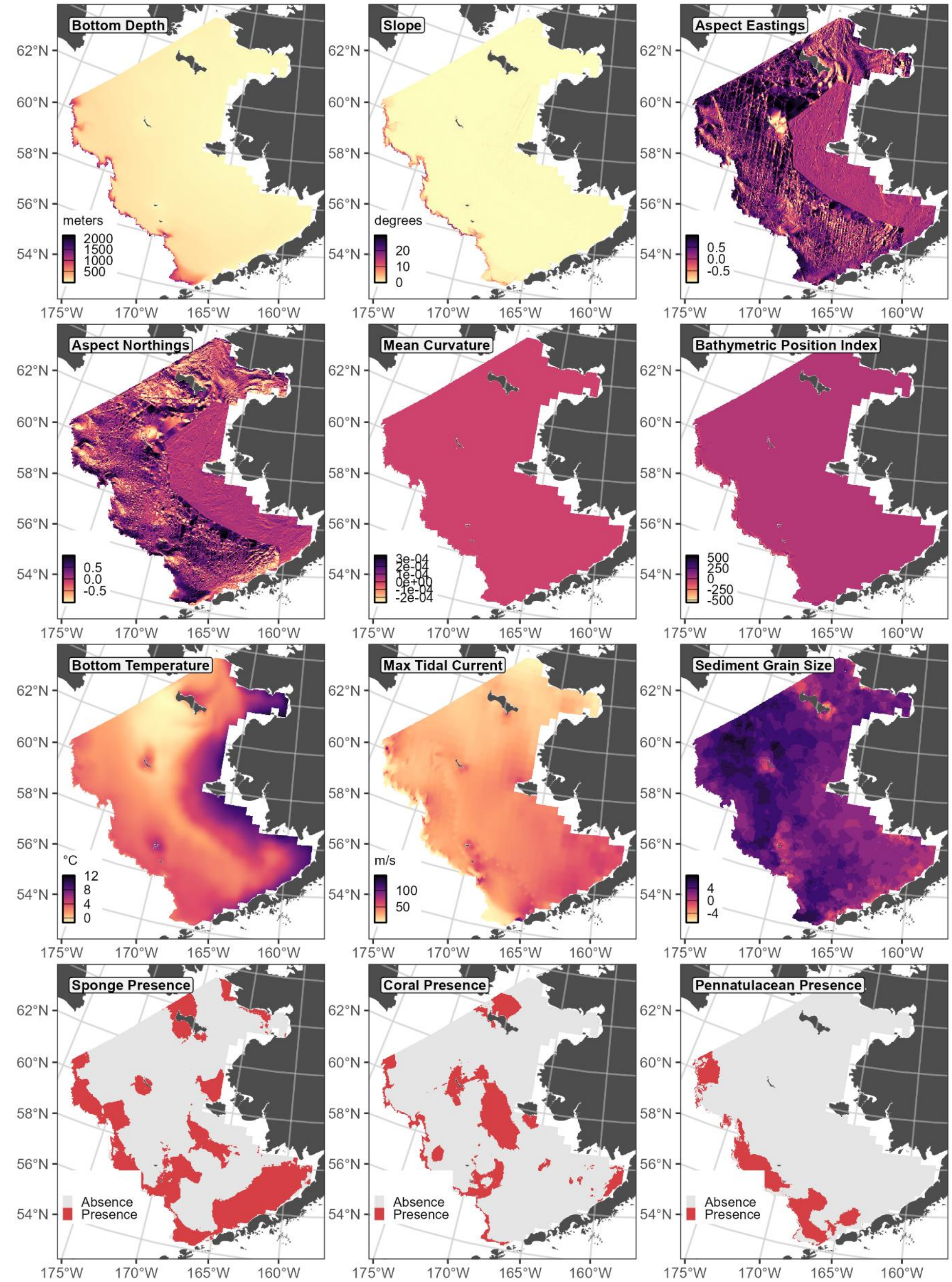

Figure 12. The suite of physical, biological, and oceanographic covariates used in the eastern Bering Sea (EBS) ensemble spatial distribution models (SDMs). Terrain and substrate characteristics include bottom depth (m), slope (degrees), aspect (as eastings and northings), curvature (mean), bathymetric position index (BPI), and sediment grain size (*phi*). Oceanographic variables are represented by bottom temperature (℃) and maximum tidal current (m/s). The final three panels display the biological covariate as distributions for Sponge, Coral, and Pennatulacean taxa, where red areas indicate recorded presence and grey areas indicate absence.

3.2 BSAI Pacific Cod Example

Once we have completed all covariate updates, we will use the methods from the 2023 EFH 5-year Review to update the ensemble SDMs with new covariates and the most recent survey data. However, to demonstrate how the results will be reported, the following results are an example from the 2023 EFH 5-year Review (Pirtle et al. 2025b).

3.2.1 Ensemble example (from 2023 EFH 5-year Review)

The habitat-based ensemble for adult Pacific cod in the eastern Bering Sea (EBS) was constructed using the weighted combination of five constituent SDMs. Covariate associations were derived, via partial effect plots, from the ensemble, identifying bottom depth, bottom temperature, and geographic position as the primary drivers of distribution (Figure 13, left panel). The partial effect plots indicate a strong preference for shelf habitats, with abundance dropping precipitously at depths exceeding the shelf break (>200 m). Temperature effects were unimodal, with peak habitat suitability occurring at bottom temperatures of approximately 3°C. Secondary drivers included tidal maximum and sediment grain size, refining the model's ability to predict local variations in density.

Ensemble-predicted numerical abundance (Figure 13, center panel) indicated that the highest densities of adult Pacific cod are concentrated over the outer shelf domain, extending from the Pribilof Canyon northward. Conversely, abundance was predicted to be low along the continental slope and the immediate nearshore inner shelf. The spatial uncertainty of these predictions, represented by the Coefficient of Variation (CV) (Figure 13, right panel), generally followed an inverse relationship with predicted abundance. The lowest CVs (indicating high model consensus) were observed across the broad continental shelf where adult Pacific cod are most abundant. Higher CVs were restricted to the shelf break and slope regions, as well as the inner shelf domain, reflecting greater uncertainty in these lower-density or data-sparse habitats. The probability of encounter for adult Pacific cod was high (>75%) across the vast majority of the EBS shelf (Figure 14). This distribution highlights the species' ubiquitous nature within the survey area, with low encounter probabilities limited almost exclusively to the deep continental slope waters (>200 m).

Reflecting the broad encounter probabilities, the EFH Level 2 map identifies an extensive area of suitable habitat (Figure 15). The highest habitat-related abundances, indicated by the EFH hotspot (yellow color) were identified in large, discontinuous patches across the middle and outer shelf. The core and principal EFH areas (green and blue colors) connect the hot spots, covering nearly the entire shelf from the Alaska Peninsula to the northern extent of the survey grid. Lastly, the full extent of EFH (dark purple) excludes only the deepest slope waters, aligning with the depth thresholds identified in the covariate analysis.

Application of Level 3 EFH models to settled early juvenile Pacific cod provided further insight into habitat quality beyond simple abundance. Temperature-dependent growth rate and lipid accumulation rate (LAR) models indicated that potential population growth is spatially distinct from pure abundance, potentially being higher in areas with historically warmer bottom temperatures. Specifically, these high-growth potential areas were identified over the inner shelf, extending from Nunivak Island northward into Norton Sound (Figure 16).

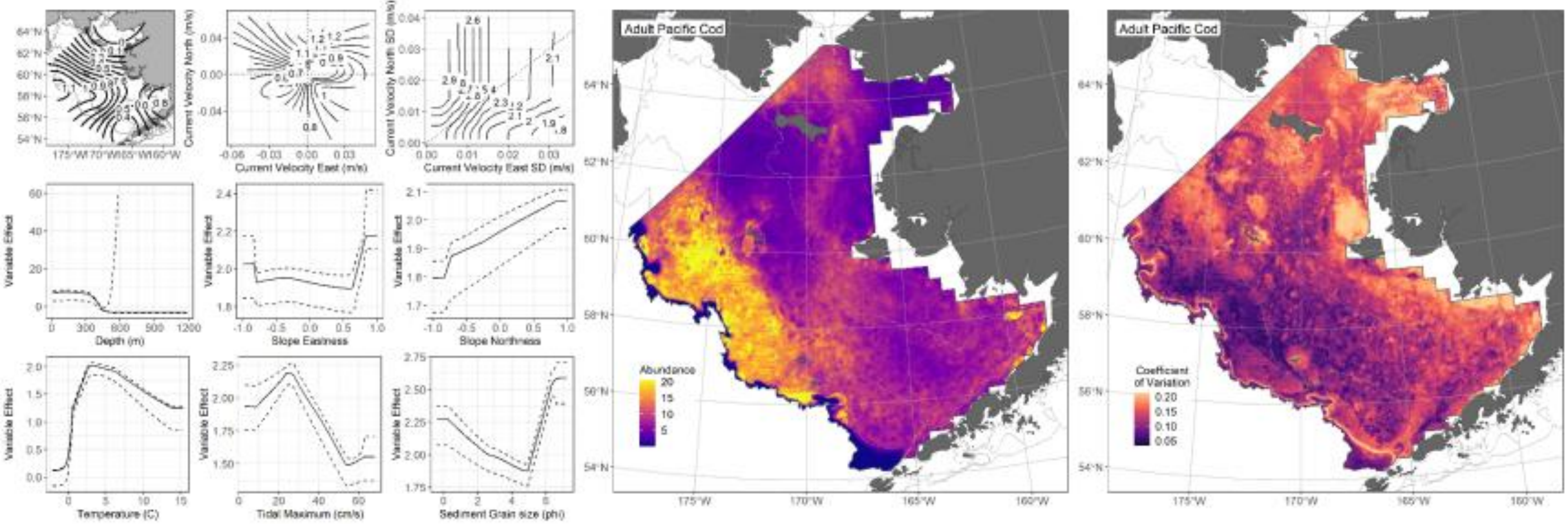

Figure 13. The top nine covariate effects (left panel) on ensemble-predicted adult Pacific cod numerical abundance across the eastern Bering Sea Shelf, Slope, and Northern Bering Sea (center panel) alongside the coefficient of variation (CV) of the ensemble predictions (right panel).

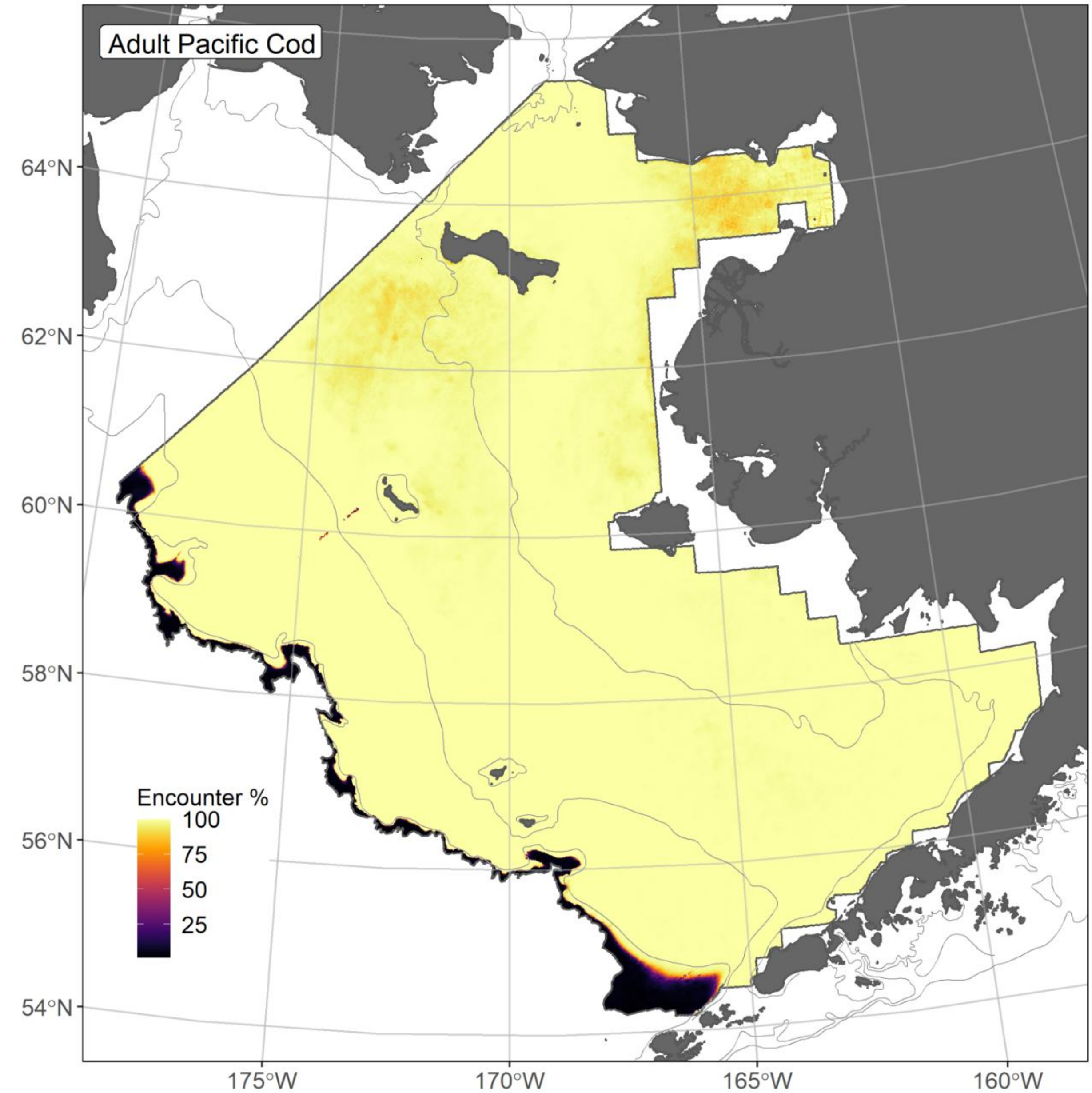

Figure 14. Encounter probability of adult Pacific cod from AFSC RACE-GAP summer bottom trawl surveys (1982–2019) of the eastern Bering Sea Shelf, Slope, and Northern Bering Sea with the 50 m, 100 m, and 200 m isobaths indicated.

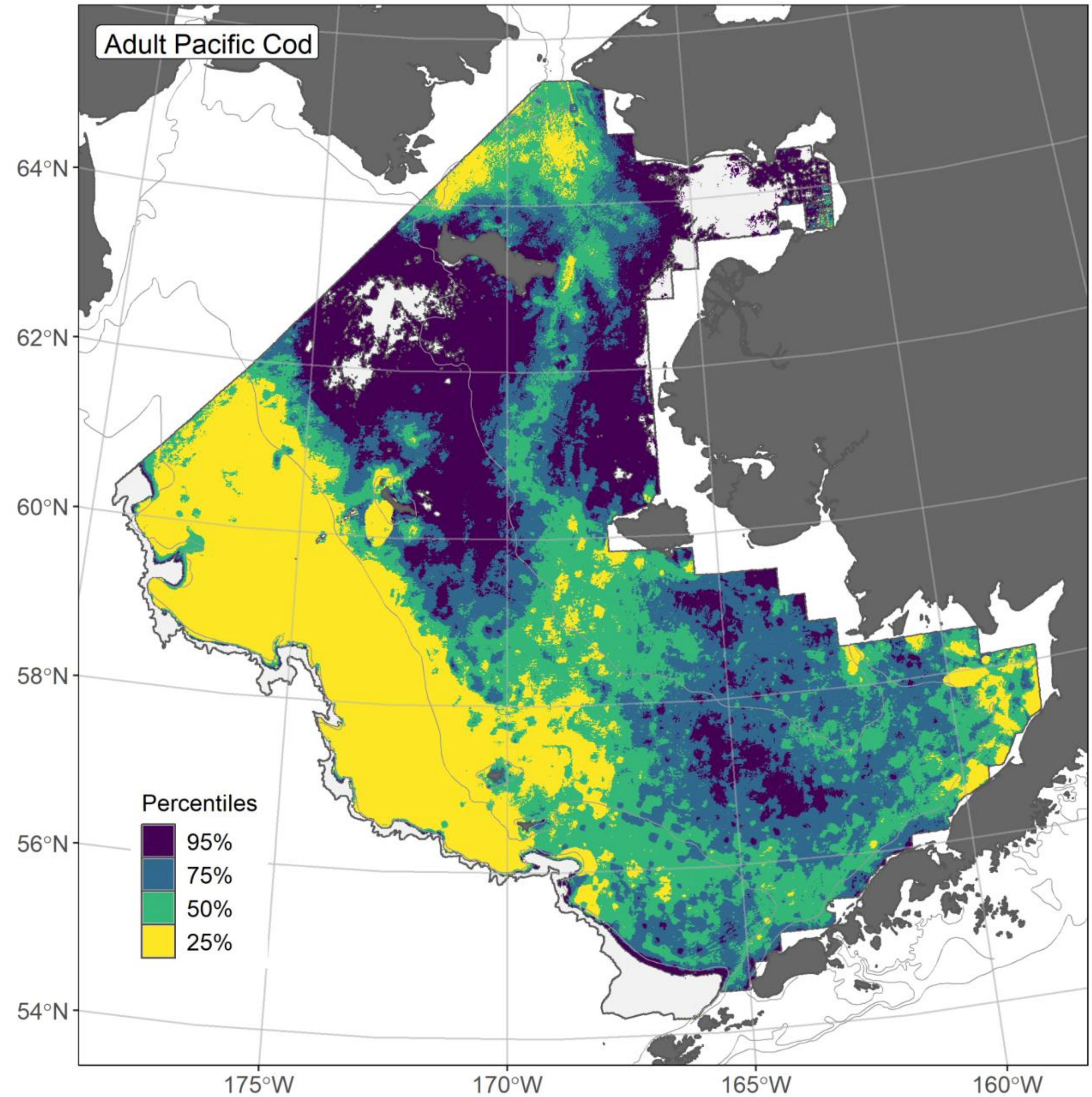

Figure 15. Essential fish habitat (EFH) is the area containing the top 95% of occupied habitat (defined as encounter probabilities greater than 5%) from a habitat-based ensemble fitted to adult Pacific cod distribution and abundance from AFSC RACE-GAP eastern Bering Sea (EBS) summer bottom trawl surveys (1982–2019) with 50 m, 100 m, and 200 m isobaths indicated; colors indicate the top 25% (EFH hot spots), top 50% (core EFH area), and top 75% (principal EFH area) of habitat-related, ensemble-predicted numerical abundance.

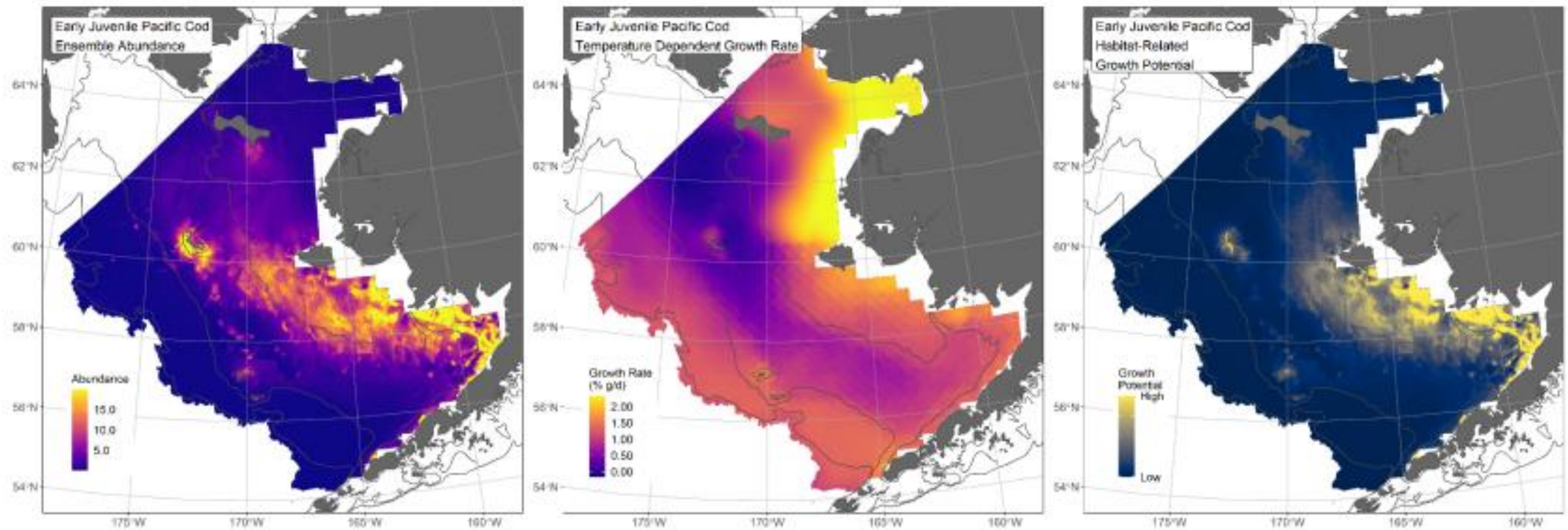

Figure 16. Settled early juvenile Pacific cod ensemble-predicted abundance from RACE-GAP summer bottom trawl surveys of the EBS (1982–2019; left panel), temperature-dependent growth rate (% body weight (g) per day; center panel), and abundance growth potential (right panel; this is the product of ensemble-predicted abundance raster and spatially-explicit, temperature-dependent growth rate raster).

3.2.2 STM example

We illustrate the spatiotemporal models (STMs) with an example of the draft predictions of EBS adult Pacific cod under varying temperature conditions (Figure 17). In this example, periods of cool (2012), average (2023), and warm (2019) are shown to address the SSC recommendation during the 2023 EFH 5-year Review that the next EFH review consider EFH under both long-term average and longer-term average temporally contrasting conditions (Pirtle et al. 2025a). This model was built using a simplified suite of dynamic covariates (bottom temperature, bottom currents, and cold pool extent) in addition to a static depth layer (Smith et al. *in review*). In this case, differences in core (top 50%) and hotspot (top 25%) areas of occupied habitat occur in areas such as around St. Matthew Island, the central EBS, and the southern shoreline along the Alaska Peninsula.

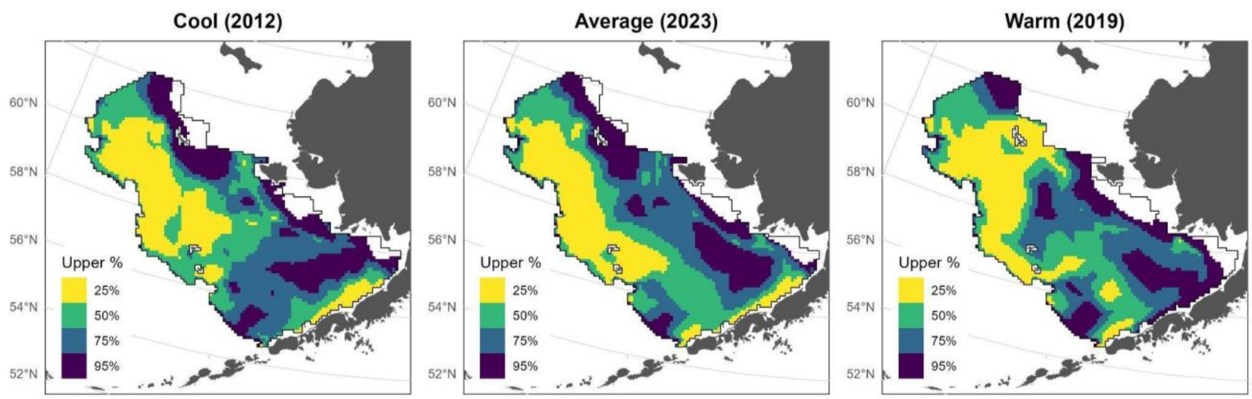

Figure 17. Essential fish habitat (EFH), the area containing the top 95% of occupied habitat (defined as encounter probabilities greater than 5%) of adult Pacific cod estimated under cool, average, and warm conditions modeled using spatiotemporal covariates of bottom temperature, bottom currents, and cold pool extent from AFSC RACE-GAP eastern Bering Sea (EBS) summer bottom trawl surveys (1982–2023); colors indicate the top 25% (EFH hot spots), top 50% (core EFH area), top 75% (principal EFH area) of habitat-related, and top 95% of occupied habitat.

4 References

Allouche, O., Tsoar, A., & Kadmon, R. (2006). Assessing the accuracy of species distribution models: prevalence-independence and the genuine alternative to AUC. Journal of Applied Ecology, 43(6), 1223-1232.

Boldt, J. L., Buckley, T. W., Rooper, C. N., and Aydin, K. 2012. Factors influencing cannibalism and abundance of walleye pollock (*Theragra chalcogramma*) on the eastern Bering Sea shelf, 1982-2006. Fish. Bull, 110.

Ciannelli, L., Fauchald, P., Chan, K. S., Agostini, V. N., and Dingsør, G. E. 2008. Spatial fisheries ecology: recent progress and future prospects. J. Mar. Sys, 71: 223–236.

Conrath, C., Malecha, P., Hoff, J., Goddard, P., Sadorus, L., Rooper, C., Waller, R., Rooney, S., Everett, M., Larson, W., and Olson, J. 2025. Deep Sea Coral Research and Technology Program: Alaska Coral and Sponge Initiative 2020-2024 Final Report. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-501, 79 p. https://repository.library.noaa.gov/view/noaa/71207

Cochran, W.G. 1977. Sampling Techniques. 3rd ed. Wiley Series in Probability and Mathematical Statistics - Applied. John Wiley & Sons. N.Y., NY 428 p.

Conner, J., Nichol, D.G., and R.R. Lauth. 2017. Results of the 2015 eastern Bering Sea continental shelf bottom trawl survey of groundfish and invertebrate resources. U.S. Dep. Commer., NOAA Tech. Memo. NMFS AFSC-353, 154 p.

Copeman, L.A., Laurel, B.J., Spencer, M., and Sremba, A. 2017. Temperature impacts on lipid allocation among juvenile gadid species at the Pacific Arctic-Boreal interface: an experimental laboratory approach. Mar. Ecol. Prog. Ser, 566: 183–198. https://www.jstor.org/stable/24898305

Copeman, L.A., Ottmar, M., Ryer, C., and Kristiansen, T. *In preparation.* Temperature-dependent survival and growth of early juvenile Bering Sea snow crab (*Chionoecetes opilio*) and Tanner crab (*Chionoecetes bairdi*): implications for optimal crab thermal habitat in a rapidly warming Bering Sea.

Drenkard, E. J., Stock, C. A., Ross, A. C., Teng, Y.-C., Cordero, T., Cheng, W., Adcroft, A., Curchitser, E., Dussin, R., Hallberg, R., Hauri, C., Hedstrom, K., Hermann, A., Jacox, M. G., Kearney, K. A., Pagès, R., Pilcher, D. J., Pozo Buil, M., Seelanki, V., and Zadeh, N. 2025. A regional physical–biogeochemical ocean model for marine resource applications in the Northeast Pacific (MOM6-COBALT-NEP10k v1.0), Geosci. Model Dev., 18, 5245–5290. https://doi.org/10.5194/gmd-18-5245-2025

Egbert, G. D., and Erofeeva, S. Y. 2002. Efficient inverse Modeling of barotropic ocean tides. Journal of Atmospheric and Oceanic Technology, 19: 183–204. Amer Meteorological Soc, Boston.

ESRI, 2024. ArcGIS Pro 3.4.0.

GEBCO Bathymetric Compilation Group 2020, 2020. The GEBCO_2020 Grid – a continuous terrain model of the global oceans and land, British Oceanographic Data Centre, National

Oceanography Centre, NERC [data set], https://doi.org/10.5285/a29c5465-b138-234d-e053-6c86abc040b9

GEBCO Bathymetric Compilation Group 2024, 2024. The GEBCO_2024 Grid - a continuous terrain model of the global oceans and land. https://doi.org/10.5285/1c44ce99-0a0d-5f4f-e063-7086abc0ea0f

Gibson, G.A., Stockhausen, W.T., Shotwell, S.K., Deary, A.L., Pirtle, J.L., Coyle, K.O., *et al.* 2023. Can seamounts in the Gulf of Alaska be a spawning ground for sablefish settling in coastal nursery grounds? Fish. Res. 261: 106625. https://doi.org/10.1016/j.fishres.2023.106625

Golden, N. E., Reid, J. A., Zimmermann, M., Lowe, E. N., and Hansen, A. S. 2016. Digitized seafloor characterization data from the Gulf of Alaska: U.S. In Geological Survey. Santa Cruz, CA, USA. http://dx.doi.org/10.5066/F7CV4FT9

Goldstein, E.D., Pirtle, J.L., Duffy-Anderson, J.T., Stockhausen, W.T., Zimmermann, M., Wilson, M.T., Mordy, C.W., 2020. Eddy retention and seafloor terrain facilitate cross-shelf transport and delivery of fish larvae to suitable nursery habitats. Limnol. Oceanogr. 65, 2800–2818. https://doi.org/10.1002/lno.11553

Harris, J., Laman, E. A., Pirtle, J. L., Siple, M. C., Rooper, C. N., Hurst, T. P., and Conrath, C. L. 2022. Advancing Model-Based Essential Fish Habitat Descriptions for North Pacific Species in the Aleutian Islands. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-458, 406 p. https://doi.org/10.25923/ffnc-cg42

Harris, J., Pirtle, J. L., Laman, E. A., Siple, M. C., and Thorson, J. T. 2024. An ensemble approach to species distribution modelling reconciles systematic differences in estimates of habitat utilization and range area. J. Appl. Ecol. 61: 351–364. https://doi.org/10.1111/1365-2664.14559

Hart, L.K.G, Cunningham, C.J., Yasumiishi, E.M., Mueter, F.J., Thorson, J.T., Pirtle, J.L., and Dimond, J.A. 2025. Species distribution models estimate time-varying juvenile salmon distributions in the north- and southeastern Bering Sea. Can. J. Fish. Aquat. Sci. 82: 1–13. https://doi.org/10.1139/cjfas-2024-0137

Harvey, C.J., deReynier, Y.L., Morrison, W.E., Cudney, J.L., Dick, D.D., Ford, T., *et al*. 2025. The U.S. Ecosystem-Based Fisheries Management Policy and Road Map: Assessing progress and applying lessons learned. Fish. Fish. 26(5): 957–974. https://doi.org/10.1111/faf.70012

Hijmans, R.J., 2024. terra: spatial data analysis. R package version 1.7-83.

Hoff, G.R. 2016. Results of the 2016 eastern Bering Sea upper continental slope survey of groundfish and invertebrate resources. U.S. Dep. Commer., NOAA Tech. Memo. NMFS AFSC-339, 272 p. Holsman, K.K., and K. Aydin. 2015. Comparative methods for evaluating climate change impacts on the foraging ecology of Alaskan groundfish. Mar. Ecol. Prog. Ser. 521: 217-235.

Horn, B.K.P., 1981. Hill shading and the reflectance map. Proc. IEEE 69, 14–47. https://doi.org/10.1109/PROC.1981.11918

Ilich, A.R., Misiuk, B., Lecours, V., Murawski, S.A., 2023. MultiscaleDTM: An open-source R package for multiscale geomorphometric analysis. Trans. GIS 27, 1164–1204. https://doi.org/10.1111/tgis.13067

Jenkins, C. J., McConnaughey, R. A., and Intelmann, S. S. 2025. Documentation for multi-parameter characterization of seafloor substrates in the U.S. EEZ off Alaska. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-AFSC-495, 64 p

Laman, E.A., Pirtle, J.L., Harris, J., Siple, M.C., Rooper, C.N., Hurst, T.P., and Conrath, C.L. 2022. Advancing Model-Based Essential Fish Habitat Descriptions for North Pacific Species in the Bering Sea. U.S. Department of Commerce, NOAA Tech. Memo. NMFS-AFSC-459, 538 p. https://doi.org/10.25923/y5gc-nk42

Laman, E. A., Rooper, C. N., Turner, K., Rooney, S., Cooper, D. W., and Zimmermann, M. 2018. Using species distribution models to describe essential fish habitat in Alaska. Can. J. Fish. Aquat. Sci. https://doi.org/10.1139/cjfas-2017-0181

Laman, E.A., Rooper, C.N., Rooney, S., Turner, K., Cooper, D., and Zimmerman, M. 2017. Model-based Essential Fish Habitat Definitions for Eastern Bering Sea Groundfish Species. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-357, 265 p.

Laurel, B.J., Spencer, M., Iseri, P., and Copeman, L.A. 2016. Temperature-dependent growth and behavior of juvenile Arctic cod (*Boreogadus saida*) and co-occurring North Pacific gadids. Polar Biology, 39: 1127-1135. https://doi.org/10.1007/s00300-015-1761-5

Lauth, R. R. 2011. Results of the 2010 eastern and northern Bering Sea continental shelf bottom trawl survey of groundfish and invertebrate fauna. U.S. Dep. Commer., NOAA Tech. Memo. NMFS AFSC-227, 256 p.

Limpinsel, D., S. McDermott, C. Felkley, E. Ammann, S. Coxe, G. A. Harrington, S. Kelly, J. L. Pirtle, L. Shaw, and M. Zaleski. 2023. Impacts to Essential Fish Habitat from Non-Fishing Activities in Alaska: EFH 5-year review from 2018-2023. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-F/AKR-30, 226 p. https://doi.org/10.25923/9z4h-n860

Lundblad, E.R., Wright, D.J., Miller, J., Larkin, E.M., Rinehart, R., Naar, D.F., Donahue, B.T., Anderson, S.M., Battista, T., 2006. A benthic terrain classification scheme for American Samoa. Mar. Geod. 29, 89–111. https://doi.org/10.1080/01490410600738021

Marsh, J., Pirtle, J.L., Mueter, F.J., and Harris, J. 2023. Model-Based Essential Fish Habitat Descriptions for Fish Resources of the Arctic Management Area. 86 pgs. NPFMC February 2023 meeting, C4 EFH. https://meetings.npfmc.org/Meeting/Details/2975

National Marine Fisheries Service (NMFS). 2005. Final Environmental Impact Statement for Essential Fish Habitat Identification and Conservation in Alaska. March 2005. https://repository.library.noaa.gov/view/noaa/17391; https://repository.library.noaa.gov/view/noaa/17392

NMFS. 2005. Final Environmental Impact Statement for Essential Fish Habitat Identification and Conservation in Alaska. https://repository.library.noaa.gov/view/noaa/17391

NMFS. 2012. Final Environmental Assessment for Essential Fish Habitat (EFH) Omnibus Amendments, October 2012. https://repository.library.noaa.gov/view/noaa/17389

NMFS. 2024. Final Environmental Assessment for Essential Fish Habitat Omnibus Amendments: July 2024. National Marine Fisheries Service, Alaska Region, 62 p. https://www.fisheries.noaa.gov/s3//2024-07/Final-EFH-EA-Omnibus-Amendment-2024.pdf

Orr, J.W., Matarese, A.C., 2000. Revision of the genus *Lepidopsetta* Gill, 1862 (Teleostei: Pleuronectidae) based on larval and adult morphology, with a description of a new species from the North Pacific Ocean and Bering Sea. Fish. Bull. 98, 539–582.

Oyafso, Z.S., L.A.K. Barnett, M.C. Siple, and S. Kotwiki. 2022. A flexible approach to optimizing the Gulf of Alaska groundfish bottom trawl survey design for abundance estimation. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-434, 142 p.

Pirtle, J.L., Shotwell, S.K., Zimmermann, M., Reid, J.A., Golden, N., 2019. Habitat suitability models for groundfish in the Gulf of Alaska. Deep. Res. Part II Top. Stud. Oceanogr. 165, 303–321. https://doi.org/10.1016/j.dsr2.2017.12.005

Pirtle, J.L., Laman, E.A., Harris, J., Siple, M.C., Rooper, C.N., Hurst, T.P., Conrath, C.L., *et al.* 2023. Advancing model-based essential fish habitat descriptions for North Pacific species in the Gulf of Alaska. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-468, 541 p. https://doi.org/10.25923/ygdf-5f65

Pirtle, J.L., Thorson, J.T., Bayer, S.R., Hurst, T.P., Matta, M.E., and Siple, M.C. 2024. Alaska Essential Fish Habitat Research Plan: A Research Plan for the National Marine Fisheries Service's Alaska Fisheries Science Center and Alaska Regional Office. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-F/AKR-33, 17 p. https://doi.org/10.25923/sf79-ym32

Pirtle, J.L., Harrington, G.A., Zaleski, M., Felkley, C., Gardiner, S., and Thorson, J. T. 2025a. Essential Fish Habitat 5-year Review Final Summary Report: North Pacific 2023 Essential Fish Habitat 5-year Review. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-F/AKR-31, 134 p. https://doi.org/10.25923/ve1v-ns96

Pirtle, J.L., Laman, E.A., Harris, J., Siple, M.C., Rooper, C.N., Hurst, T.P., Conrath, C.L., *et al*. 2025b. Synthesis Report: Advancing Model-Based Essential Fish Habitat Descriptions and Maps for North Pacific Species. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-F/AKR-28, 314 p. https://doi.org/10.25923/jvpx-ck45

Politou, C. Y., Tserpes, G., and Dokos, J. 2008. Identification of deepwater pink shrimp abundance distribution patterns and nursery grounds in the eastern Mediterranean by means of generalized additive modeling. Hydrobiol, 612: 99–107.

Prescott, M.M., Zimmermann, M., 2015. Smooth sheet bathymetry of Norton Sound. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-298. 23. https://doi.org/10.7289/V5V69GJ9

Richwine, K. A., Smith, K. R., and McConnaughey, R. A. 2018. Surficial sediments of the eastern Bering Sea continental shelf: EBSSED-2 database documentation. U.S.

Rooney, S.C., Rooper, C.N., Laman, E.A., Turner, K.A., Cooper, D.W., and Zimmermann, M. 2018. Model-based essential fish habitat definitions for Gulf of Alaska groundfish species. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-373, 370 p.

Rooper, C.N., Sigler, M.F., Goddard, P., Malecha, P., Towler, R., Williams, K., Wilborn, R., and Zimmermann, M. 2016. Validation and improvement of species distribution models for structure forming invertebrates in the eastern Bering Sea with an independent survey. Mar. Ecol. Prog. Ser. 551: 117-130. doi: 10.3354/meps11703

Rooper, C. N., Ortiz, I., Hermann, A. J., Laman, N., Cheng, W., Kearney, K., and Aydin, K. 2021. Predicted shifts of groundfish distribution in the eastern Bering Sea under climate change, with implications for fish populations and fisheries management. ICES J. Mar. Sci, fsaa215.

Ryznar, E.R., and Litzow, M.A. 2024. Predicting the distribution of red king crab bycatch in Bering Sea flatfish trawl fisheries. Fish. Res. 279: 107158. https://doi.org/10.1016/j.fishres.2024.107158

Ryznar, E.R., and Litzow, M.A. *In revision*. Fisheries-dependent model of Bering Sea red king crab distribution in the data-poor season. Submitted to Can. J. Fish. Aquat. Sci.

Shotwell, S.K., J.L. Pirtle, J.T. Watson, A.L. Deary, M.J. Doyle, S.J. Barbeaux, *et al*. 2022. Synthesizing integrated ecosystem research to create informed stock-specific indicators for next generation stock assessments. Deep-Sea Res. II, GOA SI IV. https://doi.org/10.1016/j.dsr2.2022.105070

Siddeek, MSM, J Zheng, C Siddon, B Daly, MJ Westphal, L Hulbert, and T Jackson. 2022. Aleutian Islands golden king crab stock assessment. North Pacific Fishery Management Council, Anchorage, Alaska.

Sigler, M.F., Eagleton, M.P., Helser, T.E., Olson, J.V., Pirtle, J.L., Rooper, C.N., *et al.* 2017. Alaska Essential Fish Habitat Research Plan: A Research Plan for the National Marine Fisheries Service's Alaska Fisheries Science Center and Alaska Regional Office. AFSC Processed Rep. 2015-05, 22 p. https://repository.library.noaa.gov/view/noaa/14191

Simpson, S.C., Eagleton, M.P., Olson, J.V., Harrington, G.A., and Kelly, S.R. 2017. Final Essential Fish Habitat (EFH) 5-year Review, Summary Report: 2010 through 2015. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-F/AKR-15, 115 p.

Smeltz, T.S., Harris, B.P., Olson, J.V., and Sethi, S.A. 2019. A seascape-scale habitat model to support management of fishing impacts on benthic ecosystems. Can. J. Fish. Aquat. Sci. 76(10): 1836–1844. https://doi.org/10.1139/cjfas-2018-0243

Smith, M., Yeager, M.E., Pirtle J.L., Barnes, C.L., and Thorson, J.T. *In preparation*. Effects of temporal resolution in forecasting species distributions under varying conditions.

Smith, K. R., and R. A. McConnaughey. 1999. Surficial sediments of the eastern Bering Sea continental shelf: EBSSED database documentation. U.S. Dep. Commer., NOAA Tech. Memo. NMFS AFSC-104, 41 p.

Stauffer, G. 2004. NOAA protocols for groundfish bottom trawl surveys of the Nation's fishery resources. U. S. Dep. Commer., NOAA Tech. Memo. NMFS-F/SPO-65, 205 p.

Stevenson, D. E., and G. R. Hoff. 2009. Species identification confidence in the eastern Bering Sea shelf survey (1982-2008). AFSC Processed Rep. 2009-04, 46 p. Alaska Fish. Sci. Cent., NOAA, Natl. Mar. Fish. Serv., 7600 Sand Point Way NE, Seattle, WA 98115.

Thorson, J.T., 2019. Measuring the impact of oceanographic indices on species distribution shifts: the spatially varying effect of cold-pool extent in the eastern Bering Sea. Limnology and Oceanography, 64(6), pp.2632-2645.

Turner, K.A., Rooper, C.N., Laman, E.A., Rooney, S.C., Cooper, D.W., *et al.* 2017. Model-based essential fish habitat definitions for Aleutian Islands groundfish species. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-360, 239 p.

von Szalay, P. G., and N. W. Raring. 2018. Data Report: 2017 Gulf of Alaska bottom trawl survey. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-374, 260 p.

Wakabayashi K., Bakkala R. G., Alton M. S.., Methods of the US–Japan demersal trawl surveys, International North Pacific Fisheries Commission Bulletin, 1985, vol. 44 (pg. 7-29)

Wilson, M.F.J., O’Connell, B., Brown, C., Guinan, J.C., Grehan, A.J., 2007. Multiscale terrain analysis of multibeam bathymetry data for habitat mapping on the continental slope, Marine Geodesy. https://doi.org/10.1080/01490410701295962

Yeager, M., Shotwell, S.K., Stockhausen, W.T., Gibson, G.A., and Pirtle, J.L. *In preparation*. Individual-based models inform fishery management pathways for two groundfish with contrasting early life history phenologies.

Zacher, L. S., Hennessey, S. M., Richar, J. I., Fedewa, E. J., Ryznar, E. R., and Litzow, M. A. 2024. The 2024 eastern Bering Sea continental shelf trawl survey: Results for commercial crab species. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-AFSC-491, 228 p. https://repository.library.noaa.gov/view/noaa/66166

Zaleski, M., Smeltz, T.S., Gardiner, S., Pirtle, J.L., and Harrington, G.A. 2024. 2022 Evaluation of Fishing Effects on Essential Fish Habitat. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-F/AKR-29, 205 p. https://doi.org/10.25923/c2gh-0w03

Zimmermann, M., Prescott, M.M., Rooper, C.N., 2013. Smooth Sheet Bathymetry of the Aleutian Islands. United States Dep. Commer. NOAA Tech. Memo. NMFS-AFSC-, 43.

Zimmermann, M., and Prescott, M. M. 2014. Smooth sheet bathymetry of Cook Inlet, Alaska.

Zimmermann, M., and Prescott, M. M. 2015. Smooth sheet bathymetry of the central Gulf of Alaska. NOAA Tech. Memo. NMFS-AFSC-287. 54 p.

Zimmermann, M., and Prescott, M. M. 2018. Bathymetry and Canyons of the Eastern Bering Sea Slope. Geosciences. 8: 184.

Zimmermann, M., Prescott, M. M., and Haeussler, P. J. 2019. Bathymetry and Geomorphology of Shelikof Strait and the Western Gulf of Alaska. Geosciences. 9: 409.

Zimmermann, M., Prescott, M.M., 2021. Passes of the Aleutian Islands: First detailed description. Fish. Oceanogr. 30, 280–299. https://doi.org/10.1111/fog.12519