Discussion Paper on the Assessment of the Effect of Fishing on Essential Fish Habitat in Alaska for the 2022 5-year Review

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1. Introduction 1
    1.1 Essential Fish Habitat Overview 1
    1.2 2005 Essential Fish Habitat Environmental Impact Statement 2
        1.2.1 Long-term Effects Index (LEI) model description 2
        1.2.2 Center for Independent Experts Review 3
        1.2.3 Assessment of the effects of fishing on EFH in Alaska 4
        1.2.4 Conclusions about the effects of fishing on EFH in 2005 4
    1.3 2010 Essential Fish Habitat 5-year Review 4
2 2017 Essential Fish Habitat 5-year Review 4
    2.1 Fishing Effects model description 5
    2.2 Fishing Effects model input parameters 8
        2.2.1 Fishing intensity 8
        2.2.2 Habitat categorization 9
        2.2.3 Susceptibility and recovery estimates 10
    2.3 Incorporation of longer recovery times into FE model 11
    2.4 Sensitivity analysis 12
    2.5 Assessment of the effects of fishing on EFH in Alaska 14
        2.5.1 Hierarchical impact assessment methods 14
    2.6 Conclusions about the effects of fishing on EFH in 2017 15
3 Updates to the FE model for 2022 16
    3.1 Fishing intensity 16
    3.2 Habitat categorization 17
    3.3 Susceptibility and recovery 17
    3.4 FE model code 18
    3.5 Updates to Gear table parameters 19
    3.6 Feature averaging 20
    3.7 Fishing Effects Model - New England Fishery Management Council 22
    3.8 FE as yearly indicator ESR 22
    3.9 Alaska Coral & Sponge Initiative projects 23

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3.9.1 Validation of Coral and Sponge Modeling in the GOA 24
3.9.2 Refine Estimates of Longline & Pot Gears.......... 24
3.9.3 Incorporate Coral and Sponge Covariates into FE model 25
3.9.4 Risk Assessment of Fishing on Corals and Sponges 25
3.9.5 Assessing the Effectiveness of Area Closures for DSCS Communities.......... 25
4 Stock Author Review of EFH FE Output for 2022.......... 26
4.1 Thresholds.......... 26
4.2 Example 2022 FE model output with 2017/2022 SDMs 27
4.2.1 Bering Sea Arrowtooth flounder.......... 28
4.2.2 Aleutian Islands Golden King Crab 29
4.2.3 Gulf of Alaska Pacific Cod 31
5 Reference table of responses to SSC requests 33
6 References.......... 35
Appendix 1 FE model description.......... 38
Appendix 2 Gear Parameter Table 44
Appendix 3 Susceptibility & Recovery Tables 49
Appendix 4 Incorporation of longer recovery time into FE model 53
Appendix 5 Applied Examples of the 2017 EFH Stock author review.......... 56
Example 1: Fishing impacts on pollock EFH in the Gulf of Alaska 56
Example 2: Fishing impacts on POP EFH in the Gulf of Alaska.......... 60
Appendix 6 Threshold discussion 64
SSC Review – October 2016.......... 64
Joint Groundfish Plan Team Review – September 2016.......... 65
Crab Plan Team Review – September 2016.......... 66
Appendix 7 Ecosystem Status Report FE Indicator 67

1. Introduction

The Magnuson-Stevens Fishery Conservation and Management (MSA) requires regional Fishery Management Councils to describe and identify Essential Fish Habitat (EFH) for all fishes managed under a Fishery Management Plan (FMP). Under Section 303(a)(7) of the MSA and 50 CFR 600.815(a)(2), every FMP must minimize, to the extent practicable, adverse effects of fishing on EFH. Fishery Management Councils must act to prevent, mitigate, or minimize any adverse effects from fishing to the extent practicable, if there is evidence that a fishing activity adversely affects EFH in a manner that is “more than minimal and not temporary in nature”. The North Pacific Fishery Management Council (Council) is currently evaluating updates to EFH in its FMPs, including revisions to the model-based descriptions of EFH for Bering Sea (BS), Aleutian Islands (AI), and Gulf of Alaska (GOA) groundfish and crab species, and updated output from the Fishing Effects (FE) model developed to assess the effects of fishing activities on EFH.

Chapter 1 of this discussion paper introduces the requirements for evaluating the effects of fishing activities on EFH and reviews the development of an initial numerical model used to estimate impacts to EFH from fishing activities in 2005 and 2010. Chapter 2 introduces the Fishing Effects model and methods developed to assess the impacts of fishing on managed stocks during the 2017 EFH 5-year review. Chapter 3 describes updates to the FE model for the 2022 EFH 5-year review, as well as responding to specific comments and suggestions from the Council since 2017. Chapter 4 provides a preliminary Fishing Effects analysis of three species, comparing the 2017 and 2022 FE output on the 2022 species distribution models. Chapter 5 provides a list of responses to specific SSC requests. Appendices 1-7 provide the mathematical derivation of the FE model, various input parameter tables, calculation of longer recovery times, two examples of stock author assessments from 2017, information related to choosing thresholds for stock author assessment, and FE output as used as a yearly ecosystem indicator.

1.1 Essential Fish Habitat Overview

The EFH regulations base the evaluation of the adverse effects of fishing on EFH on a ‘more than minimal and not temporary’ standard (50 CFR 600.815). Fishing operations change the abundance or availability of certain habitat features (e.g., prey availability or the presence of living or non-living habitat structure) used by managed fish species to accomplish spawning, breeding, feeding, and growth to maturity. These changes can reduce or alter the abundance, distribution, or productivity of that species, which in turn can affect the species’ ability to “support a sustainable fishery and the managed species’ contribution to a healthy ecosystem” (50 CFR 600.10). The outcome of this chain of effects depends on the characteristics of the fishing activities, the habitat, fish use of the habitat, and fish population dynamics. Conducting an analysis considering all relevant factors required the consolidation of information from a wide range of sources and fields of study to focus on the evaluation of the effects of fishing on EFH. Quantifying the effects of fishing on benthic habitats often requires best professional judgment due to the number of unknowns.

The National Research Council (NRC 2002) stated a complete assessment of the ecosystem effects of trawling and dredging requires three types of information: gear-specific effects on different habitat types (obtained experimentally); frequency and geographic distribution of bottom tows (trawl and dredge fishing effort data); and physical and biological characteristics of seafloor habitats in the fishing grounds (seafloor mapping). A complete assessment would synthesize available data and technical studies to describe the nature, severity, and distribution of risk to habitat features relevant to the marine fish population of Alaska. While some qualitative or quantitative information was available for each of these factors, it varied in quality, spatial coverage, and applicability.

The evaluation of the effect of fishing on EFH in the North Pacific has been implemented in four main steps that illustrate the increasing availability of information: an initial qualitative environmental assessment in 1999 EFH Environmental Assessment; the development of a numerical model for the EFH Environmental Impact Statement (EFH EIS) (NMFS 2005a,b); the 2010 EFH 5-year review using 2005 analysis methodology; and the development of an expanded numerical model for the 2017 review. Discussion of the 1999 qualitative approach to assessing the effects of fishing on EFH is not included here.

1.2 2005 Essential Fish Habitat Environmental Impact Statement

The duration and degree of fishing effects on habitat features depend on the intensity of fishing, the distribution of fishing with different gears across habitats, and the sensitivity and recovery rates of habitat features. While some information was available for all these factors during the EFH EIS analysis (NMFS 2005a), it varied in quality, spatial coverage, and applicability to Alaska fisheries. Moreover, in 2005, there was no accepted model or analysis for relating this information to the requirements of the EFH regulations. The Council developed an initial qualitative approach in early 2002 based on guidance from the MSA. It described the steps necessary to perform the evaluation (description of activity, evaluation of effects, identification of potential management actions, and evaluation of practicability), and combined regional statistics into a gear factor, a habitat recovery factor, and a percent coverage factor for each fishery. These factors were combined into two scores related to whether potential fishing effects are minimal or temporary. While this approach may have satisfied MSA requirements, it did not provide a quantitative assessment of fishing effects.

In mid-2002, scientists at the Alaska Fishery Science Center (AFSC) developed a numeric model as a tool to structure the relationships between available sources of information on the gear, habitat recovery, and percent coverage factors identified by the Council. This numeric model, the Long-term Effects Index (LEI), was considered a step forward from both the initial Council approach and the process described in NRC (2002) by adding recovery attributes to previously impacts-only approaches.

1.2.1 Long-term Effects Index (LEI) model description

The Long-term Effects Index model, described in Fujioka (2006), estimated the proportional reductions in habitat features relative to an unfished state, assuming that fishing would continue at current intensity and distribution until the alterations to habitat and the recovery of disturbed habitat reached equilibrium. The model provided a tool for bringing together all available information on the effects of fishing on habitats, such as fishing gear types used in Alaska fisheries (trawl, pot, hook-and-line), fishing intensity information from observer data, and gear impacts and recovery rates for different habitat types. Due to the uncertainty regarding some input parameters (e.g., recovery rates of different habitat types, spatial distribution of habitat types), the results of the model were displayed as point estimates, as well as a range of potential effects.

After considering the available tools and methodologies for assessing effects of fishing on habitat, NMFS, the Council, and the Council's Scientific and Statistical Committee (SSC) concluded that the model incorporates the best available scientific information and provided a reasonable approach to understand the impacts of fishing activities on habitat. An independent panel of outside experts also reviewed and supported the model.

1.2.2 Center for Independent Experts Review

In August 2002, a preliminary analysis based on the LEI model and applied on a 25 square kilometer (km^2) spatial scale was provided to aid the Council's EFH Committee in selecting potential alternative actions to minimize adverse effects of fishing. Improvements to that model were made based on input from participants in the Council process, scientists inside and outside of NMFS, and peer review by the Center for Independent Experts (CIE). NMFS contracted the CIE to provide an independent peer review of the technical aspects and assessment methodology used by NMFS to evaluate the effects of fishing on EFH in Alaska. Specifically, the reviewers focused on two broad issues: 1) the LEI model used to assess the impact of fishing on different habitat types, and 2) the analytical approach employed to evaluate the effects of fishing on EFH, particularly the use of stock abundance relative to the Minimum Stock Size Threshold (MSST) to assess the possible influence of habitat degradation on the productivity of fish stocks. The CIE panel chair's summary report includes many of the panel's comments, criticisms, and concerns and are embodied as a succinct set of short-term and long-term recommendations (Drinkwater 2004). The CIE panel report included the following findings:

- The model was well conceived and is useful in providing estimates of the possible effects of fishing on benthic habitat. However, as acknowledged in the DEIS, the parameters estimates are not well resolved and have high uncertainty due in large part to a paucity of data. Results must be viewed as rough estimates only.
- The use of stock status relative to the MSST to assess possible influence of habitat degradation on fish stocks is inappropriate. MSST is not a sufficiently responsive indicator and provides no spatial information about areas with potential adverse effects. Instead, the approach should include examination of time series indices such as size-at- age, population size structure, fecundity, gut fullness, spatial patterns in fish stocks relative to fishing effort, and the history of stock abundance.
- The analysis did not give adequate consideration to localized (versus population level) habitat impacts.

Following the CIE review, the AFSC published a response to numerous criticisms highlighted by the CIE, foremost being the use of MSST. NMFS scientists agreed that only considering stock abundance relative to MSST does not provide a sufficiently detailed analysis of the influence of habitat degradation on the productivity of fish stocks. They noted that the evaluations of habitat effects provided by stock assessment authors were not limited to an assessment of stock status relative to MSST. The evaluation considered a full set of more detailed information on stock status; information not thoroughly described and incorporated into the materials provided to the CIE reviewers.

1.2.3 Assessment of the effects of fishing on EFH in Alaska

In 2005, AFSC stock assessment authors were asked to assess whether the fisheries, as they are currently conducted off Alaska, affected habitat essential to the welfare of the species in question in a way that is more than minimal and not temporary. The information provided to authors for this analysis included: results of the LEI - effects of fishing analysis; literature and other sources of knowledge regarding what each species requires to accomplish spawning, breeding, feeding, and growth to maturity; species life cycle requirements; knowledge of the responses of the recruitment, biomass, and growth of these species during periods with similar fishing intensities; spatial and temporal length, weight, age, diet, and catch-per-unit-of-effort (CPUE) data from NMFS surveys; and professional judgement of scientists who manage and study these species. The standard for evaluation was whether the expected effect of fishing on the species' ability to support a sustainable fishery or its role in a healthy ecosystem is more than minimal. This complete analysis is available in Appendix B of the 2005 EFH EIS (NMFS 2005b)

1.2.4 Conclusions about the effects of fishing on EFH in 2005

Based on the best available scientific information, NMFS concluded that no Council-managed fishing activities had more than minimal and temporary adverse effects on EFH for any FMP species, which is the regulatory standard requiring action to minimize adverse effects under the MSA (50 CFR 600.815(a)(2)(ii)) (NMFS 2005a). The analysis found no indication that continued fishing activities at the current rate and intensity. These findings indicate that no additional actions are required according to the EFH regulations. However, as noted above, the analysis has many limitations and the effects of fishing on EFH for some managed species are unknown. The Council acknowledged that considerable scientific uncertainty remained regarding the consequences of habitat alteration for the sustained productivity of managed species. Consequently, the Council adopted a suite of precautionary management measures designed to reduce adverse effects to habitat, including expanded closures for bottom contact fishing gear in the Bering Sea, Aleutian Islands, and Gulf of Alaska.

1.3 2010 Essential Fish Habitat 5-year Review

NMFS reconsidered the effects of fishing on EFH in the 2010 EFH 5-year review (NPFMC 2010). NMFS examined and compared inputs to the LEI model used for the 2005 EFH EIS against new information available since 2005. This analysis identified only minor changes to the existing EFH descriptions, with none of the proposed changes requiring regulatory action. Fishing intensity had decreased overall, with moderate shifts causing increases or decreases in limited areas. Therefore, there were no substantial changes to the model inputs. The 2010 EFH 5-year review concluded that no change was warranted to the 2005 conclusions regarding fishing effects on EFH based on new information from the preceding five years (2005-2010). The 2005 impacts analysis was incorporated by reference, including the discussions of uncertainty that were fully disclosed and analyzed in that document.

2 2017 Essential Fish Habitat 5-year Review

The 2005 EFH EIS (NMFS 2005a) and 2010 EFH 5-year review (NPFMC 2010) included the application of a numerical model that provided spatial distributions of an index of the effects of fishing on several classes of habitat features, such as infauna prey and shelter created by living organisms. The Long-term Effect Index estimated the eventual proportional reduction of habitat features from a theoretical unaffected habitat state, should the recent pattern of fishing intensities be continued indefinitely. For the 2005 and 2010 analyses, the LEI generated habitat estimates representing a 5-year interval.

During the 2017 EFH 5-year review, the Council requested updates to methods used to assess the effects of fishing on EFH (FAST 2014). In response, the Fishing Effects (FE) model was developed to make input parameters more intuitive and to draw on the best available data. The FE model estimates benthic habitat disturbance from commercial fishing activities, especially as it occurs within Essential Fish Habitat. Like the LEI model, the FE model uses a 25km^2 grid cells throughout the BS, AI, and GOA. It is based on the interaction between the amount and spatial extent of fishing effort, types of fishing gear, habitat susceptibility to fishing gear, the rate at which habitat recovers, and information about the spatial extent of habitat types. The FE model updated the LEI model in the following ways:

- The FE model is cast in a discrete-time framework. Rates such as impact or recovery are defined over a specific time interval, compared to the LEI model that used continuous time. Using discrete time makes fishing impacts and habitat recovery more intuitive to interpret compared to continuous time.

- The FE model implements sub-annual (monthly) tracking of fishing impacts and habitat disturbance. This allows for queries of habitat disturbance for any month from the start of the model run (January 2003). While this was possible in the LEI model, the LEI model was developed primarily to estimate long-term equilibrium habitat disturbance given a constant rate of fishing and recovery. The FE model also allows for queries of habitat disturbance for any month in the time series. This aids in assessing the implications of variable fishing effort within a season and over years.

- The FE model draws on spatially explicit vessel monitoring system (VMS) data to determine fishing locations as line segments representing the locations of individual tows or other bottom contact fishing activities. This provides a more accurate allocation of fishing effort among grid cells. In comparison, the LEI model used haul-back locations summarized to the 25 km^2 grids to represent fishing activity. The description of fishing gears that may contact benthic habitat was also greatly improved with significant input from fishing industry representatives; the LEI model listed 4 gear types, whereas the FE model contains over 60 region/gear/target-specific categories.

- The FE model incorporates an extensive, global literature review and vulnerability assessment from Grabowski et al. (2014) to estimate habitat susceptibility and recovery dynamics. The FE model identifies 26 unique categories of habitat features and incorporates impact and recovery rates to predict habitat reduction and recovery over time.

2.1 Fishing Effects model description

The Fishing Effects model was conceptualized as an iterative model, tracking habitat transitions between disturbed and undisturbed states in monthly time steps within 5 km X 5 km (25km^2) grid cells across the North Pacific domain (Figure 1). The amount of undisturbed habitat in any given time step reflects the undisturbed habitat from the previous time step that remained undisturbed (not impacted by fishing activity) plus the disturbed habitat from the previous time that recovered. Conversely, the amount of disturbed habitat in any given time step reflects the undisturbed habitat from the previous time step that did not recover plus the undisturbed habitat that was impacted by fishing.

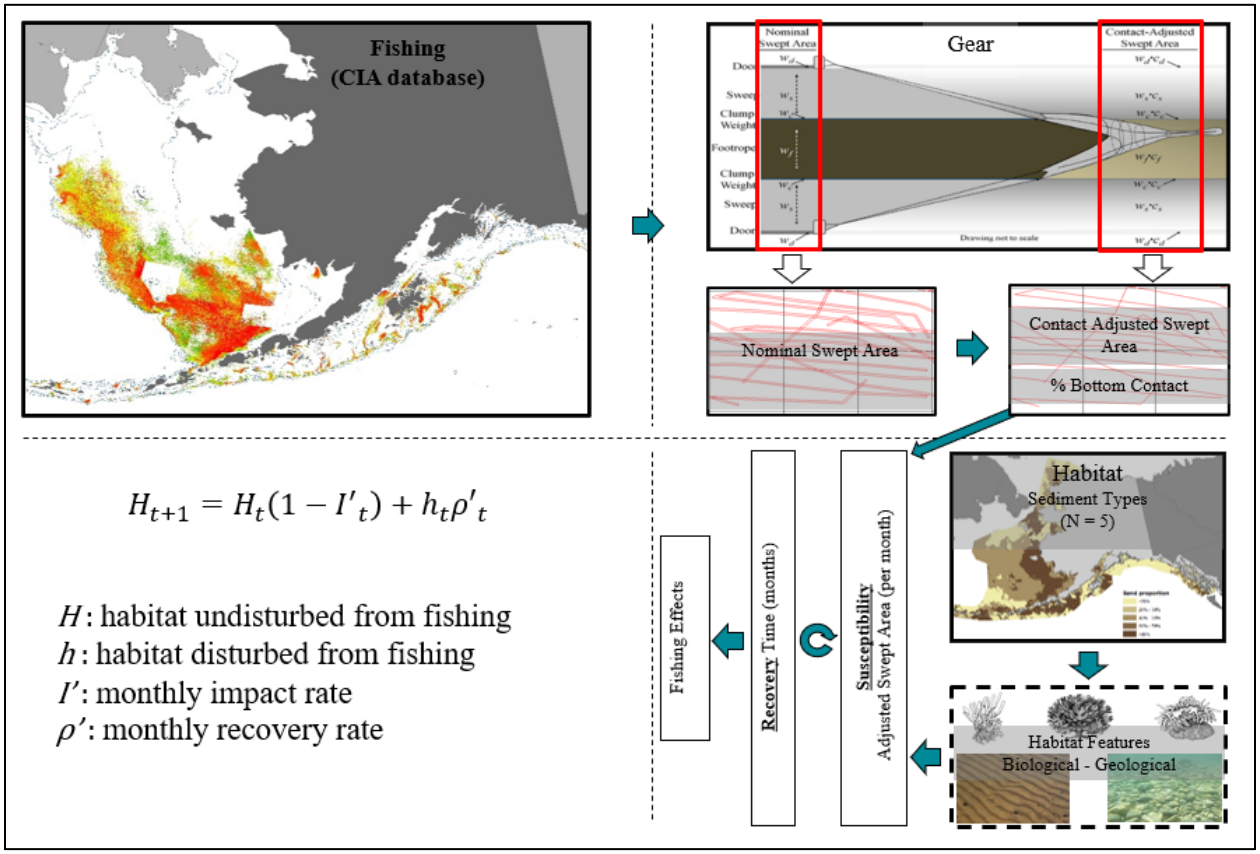

Figure 1. Conceptual diagram of the Fishing Effects model

Fishing impacts, the proportion of undisturbed habitat that transitions to disturbed habitat within each time step, are determined by 1) the location (grid cell) where fishing events occur, 2) the type of gear was used, and 3) the sediment type (as a proxy for habitat features) at that location. The location, gear used, vessel information, and fishery target are provided by the Catch-in-Areas database (Alaska Regional Office 2020), a spatially explicit GIS database of commercial fishing activity dating back to 2003. Sediment type is determined from a sediment distribution map created specifically for the FE model from over 250,000 sediment samples. Sediment is mapped as the relative proportion of mud, sand, granule/pebble, cobble, and boulder in each 25 km^2 grid cell. The impacts from a single fishing event are calculated as the product of the nominal area swept of the fishing gear (as a proportion of the total area of the grid cell), the proportion of gear that is in contact with the sea floor within the nominal area, and the susceptibility of habitat features to that gear.

Susceptibility is the proportion of habitat disturbed if contacted by fishing gear and is defined for 26 categories of habitat features (e.g., sponges, macroalgae, boulder piles) on each gear- sediment combination with a four-interval scale: 0 - 10%; 10% - 25%; 25 - 50%; and >50%. At each monthly time step, the susceptibility score for a habitat feature is randomly drawn from its corresponding susceptibility interval. Because the distribution of individual habitat features is not known, the susceptibility values for habitat features are averaged for each sediment type based on the habitat features that may occur on that sediment. When multiple fishing events occur within a grid cell in a given time step, the overlap of the fishing events is accounted for to calculate a total impact for that cell for that month with fishing overlaps not counted multiple times.

Recovery, which determines the proportion of disturbed habitat that returns to an undisturbed state each time step, is driven by the sediment profile of the grid cell. Like susceptibility, recovery is calculated for each sediment type as the mean recovery of all habitat features associated with that sediment. Recovery for each habitat feature is estimated on a four-interval scale representing average time to recovery: <1 year; 1 – 2 years; 2 – 5 years; and 5 – 10 years. Like susceptibility, a recovery time is randomly selected for each habitat feature from its associated recovery interval. Recovery for a given sediment type is averaged over all habitat features associated with that sediment, and recovery times are converted to the proportion of disturbed habitat recovered each month. A time-to-failure equation (i.e., failure of habitat to remain disturbed) is used to make the conversion from years to monthly proportions, where the proportion of habitat that recovers in a month and τ is average years to recovery.

The FE model outputs proportion of disturbed or undisturbed habitat on 25km^2 grid cells for each month of the model run (Figure 2). The output can be clipped and averaged over any region of interest (e.g., Management Area, EFH for a specific species), producing a monthly time series of habitat reduction for that region (Figure 3).

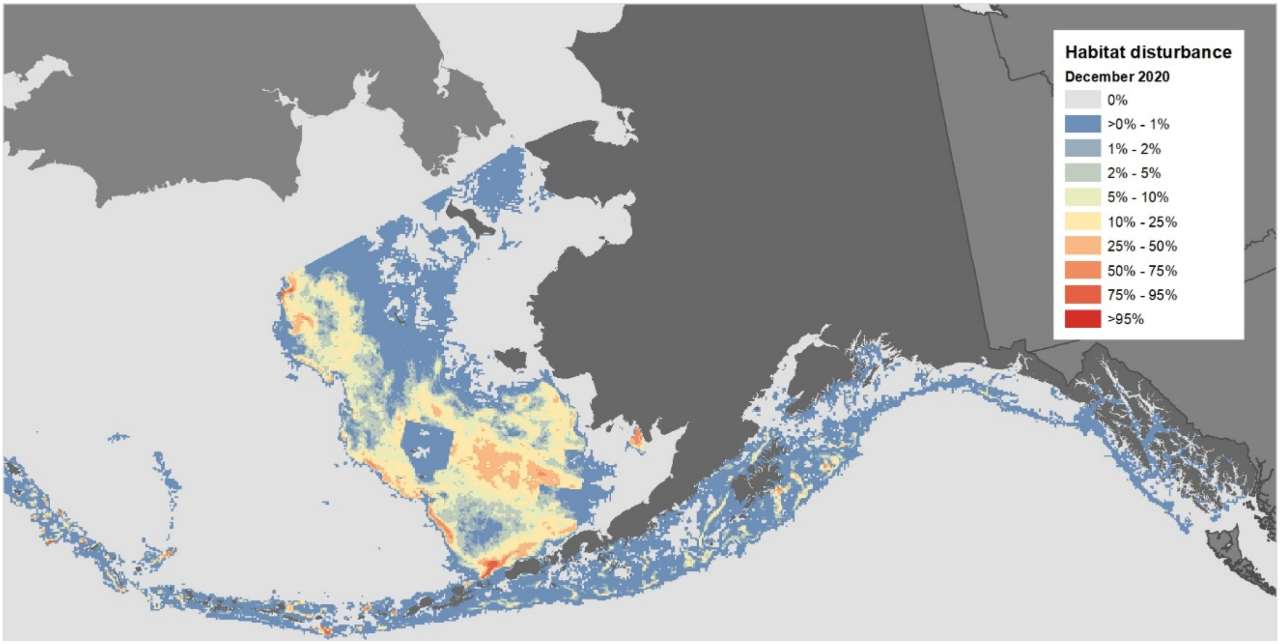

Figure 2. Habitat disturbance in 25 km^2 grid cells across the North Pacific for December 2020.

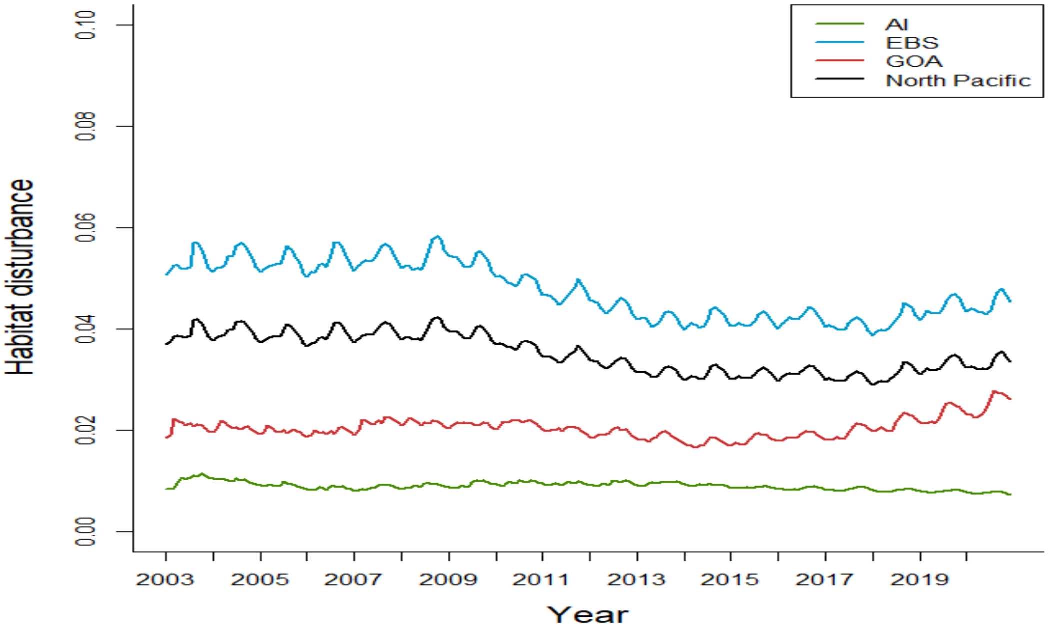

Figure 3. A basic time-series output of the Fishing Effects Model showing habitat disturbance aggregated for all areas less than 1000 m depth for the Aleutian Islands, Eastern Bering Sea, Gulf of Alaska, and the North Pacific at large

The SSC concurred that these updated models and the additional data that inform them could allow more systematic methods and criteria to assess the effects of fishing on EFH, and to determine when management measures may be necessary to mitigate adverse effects of fishing. NPMFC committees (SSC, Advisory Panel, Ecosystem Committee) and Joint Plan Teams reviewed the FE model structure, inputs, and implementation between 2015 and 2017.

Appendix 1 provides a complete description of the Fishing Effects model, including equations.

2.2 Fishing Effects model input parameters

This section describes the inputs to the FE model, including fishing intensity, habitat categorization, susceptibility and recovery of features, and the treatment of structure-forming invertebrates such as corals and sponges.

2.2.1 Fishing intensity

In 2004, NMFS Alaska Regional Office (AKRO) started the development of a fisheries harvest database that integrated onboard observer data and vessel position acquired through VMS data, referred to as the Catch-in-Areas database (CIA). The CIA brought increased spatial resolution to the existing data systems for the observed and unobserved vessel fleet to facilitate a more accurate analysis of fisheries management issues. Yearly catch data includes the approximately 2.2 million metric tons Alaska groundfish. The CIA is an extension of the Catch Accounting System (CAS) that provides estimates of total catch in the groundfish and halibut fisheries and allow the in-season monitoring of catch against limits in Alaskan waters (Cahalan 2014). The CAS is a primary data source for the CIA and spatially tracks catch into NMFS reporting areas and State Statistical areas.

Vessel fishing tracks, known as vms-obs-unobs-lines within the CIA system, are created from the cleaned vessel position data and represent the path that a fishing vessel traveled while in a fishing operational mode. Each fishing event is correlated to a haul, enabling catch to be associated with the vessel's fishing event. This data set is based on 'fishing lines' of both observed and unobserved groundfish vessels from 2003 to present. A fishing line is an observed haul for a catcher vessel or catcher processor. VMS is appended to observed data based on vessel identification and gear deployment and retrieval date time. For fixed gear vessels, including pot and hook-and-line vessels, VMS data is removed from observed line since the vessel often drops their gear and then goes to a different fishing location while the fixed gear is soaking.

Fishing effort in the FE model is calculated for each cell, month, and gear type using the CIA data set. Nominal widths (the footprint of the fishing gear when deployed, in meters) were joined to each fishing event in the CIA dataset based on the following attributes: vessel type, subarea, gear, target species, vessel length, season (date), and grid cell depth. Buffers were created around the polylines based on the nominal width of the fishing gear as detailed in the fishing gear description table (Appendix 2). Square buffer ends were used to ensure the area swept did not exceed the extent of the polyline as well as to increase the efficiency of subsequent spatial operations by reducing the number of vertices compared to a rounded buffer. The buffered tows were then intersected with the 25km2 grid creating a nominal area swept for individual tows within each cell. Each of these nominal areas was multiplied by a contact adjustment (the amount of time a fishing gear actually contacts the seafloor) to calculate total ground contact. Ground contacts for each FE model gear type were summed over each grid cell and month and divided by the grid cell area to calculate fishing intensity.

2.2.2 Habitat categorization

The FE and LEI models consider habitat impacts and recovery at the level of habitat features. Aside from structural differences between models (i.e., continuous vs discrete time), both models treat habitat features in the same way, just define them differently. In the 2005 EFH EIS, NMFS divided the Bering Sea into 4 habitat types based on approximately 2,000 sediment samples – sand, mixed sand and mud, mud, and Bering Sea slope mud and sand. Rocky substrates were not included. The ability to classify habitats in the Aleutian Islands and Gulf of Alaska was highly constrained due to the lack of sediment distribution data; therefore, AFSC survey strata (shallow, deep, and slope) were used. Additional categories were added for the slope below 200 m depth and the northern shelf. The LEI model defined four broad categories of habitat features: infaunal prey, epifaunal prey, biological structure, and physical structure. The FE model, in contrast, defines 26 categories of habitat features that are grouped into biological or geological features.

For the 2017 EFH 5-year review, sediment data were compiled from various surveys collected across the North Pacific domain, and now includes over 250,000 individual points. The data consist of spatially explicit points attributed with sediment descriptions, although the various surveys varied widely in methodology, sediment descriptions, and point density. Sediment points in the Eastern Bering Sea are separated on average by approximately 10.5 km, while some localized sampling efforts, especially near shore, collected data at much greater densities. Very few points were located deeper than 500 meters or in areas of boulder or hard rock habitat. Typical sampling methods (core, grab samplers) are not capable of sampling boulder and hard rock habitats, so those habitat types are under-represented.

Initial processing of the data consisted of parsing through the various sediment descriptions to map them to a sediment category used in the FE model (mud, sand, granule/pebble, cobble, or boulder). The mapping was not one-to-one, however, such that more than one sediment category could be described by a single sediment description. Each point was attributed as present or absent for each sediment category. An indicator Kriging algorithm was used (Geostatistical Wizard, ArcMap v10.2) to interpolate a probability surface for each sediment category over a 2.5 km grid aligned to the 5 km grid used for the FE model. A probability threshold of 0.5 to indicate presence/absence of each sediment category was set, so four sediment grid cells were located within each 5 km grid cell, providing a pseudo area-weighted measure of each sediment type within each 5 km grid cell. For each 5 km grid cell, the proportion of each sediment type was calculated as the sum of all 2.5 km grid cells with sediment present (up to four for each sediment class) divided by the sum of all present cells across all sediments (up to 20 possible, 4 cells X 5 sediment classes). In ~10% of the 25 km^2 grid cells, no sediment class was predicted present. In these cases, sediment proportions from the nearest 25 km^2 grid cell were used.

2.2.3 Susceptibility and recovery estimates

Previous EFH fishing effects analyses (2005 EFH EIS and 2010 EFH 5-year review) provided an overview of new and existing literature and research on the effects of fishing on habitat, and fisheries managers and scientists based their assessment of the effects of fishing on habitat based on LEI output (including the distribution of fishing intensity for each gear type, spatial habitat classifications, categories of habitat features, habitat- and feature-specific recovery rates, and gear- and habitat-specific sensitivity of habitat features) and best professional judgment.

The 2017 EFH 5-year review incorporated a global literature review and vulnerability assessment developed by the New England Fishery Management Council's Habitat Plan Development Team (Grabowski 2014). A Microsoft Access database was developed to identify in detail the gear types and habitat features evaluated in each study. In addition to identifying gear types and features, the database included field codes for basic information about study location and related research; study design, relevance and appropriateness to the vulnerability assessment; depth; whether recovery of features is addressed; and substrate types found in the study area. Over 115 studies were initially selected for evaluation based on their broad relevance to Northeast Region habitats and fishing gears, including 14 from the North Pacific. Synthesis papers and modeling studies were excluded from the review but the research underlying these publications was included when relevant. Most of the studies reviewed were published peer-reviewed journal articles; however, conference proceedings and reports were considered as well.

As a model parameterization tool, the Grabowski vulnerability assessment quantifies both the magnitude of the impacts that result from the physical interaction of fish habitats and fishing gears, and the duration of recovery following those interactions. The vulnerability information from this database has been modified to condition area swept (i.e., fishing effort) in the FE model via a series of susceptibility and recovery parameters (Appendix 3).

A critical point about the vulnerability assessment and accompanying FE model is that they consider EFH and impacts to EFH in a holistic manner rather than separately identifying impacts to EFH designated for individual species and life stages. This is consistent with the EFH final rule, which indicates "adverse effects to EFH may result from actions occurring within EFH or outside of [designated] EFH and may include site-specific or habitat-wide impacts, including individual, cumulative, or synergistic consequences of actions" (50 CFR 600.810). To the extent that key features of species' EFH can be related to the features in the vulnerability assessment, post-hoc analysis of model outputs can be conducted to better evaluate the vulnerability of a particular species' essential habitat components to fishing gear effects.

2.3 Incorporation of longer recovery times into FE model

The Fishing Effects model was developed to estimate benthic habitat disturbance from commercial fishing activities, especially as it occurs within EFH. The model tracks habitat reductions at monthly time steps by calculating the impacts to habitat from fishing activities each month and simultaneously accounting for habitat recovery from past impacts. A key component of the model is the recovery parameter represented as average time to recovery (in years) for 26 categories of habitat features (e.g., corals, sea pens, cobble piles). Because the spatial extent of each habitat feature is not known for the entire domain, five sediment types are used to define habitat. Thus, an average recovery is estimated for each sediment type as the mean recovery time of all habitat features associated with that sediment type. In the initial FE model runs, these recoveries were drawn from tables in Grabowski (2014) using a global literature review of habitat recovery. The table gives a recovery score for each habitat feature-sediment combination. Recovery scores were based on a four-interval scale (0 – 3) with each score representing recovery times. Importantly, the highest score of 3, representing the longest recovery times, corresponds to a recovery of 5 – 10 years.

At the October 2016 Council meeting, the SSC supported the use of the FE model as a tool for assessing the effects of fishing on EFH. In response to public comment, however, the SSC raised concern that the longest recovery time incorporated into the model (5-10 years) may not capture the recovery needed for long-lived species such as hard corals that live on rocky substrate at deep depths. To address these concerns, a deep and rocky substrate habitat feature was added (resulting in 27 categories). Three Aleutian Island cruises conducted by NMFS in 2003-2004 resulted in 71 submersible and ROV transects (Stone 2006, 2014). Video analysis of those transects indicated that corals have the highest density at depths of 400 to 700 m with bedrock or cobbles substrates, moderate to very high roughness, and slopes greater than 10 percent. To be precautionary, the new habitat feature was defined as cobble or boulder habitats deeper than 300 m. Cobble and boulder substrate was defined using the original sediment map for the FE model; depth was determined from a domain-wide 100 m (hectare) resolution bathymetric model. All cobble and boulder sediments categories in grid cells with an average depth deeper than 300 m were converted to the deep/rocky category. Habitat features originally in the cobble or boulder categories were mapped to deep/rocky category with their original recovery scores. To account for the long-lived species expected in these habitats, a new "long-lived species" recovery interval (10 – 50 years) was added with a new recovery score of 4. The 50-year upper limit of recovery time was calculated with the expectation that 5% of these long-lived species would require 150 years to recover (see Appendix 4 for an explanation of this calculation).

The new deep/rocky habitat feature occurs in 2.4% of grid cells within the 1000 m depth contour bounding the FE model domain. The inclusion of this new category resulted in an average increase of 0.03% more habitat in a disturbed state compared to the original model predictions. Predicted habitat reduction was about 70% less in grid cells that contained Deep/Rocky substrate compared to the entire domain (Figure 2). The less habitat disturbance in Deep/Rocky habitats reflects less fishing effort in these areas as only 0.4% of fishing effort occurred in grid cells with Deep/Rocky substrate compared to its areal representation of 2.4%.

At the April 2017 Council meeting, the SSC stated that techniques are emerging that would allow future assessment of corals as an ecosystem component, as opposed to a living structure. The SSC encouraged FE analysts to consider this in future assessments. Projects that may be useful in these assessments are part of the 2020-2023 Alaska Coral and Sponge Initiative, described in section 3.9.

2.4 Sensitivity analysis

During initial development of the model, the contact adjustment, susceptibility, and recovery parameters were chosen to include random variables from uniform distributions with the intent that running multiple iterations of the model would allow for estimation of uncertainty. While this approach does produce reasonable estimates of uncertainty at the grid cell level, when aggregating results across large spatial domains this measure of uncertainty was less useful due to aggregation of many grid cells. The key sources of uncertainty unaccounted for in this stochastic approach is either 1) potential bias in the parameter estimates, or 2) misspecification of model parameters. To evaluate these potential uncertainties, we ran several versions of the model to bound the estimate of habitat disturbance.

To evaluate potential uncertainty due to bias in the parameters, we ran the FE model with each of the stochastic parameters fixed to their upper and lower bounds, producing a range of habitat disturbance estimates that bounds habitat disturbance within the parameter space. In other words, estimates of habitat disturbance will always be in this range assuming that the model is well specified and that no parameters exceed their defined bound. Generally, this produces a conservative band of uncertainty (i.e., much wider than reasonably expected) as it is unlikely that all parameters are biased consistently high or low with similar magnitude.

To evaluate potential misspecification of the model, we ran three alternate models with restricted parameters in a hierarchical manner to demonstrate the effect of each parameter on model estimates. Each restricted model provides a hard upper boundary of potential habitat disturbance for each of the more complex models. Notably, each of the restrictive models has a relevant physical interpretation that can be used to better understand habitat disturbance dynamics.

The first restricted model fixed contact adjustment and susceptibility to unity and did not include recovery ($\tilde{\rho} = 0$). This model is equivalent to the spatial footprint fishing activity (including pelagic fishing activity) and will be referred to as the “fishing footprint.” This model provides a hard upper limit of habitat disturbance if we assume fishing activities do not disturb habitat features outside of their spatial footprint. The second restricted model fixed susceptibility at unity with no recovery but included the standard contact adjustment parameters. This model provides an estimate of how much of the seafloor has ever been contacted by fishing gear and referred to here as the “benthic footprint”.

This will always be less than the fishing footprint, with the difference representing the area that has only ever had pelagic (or at least off-bottom) fishing activity and represents an upper bound of habitat disturbance if contact adjustment is well defined. A third restricted model was run that also did not include recovery but included the standard contact adjustment and susceptibility parameters. This model is a measure of the proportion of benthic feature have ever been impacted by fishing activity and referred to as the "impacted footprint". This model provides an upper bound of habitat disturbance assuming contact adjustment and susceptibility are well specified in the model. Results for each of these models are given below in Table 1 and displayed in Figure 4.

Table 1. Model outputs for low/high habitat disturbance parameter scenarios and restricted models

Model version	*Dec 2020 model estimate (% of North Pacific)*
Habitat disturbance (lower – upper bound)	3.4% (1.0% - 6.7%)
Fishing footprint	31%
Benthic footprint	26%
Impact footprint	17%

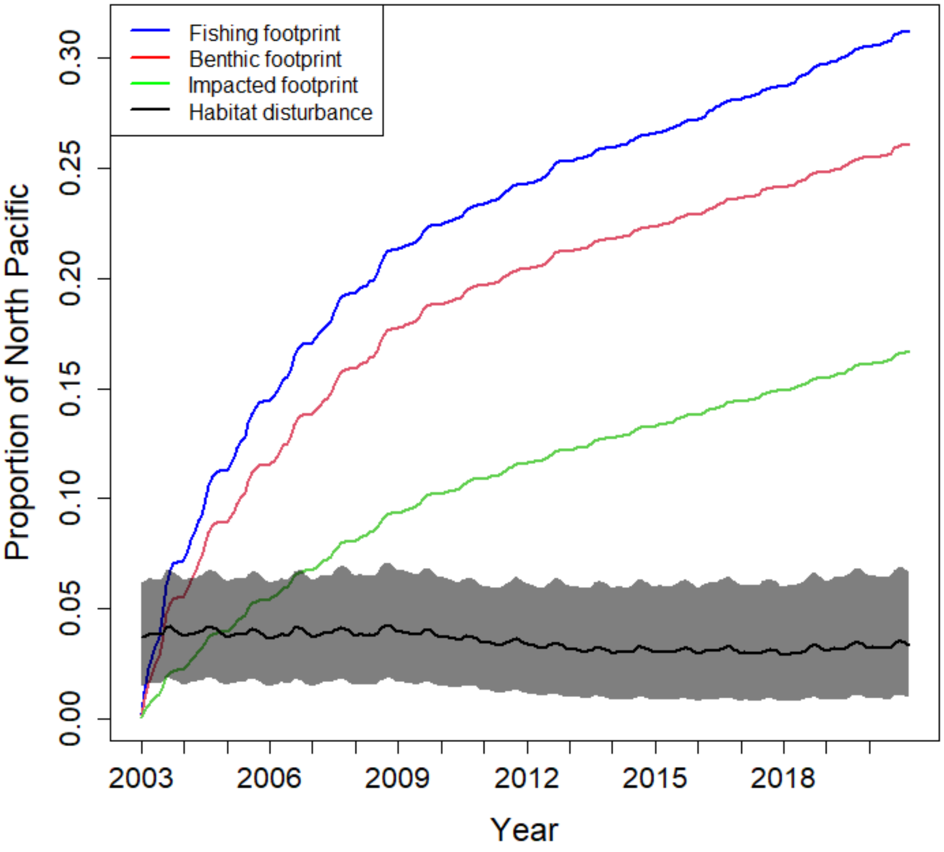

Figure 4. Model outputs for habitat disturbance and each of the restricted models. The grey band shows the bounds of habitat disturbance with all parameters fixed to their highest or lower values.

2.5 Assessment of the effects of fishing on EFH in Alaska

In 2005, the distribution of LEI values for each class of habitat feature were provided to experts on each managed species, to use in their assessment of whether such effects were likely to impact life history processes in a way that indicated an adverse change to EFH. Experts were asked to assess connections between the life history functions of their species at different life stages and the classes of habitat features used in the LEI model. Then, considering the distribution of LEIs for each of those features, they were asked whether such effects raised concerns for their species. Experts also considered the history of the status of species stocks in their assessments. While this process provided the first attempts at assessing the effects of fishing on stocks, it was a qualitative approach.

2.5.1 Hierarchical impact assessment methods

The SSC reviewed and approved the FE model in April 2016. At that time, the SSC recommended the development of new methods and criteria to evaluate whether the effects of fishing on EFH are more than minimal and not temporary. An SSC subcommittee composed of scientists and managers from AFSC, AKRO, and Alaska Pacific University developed criteria, and the Council approved a three-tiered method (Figure 5) to evaluate whether there are adverse effects of fishing on EFH in April 2016 (NPFMC 2016).

This analysis considers the impacts of commercial fishing first at the population level, then uses objective criteria to determine whether additional analysis is warranted to evaluate if habitat impacts caused by fishing are adverse and more than minimal or not temporary.

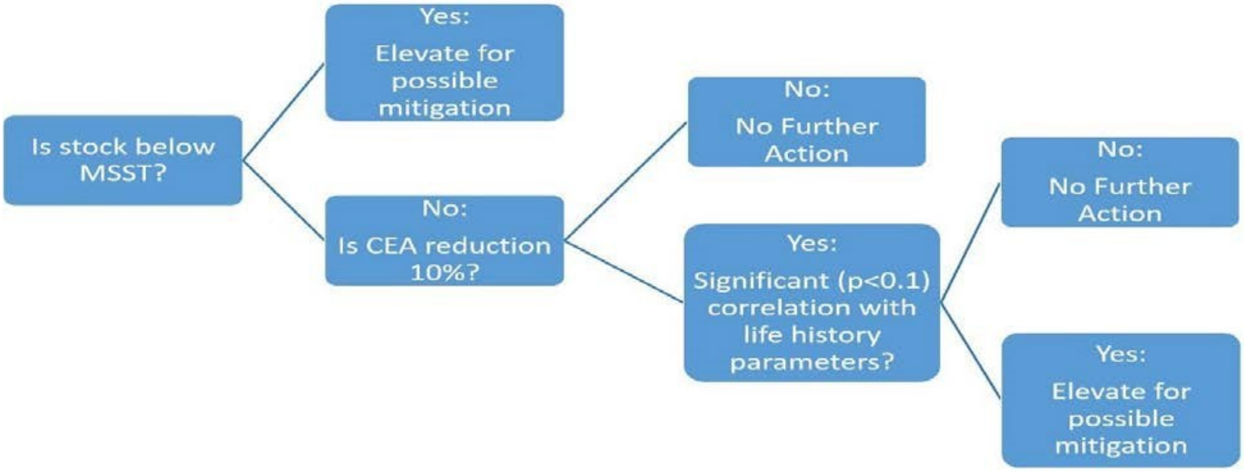

Figure 5. Three-tiered method to evaluate effects of fishing on Essential Fish Habitat in Alaska.

Because EFH is defined for populations managed by Council FMPs, stock authors first considered whether the population is (1) above or below the Minimum Stock Size Threshold, defined as 0.5*maximum sustainable yield (MSY) stock size or (2) the minimum stock size at which rebuilding to MSY would be expected to occur within 10 years if the stock were exploited at the Maximum Fishing

Mortality Threshold. Stock authors were asked to identify any stock that is below MSST for review by the Plan Teams. Mitigation measures could be recommended by the Plan Team if they found that a stock below MSST has a plausible connection to reductions of EFH as the cause.

To investigate the potential relationships between fishing effects and stock production, the stock assessment authors examined trends in life-history parameters and the amount of disturbed habitat in the “core EFH Area” (CEA) for each species. The CEA is identified as the predicted 50 percent quantile threshold of suitable habitat of summer abundance as defined in the species distribution models reviewed by the Council in April 2016 (Laman et al. 2017, Turner et al. 2017, Rooney et al 2018). Stock assessment authors evaluated whether 10 percent or more of the CEA was impacted by commercial fishing in November 2016 (the end of the time series). The 10 percent threshold was selected based on the assumption that impacts to less than 10 percent of the CEA means that more than 90 percent of the CEA (top 50 percent of suitable habitat or summer abundance) was undisturbed, and therefore represented minimal disturbance. If 10 percent or more of the CEA was impacted, the stock assessment authors examined indices of growth-to-maturity, spawning success, breeding success, and feeding success to determine whether there are correlations between those parameters and the trends in the proportion of the CEA impacted by fishing. If a correlation exists, positive or negative, stock assessment authors determined whether the correlation is significant at a p-value of 0.1. If a significant correlation was found, stock assessment authors used their expert judgment to determine whether there is a plausible connection to reductions in EFH as the cause. Stock assessment authors identified the correlation and the significance in their reports. Discussion from the SSC and Plan Teams on the thresholds used for this analysis are available in Appendix 6.

Reports from the stock assessment authors were collated and presented to representatives of the GOA and BSAI Groundfish and Crab Plan Teams. Plan Team representatives reviewed the reports in March 2017 and concurred with stock assessment authors' determinations in all cases. None of the stock assessment authors concluded that habitat reduction within the CEA for their species was affecting their stocks in ways that were more than minimal or not temporary (NPFMC 2017). None of the authors recommended any change in management with regard to fishing within EFH.

2.6 *Conclusions about the effects of fishing on EFH in 2017*

The 2005 EFH EIS and 2010 EFH review both concluded that fisheries do have long-term effects on habitat, and these impacts were determined to be minimal and not detrimental to fish populations or their habitats (NMFS 2005a, NPFMC 2010). While the 2010 EFH 5-year review provided incremental improvements to our understanding of habitat types as well as the sensitivity and recovery of seafloor habitat features, these new results were consistent with the sensitivity and recovery parameters and distributions of habitat types used in the prior analysis of fishing effects for the 2005 EFH EIS. These previous EFH analyses, as well as the CIE review, indicated the need for an improved fishing effects model as well as more robust input parameters.

With the FE model, NMFS ability to analyze fishing effects on habitat has greatly improved. CIA data provides a more detailed treatment of fishing intensity and better assessments of the effects of overlapping effort and distribution of effort between and within grid cells. The development of a literature-derived fishing effects database increased our ability to estimate gear-specific susceptibility and recovery parameters. The distribution of habitat types, derived from increased sediment data availability, was vastly improved. The combination of these parameters greatly enhanced our ability to estimate fishing impacts.

The Fishing Effects analysis considers impacts of commercial fishing first at the population level, then uses objective criteria to determine whether additional analysis is warranted to evaluate if habitat impacts caused by fishing are adverse and more than minimal or not temporary. In April 2017 the SSC and Council concurred with species-specific EFH fishing effects analyses conducted by stock assessment authors, and reviewed by Plan Teams and the SSC, that no stocks needed mitigation review, and that the effects of fishing on the EFH of fisheries species managed by the NPFMC are minimal and temporary (NPFMC 2017).

3 Updates to the FE model for 2022

At the conclusion of the 2017 EFH 5-year review, the SSC provided several recommendations related to the FE model. These included continuing to refine FE model parameters, examining the potential benefits of gear modifications, requesting sensitivity analyses and the release of species-specific CEA maps, and more explicit consideration of corals and other living structure in the model.

Since that time, the development and use of the FE has advanced. The FE model was published (Smeltz et al. 2019). Model parameters involving fishing intensity, habitat categorization, and susceptibility and recovery are updated regularly, and the base code of the FE model continues to be refined. A sensitivity analysis is now available as a standard FE model output, and updated gear descriptions are available for several gear types. Analysts continue to look at options to address questions from the SSC and constituents regarding categories of biological and geological habitat, as well as issues with feature averaging. Alaska Pacific University was contracted by the New England Fishery Management Council to modify the FE model as their primary method to assess fishing impacts on EFH, providing another avenue for FE model review and development. Yearly FE model output is available as an indicator in the Ecosystem Assessment Reports (Appendix 7). And finally, the 2020-2024 Alaska Deep-Sea Coral and Sponge Initiative includes several projects which may provide new information on coral and sponge susceptibility to fishing gears and potential for recovery from impacts; however, any updates from this initiative will not be available for this review.

3.1 Fishing intensity

The AKRO provides the high-resolution CIA fishing event information that is the basis of the FE model (from the CIA database) is provided yearly by the AKRO, generally in February. This timing allows the previous year's data to be fully incorporated into the CIA database. Observed fishing data from 2003-2020 are included in the 2022 5-year Review.

Exploratory analyses to incorporate unobserved fishing events for the entire time series (2003-2020) have been conducted. Although those unobserved lines represent between 7-12% of overall events, inspecting the *minutes fished* or *line length* (time or distance) of those events represent up to 50% of the total minutes or line length of all events (observed and unobserved), likely due to the methods used to determine "fishing" rather than "non-fishing" (transit, processing) segments. The FE team continues to communicate with CIA authors at the AKRO on how best to incorporate unobserved fishing events into the FE model. We are not incorporating unobserved fishing into the FE model for the 2022 EFH 5-year review.

3.2 Habitat categorization

The 2017 FE impacts analysis included over 250,000 sediment records across the BS, AI, and GOA domains. These data represented a large increase of the 2,000 sediment records and generic habitat categories based on depth and survey strata used in the 2005 and 2010 LEI analyses. For the 2022 EFH 5-year review, analysts identified few additional data to add to the sediment record. Other sources of sediment data are available, such as dbSEABED (http://instaar.colorado.edu/~jenkinsc/dbseabed/), but this dataset does not represent a significant new source of information over the current sediment records used by the FE model.

Sediment type continues to be used as a proxy for habitat types because spatially explicit data for biological and geological habitat types are not available. While an area like the Bering Sea may be well-sampled by the trawl survey, the Aleutian Islands and Gulf of Alaska are not nearly as well sampled (Baker et al 2019). Until validated spatial models are available for all habitat features, sediment-based categories are the best available science. It may be possible to incorporate the coral and sponge models developed by Rooper et al (2014) into the FE workflow; however, the GOA coral and sponge models have not been validated at this time. The validation cruise is scheduled to occur in June/July 2022 (Section 10.5.1), with results in 2023.

3.3 Susceptibility and recovery

Susceptibility and recovery literature regarding fishing impacts are reviewed by both AKRO and academic collaborators annually. In 2020, the FE model was implemented in New England (see section 3.7) and a full literature review to update the parameters in the Grabowski et al (2014) was conducted. The lack of Before-After-Control-Impact (BACI) and long-term recovery studies noted in previous EFH documents persists, so estimates of susceptibility and recovery generally, and particularly for long-lived corals and sponges, lack empirical evidence. A project that could provide more information on coral and sponge impacts and recovery in the Aleutian Islands is scheduled for 2023 and is described in Section 3.9.5.

Studies by Pitcher et al. (2017) and Hiddink et al. (2017) provide an interesting comparison to the susceptibility and recovery rates used in the FE model. Pitcher calculated the “relative benthic status” of the seabed against an unimpacted baseline to evaluate how trawled habitats (and benthic invertebrate communities) change with varying degrees of trawl impact, recovery rate, and exposure to trawling. Pitcher found gravel habitats to be most impacted by trawl gears, followed by muddy-sand and sand habitats as least affected by trawling. The benthic invertebrate community recovery rates followed a similar pattern: gravel had the greatest time to recover to a reference state (500 days), with 300 days to recover in muddy-sand, 200 days to recover in mud, and 100 days to recover in sand.

Hiddink evaluated depletion and recovery rates of benthic communities after trawling impacts and generally found more biota were removed as trawl penetration depth increased. Depletion is measured as the proportion of biota remining after a single trawl pass and is equivalent to FE model parameterization as: *depletion = contact adjustment x susceptibility*. For otter trawl gears (applicable to all trawl gears in Alaska), Hiddink estimated depletion to be 6% with a penetration depth of 2.4 cm. For comparison, calculation of mean depletion from FE model parameters for Bering Sea pollock and flatfish trawls is ≈10%, a more conservative estimate than Hiddink et al. (2017).

The same study also estimated that recovery rates varied between ~2 and 6.4 years to recover from 5% to 95% unimpacted biomass on soft sediments. Community biomass did not seem to be affected by the interaction between gear type and habitat type, however, the sample size was small for this evaluation. Substrates with higher percentages of gravel experienced a greater reduction in benthic community numbers. These recovery values are not directly comparable to those used in the FE model, as the τ parameter of the FE model is parameterized by mean recovery time, rather time from 5% - 95% unimpacted biomass. However, this quantity (noted as τ^*) can be calculated from τ as:

$$\tau^* = \tau\,[\log(1-0.05) - \log(1-0.95)]$$

For comparison, using FE model parameters, mean values ofτ^* are 9.5 and 9.2 years for mud and sand, respectively, which are again more conservative than the Hiddink et al. (2017) estimates of recovery of soft sediment habitats.

Much discussion has surrounded the applicability of sediment-based measures of recovery when these habitats are often comprised of a complex of organisms that may each have differing capacity to recover or competitive interactions that may affect their recovery trajectory. While the FE model does use tables of individual habitat features to calculate recovery, the model itself is run on a sediment-based categorization of habitats. This largely due to the state of best available science. The distribution of those habitat features is not sufficiently well understood to parameterize within the model. Recent studies have also grappled with the same issue, concluding that sediment-based habitat categories are sufficient to describe the aggregate properties of benthic communities (Hiddink et al. 2022).

The initial stage in developing a risk assessment for corals and sponges (described in 3.9.4) involved an overlap analysis using CIA fishing events and species distribution models developed by Rooper (2014, 2018). This preliminary analysis was conducted only in the Aleutian Islands. For all gears from 2003-2019, the total overlap of fisheries by gear and target across the top one-third of predicted coral and sponge presence was 8-9% across the Aleutians, with lower values in the east, intermediate in the central, and higher values in the west (approximately 5, 10, 20 percent). When this analysis is performed for gear target combinations, rockfish and mackerel trawl fisheries generally have a higher overlap than do cod trawl. Longline sablefish and longline cod and pot fisheries are less than two percent. It is important to note that this preliminary analysis was conducted with the nominal footprint values and was not contact adjusted. These quantitatively derived values are significantly lower than the qualitative assessment (LEI values) used during the 2005 EFH EIS (23-59 percent).

3.4 FE model code

The Fishing Effects model is run on a combination of Python and R code. The 2017 EFH 5-year review was the initial implementation of the model, and the code was constructed in such a way that did not provide for great flexibility when porting the model to other applications (e.g., running the model for New England, Section 3.7). Since 2017, the model code has undergone various updates and improvements with an aim toward flexibility and efficiency. In 2018, an error was discovered in the 2017 model code that transposed the susceptibility for trawl and longline gears. Because susceptibility is generally higher for trawls than longlines, the effect was an underestimation of impacts from trawls and an overestimation of impacts from longlines. Because the total footprint of trawling throughout the

North Pacific is much greater than the footprint of longlines, the net effect of this error resulted in an underestimate of habitat disturbance (Fig. 6), with the largest difference evident in the Bering Sea.

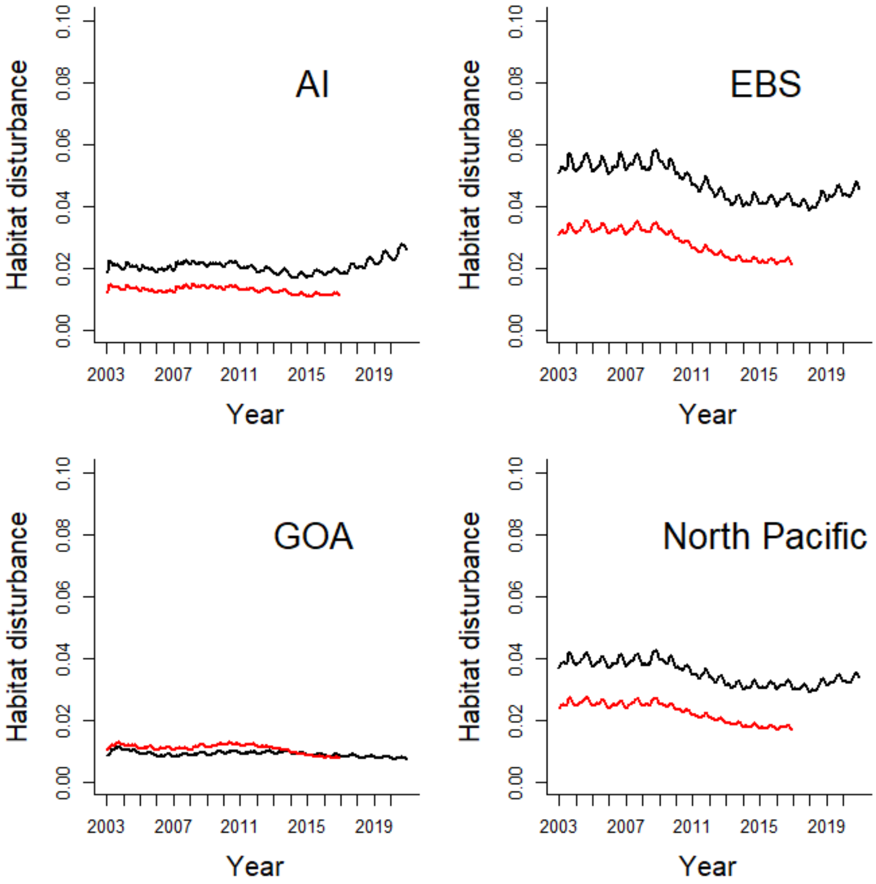

Figure 6. Comparison of 2017 FE output (red lines) and 2022 FE model output (black lines) among subregions and the North Pacific at large

The differences between the outputs are due to the correction made to properly attribute susceptibility to trawl and longline, as well as updates to the Gear Table parameters.

3.5 Updates to Gear table parameters

The benthic impacts of static fishing gears (hook-and-line longline, single pots, and longline pots) have received relatively little study when compared to larger mobile gears like trawls and dredges. Two recent studies are useful in updating estimates in the gear parameter tables (Appendix 2), and one update was in response to stakeholder testimony and further analysis.

Welsford et al. (2014) developed the Benthic Image Camera System (BICS) to assess longline impacts in the Australian Exclusive Economic Zone for the Patagonia toothfish fishery. In assessing the area swept by longlines, Welsford identified line shear and hooking interactions as the most likely source of impacts to structure-forming invertebrates. Lines were generally deployed in a series of 1200 m sets in length, with an average total distance between lines of 9 km and depth of greater than 800 m. In the 48 BICS camera deployments, 27 included images of both deployment and retrieval. Line movement between deployment and retrieval was not detected in 26 of 27 sets, nor was lateral movement exceeding 1m detected. A mean lateral movement of 6.2m was recorded, with a maximum lateral movement of over 30 m. Welsford states that variation in lateral movement was not related to depth, and that the highest longitudinal movement was seen on a line that was not under tension.

Doherty et al. (2017) estimated the bottom footprint of longline trap gear in the British Columbia sablefish pot fishery. They found certain fishing characteristics (e.g., hauling speed, haul direction, catch, crew experience) combine with environmental conditions (e.g., depth, slope, rugosity, current, wind) to affect the size of the pot footprint. Longline trap gear used in the British Columbia sablefish fishery was shown to have gear components with little bottom contact, i.e. the groundline on sablefish trap gear is buoyant even at extreme depths, so it's unlikely the groundline would contact the bottom. Conical traps with a circular base create small furrows while dragging compared with a square trap base of the same total area. observed contact area created by box-shaped king crab pots on longlines in Alaska had widths ranging from 2 to 9 m (Stone 2006) for 2.4 m × 2.4 m pots. The estimated drag window and drag time for the excluded set were 5.9 min and 0.4 min, respectively. The mean estimated bottom-contact area for a 54-inch trap was $53 m^2$, almost 36 times the static trap footprint of $1.47 m^2$. Variability in the estimated drag times and drag lengths dominated bottom area calculations compared with less variable haul speeds and drag widths.

Based on public comment to the SSC, the bottom contact adjustment for GOA CV/CP Rockfish Pelagic Trawl were adjusted to values corresponding with GOA CV/CP Pollock Pelagic Trawl. Previously those contact adjustments reflected no bottom contact.

3.6 Feature averaging

During previous NPFMC meetings, both the SSC and public testimony expressed interest in a clearer explanation of feature averaging. To illustrate and clarify, we provide this example:

The Fishing Effects model computes the amount recovery each time step based on one of five sediment-based habitat types. To calculate an average recovery time for each sediment class, a recovery time (τ, in years) was first randomly selected for each habitat feature based on its score for that sediment. The mean of these recovery times was then calculated over all habitat features associated with the sediment class. The inverse of this averaged recovery time was then used in the following equation to convert the time to recovery into a proportional recovery ($\tilde{\rho}$) for each time step,

$$\tilde{\rho} = 1 - e^{-1/\tau}$$

In practice, τ is multiplied by twelve before conversion to ρ to convert it to months, which is the time step of the FE model. This process was repeated for each grid cell at a monthly time step. The following example illustrates feature averaging for mud and deep/rocky sediments.

Simplified table of recovery scores

Habitat feature	Mud	Sand	Deep/rocky
Biogenic depression	0	0	
Anemones, cerianthid burrowing	2	2	
Mollusks, epifaunal bivalve, *Modiolus modiolus*	3	3	3
Long-lived species			4

Recovery codes:
0: < 1 year
1: 1 - 2 years
2: 2 - 5 years
3: 5 - 10 years
4: 10 – 50 years

To calculate monthly recovery on mud in one grid cell for one specific time step:

Habitat feature	Mud score (range)	Random selection from range (τ)
Biogenic depression	0 (0 -1 years)	0.3 years
Anemones, cerianthid burrowing	2 (2 – 5 years)	4.1 years
Mollusks, epifaunal bivalve, *Modiolus modiolus*	3 (5 – 10 year)	6.3 years
Long-lived species	Not present	
		mean = 3.57 years

$$\tau = 3.57\ years = 42.8\ months$$
$$\tilde{\rho} = 1 - e^{-\frac{1}{42.8}} = 0.023 = 2.3\%$$

Thus, on the proportion of mud sediment within this grid cell and time step, 2.3% of the disturbed habitat would recover (i.e. convert to an undisturbed state in the model) for the next time step.
To calculate monthly recovery on deep/rocky sediment in one grid cell for one specific time step using the simplified table:

Habitat feature	Deep/rocky score (range)	Random selection from range (τ)
Biogenic depression	Not present	
Anemones, cerianthid burrowing	Not present	
Mollusks, epifaunal bivalve, *Modiolus modiolus*	3 (5 – 10)	5.1 years
Long-lived species	4 (10 -50)	39.8 years
		mean = 22.5 years

$$\tau = 22.5\, years = 270\, months$$
$$\tilde{\rho} = 1 - e^{-1/270} = 0.0037 = 0.37\%$$

Thus, on the proportion of deep/rocky sediment within this grid cell and time step, 0.37% of the disturbed habitat would recover (i.e. convert to an undisturbed state in the model) for the next time step.

3.7 Fishing Effects Model - New England Fishery Management Council

Managers and scientists from the New England Fishery Management Council and Alaska Pacific University adapted the Swept Area Seabed Impacts (SASI, NEFMC 2011) model and the Fishing Effects model into the Fishing Effects Model Northeast Region (NEFMC 2020), revising and refining certain aspects of the approach to address concerns raised during reviews of SASI and to reflect regional data availability. Both SASI and FE increase the utility of habitat science to fishery managers via the translation of susceptibility and recovery information into quantitative modifiers of swept area. The models combine area swept fishing effort data with substrate data and benthic boundary water flow estimates in a geo-referenced, GIS-compatible environment. Contact and vulnerability-adjusted area swept, a proxy for the degree of adverse effect, is calculated by conditioning a nominal area swept value, indexed across units of fishing effort and primary gear types, by the nature of the fishing gear impact, the susceptibility of benthic habitats likely to be impacted, and the time required for those habitats to return to their pre-impact functional value.

The vulnerability assessment and associated literature review to support SASI were originally developed over an approximately two-year period by members of the New England Fishery Management Council's Habitat Plan Development Team. The assessment served two related purposes: (1) a review of the habitat impacts literature relevant to Northeast US fishing gears and seabed types, and (2) a framework for organizing and generating quantitative susceptibility and recovery parameters for use in the SASI model. As a model parameterization tool, the vulnerability assessment quantifies both the magnitude of the impacts that result from the physical interaction of fish habitats and fishing gears, and the duration of recovery following those interactions. This vulnerability information is used to condition area swept (i.e., fishing effort) in both SASI and FE via a series of susceptibility and recovery parameters. Related to the vulnerability assessment, this document summarizes additional literature reviewed, susceptibility and recovery parameters for additional habitat types fished by hydraulic dredges, as well as the development of parameters for deep-water coral habitat features.

Additionally, managers from NEMFC, the Greater Atlantic Regional Field Office (GARFO), and AKRO are discussing ways in which the susceptibility and recovery information derived from the Grabowski (2014) document might be more easily updated and provide accessibility to managers and scientists outside the fishing effects field.

3.8 FE as yearly indicator ESR

In 2017, AKRO analysts began to contribute output of the Fishing Effects model to the yearly Ecosystem Status Report (ESR) published by the AFSC as an indicator titled "Area Disturbed by Trawl Fishing Gear in the Aleutian Islands, Bering Sea, and Gulf of Alaska". This ESR contribution includes a description of the indicator, status and trends of area disturbed by fishing activity, factors causing those trends, and the implications of fishing to managed stocks. Although this indicator uses output from the FE model, the data are summarized based on the ecoregions used in the ESR (figure 7), so the results are not directly comparable. The complete 2021 habitat disturbed indicator contribution is found in Appendix 7.

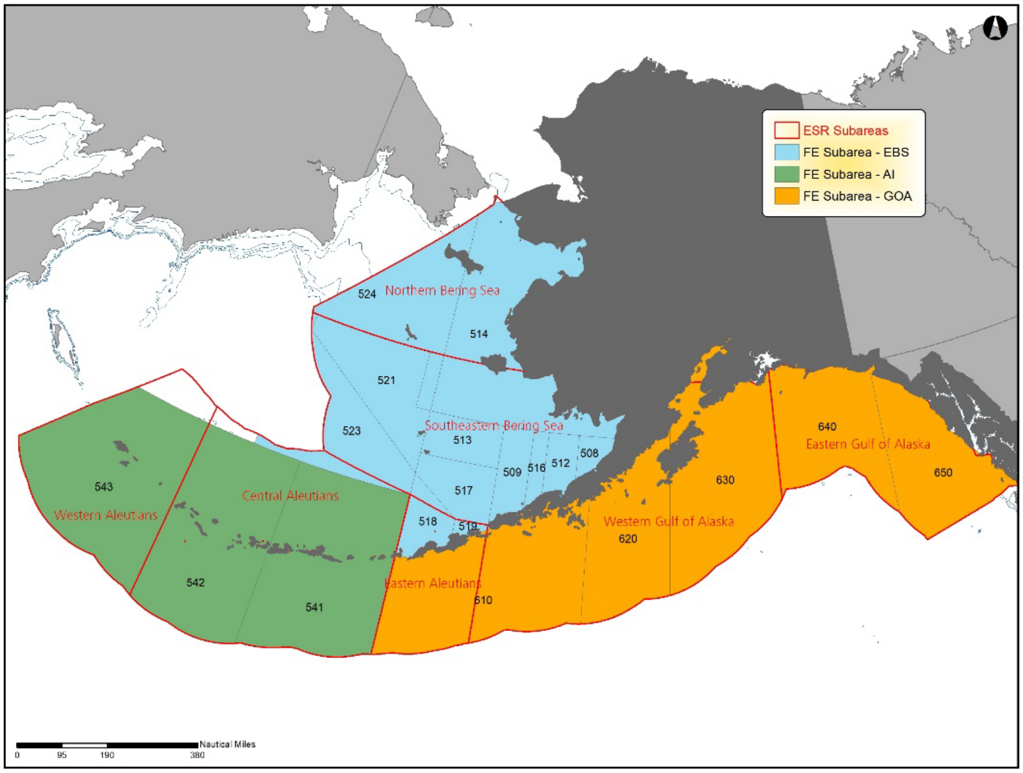

Figure 7. Comparison of boundaries used by NPFMC and ESR for FE output

3.9 Alaska Coral & Sponge Initiative projects

The objective of the 2020-23 Alaska Coral and Sponge Initiative (AKCSI) is to support research that addresses management needs and contributes to the conservation and protection of DSCS throughout the sub-Arctic waters of Alaska. This USD 2.4m initiative, funded by the NOAA Deep-Sea Coral Research and Technology program, will address many information gaps needed to understand and conserve important deep-sea coral and sponge (DSCS) habitats and to leverage additional partnerships to integrate research priorities and resources. A focus is on field research and collection of new information on DSCS taxonomy, distribution, diversity, and life history, as well as natural and induced habitat changes. Specifically, research will address the priorities identified in the AKCSI priorities workshop report (Hoff et al. 2020) and science plan (Hoff et al. 2021)

3.9.1 Validation of Coral and Sponge Modeling in the GOA

An important accomplishment of the previous AKCSI was the production of maps that predicted occurrence of DSCS on a 1 ha scale for each of the three major regions of Alaska -- the eastern Bering Sea, Aleutian Islands and Gulf of Alaska (Rooper et al. 2017, Rooper et al. 2014, Sigler et al. 2015). The maps and models created for the eastern Bering Sea (Rooper et al. 2016) and Aleutian Islands (Rooper et al. 2017) have been validated with visual observations in the field that confirmed that coral and sponge ecosystems occur at predictable locations where hard bottom substrate is present. The maps and models created for the Gulf of Alaska, based on trawl survey data, have not been validated with visual surveys.

Visual surveys will be conducted at 300 randomly selected stations in the Gulf of Alaska. The survey design will be stratified by depth, trawlability of the seafloor habitats (both untrawlable and trawlable sites will be surveyed), and model predictions of species presence and will occur from ~30 to ~900 m. At each station, a stereo drop camera system will be deployed and collect 15 minutes of on-bottom imagery from a random starting point, drifting with the prevailing current. Images will be analyzed by identifying and measuring (using stereoscopy) benthic invertebrates and fishes for determining the presence or absence of sponge and coral, species identifications, abundance, and size. Seafloor substrate type will also be recorded. Additionally, ES60 acoustic data that may be used to infer seafloor characteristics, water temperature data, and vessel trackline, depth and position data, will also be collected. In situ water samples will used for eDNA analyses that will be compared with the visual observations of corals, sponges, and fish.

Products will include the development of validated species distribution models/maps for the GOA using seafloor imagery, coral and sponge size data, and potentially eDNA presence/absence data. Species associations between benthic invertebrates and commercially important fishes will also be determined from both visual and eDNA observations.

3.9.2 Refine Estimates of Longline & Pot Gears

The objectives of this project are to obtain more accurate estimates of bottom footprints of longline and pot gears, as well as to examine the susceptibility of corals and sponges to these gears. Once determined, these values can be used to refine and improve the outputs from an already published fishing effects model. In the previous AKCSI, a project was funded to look at the impacts of longline gear on corals and sponges; however, success was limited due to the available camera technology. A benthic impacts camera system (BICS) has been developed in Australia and is a proven system that can be attached to non-rigid fishing gears such as longlines, allowing direct observations of the gear as it interacts with benthic habitats. The footage can be used to determine the footprint of the gear, as well as susceptibility of benthic habitats, such as corals and sponges. This project will attach a benthic impacts camera system onto longline sets made on the AFSC longline survey in the Gulf of Alaska. Utilizing the survey provides a low-cost opportunity to deploy this technology for enhancing our understanding of fishery impacts on corals and sponges. This project may also be expanded to include in-kind support from Alaska Department of Fish and Game (ADFG), who operate pot and longline surveys across Alaska. Video review will be conducted using the Sebastes software package (Williams et al. 2016).

3.9.3 Incorporate Coral and Sponge Covariates into FE model

A Fishing Effects (FE) model was developed to analyze the effects of fishing on habitat during the 2017 Essential Fish Habitat 5-year review. This model was designed to track habitat reductions at monthly time steps by calculating the impacts to habitat from fishing activities each month and simultaneously accounting for habitat recovery from past impacts. At the October 2016 North Pacific Fishery Management Council meeting, the Science and Statistical Committee raised concerns that the longest recovery time incorporated into the FE model (10 years) may not capture the recovery needed for long-lived species; in response, analysts added a new "Long-lived species" feature that lengthened recovery times such that the 50-year upper limit of recovery time was calculated with the expectation that 5% of these long-lived species would require 150 years to recover.

The objective of this project is to incorporate validated coral and sponge species distribution models into the FE workflow, which will allow more precise estimates of the effects of fishing on corals and sponges. During the previous AK DSCSI, models of predicted occurrence of corals and sponges for each of the three major regions of Alaska were developed (Rooper et al. 2014, Sigler et al. 2015, Rooper et al. 2017). Updating the Fishing Effects model to incorporate these data products will require three initial steps: 1) integrate the coral and sponge distribution maps with the existing sediment-based habitat maps, 2) update the corresponding recovery and susceptibility data tables by reviewing the literature of coral and sponge vulnerability studies, and 3) acquire and process the most recently available VMS fishing data. We will then run the Fishing Effects model with these updated data inputs to produce improved estimate of impacts to coral and sponge habitats.

3.9.4 Risk Assessment of Fishing on Corals and Sponges

There are very few Alaska-specific studies on the effects of fishing and the susceptibility of epibenthic organisms to fishing gears and their subsequent recovery. Utilizing VMS data from the Catch-in-Areas database and outputs from the Fishing Effects model, the objective of this study is to develop a risk assessment for corals and sponges in Alaska utilizing the Ecological Risk Assessment for the Effects of Fishing methodology (ERAEF, Hobday et al. 2007, 2011), likely at Level 2. The ERAEF is a framework developed in Australia and adopted by the Marine Stewardship Council. This method has a scoping phase and a three-stage analysis that rates fishing activities for their effects on five ecological components of the ecosystem: target species, bycatch (non-target) species, threatened, endangered, and protected species, habitats, and ecological communities. The scoping phase describes the activities and management of the fishery and its ecological components and compiles all available data and information. The subsequent process becomes more complex with each of the three stages. Each level, however, screens out issues of low or lesser concern, so that the focus is on high-risk issues.

3.9.5 Assessing the Effectiveness of Area Closures for DSCS Communities

The effectiveness of fishing closures has been identified as an "important (near term)" research priority for the North Pacific Fishery Management Council (Research Priority #184 - Evaluate efficacy of habitat closure areas and habitat recovery). This research project will seek to answer both of these questions using a combination of a new field study, vessel monitoring system data from the commercial fishery, and population parameters from literature studies. At the end of the study, we will synthesize these data sources to produce a stock assessment for corals in the Aleutian Islands that will provide preliminary estimates of sustainable bycatch rates for these communities. This would be the first stock assessment of coral in Alaska and perhaps the first for any northern temperate waters.

The objectives of this project are to evaluate the effectiveness of fisheries closures to protect benthic habitat in the Aleutian Islands and western Gulf of Alaska. Specifically, we will address the following: 1) Compare densities of corals and sponges in areas that were closed to mobile bottom contact gear to adjacent open areas where mobile bottom contact fishing has occurred since 2003 or 2005; (2) Compare size structure of corals and sponges in closed and open areas; (3) Compare incidence rates of damaged versus undamaged corals and sponges observed in closed and open areas and examine evidence of fishing in these areas; (4) Examine patterns in fishing effort from vessel monitoring system (VMS) data and compare these to terrain metrics such as slope, depth and ruggedness to determine common habitat features among fished areas; and (5) Use available size data and estimates of growth rates from the literature to make the first estimate of sustainable harvest rates for corals in the Aleutian Island.

A field study to collect data will be conducted in summer 2023 at nine study locations. These study locations have been identified as having high densities of coral and sponge (> 1 colonies/ha) at multiple transects during the 2012 and 2014 underwater camera surveys (Wilborn et al. 2018). In addition to having high densities of corals and sponges, the nine selected sites are all located in areas that have adjacent bottom trawl tows targeting Pacific cod, Atka mackerel, or Pacific ocean perch. Ten or fifteen transect locations will be placed at each of the nine study sites, evenly split among areas closed to fishing, areas with reduced fishing, and areas having continuous fishing (n = 5 per treatment) or evenly split among no fishing and reduced (n = 5 per treatment). To account for potential confounding factors, the depth ranges and substrate classifications for each treatment will be the same. For example, at a site where fishing is occurring over cobble-boulder habitats at 150-200 m depths, only the same types of habitat from non-fishing areas will be used for comparisons.

4 Stock Author Review of EFH FE Output for 2022

Incorporating stock author review of FE-derived habitat disturbance on Core EFH Areas continues to be an integral part of the EFH 5-year review process. The FE team has been in contact with BSAI and GOA Plan Team co-chairs and have agreed the 2017 review process (NPFMC 2016, 2017) will be used for the current review. This approach is detailed in section 2.5.1. Two examples of the stock author reviews conducted in 2017 are provided in Appendix 5.

4.1 Thresholds

The SSC may wish to discuss if the thresholds set by SSC sub-committee in 2016 (NPFMC 2016, Appendix 6) are appropriate following the 2017 EFH 5-year review. These thresholds include: the use of MSST; the 50% quantile threshold of suitable habitat of summer abundance as Core EFH Area; and the use of 10% CEA habitat disturbed as an indicator for stock assessment authors to examine indices of growth-to-maturity, spawning success, breeding success, and feeding success to determine whether there are correlations between those parameters and the trends in the proportion of the CEA impacted by fishing.

We note that the error detected in the 2017 FE model runs (section 3.4) result in some species-specific CEAs over 10%, where there were none in 2017. The FE team will assemble the information necessary for stock authors, Plan Teams, and advisory bodies of the NPFMC to fully review outputs of the FE model as they pertain to managed stocks.

4.2 Example 2022 FE model output with 2017/2022 SDMs

In 2022, the SDMs developed for all EFH species and reviewed by Plan Teams and SSC will be used as the Core EFH Areas for stock author review. The SSC requested examples of 2022 FE output applied to 2022 CEAs. The following sections include preliminary model runs comparing 2017/2022 FE output based on 2017/2022 SDMs for three species; Bering Sea Arrowtooth flounder, which had a 15 percent smaller CEA than in 2017, Aleutian Islands Golden king crab, which had a 98 percent larger CEA than in 2017, and Gulf of Alaska Pacific cod, which had a similar (4 percent smaller) CEA than in 2017. The first figure in each section shows the areal difference between 2017 and 2022 SDMs. The second and third figures are provided to stock authors (as well as a tabular time series) illustrating a map of FE output (habitat disturbance) clipped to the individual species 2022 CEA, as well as the time series of model runs from 2017 and 2022 on each species CEA. Note: the 2022 FE output includes the changes described in Sections 3.4 and 3.5.

4.2.1 Bering Sea Arrowtooth flounder

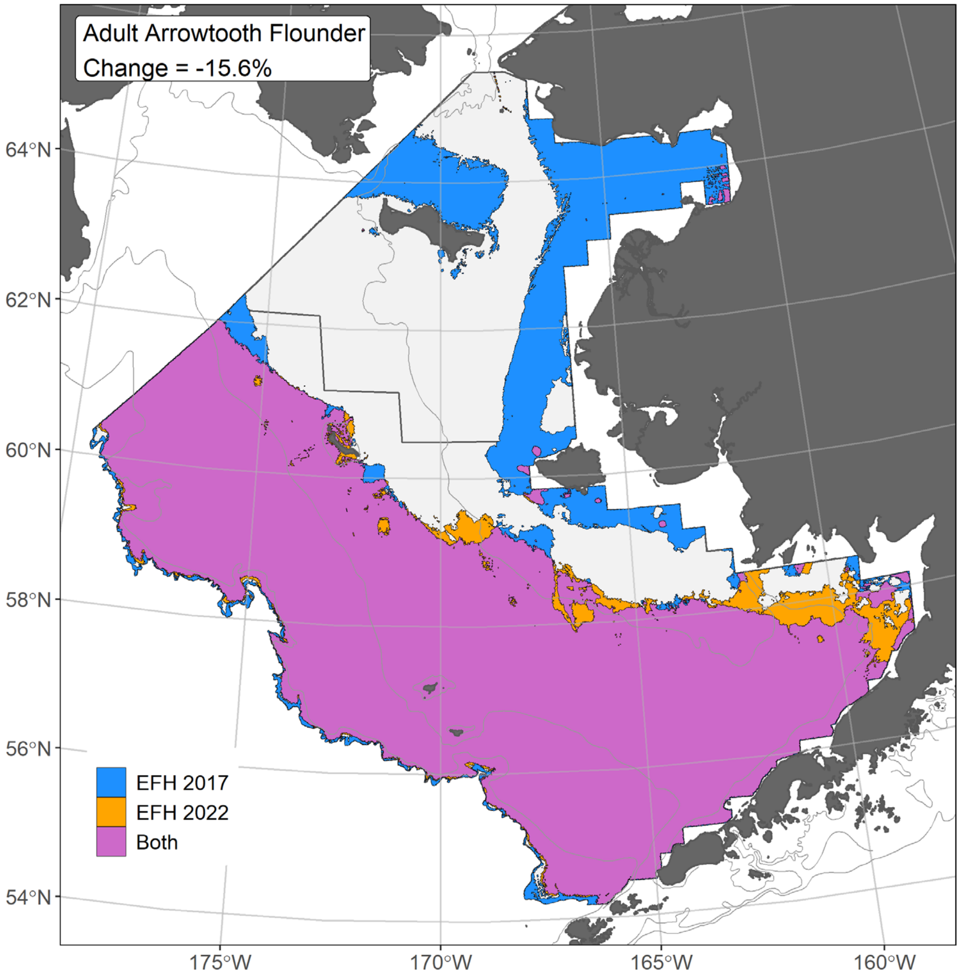

Figure 8: BS Arrowtooth flounder EFH 2017/2022 SDM

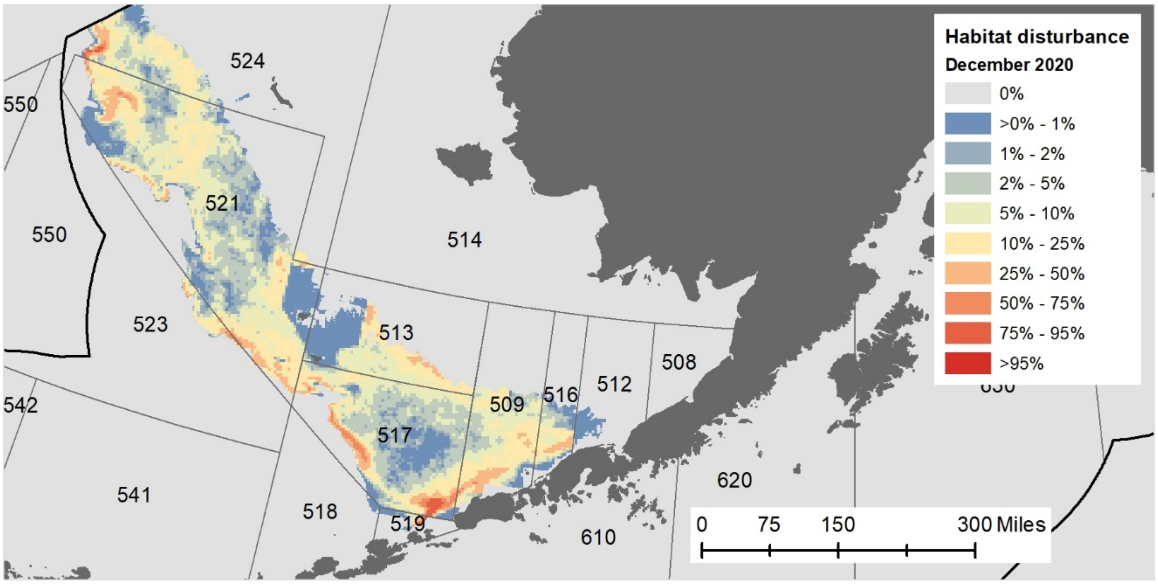

Figure 9: Habitat disturbance - BS Arrowtooth flounder CEA, 2022 FE + 2022 SDM

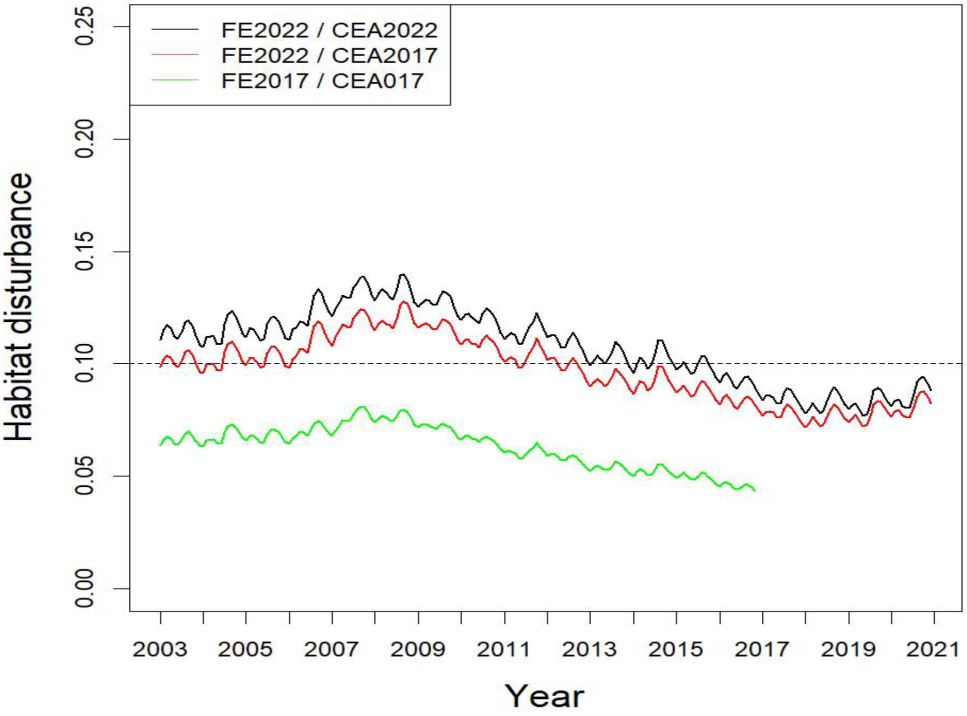

Figure 10: Time series of habitat disturbance – BS Arrowtooth flounder CEA comparison

4.2.2 Aleutian Islands Golden King Crab

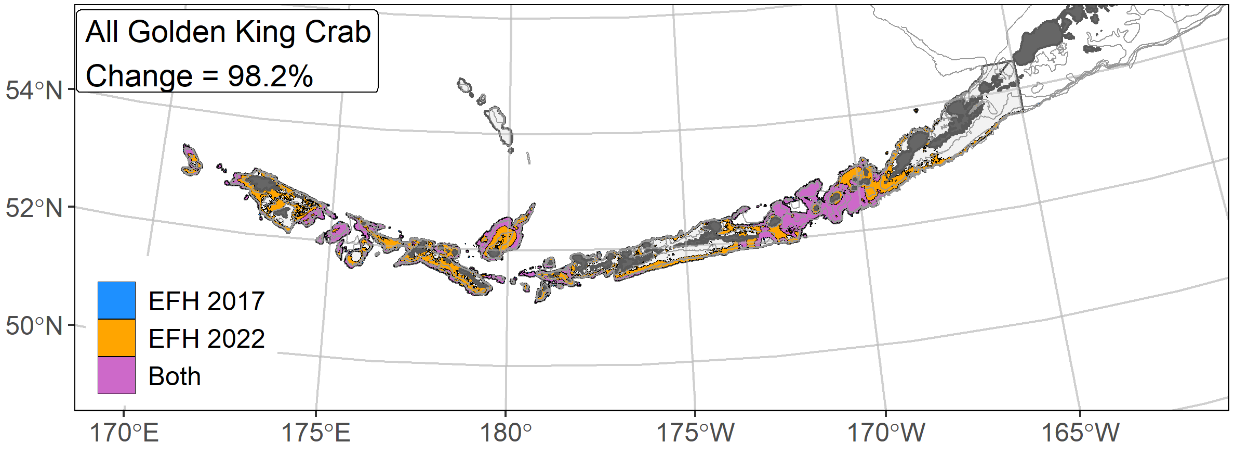

Figure 11: AI Golden king crab EFH 2017/2022 area change

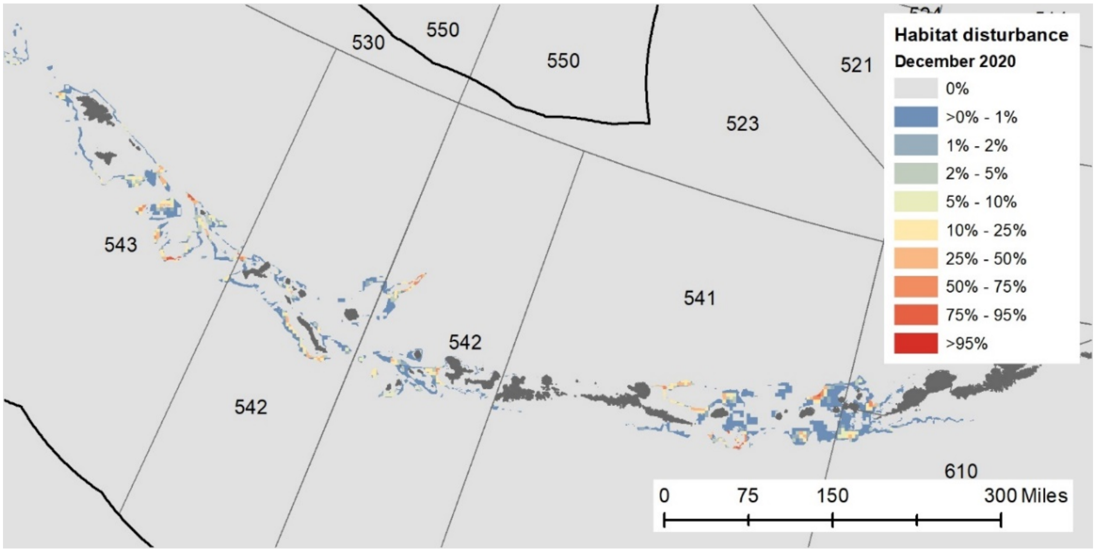

Figure 12: Proportion of habitat disturbance - AI Golden king crab CEA, 2022 FE + 2022 SDM

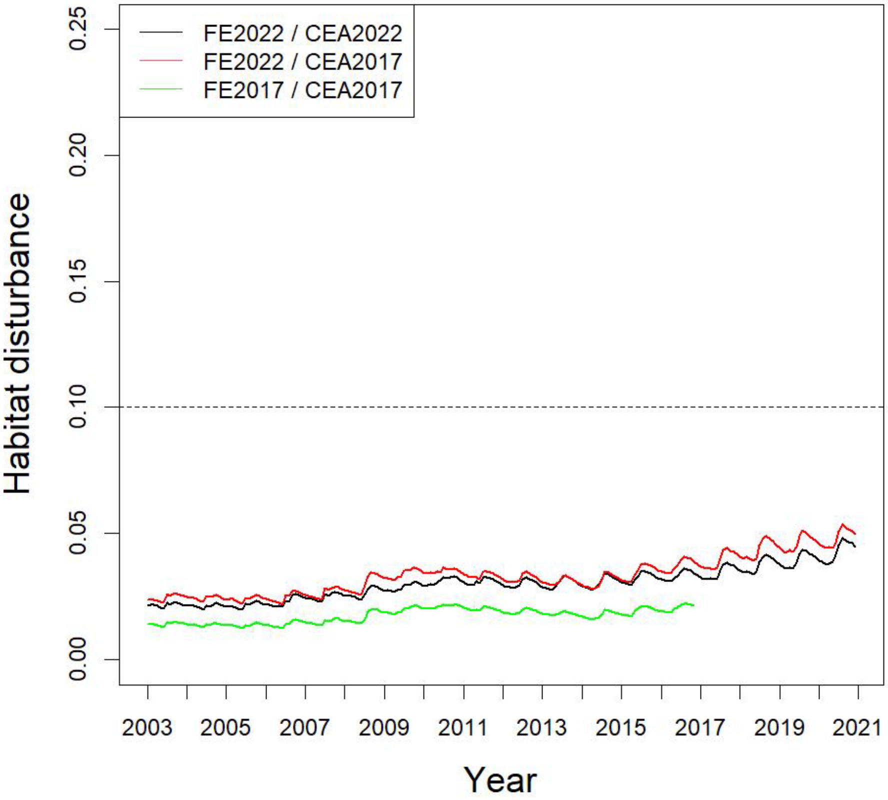

Figure 13: Time series of habitat reduction - AI Golden king crab CEA comparison

4.2.3 Gulf of Alaska Pacific Cod

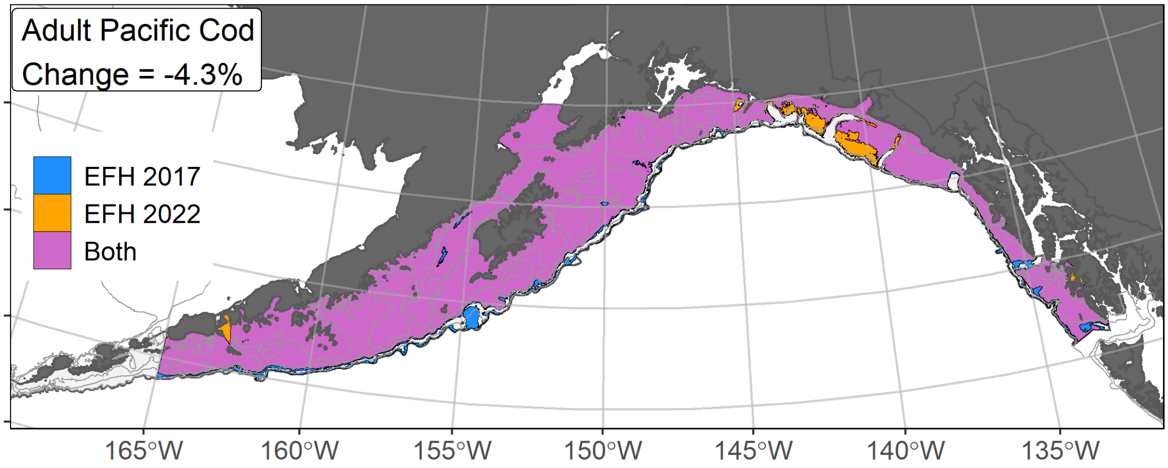

Figure 14: GOA Pacific cod EFH 2017/2022 area change

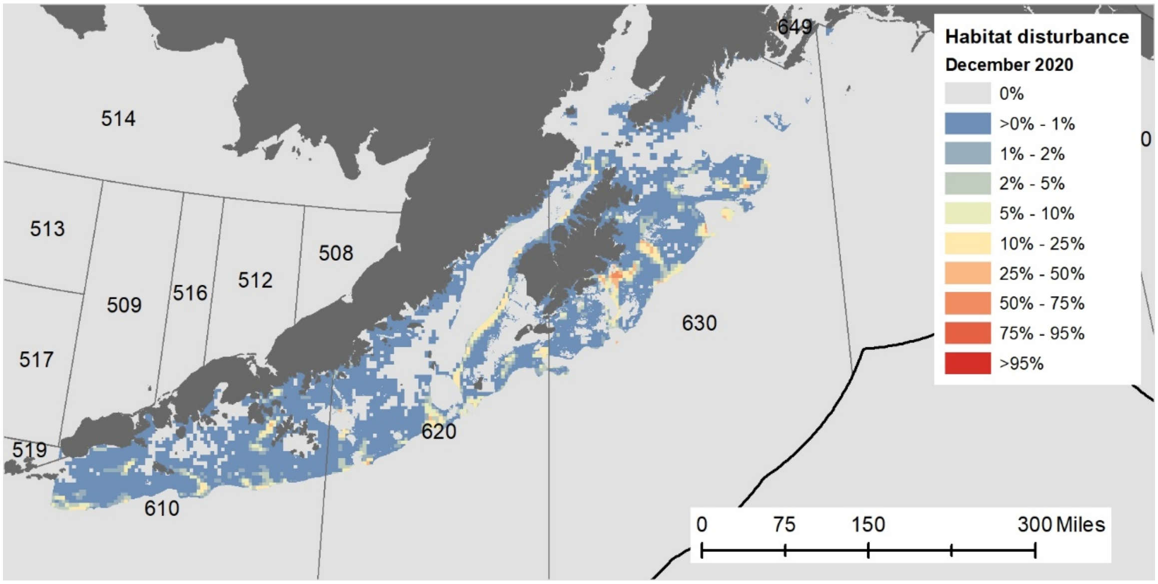

Figure 15: Proportion of habitat disturbance in GOA Pacific cod CEA, 2022 FE + 2022 SDM

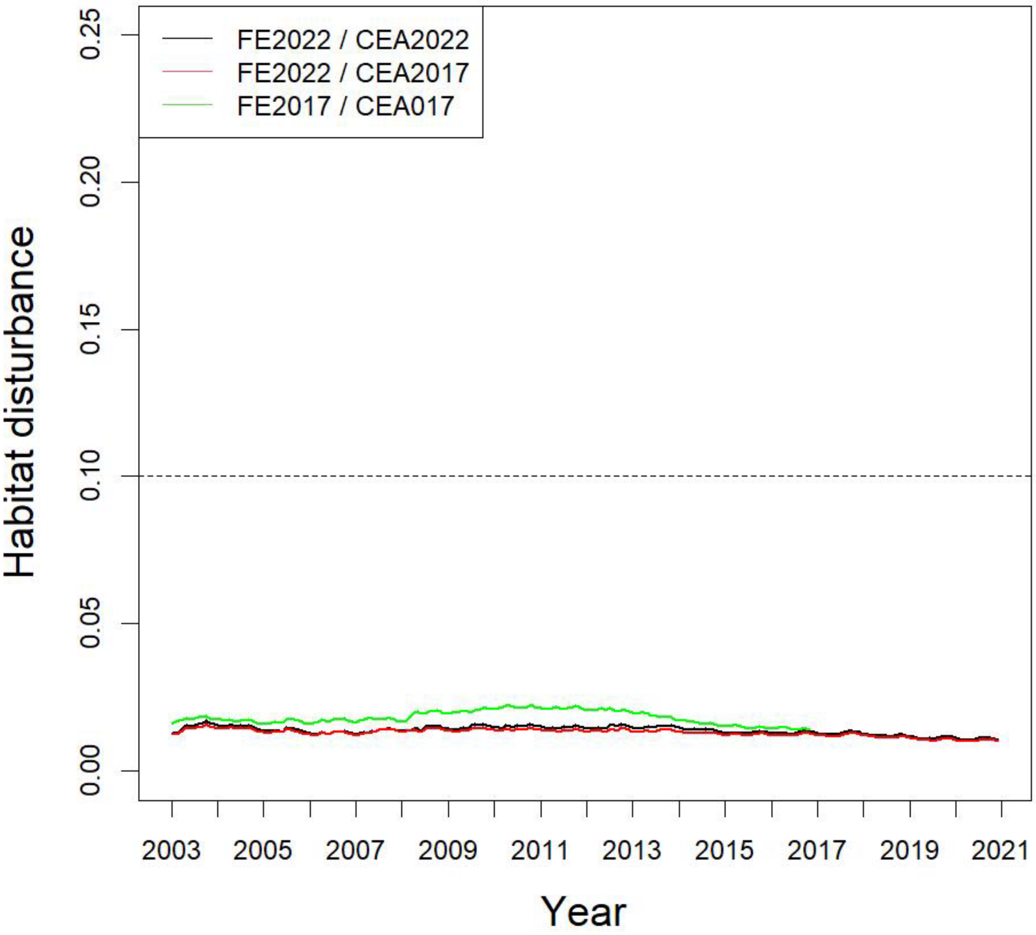

Figure 16: Time series of habitat disturbance - GOA Pacific cod CEA comparison

5 Reference table of responses to SSC requests

Requests from the current EFH review cycle:

1. **Perhaps run the old dataset with old parameters and new parameters to see how they contrast. Then run new data with new parameters**

- Section 3.4, “FE model code”, figure 6

2. **Consider 2017 SSC minutes concerning the use of averages or alternatives for estimation of susceptibility and recovery**.

- Section 3.6, “Feature averaging”

3. **Explain why sediment type must continue to be used as a proxy for habitat susceptibility and recovery rates.**

- Sections 3.2, “Habitat categorization” and 3.3, “Susceptibility and recovery”

4. **Isolate how the new 2022 parameters affect results**

- Section 3.4, “FE model code”

5. **Description of updated data inputs (including those to the catch in area database), new data sets not previously considered, and any methodological changes to the model or treatment of input data.**

- Section 3.1, “Fishing intensity”

6. **Consider including a few key examples of overlays of updated SDMs and FE model results for species that are informative – say ones with large differences.**

- Section 4.2, “Example 2022 FE model output with 2017/2022 SDMs”

7. **Describe whether the EFH Team plans to use the evidence-based approach for evaluation of impacts on spawning, feeding, growth to maturity used in 2017 to evaluate impacts and provide a timeline for completion of this analysis.**

- Section 2.5.1, “Hierarchical impact assessment methods”, Section 4.1 “Thresholds”

Requests from the 2017 EFH review cycle

8. **The SSC requests that the results of sensitivity analyses conducted on the FE model be made available through hyperlinks or other mechanisms to Council documents. These sensitivity analyses provided confidence in the model outcomes and would assist future reviewers in fully evaluating the model.**

- Section 2.4, “Sensitivity analysis”

9. **The SSC requests that maps of fishing effects by species-specific CEA be included in the assessment through hyperlinks. If the authors are willing to release their full discussions of the assessment of effects of fishing on EFH, then the SSC requests that these be included as an appendix to the document.**

- We will include CEA links for the June 2022 meeting and discuss the release of author assessments with Plan Team chairs.

10. **The SSC notes that for the purposes of this assessment, corals were considered a living structure. However, techniques are emerging that would allow the assessment of corals to be assessed as an ecosystem component.**

- Section 2.3, “Incorporation of longer recovery times into FE model”, Section 3.9, “Alaska Coral & Sponge Initiative projects “

11. **A summary of major EFH elements that have already been peer-reviewed (e.g., the fishing effects model and research outlined in the initial June 2019 work plan).**

- Smeltz, T.S., Harris, B., Olson, J., and Sethi, S. 2019. A seascape-scale habitat model to support management of fishing impacts on benthic ecosystems. Canadian Journal of Fisheries and Aquatic Sciences, 2019, 76(10): 1836-1844, https://doi.org/10.1139/cjfas-2018-0243
- NEFMC. 2020. Fishing Effects Model Northeast Region. https://s3.amazonaws.com/nefmc.org/Fishing_Effects_Northeast_Report_edited-May-22-2020.pdf

12. **Specifically, we encourage continuation of studies that examine the potential benefits of gear modifications. The document provides insight into locations where habitat impacts are intensely and lightly impacted. This might provide an opportunity for future comparative approaches**.
    - No gear modification research has been conducted relative to habitat effects since the 2017 EFH 5-year review.
    - One funded project in development will refine the impact estimates for longline and pots gears, Section 3.9.2 "Refine Estimates of Longline & Pot Gears ". Initial field deployment expected on the 2022 AFSC longline survey.

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Appendix 1 FE model description

Habitat states

The Fishing Effects model incorporates two mutually exclusive habitat states: undisturbed habitat, H, and disturbed habitat, h (see Table 1 for a list of all model parameters). Casting H and h as proportions of a spatial domain, then:

$$H + h = 1 \qquad (1),$$

where $H \in [0,1]$ and $h \in [0,1]$. The Fishing Effects model considers transitions between H and h in discrete time steps, t. Let $\tilde{I}_t$ represent the proportion of H that transitions to h by fishing impacts from one time step to the next, and $\tilde{\rho}_t$ as the proportion of h that recovers to H over the same time step, leading to the discrete-time habitat state equation:

$$H_{t+1} = H_t(1 - \tilde{I}_t) + h_t\tilde{\rho}_t \qquad (2),$$

where $\tilde{I}_t \in [0,1)$ and $\tilde{\rho}_t \in [0,1)$. Thus far, Eqs. 1-2 imply a single generic model spatial domain. In practice, the fishing impacts model is implemented on a spatially explicit grid, with H indexed by both time, t, and cell, i.

A given model grid cell can contain multiple types of habitat, indexed by s. As outlined below, the Fishing Effects model accounts for impacts and recovery at the level of specific habitat types. Subsequently, for the purposes of calculating the aggregate proportion of disturbed habitat within a given cell at a point in time, $H_{i,t}$ is calculated as a weighted mean over k habitat types based on the proportion of each habitat type in the cell, $\phi_{i,s}$,

$$H_{i,t} = \sum_{s=1}^{k} H_{t,\mathrm{i},s}\,\phi_{i,s} \qquad (3),$$

where $\phi_{i,s} \in [0,1]\ \forall s = 1, \ldots, k$ and $\sum_{s=1}^{k} \phi_{i,s} = 1$. Although habitat types may be treated as spatially explicit regions within a grid cell, in practice such fine resolution habitat information is usually not available. Thus, it is assumed that each habitat type is distributed uniformly throughout a grid cell, and habitat proportions, $\phi_{i,s}$, are not indexed on t in the model formulation. An implication of this is that the *relative* proportions of habitat types within cells remains fixed across time, regardless of where and to what extent fishing events occur within cells.

Impacts

The impacts process translates fishing activity into disturbed habitat outcomes, i.e. governing the transition of H to h. Impacts, $I_{i,t,s,j(g)}$, represent a proportionate area of a habitat type in a grid cell that could convert from undisturbed to disturbed in a time step from a single fishing event j (e.g. a single tow, deployment of a longline, etc.). For what follows, the notation "(g)" is used to emphasize dependencies on gear configuration for a given model quantity where appropriate (i.e. $j(g)$ and $s(g)$). $I_{i,t,s,j(g)}$, are decomposed as the product of $f_{i,t,s,j(g)}$, the proportionate area of a habitat in a cell contacted during a fishing event with gear, g, and susceptibility, $q_{s(g)}$, the proportion of a habitat impacted by contact with the gear, where susceptibility is unique to each habitat-gear combination:

$$I_{i,t,s,j(g)} = f_{i,t,s,j(g)} q_{s(g)} \qquad (4),$$

where $f_{i,t,s,j(g)} \in [0, \infty)$ and $q_{s(g)} \in [0,1]\ \forall \mathrm{s} = 1, \ldots, k$.

Generally, $f_{i,t,s,j(g)}$, represents the amount of contact with the seafloor by fishing gear and will often be less than the nominal area swept by a gear because only certain gear elements are actually in contact with the seafloor. Furthermore, explicit inclusion of a contact adjustment parameter provides functionality to model gear modifications that lift gear elements off the seafloor. To accommodate this feature, $f_{i,t,s,j(g)}$ is decomposed as the product of nominal area swept, $A_{i,t,s,j(g)}$, and gear specific contact adjustment, $c_{j(g)}$:

$$f_{i,\mathrm{t},s,j(g)} = A_{i,t,s,j(g)} c_{\mathrm{j}(g)} \qquad (5),$$

where $A_{i,t,s,j(g)} \in [0, \infty)$ and $c_{j(g)} \in [0,1]\ \forall\ g = 1, \ldots, r$ for r gear types. In practice, since the distribution of habitats within a grid cell is not spatially explicit, $A_{i,t,s,j(g)}$ is distributed proportionally among all habitat types within a grid cell. Because $A_{i,t,s,j(g)}$ is measured as a proportion itself, $A_{i,t,s,j(g)}$ will simply equal the proportional swept area of the grid cell for all habitat types (i.e. $A_{i,t,s,j(g)} = A_{i,t,j(g)}$).

Note that $A_{i,t,s,j(g)}$, and the related quantities $f_{i,t,s,j(g)}$ and $I_{i,t,s,j(g)}$, are unbounded in the positive direction, indicating proportions that exceed unity. This arises if a fishing event within a cell has a nominal swept area that exceeds the area of the cell. The only way this could occur at the level of a single fishing event is if the tow overlapped with itself. Furthermore, in most fishing applications, a given grid cell will experience multiple fishing events, possibly from multiple fisheries and possibly with overlapping swept area. Thus, the Fishing Effects model need account for aggregate impacts in a cell, and accommodating potentially overlapping fishing effort. To get an aggregate value of $I_{i,t,s,j(g)}$ in a cell, $I_{i,t,s,\bullet}$, we sum impacts across m fishing events that occur in a time step in a cell for a respective habitat type:

$$\mathrm{I}_{i,t,s,\bullet} = \sum_{j=1}^{m} I_{i,t,s,j} \qquad (6).$$

Because$I_{i,t,s,\bullet}$ is a sum of potentially multiple events which can overlap, it often exceeds unity in practice. We account for this aggregate impact by calculating $\tilde{I}$ from Eq. 2 as a strict proportion of impacted area as:

$$\tilde{I}_{i,t,s} = 1 - \mathrm{e}^{-I_{\mathrm{i,t,s,}\bullet}} \qquad (7),$$

producing the constraint of $\tilde{I} \in [0,1)$. While not obvious, the relationship in Eq. 7 which accounts for potentially overlapping effort implies that fishing events are randomly distributed within a grid cell (see Smeltz et *al*. 2019 Supplemental Materials for derivation and test of this assumption). If fishing activity is more aggregated in space than random (within a grid cell), Eq. 7 would produce an overestimation of $\tilde{I}$; uniformly distributed fishing activity would result in an underestimation (Ellis *et al.*, 2014). Note, the scale of the grid cell will affect this assumption. At a seascape scale, fishing activity is clearly aggregated, but at smaller scales (e.g., an area smaller than the swept area of a single tow) fishing becomes uniformly distributed. It is also important to note that because habitat states are binary in the model, repeated impacts do not continue to produce an increased intensity of disturbed habitat. For example, if $\tilde{I}_{i,t,s}$ is large, but the proportion of disturbed habitat in a grid cell is already high from past impacts, there will be little additional disturbance caused by a high $\tilde{I}_{i,t,s}$.

Recovery

In the Fishing Effects model, recovery $\tilde{\rho}_{i,t,s}$, is the proportion of disturbed habitat, $h_{i,t,s}$, that transitions to undisturbed habitat, $H_{i,t,s}$, from one time step to the next. Since $\tilde{\rho}_{i,t,s}$ is indexed by *t,* it can be time-varying and incorporate seasonality or other dynamic features. In the simpler case where $\tilde{\rho}_{i,t,s}$ is held constant through time, reflecting a fixed proportional recovery each time step, recovery occurs most rapidly when $H = 0$ and slows asymptotically as $H \to 1$. In practice, most benthic habitat empirical studies estimate the time required for disturbed habitat to recover to pre-disturbance conditions (e.g Grabowski *et al.*, 2014). To accommodate this form of recovery information, we cast $\tilde{\rho}_{i,t,s}$ as a discretized rate based upon a mean time to recovery parameter, τ_s:

$$\tilde{\rho}_{i,t,s} = 1 - e^{(-1/\tau_s)} \qquad (8),$$

where τ_s is strictly positive. This model is consistent with an exponential time-to-event recovery process parameterized with a mean time to recovery, producing a concave asymptotic recovery curve.

Model implementation

Requirements to implement the Fishing Effects model include: 1) a defined spatial domain with an appropriate-sized grid overlay; 2) the spatial distribution of habitats within the model domain; 3) fishing event locations, most likely derived from electronic monitoring such as vessel monitoring system (VMS) data; 4) nominal gear width and gear contact adjustments for each fishing event; and 5) habitat susceptibility and recovery parameters.

Spatial domain and habitat distribution

The model implemented for the 2022 NPFMC EFH 5-year review was run for the North Pacific within the United States Exclusive Economic Zone, and depths less than 1,000 m to define the continental shelf, resulting in a total domain area of 1.2 million km^2. A 5 km x 5 km grid overlay was used for the analysis reflecting availability of fishing and habitat information within the North Pacific fishery management system (e.g. NOAA, 2017b). High resolution information on the spatial distribution of specific benthic habitat features was not domain-wide, however, observations from sediment surveys in the North Pacific were more widely available. Thus, we used sediment-based habitat categories (mud, sand, granule/pebble, cobble, and boulder) and developed a GIS workflow to map the sediment observations across the domain. Sediment observations (232,517 total points) were combined in a GIS, and parsed using a text mining algorithm (Feinerer and Hornik, 2017) to map over 8,861 different sediment labels onto the five primary sediment categories. Subsequently, indicator kriging interpolation (Geospatial Analyst, ArcGIS v10.4.1) was used to create a presence/absence surface for each sediment on a 2.5 km grid. This resulted in four sediment grid cells nested within each 5 km model grid. To calculate the sediment proportions for a respective 5 km model grid, $\phi_{i,s}$, we found the ratio of the sum of the four sediment cells, k, with a specific sediment present, $\pi_{i,s} \in \{0, 1\}$, to the sum of sediment cells present for all five sediments,

$$\phi_{i,s} = \frac{\sum_{k=1}^{4} \pi_{i,s,\mathrm{k}}}{\sum_{s=1}^{5} \sum_{k=1}^{4} \pi_{i,s,\mathrm{k}}} \qquad (9).$$

Fishing gear and fishing effort

Spatially explicit fishing effort was obtained from the Catch-In-Areas database from the US National Marine Fisheries Service, consisting of VMS tracks of all commercial fishing vessels from 2003 – 2016 in the North Pacific. Gear specific nominal widths and contact adjustment parameters were taken from a database of gear compiled by the NPFMC (2017). Gear widths ranged from 50.0 m – 259.0 m for trawls, 2.0 meters for longlines, and 0.2 m for pots. The polylines of fishing activity were buffered by one-half the nominal widths and intersected with the 5 km grid (ArcGIS v10.4.1). Contact adjustment was reported in the database as a range for each gear type. A value was randomly selected from within these ranges when calculating impacts for each fishing activity. Contact adjustment was set to unity (complete contact) prior to 2011 and 2014 for Bering Sea and Gulf of Alaska flatfish trawls, respectively, and ranged from 0.20 to 0.75 afterwards (i.e. 25% - 80% reduction in seafloor contact) to reflect the implementation of required raised sweep gear modifications on flatfish targeting vessels.

Susceptibility and recovery

Susceptibility, $q_{s(g)}$, and recovery, τ_s, characterize benthic ecosystem vulnerability to fishing impacts, translating fishing events into temporally explicit estimate of habitat disturbance. For this implementation, we adapted $q_{s(g)}$and τ_s from the Grabowski *et al.* (2014) review of habitat vulnerabilities to fishing activity. Grabowski *et al.* (2014) report scores for $q_{s(g)}$and τ_s that represent a range of values for habitat features associated with each of the sediment categories used in this case study. For example, habitat features with the lowest susceptibility score represented a $q_{s(g)}$ range of 0% – 10%, whereas the highest $q_{s(g)}$ range was 50% – 100%. The scores for recovery represented a τ_s of 0 – 1 year for the fasting recovering habitat features and >5 years for the slowest, though for this implementation we capped the maximum recovery to 10 years. For some habitat features, separate scores for low and high physical energy levels based on benthic boundary shear stress (low energy: <0.194 Nm^{-2}) or depth (low energy: >60 m depth). In these cases, we used the low energy values because fishing locations in the North Pacific are generally at depths greater than 60 m. To reflect parameter uncertainty in incorporating these recovery and susceptibility values into the Fishing Effects models, we drew random values from within the reported ranges of individual habitat features then averaged these over all habitat features associated with a given habitat type. This random selection was conducted for each grid cell and time step.

Initial conditions

Options for initial habitat conditions for a model run, H_0, include starting from "pristine" undisturbed habitat, a case-specific set of initial conditions that match a known habitat states, or equilibrium initial conditions based upon a "burn in" period under constant fishing effort. With insufficient data available to determine the spatial distribution of impacts prior to 2003, but operating on the assumption that impacts were present, we used a "burn in" approach for the North Pacific. To calculate H_0, we first randomly selected a value for an initial H_0 from a uniform distribution (zero to unity) for all grid cells that had nonzero fishing effort from 2003 – 2016. We then ran the model using the first three years of fishing data (2003 – 2005) repeated ten times, resulting in a total burn-in of 30 years which provided ample time for the model to lose dependence on the initial H_0 and reach a stable habitat state. The terminal month of the burn-in period was then used as H_0 for the actual model run.

Table 1. Model parameters and indices.

Model Parameters	Description
H	Undisturbed habitat
h	Disturbed habitat
$\tilde{I}$	Proportional impacts
$\tilde{\rho}$	Proportional recovery
$I_{i,t,s,j(g)}$	Impact from a fishing event
$f_{i,t,s,j(g)}$	Ground contact by a fishing event
$q_{s(g)}$	Susceptibility
$A_{i,t,s,j(g)}$	Nominal swept area by a fishing event
$c_{j(g)}$	Contact adjustment

τ_s	Mean time to recover
$\phi_{i,s}$	Proportional habitat cover
Model indices	
i	Grid cell, for n total cells
t	Time step
s	Habitat types, for k total habitats
j	Fishing event, for m total events
g	Gear type, for r total gears

Appendix 2 Gear Parameter Table

Fishery	Vessel type	Area	Gear	Target 1	Target 2	Vessel Length (ft)	Season	Depth Range (fath.)	Nom Width (m)	Adj Low	Adj Med	Adj
GOA Pollock Pelagic Trawl Sand Point	CV	GOA	PTR	P	all others	<75			50	1	1	1
GOA Pollock Pelagic Trawl	CV	GOA	PTR	P	all (but K, S)	≥75			75	0	0.2	0.4
GOA Slope Rockfish Pelagic Trawl	CV	GOA	PTR	K	S	≥75			75	0	0.2	0.4
GOA Slope Rockfish Pelagic Trawl	CP	GOA	PTR	K	W	all			100	0	0.2	0.4
GOA PCod Bottom Trawl Inshore	CV	GOA	NPT	C	B, P	≥75			90	1	1	1
GOA Deepwater Flatfish Bottom Trawl	CV	GOA	NPT	D	W, X	≥75			90	0.26	0.26	0.26
GOA Shallowwater Flatfish Bottom Trawl	CV	GOA	NPT	H	all others	≥75			90	0.26	0.26	0.26
GOA PCod Bottom Trawl Sand Point	CV	GOA	NPT	C	all others	<75			55	1	1	1
GOA Deepwater Flatfish Bottom Trawl CP	CP	GOA	NPT	D, W	X	all			193	0.26	0.26	0.26
GOA Shallowwater Flatfish/Cod Bottom Trawl CP	CP	GOA	NPT	H, C	L, all others	all			193	0.26	0.26	0.26
GOA Slope Rockfish Bottom Trawl CP	CP	GOA	NPT	K	S	all			75	1	1	1
BS Pollock Pelagic Trawl (incl Mothership)	CV	BS	PTR	P	B, all others	<125 ≥300	A	≥90	62	0.2	0.4	0.6
BS Pollock Pelagic Trawl (incl Mothership)	CV	BS	PTR	P	B, all others	<125 ≥300	A	60-90	58	0.2	0.4	0.6
BS Pollock Pelagic Trawl (incl Mothership)	CV	BS	PTR	P	B, all others	<125 ≥300	A	<60	50	0.2	0.4	0.6
BS Pollock Pelagic Trawl (incl Mothership)	CV	BS	PTR	P	B, all others	<125 ≥300	B	≥90	77	0.2	0.4	0.6

Fishery	Vessel type	Area	Gear	Target 1	Target 2	Vessel Length (ft)	Season	Depth Range (fath.)	Nom Width (m)	Adj Low	Adj Med	Adj
BS Pollock Pelagic Trawl (incl Mothership)	CV	BS	PTR	P	B, all others	<125 ≥300	B	60-90	73	0.2	0.4	0.6
BS Pollock Pelagic Trawl (incl Mothership)	CV	BS	PTR	P	B, all others	<125 ≥300	B	<60	64	0.2	0.4	0.6
BS Pollock Pelagic Trawl	CV	BS	PTR	P	B, all others	125-151	A	≥90	93	0.2	0.4	0.6
BS Pollock Pelagic Trawl	CV	BS	PTR	P	B, all others	125-151	A	60-90	87	0.2	0.4	0.6
BS Pollock Pelagic Trawl	CV	BS	PTR	P	B, all others	125-151	A	<60	75	0.2	0.4	0.6
BS Pollock Pelagic Trawl	CV	BS	PTR	P	B, all others	125-151	B	≥90	115	0.2	0.4	0.6
BS Pollock Pelagic Trawl	CV	BS	PTR	P	B, all others	125-151	B	60-90	109	0.2	0.4	0.6
BS Pollock Pelagic Trawl	CV	BS	PTR	P	B, all others	125-151	B	<60	96	0.2	0.4	0.6
BS Pollock Pelagic Trawl	CV	BS	PTR	P	B, all others	151-300	A	≥90	132	0.2	0.4	0.6
BS Pollock Pelagic Trawl	CV	BS	PTR	P	B, all others	151-300	A	60-90	124	0.2	0.4	0.6
BS Pollock Pelagic Trawl	CV	BS	PTR	P	B, all others	151-300	A	<60	106	0.2	0.4	0.6
BS Pollock Pelagic Trawl	CV	BS	PTR	P	B, all others	151-300	B	≥90	163	0.2	0.4	0.6
BS Pollock Pelagic Trawl	CV	BS	PTR	P	B, all others	151-300	B	60-90	154	0.2	0.4	0.6
BS Pollock Pelagic Trawl	CV	BS	PTR	P	B, all others	151-300	B	<60	137	0.2	0.4	0.6
BS Pollock Pelagic Trawl	CP	BS	PTR	P	B, all others	all	A	≥90	142	0.7	0.8	0.9
BS Pollock Pelagic Trawl	CP	BS	PTR	P	B, all others	all	A	60-90	133	0.7	0.8	0.9
BS Pollock Pelagic Trawl	CP	BS	PTR	P	B, all others	all	A	<60	114	0.7	0.8	0.9

Fishery	Vessel type	Area	Gear	Target 1	Target 2	Vessel Length (ft)	Season	Depth Range (fath.)	Nom Width (m)	Adj Low	Adj Med	Adj
BS Pollock Pelagic Trawl	CP	BS	PTR	P	B, all others	all	B	≥90	175	0.8	0.9	1
BS Pollock Pelagic Trawl	CP	BS	PTR	P	B, all others	all	B	60-90	166	0.8	0.9	1
BS Pollock Pelagic Trawl	CP	BS	PTR	P	B, all others	all	B	<60	147	0.8	0.9	1
BS Pcod Bottom Trawl	CV	BS	NPT	C	all others	LE 100			90	1	1	1
BS Pcod Bottom Trawl	CV	BS	NPT	C	all others	GT100 LE250			110	1	1	1
BS Pcod YFS Bottom Trawl mothership	CV	BS	NPT	Y	C, all others	GT250 (or Processor M)			90	1	1	1
BS Pcod Bottom Trawl	CP	BS	NPT	C	B,P	<150			193	0.27	0.27	0.27
BS Rock Sole Bottom Trawl	CP	BS	NPT	R		<150			193	0.27	0.27	0.27
BS Yellowfin Sole Bottom Trawl a80	CP	BS	NPT	Y		<150			193	0.27	0.27	0.27
BS Flathead Sole/ Other Flat Bottom Trawl	CP	BS	NPT	L	F, W, all others	<150			193	0.27	0.27	0.27
BS Pcod Bottom Trawl	CP	BS	NPT	C	B, P	≥150 <225			259	0.27	0.27	0.27
BS Rock Sole Bottom Trawl	CP	BS	NPT	R		≥150 <225			259	0.27	0.27	0.27
BS Yellowfin Sole Bottom Trawl a80	CP	BS	NPT	Y		≥150 <225			259	0.27	0.27	0.27
BS Flathead Sole/ Other Flat Bottom Trawl	CP	BS	NPT	L	F, W, all others	≥150 <225			259	0.27	0.27	0.27
BS Bottom Trawl - non a80	CP	BS	NPT	Y	all others	225+			259	0.27	0.27	0.27
BS POP Bottom Trawl	CP	BS	NPT	K	S, T	<250			100	1	1	1

Fishery	Vessel type	Area	Gear	Target 1	Target 2	Vessel Length (ft)	Season	Depth Range (fath.)	Nom Width (m)	Adj Low	Adj Med	Adj
AI Pcod Bottom Trawl mothership	CV	AI	NPT	C	all others	>250 (or Processor M)			75	1	1	1
AI Pcod Bottom Trawl	CV	AI	NPT	C	all others	<99			55	1	1	1
AI Pcod Bottom Trawl	CV	AI	NPT	C	all others	≥99			90	1	1	1
AI Atka and Rockfish Bottom Trawl	CP	AI	NPT	A	K, all others	all			100	1	1	1
AI Pollock		AI	PTR	P	all				100	0	0.1	0.2
GOA PCod Pot		GOA	POT	C	all others				5.6	0.5	0.75	1
BSAI Pcod Pot		BSAI	POT	C	all others				5.6	0.5	0.75	1
BSAI Sablefish Pot		BSAI	POT	S	T				5.6	0.5	0.75	1
GOA Sablefish Pot (few, but future) can combine BS for now		GOA	POT	S	T				5.6	0.5	0.75	1
GOA Sablefish Longline		GOA	HAL	S	T				6	0	0.5	1
GOA SE Demersal Shelf Rock Longline		GOA	HAL	K					6	0	0.5	1
GOA Halibut longline		GOA	HAL	I					6	0	0.5	1
GOA Pcod Longline		GOA	HAL	C	all others				6	0	0.5	1
BSAI Pcod Longline		BSAI	HAL	C	all others				6	0	0.5	1
BSAI Sabelfish/ Greenland Turbot Longline		BSAI	HAL	S	T				6	0	0.5	1
BSAI Halibut longline		BSAI	HAL	I					6	0	0.5	1
PCod Jig (also rockfish and halibut)		GOA	JIG	C	all others				0.2	0	0.5	1
BS Pcod Jig		BS	JIG	C	all others				0.2	0	0.5	1

Fishery	Vessel type	Area	Gear	Target 1	Target 2	Vessel Length (ft)	Season	Depth Range (fath.)	Nom Width (m)	Adj Low	Adj Med	Adj
AI Jig		AI	JIG	C	all others				0.2	0	0.5	1

Appendix 3 Susceptibility & Recovery Tables

Table 1. Hook-and-line (HAL) susceptibility codes

Feature Class	Feature	Mud	Sand	Gran/Peb	Cobble	Boulder	Deep/rocky
G	Bedforms		0				
G	Biogenic burrows	1	1				
G	Biogenic depressions	0	1				
G	Boulder, piled					0	0
G	Boulder, scattered, in sand					0	0
G	Cobble, pavement				0		0
G	Cobble, piled				1		1
G	Cobble, scattered in sand				0		0
G	Granule-pebble, pavement			0			
G	Granule-pebble, scattered, in sand			0			
G	Sediments, suface/subsurface	0	0				
G	Shell deposits		0	0			
B	Amphipods, tube-dwelling	1	1				
B	Anemones, actinarian			1	1	1	1
B	Anemones, cerianthid burrowing	1	1	1			
B	Ascidians		1	1	1	1	1
B	Brachiopods			1	1	1	1
B	Bryozoans			1	1	1	1
B	Corals, sea pens	1	1				
B	Hydroids	1	1	1	1	1	1
B	Macroalgae			1	1	1	1
B	Mollusks, epifaunal bivalve, Modiolus modiolus	0	0	0	0	0	0
B	Mollusks, epifaunal bivalve, Placopecten magellanicus	0	0	0	0	0	0
B	Polychaetes, Filograna implexa		1	1	1	1	1
B	Polychaetes, other tube-dwelling			1	1	1	1
B	Sponges		0	1	1	1	1

Adapted from longline susceptibility table (Grabowski et al. 2014)

Susceptibility codes: 0: 0-10%; 1: 10-25%; 2: 25-50%; 3: >50%

Blank spaces are habitat features not associated with the given sediment class

G = Geological features; B = Biological features

Table 2. Pot (POT) susceptibility codes

Feature Class	Feature	Mud	Sand	Gran/Peb	Cobble	Boulder	Deep/rocky
G	Bedforms		0				
G	Biogenic burrows	1	1				
G	Biogenic depressions	1	1				
G	Boulder, piled					0	0
G	Boulder, scattered, in sand					0	0
G	Cobble, pavement				0		0
G	Cobble, piled				1		1
G	Cobble, scattered in sand				0		0
G	Granule-pebble, pavement			0			
G	Granule-pebble, scattered, in sand			0			
G	Sediments, suface/subsurface	1	1				
G	Shell deposits		0	0			
B	Amphipods, tube-dwelling	1	1				
B	Anemones, actinarian			1	1	1	1
B	Anemones, cerianthid burrowing	1	1	1			
B	Ascidians		1	1	1	1	1
B	Brachiopods			1	1	1	1
B	Bryozoans			1	1	1	1
B	Corals, sea pens	1	1				
B	Hydroids		1	1	1	1	1
B	Macroalgae			1	1	1	1
B	Mollusks, epifaunal bivalve, Modiolus modiolus	0	0	1	1	1	1
B	Mollusks, epifaunal bivalve, Placopecten magellanicus		0	0	0		
B	Polychaetes, Filograna implexa		1	1	1	1	1
B	Polychaetes, other tube-dwelling			1	1	1	1
B	Sponges		0	1	1	1	1

Adapted from trap susceptibility table (Grabowski et al. 2014)

Susceptibility codes: 0: 0-10%; 1: 10-25%; 2: 25-50%; 3: >50%

Blank spaces are habitat features not associated with the given sediment class

G = Geological features; B = Biological features

Table 3. Nonpelagic (NPT) and pelagic (PTR) trawl susceptibility codes

Feature Class	Feature	Mud	Sand	Gran-Peb	Cobble	Boulder
G	Bedforms		2			
G	Biogenic burrows	2	2			
G	Biogenic depressions	2	2			
G	Boulder, piled					2
G	Boulder, scattered, in sand					0
G	Cobble, pavement				1	
G	Cobble, piled				3	
G	Cobble, scattered in sand				1	
G	Granule-pebble, pavement			1		
G	Granule-pebble, scattered, in sand			1		
G	Sediments, suface/subsurface	2	2			
G	Shell deposits		1	1		
B	Amphipods, tube-dwelling	1	1			
B	Anemones, actinarian			2	2	2
B	Anemones, cerianthid burrowing	2	2	2		
B	Ascidians		2	2	2	2
B	Brachiopods			2	2	2
B	Bryozoans			1	1	1
B	Corals, sea pens	2	2			
B	Hydroids	1	1	1	1	1
B	Macroalgae			1	1	1
B	Mollusks, epifaunal bivalve, Modiolus modiolus	1	1	2	2	2
B	Mollusks, epifaunal bivalve, Placopecten magellanicus		2	1	1	
B	Polychaetes, Filograna implexa		2	2	2	2
B	Polychaetes, other tube-dwelling			2	2	2
B	Sponges		2	2	2	2

Adapted from trap susceptibility table (Grabowski et al. 2014)

Susceptibility codes: 0: 0-10%; 1: 10-25%; 2: 25-50%; 3: >50%

Blank spaces are habitat features not associated with the given sediment class

G = Geological features; B = Biological features

Table 4. Recovery codes

Feature Class	Features	Mud	Sand	Gran/Peb	Cobble	Boulder	Deep/rocky
G	Bedforms		0				
G	Biogenic burrows	0	0				
G	Biogenic depressions	0	0				
G	Boulder, piled					3	3
G	Boulder, scattered, in sand					0	0
G	Cobble, pavement				0		0
G	Cobble, piled				3		3
G	Cobble, scattered in sand				0		0
G	Granule-pebble, pavement			0			
G	Granule-pebble, scattered, in sand			2			
G	Sediments, suface/subsurface	0	0				
G	Shell deposits		2	2			
B	Amphipods, tube-dwelling	0	0				
B	Anemones, actinarian			2	2	2	2
B	Anemones, cerianthid burrowing	2	2	2			
B	Ascidians		1	1	1	1	1
B	Brachiopods			2	2	2	2
B	Bryozoans			1	1	1	1
B	Corals, sea pens	2	2				
B	Hydroids	1	1	1	1	1	1
B	Macroalgae			1	1	1	1
B	Mollusks, epifaunal bivalve, Modiolus modiolus	3	3	3	3	3	3
B	Mollusks, epifaunal bivalve, Placopecten magellanicus		2	2	2		
B	Polychaetes, Filograna implexa		2	2	2	2	2
B	Polychaetes, other tube-dwelling			1	1	1	1
B	Sponges		2	2	2	2	2
B	Long-lived features[1]						4

Adapted from trawl recovery table (Grabowski et al. 2014)

Recovery codes: 0: < 1 year; 1: 1 – 2 years; 2: 2 – 5 years; 3: 5 – 10 years; 4: 10 – 50 years

Blank spaces are habitat features not associated with the given sediment class

G = Geological features; B = Biological features

[1] Long-lived features added to deep and rocky habitat category at request of SSC

Appendix 4 Incorporation of longer recovery time into FE model

The FE model uses an exponential decay curve to estimate the proportion of habitat that recover each time step (ρ') from the average time to recovery (τ) using the following equation,

$$\rho' = 1 - \exp(\frac{-1}{\tau}) \tag{1}$$

The proportion undisturbed habitat in each time step (H_t) is calculate from the disturbed habitat (h_t) multiplied by ρ' plus the proportion of H_t that is not impacted ($1 - I'$),

$$H_{t+1} = h_t\rho' + H_t(1 - I') \tag{2}$$

The dynamics of various recovery parameters can be explored by considering a scenario that begins with a completely disturbed habitat ($h_0 = 1$) and involves no future impacts using the following equation,

$$h_t = (1 - \rho')^t \tag{3}$$

Although the FE model uses a monthly time step, t can be modeled in years to simplify interpretation. Figure A1 shows the recovery curve from Eq. 3 using various values and ranges for τ. Combing Eq. 1 and Eq. 2 and rearranging, we get,

$$\tau = -\frac{t}{\ln(h_t)} \tag{4}$$

Eq. 4 allows us to back calculate a recovery parameter, τ, if we have a known expectation for the proportion of a habitat remaining disturbed (h_t) after a certain number of years (t). For example, if we expect that 150 years following a complete disturbance, 5% of the habitat would still not have recovered, we can use Eq. 4 to calculate $\tau = -\frac{150}{\ln(0.05)} \approx 50$ years.

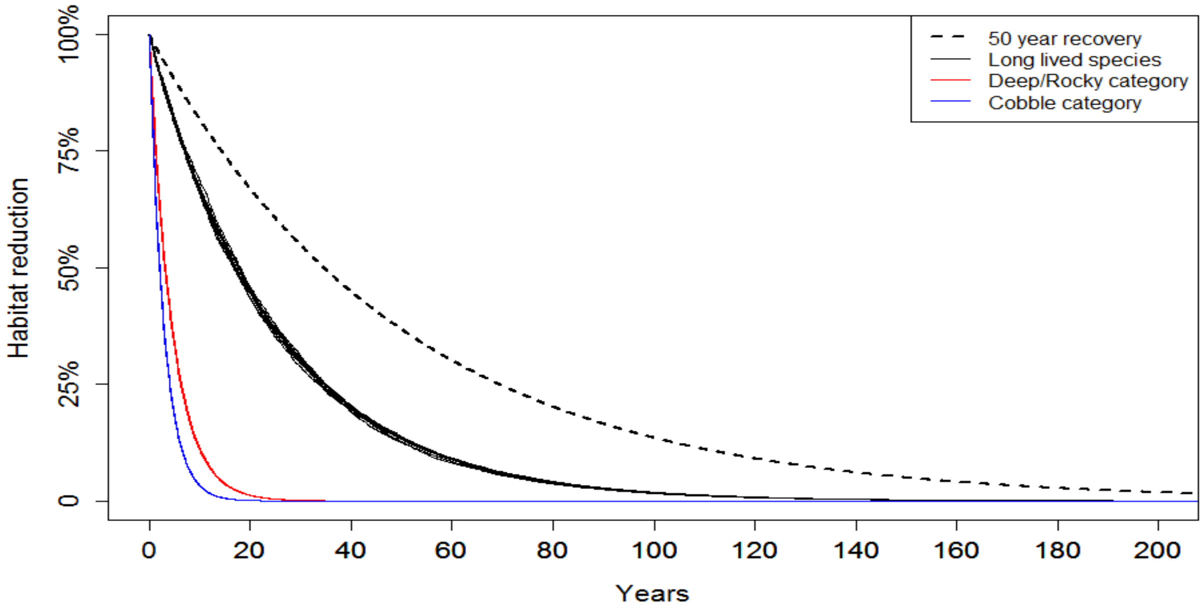

Figure 1. Recovery curves of various recovery parameters used in FE model. The 50-year recovery (dashed black line) represents the upper limit of recovery in the model. The long-lived species curves (solid black lines) represent 10 runs, randomly sampling from a 10 – 50 year recovery range. The Deep/Rocky curves (solid red lines) represent 10 runs averaging over the full suite of habitat features in the Deep/Rocky habitat category. The Cobble curves (solid blue lines) represent 10-run averaging over the full suite of habitat features in the Cobble habitat category.

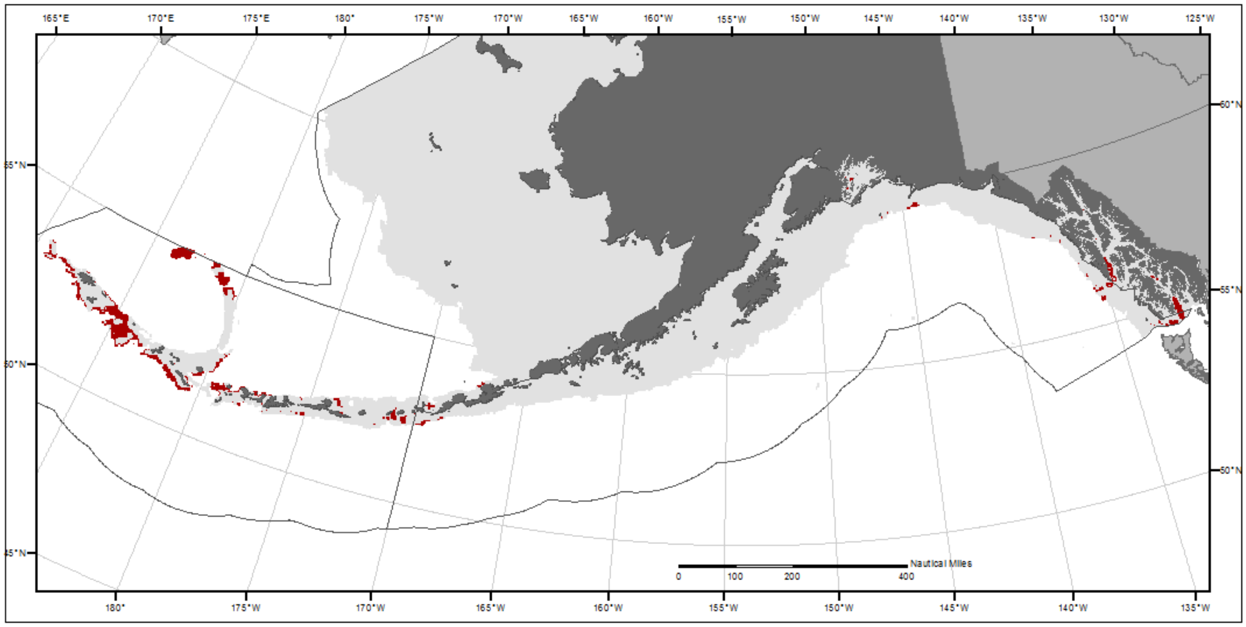

Figure 2. Map of Deep/Rocky habitat within model domain. Red areas show grid cells that contain the Deep/Rocky habitat category. The light grey region is the FE model domain (<1000m depth).

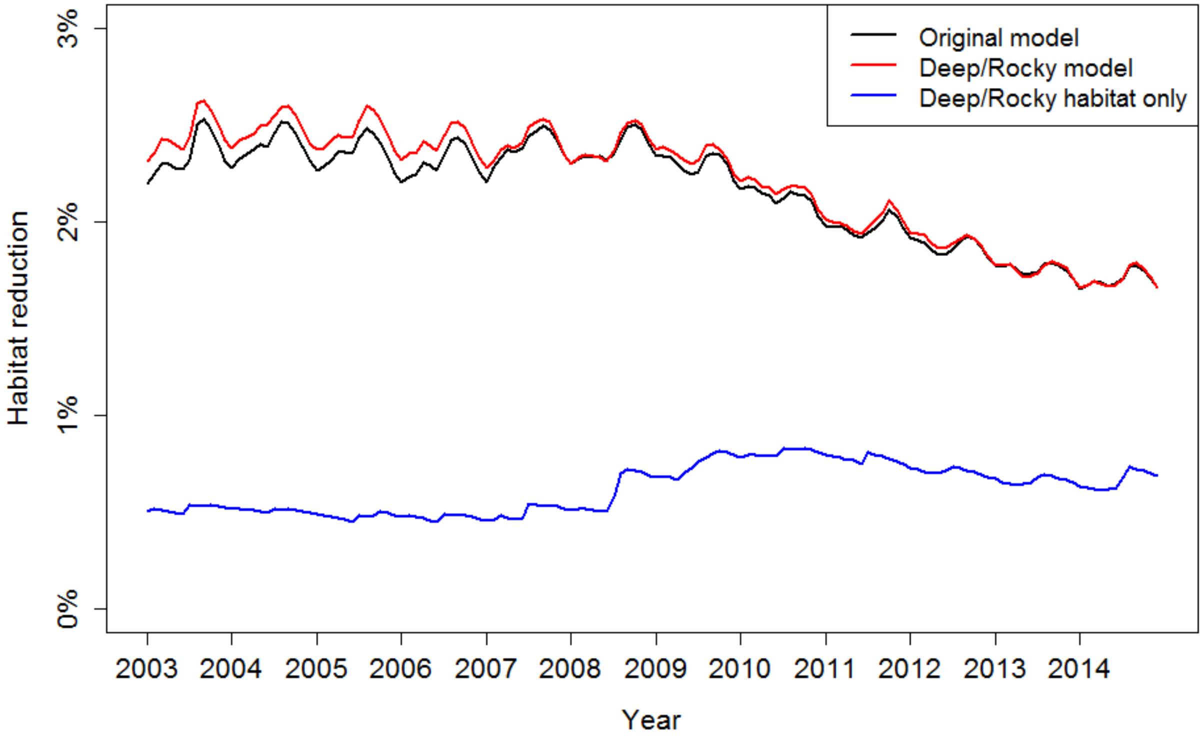

Figure 3. Comparison of habitat reduction among three models. The black line the domain-wide original model. The red line is the domain-wide model with Deep/Rocky habitats added. The blue line is habitat reduction on only grid cells that contain Deep/Rocky habitat.

Appendix 5 Applied Examples of the 2017 EFH Stock author review

Example 1: Fishing impacts on pollock EFH in the Gulf of Alaska

For pollock in the Gulf of Alaska, two maps of habitat impact were developed. The first map is based on summer bottom trawl survey data. A spatial generalized additive model (GAM) was fit to CPUE data and used to develop a map of relative abundance of pollock in the Gulf of Alaska. The core EFH area was defined as 50% percentile of the cumulative distribution of pollock. It is the area within the Gulf of Alaska where the highest abundances of pollock occur so that 50% of the total abundance is within that area (Figure 4). Impacts on pollock habitat were evaluated by overlying the results from the FE model and summing impacts (percent reduction in habitat) within the pollock core EFH area.

An example of the habitat impacts is shown in Figure 5 for December 2014, but other time periods are likely to show a similar pattern. Although the overall picture is one of low impact on habitat, there small areas of higher habitat reduction (>25%) distributed throughout the GOA shelf. The largest area habitat reduction occurs on the east side of Kodiak Island in area 630 in Barnabus and Chiniak Gullies, which is to be expected as this is an important fishing grounds for the Kodiak trawl fleet. Smaller areas of higher habitat reduction also occur near Sand Point, suggesting that areas closer to major fishing ports may experience high levels of habitat reduction.

Overall fishing impacts in the pollock core EFH area are very low. The average percent reduction for the Gulf of Alaska as a whole is 1.7%, and the average for area 630, where trawl impacts are highest, is 3%, and did not exceed 4.1% in any month (Figure 6). All these values are much below the 10% habitat impact that was established as the trigger for further analysis. The time trend of habitat impacts is relatively stable, but there was in uptick in area 630 in spring of 2008, which may be associated with increase in effort due to the central GOA rockfish pilot program.

If the 10% threshold for additional analyses had been exceeded, the recommendation for further analysis is to examine indices of growth- to- maturity, spawning success, breeding success and feeding success (e.g., time trends in size-at-age, recruitment, spawning distributions and feeding distributions) to determine whether there are correlations between those parameters and the trends in the proportion of the CEA impacted by fishing. Below we provide a correlation analysis with the annual average percent habitat distributed in areas 610-630 with 1) the weight at age anomaly from the Shelikof Strait acoustic survey 2) log recruitment and 3) length at 50% mature from the Shelikof Strait acoustic survey (Figure 7). The weight at age anomaly was calculated by subtracting the mean weight at age for 2004-2015, then averaging across ages 2-10. Since the Shelikof Strait survey occurs in the beginning of the year, we examined lagged indicators, that is, habitat impacts for one year were correlated with the indicator from Shelikof Strait in the following year. Similarly, habitat impacts were correlated with estimated recruitment in the following year. Results indicate a positive correlation between the proportion of habitat disturbed and the weight at age anomaly, but no obvious relationship for log recruitment, and the length at 50% mature. P-values based on the Pearson correlation coefficient and a t-test with n=2 degrees of freedom were as follows:

> Habitat impact vs weight at age anomaly: p=0.12.
>
> Habitat impact vs log recruitment: p = 0.99.
>
> Habitat impact vs length at 50% mature: p=0.61.

Since none of the p-values were less than 0.1, the conclusion is that habitat impacts on pollock growth- to- maturity, spawning success, breeding success and feeding success are not detectable, and that mitigation measures are not needed. Interestingly, the correlation between habitat impacts and the weight at age anomaly is relatively strong and positive, which would suggest that habitat impacts lead to increases in pollock growth, the since both time series are strong autocorrelated, the p-value almost certainly overstates the strength of the relationship.

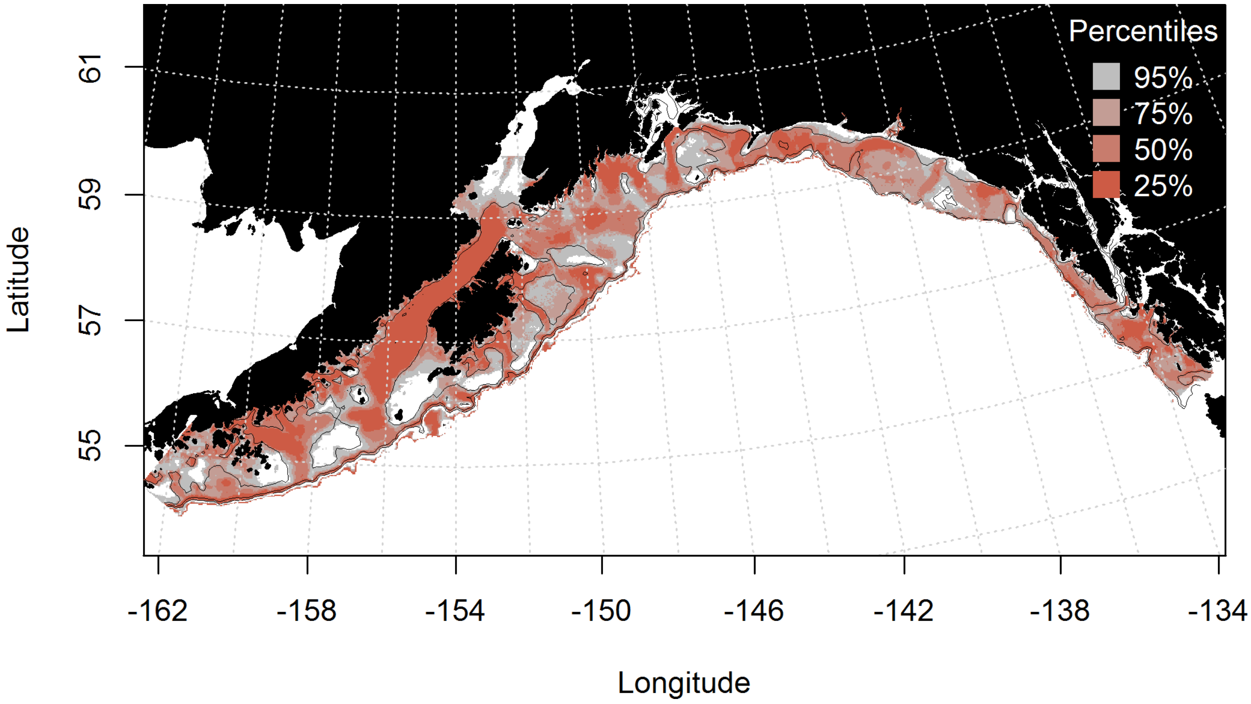

Figure 4 Areas representing various cumulative percentiles of pollock abundance in the Gulf of Alaska.

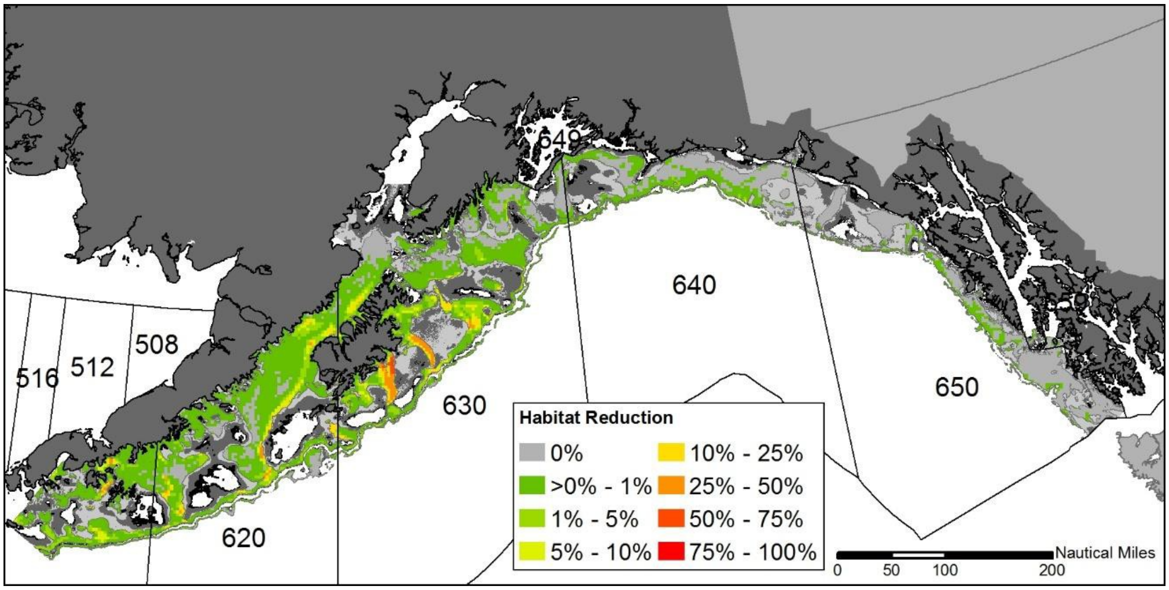

Figure 5 Habitat reduction for December 2014 in GOA pollock summer core EFH area.

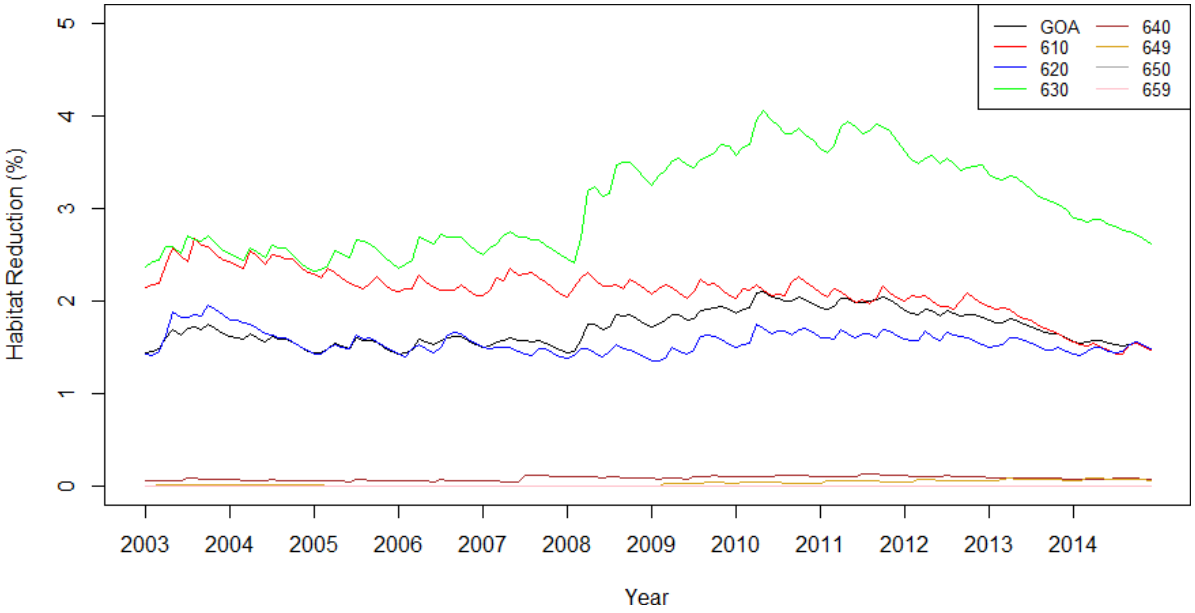

Figure 6 Monthly time series of habitat reduction for GOA pollock summer core EFH area, by management area and the entire GOA.

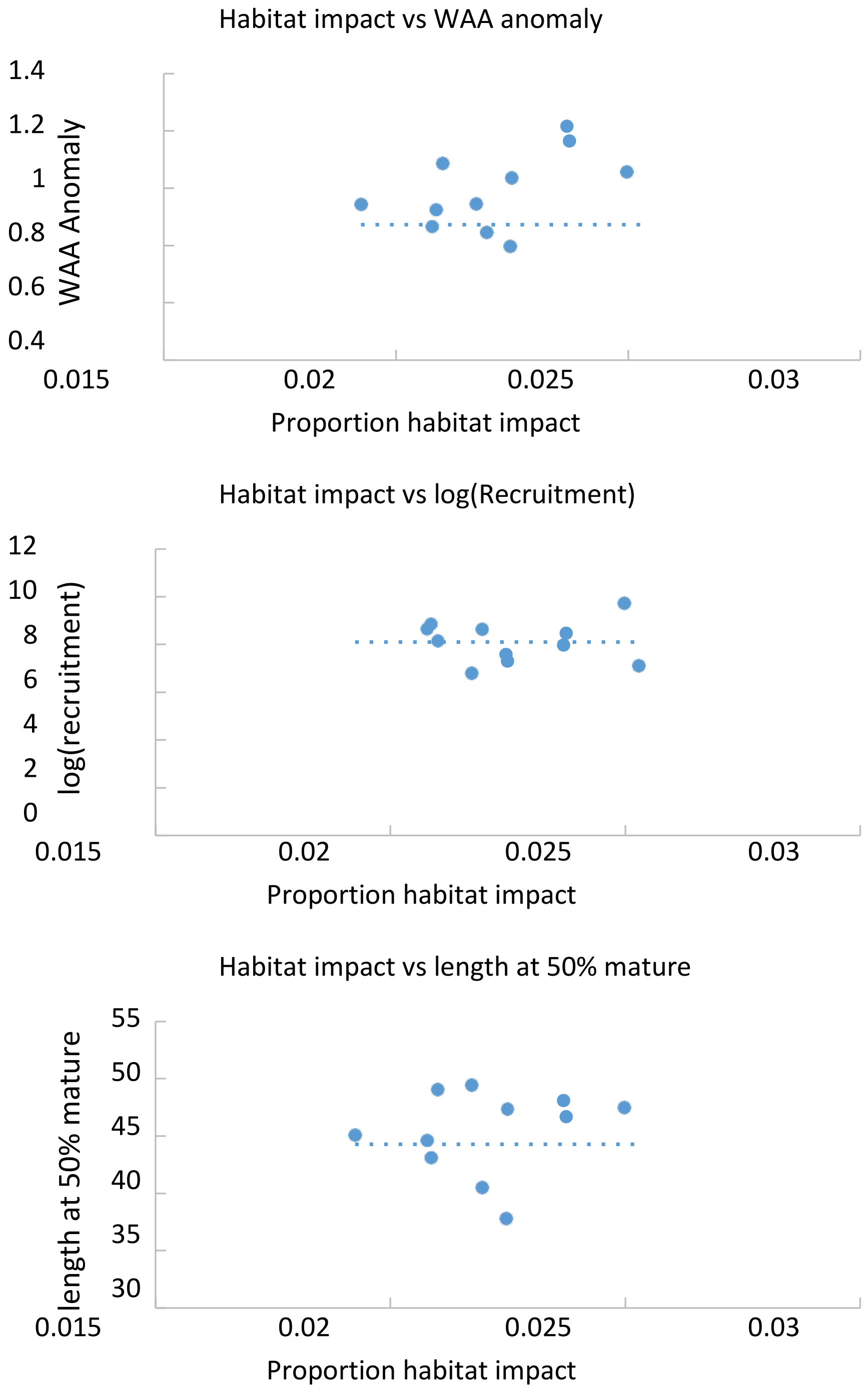

Figure 7 Correlations between annual habitat impact (2003-2014) in areas 610-630, and GOA pollock indicators for growth, recruitment, and maturation.

Example 2: Fishing impacts on POP EFH in the Gulf of Alaska

Similar to pollock in the Gulf of Alaska (GOA), two maps of habitat impact were developed for Pacific ocean perch (POP) in the GOA. The first map is based on summer bottom trawl survey and fishery observer data. A spatial GAM was fit to CPUE data, and used to develop a map of relative abundance of POP in the GOA. The core EFH area was defined as 50% percentile of the cumulative distribution of POP. It is the area within the GOA where the highest abundances of POP occur so that 50% of the total abundance is within that area, shown in Figure 8.

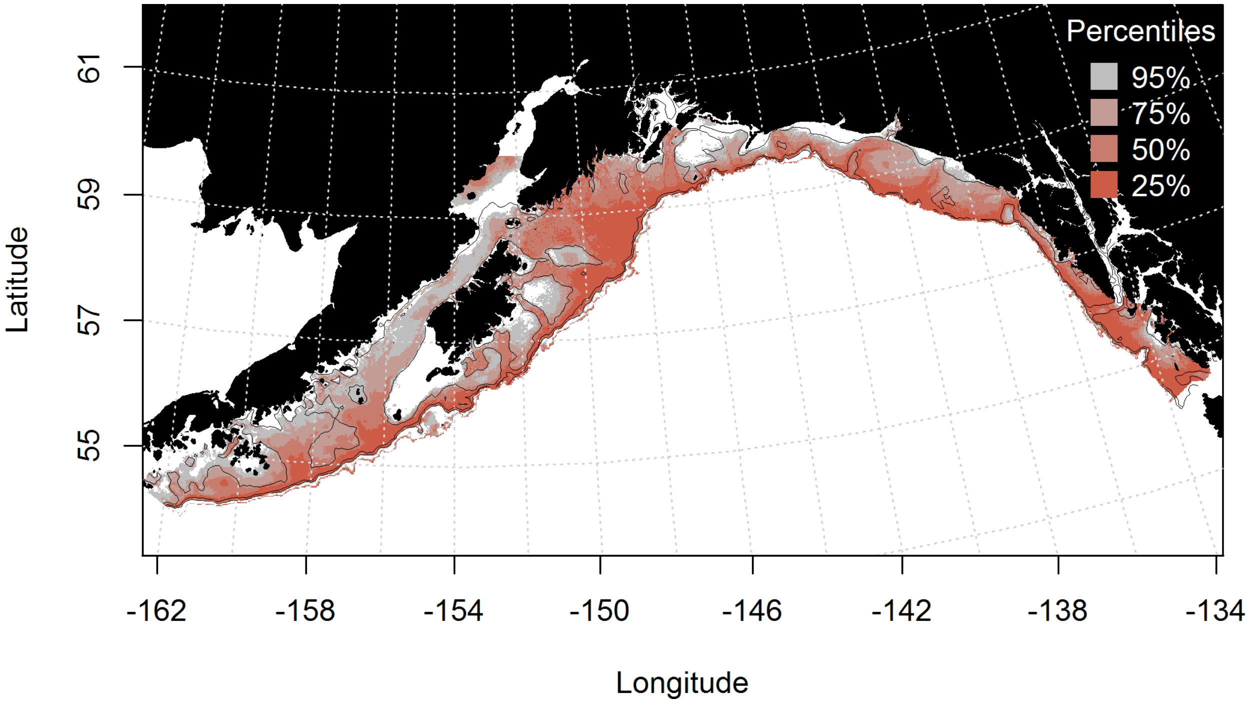

Figure 8 Areas representing various cumulative percentiles of POP abundance in the Gulf of Alaska.

Impacts on POP habitat were evaluated by overlying the results from the FE model and summing impacts (percent reduction in habitat) within the POP core EFH area. Figure 9 is an example of the proportion of habitat reduction in the GOA POP Core EFH area (shown for December 2014, other time periods of the year may also presumably show a similar pattern).

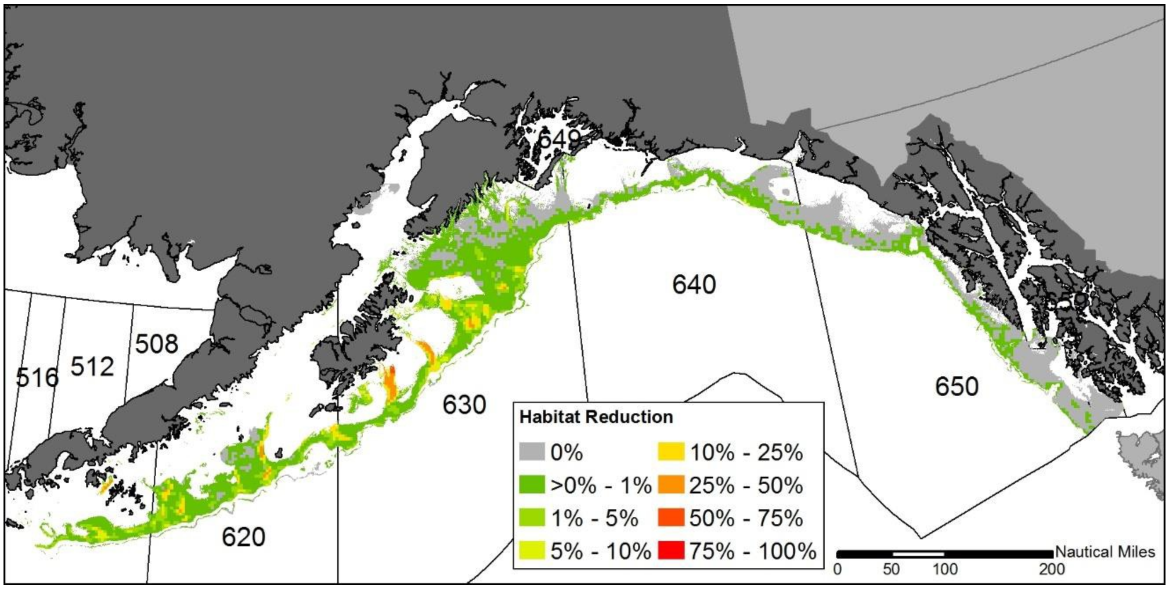

Figure 9 Habitat reduction for December 2014 in GOA POP summer core EFH area.

The majority of habitat reduction occurs south of Kodiak in area 630, which is to be expected as this is a focus area for the trawl fleet to capture POP as well as other groundfish species. The habitat reduction time series by month for the POP CEA by management area and across the entire GOA is shown in Figure 10.

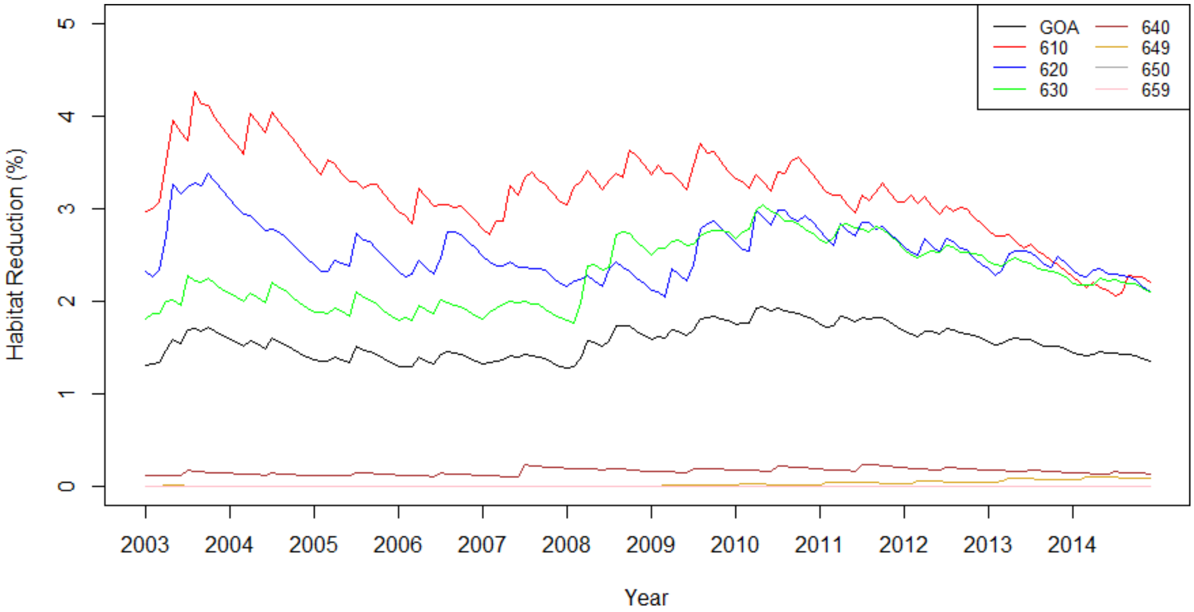

Figure 10 Monthly time series of habitat reduction for GOA pollock summer core EFH area, by management area and the entire GOA.

As seen in the example map above, the area with the most habitat reduction impact by fishing gear is area 630, but, integrated over the entire 630 area the proportion of habitat reduction does not exceed

5%, nor do any of the other areas or the entire GOA exceed 3.5%.

To more closely investigate the time series of habitat reduction across the entire GOA four time periods were evaluated for the proportion of habitat disturbed by fishing in the GOA CEA for POP. These time periods coincided with important life-history events including an annual index, an index of what is believed to be the peak spawning period (March to April), an index of when the majority of fishing occurs that targets POP (May-June), and an index of when breeding is believed to be occurring (October-November). These time periods are plotted in Figure 11.

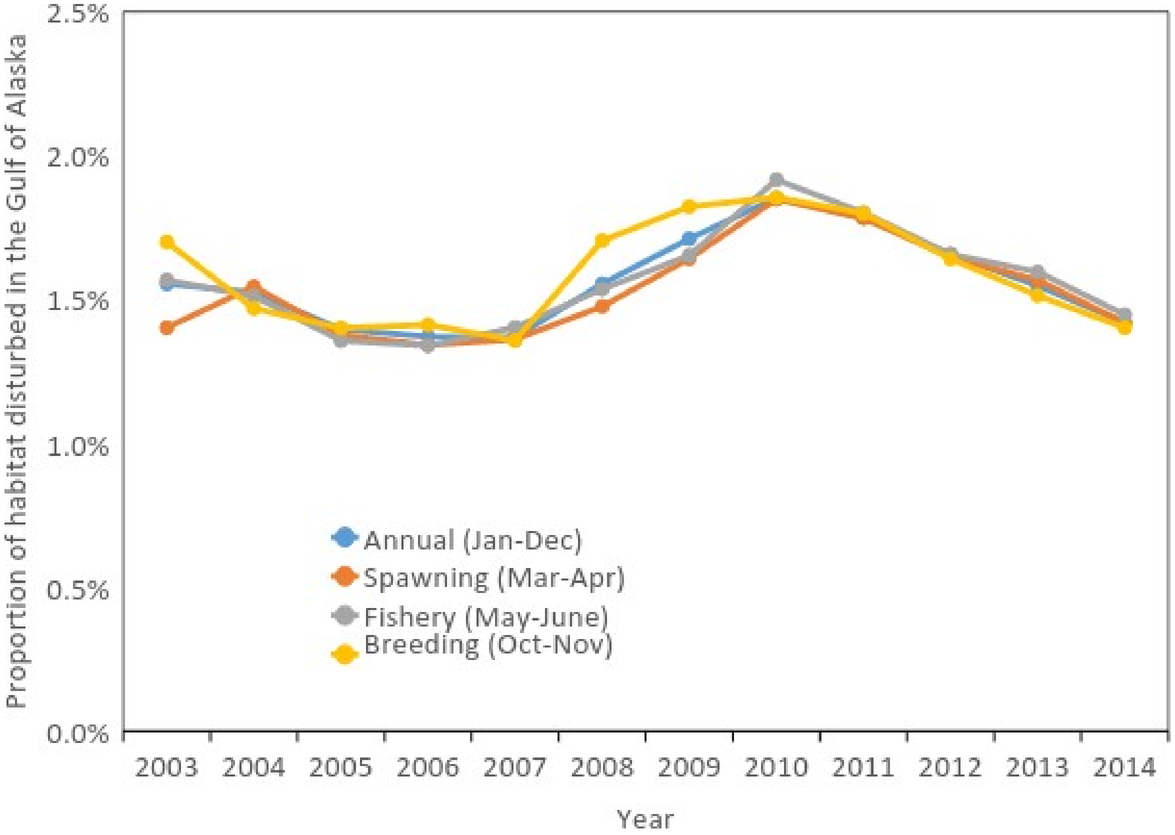

Figure 11 Proportion of habitat disturbed by fishing in the GOA CEA for POP during important life-history events, 2003 – 2014.

None of these time periods, or any other combination of months across the years for which the proportion of habitat distributed index is available exceeded 10%, indeed, no year exceeded 2% when the habitat disturbed by fishing in the GOA POP CEA was averaged across months. In addition, the trends across time for each of the four time periods are very similar.

If the 10% threshold for additional analyses is exceeded, correlation between the proportion of habitat disturbed by fishing with time trends in indices of growth-to-maturity, spawning success, breeding success, and feeding success are requested. Even though the 10% threshold was not exceeded for POP correlations were performed for evaluation. To satisfy the request with growth-to-maturity, correlation analysis was performed between the proportion of habitat disturbed and indices of growth from the AFSC bottom trawl survey in the GOA (the dome- shaped selectivity for POP from the commercial fishery is such that growth parameters are difficult to estimate). These indices of growth included average size-at-age of the most frequently caught ages in the bottom trawl survey (age-3 to age-15) and annual Von Bertalanffy function growth parameter estimates. Spawning success in this case was defined as the recruitment (age-2) estimated from the stock assessment model that survived to join the adult population. There is no time series of maturity data available for POP for correlation analysis. It is also unclear how to perform correlation with spawning or feeding distributions. However, to satisfy this request the simplifying assumption made here is that the stock assessment model's estimates of total (feeding) and spawning biomass across time are proportional to spatial distribution contraction/expansion so that correlation with the proportion of habitat disturbed could be performed. As the time series of average proportion of habitat disturbed across the time periods investigated were extremely similar the annual index of proportion of habitat disturbed by fishing was used to correlate with the life-history indices. The results of the correlation analysis, along with the *p*-values, are shown in Table 1. Correlations for which the *p*-value were ≤0.1 are shown in bold

Table 2. Results of correlation analyses of CEA habitat reduction and POP life history parameters

		ρ	*p*-value
Average size-at-age	age-3	-0.49	0.33
	age-4	-0.25	0.63
	age-5	-0.56	0.24
	age-6	-0.58	0.23
	age-7	-0.20	0.71
	age-8	-0.71	0.11
	age-9	-0.25	0.63
	age-10	-0.60	0.21
	age-11	0.02	0.97
	age-12	-0.40	0.43
	age-13	-0.38	0.46
	age-14	0.42	0.41
	age-15	-0.14	0.79
LVB params	L_∞	0.56	0.33
	κ	-0.64	0.24
	t_0	-0.64	0.24
Assessment output	Spawning biomass	0.43	0.17
	Total biomass	0.37	0.24
	Recruitment	0.33	0.30

The results of the correlation analysis did not result in *p*-values ≤0.1 Overall, the proportion of habitat disturbed in the POP CEA is minimal (<5%), and no life-history correlation with fishing effects is cause for concern at this point in time.

Appendix 6 Threshold discussion

In April 2016, the SSC recommended the formation of a sub-committee to develop criteria for evaluating the impact of fishing effects on EFH. This sub-committee was formed with membership including SSC and Plan Team members as well as the leads for the EFH workgroup and scientists from Alaska Pacific University. The sub-committee met during the summer and developed a white paper describing impact assessment methods. This white paper was presented to the CPT and GPTs in September (NPFMC 2016).

The proposed methods outline a hierarchical impact analysis framework that utilizes the availability of time-varying estimates of fisheries effects. This framework provides an evidence-based impact assessment to assess the potential effects of fishing on EFH for crab and groundfish resources. The goal of the framework is to assess whether there is a fishing effect on EFH that is more than minimal and produces significant and temporary impact(s) on the growth-to-maturity, spawning success, breeding success, and/or feeding success of species managed by the NPFMC. The improved analytical products allow analysts to evaluate linkages between time trends in fishing effects on EFH and independently determined time trends in size-at-age, recruitment, spawning distributions and feeding distributions. It will be important to develop a mechanistic tie between the effect on EFH and the impact on the fish.

SSC Review – October 2016

https://meetings.npfmc.org/CommentReview/DownloadFile?p=7c0836ef-82d9-4b4f-b9b0-8d4c65e22fea.pdf&fileName=SSC%20Report%20FINAL%20Oct2016.pdf

The SSC discussed the white paper to provide guidance in response to questions posed by the sub-committee.

1. Are the assessment cutoffs correct?

The white paper proposes that analysts identify a core area for each species that represents the upper 50th percentile of predicted abundance or suitable habitat. The rationale for the 50th percentile cut-off was that analysts wanted to find a balance between an area that represented a high likelihood of the species being present and an area big enough to include adaptive movement options for the species. The SSC recommends that in addition to the 50th percentile cut-off, the analysts consider including use of higher (larger region, 95th percentile) or lower percentiles (smaller region, 25th percentiles). The SSC recognized that inclusion of a larger region would dampen the fishing effects and thus, if a threshold effect of habitat disturbance was not detected at the 50th percentile it was unlikely that it would be detected at the 95th percentile. To test this hypothesis, the SSC requests that the sub-group examines the relationship between impacts assessed using the core area cut-offs of 50% and 95% for a sub-set of species with a range of distributional attributes.

The SSC discussed the merits of the proposed impact threshold of 10% of EFH being in the disturbed state. The SSC recognizes that the selection of the impact threshold is critical because if habitat reductions are below the threshold, then no further assessment would be needed. The SSC saw the merits of the 10% threshold but asks the sub-committee to examine the frequency that other cut-offs (say 5% and 20%) would be reached for the same sub-set of species for which the different core area definitions are assessed.

The SSC noted the "curse of dimensionality" when analysts conduct exploratory correlation studies, especially when using a relaxed p – value of 0.1. To address this issue the SSC recommend that P-values be corrected for multiple comparisons, or that guidelines be established for the number of comparisons to evaluate.

The SSC considered the data sets available for the evaluation of fishing effect impacts on the growth-to-maturity, spawning success, breeding success, and feeding success of species. The SSC agrees that the proposed time series of recruitment, spawning biomass and size or weight-at-age should be considered. For stocks in the Bering Sea, the SSC recommends that the sub-group explores the possibility of examining indices of stomach fullness as another factor related to feeding success.

2. Should assessments be based on regional boundaries for the stock/species?

The SSC discussed the pros and cons of utilizing stock boundaries to conduct the impact assessments. They considered alternative options such as evaluating GOA for only those regions open to trawling. The SSC recognized that many rockfish and flatfish species in the Bering Sea are managed as a single BSAI wide stock yet the topography in the AI differs substantially from the EBS shelf. After considerable discussion, the SSC recommends that the authors use their best judgement on the boundaries for their impact assessment. The SSC did not support the concept of dropping the eastern Gulf of Alaska from the analysis simply because no trawling occurs in this region. The possible benefits of habitat protection realized by the trawl closures in the EGOA should be considered in the impacts assessment of mobile species.

3. Management response

The SSC reviewed the proposed framework for pursuing next steps if an analyst identifies a potential fishing effect impact concern. The SSC agrees with the plan for the analyst to bring his or her concerns to the Plan Team(s) and SSC for review, comment, and evaluation. The GPTs recognized that a process will need to be developed that addresses how to move forward if an adverse impact is indicated. The SSC noted that these next steps may include focused research projects to verify the proposed cause and effect relationships between habitat disturbance rates and stock demographics.

4. Comments on Fishing Effects model

The SSC supports the use of the Fishing Effects model in the EFH analysis with the following additions. The SSC received public testimony on the methods used to estimate recovery in the model indicating that there was concern regarding the ability of the model to track the effects to long-lived corals and sponges due to the averaging of recovery rates among all taxa. The recovery rates used in the model were provided to the SSC in April 2016 but were not included in this review packet. Given that these values play a crucial role in the estimation of fishing effects used in the assessment, the SSC requests that the sub-committee include these values in the next iteration of the EFH impacts review. The SSC recommends that the sub-committee include an additional biological feature category for long-lived corals/sponges and develop a white a paper describing the expected fishing effects to this group.

Joint Groundfish Plan Team Review – September 2016

https://meetings.npfmc.org/CommentReview/DownloadFile?p=d937109d-f19f-49b7-b0e3-019c99e7ce2b.pdf&fileName=C2-1%20Groundfish%20Plan%20Team%20Minutes%200916-final.pdf

1. Are the assessment cutoffs correct?

- Core area = upper 50th percentile of predicted abundance or suitable habitat
- Impact threshold for further impact assessment: 10% reduction in habitat
- P-value of 0.1 for significance of correlation with time trend in habitat disturbance in core area

The Teams recommend that the analysts consider alternatives to using the 50th percentile to define the core area, including use of higher or lower percentiles and also dispensing with the core area concept altogether by weighting the location-specific impacts by the relative density of fish in each location. The Teams also recommend that P-values be corrected for multiple comparisons, or that guidelines be established for the number of comparisons to evaluate.

2. Should assessments be based on regional boundaries for the stock/species?

The Teams recommend that the analysts consider evaluating GOA for only those regions open to trawling. For example, the Eastern Gulf of Alaska trawl closure area could be removed from the analysis for certain species such as rockfish that have subarea-based stocks.

The Teams also recommend that the analysts evaluate the extent to which their methodology addresses the concern raised in the CIE report on EFH that the previous EFH impact analyses did not give adequate consideration to localized (versus population level) habitat impacts.

Team members also inquired about how best to analyze impacts on stocks whose distribution is shifting

Crab Plan Team Review – September 2016

https://meetings.npfmc.org/CommentReview/DownloadFile?p=916b4a4a-b087-4801-b32d-c0109c535329.pdf&fileName=C1%20Crab%20Plan%20Team%20Report.pdf

1. Should assessments be based on regional boundaries for the stock or species?

The CPT evaluates multiple stocks within a region, so fishing impacts should perhaps be evaluated at the stock level as identified by the individual assessment authors.

2. Is the 50% threshold the right one?

This threshold balances making sure enough areas are covered without covering areas of marginal importance. The CPT considered whether analysis should look at a 25% threshold, or others, to see differences. One possible method is to weigh the habitat disturbance proportional to abundance. Problems with weighting according to abundance in an area are: (1) animals may move to avoid areas of high impact, (2) we don't know how the models react to changes in distribution or detect movement, and (3) we don't know what impacts movement has on population level effects. A time series of maps could illustrate movement over time. Also, we could look at abundance in closed areas compared to open areas. The CPT discussed whether it would be possible to detect impacts given we only have population level data and we don't have the information necessary to make correlations. One suggestion was to overlay habitat maps over time with population distributions to indicate if there appears to be some inherent response mechanism. The CPT expressed concern that finding will likely always be of no impact as a result of weak factors to correlate due to paucity of information for crab. A suggestion was made to look at the change in disturbance and then go back and evaluate how recruitment changes (or other variable) have changed since that time to see if there is correlation. The effects will be most likely subtle and chronic.

3. Continue the 10% habitat reduction threshold?

The CPT concurred that it is not possible to answer this question because the model has not yet been applied to crab stocks.

4. Is p-value of 0.1 reasonable?

Probably, but it would be good to see the results for crab; if a lot of crab stocks fall on $p<0.05$, we may want to reconsider.

Appendix 7 Ecosystem Status Report FE Indicator

Ortiz, I. and S. Zador (eds.). 2020. Ecosystem Status Report 2020: Aleutian Islands. https://appsafsc.fisheries.noaa.gov/REFM/docs/2020/AIecosys.pdf.

Siddon, E. (ed.). 2020. Ecosystem Status Report 2020: Eastern Bering Sea. https://appsafsc.fisheries.noaa.gov/REFM/docs/2020/EBSecosys.pdf.

Area Disturbed by Trawl Fishing Gear in the Aleutian Islands, Bering Sea, and Gulf of Alaska

Description of indicator: Fishing gear can impact habitat used by a fish species for the processes of spawning, breeding, feeding, or growth to maturity. This indicator uses output from the Fishing Effects (FE) model to estimate the area of geological and biological features disturbed in the Aleutian Islands, Bering Sea, and Gulf of Alaska, utilizing spatially-explicit VMS data. The time series for this indicator is available since 2003, when widespread VMS data became available.

Status and Trends: The percent of area disturbed due to commercial fishing interactions (pelagic and non-pelagic trawl, longline, and pot) decreased steadily from 2008 to the present in the Bering Sea, with slightly decreasing or steady trends in the Gulf of Alaska and Aleutian Islands

Factors Causing Trends: Trends in seafloor area disturbed can be affected by numerous variables, such as fish abundance and distribution, management actions (e.g., closed areas), changes in the structure of the fisheries due to rationalization, increased technology (e.g., increased ability to find fish, acoustics to fish near the bottom without contact), markets for fish products, and changes in vessel horsepower and fishing gear. Intensive fishing in an area can result in a change in species diversity by attracting opportunistic fish species which feed on animals that have been disturbed by fishing activity, or by reducing the suitability of habitat used by some species. It is possible that increased effort in fisheries that interact with both living and non-living bottom substrates could result in increased habitat loss/degradation due to fishing gear effects. The footprint of habitat damage varies with gear (type, weight, towing speed, depth of penetration), the physical and biological characteristics of the areas fished, recovery rates of living substrates in the areas fished, and management or economic changes that result in spatial redistribution of fishing effort.

Between 2003 and 2008, variability in area disturbed were driven largely by the seasonality of fishing in the Bering Sea. In 2008, Amendment 80 was implemented, which allocated BSAI yellowfin sole, flathead sole, rock sole, Atka mackerel, and Aleutian Islands Pacific ocean perch to the head and gut trawl catcher processor sector, and allowed qualified vessels to form cooperatives. The formation of cooperatives reduced overall effort in the fleet while maintaining catch levels. In 2010, trawl sweep gear modifications were implemented on non-pelagic trawls in the Bering Sea, resulting in less gear contacting the seafloor and less habitat impact. Trawl sweep modifications were implemented in the Gulf of Alaska in 2014.

Implications: The effects of changes in fishing effort on habitat are largely unknown, although our ability to quantify those effects has increased greatly with the development of a Fishing Effects model as a part of the 2017 EFH 5-year review (NMFS 2017). The 2005 EFH FEIS, 2010 EFH 5-year review, and 2015 EFH 5-year review concluded that fisheries do have long term effects on habitat; however, those impacts were determined to be minimal and not detrimental to fish populations or their habitats. These previous EFH analyses indicated the need for improved fishing effects model parameters. With the FE model, NMFS ability to analyze fishing effects on habitat has grown exponentially. Vessel Monitoring System data provides a much more detailed treatment of fishing intensity, allowing better assessments of the effects of overlapping effort and distribution of effort between and within grid cells. The development of literature-derived fishing effects database has increased our ability to estimate gear-specific susceptibility and recovery parameters. The distribution of habitat types, derived from increased sediment data availability, has improved. The combination of these parameters has greatly enhanced our ability to estimate fishing impacts.

New methods and criteria were developed to evaluate whether the effects of fishing on EFH are more than minimal and not temporary on managed fish stocks in Alaska. Criteria were developed by and reviewed by the Council and its advisory committees in 2016, and stock assessment authors in 2017. In April 2017, based on the analysis with the FE model, the Council concurred with the Plan Team consensus that the effects of fishing on EFH do not currently meet the threshold of more than minimal and not temporary, and mitigation action is not needed at this time. The output of the FE model will be available for stock assessment authors on a yearly basis. Although the impacts of fishing across the domain are very low, it is possible that localized impacts may be occurring. The issue of local impacts is an area of active research.

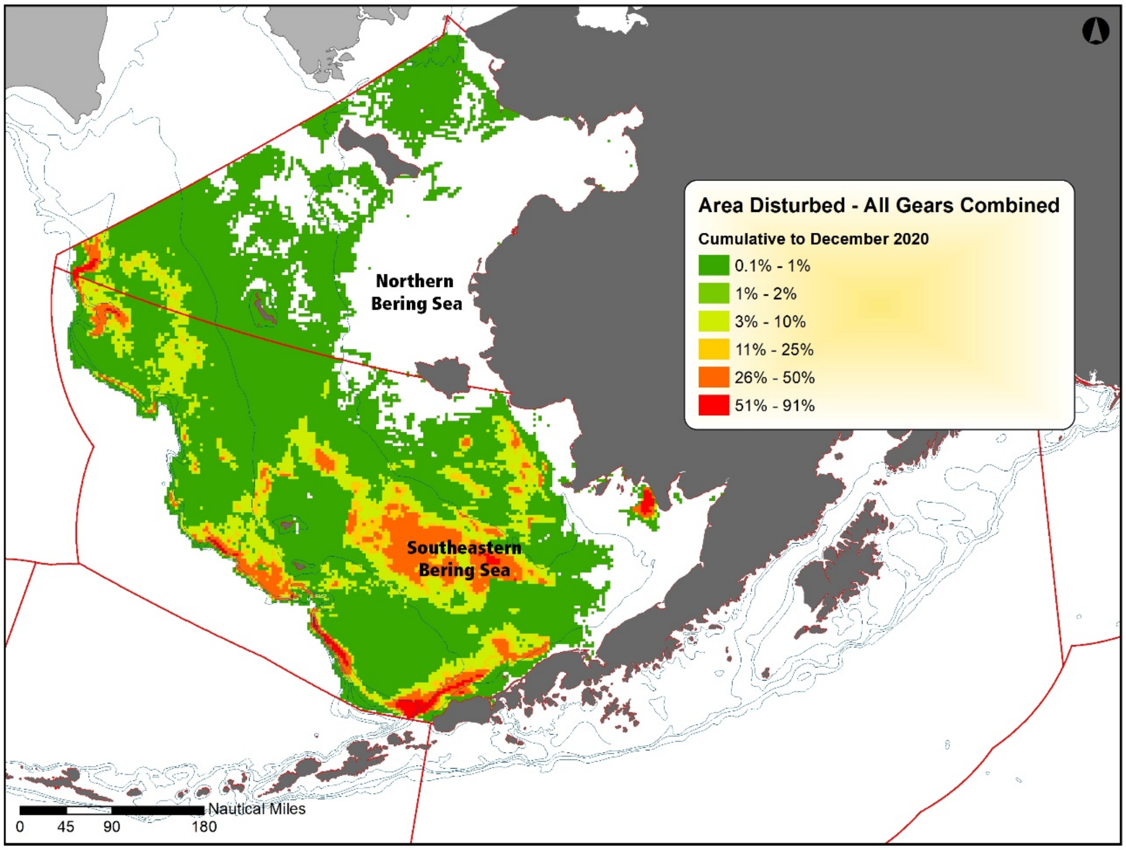

Figure 12: Map of percentage area disturbed per grid cell for all gear types in the Bering Sea. Effects are cumulative and consider impacts and recovery of features from 2003 to 2020.