Appendix 2.1. Ecosystem and Socioeconomic Profile of the Pacific cod stock in the Gulf of Alaska

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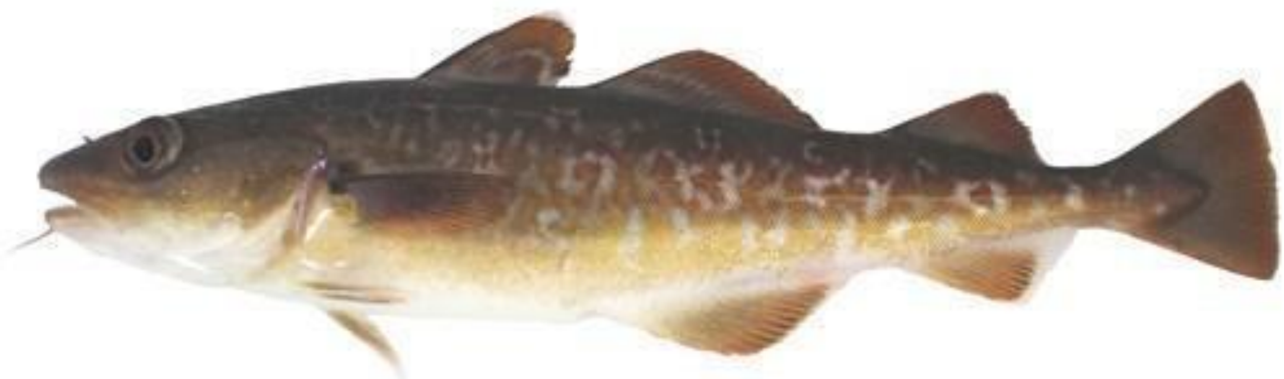

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Executive Summary

National initiatives and AFSC research priorities support conducting an ecosystem and socioeconomic profile (ESP) for Gulf of Alaska (GOA) Pacific cod. Annual guidelines for the AFSC support research that improves our understanding of environmental and climate forcing of ecosystem processes with a focus on variables that can provide direct input into or improve stock assessment and management. The GOA Pacific cod ESP follows the new standardized framework for evaluating ecosystem and socioeconomic considerations for GOA Pacific cod and may be considered a proving ground for potential use in the main stock assessment.

We use information from a variety of data streams available for the GOA Pacific cod stock and present results of applying the ESP process through a metric and subsequent indicator assessment. Analysis of the ecosystem and socioeconomic processes for GOA Pacific cod by life history stage along with information from the literature identified a suite of indicators for testing and continued monitoring within the ESP. Results of the metric and indicator assessment are summarized below as ecosystem and socioeconomic considerations that can be used for evaluating concerns in the main stock assessment.

Ecosystem Considerations

- Hatch timing and success is highly temperature dependent with optimal hatch occurring in waters between 4-6^{o}C and has implications for spawning habitat suitability and subsequent recruitment
- Warm temperatures can increase susceptibility of starvation for larval Pacific cod when mismatched to prey or reduce growth during shifts in the lipid/fatty acid composition of prey
- Cross-shelf transport may assist larvae and early juveniles to nearshore nurseries for settlement and eddies and gap winds may disrupt along-shore currents to increase growth and survival
- Copepods and euphausiids low since 2009 and returned to average in 2019, and condition of juvenile Pacific cod were poor for 2015 and 2017 surveys
- Annual eddy kinetic energy has shifted from high periods of eddy activity from 2003 to 2015 to a lower energy system in 2016 to 2019 and a strong, persistent eddy around Kodiak in 2020
- The overall spatial distribution of the stock has spread out substantially from 2009 to 2019 with a shift to the farthest northeast in 2019 from the farthest southwest in 2017
- Predators of Pacific cod have steadily decreased over the time series but have recently stabilized suggesting the primary pressure on the 2012 year-classes may be the lack of preferred prey
- Overall, ecosystem indicators have been decreasing since 2012 with a slight recovery to near normal conditions in 2017, when the heat in the system was reduced but return to low values in 2018 and 2019, similar to the GOA pollock
- Highest ranked predictor for recruitment regression model was spawning habitat suitability and eddy kinetic energy on the GOA shelf (inclusion probability > 0.5)

Socioeconomic Considerations

- Kodiak and a combined group of small communities were selected as highly engaged communities when evaluating commercial processing and harvesting engagement
- Ex-vessel value has been decreasing since about 2011 with price per pound very low from 2013 to 2017 with a recent increase and revenue per unit effort has been increasing since 2016
- Processing and harvesting regional quotient (RQ) in Kodiak has been steadily decreasing since 2015 with small communities declining in both measures since 2014, a year earlier

Responses to SSC and Plan Team Comments on ESPs in General

"Regarding ESPs in general, the SSC recommends development of a method to aggregate indices into a score that could be estimated over time and compared to stock history. One potential pathway forward may be to normalize and use an unweighted sum of all the indicators where all time series overlap, or just assign +1 or -1 to each indicator so that a neutral environment would be zero." (SSC, February 2020)

"The Teams discussed concerns of over-emphasizing the 1:1 weighting on the first stage. In the absence of information to indicate an appropriate weighting strategy, it is recommended to not rely too heavily on the uninformed 1:1 weighting to select appropriate indicators. The Teams also requested that the ESP team/authors consider appropriately caveating the indicators to ensure they are interpreted species-specific and not over generalized. The Teams support continuing with the current 3-stage indicator analyses for now, and re-evaluate as the ESP process develops, recognizing that the actual value of the integrated index is yet to be clearly demonstrated although it is one high-level summary statistic that may be valuable to examine." (Joint Groundfish Plan Team, September 2020)

"The JPT were in support of the current templates and the current 3-stage indicator analysis, but noted concerns of over-emphasizing weighting in the first stage and recommended that indicators should be appropriately caveated to not over-generalize indicators across species. The JPT also fully supported the development of the ESP dashboard on AFKIN that includes metadata for each data source, but suggested a staged approach to the integration of data that have not been thoroughly vetted and published.

The SSC endorses the recommendations, comments, and suggestions from the JPT, all of which are consistent with previous SSC recommendations and guidance." (SSC, October 2020)

We provide a simple score following the SSC recommendation and compare the 1:1 weighting of indicators in the "Beginning Stage: Traffic Light Test" with the results of the "Intermediate Stage, Importance Test" section. In the intermediate stage we use a Bayesian Adaptive Sampling (BAS) method that produces inclusion probabilities for a subset of indicators with the most potential for informing a stock assessment parameter of interest (e.g., recruitment of GOA Pacific cod). This second stage may provide insight on how to weigh the indicators in the beginning stage for a more informed score.

We have also initiated a new document called the request for indicators or RFI to initiate the ESP process once an ESP is recommended for a stock. The RFI begins with a summary of the dominant ecosystem and socioeconomic processes influencing the stock and then provides the requested list of potential indicators representing those dominant pressures. Instructions for how to contribute an indicator in response to the stock request are included along with details on the indicator review process and associated guideline criteria, the role and responsibilities of ESP teams and contributors, and use and acknowledgement of the indicator if selected for the ESP. The standardized structure of the RFIs and the included guideline criteria will help with vetting indicators and assist with the review of indicators by the ESP teams. We plan to create RFIs for those stocks that already have an ESP completed using the "Data Gaps and Research Priorities" section and intend to complete these in January to begin the 2022 ESP cycle.

"In general, however, the SSC recommends the continued inclusion of community engagement and dependency indices at varying scales in ESPs, ESRs, and SAFEs. For ESPs specifically, changes in patterns of community engagement and dependency at the stock level have the potential to inform not only stock assessments and analyses that support fishery management, but they may also function as early indicators of larger ecosystem changes." (SSC, December 2020)

Community indicators are currently available in the Annual Community and Participation Overview (ACEPO) report (Wise et al., 2021), that presents social and economic information for communities that are substantially engaged in the commercial groundfish and crab fisheries in Alaska. Moving forward, we plan to include socioeconomic indicators in the ESP that reflect the condition or health of the stock and will be evaluating how to reference the products available in the ACEPO report with what might inform on stock health. We plan to address this in the next full or partial ESP for GOA Pacific cod.

Responses to SSC and Plan Team Comments Specific to this ESP

"Given the results of the stock assessments and the vital historic economic, social, and community importance of Pacific cod, the SSC recommends that within the recognized constraints of available time and resources, Ecosystem and Socioeconomic Profiles (ESPs) of EBS Pacific cod (as well as AI and GOA Pacific cod) be prioritized as new ESPs are developed." (SSC, December 2019, pg. 24)

In 2020, we developed a first draft of the ESP for GOA Pacific cod, but some delays in production occurred due to the limitations under COVID-19. In this final ESP report we have updated the life history tables and references and allowed for more internal review of the whole document from the Pacific cod ESP team.

"The Team noted that consideration of expanding the spawning habitat suitability index using ROMS and potentially including wind information should be discussed at the ESP workshop in the spring. While discussion was focused on indices related to recruitment, it was noted that exploration of indices towards informing other assessment model parameters such as natural mortality would also be good to explore.

The climate enhanced model, Model 20.1, was presented and showed similar results to model 19.1 in spawning biomass trends. The Team encourages the author to continue to research this model. It was noted that research models like this could benefit from discussion at the ESP workshop." (GOA GPT, November 2020)

Several climate enhanced models for crab and groundfish stocks were presented at the March 2021 ESP Advice workshop. Specifically, Steve Barbeaux provided an overview of his current ecosystem linked models. Model 19.1 includes a temperature index linked to catchability of the longline survey and a natural mortality time block linked to the heatwave years for 2014-2016. Model 20.1 is the same as Model 20.1 with the addition of a June temperature anomaly linked to growth and a spawning heatwave index (heatwave calculated during Pacific cod spawning season) linked to recruitment. Model 21.1 builds off Model 20.1 but replaces the natural mortality time block with time-varying natural mortality that is linked to the spawning heatwave index.

This presentation was very helpful for the discussion during the ESP workshop regarding the utility of these ecosystem linked models and providing advice for management decisions. The presentation also included climate projections from CMIP5 for Models 20.1 and 21.1. which was used to compare the differences in projected spawning biomass between the two models. The output of these climate projections may be helpful for understanding the future productivity of the stock in response to a shifting climate and very relevant for management strategy evaluations.

There are several age structured ecosystem-linked models in development for the 2021 GOA Pacific cod stock assessment that explore the use of ecosystem indices to inform catchability, natural mortality, growth, and recruitment. Although the spawning habitat suitability index was examined for 2021 as an age-0 index, the age-0 beach seine index provided by Ben Laurel and Mike Litzow was found to perform better for this purpose and will be presented as an alternative in the 2021 assessment. The age-specific mortality estimates from the GOA CEATTLE model are being tested as priors for age-specific mortality within the model, however fitting age-specific annually varying mortality within the model has proven to be challenging given the lack of data on younger fish (age 0-3) and will require further development.

"The first ESP for GOA Pacific Cod was completed during this assessment cycle, and the SSC commends the authors, Dr. Shotwell, and other ESP collaborators and contributors in its development. The SSC supports continued exploration of additional habitat, biological, or environmental indicators that may be appropriate for describing trends in recruitment. With respect to socioeconomic considerations within the

ESP, the SSC recommends trying to separate fishery engagement from fishery dependency, given that a focus only on engagement may provide a biased perspective toward the most successful fishery participants. As such, the SSC supports exploration of dependency indices for inclusion in the next ESP for this stock. The SSC further suggests that ESP authors consider avenues for allowing coastal community members to provide review of, and feedback on, subsequent ESPs. The SSC finds aggregating small communities to address confidentiality concerns to be effective in capturing regional socioeconomic trends." (SSC, December 2020)

We thank the SSC for their support of exploring indicators to describe trends in recruitment for the GOA Pacific cod stock and plan to continue this exploration through the request for indicators (RFI) document in future years. We plan to evaluate the information provided in the Economic SAFE and ACEPO report to determine what socioeconomic indicators could be provided in the ESP that are not redundant with those reports and related directly to stock health. This may result in a transition of indicators currently reported in this ESP to a different series of socioeconomic indicators in future ESPs and may include a shift in focus from engagement to dependency. Additional considerations should be given for the timing of the economic and community reports that are delayed by 1-2 years depending on the data source from the annual stock assessment cycle.

Introduction

Ecosystem-based science is becoming a component of effective marine conservation and resource management; however, the gap remains between conducting ecosystem research and integrating it with the stock assessment. A consistent approach has been lacking for deciding when and how to incorporate ecosystem and socioeconomic information into a stock assessment and how to test the reliability of this information for identifying future change. This new standardized framework termed the ecosystem and socioeconomic profile (ESP) has recently been developed to serve as a proving ground for testing ecosystem and socioeconomic linkages within the stock assessment process (Shotwell *et al., In Review*). The ESP uses data collected from a variety of national initiatives, literature, process studies, and laboratory analyses in a four-step process to generate a set of standardized products that culminate in a focused, succinct, and meaningful communication of potential drivers on a given stock. The ESP process and products are supported in several strategic documents (Sigler *et al.,* 2017; Dorn *et al.*, 2018; Lynch *et al.,* 2018) and recommended by the North Pacific Fishery Management Council's (NPFMC) groundfish and crab Plan Teams and the Scientific and Statistical Committee (SSC).

This ESP for Gulf of Alaska (GOA) Pacific cod (*Gadus macrocephalus*) follows the template for ESPs (Shotwell *et al., In Review*) and replaces the previous ecosystem considerations section in the main GOA Pacific cod stock assessment and fishery evaluation (SAFE) report. Information from the original ecosystem considerations section may be found in Barbeaux et al. (2019).

The ESP process consists of the following four steps:

1) Evaluate national initiative and stock assessment classification scores (Lynch *et al.,* 2018) along with regional research priorities to assess the priority and goals for conducting an ESP.
2) Perform a metric assessment to identify potential vulnerabilities and bottlenecks throughout the life history of the stock and provide mechanisms to refine indicator selection.
3) Select a suite of indicators that represent the critical processes identified in the metric assessment and monitor the indicators using statistical tests appropriate for the data availability of the stock.
4) Generate the standardized ESP report following the guideline template and report ecosystem and socioeconomic considerations, data gaps, caveats, and future research priorities.

Justification

National initiatives and AFSC research priorities support conducting an ESP for the GOA Pacific cod stock. The high commercial importance of the stock and the early life history habitat requirements created a high score for both stock assessment and habitat assessment prioritization (Hollowed *et al.,* 2016; McConnaughey *et al.,* 2017). The vulnerability scores were in the low to moderate of all groundfish scores based on productivity, susceptibility (Ormseth and Spencer, 2011), and sensitivity to future climate exposure (Spencer *et al.,* 2019). The new data classification scores for GOA Pacific cod suggest a data-rich stock with high quality data for catch, size/age composition, abundance, life history categories, and ecosystem linkages (Lynch *et al.*, 2018). These initiative scores and data classification levels suggest a high priority for conducting an ESP for GOA Pacific cod particularly given the high level of life history information and current application of ecosystem linkages in the stock assessment model for natural mortality and catchability. Additionally, AFSC research priorities support studies that improve our understanding of environmental and climate forcing of ecosystem processes with focus on variables that provide direct input into stock assessment and management. Specifically, research that improves our understanding of Pacific cod dynamics in the Gulf of Alaska and the Bering Sea..

Data

Initial information on GOA Pacific cod was gathered through a variety of national initiatives that were conducted by AFSC personnel in 2015 and 2016. These include (but were not limited to) stock assessment prioritization, habitat assessment prioritization, climate vulnerability analysis, and stock assessment classification. Data from an earlier productivity susceptibility analysis conducted for all groundfish stocks in Alaska were also included (Ormseth and Spencer, 2011). Data derived from this effort served as the initial starting point for developing the ESP metrics for stocks in the Bering Sea and Aleutian Islands (BSAI) and Gulf of Alaska (GOA) groundfish fishery management plans (FMP). Please see Shotwell *et al.*, *In Review*, for more details.

Supplementary data were also collected from the literature and a variety of process studies, surveys, laboratory analyses, accounting systems, and regional reports (Table 2.1.1). Information for the first year of life was derived from ecosystem surveys and laboratory analyses run by multiple programs and divisions at the AFSC (e.g., Ecosystems and Fisheries Oceanography Coordinated Investigations (EcoFOCI), Recruitment Processes Alliance (RPA), Resource Assessment and Conservation Engineering (RACE) Division, Resource Ecology and Fisheries Management (REFM) Division, Auke Bay Laboratory (ABL) Division, Marine Mammal Laboratory (MML) Division). Data for juveniles (less than 42 cm) through adults were consistently available from the AFSC bottom trawl surveys, and the North Pacific Observer Program administered by the Fisheries Monitoring and Analysis (FMA) division.

Data from Ecosystem Status Report (ESR) contributions were provided through personal communication with the contact author of the contribution (e.g., Ressler *et al.*, 2019). Essential fish habitat (EFH) model output and maps were provided by personal communication with the editors of the EFH update (e.g., Rooney *et al.*, 2018). Remote sensing data were collected through coordination with CoastWatch personnel at the Southwest Fisheries Science Center and initial development of an AFSC-specific ERDDAP (Simons, 2019). High resolution regional ocean modeling system (ROMS) and nutrient-phytoplankton-zooplankton (NPZ) data were provided through personal communication with authors of various publications (e.g., Kearney *et al.*, 2020) that develop these models.

The majority of GOA Pacific cod economic value data were compiled and provided by the Alaska Fisheries Information Network (AKFIN). GOA Pacific cod ex-vessel pricing data were derived from the NMFS Alaska Region Blend and Catch Accounting System, the NMFS Alaska Region At-sea Production Reports, and the ADFG Commercial Operators Annual Reports (COAR). GOA Pacific cod first-wholesale data were from NMFS Alaska Region At-sea and Shoreside Production Reports and ADFG Commercial Operators Annual Reports (COAR). Global catch statistics were found online at FAO Fisheries & Aquaculture Department of Statistics (http://www.fao.org/fishery/statistics/en), NOAA Fisheries, Fisheries Statistics Division, Foreign Trade Division of the U.S. Census Bureau (http://www.st.nmfs.noaa.gov/commercial-fisheries/foreign-trade/index), and the U.S. Department of Agriculture (http://www.ers.usda.gov/data-products/agricultural-exchange-rate-data-set.aspx). Information regarding the community involvement and percent value was derived from reports of the Community Development Quota (CDQ) Program.

Metrics Assessment

We first provide the analysis of the national initiative data used to generate the baseline metrics for this second step of the ESP process and then provide more specific analyses on relevant ecosystem and/or socioeconomic processes. Metrics are quantitative stock-specific measures that identify vulnerability or resilience of the stock with respect to biological or socioeconomic processes. Over a century of process studies on cod stocks around the world, including research conducted by the FOCI program, revealed that evaluating ecosystem linkages by life history stage can highlight potential bottlenecks and improve mechanistic understanding of ecosystem or socioeconomic pressures on the stock (Pepin, 1991; Bailey *et al.*, 1996; Megrey *et al.*, 1996; Bailey, 2000; Bailey, 2005; Ciannelli *et al.*, 2005; Sundby and Nakken, 2008; Reum *et al.*, 2020).

National Metrics

The national initiative data were summarized into a metric panel (Figure 2.1.1) that acts as a first pass ecosystem and socioeconomic synthesis. Metrics range from estimated values to qualitative scores of population dynamics, life history, or economic data for a given stock (see Shotwell *et al., In Review* for more details). To simplify interpretation, the metrics are rescaled by using a percentile rank for GOA Pacific cod relative to all other stocks in the groundfish FMP. Additionally, some metrics are inverted so that all metrics can be compared on a low to high scale between all stocks in the FMP. These adjustments allow for initial identification of vulnerable (percentile rank value is high) and resilient (percentile rank value is low) traits for GOA Pacific cod. Data quality estimates from the lead stock assessment author are also provided (0 or green shaded means no data to support answer, 4 or purple shaded means complete data), and if there are no data available for a particular metric then an "NA" will appear in the panel. GOA Pacific cod did not have any data gaps for the metric panel and the data quality was rated as good to complete for nearly all metrics. The metric panel gives context for how GOA Pacific cod relate to other groundfish stocks in the FMP and highlights the potential vulnerabilities for the GOA Pacific cod stock.

The 80th and 90th percentile rank areas are provided to highlight metrics indicating a high level of vulnerability for GOA Pacific cod (Figure 2.1.1). Ecosystem value, depth range, and spawning duration fell within the 80th percentile rank when compared to other stocks in the groundfish FMP. For socioeconomic metrics, constituent demand and commercial demand fell within the 90th percentile rank. Additionally, GOA Pacific cod ecosystem value, commercial importance, and mean trophic level exceeded a threshold of highly vulnerable established in the national initiatives (e.g., Methot, 2015; Patrick et al., 2010). GOA Pacific cod were relatively resilient for habitat dependence, breeding strategy, geographic concentration, population growth rate, age 50% mature, age at 1st maturity, prey specificity, dispersal ELH, maximum age, temperature sensitivity, recruitment variability, reproductive strategy, mean age, habitat specificity, adult mobility, fecundity, and latitude range.

Ecosystem Processes

Pacific cod release all their eggs near the bottom in a single event during the late winter/ early spring period in the Gulf of Alaska (Stark, 2007). Unlike most cod species, Pacific cod eggs are negatively buoyant and are semi-adhesive to the ocean bottom substrate during development (Alderdice and Forrester 1971, Ormseth and Norcross, 2009). Hatch timing/success is highly temperature-dependent (Laurel *et al.*, 2008), with optimal hatch occurring in waters ranging between 4-6°C (Bian *et al.*, 2016; Laurel and Rogers 2020) over a broad range of salinities (Alderdice and Forrester 1971). Eggs hatch into 4 mm larvae in ~2 weeks at 5°C (Laurel *et al.*, 2008) and become surface oriented and available to pelagic ichthyoplankton nets during the spring (Doyle and Mier 2016). During this period, Pacific cod larvae are feeding principally on eggs, nauplii and early copepodite stages of copepod prey <300 um (Strasburger *et al.,* 2014). Warm surface waters can accelerate larval growth when prey are abundant (Hurst *et al.* 2010), but field observations indicate a negative correlation between temperature and abundance of Pacific cod larvae in the Central and Western Gulf of Alaska (Doyle *et al.,* 2009, Doyle and Mier 2016). Laboratory studies suggest warm temperatures can also indirectly impact Pacific cod larvae by way of two mechanisms: 1) increased susceptibility to starvation when the timing and biomass of prey is 'mis-matched' under warm spring conditions (Laurel *et al.*, 2011), and 2) reduced growth by way of changes in the lipid/fatty acid composition of the zooplankton assemblage (Copeman and Laurel 2010).

The spatial-temporal distribution of Pacific cod larvae shifts with ontogeny and is dependent on a number of behavioral and oceanographic processes. In early April, Pacific cod larvae are most abundant around Kodiak Island before concentrations shift downstream to the SW in the Shumagin Islands in May and June (Doyle and Mier 2016). Newly hatched larvae are surface oriented and make extended diel vertical migrations with increased size and development (Hurst *et al.* 2009). Larvae reach a developmental milestone ('flexion') between 10-15 mm and gradually become more competent swimmers with increasing size (Voesenek *et al.,* 2018). Very late stage larvae ('pelagic juveniles') eventually settle to the bottom in early summer around 30-40 mm and use nearshore nurseries through the summer and early fall in the Gulf of Alaska (Laurel *et al.*, 2017). Cross-shelf transport may be an important process for assisting larvae and early juveniles to the nearshore nurseries for settlement. Sustained along shore currents may sweep eggs and larvae from the system before they can settle to the bottom as juveniles (Hinckley *et al.*, 2019). Mesoscale oceanographic features such as eddies or gap winds may assist in entraining eggs and larvae in the system to allow time for growth to a large enough size to settle in preferred nearshore habitat (Sinclair and Crawford, 2005). Eddies have also been shown to influence distribution of nutrients, phytoplankton, and ichthyoplankton in the GOA and areas near Kodiak are known to have high persistent mesoscale energy (Ladd, 2020). Additionally frequent gap wind events can affect the regional oceanography resulting in disruption of the Alaska Coastal Current and decreased flow down Shelikof Strait. Correlative studies reveal that recruitment of Pacific cod in Hecate Strait, BC, Canada was negatively related to sea level pressure which is influenced by the Haida Eddy (Sinclair and Crawford, 2005) and GOA Pacific cod was positively related to gap wind events in the Kodiak region (Ladd *et al.*, 2016).

Shallow, coastal nursery areas provide age-0 juvenile Pacific cod ideal conditions for rapid growth and refuge from predators (Laurel *et al.*, 2007). A benthic habitat suitability analysis for the most recent EFH update for Alaska groundfish (Figure 2.1.3) indicates depth as the top contributing habitat predictor for the early and late juvenile life stages (79% and 72%, respectively) (Pirtle *et al.*, 2019). A fairly narrow and shallow depth range for the early juveniles suggesting the importance of these nearshore habitats for GOA Pacific cod. Tidal current also contributes to the spatial distribution in the early juvenile stage suggesting some influence of transport mechanisms in this stage as well. A preference for mixed mud, sand, and pebble sediments with some structural complexity was also noted (Pirtle *et al.*, 2019). Settled juvenile cod associate with bottom habitats and feed on small calanoid copepods, mysids, and gammarid amphipods during this period (Abookire *et al.*, 2007). At the end of August, age-0 cod become less associated with structural habitats and transition into deeper water in the fall (Laurel *et al.*, 2009). Overwintering dynamics are currently unknown for Pacific cod, although laboratory-held age-0 juveniles are capable of growth and survival at very low temperature (0°C) for extended periods (Laurel *et al.*, 2016a).

Pelagic age-0 juvenile surveys of Pacific cod have been conducted in some years (Moss *et al.*, 2016), but they are prone to significant measurement error if they are conducted across the settlement period (Mukhina *et al.*, 2003). Therefore, first year assessments of Pacific cod in the Gulf of Alaska are better suited during the early larval or later post-settled juvenile period. There are two surveys that routinely survey early life stages of Pacific cod in the Gulf of Alaska during these phases: 1) the RACE EcoFOCI ichthyoplankton survey in the western GOA (1979 – present; https://access.afsc.noaa.gov/ichthyo/index.php), and 2) the RACE Fisheries Behavioral Ecology (FBE) nearshore seine survey in Kodiak (2006 – present). The EcoFOCI ichthyoplankton survey is focused in the vicinity of Kodiak Island, Shelikof Strait and Shelikof Sea Valley and captures Pacific cod larvae primarily in May when they are 5-8 mm in size (Matarese *et al.*, 2003). The Kodiak seine survey occurs in two embayments and is focused on post-settled age-0 juveniles later in the year (mid-July to late August) when fish are 40-100 mm in length (Laurel *et al.*, 2016b). In 2018, Cooperative Research between the AFSC and academic partners spatially extended the Kodiak seine survey to include 14 different bays on Kodiak Island, the Alaska Peninsula, and the Shumagin Islands (Fig 1; Litzow and Abookire, 2018). This spatially extended survey is currently in its 3rd year and has thus far validated that the highly variable annual CPUEs observed in the small-scale surveys in Kodiak are largely mirrored across the Central and Western GOA.

The summer thermal conditions in the Central/Western GOA have historically been well-suited for high growth and survival potential for juvenile Pacific cod (Laurel *et al.*, 2017), but may have been suboptimal during the 2014-16 marine heatwave (Barbeaux *et al.*, 2020). However, the absence of age-0 fish arriving to nurseries in years with warm springs strongly suggests pre-settlement processes (egg/larval) are determining annual cohort strength in the GOA. Reductions in spawning habitat from subsurface warming appears to be an important mechanism limiting reproductive output in the GOA (Laurel and Rogers 2020), but it is likely one of several mechanisms driving recruitment dynamics. Post-settlement processes (e.g., overwintering processes) may also be important. For example, age-0 CPUEs returned to relatively high numbers in 2017 and 2018 after the heatwave, but few age-1 fish from these cohorts were observed the following year in these surveys. It is unclear whether older juvenile stages have shifted to deeper water (beyond the survey) or if age-0 fish failed to successfully overwinter.

The direct impacts of temperature on life history processes in Pacific cod are stage- and size-dependent but these relationships generally are 'dome shaped' like other cod species (e.g., Hurst et al. 2010; Laurel et al. 2016a). In the earliest stages (eggs, yolk-sac larvae), individuals have less flexibility to behaviorally adapt and have finite energetic reserves (non-feeding). In later juvenile stages, individuals can move to more favorable thermal or food habitats that better suit their metabolic demands. Changes in seasonal temperatures also influence how energy is allocated. A recent laboratory study indicated age-0 juvenile Pacific cod shift more energy to lipid storage than to growth as temperatures drop, possibly as a strategy to offset limited food access during the winter (Copeman *et al.*, 2017).

The AFSC continues investigating environmental regulation of 1st year of life processes in Pacific cod to better understand the interrelationship between processes occurring during pre-settlement (spawning/larvae), settlement (summer growth) and post-settlement (1st overwintering) phases. Transport processes and connectivity between larval and juvenile nursery areas will continue to be an important area of research as the Regional Oceanographic Model (ROMS) for the GOA is updated.

Pacific cod are opportunistic predators, eating a variety of zooplankton, crab, and fish species (Aydin *et al.*, 2007). Decreased prey availability and quality can lead to growth-dependent mortality (Gallego and Heath, 1997; Beaugrand *et al.*, 2004). In the absence of abundance estimates of prey resources, the reproductive success of piscivorous (e.g., Common Murre, *Uria aalge*) and planktivorous seabirds (e.g., planktivorous auklets, *Aethia* spp.) in the GOA can be used to inform prey quality and quantity (e.g., Piatt, 2002). Fish condition (length-weight residuals of Pacific cod) is another proxy for prey availability (Brodeur *et al.*, 2004).

Walleye pollock and halibut account for the greatest sources of predation mortality for Pacific cod in the GOA, followed by sperm whales (*Physeter microcephalus*), Steller sea lions (*Eumetopias jubatus*), and dogfish (*Squaliformes*) (Aydin *et al.*, 2007).

Socioeconomic Processes

Pacific cod has been a critical species in the catch portfolio of the Gulf of Alaska (GOA) fisheries (Fissel *et al.*, 2019). From 2009-2016 Pacific cod typically accounted for just under 30% of the GOA's FMP groundfish harvest and over 20% of the total Pacific cod catch in Alaska. By 2019 these shares fell to approximately 7%. Catch of Pacific cod in the GOA was down 70% from 2017 with a total catch of 15.7 thousand t and retained catch 14.5 thousand t (Table 2.1.3a). Ex-vessel prices increased 9% to $0.49 per pound in 2019. Ex-vessel revenues in 2018 were up 9% to $15.7 million with the increase in prices (Table 2.1.3a). The Pacific cod total allowable catch (TAC) is allocated to multiple sectors. In the GOA, sectors are defined by gear type (hook and line, pot, trawl and jig) and processing capacity (catcher vessel (CV) and catcher processor (CP)). Within the sectoral allocations the fisheries effectively operate as open access with limited entry. The majority of GOA Pacific cod is caught by CVs which make deliveries to shore-based processors and accounts for 90% of the total GOA Pacific cod catch (Table 2.1.3a). Approximately 25% is caught by the trawl, 55% is caught by pot gear, and 20% caught by hook and line, though the number of hook and line vessels is far greater. The number of catcher processors has dropped from 11 in 2016 to 3 in 2019 and the number of catcher vessels has dropped from 360 in 2016 to 176 in 2019. Poor fishing conditions may have contributed to the significant reduction in jig fleet participation since 2017. Prior to 2016, approximately 60% of the retained catch volume and value was in the Central Gulf fisheries, 40% in the Western Gulf, and 1-2% occurring in other regions of the GOA. Since 2016 the distribution has shifted to about 50% with proportionally more cod being caught in the Western Gulf. Harvests from catcher vessels that deliver to shoreside processors account for approximately 90% of the retained catch (Table 2.1.3a). Catch from the fixed gear vessels (which includes hook-and-line and pot gear) typically receive a slightly higher price from processors because they incur less damage when caught. This price differential was $0.04 per pound in 2019.

The products made from GOA Pacific cod had a first-wholesale value of $35 million in 2019, which was up 10% from 2018 and below the 2010-2014 average of $112 million (Table 2.1.3b). The two primary product forms produced from cod in the GOA are fillets and head and gut (H&G), which comprised approximately 60% and 25% of the value in 2019, though the relative share can fluctuate year over year depending on relative prices and processing decisions. The average price of GOA Pacific cod products in 2019 decreased 17% to $2.14 per pound as fillet prices decreased 5% to $4.13 per pound and H&G prices decreased 37% to $1.28 per pound (Table 2.1.3b). Since 2016 reductions in global supply have put upward pressure on prices resulting in significant year over year price increases in 2017 and 2018. In 2019 prices leveled off, decreasing slightly, as markets have adjusted. These price decreases were also reflected in Pacific cod export prices which fell 3%.

U.S. exports of cod are roughly proportional to U.S. cod production. More than 90% of the exports are H&G, much of which goes to China for secondary processing and re-export (Table 2.1.3c). China’s rise as a re-processor is fairly recent. Between 2001 and 2011 exports to China increased nearly 10 fold and continued to increase up to 2016. Since 2017 China’s share of exports has declined slightly going from 55% in 2016 to 41% in 2019. The cod industry has largely avoided U.S. tariffs that would have a significant negative impact on them in the U.S.-China trade war. However, Chinese tariffs on U.S. products could be inhibiting growth in that market and putting downward pressure on Pacific cod export prices. Japan and Europe (mostly Germany and the Netherlands) are also important export destinations. Japan and Europe accounted for 12% and 22% of the export volume respectively. Approximately 35% of Alaska’s cod production is estimated to remain in the U.S. Because U.S. cod production is approximately 15% of global production and the GOA is approximately 6% of U.S. production, the GOA Pacific cod is a relatively small component of the broader cod market. Strong demand and tight supply in 2017-2018 from the U.S. and globally contributed to increasing prices. The Barents Sea quota was reduced by 13% in 2018 and the global cod supply will remain constrained. Groundfish forum estimates for 2019 indicate global catches of Atlantic and Pacific cod will be reduced by approximately 100 thousand t. A portion of the Russian catch of Pacific cod became MSC certified in Oct. 2019 which could put further downward pressure on prices going forward.

In order to examine participation trends for those communities substantially engaged in the commercial GOA Pacific cod fishery commercial processing and harvesting data were analyzed. This community engagement analysis has been conducted for several groundfish stocks in Alaska as part of the Annual Community Engagement and Participation Overview (ACEPO). This is a new summary document that focuses on providing an overview of harvesting and processing sectors of identified highly engaged communities for groundfish and crab fisheries in Alaska. The analysis presented here is similar to that conducted for the ACEPO report but on the stock level rather than the community level. The analysis separates variables into two categories of fisheries involvement: commercial processing and commercial harvesting. Processing engagement is represented by the amount of landings and associated revenues from landings in the community, the number of vessels delivering in the community, and the number of processors in the community. Harvesting engagement is represented by: the landings, revenues associated with vessels owned by community residents, the number of vessel landings owned by residents in the community, and the number of distinct resident vessel owners whose vessels made landings in any community. By separating commercial processing from commercial harvesting, the engagement indices highlight the importance of fisheries in communities that may not have a large amount of landings or processing in their community, but have a large number of fishers and/or vessel owners that participate in commercial fisheries who are based in the community. To examine the relative harvesting and processing engagement of each community, a separate principal components factor analysis (PCFA) was conducted each year for each category to determine a community's engagement relative to all other Alaska communities. Top communities were then selected for each sector based on the value and volume of GOA Pacific cod landed (for processing engagement) and value and volume harvested for harvesting engagement. To examine sustained participation in the commercial GOA Pacific cod fishery, engagement indices were calculated from 2000-2019. Within the processing sector four ports emerged as highly engaged: Akutan, King Cove, Kodiak, and Sand Point. Kodiak remained highly engaged for all years analyzed, and At Sea processing also registered as highly engaged. In the last five years, Kodiak accounted for an average of 47% of GOA Pacific cod landings revenue, with Sand Point, King Cove, and Akutan combined landed 53%.

In 2019, the total volume of GOA Pacific cod processed in all communities was 27.8 million pounds, bringing in $12.7 million in associated value. One indication of community engagement in processing activities for the GOA Pacific cod fishery is calculating the portion of the total volume landed, as well as the percentage of the total revenue landed by vessels owned by residents of the specific community. Over the past two decades, the volume landed in these four communities showed a substantial dip in 2009 before peaking in 2011 and beginning to fall downward until 2017 (when volume decreased by 24%, and by an additional 78% in 2019. Kodiak). Akutan shows a continued downward slope; however King Cove and Sand Point have slight upticks in 2018. The landed value in the processing sector has decreased, falling from 21.4% of revenue attributed to GOA Pacific cod in 2000 to 3.21% in 2019 (Figure 2.1.4a). Over the last two decades, at sea processors have accounted for 10-20% of the GOA Pacific cod volume landed; however the amount has consistently diminished over time, and was not recorded for the past two years.

Within the GOA Pacific cod harvesting sector, four communities emerged as highly engaged: Kodiak and Sand Point again, Homer, and Seattle MSA (metropolitan statistical area). Kodiak has historically had the highest harvest engagement, bringing in an average of 50% of all the GOA Pacific cod harvested since 2015. The number of vessels owned by community residents declined substantially from 2015 to 2019 in all four highly engaged communities: in Kodiak, the number of vessels has decreased by 73% (90 vessels); Seattle MSA by 44% (12 vessels); Homer and Sand Point combined has declined (12 vessels) (Figure 2.1.4b).

In order to explore community participation in harvesting activities for GOA Pacific cod, the associated harvest value by vessels owned by residents from 2000 to 2019 was examined. Overall, there has been a decrease in the volume of GOA Pacific cod harvested since 2000 with the largest declines since 2015. Between 2015-2019, Kodiak is down 91% in harvested volume (86% since 2000); Seattle MSA down 82% since 2000 (66% compared to 2015); Homer and Sand Point are down since 2000. The value of Pacific cod harvested has also declined for all communities 2015-2019 Seattle were down 56% (82% since 2000); Kodiak is down 84% (79% since 2000); Homer is down and Sand Point is down 42% (72% since 2000). The number of vessels participating in the GOA Pacific cod fishery decreased across highly engaged communities by 70% (268 vessels) since 2000. These decreases depict an overall decline in sustained participation (Figure 2.1.4b).

Indicators Assessment

We first provide information on how we selected the indicators for the third step of the ESP process and then provide results on the indicators analysis. In this indicator assessment a time-series suite is first created that represents the critical processes identified by the metric assessment. These indicators must be useful for stock assessment in that they are regularly updated, reliable, consistent, and long-term. The indicator suite is then monitored in a series of stages that are statistical tests that gradually increase in complexity depending on the data availability of the stock (Shotwell *et al., In Review*).

Indicator Suite

GOA Pacific cod are vulnerable to changes in ocean temperature, relative to other groundfish, due to their short life spans and rapid growth rates. Temperature can influence recruitment due to a narrow temperature tolerance for egg development and larval survival (Alderdice and Forrester, 1971; Laurel *et al.,* 2008; Hurst *et al.*, 2009; Laurel *et al.*, 2011; Laurel and Rogers, 2020). The seasonality and duration of extended warm ocean conditions (e.g., marine heatwaves) can influence productivity and prey availability (Barbeaux *et al.,* 2020). High larval abundance of Pacific cod is associated with years of cooler winters and stronger alongshore winds in the spring (Doyle *et al.*, 2009). Adult Pacific cod can respond to warming shelf temperatures by moving to thermally optimal locations, including deeper depths (Li *et al.,* 2019; Yang *et al.*, 2019), presumably responding to metabolic demands (Paul *et al.*, 1988; Claireaux *et al.*, 1995; Holsman and Aydin, 2015) and prey availability (Nichol *et al.*, 2013).

The current GOA Pacific cod stock assessment includes a June temperature index (temperature at ~40m which is the average depth of 20-40 m fish) to increase AFSC longline survey catchability values (below 150m depth) in warmer years, as shown in Yang et al. (2019). The risk table considers sea surface temperature (including marine heatwaves), indicators of prey quantity and quality (e.g., estimates of euphausiid abundance, seabird reproductive success, seabird diet composition, and Pacific cod condition), and predation mortality (e.g., population estimates of walleye pollock and Steller sea lions).

We generated a suite of ecosystem and socioeconomic indicators using the mechanisms and tested relationships listed above from previous studies and the relevant ecosystem processes identified in the metric assessment (Table 2.1.2b, Figure 2.1.2). The following list of indicators for GOA Pacific cod is organized by categories, three for ecosystem indicators (physical, lower trophic, and upper trophic) and three for socioeconomic indicators (fishery performance, economic, and community) and provides information on whether the indicator was updated or new this year with references where possible. Time series of the ecosystem and socioeconomic indicators are provided in Figure 2.1.5a and Figure 2.1.5b, respectively

Ecosystem Indicators:

1. Physical Indicators (Figure 2.1.5a.a-f)
   - Spawning marine heatwave cumulative index over the central GOA, 1982 to present (contact: S. Barbeaux). The daily sea surface temperatures for 1 September 1981 through 13 October 2020 were retrieved from the NOAA High-resolution Blended Analysis Data database (National Oceanographic and Atmospheric Administration 2017) and filtered to only include data from the central GOA between 145°W and 160°W longitude for waters less than 300 m in depth. The overall daily mean sea surface temperature was then calculated for the entire region by averaging all points. The daily mean sea surface temperature data were processed through the R package heatwaveR (Schlegel and Smit 2018) to obtain the marine heatwave cumulative intensity (MHCI) value (Hobday *et al*., 2016) where we defined a heatwave as 5 days or more with daily mean sea surface temperatures greater than the 90th percentile of the 1 January 1982 through 31 December 2012 time series. MHCI were then summed for each year for the months of January through March, November, and December to create a winter marine heatwave cumulative index (WMHCI), and summed for February and March for the spawning marine heatwave cumulative index (SMHCI).
   - Spawning habitat suitability index, 1994 to present (contact: L. Rogers and B. Laurel,). A temperature-dependent hatch success rate (derived from laboratory experiments) is applied to GAK-1 temperature-at-depth data and averaged over January to April for depths 100 to 250 m (Laurel and Rogers, 2020). While GAK-1 is located in the central

GOA, it broadly represents interannual variation in thermal conditions across the central and western GOA shelf.

- Summer bottom temperature over the GOA shelf from the CFSR dataset across the depth ranges where 20 to 40 cm Pacific cod have been sampled on the AFSC bottom trawl survey (contact: S. Barbeaux, see SAFE for more details regarding the index creation). Data available from 1979 to present.
- Annual eddy kinetic energy (EKE) calculated from sea surface height in the Kodiak area as a measure of mesoscale energy in the ocean system (Ladd, 2020). Suite of satellite altimeters provides sea surface height. The Ssalto/Duacs altimeter products were produced and distributed by the Copernicus Marine and Environment Monitoring Service (CMEMS) (http://www.marine.copernicus.eu). Data available from 1994 to 2019 (contact: C. Ladd)
- Peak timing of the spring bloom was calculated for the western and central GOA (WCGOA) region and derived from chlorophyll a concentration data obtained from MODIS satellite sensor at a 4x4 km resolution and aggregated 8-day composites (Watson *et al.*, 2020). The data are served through the ERDDAP maintained by NOAA CoastWatch West Coast Regional Node and Southwest Fisheries Science Center's Environment Research Division. Data available from 2003 to present (contact: J. Watson).

2. Lower Trophic Indicators (Figure 2.1.5a.g-i)
    - Summer large copepods for young-of-the-year (YOY) GOA Pacific cod from the EcoFOCI summer surveys (Kimmel *et al.,* 2019), 2000 to 2019, various years (contact: L. Rogers).
    - Summer euphausiid abundance is represented as the acoustic backscatter per unit area (sA at 120 kHz, m2 nmi-2) classified as euphausiids and integrated over the water column and then across the surveyed area to produce an annual estimate of acoustic abundance (sA * area, proportional to the total abundance of euphausiids). The index is for the Kodiak core survey area (Ressler *et al.,* 2019), available for variable years historically and biennially since 2013 (contact: P. Ressler).
    - Spring Pacific cod larvae catch-per-unit-of-effort (CPUE) from the EcoFOCI spring surveys (Dougherty *et al.,* 2019), 1981 to 2019, various years (contact: L. Rogers).
    - Summer Pacific cod CPUE of YOY from the AFSC Kodiak beach seine survey, 2006 to 2020 (contact: B. Laurel).
    - Common murre reproductive success at Chowiet Island, 1979 to present, various years (contact: H. Renner).
3. Upper Trophic Indicators (Figure 2.1.5a.g-i)
    - Summer condition for juvenile (< 42 cm) and adult (≥ 42 cm) Pacific cod. Body condition was estimated using a length-weight relationship (Laman and Rohan, 2020) from data collected randomly for otoliths in the GOA bottom trawl survey, 1984 to present, various years (contact: S. Rohan).
    - We calculate the effective area occupied and center of gravity for abundance (numbers) in the bottom trawl survey for the Gulf of Alaska. Spatio-temporal delta-generalized linear mixed model using recommended settings for an "index standardization" model (Thorson 2019), implemented using the package VAST (Thorson and Barnett 2017) in the R statistical environment. This configuration includes spatial and spatio-temporal variation in two linear predictors of a Poisson-link delta model (Thorson 2018), using a gamma distribution for residual variation in positive catch rates. We specified a model with 750 "knots" while using the "fine_scale=TRUE" feature to conduct bilinear interpolation from the location of knots to the location of extrapolation-grid cells. For the

extrapolation grid, we used the Gulf of Alaska grid that covers the spatial domain from which the bottom trawl survey randomizes sampling stations. We restricted this extrapolation grid to include only those cells that were shallower than 700 m and west of 140˚W. Knots were distributed proportional to the spatial distribution of extrapolation-grid cells within this spatial domain. We calculated center of gravity as the biomass-weighted average of the location of extrapolation-grid cells (Thorson *et al.* 2016a), with a northeast rotation when projecting geographic coordinates to UTM coordinates. This rotation was performed to improve the interpretation of shifts in center of gravity, such that the axes along which this metric was summarized are approximately parallel and perpendicular to the continental shelf within the core distribution of Pacific cod. We also calculated the effective area occupied as the area required to contain the population at its average biomass (Thorson *et al.* 2016b). We used epsilon bias-correction to correct for retransformation bias (Thorson and Kristensen, 2016) (contact: Z. Oyafuso).

- Arrowtooth flounder total biomass (metric tons) from the most recent stock assessment model (Shotwell *et al.,* 2020), available 1976 to present (contact: K. Shotwell).
- Steller sea lion non-pup estimates for the GOA portion of the western Distinct Population Segment (known as the west, central and east GOA) (Sweeney and Gelatt, 2020), 1978 to present (contact: K. Sweeney).

Socioeconomic Indicators:

1. Economic Indicators (Figure 2.1.5b.a-d)
   - Annual estimated real ex-vessel value measured in millions of dollars and inflation adjusted to 2019 USD (contact: B. Fissel).
   - Average real ex-vessel price per pound of GOA Pacific cod measured in millions of dollars and inflation adjusted to 2019 USD (contact: B. Fissel).
   - Annual estimated real revenue per unit effort measured in weeks fished and inflation adjusted to 2019 USD (contact: B. Fissel).
2. Community Indicators (Figure 2.1.5b.e-h)
   - The suite of community indicators are expressed as regional quotient (RQ) which is a measure of the importance of the community relative to all Alaska fisheries as calculated in pounds landed or revenue generated from specific fisheries. The RQ is calculated as the landings or revenue attributable to a community divided by the total landings or revenue from all communities and community groupings. Indicators of the annual RQ (expressed as percentage) for processing and harvesting revenue are evaluated for the highly engaged communities of Kodiak and a combined summary of three smaller highly engaged communities (Sand Point, King Cove, and Akutan). These three smaller communities were combined for confidentiality concerns. Data were available from 2000-2019 for processing engagement and 2008 to 2019 for harvesting engagement (contact: S. Wise).

Indicator Monitoring Analysis

We provide the list and time-series of indicators (Figure 2.1.5) and then monitor the indicators using three stages of statistical tests that gradually increase in complexity depending on the stability of the indicator for monitoring the ecosystem or socioeconomic process and the data availability for the stock (Shotwell *et al., In Review*). At this time, we report the initial results of the beginning and intermediate stage statistical tests of the indicator monitoring analysis for GOA Pacific cod and a review of current ecosystem linked modeling developments for the advanced stage.

Beginning Stage, Traffic Light Test:

The beginning stage of the indicator analysis is a simple traffic-light style assessment of the time series values (log-transformed where applicable) relative to one standard deviation from the long-term mean of the time series. Following recommendations from the SSC in February 2020, we include a scoring calculation to this test. The indicator values are evaluated if they are greater than (+), less than (-), or within (•) one standard deviation of the long-term mean for the time series. A value is then provided for the traffic-light based on whether the indicator creates conditions that are good (1), neutral (0), or poor (-1) for GOA Pacific cod (Caddy *et al.,* 2015). This is based on the conceptual model and associated processes tables (Figure 2.1.2, Table 2.1.2b. We then assign a qualitative score based on the value compared to the long term mean and the traffic light code. If a high value of an indicator generates good conditions for GOA Pacific cod and is also greater than one standard deviation from the mean, then that value receives a +1 score. If a high value generates poor conditions for GOA Pacific cod and is greater than one standard deviation from the mean, then that value receives a -1 score. All values less than or equal to one standard deviation from the long-term mean are average and receive a 0 score. The scores are summed by the three organizational categories within the ecosystem (physical, lower trophic, and upper trophic) or socioeconomic (fishery performance, economic, and community) indicators and divided by the total number of indicators available in that category for a given year. We also calculate the overall ecosystem and socioeconomic score and provide these aggregated scores for the past twenty years as the majority of indicators were available throughout this time period. The scores over time allow for comparison of the indicator performance and the history of stock productivity. Future iterations of this score could recognize that these qualitative indicators represent sequential events through the live history and therefore stopping rules should be considered where a mortality event in the early life history could govern a year class (see the “switch model proposed for GOA pollock in 1996 (Megrey *et al.,* 1996)).

We evaluate the list of ecosystem indicators to understand the pressures on the GOA Pacific cod stock regarding recruitment and stock productivity. We start with the physical indicators and proceed through the increasing trophic levels as the indicators are listed above. There has been increased ocean temperatures in the GOA ecosystem resulting in a series of major marine heatwaves being declared for 2014-2016 and again in 2019 (Suryan *et al.*, 2021; Figure 2.1.5a.a). The severity, extent, and duration of the ocean warming have had a large impact on the productivity of the GOA Pacific cod stock (Barbeaux *et al.*, 2020, Laurel and Rogers, 2020). The suitability of Pacific cod spawning habitat has fluctuated throughout the time series but showed a steep continuous decline from a time series high in 2012 to a time series low in 2016 basically responding to the increased heat in the system from the marine heatwave. The suitability rebounded to near average conditions in 2017 and 2018, concurrent with increases in GOA pollock recruitment (Dorn *et al.*, 2020) and dropped again during the 2019 marine heatwave and is back up to near average conditions in 2020 (Figure 2.1.5a.b). This suitability index mirrors the summer bottom temperatures on the shelf which suggests that the heat remains in the system well through the summer months (Figure 2.1.5a.c). This seems to have some impact on the timing of the spring bloom which appears to be somewhat delayed during years with a marine heatwave (Figure 2.1.5a.e). We also see a shift in the annual eddy kinetic energy from high periods of eddy activity from 2003 to 2015 to a lower energy system in 2016 to 2019 (Figure 2.1.5a.d). Preliminary estimates of near real-time 2020 eddy activity in this region suggest EKE was high in spring 2020 due to a strong persistent eddy in the region near Kodiak but had moved westward out of the region by summer (Ladd, 2020).

For the lower trophic level indicators, the summer copepods decreased rather linearly from a high near the start of the time series in 2001 to a low in 2009 and only recovered to average in 2019. Similarly, euphausiid abundance has dropped from a high in 2011 to a low in 2017 and only moderate recovery in 2019 (Figure 2.1.5a.f-g). The CPUE of larvae in the spring EcoFOCI survey has been variable for the time series with peaks in 2007 and 2013 similar to GOA pollock. However, CPUE has remained low since 2013 consistent with the period of low recruitment estimates for this stock since the last large year class in 2012, and was particularly low in 2015 and 2019, during the heatwave years. The nearshore surveys in Kodiak showed above average CPUE in 2012 and high abundance in both 2017 and 2018, and very high abundance in 2020 (Figure 2.1.5a.h-i). It is possible that the diet of piscivorous seabirds in the Kodiak region may serve as a proxy for larval fish productivity in the region and this could be detected in the subsequent reproductive success of the seabirds. The common murre reproductive success on Chowiet

(Figure 2.1.5a.j) appears to be very high in 2015 consistent with the drop in spawning biomass for this stock, but has recovered to very high success from 2017 to 2019, suggesting there may be large spatial shifts in the available prey base.

Condition of juveniles from the summer bottom trawl survey suggests poor condition for the 2015 and 2017 surveys and a return to average condition in 2019. Adult condition shows a slightly different pattern with only poor condition in 2015 and recovery to moderate to high condition in 2017 and 2019 (Figure 2.1.5a.k-l). The overall spatial distribution of the stock has spread out substantially from 2009 to 2019 with a shift to the farthest northeast in 2019 from the farthest southwest in 2017 (area occupied is trending high with increase then decrease in the northeast center of gravity, Figure 2.1.5a.m-n). This trend may suggest a change in the clustering of the stock over time as there was high biomass in 2009 with a single very large tow and then low stock biomass in 2017 and 2019 that was spread out throughout the survey area. Predator biomass of arrowtooth flounder and Steller sea lions has been decreasing and/or stable for the most recent years (Figure 2.1.5a.o-p), suggesting that the primary pressure on the 2012 and recent year-classes may be the lack of preferred prey. Pacific cod are generalist predators and so can switch to eating a variety of prey, so it may be a decrease in the overall prey base in the GOA causing recent declines rather than any particular prey item. We see that with decreases in many groundfish stocks and forage fish in recent years (Dorn *et al.,* 2020, Spies *et al.,* 2019, Ormseth *et al.,* 2019, Arimitsu *et al*., 2021).

For the socioeconomic indicators (Figure 2.1.4b), there has been a decreasing trend in real ex-vessel value since 2011 to the projected lowest value in the time series in 2020. Conversely, there has been an increase in price since 2017 and since 2016 in revenue per unit effort. This is consistent with the large decreases in the spawning biomass of this stock during the marine heatwave years. (Figure 2.1.4a.a-c). Processing and harvesting regional quotient (RQ) in Kodiak has been on an decreasing trend since 2015 and is now at the lowest value for the time series. A more dramatic trend has occurred in the processing and harvesting RQ for small communities, decreasing rapidly from a time series high in 2014 to a low in 2018. There has been some recovery in 2019 but still well below the long term average of the time series. These trends may be due to the large decreases in the GOA Pacific cod stock at the onset of the recent series of marine heatwaves in 2014.

Traffic light scores by category and overall are provided in Table 2.1.4. Overall, ecosystem indicators have been decreasing since 2013 and have shown some modest recovery since 2017, when the heat in the system was reduced (Figure 2.1.6). For the indicators available in the current year, the traffic light analysis shows improved condition in the physical and lower trophic indicators, and stable in the upper trophic indicators. This is consistent with last year except the lower trophic level indicators were trending down. It should be noted that only 6 of the potential 16 indicators were available this year for the ecosystem indicators (Table 2.1.4a). Socioeconomic indicators have also been trending down overall since 2014 with only slight recovery in 2019 and 2020. Also note only 2 of the potential 6 were available this year for the socioeconomic indicators (Table 2.1.4b). No community indicators were available this year as that information data lags the current year by at least one year. We also provide the direction of the current year score from the previous year score for these categories on the conceptual model graphic for quick reference (Figure 2.1.2). The historical traffic light score over all ecosystem and socioeconomic indicators is somewhat decoupled, with a lag in the socioeconomic indicators of about two years (Figure 2.1.6). This may reflect the delayed interaction between the decreases in Pacific cod revenue and community impacts and the recent large decreases of the stock during the recent severe marine heatwave years.

Intermediate Stage, Importance Test:

Bayesian adaptive sampling (BAS) was used for the intermediate stage statistical test to quantify the association between hypothesized predictors and GOA Pacific cod recruitment and to assess the strength of support for each hypothesis. BAS explores model space, or the full range of candidate combinations of predictor variables, to calculate marginal inclusion probabilities for each predictor, model weights for each combination of predictors, and generate Bayesian model averaged predictions for outcomes (Clyde *et al.*, 2011). In this intermediate test, the full set of indicators is first winnowed to the predictors that could directly relate to recruitment and highly correlated covariates are removed (Figure 2.1.7a). We further restrict potential covariates to those that can provide the longest model run and through the most recent estimate of recruitment that is well estimated in the current operational stock assessment model. This results in a model run from 1994 through the 2017 estimate of age 0 or the 2017 year-class. We then provide the mean relationship between each predictor variable and log GOA Pacific cod recruitment over time (Figure 2.1.7b, left side), with error bars describing the uncertainty (95% confidence intervals) in each estimated effect and the marginal inclusion probabilities for each predictor variable (Figure 2.1.7b, right side). A higher probability indicates that the variable is a better candidate predictor of GOA Pacific cod recruitment. The highest ranked predictor variables (inclusion probability > 0.5) based on this process were the spawning habitat suitability index in the GOA and the eddy kinetic energy in Kodiak area D (Figure 2.1.7).

The BAS method requires observations of all predictor variables in order to fit a given data point. This method estimates the inclusion probability for each predictor, generally by looking at the relative likelihood of all model combinations (subsets of predictors). If the value of one predictor is missing in a given year, all likelihood comparisons cannot be computed. When the model is run, only the subset of observations with complete predictor and response time series are fit. It is possible to effectively “trick” the model into fitting all years by specifying a 0 (the long-term average in z-score space) for missing predictor values. However, this may bias inclusion probabilities for time series that have more zeros and result in those time series exhibiting low inclusion probability, independent of the strength of the true relationship. Due to this consideration of bias, we only fit years with complete observations for each covariate at the longest possible time frame. This resulted in a smaller final subset of covariates. We plan to explore alternate model runs (e.g., biennial) to potentially include more covariates in the future. As noted above, Megrey et al. (1996) found that a critical step in multivariate statistical searches of processes governing recruitment required that the analysts considered the temporal sequence of mortality events. Temporal sequencing of mortality events will be considered future versions of this statistical approach. Efforts to include mortality switches could be informed by the planned Individual Based Models.

Advanced Stage, Research Model Test:

In the 2020 Pacific cod Stock assessment (Barbeaux et al. 2020) research models which incorporated links for catchability, mortality, growth, and recruitment using CFSR predicted bottom temperatures, NOAA reanalysis predicted surface temperatures, and heatwave indices were presented. The authors indicate in the 2020 assessment that these linked models had not been adequately validated for use in tactical management of the stock. However, projections based on CMIP 5 were provided to the end of the century for strategic considerations and evaluating the performance of the current control rules. Further development and evaluation of these research models is expected for the stock assessment models to be presented in 2021.

In the future, mortality switches could be evaluated in the advanced stage statistical test, which is a modeling application that analyzes predictor performance and estimates risk probabilities within the operational stock assessment model. Output of two new model developments could be used to generate or enhance an ecosystem-linked model for GOA Pacific cod. First, a new multi-species statistical catch-at-age assessment model (known as CEATTLE; Climate- Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics; Holsman *et al.*, 2016) has recently been developed for understanding trends in age-1 total mortality for Pacific cod, walleye pollock, and arrowtooth flounder from the GOA (G. Adams, *pers., commun*.). Total mortality rates are based on residual mortality inputs (M1), model estimates of annual predation mortality (M2), and fishing mortality (F). CEATTLE has been modified for the GOA and implemented in Template Model Builder (Kristensen *et al.*, 2015) to allow for the fitting of multiple sources of data, time-varying selectivity, time-varying catchability, and random effects. The model is based, in part, on the parameterization and data used for the most recent stock assessment model of each species (Barbeaux *et al.*, 2019, Dorn *et al.*, 2019, and Spies *et al.*, 2019). The model is fit to data from five fisheries and seven surveys, including both age and length composition assumed to come from a multinomial distribution. Model estimates of M2 are empirically driven by bioenergetics-based consumption information and diet data from the GOA to inform predator-prey suitability. The model was fit to data from 1977 to 2020.

A spatially-explicit individual-based model (IBM) for the early life stages of Pacific cod was developed as part of the GOA Integrated Ecosystem Research Program (GOAIERP) (Hinckley *et al.*, 2019) using the DisMELS (Dispersal Model for Early Life Stages) IBM framework. It has since been updated to include temperature-dependent egg development and a better characterization of juvenile nursery habitat based on a Habitat Suitability Model. The IBM tracks the 3-dimensional location, growth, and other characteristics of simulated individuals from the egg stage to the benthic juvenile stage using stored 4-dimensional (3-d space and time) ROMS model output to provide the spatiotemporally-varying environment (e.g., 3-dimensional temperature, NPZ, and current fields) in which the individuals "exist". Egg development and larval/juvenile growth rates depend on *in situ* temperature. Vertical movement in the water column is also stage-specific, but horizontal dispersion is currently assumed to be passive. Individual location and other characteristics are updated using Lagrangian particle tracking with a 20-minute integration time step. It would be possible to derive several types of indices using the IBM and ROM model output for the current year, including: 1) changes in connectivity between presumed spawning and juvenile nursery habitats; 2) spatiotemporally-averaged, temperature-dependent egg development success; and 3) life stage-specific, spatiotemporally-averaged, temperature-dependent growth rates. Once the ROMS model output is available, it takes several hours on a laptop to run the IBM for a year simulating ~100,000 individuals. Additional time would be required to calculate the desired indices, but turn-around could be reasonably quick.

Once the GOA CEATTLE model is more developed and published, the age-1 mortality index could provide a gap free estimate of predation mortality. Indeed, the age-specific mortality estimates from the GOA CEATTLE model are being tested as priors for age-specific mortality within the age-structured model, however fitting age-specific annually varying mortality within the model has proven to be challenging given the lack of data on younger fish (age 0-3) and will require further development. Additionally, the spawning habitat suitability index was examined for use in the 2021 age-structured model as an age-0 index, but the age-0 beach seine index (contact: B. Laurel and M. Litzow) was found to perform better for this purpose and will be presented as an alternative model in the 2021 assessment. Potentially in the future, the kinetic energy in Kodiak indicator could also be used directly to help explain the variability in recruitment deviations and predict pending recruitment events for GOA Pacific cod.

Conclusion

The GOA Pacific cod ESP follows the standardized framework for evaluating the various ecosystem and socioeconomic considerations for this stock (Shotwell *et al., In Review*). Given the metric and indicator assessment we provide the following set of considerations:

Ecosystem Considerations

- Hatch timing and success is highly temperature dependent with optimal hatch occurring in waters between 4-6°C and has implications for spawning habitat suitability and subsequent recruitment
- Warm temperatures can increase susceptibility of starvation for larval Pacific cod when mismatched to prey or reduce growth during shifts in the lipid/fatty acid composition of prey
- Cross-shelf transport may assist larvae and early juveniles to nearshore nurseries for settlement and eddies and gap winds may disrupt along-shore currents to increase growth and survival

- Copepods and euphausiids low since 2009 and returned to average in 2019, and condition of juvenile Pacific cod were poor for 2015 and 2017 surveys
- Annual eddy kinetic energy has shifted from high periods of eddy activity from 2003 to 2015 to a lower energy system in 2016 to 2019 and a strong, persistent eddy around Kodiak in 2020
- The overall spatial distribution of the stock has spread out substantially from 2009 to 2019 with a shift to the farthest northeast in 2019 from the farthest southwest in 2017
- Predators of Pacific cod have steadily decreased over the time series but have recently stabilized suggesting the primary pressure on the 2012 year-classes may be the lack of preferred prey
- Overall, ecosystem indicators have been decreasing since 2012 with a slight recovery to near normal conditions in 2017, when the heat in the system was reduced but return to low values in 2018 and 2019, similar to the GOA pollock
- Highest ranked predictor for recruitment regression model was spawning habitat suitability and the eddy kinetic energy temperature on the GOA shelf (inclusion probability > 0.5)

Socioeconomic Considerations

- Kodiak and a combined group of small communities were selected as highly engaged communities when evaluating commercial processing and harvesting engagement
- Ex-vessel value has been decreasing since about 2011 with price per pound very low from 2013 to 2017 with a recent increase and revenue per unit effort has been increasing since 2016
- Processing and harvesting regional quotient (RQ) in Kodiak has been steadily decreasing since 2015 with small communities declining in both measures since 2014, a year earlier.

Data Gaps and Future Research Priorities

While the metric and indicator assessments provide a relevant set of proxy indicators for evaluation at this time, there are certainly areas for improvement. The majority of indicators collected for GOA Pacific cod have a fair number of gaps due to the biennial nature of survey sampling in the GOA. This causes issues with updating the ESP and the ecosystem considerations during off-cycle years and can lead to difficulty in identifying impending shifts in the ecosystem that may impact the GOA Pacific cod population. Development of high-resolution remote sensing (e.g., regional surface temperature, transport estimates, primary production estimates) or climate model indicators (e.g., bottom temperature, NPZ variables) would assist with the current multi-year data gap for several indicators if they sufficiently capture the main trends of the survey data and are consistently and reliably available.

Additional refinement on the GOA CEATTLE model and the Pacific cod IBM might also allow for the addition of several gap-free indicators for GOA Pacific cod. An updated set of indicators may then be used in the second and third stage modeling applications that provide direction of relationships, inclusion probabilities, and evaluation of performance and risk within the operational stock assessment model. Also, a new project has recently been funded involving a multi-model approach including the development of the GOA Ecopath models and an Atlantis ecosystem model. This project is part of the GOA Regional Action Plan and will start in 2021 with the goal of evaluating the biological reference points used for status determination of individual stocks (e.g., Pacific cod) under projected climate scenarios (M. Dorn, *pers., commun.*). The project has a three-year timeline and we hope to incorporate the results of this effort as they become available.

We currently lack an indicator of predation on YOY Pacific cod during their first autumn and winter, during a period when predation mortality is thought to be significant. Sampling of predator diets in fall and winter would help to fill this gap. Additionally, evaluating condition and energy density of juvenile and adult Pacific cod samples at the outer edge of the population may be useful for understanding the impacts of shifting spatial statistics such as center of gravity and area occupied. Information is available from the GulfWatch Alaska program that could be helpful for evaluating the eastern edge of the GOA Pacific cod population.

Demographic differences in the YOY population need to be evaluated within and among larval and juvenile surveys conducted in the Central and Western GOA (currently sampling ~1000km of coastline). Size shifts in the YOY population have already been observed in marine heatwave years, but it is unclear if one or more of the following processes are involved: 1) spawning (earlier); 2) larval/juvenile growth (higher); and/or 3) larval/juvenile mortality (higher/size-selective). Climate-driven changes in size and age may also impact survival trajectories of YOY cohorts and their potential to recruit to the fishery.

As indicators are improved or updated, they may replace those in the current set of indicators to allow for refinement of the BAS model and potential evaluation of performance and risk within the operational stock assessment model. This could be accomplished in the next full ESP assessment and the timing of that will depend on how the ESP process matures.

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*Superscript numbers refer to references in Table 2.1.2a and Table 2.1.2b

Tables

Table 2.1.1: List of data sources used in the ESP evaluation. Please see the main GOA Pacific cod SAFE document, the Ecosystem Considerations Report (Zador *et al.*, 2019; Ferriss and Zador, 2020) and the Economic Status Report (Fissel *et al.*, 2019, 2021) for more details.

Title	Description	Years	Extent
EcoFOCI Spring Survey	Shelf larval survey in spring on the eastern Bering Sea shelf using oblique 60 cm bongo tows, fixed-station grid, catch per unit effort in numbers per 10 m^2	1978 – present	Gulf of Alaska annual, biennial
FBE Beach Seine Survey	Age-0 gadid survey in mid-July through late August on 16 fixed-site stations, northeast Kodiak Island using 36-m demersal beach seine, gadids count, length in mm	2006 – present	Kodiak annual
AFSC Summer Survey	Midwater trawl survey of groundfish and forage fish from August-September using Stauffer trawl and bongo tows in the eastern Bering Sea shelf, fixed-station grid	2000 – present	Gulf of Alaska biennial
AFSC Bottom Trawl Survey	Bottom trawl survey of groundfish in June through August, eastern Bering Sea using Poly Nor'Eastern trawl on stratified random sample grid, catch per unit of effort in metric tons	1982 – present	Gulf of Alaska annual
AFSC Acoustic Survey	Mid-water acoustic survey in June to August for pollock in the Gulf of Alaska shelf and nearshore bays	1981 – present	Gulf of Alaska annual, biennial
Seabird Surveys	Ecological monitoring for status and trend of suite of seabird species conducted by Institute for Seabird Research and Conservation	1978 – present	Gulf of Alaska
REEM Diet Database	Food habits data and associated analyses collected by the Resource Ecology and Ecosystem Modeling (REEM) Program, AFSC on multiple platforms	1990 – present	Gulf of Alaska annual
Climate Model Output	Daily sea surface temperatures from the NOAA High-resolution Blended Analysis Data	1977 – present	Central GOA
MODIS	4 km MODIS ocean color data aggregated 8-day composites.	2003-present	Global
ROMS/NPZ Model Output	Coupled hydrographic Regional Ocean Modeling System and lower tropic Nutrient-Phytoplankton-Zooplankton dynamics model	1996 – 2013	Alaska variable

Table 2.1.1 (cont.): List of data sources used in the ESP evaluation. Please see the main GOA Pacific cod SAFE document, the Ecosystem Considerations Report (Zador et al., 2019; Ferriss and Zador, 2020) and the Economic Status Report (Fissel et al., 2019, 2021) for more details.

Title	Description	Years	Extent
Essential Fish Habitat Models	Habitat suitability MaxEnt models for describing essential fish habitat of groundfish and crab in Alaska, EFH 2016 Update	1970 – 2016	Alaska
FMA Observer Database	Observer sample database maintained by Fisheries Monitoring and Analysis Division	1988 – present	Alaska annual
NMFS Alaska Regional Office	Catch, economics, and social values for fishing industry, data processed and provided by Alaska Fisheries Information Network	1992 – 2018	Alaska annual
Reports & Online	ADFG Commercial Operators Annual Reports, AKRO At-sea Production Reports, Shoreside Production Reports, FAO Fisheries & Aquaculture Department of Statistics	2011 – 2018	Alaska, U.S., Global annual

Table 2.1.2a: Ecological information by life history stage for GOA Pacific cod.

Stage	Habitat & Distribution	Phenology	Age, Length, Growth	Energetics	Diet	Predators/Competitors
Recruit	Shore to Shelf (0-500 m), depth varies by age then size(24), sublittoral-bathyal zone, move w/in, between LMEs(24)	Recruit to survey and fishery age-1, length 20-27 cm(24)	Max: 25 yrs, 147♀/134♂ cm L_inf=94 cm, K= 0.2 (24,AFSC)		Opportunistic, small on inverts, large on fish(20, 21, 24, AFSC)	Halibut, Steller sea lions, whales, tufted puffins, fisheries(24); shelf groundfish(24)
Spawning	Shelf (40-290 m)(13-16,24), semi-demersal in shelf areas(13,15,16), seasonal migrations variable duration(26)	Winter-spring, peak mid-March, 13 wks (1,20,25)	1st mature: 2 yr, 26♀/36♂cm, 50%: 4-5yr, 45-65cm (24,AFSC)	Oviparous, high fecundity (250-2220·10^3) eggs (13,15), range 4-6 °C(14,16)	Opportunistic (20,21)	Halibut, Steller sea lions, whales, tufted puffins, fisheries(24); shelf groundfish(24)
Egg	Shelf (20-200 m), demersal, adhesive eggs(13,15-17,24)	Incubation is ~20 days, 6 wks(14,22)	Egg size: 0.98-1.08 mm (28)	Optimal incubation 3-6°C, 13-23 ppt, 2-3ppm dO_2 (27)	Yolk is dense and homogenous (AFSC)	
Yolk-sac Larvae	Epipelagic, nearshore shelf, coastal, upper 45 m, semi-demersal at hatching(13-15,18,24)	Spring, peak mid May, 14 wks(22,29)	3-4.5 mm NL at hatch (13-15,24,28)	Hatch temperature 4.5-5.8°C(2)	Endogenous	Share larval period with pollock(13)
Feeding Larvae	Epipelagic, nearshore shelf(13-15,24), 0-45 m (24)	Late spring, April – June, (22	25-35 mm SL at transformation (3,13-15,24)	1-2 weeks before onset of feeding(28,29)	Copepod eggs, nauplii, and early copepodite stages (Strasburger et al. 2014)	Share larval period with pollock(13)
Juvenile	Nearshore (2-110 m), 15-30 m peak density, inside bays, coastal, mixed, structural complexity (1-6,10,11,21)	Nearshore settlement in June, deeper water migrations in October(3,10,13-15)	YOY: 35-110 mm FL(2), age 1+: 130-480 mm FL(1,3,4,6,10); growth sensitive to temp	Energy density ↑ with length, lower in pelagic stage	Copepods, mysids, amphipods(2), small fish(10), crabs(19-21)	Pollock, halibut, arrowtooth flounder(19,20); macroalgae, eelgrass, structural inverts, king crab, skate egg case, juvenile pollock (1-5,7-9,11)
Pre-Recruit	Nearshore, shelf (10-216 m)(4), inside bays, coastal, mixed, mud, sand, gravel, rock pebble(1,2,4,6)	Age-2 may congregate more than age-1(25)	Begin to mature age 2-3, 480-490 mm FL (15)	Energy density and condition lower than in pelagic stage	Opportunistic, benthic invert, pollock, small fish, crabs(19-21)	Pacific cod, halibut, salmon, fur seal, sea lion, porpoise, whales, puffin(24); macroalgae, macroinvertebrate, king crab, skate egg case(4-5,7-9)

Table 2.1.2b. Key processes affecting survival by life history stage for GOA Pacific cod.

Stage	Processes Affecting Survival	Relationship to GOA Pacific cod
Recruit	1. Competition 2. Predation 3. Temperature	Increases in main predator of Pacific cod would be negative but minor predators may indicate Pacific cod biomass increase. Increases in overall prey biomass would be positive for Pacific cod but generalists.
Spawning	1. Spawning Habitat Suitability 2. Distribution	Temperatures outside the 3-6º C range contribute to poor hatching success and may impact physiological and behavioral aspects of spawning. Spring bottom temperatures outside this range are linked to observed pre-recruits and recruitment estimates$_{(27)}$
Egg	1. Temperature$_{(14,18,29,30)}$	Eggs are highly stenothermic$_{(27)}$
Yolk-sac Larvae	1. Temperature$_{(14,18,29,30)}$ 2. Timing of spring bloom$_{(13)}$ 3. Onshore shelf transport$_{(13,31,32)}$	Increases in temperature would increase metabolic rate and may result in rapid yolk-sac absorption that may lead to mismatch with prey. Current direction to preferred habitat would be positive for Pacific cod.
Feeding Larvae	1. Temperature$_{(14,18,29,30)}$ 2. Prey availability 3. Onshore shelf transport$_{(13,31,32)}$	Increases in temperature would increase metabolic rate and may result in poor condition if feeding conditions are not optimal. Onshore transport to nursery habitat would be positive for Pacific cod while predation increases would be negative.
Juvenile	1. Competition$_{(33)}$ 2. Predation$_{(33)}$ 3. Temperature$_{(34)}$	Evidence of density-dependent growth in coastal nurseries$_{(33)}$ would suggest that increases in competitors or predators would be negative for Pacific cod condition and therefore survival. Temperature increases may amplify risk of food availability and energy allocation$_{(34)}$
Pre-Recruit	1. Competition$_{(33)}$ 2. Predation$_{(33)}$ 3. Temperature$_{(34)}$	Evidence of density-dependent growth in coastal nurseries$_{(33)}$ would suggest that increases in competitors or predators would be negative for Pacific cod condition and therefore survival. Temperature increases may amplify risk of food availability and energy allocation$_{(34)}$

Table 2.1.3a. Gulf of Alaska Pacific cod catch and ex-vessel data. Total and retained catch (thousand metric tons), ex-vessel value (million US$) and price (US$ per pound), hook and line and pot gear share of catch, inshore sector share of catch, number of vessels; 2010-2014 average and 2015-2019.

	Avg 10-14	2015	2016	2017	2018	2019
Total catch K mt	79.06	79.5	64.1	48.7	15.2	15.7
Retained catch K mt	75.7	77.5	63.1	48.0	14.4	14.5
Ex-vessel value M $	$50.8	$50.3	$41.0	$35.3	$14.5	$15.7
Ex-vessel price lb $	$0.304	$0.293	$0.294	$0.334	$0.452	$0.492
Hook & line share of catch	25%	21%	17%	18%	23%	23%
Pot gear share of catch	49%	52%	60%	55%	53%	52%
Central Gulf share of catch	61%	60%	53%	43%	47%	47%
Shoreside share of catch	90%	92%	92%	87%	88%	89%
Vessels #	421.4	386	360	246	154	176

Table 2.1.3b. Gulf of Alaska Pacific cod first-wholesale market data. First-wholesale production (thousand metric tons), value (million US$), price (US$ per pound), fillet and head and gut volume (thousand metric tons), value share, and price (US$ per pound), inshore share of value; 2010-2014 average and 2015-2019.

		Avg 10-14	2015	2016	2017	2018	2019
All Products	volume K mt	31.16	32.00	21.65	17.39	5.58	7.47
All Products	value M $	$111.5	$102.5	$91.8	$75.5	$31.9	$35.2
All Products	price lb $	$1.62	$1.45	$1.92	$1.97	$2.59	$2.14
Fillets	volume K mt	9.41	6.39	7.87	6.52	2.00	2.36
Fillets	value share	55.3%	36.3%	62.5%	60.0%	60.1%	61.0%
Fillets	price lb $	$2.97	$2.64	$3.30	$3.15	$4.35	$4.13
Head & Gut	volume K mt	13.43	19.05	8.43	6.11	1.92	3.02
Head & Gut	value share	32.2%	50.9%	24.7%	26.9%	27.0%	24.1%
Head & Gut	price lb $	$1.21	$1.24	$1.22	$1.51	$2.04	$1.28

Table 2.1.3c. GOA Pacific cod global catch (thousand metric tons), U.S. and AK shares of global catch; WA & AK export volume (thousand metric tons), value (million US$), price (US$ per pound) and the share of export value from trade with Japan and China, 2009-2013 average and 2014-2019.

		Avg 10-14	2015	2016	2017	2018	2019
Global cod catch K mt		1,631	1,762	1,789	1,761	1,633	-
U.S. P. cod share of global catch		18.5%	18.0%	18.0%	16.9%	14.2%	-
Europe share of global catch		74.7%	74.8%	74.9%	75.9%	78.3%	-
Pacific cod share of U.S. catch		97.8%	99.3%	99.5%	99.5%	99.7%	-
U.S. cod consumption K mt (est.)		97	108	114	118	114	106
Share of U.S. cod not exported		29%	26%	29%	32%	36%	37%
Export volume K mt		103.8	113.2	105.3	92.8	73.1	65.1
Export value M US$		$325.2	$335.0	$312.0	$295.5	$253.4	$218.1
Export price lb US$		$1.421	$1.342	$1.344	$1.445	$1.571	$1.519
Frozen (H&G)	volume Share	81%	91%	94%	94%	91%	92%
	value share	81%	90%	92%	92%	90%	91%
Fillets	volume Share	7%	3%	3%	4%	5%	5%
	value share	9%	4%	4%	5%	6%	6%
China	volume Share	44%	53%	55%	52%	48%	41%
	value share	41%	51%	52%	50%	46%	40%
Japan	volume Share	17%	13%	14%	16%	15%	12%
	value share	17%	14%	15%	18%	17%	13%
Europe*	volume Share	27%	19%	17%	17%	16%	22%
	value share	29%	19%	18%	18%	18%	23%

Note: Pacific cod in this table is for all U.S. Unless noted, `cod' in this table refers to Atlantic and Pacific cod. Russia, Norway, and Iceland account for the majority of Europe's cod catch which is largely focused in the Barents sea.

*Europe export statistics refers to: Austria, Belgium, Denmark, France, Germany, Greece, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and United Kingdom.

Source: NMFS Alaska Region Blend and Catch-accounting System estimates; NMFS Alaska Region At-sea and Shoreside Production Reports; and ADF&G Commercial Operators Annual Reports (COAR). Data compiled and provided by the Alaska Fisheries Information Network (AKFIN). FAO Fisheries & Aquaculture Dept. Statistics http://www.fao.org/fishery/statistics/en. NMFS Alaska Region Blend and Catch-accounting System estimates. NOAA Fisheries, Fisheries Statistics Division, Foreign Trade Division of the U.S. Census Bureau, http://www.st.nmfs.noaa.gov/commercial-fisheries/foreign-trade/index. U.S. Department of Agriculture http://www.ers.usda.gov/data-products/agricultural-exchange-rate-data-set.aspx.

Table 2.1.4a. Beginning stage ecosystem indicator score analysis for GOA Pacific cod by four main categories (physical, lower trophic, upper trophic, and overall ecosystem). Each indicator is scored based on the traffic light evaluation for that indicator (1 if a positive value increase creates good conditions for GOA Pacific cod, -1 if positive increase creates poor conditions for GOA Pacific cod, 0 otherwise), multiplied by the value relative to the long-term mean of the time series (greater than, less than, or within 1 standard deviation). Those scores are summed by category and then divided by the total number of indicators for that category. Number of indicators for each category are also provided. NA = no indicators available. Color coding based on column, blue = 1 shading through white = 0 shading through red = -1.

	Physical		Lower Trophic		Upper Trophic		Total Ecosystem	
Year	Score	# Indicators	Score	# Indicators	Score	# Indicators	Score	# Indicators
2000	0.00	4	0.00	2	0.50	2	0.13	8
2001	-0.25	4	0.50	2	0.17	6	0.08	12
2002	0.25	4	0.00	2	-0.50	2	0.00	8
2003	-0.60	5	0.00	3	-0.50	6	-0.43	14
2004	0.20	5	0.00	2	-0.50	2	0.00	9
2005	0.00	5	-0.25	4	-0.50	6	-0.27	15
2006	0.00	5	0.00	3	-0.50	2	-0.10	10
2007	0.60	5	0.25	4	-0.17	6	0.20	15
2008	0.20	5	0.00	2	-0.50	2	0.00	9
2009	0.00	5	-0.25	4	-0.33	6	-0.20	15
2010	0.20	5	0.00	3	0.00	2	0.10	10
2011	0.00	5	0.00	4	-0.17	6	-0.07	15
2012	0.80	5	0.50	2	0.00	2	0.56	9
2013	0.00	5	0.25	4	0.00	6	0.07	15
2014	-0.20	5	0.00	2	0.00	2	-0.11	9
2015	-0.20	5	-0.60	5	-0.17	6	-0.31	16
2016	-0.20	5	-0.50	2	0.00	2	-0.22	9
2017	-0.20	5	-0.40	5	0.33	6	-0.06	16
2018	-0.40	5	0.00	2	0.00	2	-0.22	9
2019	-0.40	5	-0.20	5	0.00	6	-0.19	16
2020	-0.25	4	1.00	1	0.00	1	0.00	6

Table 2.1.4b. Beginning stage socioeconomic indicator score analysis for GOA Pacific cod by four main categories (performance, economic, community, and overall socioeconomic). Each indicator is scored based on the traffic light evaluation for that indicator (1 if a positive value increase creates good socioeconomic environment for GOA Pacific cod, -1 if positive increase creates poor conditions for GOA Pacific cod, 0 otherwise), multiplied by the value relative to the long-term mean of the time series (greater than, less than, or within 1 standard deviation). Those scores are summed by category and then divided by the total number of indicators for that category. Number of indicators for each category are also provided. NA = no indicators available. Color coding based on column, blue = 1 shading through white = 0 shading through red = -1.

	Fishery Performance		Economic		Community		Total Socioeconomic	
Year	Score	# Indicators	Score	# Indicators	Score	# Indicators	Score	# Indicators
2000	NA	NA	0.00	0	1.00	2	1.00	2
2001	NA	NA	0.00	0	0.00	2	0.00	2
2002	NA	NA	0.00	0	0.00	2	0.00	2
2003	NA	NA	0.00	3	0.00	2	0.00	5
2004	NA	NA	-0.33	3	0.00	2	-0.20	5
2005	NA	NA	-0.33	3	0.00	2	-0.20	5
2006	NA	NA	0.00	3	0.00	2	0.00	5
2007	NA	NA	1.00	3	0.00	2	0.60	5
2008	NA	NA	1.00	3	0.50	4	0.71	7
2009	NA	NA	-0.33	3	0.00	4	-0.14	7
2010	NA	NA	0.00	3	0.25	4	0.14	7
2011	NA	NA	0.67	3	0.00	4	0.29	7
2012	NA	NA	0.33	3	0.00	4	0.14	7
2013	NA	NA	-0.33	3	-0.25	4	-0.29	7
2014	NA	NA	0.00	3	0.50	4	0.29	7
2015	NA	NA	0.00	3	0.25	4	0.14	7
2016	NA	NA	-0.33	3	0.00	4	-0.14	7
2017	NA	NA	0.00	3	-0.50	4	-0.29	7
2018	NA	NA	-0.33	3	-1.00	4	-0.71	7
2019	NA	NA	0.33	3	-1.00	4	-0.43	7
2020	NA	NA	-0.50	2	0.00	0	-0.50	2

Figures

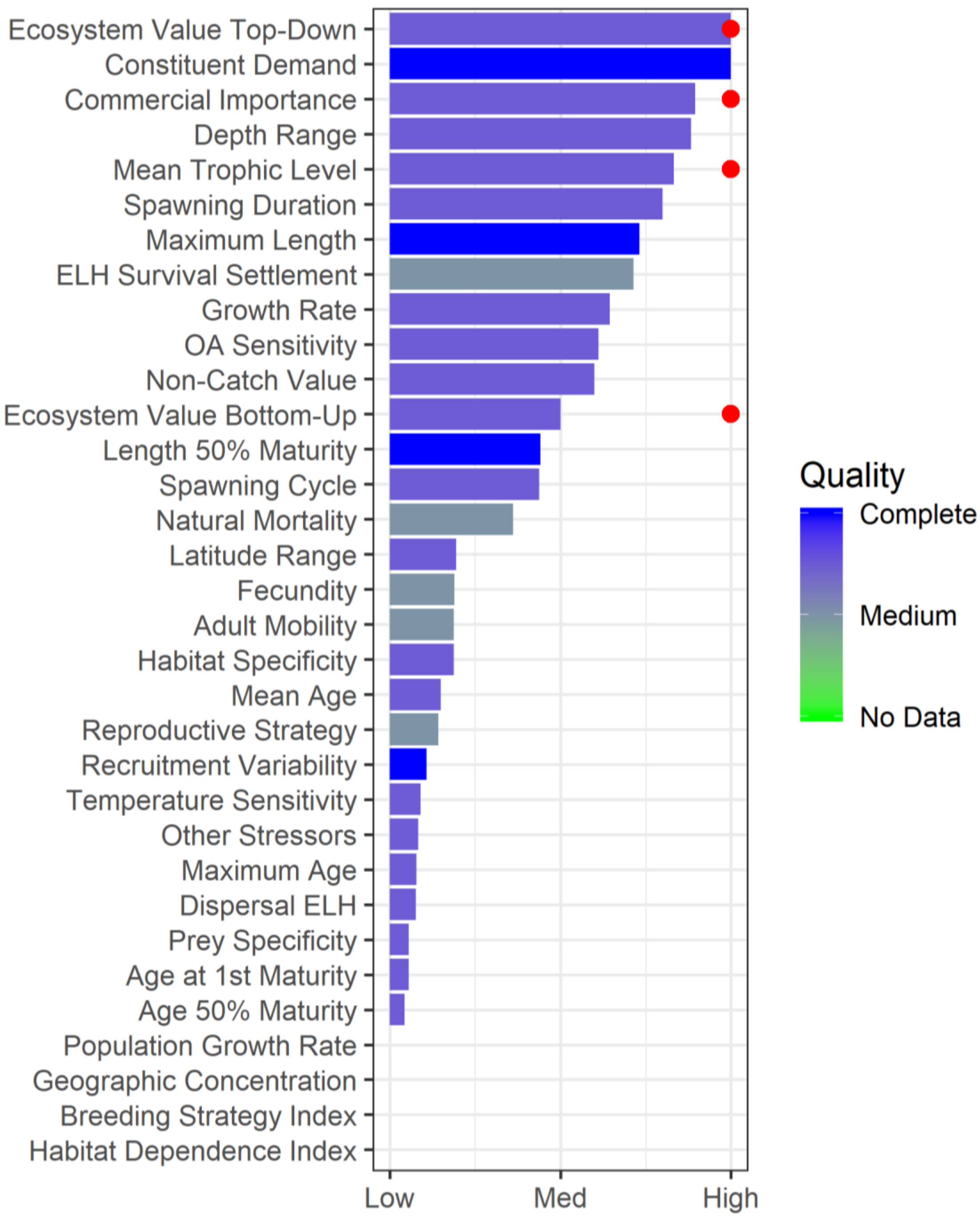

Figure 2.1.1. Baseline metrics for GOA Pacific cod graded as percentile rank over all groundfish in the FMP. Red dots indicate value passes a national threshold for vulnerability. Higher rank values indicate a vulnerability and color of the horizontal bar describes data quality of the metric (see Shotwell *et al., In Review*, for more details on the metric definitions and thresholds).

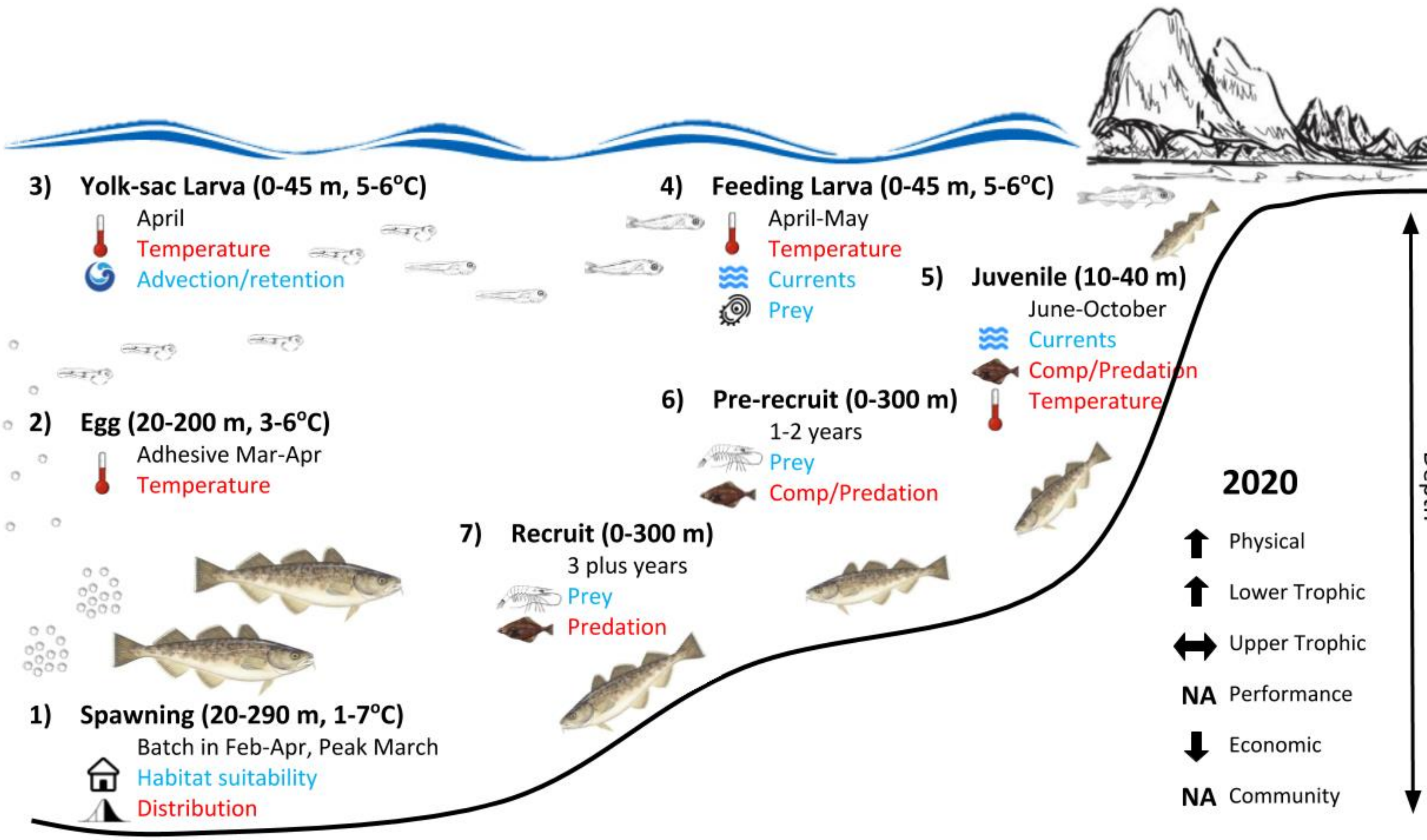

Figure 2.1.2: Life history conceptual model for GOA Pacific cod summarizing ecological information and key ecosystem processes affecting survival by life history stage. Red text means increases in process negatively affect survival, while blue text means increases in process positively affect survival. Trend of current year value compared to last year's value depicted with arrows on the right. NA means no indicators for that category.

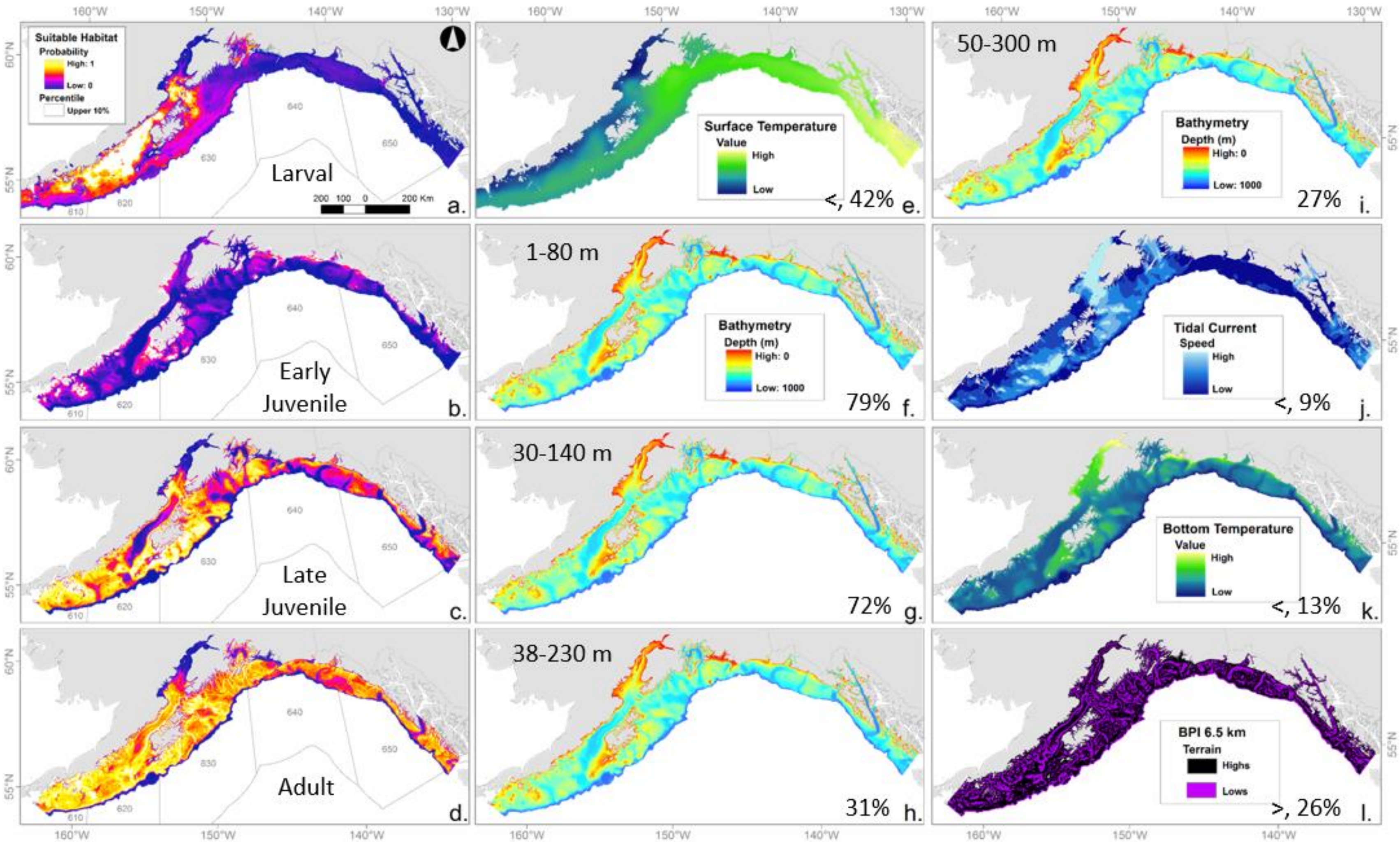

Figure 2.1.3. GOA Pacific cod probability of suitable habitat by life stage (a=larval, b=early juvenile, c=late juvenile, and d=adult) with predictor habitat variables representing the highest (e=depth, f=tidal current speed, g=depth, h=depth) and second highest contribution (i=surface temperature, j=bottom temperature, k=bottom temperature, and l=tidal current speed). Upper 10 %-ile of suitable habitat is shown in white within the probability of suitable habitat range (yellow to purple). Sign (<, >, <>) of the deviation from mean direction and the percent of contribution to predict suitability provided for each non-depth variable. Range provided for depth. See Shotwell *et al.*, *In Review* for more details.

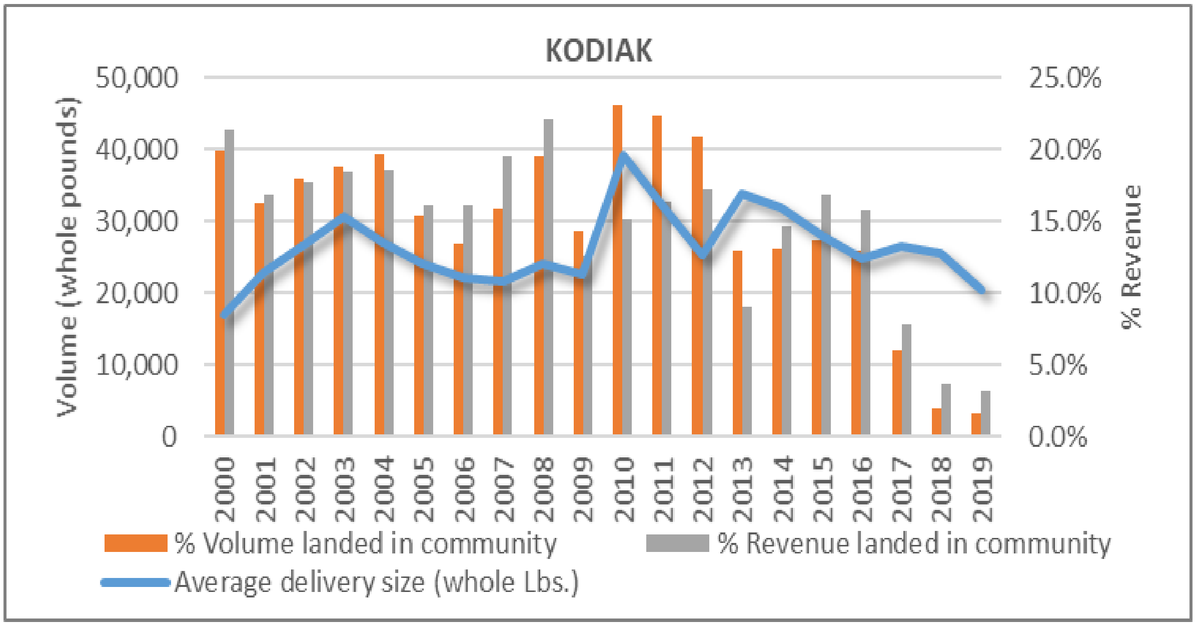

Figure 2.1.4a: Processing engagement for Kodiak: Average pounds delivered and percentage of value landed attributed to GOA Pacific cod for the highly engaged community of Kodiak (2000-2019).

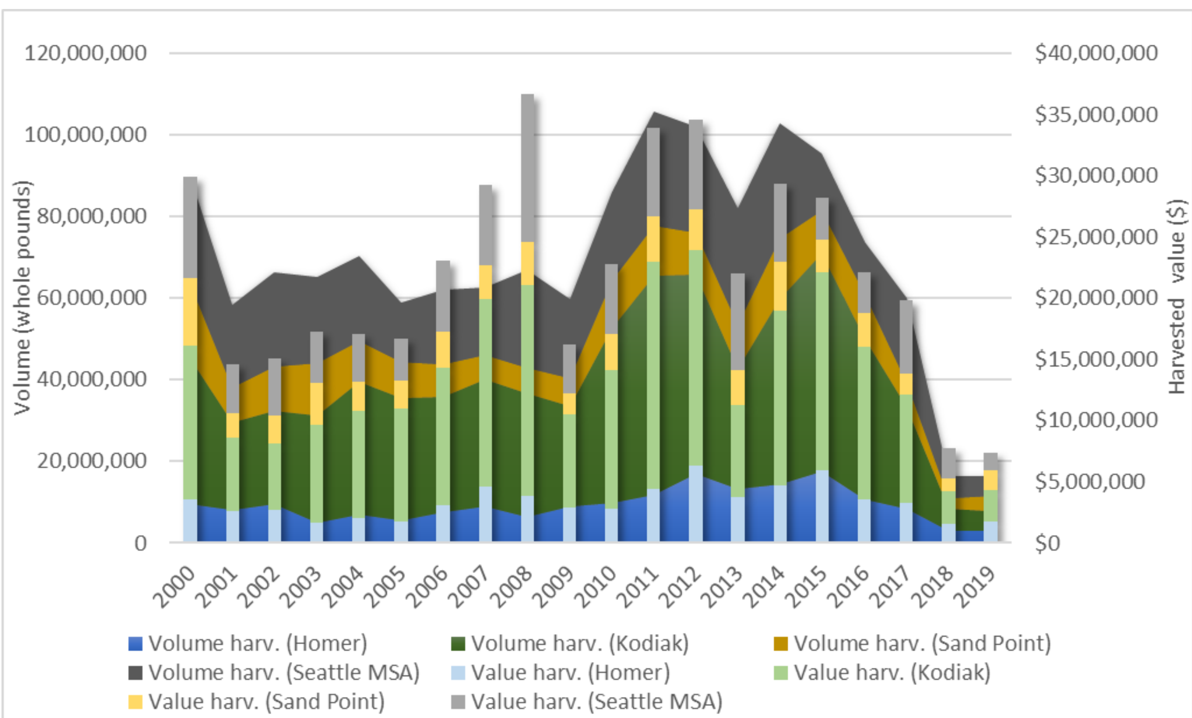

Figure 2.1.4b: Harvesting engagement: Average volume and value of GOA Pacific cod harvested by vessels owned by community residents (2000-2019).

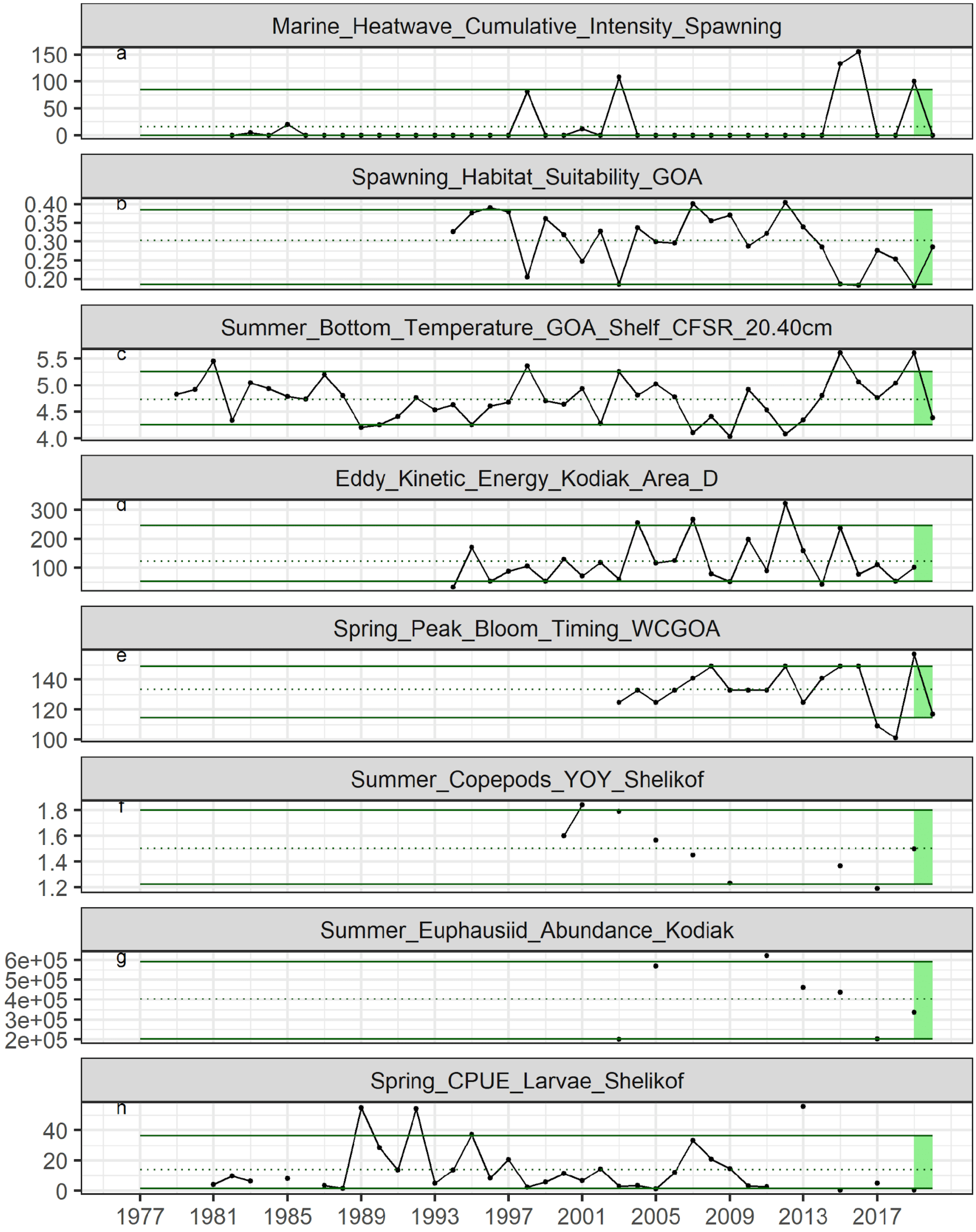

Figure 2.1.5a. Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines are 90th and 10th percentiles of time series. Dotted green horizontal line is mean of time series. Light green shaded area represents most recent year for traffic light analysis.

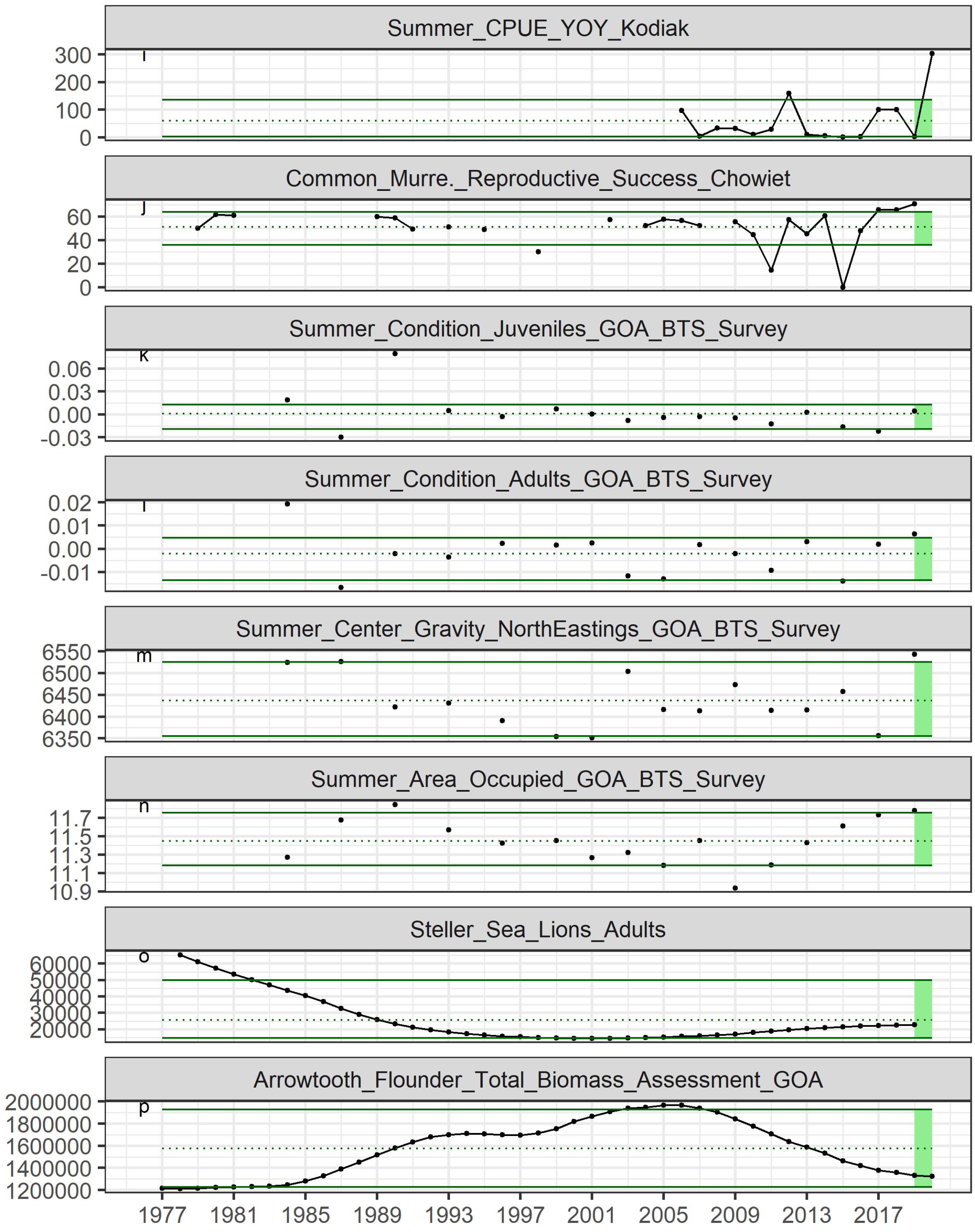

Figure 2.1.5a (cont.). Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines are 90th and 10th percentiles of time series. Dotted green horizontal line is mean of time series. Light green shaded area represents most recent year for traffic light analysis.

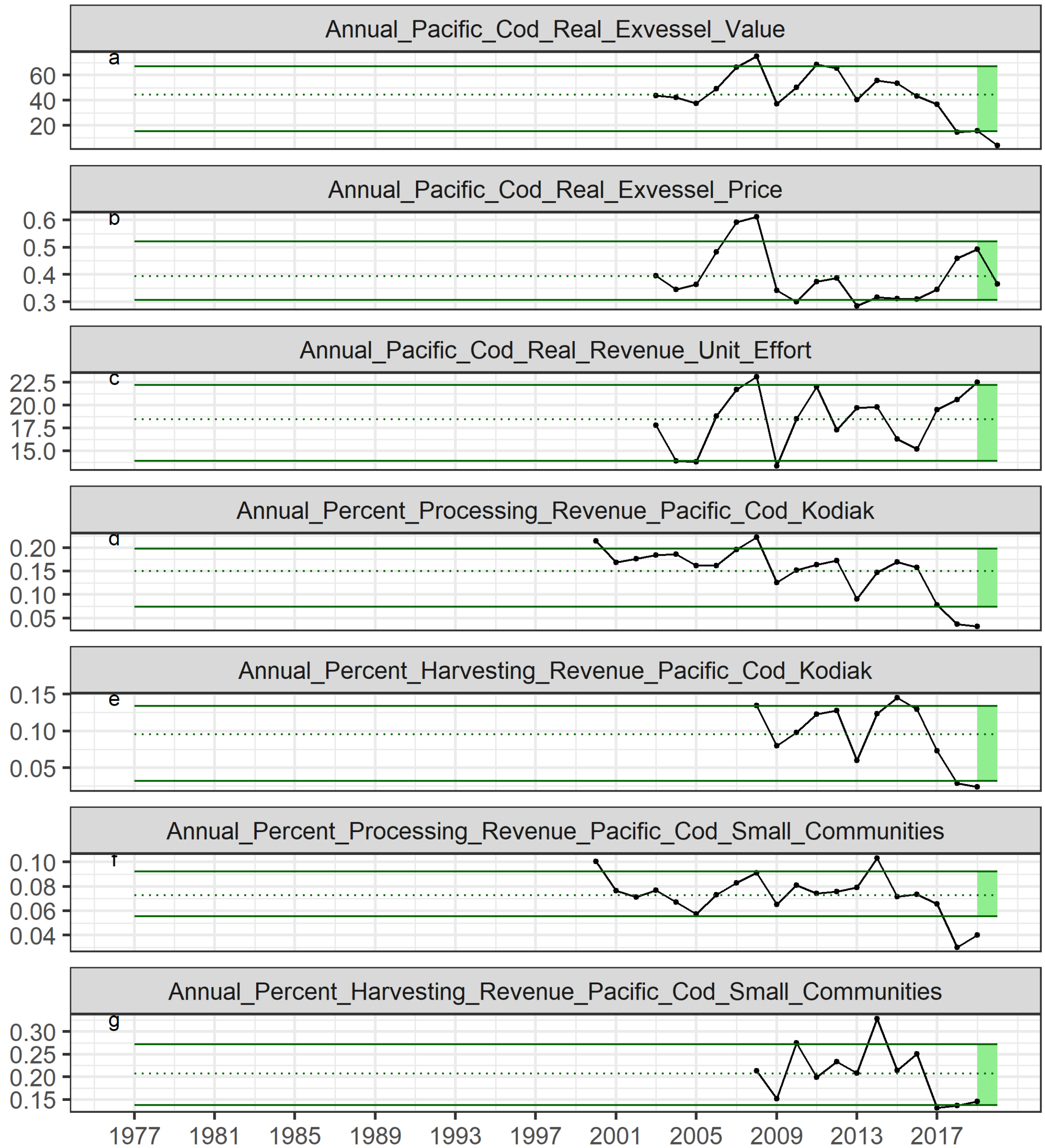

Figure 2.1.5b. Selected socioeconomic indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines are 90th and 10th percentiles of time series. Dotted green horizontal line is mean of time series. Light green shaded area represents most recent year for traffic light analysis.

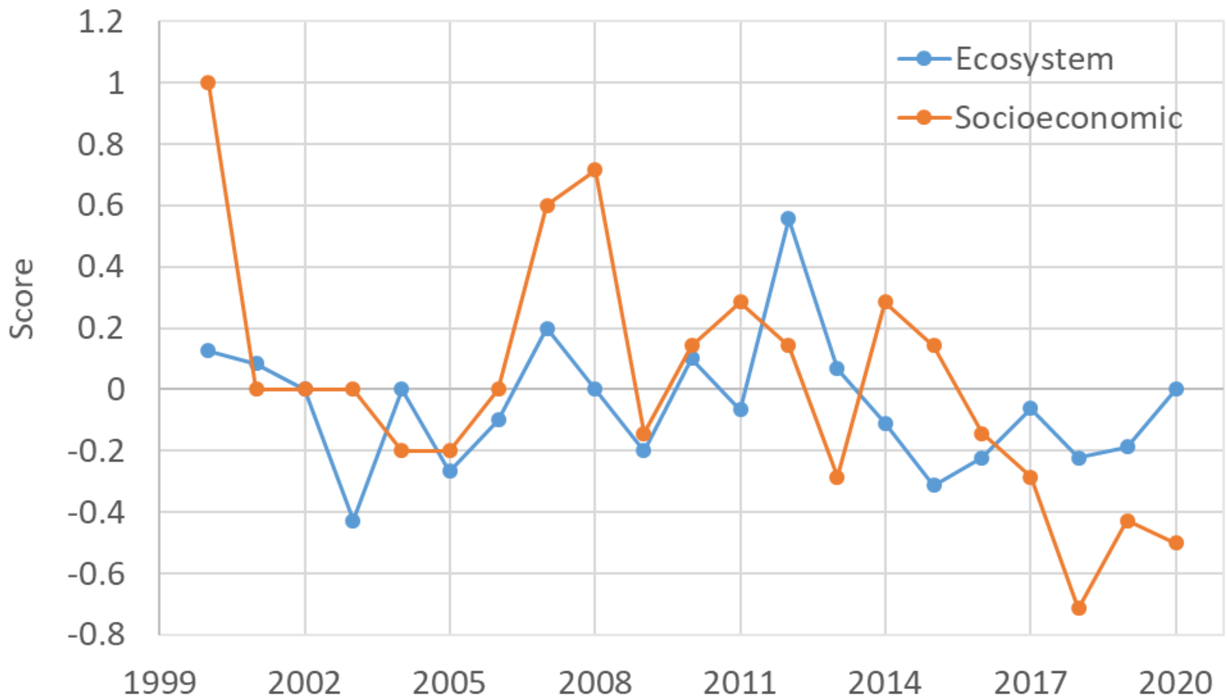

Figure 2.1.6: Beginning stage traffic light score for overall ecosystem and socioeconomic categories from 2000 to present.

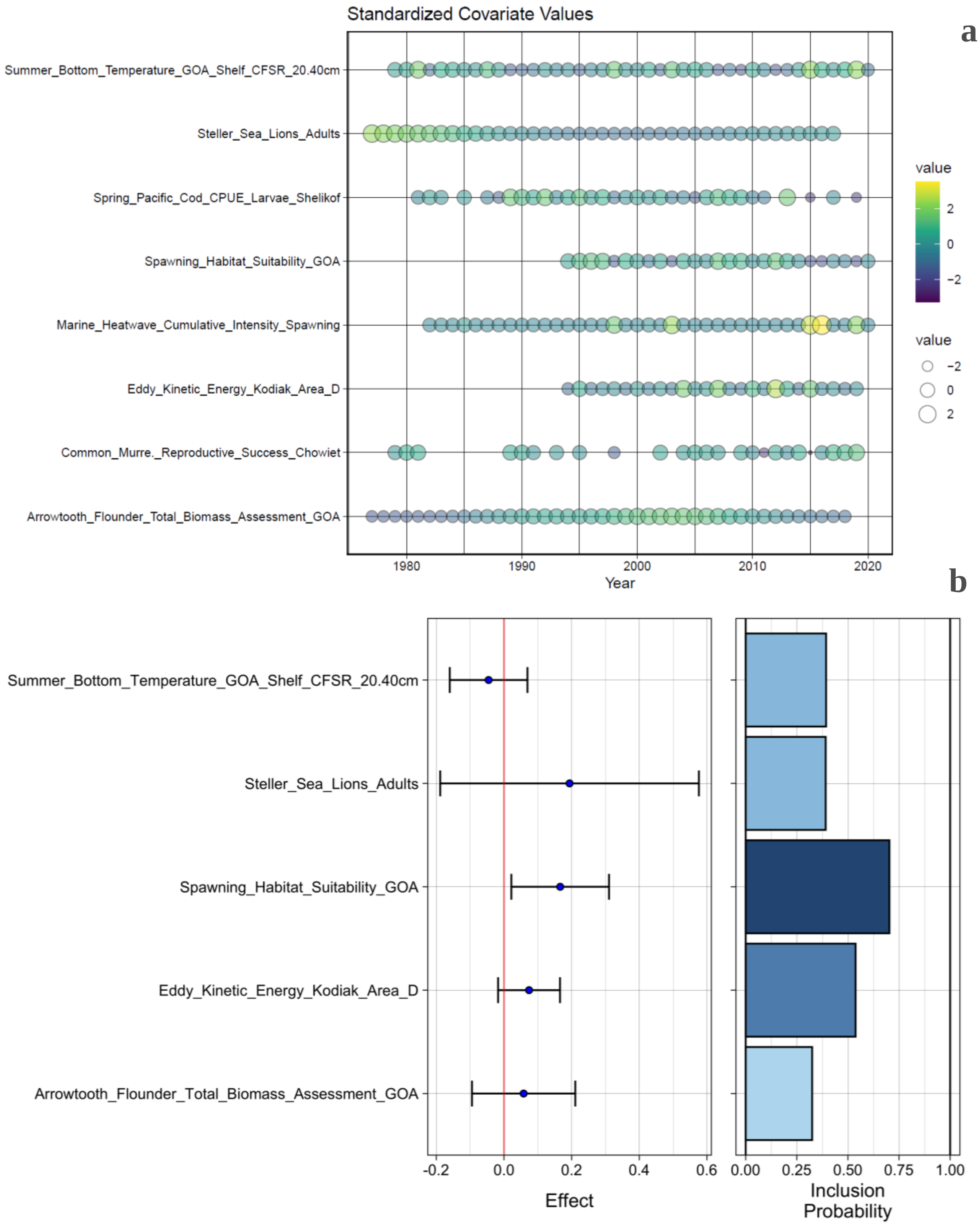

Figure 2.1.7: Bayesian adaptive sampling output showing (a) standardized covariates prior to subsetting and (b) the mean relationship and uncertainty (95% confidence intervals) with log GOA Pacific cod recruitment, in each estimated effect (left bottom graph), and marginal inclusion probabilities (right bottom graph) for each predictor variable of the subsetted covariate set.