Appendix 2.1 Ecosystem and Socioeconomic Profile of the Pacific cod stock in the Gulf of Alaska - Report Card

S. Kalei Shotwell and Russel Dame (Editors)

November 2024

With Contributions from:

ESP Team: Bridget Ferriss, Peter-John F. Hulson, Ben Laurel, Beth Matta, Krista Oke, Lauren Rogers

ESP Data: Anna Ableman, Alisa Abookire, Grant Adams, Kerim Aydin, Steven Barbeaux, Matt Callahan, Wei Cheng, Curry Cunningham, Brian Garber-Yonts, Kirstin Holsman, Ben Laurel, Sandi Neidetcher, Krista Oke, Zack Oyafuso, Patrick Ressler, Heather Renner, Lauren Rogers, Sean Rohan, Elizabeth Siddon, Ingrid Spies, Kalei Shotwell, Katie Sweeney, Muyin Wang, Stephani Zador

This report may be cited as: Shotwell, S.K., and Dame, R. 2024. Appendix 2.1. Ecosystem and Socioeconomic Profile of the Pacific cod stock in the Gulf of Alaska - Report Card. In: Hulson, P.J.F., Barbeaux, S.J., Ferriss, B., Echave, K., Nielsen, J., McDermott, S., Laurel, B., Abookire, A., Spies, I., S.K., Shotwell. 2024. Assessment of the Pacific cod stock in the Gulf of Alaska. North Pacific Fishery Management Council, Anchorage, AK. Available from https://www.npfmc.org/library/safe-reports/.

Table of Contents

Executive Summary

The ecosystem and socioeconomic profile (ESP), is a standardized framework for compiling and evaluating relevant stock-specific ecosystem and socioeconomic indicators. It also communicates linkages and potential drivers of the stock within the stock assessment process (Shotwell et al., 2023a). The ESP process creates a traceable pathway from the initial development of indicators to management advice and serves as an on-ramp for developing ecosystem-linked stock assessments.

The ESP report card provides data updates to the most recent year available of the indicator suite created in the initial full ESP (Shotwell et al., 2021a). For more information regarding the ecosystem and socioeconomic linkages for this stock, please refer to the last full ESP and most recent report card documents (Shotwell et al., 2021a, Shotwell et al., 2023b). These documents are available as an appendix within the Gulf of Alaska (GOA) Pacific cod stock assessment and fishery evaluation (SAFE) reports.

Management Considerations

The following are summary considerations from recent updates to the ecosystem and socioeconomic indicators evaluated for GOA Pacific cod:

Acceptable Biological Catch (ABC) Information:

- No marine heatwave events but habitat suitability was again slightly lower than average due to slightly warmer than average temperature at depth, which may have a small effect on egg survival.
- Annual eddy kinetic energy was slightly below average so far in 2024, implying reduced larval retention and cross-shelf transport to suitable nearshore nursery environments.
- Reproductive success of piscivorous seabirds has remained above average since 2017 suggesting sufficient forage fish prey resources.
- Nearshore abundance of young-of-the-year (YOY) Pacific cod increased slightly to just below average.
- Evidence of time-varying natural mortality for age-1 Pacific cod within the Climate- Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics (CEATTLE) multispecies model that has been consistently above the operational stock assessment model estimate.
- Predation demand of GOA Pacific cod for prey based on the CEATTLE model has been steadily decreasing since 1990 and has been below average since 2002, reflecting decreasing population trends of GOA Pacific cod.
- Biomass consumed of GOA Pacific cod as prey by all predators in the CEATTLE model remains low reflecting the lower population trends of predators in the CEATTLE model and low predation from pollock, arrowtooth flounder, and conspecifics.

Total Allowable Catch (TAC) Information:

- Ex-vessel value decreased by 27% from 2022, falling below one-standard deviation of the historical range for the fifth time in the last six years.
- In 2023, ex-vessel price decreased to below the historical average, but remains within one-standard deviation of the historical range and above the 2013 to 2017 average.
- Revenue-per-unit-effort decreased from the historical high recorded in 2022, falling slightly below the historical average but remains within one-standard deviation of the historical range.

Modeling Considerations

The following are the summary results from the most recent intermediate (Shotwell et al., 2023b) and advanced stage ecosystem monitoring analyses for GOA Pacific cod:

- The highest ranked predictors variables of GOA Pacific cod recruitment, based on the importance methods in the intermediate stage indicator analysis were the GOA summer bottom temperature, and the annual eddy kinetic energy in the Kodiak area (inclusion probability > 0.5).
- New project evaluating several temperature metrics at depth to investigate environmental linkages to growth, recruitment, and natural mortality for GOA and eastern Bering Sea Pacific cod, results used for guiding future ecosystem linked alternative operational models.

Assessment

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) and economic performance (Table 2.1.1). Please refer to the last full ESP document (Shotwell et al., 2021a) for more details.

Indicator Suite

The following list of indicators for GOA Pacific cod is organized into categories: three for ecosystem indicators (larval to YOY, juvenile, and adult) and three for socioeconomic indicators (fishery informed, economic, and community). The indicator name and short description are provided in each heading. For ecosystem indicators, we include the proposed sign of the overall relationship between the indicator and a stock assessment parameter of interest (e.g., recruitment, natural mortality, growth), where relevant, and specify the lag applied if the indicator was tested in the ecosystem intermediate stage indicator analysis (see section below for more details). Each indicator heading is followed by bullet points that provide information on the contact and citation for the indicator data, the status and trends for the current year, factors influencing those trends, and implications for fishery management. The following nomenclature was used to describe these indicators:

- “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 2.1.2 for any value within 1 standard deviation of the mean.
- “High” or “Low”: Used 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).

This update focuses on new developments since the last ESP (Shotwell et al., 2023b). For detailed information regarding these ecosystem and socioeconomic indicators and the proposed mechanistic linkages for GOA Pacific cod, please refer to the previous ESP documents (Shotwell et al., 2021-2023b). Time series of these indicators are provided in Figure 2.1.2a (ecosystem indicators) and Figure 2.1.2b (socioeconomic indicators).

The full ESP process evaluates the indicator suite as a whole when the ESP is first created (Shotwell et al., 2023a). Report card documents maintain all these indicators but may require some modifications each year to ensure delivery of the best scientific information available.

New indicators in the 2024 suite include:

- Age-1 GOA Pacific cod time-varying natural mortality (M1+M2) estimated by the CEATTLE multispecies model.

- Annual ration of age 1+ GOA Pacific cod from the most recent CEATTLE multispecies model (Adams et al., 2024) as an estimate of bioenergetic requirements.
- Biomass of GOA Pacific cod consumed (or eaten as prey) by all predators in the CEATTLE multispecies model (Adams et al., 2024) as an estimate of predation from primary predators.

Modified indicators include:

- Updates to the length cutoff between adults and juveniles in the condition indicators to match the cutoff between subadults and adults (from 42 cm to 50.3 cm) that was used for the 2022 EFH 5-year review (accepted by the Council in 2023).
- Truncated the time series of the condition indicators to 1990-2023 to match the groundfish assessment program's standardized survey time series.

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

Removed indicators:

- Chlorophyll *a* derived indicators (concentration and peak timing of the spring bloom) were temporarily removed due to a product discrepancy that requires further evaluation.
- Summer euphausiid abundance indicator was removed because we have not had updates for this indicator since 2019 and do not anticipate future updates.
- Arrowtooth flounder total biomass was removed because it was replaced with information from the CEATTLE multispecies model regarding the biomass of GOA Pacific cod consumed as prey by all predators within the multispecies model (arrowtooth flounder, pollock, Pacific cod, and Pacific halibut) (Adams et al., 2022).

Ecosystem Indicators:

1. Larval to YOY Indicators (Figure 2.1.2a.a-g)

a. Spawning Heatwave GOA Model: 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. Proposed sign of the relationship to recruitment is negative.
    - Contact: Steve Barbeaux
    - Status and trends: Marine heatwave events are historically absent but have increased in the decade at the central GOA spatial scale. Large events have occurred in 1998, 2003, 2015-2016, and 2019, but have decreased in recent years. There were no heatwave events so far in 2024.
    - 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. Winter Spring Pacific Cod Spawning Habitat Suitability GAK1 Model: Spawning habitat suitability index, 1994 to present. 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). While GAK-1 is located in the central GOA, it broadly represents interannual variation in thermal conditions across the central and western GOA shelf. Proposed sign of the relationship to recruitment is positive and the time series is not lagged for the intermediate stage ecosystem monitoring analysis (see details below).
    - Contact: Lauren Rogers
    - Status and trends: Spawning habitat suitability was slightly lower than the long-term average in 2020 and 2021. In 2022, habitat suitability improved, and was higher than in any year since 2012, due to colder conditions at depth in the GOA. In 2023, habitat suitability was near average and decreased in 2024 to below average.
    - 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 2024 were slightly warmer at depth than 2022 and 2023, which may have a small 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 2020, conditions have improved and spawning habitat suitability has increased. Future warming may impact GOA Pacific cod through impacts on this thermally-sensitive early life stage.

c. Annual Eddy Kinetic Energy Kodiak Satellite: 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). 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 2024. Note while an "annual average" is computed for 2024, data is 2024 is only available up to August 23, 2024, so it is not a full year's average. Proposed sign of the relationship to recruitment is positive and the time series is not lagged for the intermediate stage indicator analysis.
    - Contact: Wei Cheng
    - Status and trends: The annual EKE near Kodiak in 2024 is close to its long-term (1994-2024) average of 126.9, similar to annual EKE level in 2023, 2017, 2006, 2005, 2002 and 2000.
    - Factors influencing trends: In the eastern Gulf of Alaska, interannual changes in surface winds (related to the Pacific Decadal Oscillation, El Niño, 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. Summer Large Copepod Abundance Shelikof Survey: 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 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) pollock and other groundfishes in summer. In 2023 timeseries were revised to standardize by gear type. This indicator is only updated on odd years due to the biennial sampling schedule of the EcoFOCI late-summer surveys. The proposed sign of the relationship to recruitment is positive.

- Contact: Lauren Rogers
- Status and trends: Late summer, large copepod abundance declined from the early 2000s until the marine heatwave of 2014-2016. In 2023, large copepod numbers were similar to recent years and slightly higher than the marine heat wave years.
- 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. Both are principal diet items for juvenile fish and these numbers appear to indicate adequate forage.

e. Spring Pacific Cod CPUE Larvae Shelikof Survey: 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. In 2023, the EcoFOCI survey was truncated due to vessel staffing, resulting in only partial coverage of the core survey area. Hence, 2023 estimates have greater uncertainty (see Rogers and Axler 2023 ESR Contribution). This indicator is only updated on odd years due to the biennial sampling schedule of the EcoFOCI spring surveys. The proposed sign of the relationship to recruitment is positive.

- Contact: Lauren Rogers
- Status and trends: Abundance of Pacific cod larvae has been low in recent survey years (2021, 2019), similar to the low catches observed during the marine heatwave in 2015. In 2023, Pacific cod abundance increased from 2021 but remained below the long-term mean. Catches were higher to the SW of the core sampling area.
- Factors influencing trends: With temperature conditions in 2023 being consistent with an “average” to “cool” climate year, we expected to observe increased abundances of Pacific cod relative to recent heatwave years.
- 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 2023, abundance of walleye pollock and Pacific cod larvae were again low, suggesting another poor year class, although abundances may have been higher outside the surveyed region. The low abundance of gadid larvae, combined with low to average abundance of the other indicator species, suggests poor to average forage for piscivorous predators, including seabirds, who rely on larval and juvenile fish.

f. Annual Common Murre Reproductive Success Chowiet Survey: 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 are collected by the Alaska Maritime National Wildlife Refuge staff, U.S. Fish and Wildlife Service (Higgins et al., 2018). Proposed sign of the relationship to recruitment is positive.
    - Contact: Stephani Zador
    - Status and trends: The common murre reproductive success on Chowiet was at a historic low in 2015 consistent with the drop in spawning biomass for this stock, but has recovered to very high success since 2017.
    - 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 to YOY fish productivity, such as Pacific cod, in the region and this could be detected in the subsequent reproductive success of the seabirds.

g. Summer Pacific Cod CPUE YOY Nearshore Kodiak Survey: Summer Pacific cod CPUE of YOY was estimated using the 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 2018-21 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 two 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 from shore, 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). Proposed sign of the relationship to recruitment is positive.
    - Contact: Ben Laurel
    - Status and trends: Age-0 Pacific cod numbers are annually variable in the nearshore but showed steep declines during marine heatwave period (2014-26; 2019). Pacific cod numbers have been notably higher since 2016 in non-heatwave years, with the 2006, 2012, and 2020 year class being the highest observed on record. 2024 estimates were slightly higher than 2023, both years estimated as below average.

- 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>2. Juvenile Indicators (Figure 2.1.2a.h-j)</u>

h. Pacific Cod Predation Mortality Age1 GOA Model: 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). Proposed sign of the relationship to recruitment is negative.
    - Contact: Grant Adams
    - Status and trends: Age-1 natural mortality for GOA Pacific cod peaked in 2005, steadily decreased to a low in 2014 and has since fluctuated below the long-term mean but has been near average since 2022. The 2024 value of 0.69 yr-1 is a slight decrease from 2023 and above the single species stock assessment value of 0.492 yr-1, but is still below the long-term average of 0.7 yr-1.
    - 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.

i. Summer Temperature Bottom GOA Model: 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 (contact: see Hulson et al., 2023 for more details regarding the index creation). Data available from 1979 to present. Proposed sign of the relationship to recruitment is negative and the time series is not lagged for the intermediate stage ecosystem monitoring analysis (see details below).
    - Contact: Muyin Wang
    - Status and trends: Estimates are highly variable over the time series, but the recent warm period from 2015-2019 seems to have cooled at depth (with the exception of 2022) and is slightly below average in 2024.
    - 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 deposition.

j. Summer Pacific Cod Condition Juvenile GOA Survey: Summer stratum-biomass weighted morphometric condition of juvenile (<50 cm) Pacific cod. The length cutoff between adult and juvenile Pacific cod was revised this year to match the cutoff between subadult (included under the definition of juveniles for this indicator) and adult Pacific cod used to define Essential Fish Habitat (EFH) for the 2022 EFH five-year review. The previous definition was based on the beginning of the ascending limb of the maturity curve from Stark (2007), while the updated definition is based on L50 (also from Stark). Morphometric condition was estimated using residuals of a length-weight regression fit to individual length-weight measurements collected during AFSC/RACE Gulf of Alaska bottom trawl surveys from 1990 to 2023. This indicator is only updated on odd years due to the biennial sampling schedule of the summer bottom trawl survey in the GOA. Proposed sign of the relationship to recruitment is positive.

- Contact: Sean Rohan
- Status and trends: The condition of juvenile Pacific cod in the GOA in 2023 was near average, similar to 2019 and 2021. The condition of juveniles fluctuated around average for the majority of the time series aside from above average condition in 1990 and below average condition years in 2015 and 2017.
- 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 2023. 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 2023 Gulf of Alaska Ecosystem Status Report (O'Leary and Rohan, 2023).
- 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). Below average condition suggests that juvenile Pacific cod were not able to find sufficient prey resources.

3. <u>Adult Indicators (Figure 2.1.2a.k-p)</u>

k. Summer Pacific Cod Condition Adult GOA Survey: Summer stratum-biomass weighted morphometric condition of adult (>=50 cm) Pacific cod. The length cutoff between adult and juvenile Pacific cod was revised this year to match the cutoff between subadult (included under the definition of juveniles for this indicator) and adult Pacific cod used to define Essential Fish Habitat (EFH) for the 2022 EFH five-year review. The previous definition was based on the beginning of the ascending limb of the maturity curve from Stark (2007), while the updated definition is based on L50 (also from Stark). Morphometric condition was estimated using residuals of a length-weight regression fit to individual length-weight measurements collected during AFSC/RACE Gulf of Alaska bottom trawl surveys from 1990 to 2023. This indicator is only updated on odd years due to the biennial sampling schedule of the summer bottom trawl survey in the GOA. Proposed sign of the relationship to recruitment is positive.

- Contact: Sean Rohan
- Status and trends: The condition of adult Pacific cod in the GOA in 2023 was average, which continues the trend of neutral condition observed since 2017. Adult condition has shown a declining trend from 2017 to 2023. Adult condition generally fluctuated around average for the majority of the time series except for above average condition in 1990 and below average condition in 2003, 2005, and 2015.
- 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 2023. 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 2023 Gulf of Alaska Ecosystem Status Report (O'Leary and Rohan, 2023).
- Implications: In the Gulf of Alaska, elevated temperatures during the 2014â€“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). Average condition suggests that adult Pacific cod were able to find sufficient prey resources.

l. Annual Ration Pacific Cod GOA Model: 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). Proposed sign of the relationship to recruitment is negative.
   - Contact: Grant Adams
   - Status and trends: Annual predation demand (ration) has been steadily decreasing for GOA Pacific cod since 1990, and has remained below average since 2002. There was a slight increase in 2024 from 2023.
   - 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.

m. Summer Pacific Cod Center Gravity Northeast WCGOA Model: The rotated center of gravity calculation was configured 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 walleye pollock. This metric characterizes the rotated axis that is approximately parallel to the continental shelf and is reported in km. Catch and effort data from the GOA groundfish bottom trawl survey were used to calculate this metric. This indicator is only updated on odd years due to the biennial sampling schedule of the summer bottom trawl survey in the GOA. Proposed sign of the relationship to recruitment is negative.
   - Contact: Zack Oyafuso
   - Status and trends: The center of gravity for WCGOA Pacific cod shifted slightly northeast compared to 2021.
   - Factors influencing trends: The slight northeastern shift in the center of gravity is current with a decrease in the effective area occupied and a slight increase in the design-based 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.

n. Summer Pacific Cod Area Occupied WCGOA Model: The effective area occupied is the area required to contain a population given its average density. The spatial domain is the WCGOA. This metric is reported in log-km2. Catch and effort data from the GOA groundfish bottom trawl survey were used to calculate this metric. This indicator is only updated on odd years due to the biennial sampling schedule of the summer bottom trawl survey in the GOA. Proposed sign of the relationship to recruitment is positive.
   - Contact: Zack Oyafuso
   - Status and trends: The estimated effective area occupied for WCGOA Pacific cod moderately decreased from 2021.
   - Factors influencing trends: The large expansion of effective area occupied is concurrent with an increase in the design-based estimate of total GOA Pacific cod biomass.
   - Implications: The decrease in the effective area occupied in 2023 implies a slightly contracted spatial distribution covered by Pacific cod in the GOA relative to the 1990-2023 time series. Changes in the distributional characteristics of marine populations may impact the spatial distributions of fishing activities and trophic interactions.

o. Annual Biomass Consumed Pacific Cod GOA 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). Proposed sign of the relationship to recruitment is negative.
   - Contact: Grant Adams
   - Status and trends: Estimates of total biomass consumed of Pacific cod as prey across all ages steadily decreased from 2007 to very low values during the marine heatwave events but increased slightly in 2022 but is currently below average.
   - 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.

p. Annual Steller Sea Lion Adult GOA Survey: Steller sea lion non-pup estimates for the GOA portion of the western Distinct Population Segment. Proposed sign of the relationship to recruitment is negative and the time series is lagged two years for the intermediate stage ecosystem monitoring analysis (see details below).
   - Contact: Katie Sweeney
   - Status and trends: Significant declines occurred in the 1990s through early 2000s but the population has been increasing over the past decade to high levels since 2014.
   - 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:

<u>1. Fishery Informed Indicators</u>

Information on fishery catch-per-unit-effort and other fishery-informed indicators is included within the main SAFE document (Hulson et al., 2024) and is not repeated here.

<u>2. Economic Indicators</u>

a. Annual Pacific Cod Real Ex-vessel Value GOA Fishery: Annual estimated real ex-vessel value measured in millions of dollars and inflation adjusted to 2023 USD.
   - Contact: Russel Dame
   - Status and trends: The ex-vessel value of GOA P. Cod has declined, on average, between 2011 and 2020 with a moderate increase in 2021 and 2022. In 2023, ex-vessel value decreased by 27% to $18 million. This caused the ex-vessel value to fall below the first standard deviation of the historical range for 5 of the past 6 years.
   - Factors influencing trends: In 2016, total catch of GOA P. Cod declined significantly, remaining below the historical average through 2023. The average price per-pound, however, increased during the same time period, but the reduction in catch outweighed the increase in price causing ex-vessel revenue to remain below one-standard deviation since 2018 (excluding 2022). In 2023, total catch and the average price per pound decreased, causing ex-vessel revenue to decline.
   - Implications: Reductions in ex-vessel value, due to reductions in total catch, may cause vessels to expend more effort targeting P. Cod to increase catch and capture the value from higher ex-vessel prices (compared to the 2013 through 2017 average). This may be associated with the decrease in revenue per unit effort recorded in 2023.

b. Annual Pacific Cod Real Ex-vessel Price GOA Fishery: Average real ex-vessel price per pound of GOA Pacific cod measured in millions of dollars and inflation adjusted to 2023 USD.
   - Contact: Russel Dame
   - Status and trends: The average ex-vessel price per pound decreased by 11% in 2023 to slightly less than the historical average, but remains within one standard deviation of the historical range. The average price per pound has remained within or above one-standard deviation of the historical range since 2011.
   - Factors influencing trends: Declines in the ex-vessel price in 2023 is related to decreases in the first-wholesale price per pound for H&G and fillet product forms (Table 2.1.1b). As the first-wholesale price declines, the price paid to vessels from processors may also decline.
   - Implications: The average ex-vessel price remains within the historical range and greater than 2013 through 2017 average. Despite the slight decline in prices in 2023, sustained prices greater than the long-term average may incentivize vessels to enter the fishery and target P. Cod. This is partially supported by the increase in the number of active vessels each year since 2020 (Table 2.1.1a).

c. Annual Pacific Cod Real Revenue Per Unit Effort GOA Fishery: Annual estimated real revenue per unit effort measured in weeks fished and inflation adjusted to 2023 USD.
   - Contact: Russel Dame
   - Status and trends: The revenue per unit effort of GOA P. Cod decreased significantly from the historical high in 2022, but remains near the historical mean and within the one-standard deviation of the historical range.
   - Factors influencing trends: TBD
   - 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. Alternatively, we may see vessels increase effort further to capture the value associated with relatively higher ex-vessel prices. This might reduce the revenue per-unit effort further in 2024.

<u>3. Community Indicators</u>

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 Monitoring Analysis

Ecosystem and socioeconomic indicators are monitored through distinct workflows, depending on the management decisions they are intended to inform. These workflows are defined for each indicator suite in the following sections.

Ecosystem Monitoring

Ecosystem indicators undergo up to three stages of statistical analysis (beginning, intermediate, and advanced) to monitor their impact on stock health (Shotwell et al., 2023a). The beginning stage is a relatively simple evaluation by traffic light scoring. 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 intermediate stage uses importance methods related to a stock assessment parameter of interest (e.g., recruitment, growth, catchability). These regression techniques provide a simple 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 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.

<u>Beginning Stage: Traffic Light Test</u>

The scores are summed by the ecosystem indicator categories and divided by the total number of indicators available in that category for a given year (see Shotwell et al., 2023b for method details). The ecosystem scores over time provide a history of stock productivity and comparison of indicator performance (Figure 2.1.3). We also provide a five-year indicator status table with a color for the relationship with the stock (Table 2.1.2).

Overall, the ecosystem indicators score in 2024 increased from the previous year to above average (Figure 2.1.3, black line). By category, the larval indicators increased from average to above average, juvenile and adult indicators remained average (Figure 2.1.3, green, blue, and purple lines). We note caution when comparing scores between odd to even years as there are many indicators missing in even years due to the off-cycle year surveys in the GOA. Also, there have been other cancellations due to COVID-19 and continuing issues with staffing of NOAA white ships since 2020 that have resulted in delayed or canceled surveys, reductions in survey sampling coverage and resolution, increased uncertainty in survey results, and increased costs/reduced efficiency for surveys. This has limited production and delivery timing of several indicators.

<u>Intermediate Stage: Importance Test</u>

Bayesian adaptive sampling (BAS) was used to quantify the association between hypothesized ecosystem predictors and GOA Pacific cod recruitment estimated in the operational stock assessment, and to assess the strength of support for each hypothesis (see Shotwell et al., 2023b for methods details). We provide the mean relationship between each predictor variable and the estimates of GOA Pacific cod recruitment over time (Figure 2.1.4, top left), with error bars describing the uncertainty (95% confidence intervals) in each estimated effect and the marginal inclusion probabilities for each predictor variable (Figure 2.1.4, top right). We also provide model predicted fit (1:1 line, Figure 2.1.4, bottom left) and average fit across the recruitment time series subset (1994-2019, Figure 2.1.4, bottom right). 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 the most recent BAS analysis (Shotwell et al., 2023b) were the summer bottom temperature from the CFSR model (inclusion probability = 0.97), and the annual eddy kinetic energy in the Kodiak area (inclusion probability = 0.53) (Figure 2.1.4). The direction of these effects were consistent with the proposed overall relationship with recruitment. These indicators are marked with an asterisk (*) in Table 2.1.2 and may assist with evaluation of the indicator suite within the risk table.

Many indicators were removed from the BAS analysis due to limitations around missing data, collinearity, and short time series. Incorporating additional importance methods in this intermediate stage indicator analysis may be useful for evaluating the full suite of indicators and address potential nonstationarity and missing observations of the current indicators suite. This may allow for identifying more robust indicators for potential use in the operational stock assessment model. We plan to explore additional importance techniques in future ESP report cards.

Advanced Stage: Research Model Test

Several research ecosystem models have been developed or are being developed for GOA Pacific cod. We provide a short description of those current or proposed models along with citations where relevant.

The multispecies statistical catch-at-age assessment CEATTLE model (Holsman et al., 2016) was recently developed for understanding trends in total mortality for Pacific cod, Pacific halibut, walleye pollock, and arrowtooth flounder from the GOA (Adams et al., 2022; Adams et al., 2023). Total mortality rates are based on estimates of residual mortality estimates (M1), time- and age-varying predation mortality (M2), and time- and age-varying 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., 2024, Monnahan et al., 2024, and Adams and Shotwell, 2024). 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 temperature- and bioenergetics-based consumption information and diet data from the GOA to inform predator-prey suitability. The model was fit to data from 1977 to present and has a similar trend as the single species model with slightly higher estimates overall years (Figure 2.1.5, Adams et al., 2024). The age-1 mortality index could provide a gap free estimate of predation mortality; 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.

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 ROMS 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.

For several years, the stock assessment authors for GOA Pacific cod have been exploring linkages between CFSR predicted bottom temperatures and time varying catchability and growth. The authors and collaborators began a two-year project in late 2023 that is investigating environmental linkages to growth, recruitment, and natural mortality for GOA and eastern Bering Sea Pacific cod (K. Oke, pers. commun.). As a first step, the project is evaluating several metrics of temperature at depth, to serve as potential replacements for the CFSR estimated temperature at depth metric currently included in the assessment model as an environmental link on catchability in the longline survey. Temperature at different depths, spatial scales, and times of year are also being explored, in addition to several related potential ecosystem indicators that reflect ocean conditions in the GOA. Results from this project will be used as guidance for alternative operational models in future assessments.

Socioeconomic Monitoring

Ex-vessel value decreased by 27% in 2023 to $18.4 million, remaining below the 2014 to 2018 average of $39 million. The decline in ex-vessel value from historical levels is due to significant declines in retained catch. Between 2014 and 2018, retained catch averaged 56 thousand mt. In 2023, retained catch declined 65% from the 2014 to 2018 average to 19.7 thousand mt. With decreases in retained catch, the average price per pound increased from $0.31 between 2014 to 2018 to $0.42 in 2023 (Table 2.1.1a). Similarly, with declines in total catch, the first-wholesale volume of GOA Pacific cod declined in 2023 to 7.6 thousand mt from the 2014 to 2018 average of 21.5 thousand mt. Reductions in supply did have a positive impact on the average first-wholesale price per pound, increasing from an average of $1.77 between 2014 and 2018 to $2.97 in 2023. The reductions in first-wholesale volume outweighed the increase in price as the first wholesale value decreased to $50 million in 2023, a 40% decline from the 2014 to 2018 average of $84 million. Pacific cod is primarily processed into head & gut and fillets. Unlike the BSAI, the value share of fillets is the dominant product form in GOA, representing two-thirds of first-wholesale value in 2023. The volume of Pacific cod processed to H&G and fillets has declined with retained catch, but the volume processed into H&G has declined more rapidly. As of 2022, more GOA Pacific cod is processed into fillets than H&G (Table 2.1.1b).

Similar trends are being seen in the global production of Pacific cod. Global production of Pacific cod has declined to approximately 1.5 million mt in 2022 from the 2014 to 2018 average of approximately 1.8 million mt (-7%). In 2023, export volume and value of Alaskan Pacific cod has declined from the 2014 to 2018 average of 98 thousand mt and $302 million to 45 thousand mt and $159 million. A majority of Alaskan Pacific cod exports go to Asian markets, primarily China and Japan, representing two-thirds of volume and value historically (Table 2.1.1c). Recent trends in Asian exports, however, suggest that less than one-half of Pacific cod export volume and value now go to Asian markets. This may be associated with the increased Chinese trade tariffs in 2023 against U.S. seafood and recent reports that state Russian export volumes of seafood to China increased by 36.1% from 2022 levels and is on track to increase further in 2024. Although exports to China and Japan are declining, exports to European countries have been increasing since 2021. 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 (Table 2.1.1c).

Data Gaps and Future Research Priorities

While current indicator assessments offer a valuable set of proxy indicators, 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. For more details, please refer to previous ESP documents (Shotwell et al., 2021-2023b).

Ecosystem Priorities

- Development of high-resolution remote sensing (e.g., regional surface temperature, transport estimates, primary production estimates) or climate model indicators (e.g., bottom temperature, nutrient-phytoplankton-zooplankton variables) to assist with the current multi-year data gap for many indicators.
- Refinements or updates to current indicators (e.g., chlorophyll *a*) that were only partially specialized for GOA Pacific cod such as more specific phytoplankton indicators tuned to the spatial and temporal distribution of GOA Pacific cod larvae as well as phytoplankton community structure information (e.g., hyperspectral information for size fractionation).
- 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.
- 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.
- Evaluation of climate-driven changes in size and age and how that may impact survival trajectories of YOY cohorts and their potential to recruit to the fishery.
- 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. Measures of YOY body condition during the fall may provide an indication of overwintering success (Abookire et al. 2024).
- 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 climate 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 December 2022 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).

Acknowledgements

We would like to thank all the contributors for their timely response to requests and questions regarding their data, report summaries, and manuscripts. We thank the staff of the survey programs for rapid turnaround of data to facilitate timely uptake and incorporation into this document. We also thank the reviewers of this report (Katharine Miller), the Groundfish Plan Teams, and the SSC for their helpful insight on the development of this report and future reports. We would also like to thank the AFSC personnel and divisions, the Alaska Regional Office, the Pacific Marine Environmental Laboratory, the Southwest Fisheries Science Center CoastWatch Program, and the Alaska Maritime National Wildlife Refuge for their data contributions. We thank the Alaska Fisheries Information Network and neXus Data Solutions teams for their extensive help with data management and processing for this report. Finally, we thank Dr. Abigail Tyrell for her tireless assistance with debugging code to link the data management system and the automated reports.

Literature Cited

Abookire, A. A., J. T. Duffy-Anderson, and C. M. Jump. 2007. Habitat associations and diet of young-of-the-year Pacific cod (*Gadus macrocephalus*) near Kodiak, Alaska. Marine Biology 150:713-726.

Adams, G.D., K.K. Holsman, S.J. Barbeaux, M.W. Dorn, J.N. Ianelli, I. Spies, I.J. Stewart, and A.E. Punt. 2022. An ensemble approach to understand predation mortality for groundfish in the Gulf of Alaska. Fish. Res. 251, 106303. https://doi.org/10.1016/j.fishres.2022.106303.

Adams, G., K.K. Holsman, P. Hulson, C. Monnahan, K. Shotwell, I. Stewart, and A. Punt. 2024. Multispecies model estimates of time-varying natural mortality in the GOA. *In* Ferriss, B., 2024. Ecosystem Status Report 2024: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 1007 West Third, Suite 400, Anchorage, Alaska 99501.

Alderdice, D. F., and C. R. Forrester. 1971. Effects of salinity, temperature, and dissolved oxygen on early development of Pacific cod (*Gadus macrocephalus*). Journal of the Fisheries Research Board of Canada 28:883-891.

Almeida LZ, Laurel BJ, Thalmann H, Miller J. 2024. Warmer, earlier, faster: Cumulative effects of Gulf of Alaska heatwaves on the early life history of Pacific Cod. Elementa: Science of the Anthropocene. https://doi.org/10.1525/elementa.2023.00050

Anderson, S.C., Ward, E.J., English, P.A., and Barnett, L.A.K. 2022. sdmTMB: an R package for fast, flexible, and user-friendly generalized linear mixed effects models with spatial and spatiotemporal random fields. bioRxiv. https://doi.org/10.1101/2022.03.24.485545.

Aydin, K., S. Gaichas, I. Ortiz, D. Kinzey, and N. Friday. 2007. A comparison of the Bering Sea, Gulf of Alaska, and Aleutian Islands large marine ecosystems through food web modeling. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-178, 298 p.

Barbeaux S. J, K. Holsman, and S. Zador. 2020. Marine heatwave stress test of ecosystem-based fisheries management in the Gulf of Alaska Pacific cod fishery. Front. Mar. Sci. 7:703. doi: 10.3389/fmars.2020.00703

Bian, X. D., X. M. Zhang, Y. Sakurai, X. S. Jin, R. J. Wan, T. X. Gao, and J. Yamamoto. 2016. Interactive effects of incubation temperature and salinity on the early life stages of Pacific cod *Gadus macrocephalus*. Deep-Sea Research Part II-Topical Studies in Oceanography 124:117-128.

Cheng, W. 2021. Eddies in the Gulf of Alaska. *In* Ferriss, B., and Zador, S., 2021. Ecosystem Status Report 2021: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 1007 West Third, Suite 400, Anchorage, Alaska 99501.

Copeman, L. A., and B. J. Laurel. 2010. Experimental evidence of fatty acid limited growth and survival in Pacific cod larvae. Marine Ecology Progress Series 412:259-272.

Deary, A., L. Rogers, and K. Axler. 2021. Larval fish abundance in the Gulf of Alaska 1981-2021. *In* Ferriss, B., and Zador, S., 2021. Ecosystem Status Report 2021: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 1007 West Third, Suite 400, Anchorage, Alaska 99501.

Doyle, M. J., and K. L. Mier. 2016. Early life history pelagic exposure profiles of selected commercially important fish species in the Gulf of Alaska. Deep-Sea Research Part II-Topical Studies in Oceanography 132:162-193.

Doyle, M. J., S. J. Picquelle, K. L. Mier, M. C. Spillane, and N. A. Bond. 2009. Larval fish abundance and physical forcing in the Gulf of Alaska, 1981-2003. Progress in Oceanography 80:163-187.

Fissel, B., M. Dalton, B. Garber-Yonts, A. Haynie, S. Kasperski, J. Lee, D. Lew, C. Seung, K. Sparks, M. Szymkowiak, and S. Wise. 2021. Economic status of the groundfish fisheries off Alaska, 2019. *In* Stock assessment and fishery evaluation report for the groundfish resources of the GOA and BS/AI. North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306 Anchorage, AK 99501.

Hinckley S., W. Stockhausen, K.O. Coyle, B.J. Laurel, G.A. Gibson, C. Parada, A.J. Herman, M.J. Doyle, T.P. Hurst, A.E. Punt, and C. Ladd. 2019. Connectivity between spawning and nursery areas for Pacific cod (*Gadus macrocephalus*) in the Gulf of Alaska. Deep Sea Res. Part II. Topical Studies in Oceanography 165:113-126.

Hulson, P., S. Barbeaux, and I. Spies. 2023. Summary of the 2023 Recommended Model Alternatives for Gulf of Alaska Pacific cod. Report presented at the September Gulf of Alaska Groundfish Plan Team. https://meetings.npfmc.org/Meeting/Details/3006

Hurst, T. P., D.W. Cooper, J. S. Scheingross, E. M. Seale, B. J. Laurel, and M. L. Spencer. 2009. Effects of ontogeny, temperature, and light on vertical movements of larval Pacific cod (*Gadus macrocephalus*). Fisheries Oceanography 18:301-311.

Hurst, T. P., B. J. Laurel, and L. Ciannelli. 2010. Ontogenetic patterns and temperature-dependent growth rates in early life stages of Pacific cod (*Gadus macrocephalus*). Fishery Bulletin 108:382-392.

Laurel, J., A. W. Stoner, C. H. Ryer, T. P. Hurst, and A. A. Abookire. 2007. Comparative habitat associations in juvenile Pacific cod and other gadids using seines, baited cameras and laboratory techniques. Journal of Experimental Marine Biology and Ecology 351:42-55.

Laurel, B. J., T. P. Hurst, L. A. Copeman, and M. W. Davis. 2008. The role of temperature on the growth and survival of early and late hatching Pacific cod larvae (Gadus macrocephalus). Journal of Plankton Research 30:1051-1060.

Laurel, B. J., C. H. Ryer, B. Knoth, and A. W. Stoner. 2009. Temporal and ontogenetic shifts in habitat use of juvenile Pacific cod (*Gadus macrocephalus*). Journal of Experimental Marine Biology and Ecology 377:28-35.

Laurel, B. J., T. P. Hurst, and L. Ciannelli. 2011. An experimental examination of temperature interactions in the match-mismatch hypothesis for Pacific cod larvae. Canadian Journal of Fisheries and Aquatic Sciences 68:51-61.

Laurel, B., M. Spencer, P. Iseri, and L. Copeman. 2016. Temperature-dependent growth and behavior of juvenile Arctic cod (*Boreogadus saida*) and co-occurring North Pacific gadids. Polar Biology 39:1127-1135.

Laurel, B. J., D. Cote, R. S. Gregory, L. Rogers, H. Knutsen, and E. M. Olsen. 2017. Recruitment signals in juvenile cod surveys depend on thermal growth conditions. Canadian Journal of Fisheries and Aquatic Sciences 74:511-523.

Laurel, B.J., and L.A. Rogers. 2020. Loss of spawning habitat and pre-recruits of Pacific cod following a Gulf of Alaska Heatwave. Canadian Journal of Fisheries and Aquatic Sciences 77(4):644-650.

Laurel, B. J., Abookire, A., Barbeaux, S. J., Almeida, L. Z., Copeman, L. A., Duffy-Anderson, J., Hurst, T. P., Litzow, M. A., Kristiansen, T., Miller, J. A., Palsson, W., Rooney, S., Thalmann, H. L., & Rogers, L. A. 2023. Pacific cod in the Anthropocene: An early life history perspective under changing thermal habitats. Fish and Fisheries, 00, 1–20. https://doi.org/10.1111/faf.12779.

Laurel, B.J., J. Miller, H. Thalmann, Z. Almeida, and L. Rogers. 2023. Noteworthy: Gulf of Alaska Pacific cod (2017-2023). *In* Ferriss, B., 2023. Ecosystem Status Report 2023: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 1007 West Third, Suite 400, Anchorage, Alaska 99501.

Litzow MA, Abookire A, Duffy-Anderson J, Laurel BJ, Malick MJ, Rogers L. 2022. Predicting year class strength for climate-stressed gadid stocks in the Gulf of Alaska, Fisheries Research. Volume 249: 106250. ISSN 0165-7836, https://doi.org/10.1016/j.fishres.2022.106250.

Miller, J.A., Almeida, L.Z., Rogers, L.A., Thalmann, H.L., Forney, R.M., Laurel, B.J. 2024. Age, not growth, explains larger body size of Pacific cod larvae during recent marine heatwaves. Scientific Reports. 14 (19313). https://doi.org/10.1038/s41598-024-69915-1.

O'Leary, C., Laman, N., Rohan, S. 2021. Gulf of Alaska groundfish condition. *In* Ferriss, B., and Zador, S., 2021. Ecosystem Status Report 2021: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306, Anchorage, AK 99501.

O'Leary, C. & Rohan, S. 2023. Gulf of Alaska Groundfish Condition. *In* Ferriss, B., and Zador, S., 2023. Ecosystem Status Report 2023: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306, Anchorage, AK 99501.

Ormseth, O.A. and B.L. Norcross. 2009. Causes and consequences of life-history variation in North American stocks of Pacific cod. ICES Journal of Marine Science 66(2):349-357.

Piatt, J. F. 2002. Preliminary synthesis: can seabirds recover from effects of the Exxon Valdez oil spill? In Piatt, J.F. (*ed.*), Response of Seabirds to Fluctuations in Forage Fish Density. Final report to Exxon Valdez Oil Spill Trustee Council (pp 132–171; restoration project 00163M) and Minerals Management Service (Alaska OCS Region), Alaska Science Center, United States Geological Survey, Anchorage, Alaska.

Rogers, L.A., and Axler, K. 2023. Larval Fish Abundance in the Gulf of Alaska 1981-2023. In Ferriss, B., and Zador, S., 2023. Ecosystem Status Report 2021: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 1007 West Third, Suite 400, Anchorage, Alaska 99501.

Shotwell, S.K., S. Barbeaux, B. Ferriss, B. Fissel, B. Laurel, B. Matta, L. Rogers, E. Siddon and A. Tyrell. 2021a. Ecosystem and socioeconomic profile of the Pacific cod stock in the Gulf of Alaska. Appendix 2.1 In Barbeaux, S., B. Ferriss, B. Laurel, M. Litzow, S. McDermott, J. Nielsen, W. Palsson, K. Shotwell, I. Spies, and M. Wang. 2021. Assessment of the Pacific cod stock in the Gulf of Alaska. Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska. North Pacific Fishery Management Council, 1007 W 3rd Ave, Suite 400 Anchorage, AK 99501. Pp. 161-226.

Shotwell, K., I. Spies, J.N. Ianelli, K. Aydin, D.H Hanselman, W. Palsson, K. Siwicke, and E. Yasumiishi. 2021b. Assessment of the arrowtooth flounder stock in the Gulf of Alaska. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska. North Pacific Fishery Mngt. Council, 605 W 4th Ave, Suite 306 Anchorage, AK 99501

Shotwell, S.K., P. Hulson, B. Ferriss, B. Laurel, and L. Rogers. 2022. Ecosystem and socioeconomic profile of the Pacific cod stock in the Gulf of Alaska. Appendix 2.1 *In* Hulson, P.J.F., S.J. Barbeaux, B. Ferriss, S. McDermott, and I. Spies. 2022. Assessment of the Pacific cod stock in the Gulf of Alaska. Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska. North Pacific Fishery Management Council, Anchorage, AK 99501. Pp. 112-138.

Shotwell, S.K., K., Blackhart, C. Cunningham, E. Fedewa, D., Hanselman, K., Aydin, M., Doyle, B., Fissel, P., Lynch, O., Ormseth, P., Spencer, S., Zador. 2023a. Introducing the Ecosystem and Socioeconomic Profile, a proving ground for next generation stock assessments. Coastal Management. 51:5-6, 319-352, DOI: 10.1080/08920753.2023.2291858.

Shotwell, S.K., B. Ferriss, P.J.F. Hulson, B. Laurel, B. Matta, and L. Rogers. 2023b. Appendix 2.1 Ecosystem and socioeconomic profile of the Pacific cod stock in the Gulf of Alaska - Report Card. *In* Hulson, P.J.F., S.J. Barbeaux, B. Ferriss, S. McDermott, and I. Spies. 2023. Assessment of the Pacific cod stock in the Gulf of Alaska. North Pacific Fishery Management Council, Available from https://www.npfmc.org/library/safe-reports/.

Shotwell, K., D.H Hanselman, W. Palsson, and B.C. Williams. 2023c. Assessment of the arrowtooth flounder stock in the Gulf of Alaska. North Pacific Fishery Management Council, Anchorage, AK. Available from https://www.npfmc.org/library/safe-reports/.

Shotwell, S.K., W. Stockhausen, G.A. Gibson, J. Pirtle, A. Deary, and C. Rooper. *In Prep*. Developing a novel approach to estimate habitat-related survival rates for early life history stages using individual-based models.

Sinclair, A.F., and Crawford, W.R. 2005. Incorporating an environmental stock-recruitment relationship in the assessment of Pacific cod (*Gadus macrocephalus*). Fisheries Oceanography, 14, 138–150.

Siwicke, K. 2022. Summary of temperature and depth recorder data from the Alaska Fisheries Science Center's longline survey (2005–2021). U.S. Dep. Commer., NOAA Tech. Memo. NMFSAFSC-437, 74 p.

Stark, J. W. 2007. Geographic and seasonal variations in maturation and growth of female Pacific cod (*Gadus macrocephalus*) in the Gulf of Alaska and Bering Sea. Fishery Bulletin 105:396-407.

Strasburger, W. W., N. Hillgruber, A. I. Pinchuk, and F. J. Mueter. 2014. Feeding ecology of age-0 walleye pollock (*Gadus chalcogrammus*) and Pacific cod (*Gadus macrocephalus*) in the southeastern Bering Sea. Deep-Sea Research Part II-Topical Studies in Oceanography 109:172-180.

Thorson, J.T., Pinsky, M.L., Ward, E.J., 2016. Model-based inference for estimating shifts in species distribution, area occupied, and center of gravity. Methods Ecol. Evol. 7(8), 990-1008. doi:10.1111/2041-210X.12567. URL: http://onlinelibrary.wiley.com/doi/10.1111/2041-210X.12567/full

Voesenek, C. J., F. T. Muijres, and J. L. van Leeuwen. 2018. Biomechanics of swimming in developing larval fish. Journal of Experimental Biology 221.

Whitehouse, A. and K. Aydin. 2021. Foraging guild biomass-Gulf of Alaska. *In* Ferriss, B. and Zador, S., 2021. Ecosystem Status Report 2021: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 1007 West Third, Suite 400, Anchorage, Alaska 99501.

Wise, S., S. Kasperski, A. Abelman, J. Lee, M. Parks, and J. Reynolds. 2022. Annual Community Engagement and Participation Overview. Report from the Economic and Social Sciences Program of the Alaska Fisheries Science Center. 98 pp.

Tables

Table 2.1.1a. 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; average and most recent five years.

	2014-2018 Average	2019	2020	2021	2022	2023
Total catch (K mt)	58.48	15.7	6.8	19.2	25.9	21.8
Retained catch (K mt)	56.48	14.45	4.84	16.14	24.18	19.72
Ex-vessel value (M $)	$38.63	$15.74	$4.42	$15.35	$25.11	$18.43
Ex-vessel price ($/lb)	$0.31	$0.49	$0.39	$0.39	$0.47	$0.42
Hook & line share of catch (%)	20.09%	22.64%	19.24%	28.8%	25.56%	31.76%
Pot gear share of catch (%)	53.02%	52.04%	34.56%	43.28%	43.57%	38.87%
Central Gulf share of catch (%)	54.62%	47.23%	71.71%	62.55%	66.41%	65.56%
Shoreside share of catch (%)	90.6%	89.27%	98.55%	98.95%	88.92%	89.2%
Vessels (#)	298.8	183	103	186	206	219

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 2.1.1b. 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; average and most recent five years.

	2014-2018 Average	**2019**	**2020**	**2021**	**2022**	**2023**
All Products volume (K mt)	21.54	7.47	2.97	6.54	9.72	7.58
All Products value (M $)	$83.93	$35.17	$15.03	$35.75	$66.54	$49.57
All Products price ($/lb)	$1.77	$2.14	$2.3	$2.48	$3.11	$2.97
Fillets volume (K mt)	6.53	2.37	1.12	2.7	3.85	3.03
Fillets value share (%)	53.96%	61.1%	67.41%	71.38%	70.4%	66.89%
Fillets price ($/lb)	$3.15	$4.12	$4.09	$4.28	$5.52	$4.96
Head & Gut volume (K mt)	9.89	3.02	1.15	1.69	2.92	2.65
Head & Gut value share (%)	33.9%	24.22%	23.42%	16.16%	17.04%	20.49%
Head & Gut price ($/lb)	$1.3	$1.28	$1.39	$1.55	$1.76	$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 2.1.1c. 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 share (%) for head and gut (H&G), fillets, China, Japan, and Germany and Netherlands; average & most recent 5 years.

	2014-2018 Average	2019	2020	2021	2022	2023
Global cod catch (K mt)	1,761.27	1,574.03	1,498.08	1,530.62	1,457.14	-
U.S. cod share of global catch (%)	16.9%	13.4%	11.5%	9.8%	12.5%	-
Europe Share of global catch* (%)	76%	78.3%	80.5%	82.3%	79.3%	-
Pacific cod share of U.S. catch (%)	99.7%	99.8%	99.7%	99.5%	99.5%	-
U.S. cod consumption (est.) (K mt)	113.765	106.275	103.335	107.366	134.434	95.226
Share of U.S. cod not exported (%)	30.9%	36.8%	45%	53.3%	61.4%	42.2%
Export volume (K mt)	98.36	65.1	44.48	32.51	33.23	45.07
Export value M ($)	$302.01	$217.88	$139.4	$101.67	$104.72	$158.73
Export price ($/lb)	$1.39	$1.52	$1.42	$1.42	$1.43	$1.6
Frozen (H&G) volume share (%)	92.32%	92.31%	92.32%	89.45%	87.86%	91.4%
Frozen (H&G) value share (%)	91.09%	90.71%	89.83%	84.22%	86.02%	89.73%
Fillets volume share (%)	3.45%	4.68%	5.86%	8.72%	10.89%	7.39%
Fillets value share (%)	4.63%	5.84%	7.38%	12.92%	12.14%	8.72%
China volume share (%)	52.63%	41.52%	39.52%	31.36%	47.75%	42.55%
China value share (%)	50.19%	40.21%	37.35%	28.39%	48.14%	39.73%
Japan volume share (%)	14.96%	11.86%	13.04%	10.98%	4.65%	5.83%
Japan value share (%)	16.06%	12.97%	13.89%	11.77%	4.31%	5.66%
Europe volume share* (%)	17.92%	21.6%	20.13%	11.54%	17.17%	22.62%
Europe value share* (%)	19.06%	23.12%	20.69%	10.95%	17.42%	23.93%

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

	2014-2018 Average	2019	2020	2021	2022	2023

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

Table 2.1.2. First stage ecosystem indicator analysis for GOA Pacific cod, including indicator title and the indicator status for the last five years. The indicator status is designated with text, (greater than = “high”, less than = “low”, or within 1 standard deviation = “neutral” of long-term mean). Fill color of the cell is based on the sign of the anticipated 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	2020 Status	2021 Status	2022 Status	2023 Status	2024 Status
Larval to YOY	Spawning Heatwave GOA Model	neutral	neutral	neutral	neutral	neutral
	Winter Spring Pacific Cod Spawning Habitat Suitability GAK1 Model	neutral	neutral	neutral	neutral	neutral
	* Annual Eddy Kinetic Energy Kodiak Satellite	*high*	neutral	**low**	neutral	neutral
	Summer Large Copepod Abundance Shelikof Survey	NA	NA	NA	neutral	NA
	Spring Pacific Cod CPUE Larvae Shelikof Survey	NA	neutral	NA	neutral	NA
	Annual Common Murre Reproductive Success Chowiet Survey	NA	neutral	*high*	neutral	*high*
	Summer Pacific Cod CPUE YOY Nearshore Kodiak Survey	*high*	neutral	neutral	neutral	neutral
Juvenile	Pacific Cod Predation Mortality Age1 GOA Model	*low*	neutral	neutral	neutral	neutral
	* Summer Temperature Bottom GOA Model	neutral	neutral	neutral	neutral	neutral
	Summer Pacific Cod Condition Juvenile GOA Survey	NA	neutral	NA	neutral	NA
Adult	Summer Pacific Cod Condition Adult GOA Survey	NA	neutral	NA	neutral	NA
	Annual Ration Pacific Cod GOA Model	neutral	neutral	neutral	neutral	neutral
	Summer Pacific Cod Center Gravity Northeast WCGOA Model	NA	neutral	NA	neutral	NA
	Summer Pacific Cod Area Occupied WCGOA Model	NA	neutral	NA	neutral	NA
	Annual Biomass Consumed Pacific Cod GOA Model	*low*	*low*	neutral	neutral	neutral
	Annual Steller Sea Lion Adult GOA Survey	**high**	**high**	NA	NA	NA

* Indicator has inclusion probability > 0.5 in the intermediate stage importance test.

Figures

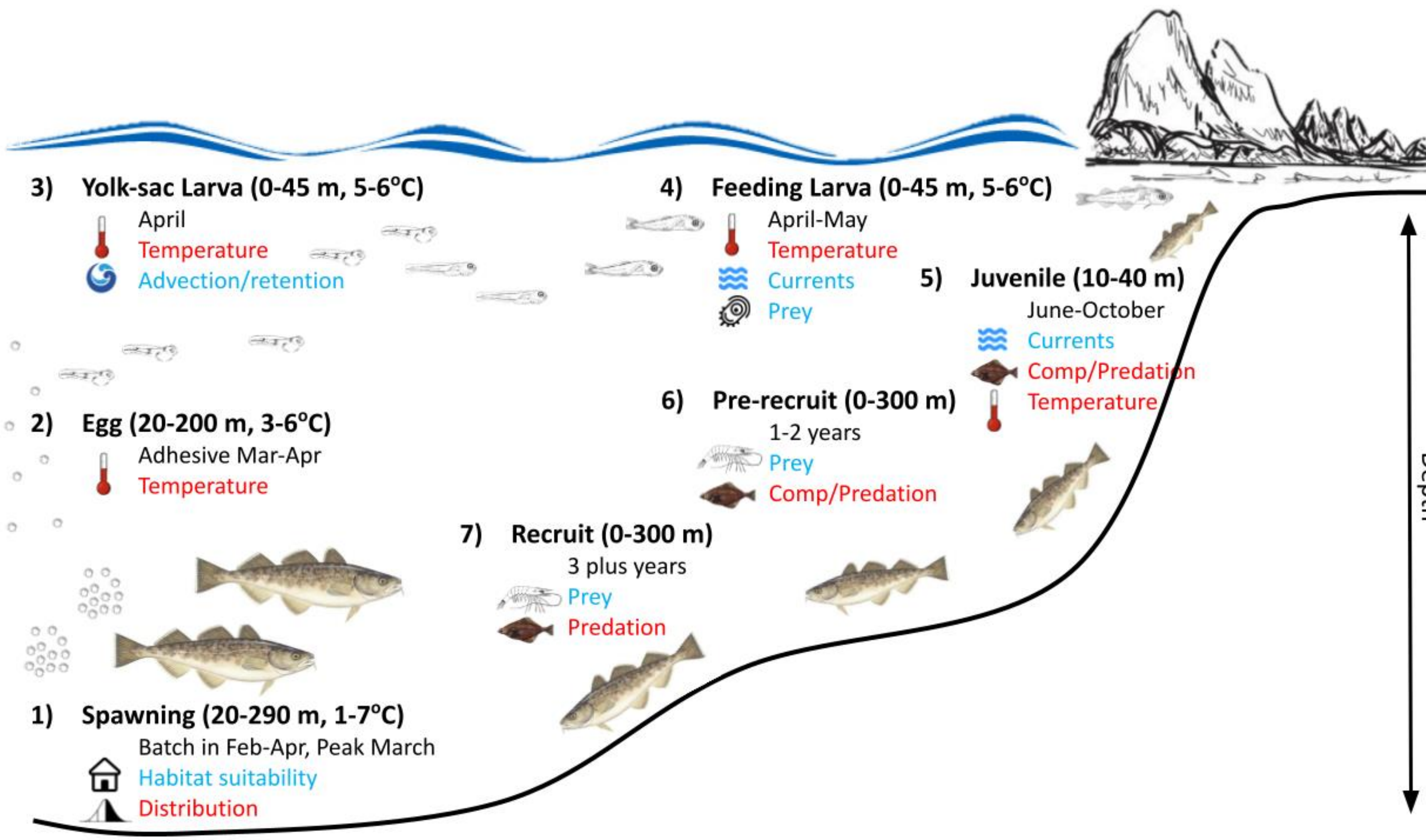

Figure 2.1.1: Life history conceptual model for GOA Pacific cod summarizing ecological information and key ecosystem processes affecting survival by life history stage. Red text means increases in the process negatively affect survival, while blue text means increases in the process positively affect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

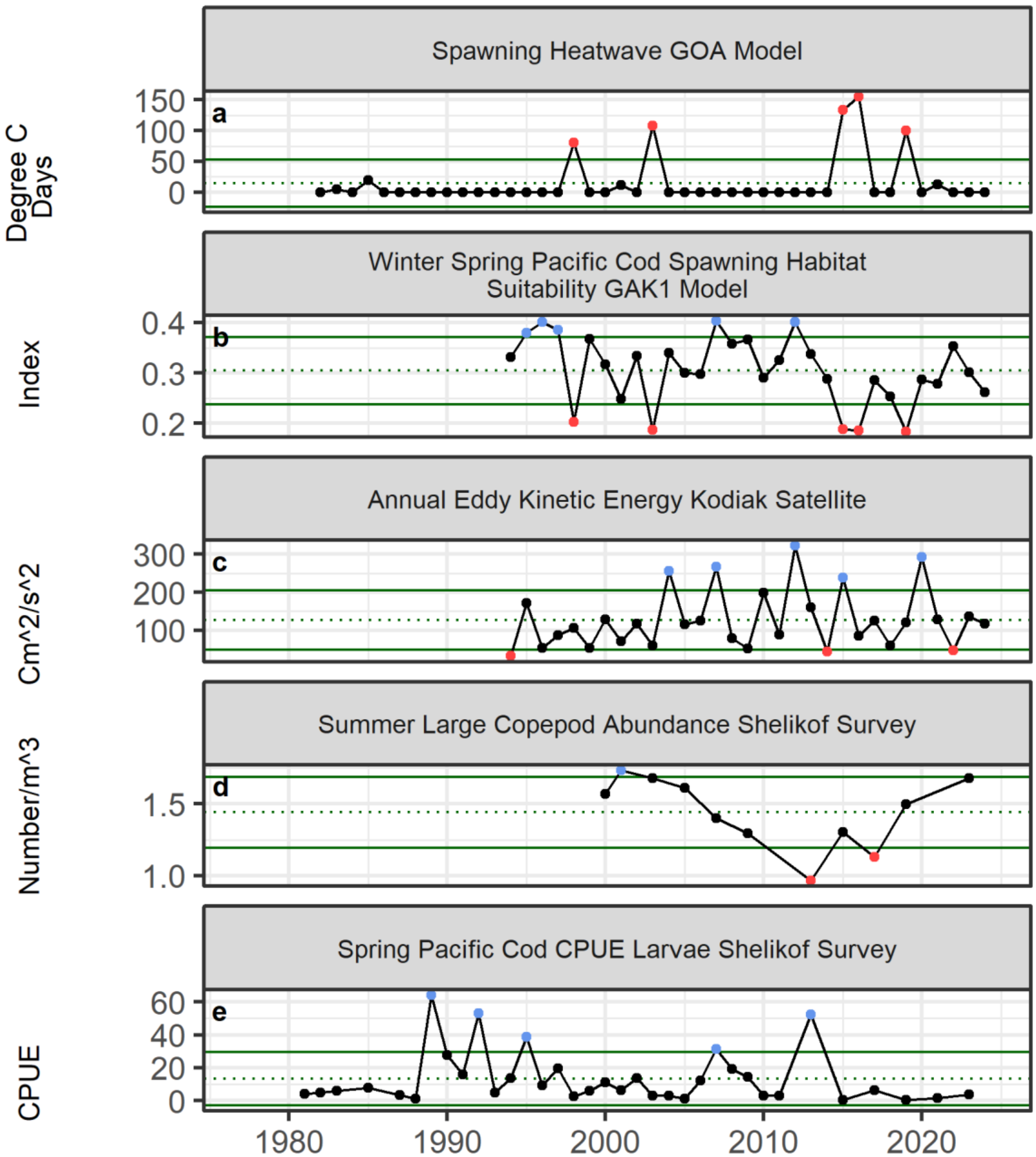

Figure 2.1.2a. Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. Dots in the time series are colored if above or below 1 standard deviation of the time series mean and the color represents the proposed relationship for stock (blue for good conditions, red for poor conditions), black circle for neutral.

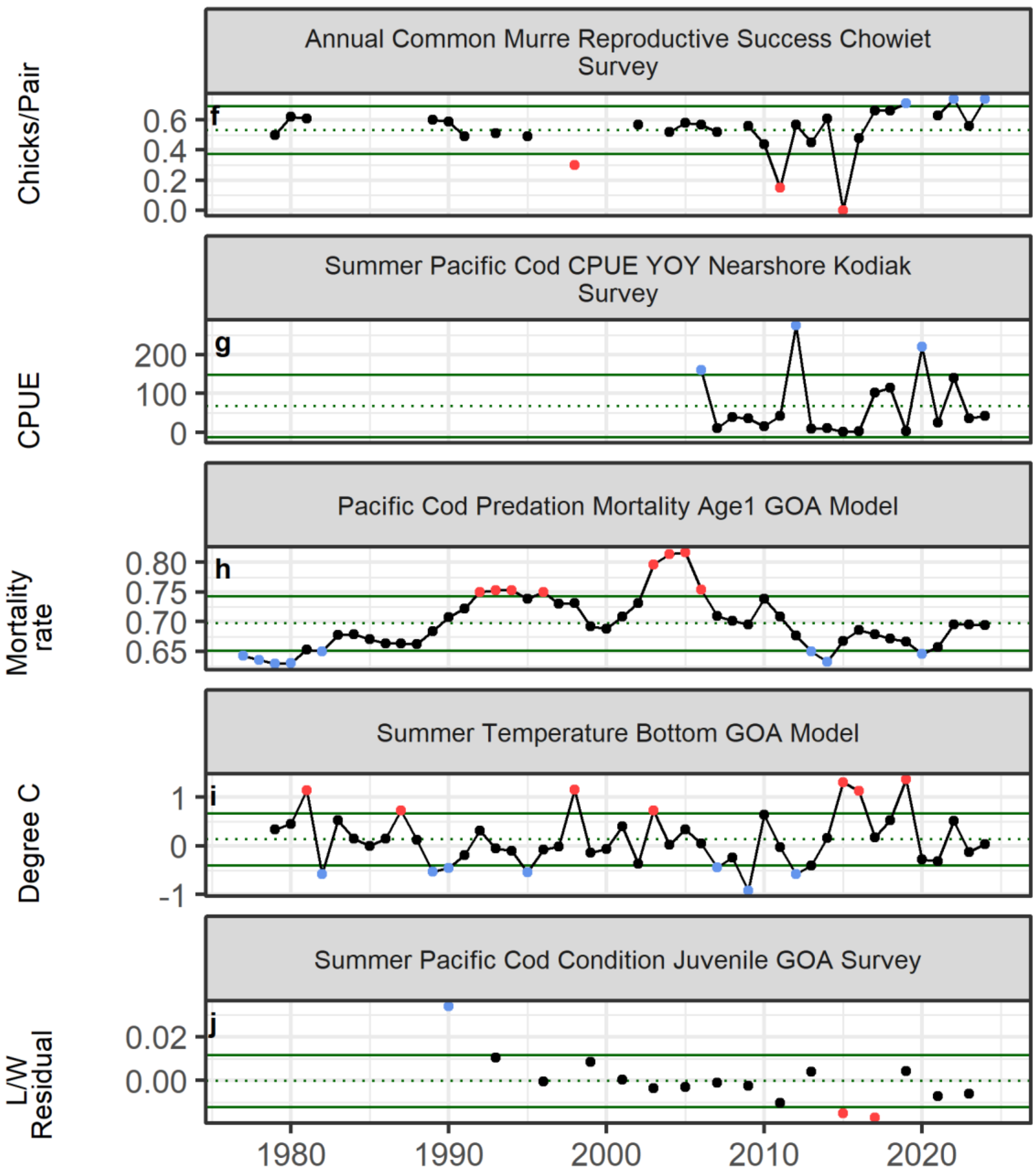

Figure 2.1.2a (cont.). Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. Dots in the time series are colored if above or below 1 standard deviation of the time series mean and the color represents the proposed relationship for stock (blue for good conditions, red for poor conditions), black circle for neutral.

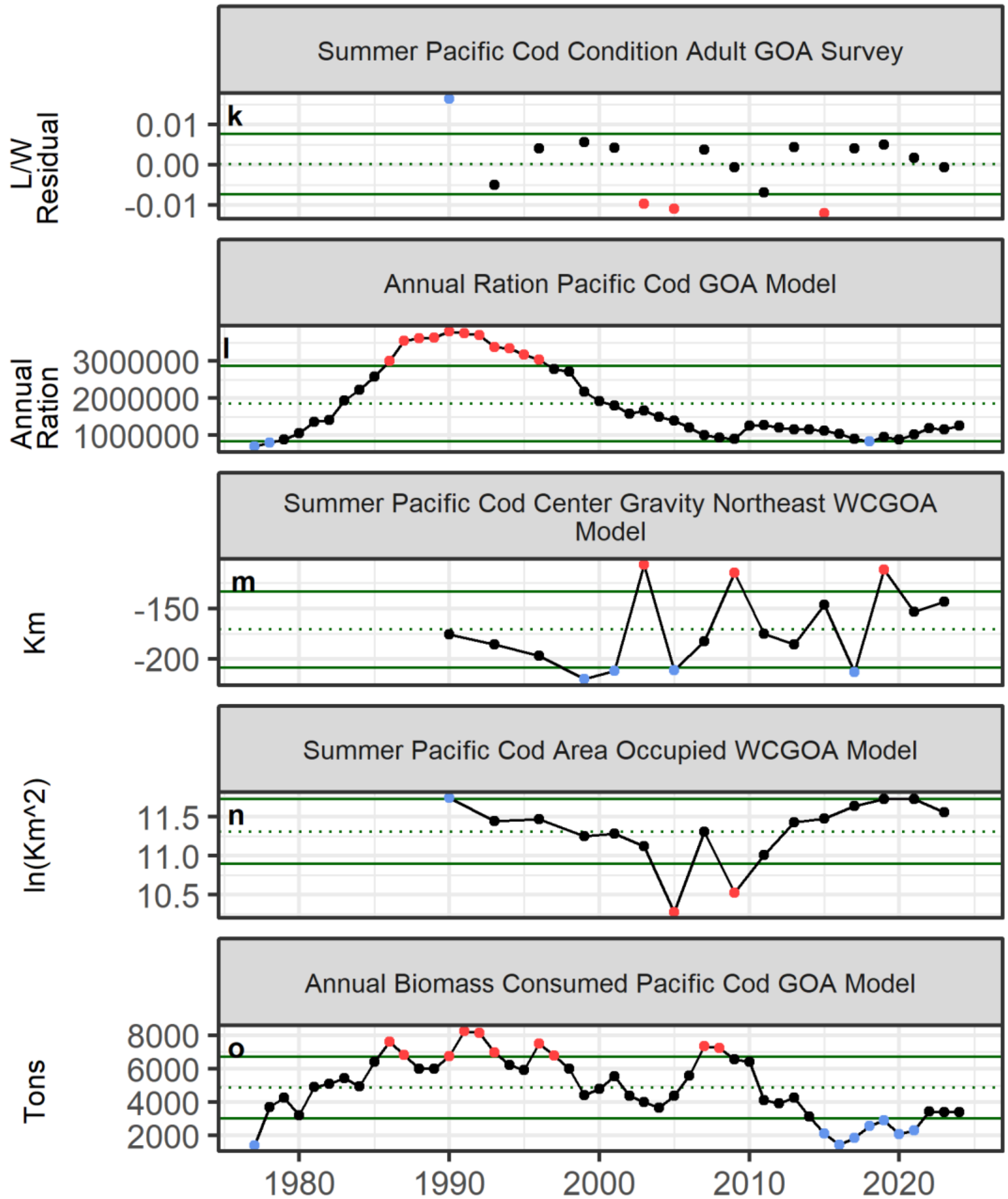

Figure 2.1.2a (cont.). Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. Dots in the time series are colored if above or below 1 standard deviation of the time series mean and the color represents the proposed relationship for stock (blue for good conditions, red for poor conditions), black circle for neutral.

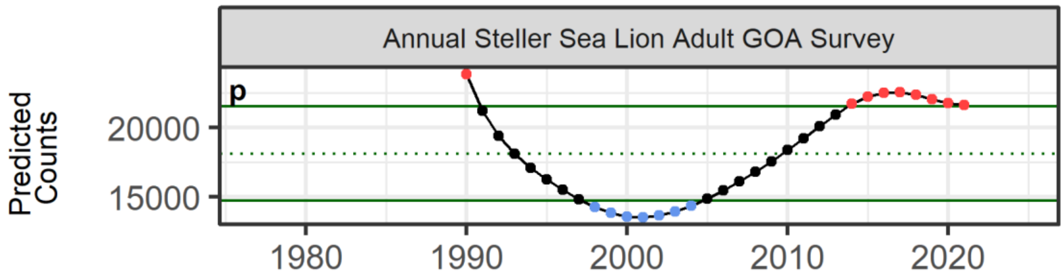

Figure 2.1.2a (cont.). Selected ecosystem indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. Dots in the time series are colored if above or below 1 standard deviation of the time series mean and the color represents the proposed relationship for stock (blue for good conditions, red for poor conditions), black circle for neutral.

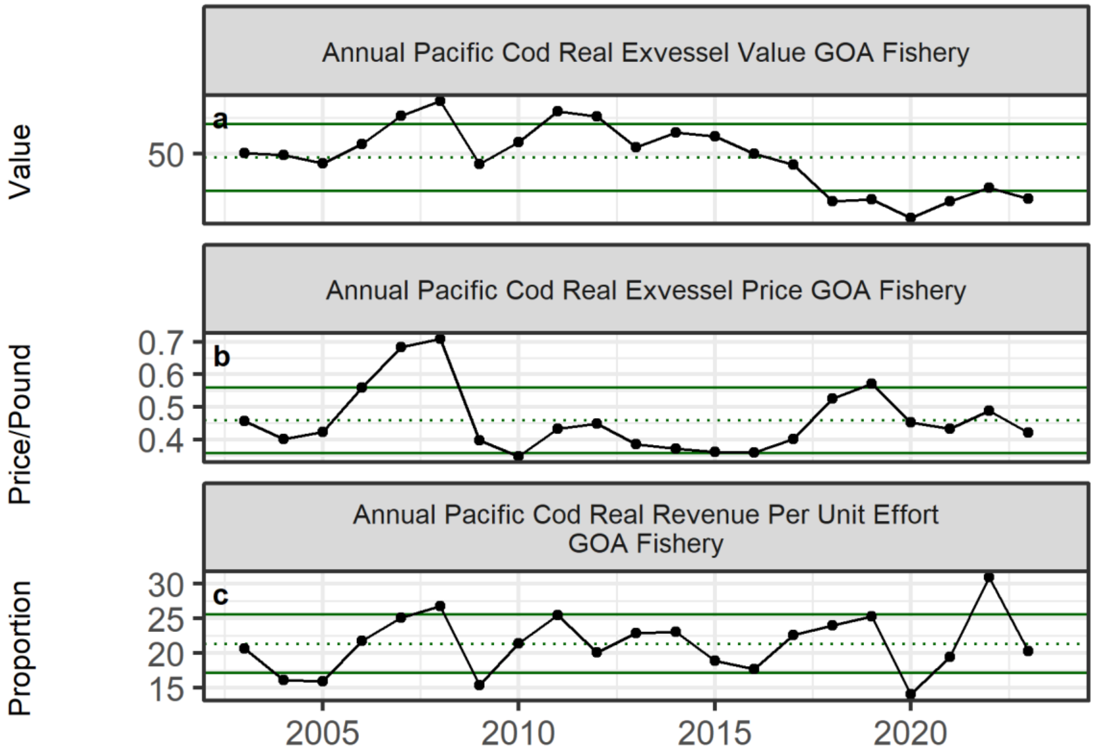

Figure 2.1.2b. Selected socioeconomic indicators for GOA Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

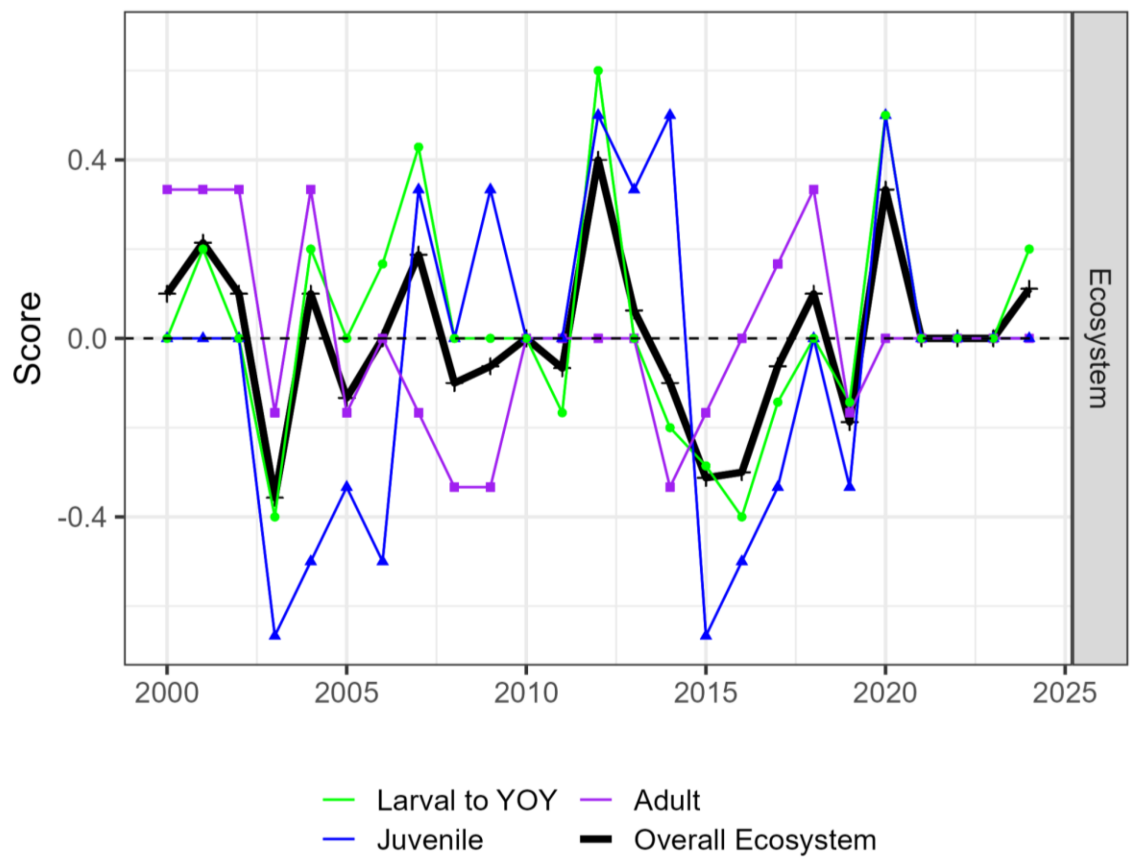

Figure 2.1.3: Simple summary traffic light score by overall ecosystem and category (larval to young-of-the-year (YOY), juvenile, and adult) for ecosystem indicators from 2000 to present.

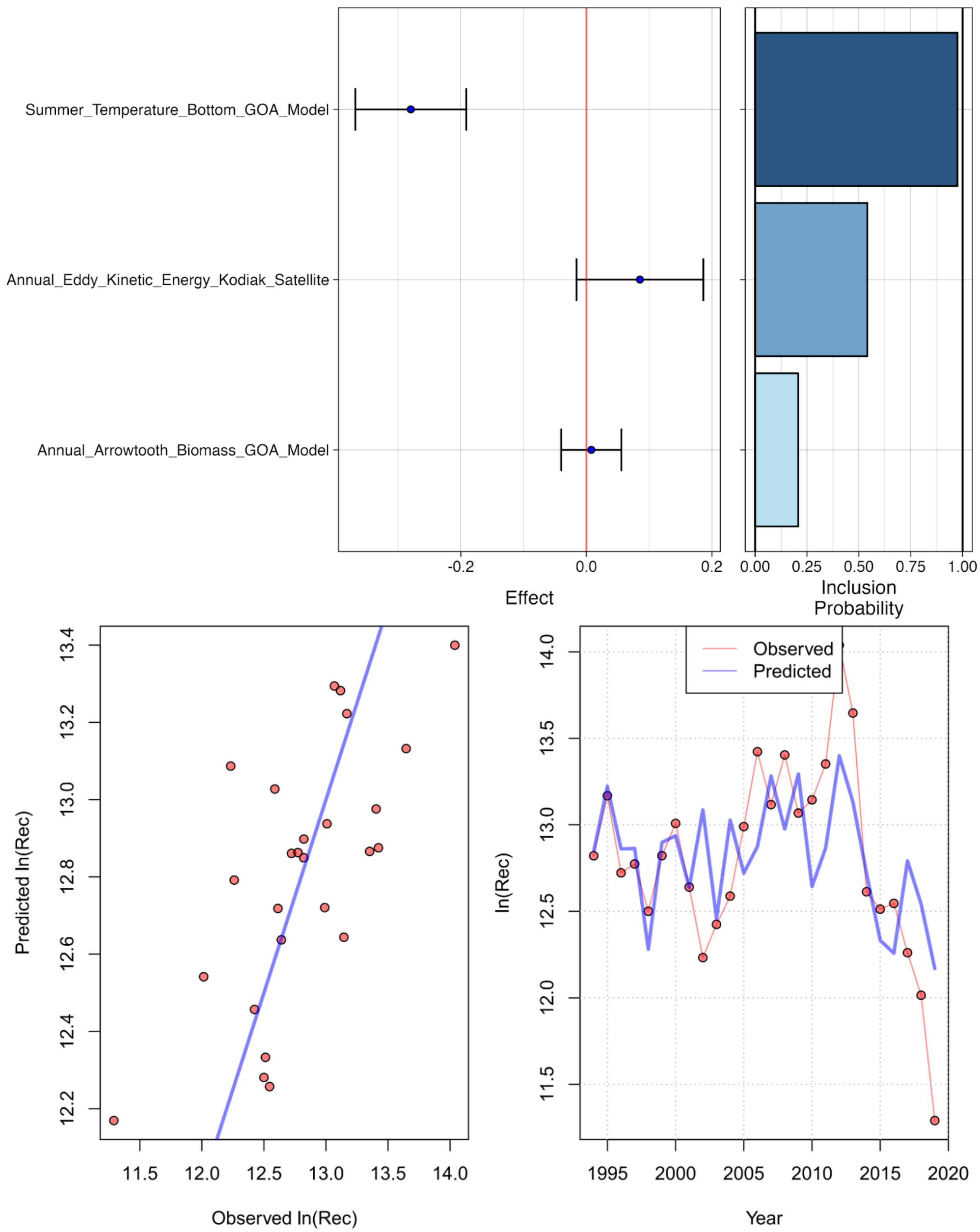

Figure 2.1.4: Bayesian adaptive sampling output showing the mean relationship and uncertainty (± 1 SD) with log-transformed estimated GOA Pacific cod recruitment from the operational stock assessment model: the estimated effect (top left) and the marginal inclusion probabilities (top right) for each predictor variable of the subsetted covariate ecosystem indicator dataset. Output also includes model predicted fit (1:1 line, bottom left) and average fit across the abbreviated recruitment time series (1994-2019, bottom right).

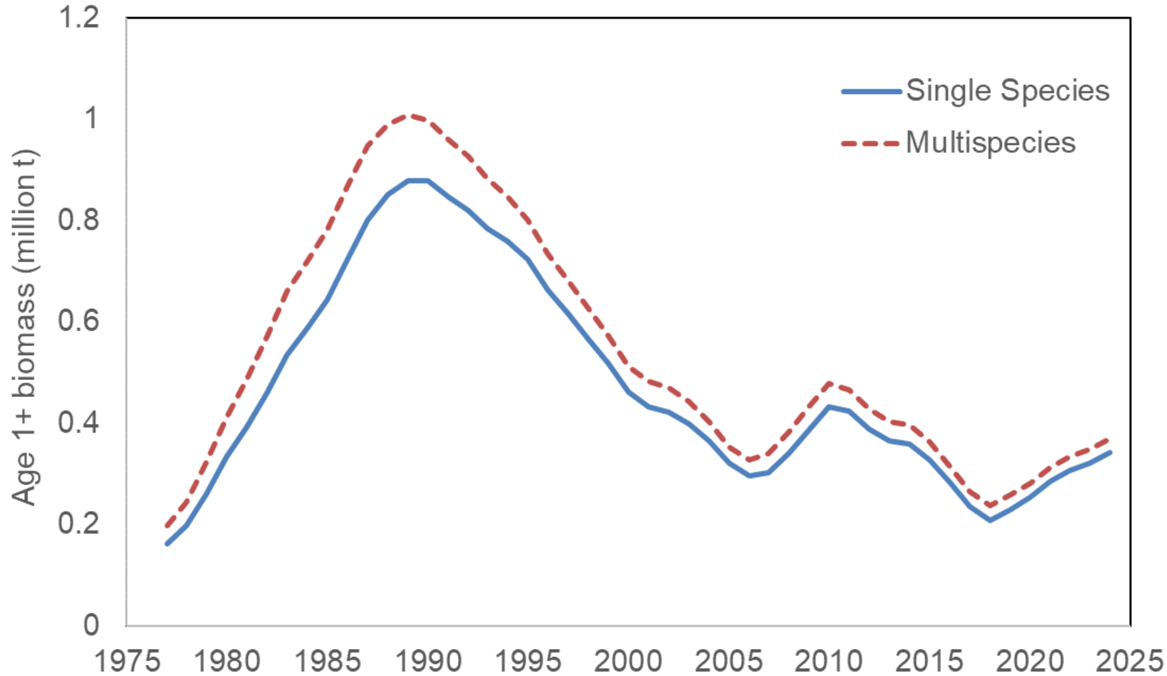

Figure 2.1.5: Age 1+ biomass for Gulf of Alaska Pacific cod from the most recent single species model (blue solid line) compared to the Climate- Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics (CEATTLE) multispecies model (red dashed line).