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

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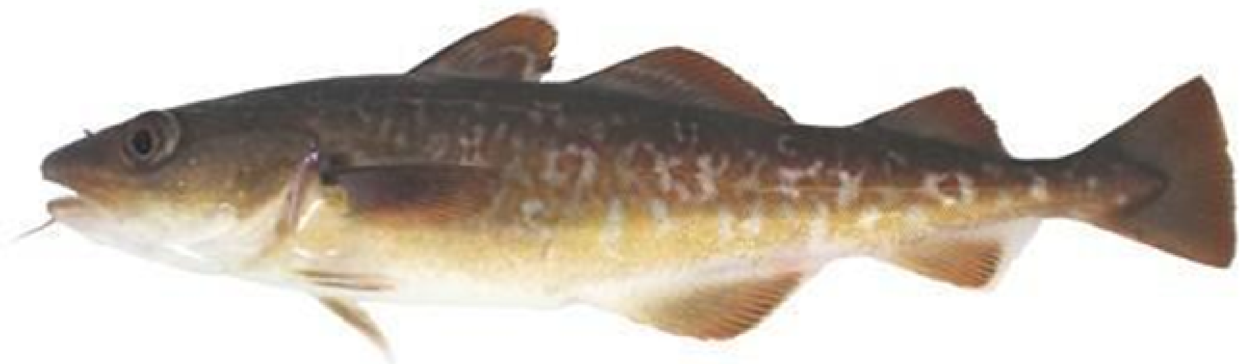

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Executive Summary

The Ecosystem and Socioeconomic Profile (ESP), is a standardized framework for compiling and evaluating relevant stock-specific ecosystem and socioeconomic indicators and communicating linkages and potential drivers of the stock within the stock assessment process (Shotwell et al., 2023a). This update report provides supporting information for the Gulf of Alaska Pacific cod (GOA) ESP report card (Shotwell and Dame, 2026) and details the methodology and results from statistical analyses used to monitor current year status and trends of ecosystem and socioeconomic indicators. The GOA Pacific cod stock was evaluated at the intermediate indicator analysis stage using the Bayesian Adaptive Sampling (BAS) importance method. Highlights of the indicator assessment are summarized below as considerations that can be used for evaluating concerns in the main stock assessment or other management decisions.

Acceptable Biological Catch (ABC) Considerations:

The following are summary results from the indicator analysis that can inform ABC decisions:

Predictive Indicators:

- Pacific cod spawning habitat suitability decreased to low due to the warmest temperature at depth since 2019, which may have a negative effect on egg survival and potentially a poor 2025 year class. This indicator demonstrated a positive effect with respect to recruitment and a high inclusion probability.
- The final model explained a moderate amount of variation in GOA Pacific cod recruitment but did not fit the magnitude of interannual variation in recruitment.

Contextual Indicators:

- Recruitment indicators of spring larvae in Shelikof and summer young-of-the-year (YOY) catch per unit effort (CPUE) from beach seine in western-central GOA were both below average supporting a potentially poor 2025 year class.
- Estimates of age-1 natural mortality from Pacific cod from the multispecies model remain near average and above the operational stock assessment model estimate.
- Ecosystem considerations indicators were overall average status with mixed directional trends from 2024 to 2025 conditions.
- Environmental indicators include an increase to average heatwave events during spawning but not at the levels of the major heatwave events in 2015, 2016, and 2019 and a decrease to below average eddy kinetic energy implying reduced larval retention and cross-shelf transport.
- Prey indicators included average spring bloom timing, sufficient forage resources for seabirds, but a decrease to below average body condition for juvenile and adult Pacific cod and a slightly increased but still below average metabolic demand based on the multispecies model.
- Predator indicators were below average biomass consumed of Pacific cod based on arrowtooth, Pacific cod, and pollock predation in the multispecies model but a steadily increasing population of Steller sea lions in the GOA.

Total Allowable Catch (TAC) Considerations:

The following are the summary results from the indicator analysis that can inform TAC decisions:

- Predictive and contextual ABC considerations above can also be used to inform TAC considerations within the purview of the Council's TAC setting process. Ecosystem indicators in the monitoring category may also be relevant to TAC considerations (Figure 2.1.2a and Table 2.1.1a)

- Ex-vessel value decreased by 26% from 2023, remaining below one-standard deviation of the historical range for the sixth time in the last seven years.
- In 2024, ex-vessel price reached an all time-series low, decreasing 40% from 2023 to below one-standard deviation of the historical range.
- Revenue-per-unit-effort decreased by 15% from 2023, falling to slightly above the one-standard deviation of the historical range.

Introduction/Background

An ESP was recommended for Gulf of Alaska (GOA) Pacific cod in 2019 and the ESP full report was created in 2021 (Shotwell et al., 2021). The ESP full report is provided as an appendix to the operational stock assessment and fishery evaluation or SAFE report for the GOA Pacific cod stock and is reviewed and evaluated at the same time as the operational stock assessment. The elements of an ESP full report include a justification supporting the ESP recommendation, description of data streams used in the ESP, comprehensive literature review, synthesis of ecosystem and socioeconomic processes, description of the selected indicator suite, statistical analysis of the indicators according to the data availability of the stock, summary conclusions, and a final section detailing data gaps and research priorities.

In years following full reports, an ESP update report may be created in conjunction with the full or updated SAFE report schedule. The ESP update includes mainly static elements in a short background to recap the ESP full report, reference the conceptual model, provide descriptions of the selected indicators used in the indicator analysis, and update the statistical analysis with new indicator data where possible. Any necessary changes to the indicator suite such as newly available indicators, modifications due to data changes, or removals can also be catalogued. The intent of an ESP update report is to provide results of new data since the last ESP full report. It is not a full re-evaluation of the indicator selection or analysis choices. If a full re-evaluation is recommended, a subsequent ESP full report can be scheduled depending on regional prioritization.

A simplified report card infographic is also created in conjunction with the ESP full or update report to highlight the most important takeaways of the ESP. The ESP report card is a rapid communication presented with the SAFE report while the ESP full or update report contains supporting information for the report card and is appended to the SAFE report. For access to the ESP full report or subsequent update reports please visit the Alaska ESP webpage at https://akesp.psmfc.org.

Ecosystem and Socioeconomic Processes

We summarize important processes that may be helpful for identifying productivity bottlenecks and dominant pressures on the stock with a conceptual model detailing ecosystem processes by life history stage (Figure 2.1.1). Please refer to the last full ESP document (Shotwell et al., 2021) for more details.

Indicator Assessment

Twenty-one indicators (eighteen ecosystem and three socioeconomic) were selected for evaluation in the GOA Pacific cod ESP based on the literature synthesis, resulting conceptual model build, and review by stock assessment, ecosystem assessment, and GOA Pacific cod subject matter experts. Selected indicators for GOA Pacific cod are organized into categories: three for ecosystem indicators (larval, juvenile, and adult) and three for socioeconomic indicators (fishery-informed, economic, and community). For detailed information regarding these ecosystem and socioeconomic indicators and the proposed mechanistic linkages for GOA Pacific cod, please refer to the last full ESP document (Shotwell et al., 2021). Time series of these indicators are provided in Figure 2.1.2a (ecosystem indicators) and Figure 2.1.2b (socioeconomic indicators).

The following nomenclature was used to describe these indicators within the list:

- "Average": Used if the value in the time series is near the long-term mean (dotted green line in Figure 2.1.2).
- "Above average" or "Below average": Used if the value is above or below the mean but was within 1 standard deviation of the mean (in between solid green lines in Figure 2.1.2).
- "Neutral": Used in Table 2.1.1 for any value within 1 standard deviation of the mean.
- "High" or "Low": Used in Table 2.1.1 if the value was more than 1 standard deviation above or below the mean (above or below the solid green lines in Figure 2.1.2).

The ESP full report evaluates the indicator suite as a whole when the ESP is first created (Shotwell et al., 2021). The ESP update report maintains all these indicators but may require some modifications each year to ensure delivery of the best scientific information available. Changes this year are documented below. Please note that the summer EcoFOCI survey was cancelled this year due to limited staffing and resources and the CSFR bottom temperature dataset has been discontinued. We discuss options for potential future replacement indicators in the Conclusion section.

Modified indicators in the 2026 suite include:

- Annual Eddy Kinetic Energy Kodiak Satellite: The resolution of the Ssalto/Duacs altimeter products has been upgraded from 0.25 degree to 0.125 degree and the resultant updated time series has a slightly lower magnitude on average but the interannual variability is consistent with the previous resolution.
- Chlorophyll *a* Peak: The previous MODIS satellite product has been decommissioned and the ESA GlobColour blended product does not update consistently. We have, therefore, transitioned to the ESA OC-CCI blended satellite product to allow for consistency in update timing from year to year and added this indicator back into the indicator suite.

Note: These modifications preclude direct comparison with previous ESP indicator time series.

Indicator Suite

Below we list 1) a short description of each indicator, including the data source and contributor, 2) the indicator relationship sign as determined by the proposed mechanistic relationship between the stock variable of interest and indicator (ecosystem indicators only), 3) the lag assigned for ecosystem indicator analysis where applicable (ecosystem indicators only), 4) factors driving indicator trends, and 5) potential implications of directional shifts in indicator trends for GOA Pacific cod. Please see the ecosystem indicator analysis section for details on whether an ecosystem indicator is included in the analysis. If it is excluded, then there is no lag assigned and this is noted in the bullet.

Ecosystem Indicators:

Larval Indicators (Figure 2.1.2a .a-h)

a. Heatwave During Spawning in GOA from OISST: Spawning marine heatwave index is calculated from daily sea surface temperatures for 1981 through present from the NOAA High-resolution Blended Analysis Data for the central GOA (< 300 m) for February and March. Data source is the NOAA Optimum Interpolation Sea Surface Temperature (OISST) v2.1 from the NOAA Centers for Environmental Information (NCEI). Daily mean sea surface temperature data were processed to obtain the marine heatwave cumulative intensity (MHWCI) (Hobday et al., 2016) value where we defined a heat wave as 5 days or more with daily mean sea surface temperatures greater than the 90th percentile of the January 1983 through December 2012 time series. Spatial resolution is

5 km satellite sea surface temperatures aggregated over longitude -145 to -160 and depth <300m polygon followed by annual summation of a cumulative heatwave index in degree Celsius days in the Gulf of Alaska. The proposed sign of the relationship to recruitment is negative.

- Contact: Steve Barbeaux
- Not included in ecosystem indicator analysis.
- Factors influencing trends: Generally, cool conditions are related to winter balances between heat loss, coastal runoff, and stratification, while warm conditions are associated with El Nino events (1998, 2003, and 2016) and marine heatwaves (Janout et al., 2010). Additionally, detection of marine heatwaves will depend on the suite of baseline years that are included for the marine heatwave calculation.
- Implications: The severity, extent, and duration of the ocean warming events have had a large impact on the productivity of the GOA Pacific cod stock (Barbeaux et al., 2020, Laurel and Rogers, 2020). Absence of marine heatwaves implies cooler conditions which may aid growth and survival during the early life history stages of GOA Pacific cod.

b. <u>Pacific Cod Spawning Habitat Suitability</u>: A temperature-dependent hatch success rate (derived from laboratory experiments) is applied to GAK-1 temperature-at-depth data (Danielson 2024) and averaged over January to April for depths 100 to 250 m (Laurel and Rogers, 2020) from 1994 to present. While GAK-1 is located in the central GOA, it broadly represents interannual variation in thermal conditions across the central and western GOA shelf. The proposed sign of the relationship to recruitment is positive.

- Contact: Lauren Rogers
- Lag assigned for ecosystem indicator analysis: 0 years
- Factors influencing trends: Recent heatwave years (2015, 2016, 2019) resulted in substantial declines in spawning habitat suitability due to temperatures at depth that were warmer than optimal for hatch success of Pacific cod eggs. Thermal conditions in 2025 were the warmest since 2019, which may have a negative effect on Pacific cod egg survival.
- Implications: During the marine heatwave years, temperatures at depth were likely too warm for successful hatching of Pacific cod eggs in the Gulf of Alaska, limiting the recruitment of this stock. Since 2014, only one year (2022) has had above average spawning habitat suitability. An extended period of warmer than average temperatures has likely contributed to prolonged low-recruitment for this stock.

c. <u>Eddy Kinetic Energy in Kodiak from CMEMS</u>: Annual eddy kinetic energy (EKE) calculated from sea surface height in the Kodiak area (region D) as a measure of mesoscale energy in the ocean system (Ladd, 2020). A suite of satellite altimeters provides sea surface height at 0.125 degree resolution. 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 2025. The proposed sign of the relationship to recruitment is positive.

- Contact: Wei Cheng
- Lag assigned for ecosystem indicator analysis: 0 years
- Factors influencing trends: In the eastern Gulf of Alaska, interannual changes in surface winds (related to the Pacific Decadal Oscillation, El Nino, and the strength of the Aleutian Low) modulate the development of eddies (Combes and Di Lorenzo, 2007; Di Lorenzo et al., 2013). Regional scale gap-wind events may also play a role in eddy formation in the eastern Gulf of Alaska (Ladd and Cheng, 2016). In the western Gulf of Alaska, variability is related both to the propagation of eddies from their formation regions in the east and to intrinsic variability.

- Implications: A lower energy period implies reduced retention in suitable habitat for young-of-the-year Pacific cod and reduced cross-shelf transport to suitable nearshore nursery environments.

d. Peak Timing of Spring Bloom in WCGOA from OC-CCI: Satellite data provide a good opportunity to capture large-scale spatio-temporal dynamics and trends of phytoplankton. Timing (day of year) of peak chlorophyll-a concentration during spring (April-June) in the western and central GOA (NMFS areas 610, 620, and 630). Bottom depths were limited to between -10 and -200m. This indicator was calculated with the European Space Agency (ESA) Ocean-Colour Climate Change Initiative (OC-CCI) blended satellite product (https://github.com/MattCallahan-NOAA/ESR-ESP). The proposed sign of the relationship to recruitment is positive.
    - Contact: Matt Callahan
    - Lag assigned for ecosystem indicator analysis: 0 years
    - Factors influencing trends: The timing and magnitude of the spring bloom directly influences the magnitude of the chlorophyll concentration which may impact the amount of energy that is transferred through trophic pathways in the Gulf of Alaska.
    - Implications: Phytoplankton provide basal resources for secondary consumers like zooplankton and larval fish. The timing and magnitude of a phytoplankton bloom varies annually and may play an important role in the success of fish cohorts each year. During warm years the timing of the spring bloom may be particularly important for Pacific cod due to their increased metabolic requirements and the implications of a later bloom may be somewhat tempered in a cooler thermal environment (Laurel et al., 2021).

e. Summer Large Copepod Abundance in Shelikof from EcoFOCI: Summer large copepods (> 2mm) were summarized as log-10 transformed mean catch per m3 for the core sampling area in Shelikof Strait and Sea Valley of the Ecosystem & Fisheries-Oceanography Coordinated Investigations (EcoFOCI) late-summer surveys (August - September). The most recent survey year is represented by a rapid zooplankton assessment to provide a preliminary estimate of zooplankton abundance and community structure (Kimmel et al., 2019). Ongoing work will determine the robustness of the rapid zooplankton assessment through comparison with quantitative data with high taxonomic resolution. Large copepods are important prey for young-of-the-year (YOY) groundfishes in summer. In 2023 time series were revised to standardize by gear type. The proposed sign of the relationship to recruitment is positive.
    - Contact: Lauren Rogers
    - Not included in ecosystem indicator analysis.
    - Factors influencing trends: Large copepod abundances are influenced by timing of the annual cohort of the dominant large species: *C. marshallae*, *N. cristatus*, and *Neocalanus* spp. The dominant large species in summer is *C. marshallae* as both other large species have likely entered diapause. Long-term variability in mesozooplankton in this region is thought to be driven by Pacific Decadal Oscillation (PDO) and El Nino-Southern Oscillation (ENSO) cycles.
    - Implications: Zooplankton are an important prey base for juvenile fishes in summer. Both large copepod numbers and euphausiid abundances were average during the late summer relative to long-term trends in the most recent survey. Both are principal diet items for juvenile fish and these numbers appear to indicate adequate forage.

f. Spring Pacific Cod Larvae CPUE in Shelikof from EcoFOCI: Spring Pacific cod larvae catch-per-unit-of-effort (CPUE) from the EcoFOCI spring surveys, 1981 to present, various years. The primary sampling gear used is a 60-cm bongo sampler fitted with 505-Âµm mesh nets. Oblique tows are carried out mostly from 100 m depth to the surface or from 10 m off bottom in shallower water (Matarese et al., 2003). Historical sampling has been most intense in the vicinity of Shelikof Strait and Sea Valley during mid-May through early June. From this area and time, a subset of data has been developed into time series of ichthyoplankton abundance. On-board counts give rapid estimates of relative abundance (Rapid Larval Assessment), which are presented in the year of collection, and subject to revision following detailed laboratory processing of samples. In 2023, time-series calculations were updated to use a model-based approach (sdmTMB; Anderson et al. 2022) instead of the previous area-weighted mean, in part to better account for variable survey coverage in recent years due to ship-time constraints. The proposed sign of the relationship to recruitment is positive.

- Contact: Lauren Rogers
- Not included in ecosystem indicator analysis.
- Factors influencing trends: Temperature conditions in the spring of 2025 were above average in the survey area, which has been associated with lower abundances of larval Pacific cod.
- Implications: Ichthyoplankton surveys can provide early-warning indicators for ecosystem conditions and recruitment patterns in marine fishes. In both 2015 and 2019, low abundances of walleye pollock and Pacific cod larvae were the first indicators of failed year-classes for those species. In 2025, abundances of walleye pollock and Pacific cod larvae were again low, suggesting another poor year class. The low abundance of gadid larvae, combined with low to average abundance of other indicator species, suggests poor to average forage for piscivorous predators, including seabirds, who rely on larval and juvenile fish.

g. Murre Reproductive Success on Chowiet from USFWS: Common murre reproductive success is measured at Chowiet Island during variable years since 1979. Reproductive success is defined as the proportion of nest sites with fledged chicks from the total nest sites that had eggs laid. This species is a piscivorous seabird. Data provided by the U.S. Fish and Wildlife Service, Alaska Maritime National Wildlife Refuge and the Institute for Seabird Research and Conservation. The proposed sign of the relationship to recruitment is positive.

- Contact: Stephani Zador
- Not included in ecosystem indicator analysis.
- Factors influencing trends: Changes in the availability of small, schooling fish up to approximately 90 m below the surface may impact the ability of diving seabirds to sample YOY Pacific cod. Shifts in distribution of the seabird population may also impact measures of relative biomass measured at the colony.
- Implications: It is possible that the diet of piscivorous seabirds in the Kodiak region may serve as a proxy for larval fish productivity, such as Pacific cod, in the region and this could be detected in the subsequent reproductive success of the seabirds.

h. Summer Pacific Cod YOY CPUE in WCGOA from Beach Seine: Summer Pacific cod CPUE of YOY was estimated using the Alaska Fisheries Science Center (AFSC) beach seine survey available from 2006-present. Beach seine sampling of age-0 pollock was conducted at two Kodiak Island bays during 2006-2021 and an expanded survey was conducted during 2018-present at 13 additional bays on Kodiak Island, the Alaska Peninsula, and the Shumagin Islands (n = 3 - 9 fixed stations per bay, 95 total stations). Sampling occurs during July and August (days of year 184-240), within two hours of a minus tide at the long-term Kodiak sites, and within three hours of a low tide at the expanded survey sites. At all sites, a 36 m long, negatively buoyant beach seine is deployed from a boat and pulled to shore by two people standing a fixed distance apart on shore. Wings on the seine (13 mm mesh) are 1 m deep at the ends and 2.25 m in the middle with a 5 mm delta mesh cod end bag. The seine wings are attached to 25 m ropes for deployment and retrieval from shore. The seine is set parallel to and ~ 25 m, making the effective sampling area ~ 900 m 2 of bottom habitat. Data represent model-based index of annual catch per unit effort (CPUE) for age-0 Pacific cod to resolve inter-annual differences in sampling across different bays and different days of the year. Specifically, a Bayesian zero-inflated negative binomial (ZINB) model was used invoking year as a categorical variable, day of year as a continuous variable, and site nested within bay as a group-level (random) effect. The day of year effect was modeled with thin plate regression splines to account for non-linear changes in abundance through the season and the number of basis functions was limited to 3 to avoid over-fitting data. This model was fit using Stan 2.21.0, R 4.0.2 and the brms package (Carpenter et al. 2017, Buerkner 2017, R Core Team 2021). The proposed sign of the relationship to recruitment is positive.

- Contact: Ben Laurel
- Not included in ecosystem indicator analysis.
- Factors influencing trends: Factors influencing nearshore abundance of age-0 juvenile Pacific cod are part of several ongoing investigations examining spring heat stress during spawning and the early larval period (Laurel and Rogers 2020; Almeida et al. accepted). Seine CPUE estimates have been shown to be relatively good indicators of future recruitment in GOA Pacific cod (Litzow et al. 2022) but fall and 1st winter stress may reduce their predictive value with future warming (Laurel et al. 2023). The steep declines in age-0 abundance during marine heatwaves (2014-16, 2019) suggests there is poor survival of egg and larval stages in the spring.
- Implications: Summer nearshore habitats are highly important to age-0 Pacific cod before they move to deeper, offshore waters at older life stages. Their availability to beach seines in the summer provide direct measures of abundance and can serve as indicators of future recruitment.

<u>Juvenile Indicators (Figure 2.1.2a. i-k)</u>

i. <u>Age-1 Pacific Cod Natural Mortality from Multispecies Model</u>: Estimate of Pacific cod age-1 natural mortality (model estimated time- and age-invariant residual mortality, M1, plus model estimates of time- and age-varying predation mortality, M2) from the Climate-Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics (CEATTLE) that has recently been developed for understanding trends in total mortality for walleye pollock, Pacific cod, and arrowtooth flounder from the GOA (Adams et al., 2022). The proposed sign of the relationship is negative.
    - Contact: Grant Adams
    - Not included in ecosystem indicator analysis.
    - Factors influencing trends: Temporal patterns in total natural mortality reflect annually varying changes in predation mortality by pollock, Pacific cod, and arrowtooth flounder that primarily impact age-1 fish (but also impact older age classes). Predation mortality at age-1 for all species in the model is primarily driven by arrowtooth flounder and arrowtooth flounder biomass has been low since 2017 but has increased slightly in the following years (Shotwell et al., 2023c).
    - Implications: There is evidence of time-varying predation mortality on age-1 Pacific cod due to the species modeled in CEATTLE that has been above the time-invariant single species stock assessment value in all years.

j. <u>Summer Bottom Temperature in GOA from CSFR</u>: Summer bottom temperature anomaly from the 1982-2012 mean over the GOA shelf from the Climate Forecast System Reanalysis (CFSR) dataset across the depth ranges where 0 to 20 cm Pacific cod have been sampled on the AFSC bottom trawl survey (Hulson et al., 2023 for more details regarding the index creation). Data available from 1979 to 2024. The proposed sign of the relationship to recruitment is negative.

Please note that this product has been discontinued and will be replaced with a new bottom temperature measure in future reports.

- Contact: Pete Hulson and Muyin Wang
- Not included in ecosystem indicator analysis.
- Factors influencing trends: Subsurface waters below mixed layers can absorb and store heat. These changes do not occur at the same timescales as changes in surface water temperatures, often showing delayed responses by a year or more. These temperature changes are also very small compared to surface waters. The warmer that subsurface waters become, the less cooling capacity they have to absorb heat from surface waters (Siwicke, 2022).
- Implications: Cooler bottom temperatures suggest improved conditions for spawning and egg survival.

k. Juvenile Pacific Cod Condition in GOA from GAP: Morphometric condition was estimated using residuals of a length-weight regression fit to individual length-weight measurements collected from juvenile (<50 cm) Pacific cod during AFSC Resource Assessment and Conservation Engineering (RACE) Gulf of Alaska bottom trawl surveys from 1990 to present. This indicator is only updated on odd years due to the biennial sampling schedule of the summer bottom trawl survey in the GOA. The proposed sign of the relationship to recruitment is positive.

- Contact: Sean Rohan
- Not included in ecosystem indicator analysis.
- Factors influencing trends: Many factors contribute to variation in morphometric condition so it is unclear which specific factors contributed to neutral condition of juvenile Pacific cod in the GOA in 2025. Factors that may contribute to variation in morphometric condition include environmental conditions that affect prey quality and temperature-dependent metabolic rates, survey timing, stomach fullness of individual fish, fish migration patterns, and the distribution of samples within survey strata. Additional information about the groundfish morphometric condition indicator and factors that can influence estimates of morphometric condition are described in the GOA Groundfish Morphometric Condition contribution in the 2025 Gulf of Alaska Ecosystem Status Report (Prohaska and Rohan, 2025).
- Implications: In the Gulf of Alaska, elevated temperatures during the 2014-2016 marine heatwave were associated with slower growth rates, reduced morphometric condition, and elevated mortality of Pacific cod (Barbeaux et al., 2020). Neutral condition in 2025 suggests that juvenile Pacific cod were able to find sufficient prey resources.

Adult Indicators (Figure 2.1.2a. l-r)

l. Adult Pacific Cod Condition in GOA from GAP: Morphometric condition was estimated using residuals of a length-weight regression fit to individual length-weight measurements from adult (>= 50 cm) Pacific cod collected during AFSC/RACE Gulf of Alaska bottom trawl surveys from 1990 to present. This indicator is only updated on odd years due to the biennial sampling schedule of the summer bottom trawl survey in the GOA. The proposed sign of the relationship to recruitment is positive.

- Contact: Sean Rohan
- Not included in ecosystem indicator analysis.
- Factors influencing trends: Many factors contribute to variation in morphometric condition so it is unclear which specific factors contributed to neutral condition of adult Pacific cod in the GOA in 2025. Factors that may contribute to variation in morphometric condition include environmental conditions that affect prey quality and

temperature-dependent metabolic rates, survey timing, stomach fullness of individual fish, fish migration patterns, and the distribution of samples within survey strata. Additional information about the groundfish morphometric condition indicator and factors that can influence estimates of morphometric condition are described in the GOA Groundfish Morphometric Condition contribution in the 2025 Gulf of Alaska Ecosystem Status Report (Prohaska and Rohan, 2025).

- Implications: In the Gulf of Alaska, elevated temperatures during the 2014-2016 marine heatwave were associated with lower growth rates of Pacific cod and lower morphometric condition in 2015 (adults and juveniles combined), likely because of a decrease in prey resources and increase in metabolic demand (Barbeaux et al., 2020). Neutral condition in 2025 suggests that adult Pacific cod were able to find sufficient prey resources.

m. <u>Pacific Cod Ration in GOA from Multispecies Model</u>: Estimate of ration for Pacific cod (age-1 plus) from the Climate-Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics (CEATTLE) that has recently been developed for understanding trends in total mortality for walleye pollock, Pacific cod, and arrowtooth flounder from the GOA (Adams et al., 2022). The proposed sign of the relationship is negative.
    - Contact: Grant Adams
    - Not included in ecosystem indicator analysis.
    - Factors influencing trends: Decreasing population trends for GOA Pacific cod reflect decreasing demand for prey.
    - Implications: Rates of cannibalism would decrease as the GOA Pacific cod population decreases, although the amount of cannibalism is fairly low in the GOA.

n. <u>Pacific Cod Center of Gravity North from GAP</u>: Center of gravity available as northings was estimated from the AFSC/RACE GOA bottom trawl survey for model-based indices of species distributions in the GOA. Predicted population densities from the model were used to calculate the center of gravity as the biomass-weighted average of the location of prediction-grid cells (Thorson et al. 2016) as UTM coordinates in units of km. This distribution index was computed without epsilon bias correction. This indicator is only updated on odd years due to the biennial sampling schedule of the summer bottom trawl survey in the GOA. The proposed sign of the relationship is negative.
    - Contact: Margaret Siple and Zack Oyafuso
    - Not included in ecosystem indicator analysis.
    - Factors influencing trends: The slight southern shift in the center of gravity is current with a decrease in the effective area occupied and an increase in the estimate of total GOA Pacific cod biomass.
    - Implications: Changes in the distributional characteristics of marine populations may impact the spatial distributions of fishing activities and trophic interactions.

o. <u>Pacific Cod Center of Gravity East from GAP</u>: Center of gravity available as eastings was estimated from the AFSC/RACE GOA bottom trawl survey for model-based indices of species distributions in the GOA. Predicted population densities from the model were used to calculate the center of gravity as the biomass-weighted average of the location of prediction-grid cells (Thorson et al. 2016) as UTM coordinates in units of km. This distribution index was computed without epsilon bias correction. This indicator is only updated on odd years due to the biennial sampling schedule of the summer bottom trawl survey in the GOA. The proposed sign of the relationship is negative.
    - Contact: Margaret Siple and Zack Oyafuso
    - Not included in ecosystem indicator analysis.

- Factors influencing trends: The eastern shift in the center of gravity is current with a decrease in the effective area occupied and an increase in the estimate of total GOA Pacific cod biomass.
- Implications: Changes in the distributional characteristics of marine populations may impact the spatial distributions of fishing activities and trophic interactions.

p. Pacific Cod Area Occupied from GAP: Effective area occupied was estimated from the AFSC/RACE GOA bottom trawl survey for model-based indices of species distributions in the GOA. The effective area occupied was calculated as the area required to contain the population at its average biomass (Thorson et al. 2016). This distribution index was computed without epsilon bias correction. The spatial domain is the western-central GOA. This metric is reported in log-km2. This indicator is only updated on odd years due to the biennial sampling schedule of the summer bottom trawl survey in the GOA. The proposed sign of the relationship is negative.
- Contact: Margaret Siple and Zack Oyafuso
- Not included in ecosystem indicator analysis.
- Factors influencing trends: Area occupied calculation may shift due to changes in clustering of the stock in response to environmental, prey, or predation pressures.
- Implications: The decrease in the effective area occupied in 2025 implies a slightly contracted spatial distribution covered by Pacific cod in the GOA relative to the 1990-2025 time series. Changes in the distributional characteristics of marine populations may impact the spatial distributions of fishing activities and trophic interactions.

q. Biomass Eaten of Pacific Cod from Multispecies Model: Estimate of Pacific cod biomass consumed (or eaten as prey, in tons) from the Climate-Enhanced, Age-based model with Temperature specific Trophic Linkages and Energetics (CEATTLE) that has recently been developed for understanding trends in total mortality for walleye pollock, Pacific cod, and arrowtooth flounder from the GOA (Adams et al., 2022). The proposed sign of the relationship to recruitment is negative.
- Contact: Grant Adams
- Lag assigned for ecosystem indicator analysis: 2 years
- Factors influencing trends: Population trends of predators and biomass of young cod included in the CEATTLE model (arrowtooth flounder, pollock, Pacific cod) impact total biomass consumed of Pacific cod as prey.
- Implications: As predator populations decline in the GOA so does the predation pressure on GOA Pacific cod.

r. Adult Steller Sea Lion Counts in GOA from MML: Steller sea lion non-pup estimates for the GOA portion of the western Distinct Population Segment. The proposed sign of the relationship to recruitment is negative.
- Contact: Katie Sweeney
- Lag assigned for ecosystem indicator analysis: 2 years
- Factors influencing trends: Some anomalous changes have occurred in population trends since 2017, following the heatwave event of 2014-2016 but impact on the Steller sea lion population is likely delayed as they are a long-lived species.
- Implications: Steller sea lions show some dependence on Pacific cod for their diet and predation pressure on GOA Pacific cod will increase as the sea lion populations have increased over the past decade.

Socioeconomic Indicators:

Fishery Informed Indicators

Information on fishery catch-per-unit-effort and other fishery-informed indicators is included within the main SAFE document (Hulson et al., 2026) and is not repeated here.

Economic Indicators (Figure 2.1.2b. a-c)

a. Pacific Cod Real Ex-vessel Value in GOA from ESSR: Annual reported real ex-vessel value measured in millions of dollars and inflation adjusted to 2024 USD.
    - Contact: Russel Dame
    - Factors influencing trends: The two primary factors that impact real ex-vessel value are the real ex-vessel price per pound and the total retained catch. Between 2016 and 2020, total retained catch of GOA P. cod declined significantly, reaching historical lows. During this same time period, the average price per pound steadily increased. The reductions in total catch, however, outweighed increases in price, resulting in year-over-year declines of ex-vessel revenue (with the exception of 2019) through 2020. Real ex-vessel revenue increased the following two years with increases in total catch and ex-vessel price, but declined in subsequent years due to falling prices. In 2024, the average ex-vessel price per pound decreased to the lowest value in the time series, outweighing increases in total catch, causing ex-vessel revenue to decline.
    - Implications: Reductions in ex-vessel value may cause vessels to expend less effort targeting Pacific Cod and substitute to higher valued species and/or regions. This is partially supported by the reduction in the number of active vessels that fished for GOA P. cod in 2024 (Table 2.1.2a).

b. Pacific Cod Real Ex-vessel Price in GOA from ESSR: Average real ex-vessel price per pound of GOA Pacific cod inflation adjusted to 2024 USD.
    - Contact: Russel Dame
    - Factors influencing trends: The real ex-vessel price per pound of GOA P. cod is impacted by many factors, including domestic and global supply and demand for cod (and substitute products) and market prices paid further up the supply chain. The real ex-vessel price per pound of GOA P. cod declined significantly between 2022 and 2024, reaching a historical low of $0.26 per pound. This is likely associated with reductions in high-priced fillet production, partially associated with declines in domestic demand of Pacific cod, and increased production of the lower-priced headed & gutted product form. As a result, the average first-wholesale price declined during this period (2020-2024), leading to a lower price paid to vessels (ex-vessel price).
    - Implications: The average ex-vessel price has declined to the lowest level in the time series. Reductions in price may cause vessels to expend less effort targeting Pacific Cod and spend more effort targeting higher priced species.

c. Pacific Cod Real Revenue / Unit Effort in GOA from ESSR: Annual estimated real revenue per unit effort measured in weeks fished and inflation adjusted to 2024 USD.
    - Contact: Russel Dame
    - Factors influencing trends: The share of total annual landings revenue generated by Pacific cod across all fisheries is driven by the ex-vessel prices and production volumes across the portfolio of all fishing targets. In 2022, this ratio reached a historical high before declining sharply in subsequent years, falling below the historical average by 2024. This trend is likely associated with sharp declines in ex-vessel prices, causing

reductions in Pacific cod revenue, that outweighed slight reductions in total fishing effort across all fisheries in the GOA.
- Implications: Reductions in the revenue per unit effort may disincentivize vessels from targeting GOA P. Cod. If effort is more valuable in a substitute fishery with similar gear types, then we may see vessels substitute away from Pacific Cod.

Community Indicators

An analysis of commercial processing and harvesting data may be conducted to examine sustained participation for those communities substantially engaged in a commercial fishery. The Annual Community Engagement and Participation Overview (ACEPO) report evaluates engagement at the community level and focuses on providing an overview of harvesting and processing sectors of identified highly engaged communities for groundfish and crab fisheries in Alaska (Wise et al., 2022). An example of community indicators has been included in the Alaska sablefish ESP report (Shotwell and Dame, 2024) and we plan to include a similar set of indicators in the next report card for GOA Pacific cod following review and recommendations for the Alaska sablefish ESP report.

Indicator Analysis

Ecosystem and socioeconomic indicators are monitored through distinct workflows, depending on the management decisions they are intended to inform (Figure 2.1.3). Ecosystem indicators generally inform the acceptable biological catch (ABC) and can either be incorporated directly into the model through predictive or causal inference, or indirectly through contextual avenues such as risk tables (Dorn and Zador, 2020). Socioeconomic indicators related to the performance or behavior of the fishery can also impact the ABC both directly by informing time-varying fishery selectivity and indirectly through context in the risk table. Other socioeconomic indicators such as those related to the economics of the fishery or the communities that are supported by the fishery impact decisions further downstream of the stock assessment process and generally are used in decisions related to total allowable catch (TAC). Additionally, all ecosystem indicators selected for monitoring in the ESP may inform TAC deliberations.

We evaluated the ecosystem indicators using a series of stages applying statistical tests that increase in complexity depending on the data availability of the stock (Shotwell et al., 2023). The beginning stage is a relatively simple evaluation by traffic light scoring for all the indicators in the ecosystem suite. This evaluates the indicator value from each year relative to the mean of the whole time series and includes the proposed sign of the overall relationship between the indicator and the stock health. The scoring allows for summarizing the proposed pressures on the stock overall, by life stage following the conceptual model, or another category of interest (e.g., environmental, prey, competitor, predator). The intermediate stage uses importance methods related to a stock assessment parameter of interest (e.g., recruitment, growth, catchability). These regression techniques estimate predictive performance for the parameter of interest and are run separate from the stock assessment model. They provide the direction, magnitude, uncertainty of the effect, and an estimate of inclusion probability. The importance method is used to evaluate a stock assessment parameter(s) of interest The advanced stage is used for providing visibility on current research ecosystem models and may be used for testing a research ecosystem linked stock assessment model where output can be compared with the current operational stock assessment model to understand information on retrospective patterns, prediction performance, and comparisons to model outputs.

The three stages can be considered as gates for how to monitor the indicator suite and are generally related to the data availability for the stock assessment. Data-limited stocks would only have enough information for the beginning stage and simple scoring analysis. Age- or length-structured assessment models with moderate to rich data availability would be able to move past the beginning stage or gate and evaluate the indicators using importance methods external to the assessment model. The most data rich stocks with an integrated ecosystem-linked modeling platform could move past the intermediate stage or gate and evaluate indicators using the advanced methodology (e.g., integrated age-structured stock assessment model with dynamic structural equation modeling or DSEM, Champagnat et al., *in review*).

We evaluated the socioeconomic indicators using only the beginning stage statistical tests and did not assign a proposed relationship between the indicator and stock, as the role of socioeconomic indicators in the stock assessment process is currently being evaluated by the North Pacific Fishery Management Council (NPFMC or Council, December 2023, 2024 memorandum). Once general guidance from the SSC and Council regarding priorities for ESP and socioeconomic indicators to inform decisions is provided, we will update the analysis options for socioeconomic indicators. We also note, per Scientific and Statistical Committee (SSC) guidance, that the socioeconomic indicators can provide a combination of performance and context and any overall scores by category should only include indicators that reflect performance. In this way higher scores should reflect "good" conditions and would not be influenced by indicators that are included for context (e.g., composition of product form, or market share).

Ecosystem Indicator Analysis

The GOA Pacific cod stock is data-rich with an associated age-structured operational stock assessment model; therefore the full suite of ecosystem indicators were evaluated using intermediate indicator analysis stage methods. Results from this intermediate stage analysis are used to organize ecosystem indicators into the following three categories:

- Predictive: indicators that demonstrate a robust quantitative relationship with the population process of interest.
- Contextual: indicators that lack predictive skill for the population process of interest but provide anticipatory information to inform another population process that has not been evaluated, inform a management concern, or highlight a potential red flag related directly to the status or health of the stock.
- Monitoring: indicators that do not demonstrate quantitative links to population processes, provide information that is immediately relevant to the stock and/or fishery managers, or have not been updated for several years due to lack of resources for continuing the indicator.

The intent of this indicator categorization is to succinctly communicate potential red flags for the stock based on current-year indicator trends and stock-indicator relationships, while providing a mechanism to down-weight indicators that do not quantitatively inform population processes. Monitoring indicators are reported in this document and will continue to be evaluated annually, but we limit our interpretation and synthesis to predictive and contextual indicators in an effort to communicate only the most relevant ecosystem considerations for setting biological reference points for the current year.

Analysis Methods

Bayesian adaptive sampling (BAS) was used as an intermediate stage indicator analysis to quantify the strength and direction of association between ecosystem indicators and GOA Pacific cod recruitment. 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). GOA Pacific cod recruitment, our population process of interest, was calculated using the most recently accepted operational age-structured stock assessment model (Hulson et al., 2024).

Prior to running BAS, the full suite of ecosystem indicators was winnowed to the predictors that directly relate to recruitment based on a literature review and information from subject matter experts that was conducted in the ESP full report (Shotwell et al., 2021). We then evaluated the remaining indicators for normality and transformed them as needed. We further restrict potential covariates to those that can provide the longest continuous time series for modeling (e.g., indicators from biennial surveys or gappy time series would be removed) and through the most recent estimate of recruitment that is well estimated, model end year minus X, (not just average recruitment) in the current operational stock assessment model. Remaining covariates with the strongest links to recruitment are retained and then z-scored. Ecosystem indicator lags were then assigned to the subset of indicators based on hypothesized mechanistic linkages between the proposed life history stage and the indicator. Prior to running the model, we also tested for any highly correlated indicators ($r \geq 0.6$) with the understanding that high correlations among predictors may "dilute" inclusion probabilities and render them less useful as a posterior summary of variable importance.

Indicators that were not included in the BAS model are then assigned to contextual or monitoring categories following the criteria listed above. Once all the indicators are categorized, we summarize recent indicator trends using a five year status table. Indicator status is evaluated based on being greater than ("high"), less than ("low"), or within ("neutral") one standard deviation of the long term mean. The proposed relationship with the stock is communicated as a sign and associated color relative to the indicator value and directional indicator-stock relationship. The sign of the relationship for predictive indicators is based on the importance method results, while the sign for contextual or monitoring indicators is based on the conceptual model and hypothesized relationship with the stock (Figure 2.1.1). The color of the status cell (also referred to as the "traffic light") is related to the sign of the indicator and the status. If a high value of an indicator generates good conditions for the stock and is also greater than one standard deviation above the mean, then that table cell is colored blue or italicized text. If a high value generates poor conditions for the stock and is greater than one standard deviation above the mean, then that table cell is colored red or bolded text. All values less than or equal to one standard deviation from the long-term mean are average or neutral and there is no assigned color. Finally, if the sign of the relationship between an ecosystem indicator and the stock is unclear, no relationship is assigned.

Analysis Results

This indicator preparation for BAS resulted in a final suite of 4 predictor variables: 1) Pacific Cod Spawning Habitat Suitability, 2) Eddy Kinetic Energy in Kodiak from CMEMS, 3) Peak Timing of Spring Bloom in WCGOA from OCCCI, and 4) Adult Steller Sea Lion Counts in GOA from MML (Figure 2.1.4). We eliminated the following two indicators from BAS because they are not hypothesized to drive GOA Pacific cod recruitment and instead, provide contextual information about the stock or a relevant management concern: 1) Age-1 Pacific Cod Natural Mortality from Multispecies Model, and 2) Pacific Cod Ration in GOA from Multispecies Model. We also categorized five indicators as monitoring: 1) Summer Large Copepod Abundance in Shelikof from EcoFOCI due to consistent lack of recent information, 2) Summer Bottom Temperature in GOA from CSFR due to the product being discontinued after 2024, and 3-5) Pacific Cod Center of Gravity North from GAP, Pacific Cod Center of Gravity East from GAP, and Pacific Cod Area Occupied from GAP due to the impact of this indicator on GOA Pacific Cod survival being unknown at this time.

We further removed the following indicators from the BAS analysis based on various reasons provided in parentheses after the indicator title: 1) Heatwave During Spawning in GOA (zero inflated, collinear with Pacific Cod Spawning Habitat Suitability) 2) Summer Large Copepod Abundance in Shelikof from EcoFOCI (too gappy and short), 3) Spring Pacific Cod Larvae CPUE in Shelikof from EcoFOCI (too gappy), 4) Murre Reproductive Success on Chowiet from USFWS (too gappy), 5) Summer Pacific Cod YOY CPUE in WCGOA from Beach Seine (too short), 6) Juvenile Pacific Cod Condition in GOA from GAP (too gappy), 7) Adult Pacific Cod Condition in GOA from GAP (too gappy), and 8) Biomass Eaten of Pacific Cod from Multispecies Model (collinear with Adult Steller Sea Lion Counts in GOA from MML). These indicators were all categorized as contextual.

The habitat suitability, eddy kinetic energy, and spring bloom timing indicators in the final suite listed above were assigned no lag as they affect growth and survival through the first year of life. A two year lag was assigned to the Steller Sea Lion indicator assuming impacts to survival on the late juvenile and early adult stages. Twenty-three years were dropped due to incomplete observations since BAS removed missing years and resulted in a model run from 1998 through the 2022 year-class after lags were applied.

The final BAS model identified one ecosystem indicator that quantitatively predicted GOA Pacific cod recruitment, while remaining indicators demonstrated poor predictive performance (Figure 2.1.5). The highest ranked predictor variable, Pacific Cod Spawning Habitat Suitability, had credible intervals that could be distinguished from zero, a positive effect (0.25; Figure 2.1.5 top left), and a relatively high inclusion probability (0.89; Figure 2.1.5 top right). This evidence for a positive effect is consistent with the hypothesis that increased habitat suitability due to cooler temperatures at depth are optimal for hatch success of GOA Pacific cod eggs and positively impacts survival to recruitment. The final model explained a moderate amount of variation in GOA Pacific cod recruitment ($R^2 = 0.32$), however we note that large credible intervals suggest a large degree of uncertainty in the estimated effect sizes**.** Model predicted fit (Figure 2.1.5 bottom left) and average predicted fit across the recruitment time series subset (1998 - 2022; Figure 2.1.5 bottom right) indicate that habitat suitability does a fair job at capturing general patterns in GOA Pacific cod recruitment, but fails to predict the magnitude of interannual variation in recruitment. While the BAS model does eliminate several potentially informative covariates due to method limitations that could be limiting the ability of the model to predict the recruitment magnitude, there is auxiliary information that suggests more recent recruitment. Observations of YOY from the beach seine CPUE which are not included in the operational stock assessment model suggest above average year classes in 2020 and 2022 (Figure 2.1.2a.h). Also, these relatively stronger year classes are present in the length and age compositions from the AFSC bottom trawl survey, but the assessment model estimates lower abundance than these observations (Hulson et al., 2026). So while the BAS model does not fit the most recent lower recruitment estimates, the assessment model may also be underestimating the magnitude of these recent recruitments (Hulson et al., 2026). We plan to investigate this more in the future by exploring other importance methods that can include more of the ESP indicators or through an integrated ecosystem linked assessment model when it is developed for GOA Pacific cod.

Overall, results from the status table (Table 2.1.1a) indicate that Pacific Cod Spawning Habitat Suitability in 2025 was low relative to the long-term mean. This current-year estimate represents a potential concern for the stock as it implies a poor 2025 year class and is further supported by below average larvae and YOY indicators of GOA Pacific cod abundance. All other contextual indicators with 2025 updates remained within one standard deviation of their long-term mean and have mixed trends. The Executive Summary at the beginning of this document provides a summary of predictive and contextual indicator trends that can be used to inform ABC and TAC decisions.

Socioeconomic Indicator Analysis

We summarize recent indicator trends for socioeconomic indicators using a five-year status table similar to the ecosystem indicator table described above except that the indicators use the original categories for organization and no relationship is assigned to the indicator (Table 2.1.1b). Three economic indicators were presented to depict the historical time series of key socioeconomic information for the GOA Pacific cod fishery. Overall, results from the status table indicate that both ex-vessel value and price were low relative to the long-term average. Ex-vessel value decreased by 24% from 2023, falling below one-standard deviation of the historical range for the sixth time in the last seven years. In 2024, ex-vessel price decreased sharply, falling below the historical average and below one-standard deviation of the historical range for the first time since 2013. Revenue-per-unit-effort decreased from the historical high recorded in 2022, falling below the historical average but remains within one-standard deviation of the historical range.

Detailed information from the economic performance reports (EPR) are also presented to provide a broader picture of the economic indicators (Table 2.1.2). In 2024, ex-vessel value decreased by 24% from 2023 to $14 million, remaining below the 2015 to 2019 average of $31 million. The decline in ex-vessel value from historical levels is due to significant declines in retained catch. Between 2015 and 2019, retained catch averaged 43 thousand mt. In 2024, retained catch was 24.3 thousand mt, a decline of 44% from the historical average. With decreases in retained catch, the average price per pound increased from $0.33 between 2015 to 2019 to $0.42 in 2023 (Table 2.1.2a). The ex-vessel price declined significantly to $0.26 per pound in 2024, however, the lowest recorded ex-vessel price in our time series. With declines in total retained catch from historical averages, the first-wholesale volume of GOA Pacific cod also declined to 10.24 thousand mt in 2024 from the 2015 to 2019 average of 16.8 thousand mt. Reductions in supply did have a positive impact on the average first-wholesale price per pound, increasing from an average of $1.82 between 2015 and 2019 to $2.98 in 2023. The first-wholesale price per pound declined to $2.32 in 2024 but remains above the historical average. The reductions in first-wholesale volume outweighed the increase in price as the first wholesale value decreased to $52.4 million in 2024, a 22% decline from the 2015 to 2019 average of $67.3 million. Pacific cod is primarily processed into head & gut and fillet products. Unlike the BSAI, the value share of fillets is the dominant product form in the GOA, representing one-half of first-wholesale value in 2024. The value share of Pacific cod processed into fillets, however, has declined year-over-year since 2021, falling slightly below the historical average. This is partially due to declines in the first-wholesale market price of fillets since 2022. The average first-wholesale price per pound for H&G has remained steady within the same time period while volume has doubled causing value share to increase in 2024 above the historical average (Table 2.1.2b).

Similar trends are being seen in the global production of Pacific cod. Global production of Pacific cod has declined to approximately 1.3 million mt in 2023 from the 2015 to 2019 average of approximately 1.7 million mt (-23%). In 2024, export volume and value of Alaskan Pacific cod has declined from the 2015 to 2019 average of 90 thousand mt and $283 million to 49 thousand mt and $171 million, respectively. A majority of Alaskan Pacific cod exports go to Asian markets, primarily China and Japan, representing two-thirds of volume and value historically (Table 2.1.2c). The share of export volume and value of Alaskan Pacific cod to China has returned to the historical average from recent lows recorded in 2022. Export volume and value to Japan, however, has significantly declined from 12.8 thousand mt and $44 million between 2015 and 2019 to 1.3 thousand mt and $4.8 million in 2024, representing less than 3% of export shares. The share of export volume and value of Alaskan Pacific cod to Europe has declined from 2023 levels but remains stable compared to historical averages. Additionally, the share of cod consumed domestically has increased year-over-year between 2019 and 2022, when demand for frozen products increased during the COVID-19 pandemic but has declined in subsequent years (Table 2.1.2c).

The Executive Summary at the beginning of this document provides a summary and interpretation of socioeconomic indicator trends that can be used to inform ABC and TAC decisions. Economic indicators in the context of the ESP are exclusively intended to inform TAC deliberations.

Conclusion

The GOA Pacific cod ESP follows the standardized framework for evaluating the various ecosystem and socioeconomic considerations for this stock (Shotwell et al., 2023). The conceptual model provides a reference for the comprehensive literature review and associated tables of the ESP full report (Shotwell et al., 2021). Eighteen ecosystem and three socioeconomic indicators were identified to monitor for the GOA Pacific cod stock. Ecosystem indicators were evaluated using intermediate indicator analysis stage methods because GOA Pacific cod is a data-rich stock with fishery-independent surveys to assess population status. We provide several overarching takeaways from the indicator assessment results. This information can be used for evaluating concerns in the main stock assessment or other management decisions and we organize the results by acceptable biological catch (ABC) and total allowable catch

(TAC) considerations. Indicators that can inform ABC and risk tables include predictive, contextual, or fishery-informed indicators. Indicators that can inform TAC include all ABC indicators as well as economic and community indicators.

Overall, ecosystem indicators decreased from slightly above average to slightly below average in 2025. The predictive Pacific Cod Spawning Habitat Suitability indicator was low, suggesting poor spawning conditions which may have a negative effect on egg survival and a potentially poor 2025 year class. Contextual indicators were overall average with mixed trends. Recruitment indicators of spring larvae in Shelikof and summer young-of-the-year (YOY) catch per unit effort (CPUE) from beach seine in western-central GOA were both below average supporting a potentially poor 2025 year class. Estimates of age-1 natural mortality from Pacific cod from the multispecies model remain near average and above the operational stock assessment model estimate. Ecosystem considerations indicators are organized into three categories, environmental, prey, and competitors/predators similar to the Ecosystem Status Report organization (Ferriss, 2026). Environmental indicators include an increase to average heatwave events during spawning but not at the levels of the major heatwave events in 2015, 2016, and 2019 and a decrease to below average eddy kinetic energy implying reduced larval retention and cross-shelf transport. Prey indicators included average spring bloom timing, sufficient forage resources for seabirds, but a decrease to below average body condition for juvenile and adult Pacific cod and a slightly increased but still below average metabolic demand based on the multispecies model. Predator indicators were below average biomass consumed of Pacific cod in the multispecies model but a steadily increasing population of Steller sea lions in the GOA. Socioeconomic indicators were only represented by three economic indicators, all of which were lower than the historical mean, and continued to decline from 2023 levels.

While the current indicator assessments offer a valuable set of proxy indicators for understanding drivers of the GOA Pacific cod stock, there are notable areas for improvement. The list below summarizes the data gaps and future research priorities for this ESP by ecosystem and socioeconomic category. Some of the bullets also include "high priority" in parentheses after the description denoting a current higher priority for GOA Pacific cod.

Ecosystem Priorities

- Development of hydrographic model indicators (e.g., bottom temperature from MOM6) to assist with the loss from discontinued model products. (high priority)
- Refinements or updates to current high-resolution remote sensing indicators (e.g., eddy kinetic energy and peak timing of spring bloom) that were only partially specialized for GOA Pacific cod during initial development.
- Development of large-scale indicators from multiple data to understand prey trends at the spatial scale relevant to management (e.g., regional to area-wide estimates of zooplankton biomass, offshore to nearshore monitoring of Pacific cod larvae) and align the spatial and temporal extent of available zooplankton or other productivity indicators to the specific needs of the GOA Pacific cod stock in the future. (high priority)
- Evaluation of demographic differences in the YOY population within and among larval and juvenile surveys conducted in the Central and Western GOA.
- Recent changes in annual average size in nearshore YOY Pacific cod samples (e.g., 50-90% increased length observed in age-0 juveniles in summer since 2006) are more attributed to earlier spawning times (age) than growth based on otolith increment analyses (Almeida et al., 2024; Miller et al., 2024). A size-based phenology index (which would be tightly coupled to hatch date) could provide mechanistic understanding of downstream impacts to mortality, maturity schedules, and genetic selection for Pacific cod.

- Investigating environmental regulation of first year of life processes in Pacific cod to understand the interrelationship between processes occurring during pre-settlement (spawning/larvae), settlement (summer growth) and post-settlement (first overwintering) phases.
- Exploration of spatial distribution of egg and larvae stages, transport processes, and connectivity between spawning and juvenile nursery areas using the ROMS-NPZ coupled with an IBM.
- Spatially broad investigation of nearshore nursery habitat characteristics (e.g. year around temperature, salinity) in relation to summer growth and overwinter survival.
- Increased sampling of predator diets in fall and winter to understand predation on YOY Pacific cod during their first autumn and winter, when predation mortality is thought to be significant.
- Investigation of an age-1 index of Pacific cod from the Kodiak beach seine survey to gain understanding of overwinter survival in reference to the age-0 index. Measures of YOY body condition during the fall may additionally provide an indication of overwintering success (Abookire et al. 2024).
- Evaluation of condition and energy density of juvenile and adult Pacific cod samples at the outer edge of the population from the GulfWatch Alaska program or longline surveys to understand the impacts of shifting spatial statistics such as center of gravity and area occupied.
- Evaluation of biological references points under projected scenarios using GOA Ecopath and the Atlantis ecosystem model as part of the GOA Regional Action Plan.

Socioeconomic Priorities

- Reorganization of indicators by scale, structure, and dependence per recent SSC request that may result in a transition of indicators currently reported and a potential shift in focus.
- Re-evaluation of fishery performance indicators to potentially include:
    - CPUE measures (e.g., proportion of the catch by gear, level of effort by gear)
    - Fleet characteristics (e.g., number of active vessels, number of processors)
    - Spatial distribution measures (e.g., center of gravity, area occupied)
- Re-evaluation of economic indicators to potentially include:
    - Percentage of total allowable catch (TAC) harvested by active vessels
    - Measures by product type (e.g., proportion landed, price per pound)
    - Revenue per unit effort by area, gear, and product type
- Evaluation of additional sources of socioeconomic information to determine what indicators could be provided in the ESP that are not redundant with indicators already provided in the Economic SAFE and the ACEPO report.
- Consideration of the timing of indicators that are delayed by 1 to several years depending on the data source from the annual stock assessment cycle and when updates can be available.
- Consideration on how to include local knowledge, traditional knowledge, and subsistence information to understand recent fluctuations in stock health, shifts in stock distributions, or changes in size or condition of species in the fishery per SSC recommendation.

As indicators are improved or updated, they may replace those in the current set of ecosystem or socioeconomic indicators to allow for refinement of the indicator analyses and potential evaluation of performance and risk. Incorporating additional importance methods in the intermediate stage indicator analysis may also be useful for evaluating the full suite of indicators and may allow for identifying robust indicators for potential use in the operational stock assessment model. The annual request for information (RFI) for the GOA Pacific cod ESP will include these data gaps and research priorities that could be developed for the next full ESP assessment (please contact Kalei Shotwell at kalei.shotwell@noaa.gov for more details).

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Tables

Table 2.1.1a: First stage ecosystem indicator analysis for GOA, including indicator title and the indicator status of the last five years. The indicator status is designated with text, (greater than = "high", less than = "low", or within 1 standard deviation = "neutral" of the long-term mean). Fill color of the cell is based on the proposed sign of the overall relationship between the indicator and the stock (blue or italicized text = good conditions for the stock, red or bold text = poor conditions, white = average conditions). A gray fill and text = "NA" will appear if there were no data for that year.

Indicator category	Indicator	2021 Status	2022 Status	2023 Status	2024 Status	2025 Status
Predictive	Pacific Cod Spawning Habitat Suitability	neutral	neutral	neutral	neutral	**low**
Contextual	Heatwave During Spawning in GOA from OISST	neutral	neutral	neutral	neutral	neutral
	Eddy Kinetic Energy in Kodiak from CMEMS	neutral	neutral	neutral	neutral	neutral
	Peak Timing of Spring Bloom in WCGOA from OCCCI	neutral	neutral	neutral	neutral	neutral
	Spring Pacific Cod Larvae CPUE in Shelikof from EcoFOCI	neutral	NA	neutral	NA	neutral
	Murre Reproductive Success on Chowiet from USFWS	neutral	*high*	neutral	*high*	neutral
	Summer Pacific Cod YOY CPUE in WCGOA from Beach Seine	neutral	neutral	neutral	neutral	neutral
	Age-1 Pacific Cod Natural Mortality from Multispecies Model	neutral	neutral	neutral	neutral	neutral
	Juvenile Pacific Cod Condition in GOA from GAP	neutral	NA	neutral	NA	neutral
	Adult Pacific Cod Condition in GOA from GAP	neutral	NA	neutral	NA	neutral
	Pacific Cod Ration in GOA from Multispecies Model	neutral	neutral	neutral	neutral	neutral
	Biomass Eaten of Pacific Cod from Multispecies Model	*low*	neutral	neutral	neutral	neutral
	Adult Steller Sea Lion Counts in GOA from MML	neutral	neutral	neutral	neutral	NA
Monitoring	Summer Large Copepod Abundance in Shelikof from EcoFOCI	NA	NA	neutral	NA	NA
	Summer Bottom Temperature in GOA from CSFR	neutral	neutral	neutral	neutral	NA
	Pacific Cod Center of Gravity North from GAP	neutral	NA	neutral	NA	neutral
	Pacific Cod Center of Gravity East from GAP	neutral	NA	neutral	NA	neutral
	Pacific Cod Area Occupied from GAP	*high*	NA	neutral	NA	neutral

Table 2.1.1b: First stage socioeconomic indicator analysis for GOA, including indicator title and the indicator status of the last five years. The indicator status is designated with text, (greater than = “high”, less than = “low”, or within 1 standard deviation = “neutral” of the long-term mean). A gray fill and text = “NA” will appear if there were no data for that year. A red color indicates a fishery closure and the text = “Closed” will appear.

Indicator category	Indicator	2020 Status	2021 Status	2022 Status	2023 Status	2024 Status
Economic	Pacific Cod Real Ex-vessel Value in GOA from ESSR	low	low	neutral	low	low
	Pacific Cod Real Ex-vessel Price in GOA from ESSR	neutral	neutral	neutral	neutral	low
	Pacific Cod Real Revenue / Unit Effort in GOA from ESSR	low	neutral	high	neutral	neutral

Table 2.1.2a: 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 vessel; 2015-2019 average and 2020-2024.

	2015-2019 Average	**2020**	**2021**	**2022**	**2023**	**2024**
Total catch K mt	44.64	6.8	19.2	25.9	21.7	25.9
Retained catch K mt	43.47	4.84	16.14	24.16	19.72	24.29
Ex-vessel value M $	$31.29	$4.42	$15.35	$25.1	$18.43	$13.98
Ex-vessel price lb $	$0.33	$0.39	$0.39	$0.47	$0.42	$0.26
Hook & line share of catch	19.24%	19.24%	28.8%	25.51%	31.75%	28.81%
Pot gear share of catch	54.81%	34.56%	43.28%	43.59%	38.87%	42.89%
Central Gulf share of catch	52.47%	71.71%	62.55%	66.45%	65.56%	75.3%
Shoreside share of catch	90.36%	98.55%	98.95%	88.91%	89.2%	90.33%
Vessels #	265.2	103	186	206	219	175

Source: NMFS Alaska Region Blend and Catch-accounting System estimates; NMFS Alaska Region At-sea Production Reports; and ADF&G Commercial Operators Annual Reports (COAR). Data compiled and provided by the Alaska Fisheries Information Network (AKFIN).

Table 2.1.2b: 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; 2015-2019 average and 2020-2024.

	2015-2019 Average	**2020**	**2021**	**2022**	**2023**	**2024**
All Products volume K mt	16.82	2.97	6.54	9.72	7.58	10.24
All Products value M $	$67.36	$15.03	$37.27	$66.54	$49.73	$52.42
All Products price lb $	$1.82	$2.3	$2.59	$3.11	$2.98	$2.32
Fillets volume K mt	5.03	1.12	2.7	3.85	3.03	2.72
Fillets value share	53.59%	67.41%	72.39%	70.4%	67.08%	49.8%
Fillets price lb $	$3.26	$4.09	$4.53	$5.52	$5	$4.36
Head & Gut volume K mt	7.71	1.15	1.69	2.92	2.65	5.19
Head & Gut value share	33.38%	23.42%	15.48%	17.04%	20.58%	37.9%
Head & Gut price lb $	$1.32	$1.39	$1.55	$1.76	$1.75	$1.74

Source: NMFS Alaska Region Blend and Catch-accounting System estimates; NMFS Alaska Region At-sea Production Reports; and ADF&G Commercial Operators Annual Reports (COAR). Data compiled and provided by the Alaska Fisheries Information Network (AKFIN).

Table 2.1.2c: Cod U.S. trade and global market data. Global production (thousand metric tons), U.S. share of global production, and Europe's share of global production; U.S. export volume (thousand metric tons), value (million US$), and price (US$ per pound); U.S. cod consumption (estimated), and share of domestic production remaining in the U.S. (estimated); and the share of U.S. export volume and value for head and gut (H&G), fillets, China, Japan, and Germany and Netherlands; 2015-2019 average and 2020-2024.

	2015-2019 Average	**2020**	**2021**	**2022**	**2023**	**2024**
Global cod catch K mt	1706.58	1498.15	1531.7	1457.4	1312.27	-
U.S. P. cod share of global catch	16.1%	11.5%	9.8%	12.5%	12.9%	-
Europe Share of global catch*	76.5%	80.5%	82.3%	79.3%	77.5%	-
Pacific cod share of U.S. catch	99.7%	99.7%	99.5%	99.5%	99.7%	-
U.S. cod consumption K mt (est.)	112.045	103.335	107.366	134.434	95.454	101.137
Share of U.S. cod not exported	32%	45%	53.3%	61.4%	42.4%	40.8%
Export volume K mt	89.92	44.48	32.51	33.23	45.07	49.1
Export value M US$	$282.75	$139.4	$101.67	$104.72	$158.73	$171.02
Export price lb US$	$1.43	$1.42	$1.42	$1.43	$1.6	$1.58
Frozen (H&G) volume share	92.39%	92.32%	89.45%	87.86%	91.4%	93.54%
Frozen (H&G) value share	91.08%	89.83%	84.22%	86.02%	89.73%	90.77%
Fillets volume share	3.87%	5.86%	8.72%	10.89%	7.39%	5.57%
Fillets value share	5.03%	7.38%	12.92%	12.14%	8.72%	7.92%
China volume share	50.73%	39.52%	31.36%	47.75%	42.55%	50.88%
China value share	48.36%	37.35%	28.39%	48.14%	39.73%	47.79%
Japan volume share	14.18%	13.04%	10.98%	4.65%	5.83%	2.68%
Japan value share	15.55%	13.89%	11.77%	4.31%	5.66%	2.83%
Europe volume share*	17.96%	20.13%	11.54%	17.17%	22.62%	18.69%
Europe value share*	18.97%	20.69%	10.95%	17.42%	23.93%	18.28%

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

Notes: 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.
Source: FAO Fisheries & Aquaculture Dept. 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. U.S. Department of Agriculture http://www.ers.usda.gov/data-products/agricultural-exchange-rate-data-set.aspx

Figures

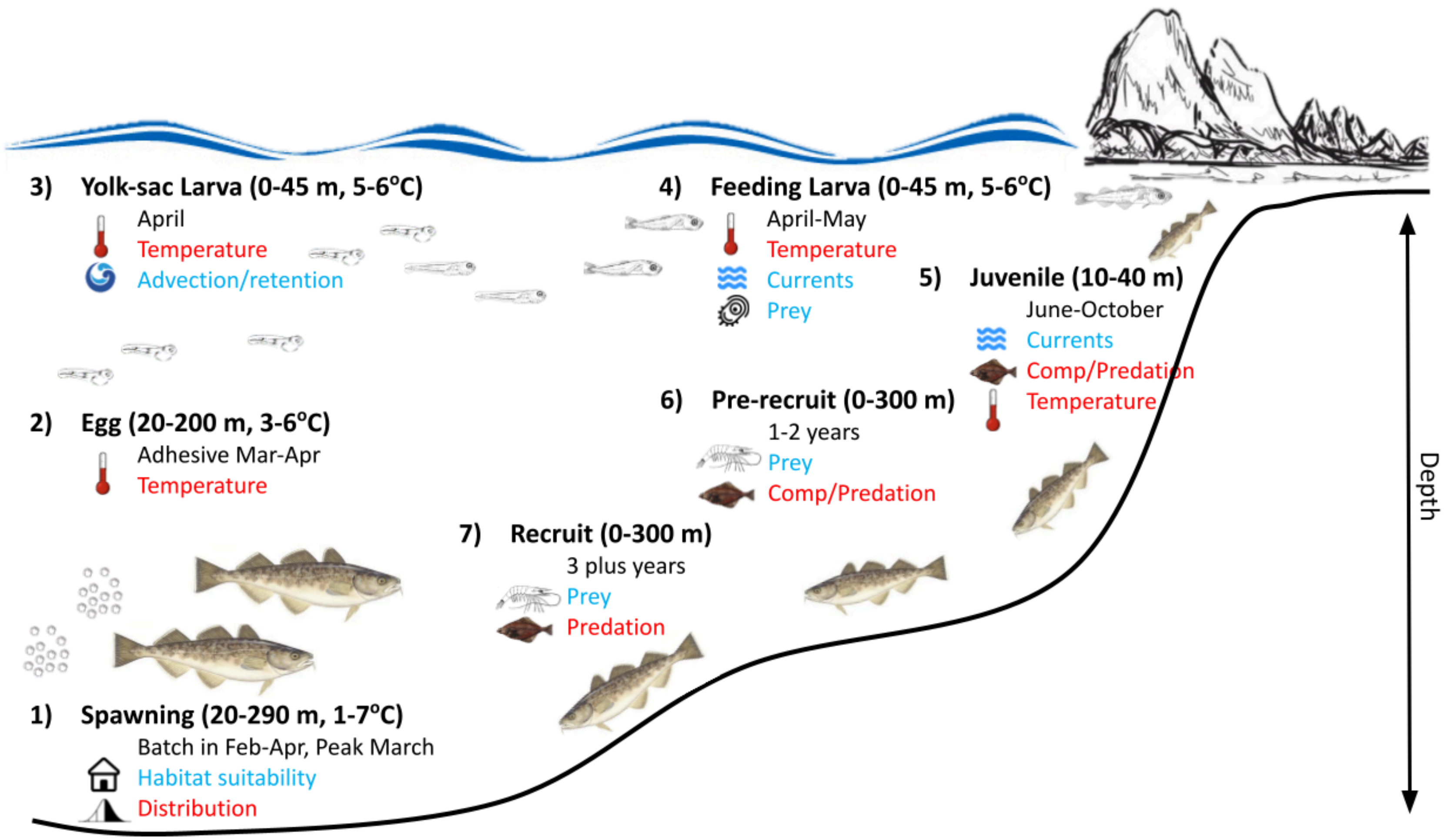

Figure 2.1.1: Life history conceptual model for GOA Pacific cod summarizing ecological information and key ecosystem processes affecting survival by life history stage. Red text indicates that increases in the process negatively affect survival of the stock, while blue text means that increases in the process positively affect survival.

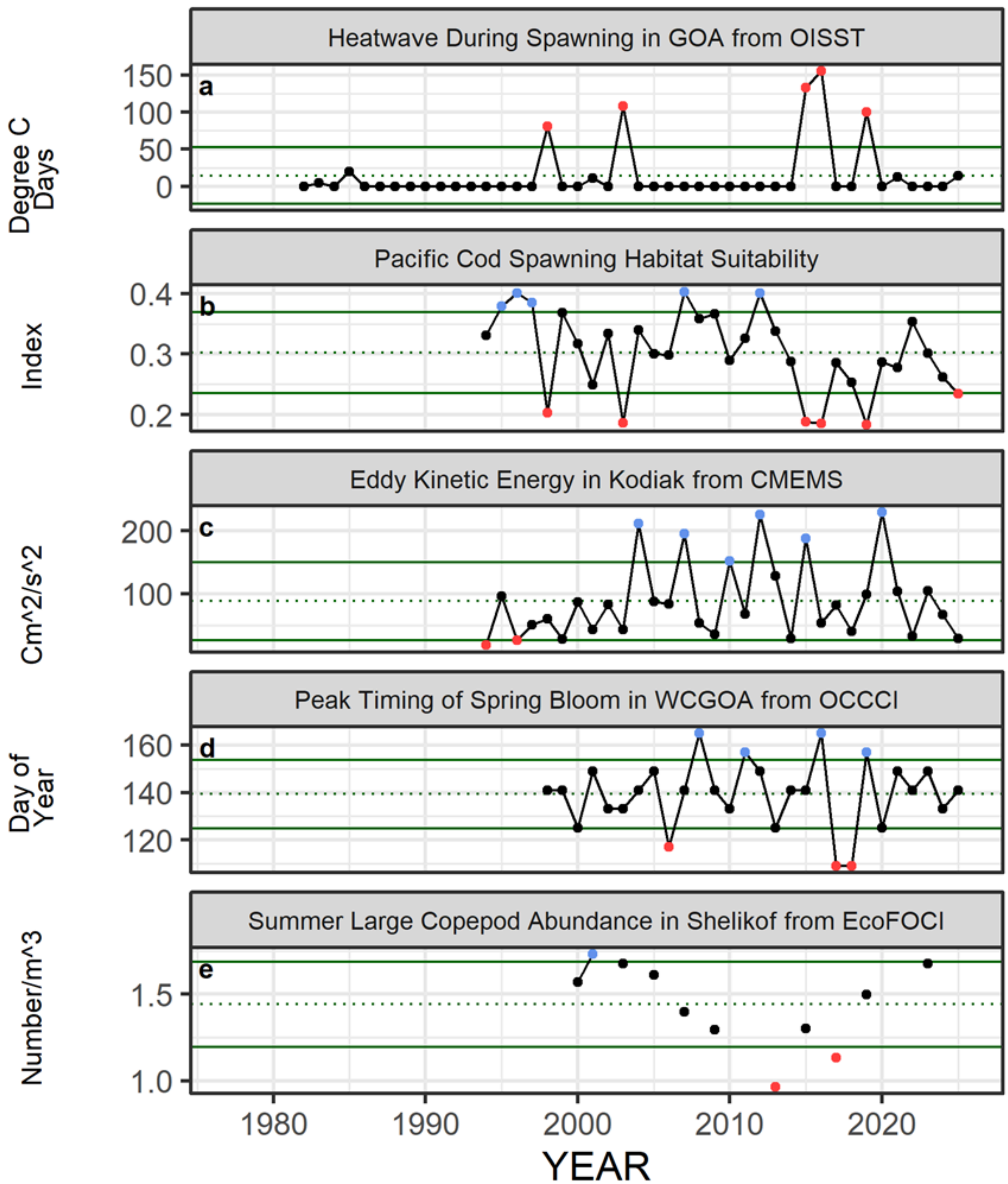

Figure 2.1.2a: Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1963 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

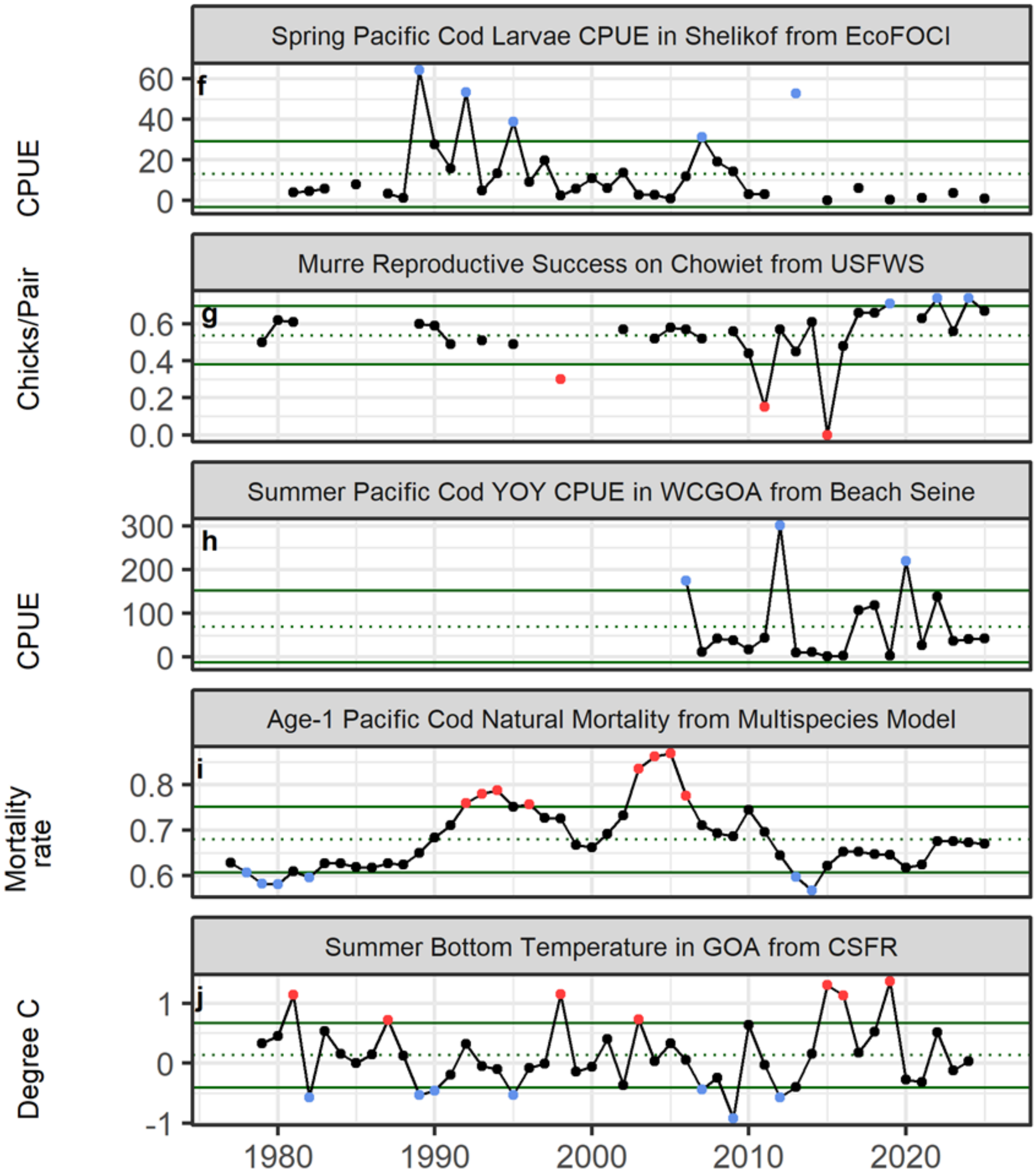

Figure 2.1.2a (cont.): Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1963 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

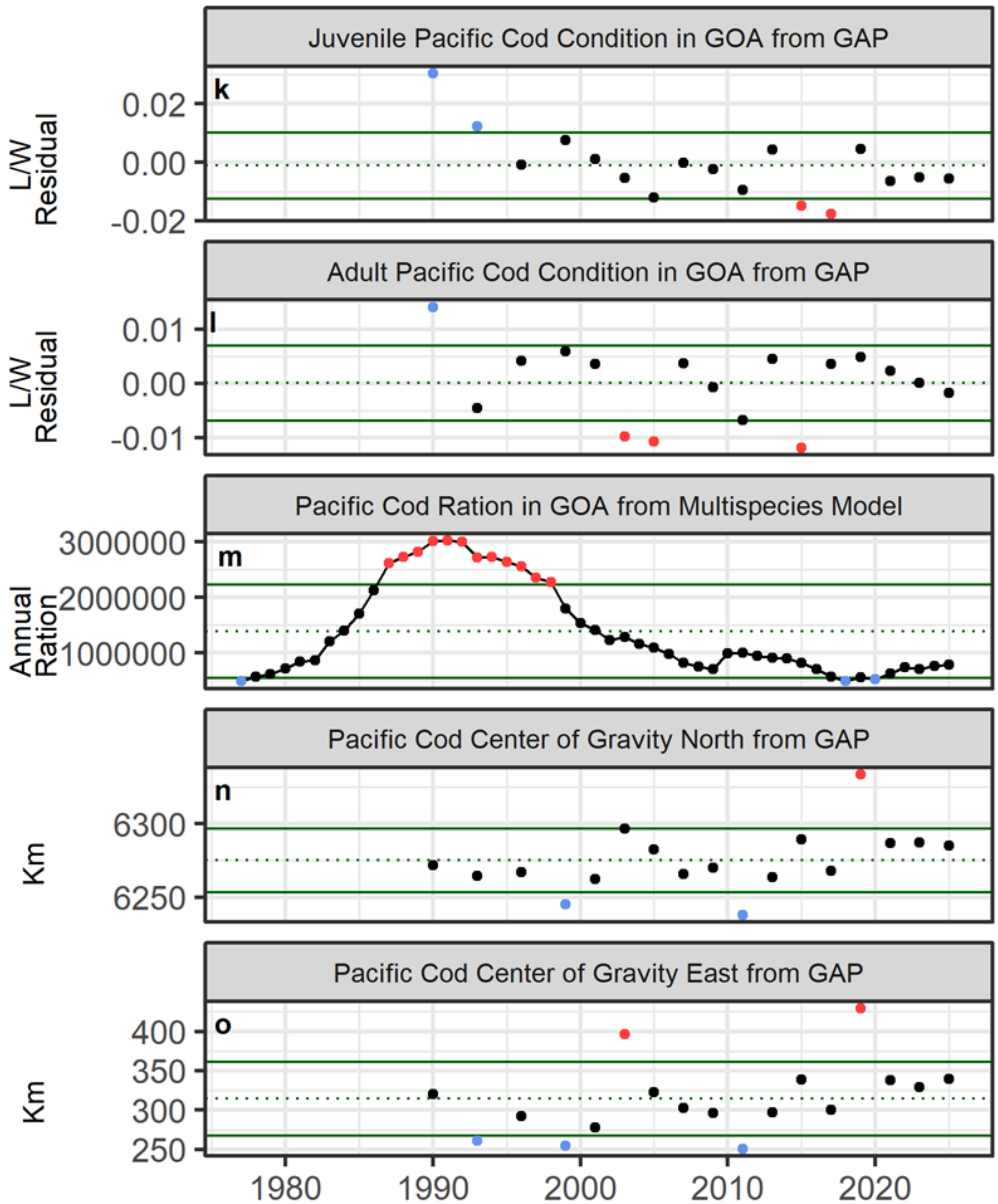

Figure 2.1.2a (cont.): Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1963 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

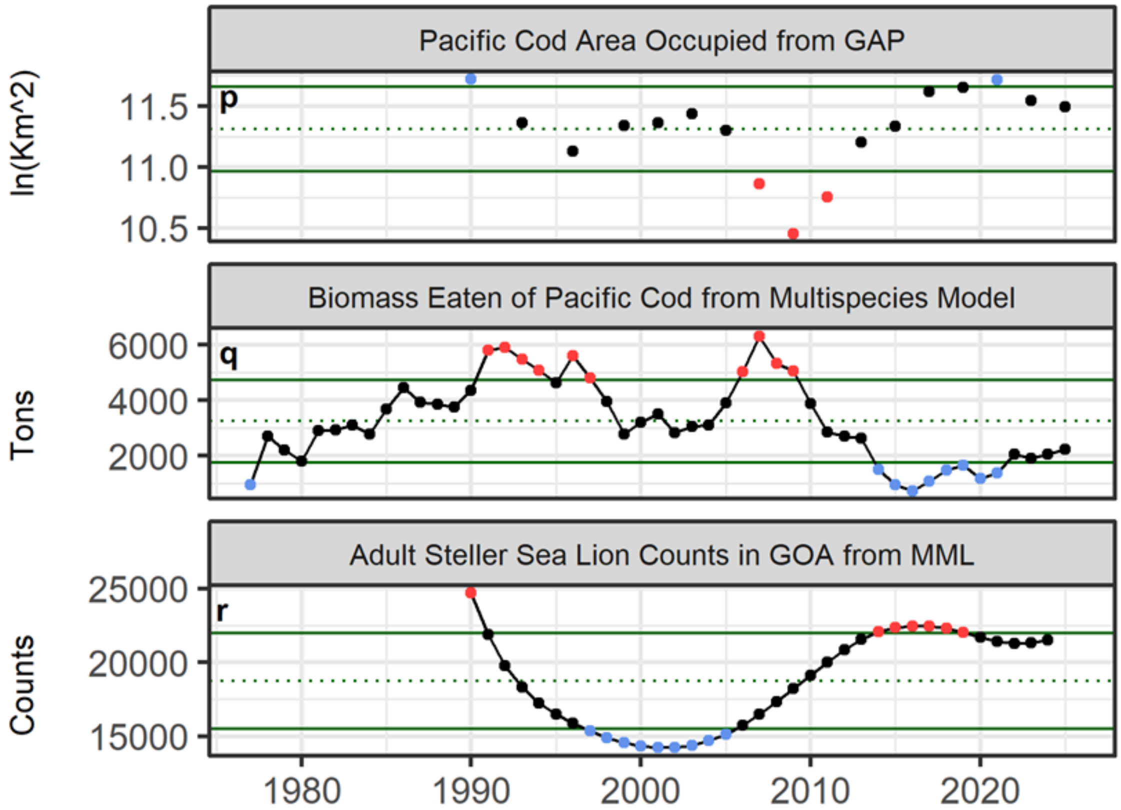

Figure 2.1.2a (cont.): Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1963 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

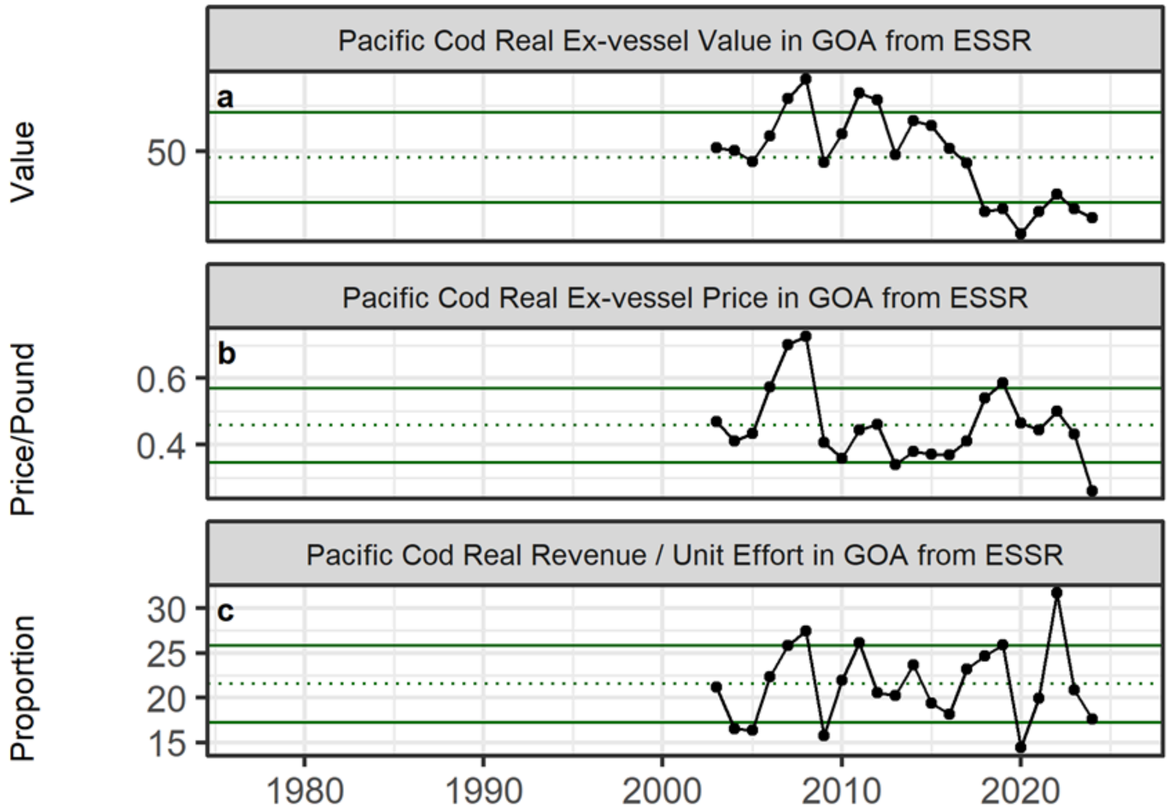

Figure 2.1.2b: Selected socioeconomic indicators for GOA Pacific cod with time series ranging from 1966 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

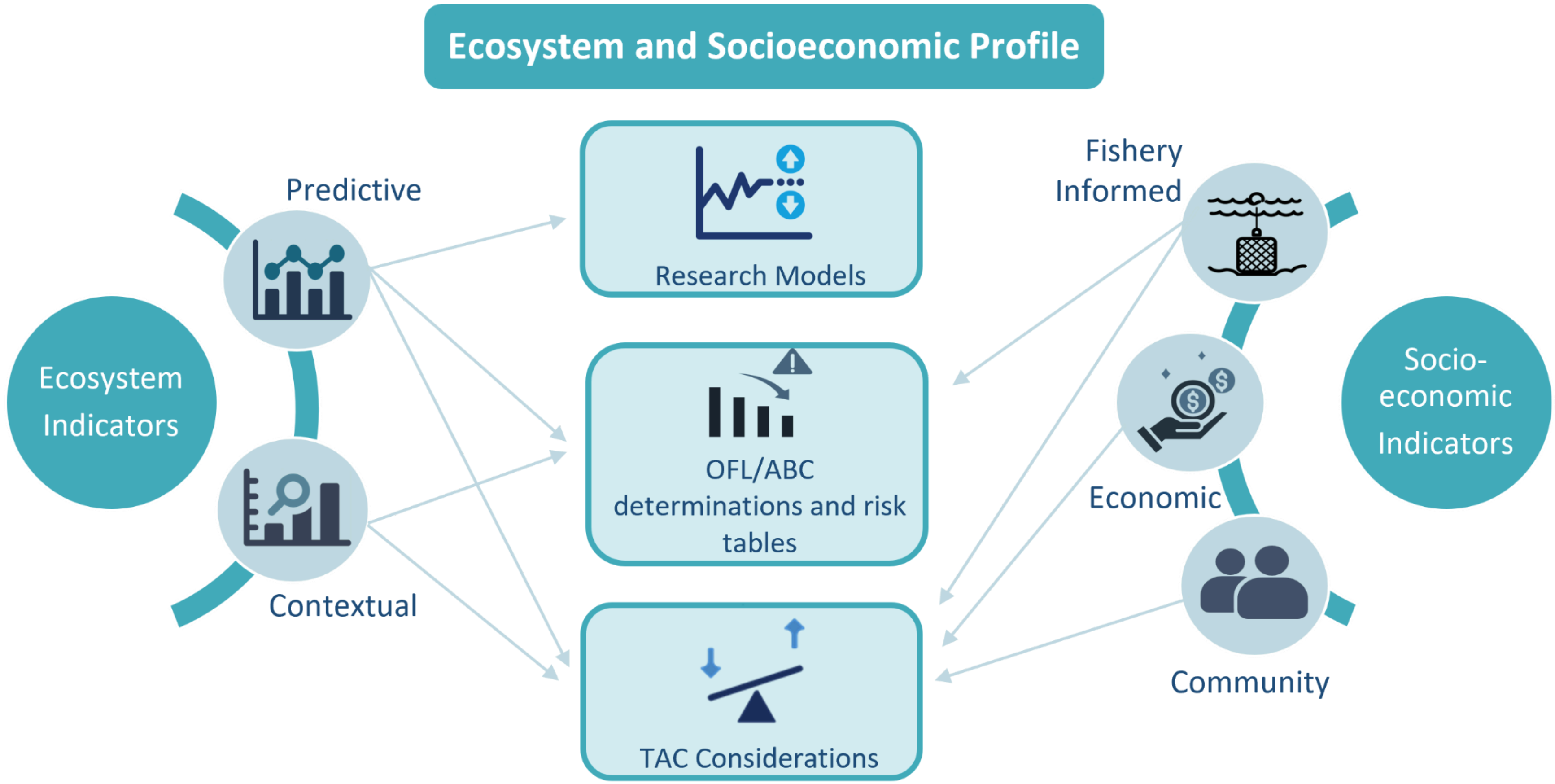

Figure 2.1.3: Schematic of decision pathways for ecosystem and socioeconomic indicators.

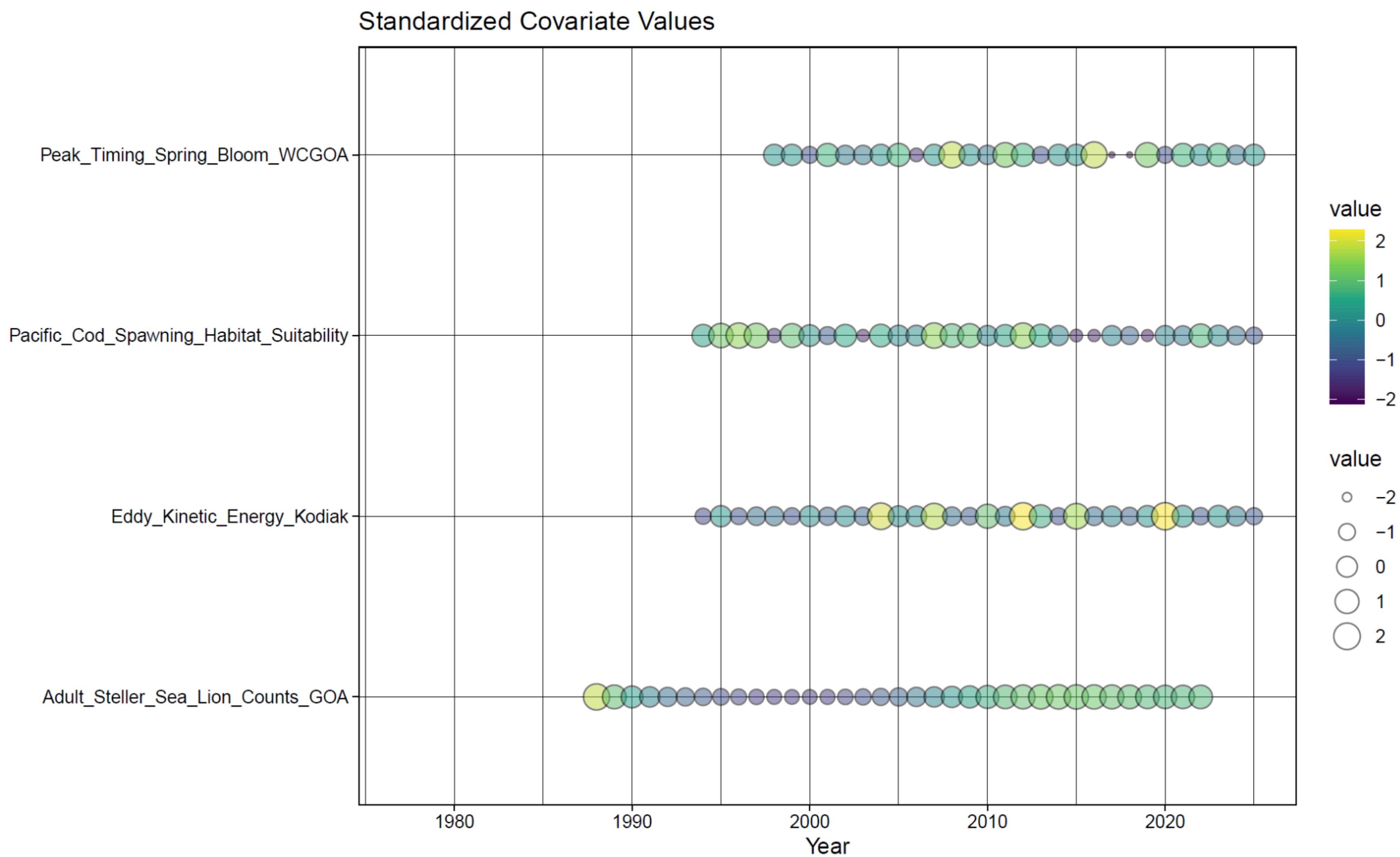

Figure 2.1.4: Standardized ecosystem covariates tested in the final GOA Pacific cod Bayesian adaptive sampling (BAS) model.

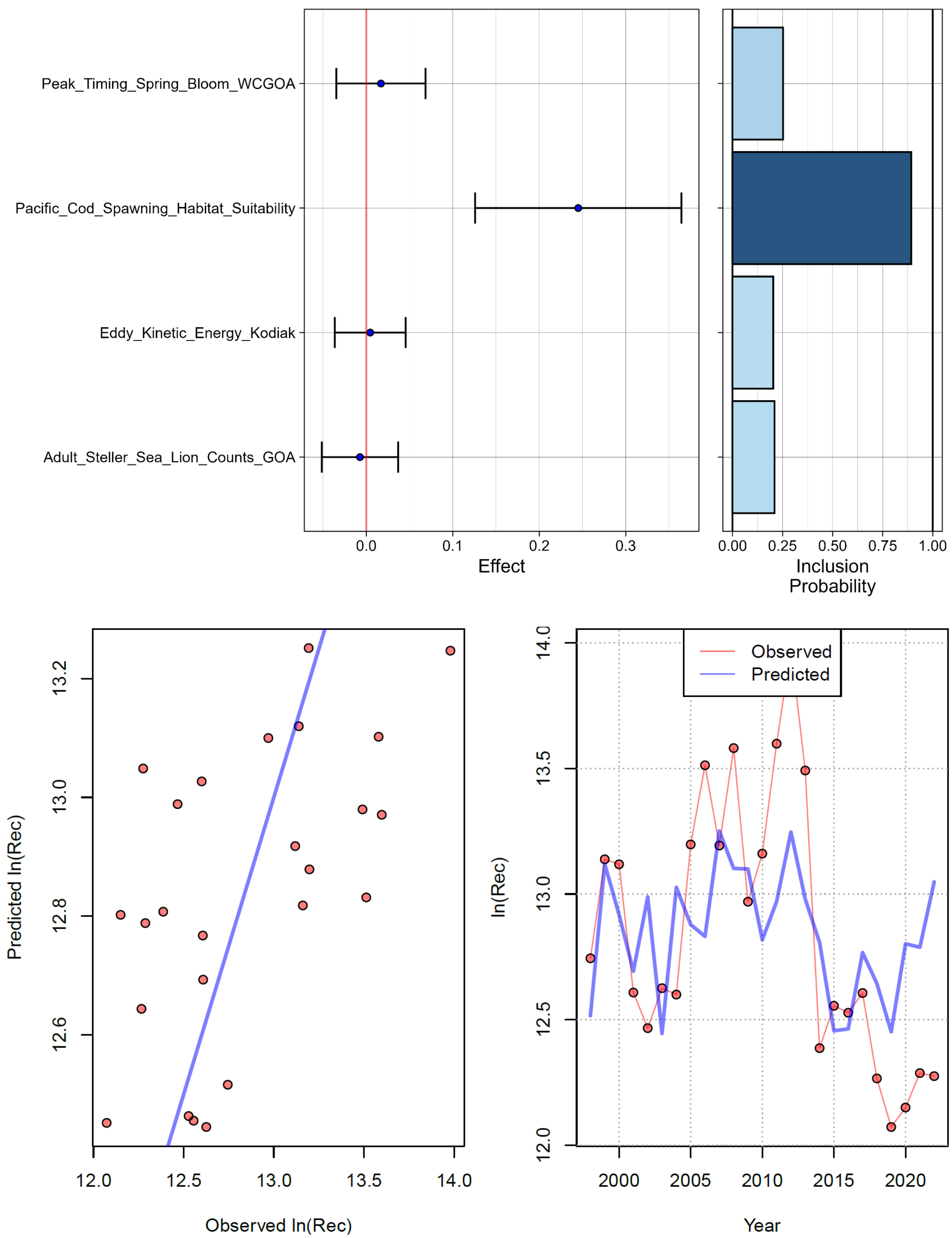

Figure 2.1.5: Bayesian adaptive sampling output showing the mean relationship and uncertainty (± 1 SD) with log-transformed estimated GOA Pacific cod recruitment from the operational stock assessment model: the estimated effect (top left) and the marginal inclusion probabilities (top right) for each predictor variable of the subsetted covariate dataset. Output also includes model predicted fit (1:1 line, bottom left) and average fit across the abbreviated recruitment time series (1998-2022, bottom right).