Appendix 2.2 Ecosystem and Socioeconomic Profile of the Pacific cod stock in the Eastern Bering Sea - Report Card

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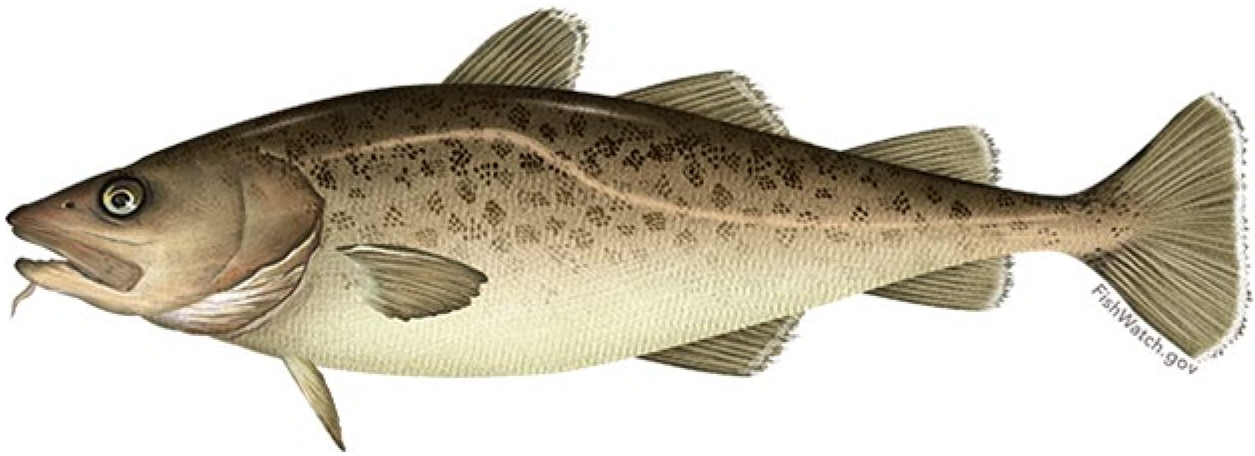

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Current Year Update

The ecosystem and socioeconomic profile or 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., *In Review*). 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.

Please refer to the last full ESP for further information regarding the ecosystem and socioeconomic linkages for this stock (Shotwell et al., 2021, available online within the Eastern Bering Sea (EBS) Pacific cod stock assessment and fishery evaluation report of Thompson et al., 2021, Appendix 2.2, pp. 347-411).

Management Considerations

The following are the summary considerations from current year updates to the ecosystem and socioeconomic indicators evaluated for EBS Pacific cod:

- North Pacific Index remains high signifying a weak Aleutian Low, high sea level pressure, warming sea surface temperatures, higher precipitation, increased downwelling, and generally calmer conditions
- Winter sea-ice extent during the advance season increased to above the time series mean from a period of below average extent since 2014, while ice extent during the retreat season is just below average increasing steadily since 2020
- Spring and summer surface temperature decreased but remains above average while bottom temperature decreased to below the time series mean
- Spring bloom peak timing was earlier than the time series mean, but bloom timing varies spatially and match would be dependent on spawning and movement of the Pacific cod population
- Condition for juvenile and adult Pacific cod were both above average, which is an increase from 2021, suggesting prey resources are sufficient
- Center of gravity estimates suggest the Pacific cod population has moved slightly more east and south in 2022, with a slightly above average area occupied, similar to the 2019 survey
- Arrowtooth flounder biomass has steadily increased over the time series but has stabilized since 2009, with a 14% increase in the 2022 bottom trawl survey
- Ex-vessel value decrease to below one standard deviation of the time series mean, and price and revenue-per-unit-effort also decreased from above average to below average in 2021
- Overall, ecosystem indicators were average in 2022 with socioeconomic indicators below average in 2021

Modeling Considerations

The following are the summary results from the intermediate and advanced stage monitoring analyses for EBS Pacific cod:

- Highest ranked predictor variable of EBS Pacific cod recruitment based on the importance methods in the intermediate stage indicator analysis was the spring and summer sea surface temperature on the southern EBS shelf (inclusion probability > 0.5)

Assessment

Ecosystem and Socioeconomic Processes

Figure 2.2.1 provides a life history conceptual model for EBS Pacific cod that summarizes ecological information and key ecosystem processes affecting survival by life stage. Pacific cod release all their eggs near the bottom in a single event during the late winter/ early spring period in the Bering Sea (Stark, 2007). Unlike most cod species, Pacific cod eggs are negatively buoyant and are semi-adhesive to the ocean bottom substrate during development (Alderdice and Forrester, 1971). Known areas of EBS Pacific cod spawning occur north of Unimak Island, near the Pribilof Islands, and on the shelf break in the vicinity of Zhemchug Canyon with spawning occurring in late-March and early April (Shimada and Kimura, 1994; Neidetcher et al., 2014). It is unknown whether recent warming events have allowed a northward expansion of the spawning distribution or a shift in the timing of spawning. Preliminary results from a recent tagging study in the northern Bering Sea (NBS) suggest that EBS Pacific cod tagged in the NBS in late summer and fall left the NBS and moved southward into deeper waters in the EBS and EBS slope as sea ice advanced in January to March. Tagged fish also traveled as far south as the Gulf of Alaska or west to Russian waters (S. McDermott, *pers. commun*.). Hatch timing/success is highly temperature-dependent (Laurel et al., 2008), with optimal hatch occurring in waters ranging between 4-6°C (Bian et al., 2016; Laurel and Rogers, 2020) over a broad range of salinities (Alderdice and Forrester, 1971). Eggs hatch into 4 mm larvae in ~2 weeks at 5°C (Laurel et al., 2008) and become surface oriented and available to pelagic ichthyoplankton nets during the spring (Doyle and Mier, 2016). During this period, Pacific cod larvae are feeding principally on eggs, nauplii and early copepodite stages of copepod prey <300 um (Strasburger et al., 2014). Warm surface waters can accelerate larval growth when prey are abundant (Hurst et al., 2010). Laboratory studies suggest warm temperatures can also indirectly impact Pacific cod larvae by way of two mechanisms: 1) increased susceptibility to starvation when the timing and biomass of prey is 'mis-matched' under warm spring conditions (Laurel et al., 2011), and 2) reduced growth by way of changes in the lipid/fatty acid composition of the zooplankton assemblage (Copeman and Laurel, 2010). Recent work has shown a stage-dependent sensitivity of cod larvae to elevated CO2 associated with ongoing ocean acidification (Hurst et al., 2019). Pacific cod larvae are known to occur in the southeastern Bering Sea along the Alaska Peninsula, but the full distribution of larvae is not well known due to spatial and temporal limitations of historical ichthyoplankton sampling. Newly hatched larvae are surface oriented and make extended diel vertical migrations with increased size and development (Hurst et al., 2009). Larvae reach a developmental milestone ('flexion') between 10-15 mm and gradually become more competent swimmers with increasing size (Voesenek et al., 2018). The dominant current regimes suggest a dispersal from south to north over the shelf and to the east along the Alaska Peninsula, and there is evidence of coherent patterns of dispersal which may link juvenile distributions to specific spawning areas (Miller et al., 2016). Age-0 Pacific cod are found in coastal areas along the Alaska Peninsula and in surface and sub-surface waters over the middle shelf (Hurst et al., 2012, 2015; Parker-Stetter et al., 2013). Meso-scale distributions have been linked to conditions with higher abundances at sites with higher local temperatures and growth potential (Hurst et al., 2012, 2018), suggesting a behavioral mechanism contributing to shifting juvenile distributions.

Juvenile cod feed predominantly on copepods and euphausiids, with additional contributions of pteropods, shrimp, crab zoea, and fishes (Strasburger et al., 2014; Farley et al., 2016). Growth conditions in summer-fall are related to temperature and foraging conditions with warm years resulting in larger body sizes but lower energy content (i.e., lower lipid content) (Farley et al., 2016). Bioenergetic model estimates of growth potential suggest that temperatures above the thermal optimal for growth combined with lower energetic content of the diet may lead to reduced late-summer growth during warm years in the southeastern Bering Sea (Hurst et al., 2018). Adult Pacific cod are opportunistic predators, eating a variety of zooplankton (including euphausiids), crab, and fish species (Aydin and Mueter, 2007) and are able to switch between benthic and demersal foraging based on prey availability (Aydin, 2020). In the eastern Bering Sea, Pacific cod feed on zooplankton until reaching approximately 20cm fork length, then feed primarily on benthic epifauna between 20-60cm fork length, and at larger sizes (60cm+) switch to feeding on fish, crustaceans, and other large invertebrates, in particular walleye pollock (Gadus chalcogrammus) and Chionoecetes spp. of crab (snow crab and tanner crab). There have been limited surveys in the NBS but of the years surveyed, for most years Chionoecetes spp. (primarily identified as snow crab) were the largest portion of cod diet, except for 2010 in which both flatfish and forage fish were the main prey items. These diet trends may be related to the extent of the cold pool in some year. Competitors for prey resources may also provide indirect evidence of conditions experienced by Pacific cod. While historical recruitment trends between Pacific cod and walleye pollock have mirrored each other, suggesting that the species respond similarly to environmental conditions, the time series appear to decouple after approximately 2010 and may indicate broad-scale transitions in the southeastern Bering Sea ecosystem (Siddon et al., 2019). Other competitors of EBS Pacific cod may include gray whales (feeding on benthic amphipods, zooplankton) and seabirds (e.g., short-tailed shearwaters are planktivorous birds and feed on euphausiids). Pacific cod are cannibalistic and rates of cannibalism might be expected to increase as the abundance of older, larger fish increases concurrent with increases in juvenile abundance. However, a spatial mismatch may mediate that stressor; based on bottom trawl survey results, large increases of small fish occurred over the EBS while larger fish occurred over the NBS (L. Britt, pers commun.). Other predators of Pacific cod include northern fur seals, Steller sea lions, various whale species, and tufted puffin.

Catches of Pacific cod are the second largest in the Bering Sea and Aleutian Islands region. Pacific cod accounted for 10% of the BSAI's FMP groundfish harvest and 93% of the total Pacific cod harvest in Alaska (Fissel et al., 2021). The Pacific cod total allowable catch (TAC) is allocated to multiple sectors (fleets). CDQ entities receive 10% of the total BSAI quota. The largest sectoral allocation goes to the freezer longline catcher/processors (CPs), which receive roughly 44% of the total BSAI cod quota (48.7% non-CDQ quota). While not an official catch share program, the freezer longline CPs have formed a voluntary cooperative that allows them to form private contracts among members to distribute the sectoral allocation. The remaining large sectors are the trawl CPs, trawl catcher vessels (CVs), pot gear CVs, and some smaller sideboard limits to cover the catch of Pacific cod while targeting other species.

Tables 2.2.1a-c provide a stock specific summary for EBS Pacific cod of the economic information presented in the current Economic SAFE (A. Ableman, *per. commun.*). The CVs (collectively referred to as the inshore sector) make deliveries to shore-based processors, and catcher/processors process catch at-sea before going directly to the wholesale markets. Among the at-sea CPs, catch is distributed approximately three-quarters to hook-and-line and one quarter to trawl. U.S. exports of cod are roughly proportional to U.S. cod production. More than 90% of the exports are H&G, much of which goes to China for secondary processing and re-export. The cod industry has largely avoided U.S. tariffs that would have a significant negative impact on them in the U.S.-China trade war. However, Chinese tariffs on U.S. products could inhibit future growth in that market. Japan and Europe (mostly Germany and the Netherlands) are also important export destinations. Japan and Europe accounted for 12% and 22% of the export volume respectively. Approximately 35% of Alaska's cod production is estimated to remain in the U.S. Because U.S. cod production is approximately 15% of global production and the BSAI is over 90% of U.S. production, BSAI Pacific cod is a significant component of the broader global cod market. A portion of the Russian catch of Pacific cod became MSC certified in Oct. 2019, which could put further downward pressure on prices going forward.

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) is a new report that 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., 2021). In

2019, 73% of retained catch occurred At Sea. Several other communities accounted for smaller, but notable percentages of landed volume, including Akutan, Adak, and Unalaska/Dutch Harbor. The number of processors landing BSAI Pacific cod has decreased since 2000; however the number of communities engaging in processing has increased to include False Pass, St. Paul, and Nome (Wise et al., 2021).

Indicator Suite

The following list of indicators for EBS Pacific cod is organized by categories, three for ecosystem indicators (physical, lower trophic, and upper trophic) and three for socioeconomic indicators (fishery performance, economic, and community). A short description and contact name for the indicator contributor are provided. For ecosystem indicators, we also include the anticipated sign of the proposed relationship between the indicator and the stock population dynamics where relevant. Please refer to the full ESP document for detailed information regarding the ecosystem and socioeconomic indicator descriptions and proposed mechanistic linkages for this stock (Shotwell et al., 2021). Time series of the ecosystem and socioeconomic indicators are provided in Figure 2.2.2a and Figure 2.2.2b, respectively.

This year, the morphometric condition indicator was estimated using VAST (Grüss et al., 2020; Thorson, 2019) instead of the stratum biomass weighted length-weight residual method from previous years. The VAST relative condition indicator is the ratio of weight-at-length relative to the time series mean based on annual allometric intercepts. In other words, we use VAST to estimate annual allometric intercepts, a, in the length-weight equation, W=aL^b, and divide the annual intercepts by the mean allometric intercept, condition = a_year/mean(a) (S. Rohan, *pers. commun.*). Trends in the historical and new indicator are similar based on the strong correlation between the historical and new indicator (r = 0.91 for juveniles, r = 0.87 for adults), although there are notable differences in some years. Specifically, for juveniles, 2017 was a negative year using the old indicator (~1 standard deviation below the mean) but a neutral year with the new indicator, negative years in 2009 and 2012 are still negative but the anomaly is larger, and the anomaly in 1999 decreased from 3.2 standard deviations below the mean to 1.8 standard deviations below the mean (a 'cold' year with an early survey start). Specifically, for adults, the year with the lowest condition for the old indicator was 1999 (a 'cold' year with an early survey start), with an anomaly greater than two standard deviations from the mean. Based on the new VAST relative condition indicator, 1999 was a neutral year and the year with the lowest condition was 2012. Despite these differences, new indicator trends generally match the trend from the old indicator (S. Rohan, *pers. commun.*).

Ecosystem Indicators:

Physical Indicators (Figure 2.2.2a.a-e)

a.) North Pacific Index (NPI) calculated as the area-weighted sea level pressure (SLP) from November to March over the region 30°N-65°N, 160°E-140°W (contact: M. Wang). Proposed sign of relationship is positive and the time series is not lagged for the intermediate stage indicator analysis.

b.) Anomalies of average daily sea-ice extent relative to 1978-2010 mean computed over ice-advance season of December through February (contact: M. Wang). Proposed sign of relationship is positive and the time series is not lagged for the intermediate stage indicator analysis.

c.) Anomalies of average daily sea-ice extent relative to 1978-2010 mean computed over ice-retreat season of March through May (contact: M. Wang). Proposed sign of relationship is positive.

d.) Spring to summer (April-June) daily sea surface temperatures (SST) for the EBS shelf from the NOAA Coral Reef Watch Program (contact: M. Callahan). Proposed sign of relationship is negative and the time series is not lagged for the intermediate stage indicator analysis.

e.) Summer (July-September) bottom temperatures over the EBS shelf from the Bering 10K ROMS-NPZ model (contact K. Kearney). Proposed sign of relationship is negative and the time series is not lagged for the intermediate stage indicator analysis.

Lower Trophic Indicators (Figure 2.2.2a.f-g)

f.) Peak timing of the spring bloom averaged across individual ADF&G statistical areas in the EBS from the MODIS satellite (contact: J. Nielsen). Proposed sign of relationship is positive.

g.) Summer euphausiid abundance for the EBS shelf from the AFSC acoustic survey (contact: P. Ressler). Proposed sign of relationship is positive.

Upper Trophic Indicators (Figure 2.2.2a.h-m)

h.) Summer condition for juvenile (<460 mm) Pacific cod from the AFSC EBS shelf bottom trawl survey (contact: S. Rohan). Proposed sign of relationship is positive.

i.) Summer condition for adult (>=460 mm) Pacific cod from the AFSC EBS shelf bottom trawl survey (contact: S. Rohan). Proposed sign of relationship is positive.

j.) Summer Pacific cod center of gravity eastings estimated by a spatio-temporal model using the package VAST on AFSC EBS bottom trawl survey data (contact: L. DeFilippo and J. Conner). Proposed sign of relationship is positive and the time series is not lagged for the intermediate stage indicator analysis.

k.) Summer Pacific cod center of gravity northings estimated by a spatio-temporal model using the package VAST on AFSC EBS bottom trawl survey data (contact: L. DeFilippo and J. Conner). Proposed sign of relationship is negative and the time series is not lagged for the intermediate stage indicator analysis.

l.) Summer Pacific cod area occupied estimated by a spatio-temporal model using the package VAST on AFSC EBS bottom trawl survey data (contact: L. DeFilippo and J. Conner). Proposed sign of relationship is positive and the time series is not lagged for the intermediate stage indicator analysis.

m.) Arrowtooth flounder total biomass from the most recent stock assessment model in the EBS (contact: K. Shotwell). Proposed sign of relationship is negative and the time series is lagged two years for the intermediate stage indicator analysis.

Socioeconomic Indicators:

Economic Indicators (Figure 2.2.2b.a-c)

a.) Annual estimated real ex-vessel value of EBS Pacific cod (contact: J. Lee)

b.) Annual real ex-vessel price per pound of EBS Pacific cod from fish ticket information (contact: J. Lee).

c.) Annual estimated real revenue per unit effort measured in weeks fished of EBS Pacific cod (contact: J. Lee)

Community Indicators (Figure 2.2.2b.d-e)

d.) Regional quotient of Pacific cod for harvesting revenue of the highly engaged community of Unalaska Dutch Harbor (contact: S. Wise)

e.) Regional quotient of Pacific cod for processing revenue of the highly engaged community of Unalaska Dutch Harbor (contact: S. Wise)

Indicator Monitoring Analysis

There are up to three stages (beginning, intermediate, and advanced) of statistical analyses for monitoring the indicator suite listed in the previous section. The beginning stage is a relatively simple evaluation by traffic light scoring. This evaluates the current year trends relative to the mean of the whole time series, and provides a historical perspective on the utility of the whole indicator suite. The intermediate stage uses importance methods related to a stock assessment variable of interest (e.g., recruitment, biomass, catchability). These regression techniques provide a simple predictive performance for the variable 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 testing a research ecosystem linked model and output can be compared with the current operational model to understand information on retrospective patterns, prediction performance, and comparisons of other model output such as terminal spawning stock biomass or mean recruitment. This stage provides an on-ramp for introducing an alternative ecosystem linked stock assessment model to the current operational stock assessment model and can be used to understand the potential reduction in uncertainty by including the ecosystem information.

Beginning Stage: Traffic Light Test

We use a simple scoring calculation for this beginning stage traffic light evaluation. Indicator status is evaluated based on being greater than (“high”), less than (“low”), or within (“neutral”) one standard deviation of the long-term mean. A sign based on the anticipated relationship between the indicator and the stock (generally shown in Figure 2.2.1 and specifically by indicator in the Indicator Suite, Ecosystem Indicators section) is also assigned to the indicator where possible. 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 value receives a "+1" score. If a high value generates poor conditions for the stock and is greater than one standard deviation above the mean, then that value receives a "-1" score. All values less than or equal to one standard deviation from the long-term mean are average and receive a "0" score. The scores are summed by the three organizational categories within the ecosystem (physical, lower trophic, and upper trophic) or socioeconomic (fishery performance, economic, and community) indicators and divided by the total number of indicators available in that category for a given year. The scores over time allow for comparison of the indicator performance and the history of stock productivity (Figure 2.2.3). We also provide five year indicator status tables with a color (ecosystem indicators only) for the relationship with the stock (Tables 2.2.2a,b) and evaluate the current year status in the historical indicator time series graphic (Figures 2.2.2a,b) for each ecosystem and socioeconomic indicator.

We evaluate the status and trends of the ecosystem and socioeconomic indicators to understand the pressures on the EBS Pacific cod stock regarding recruitment, movement, stock productivity, and stock health. We start with the physical indicators and proceed through the increasing trophic levels, then evaluate the economic and community indicators as listed above. Here we concentrate on updates since the last ESP (Shotwell et al., 2021). Overall, the physical, lower trophic, and upper trophic level indicators scored average for 2022 (Figure 2.2.3). Compared to last year’s results, this is the same value for both physical and lower trophic indicators, and an improvement from below average for the upper trophic indicators. We also note caution when comparing scores between odd to even years as there is one lower trophic indicator missing in even years due to an off-cycle year survey. Also, there were survey cancellations due to COVID-19 or survey delays in 2020 through 2022 that have limited production of several indicators. Economic and community indicators are all lagged by at least one year due to timing of the availability of the current year information and the production of this report. Economic indicators scored below average for 2021 (data received in 2022), which is a decrease from average in 2020. There have been no updates for community indicators since 2019.

For physical indicators (Table 2.2.2a, Figure 2.2.2a.a-e), the winter to spring North Pacific Index (NPI) decreased slightly but remains high in 2022 (Figure 2.2.2a.a). The NPI effectively represents the state of the Aleutian Low with higher values signifying high sea level pressure, warming sea surface temperatures, higher precipitation, and increased downwelling (Weingartner, 2005). The extent of the sea ice during the ice advance season (Dec-Feb) decreased dramatically in 2014 and continued to decline to a time-series low in 2018, but increased somewhat in 2019-2021 but jumped to above average in 2022 (Figure 2.2.2a.b). Similarly, the extent of sea ice during the ice retreat season (Mar-May) steadily decreased from a time-series high in 2012 to the time-series low in 2018, remained low in 2019, but increased in 2020 and has been steadily increasing to just below the time-series average in 2022 (Figure 2.2.2a.c). Spring to summer surface temperatures decreased from last year but remain above average in the warm stanza that has dominated since 2014 (Figure 2.2.2a.d). The simulated 2022 conditions were very near the historical (1971-2022) average (Figure 2.2.2a.e). The mean SEBS bottom temperature in July was 2.53ºC, just below the mean of 2.78ºC. The 2ºC cold pool index was 0.39, likewise just to the cool side of the mean of 0.35. For the first time since 2017, below-0ºC water remained in the northern part of the SEBS region in the summer, resulting in a 0ºC cold pool index of 0.09 (historical mean 0.11). 2022 resembles other average-to-cool years, with a spatial pattern characterized by summer <2ºC water across much of the southeast middle shelf, patches of <1ºC water in both the northern and southern parts of the southeast middle shelf and some <0ºC water in the northern southeast middle shelf. When compared to previous years, conditions most closely resemble 2017.

For lower trophic indicators (Table 2.2.2a, Figure 2.2.2a.f-g), the timing of the spring bloom was earlier than average (Figure 2.2.2a.f). The bloom timing varies spatially, with blooms occurring earlier in the inner domain to later in the outer domain (Nielsen et al., 2021). A match or mismatch with larvae of the EBS Pacific cod stock would likely depend on where the primary spawning was occurring from year to year and thus seems dependent on movement. The euphausiid abundance index (Figure 2.2.2a.g) steadily dropped from a high in 2009 to a low in 2016, with only a moderate increase in 2018 and again in 2022 (still low for the time-series), similar to the Gulf of Alaska euphausiid index (Ressler, 2018, 2019; Kimmel et al., 2020). The 2022 year class may have encountered higher abundances of euphausiids in spring and late summer.

For upper trophic indicators (Table 2.2.2a, Figure 2.2.2a.h-m), condition of juvenile Pacific cod in the EBS in 2022 was slightly above average but within one standard deviation of the time series mean, which continues the trend of neutral morphometric condition since 2017. Historically condition of juveniles increased from 1999 to 2004, decreased from 2005 to 2009, then fluctuates around neutral from 2010 to 2022, aside from a negative year in 2012 and positive year in 2016 (Figure 2.2.2a.h). The condition of adult Pacific cod in the EBS in 2022 was above average but within one standard deviation of the time series mean, which also continues the trend of neutral morphometric condition since 2018. The neutral condition in recent years (2018–2022) represents an increase from the three prior years with below average condition from 2015–2017. Historically condition of adults increased from 1999 to 2003, decreased from 2003 to 2006, then fluctuating around neutral from 2007 to 2022, aside from negative years in 2009, 2012, 2015, and 2017 (Figure 2.2.2a.h-i). The current condition of juveniles and adults suggests that prey resources were sufficient. Many factors may contribute to the variation in morphometric condition such as temperature-dependent metabolic rates, survey timing, stomach fullness of individual fish, migration patterns, and distribution of samples within survey strata (Rohan and Prohaska, 2022). Center of gravity estimates for EBS Pacific cod have shifted from 2021, with the population center moving more east (slightly east of average) and south (still north of average) (Figure 2.2.2a.j-k). Area occupied has increased to slightly above average (Figure 2.2.2a.l). Arrowtooth flounder biomass remains well above average from the most recent stock assessment model (Shotwell et al., 2020) and 2022 survey estimates are 14% higher than in 2021 from the bottom trawl survey (shelf habitat).

For economic indicators (Table 2.2.2b, Figure 2.2.2b.a-c), ex-vessel value decreased below one standard deviation of the time series mean and similar to the previous low value of 2009 (Figure 2.2.2b.a). Price per pound and revenue per unit effort also decreased from above average to below average (but still within one standard deviation of the time series mean) (Figure 2.2.2b.b-c). Since 2016 reductions in global supply have put upward pressure on prices, resulting in significant year over year price increases in 2017 and 2018. In 2019 prices leveled off, decreasing slightly, as markets have adjusted. In 2020 COVID-19 closures resulted in increased demand for retail products and frozen products, and decreased foodservice and fresh products. Retail and foodservice are both significant components of the market for cod products. As such, the impact of COVID-19 on prices appears muted, with only marginal changes in first-wholesale and export prices. Cost pressure from COVID-19 mitigation efforts likely had impacts on net revenues as well as upstream impacts on ex-vessel prices, which decreased significantly.

The community indicators evaluated in the ESP are similar to those presented in the ACEPO report, but on the stock level rather than the community level (Table 2.2.2b, Figure 2.2.2b.d-e). The indicators are separated into two categories of fisheries involvement: commercial processing and commercial harvesting (Wise et al., 2021). By separating commercial processing from commercial harvesting, the engagement indices highlight the importance of fisheries in communities that may not have a large amount of landings or processing in their community, but have a large number of fishers and/or vessel owners that participate in commercial fisheries who are based in the community. At this time there are no updates to the community indicators. In the future we plan to evaluate how to reference the products available in the ACEPO report for use in the ESPs to inform on stock health.

Intermediate Stage: Importance Test

Bayesian adaptive sampling (BAS) was used for the intermediate stage statistical test to quantify the association between hypothesized predictors and EBS Pacific cod recruitment and to assess the strength of support for each hypothesis. In this stage, the full set of indicators is first winnowed to the predictors that could directly relate to recruitment and highly correlated covariates are removed. We further restrict potential covariates to those that can provide the longest model run and through the most recent estimate of recruitment that is well estimated in the current operational stock assessment model (Figure 2.2.4a). This results in a model run from 1985 through the 2019 year-class. We then provide the mean relationship between each predictor variable and log EBS Pacific cod recruitment over time (Figure 2.2.4b, left side), with error bars describing the uncertainty (95% confidence intervals) in each estimated effect and the marginal inclusion probabilities for each predictor variable (Figure 2.2.4b, right side). A higher probability indicates that the variable is a better candidate predictor of EBS Pacific cod recruitment. The highest ranked predictor variable (inclusion probability > 0.5) based on this process is the spring summer sea surface temperature index on the shelf (same as last year) (Figure 2.2.4).

Advanced Stage: Research Model Test

In the future, highly ranked predictor variables could be evaluated in the advanced stage statistical test, which is a modeling application that analyzes predictor performance and estimates risk within the operational stock assessment model. A multi-species statistical catch-at-age assessment model (known as CEATTLE; Climate- Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics; Holsman et al., 2016) has been developed for understanding trends in age-1 total mortality for walleye pollock, Pacific cod, and arrowtooth flounder from the EBS (Holsman et al., 2021). Total mortality rates are based on residual mortality inputs (M1), model estimates of annual predation mortality (M2), and fishing mortality (F). CEATTLE for the southeastern Bering Sea has recently been 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 (Ianelli et al., 2021, Thompson et al., 2021, and Shotwell et al., 2020). The model is fit to data from five fisheries and seven surveys, including both age and length composition (assumed to come from a multinomial distribution). Model estimates of M2 are empirically driven by bioenergetics-based consumption information and diet data from the EBS to inform predator-prey suitability. The most recent model was fit to data from 1979 to 2021 and showed evidence of continued decline in predation mortality on age-1 EBS Pacific cod, pollock, and arrowtooth flounder. The warm temperatures in this system continue to lead to high metabolic (and energetic) demand of predators; however, declines in total predator biomass may be contributing to an overall decline in total consumption and therefore reduced predation rates and mortality.

The EBS CEATTLE model can provide gap-free estimates of predation mortality that could be tested in the operational stock assessment model. Additionally, the time series of bioenergetics-based consumption input to the CEATTLE model could be compared to condition indicators from the surveys for context on recent condition trends. The spring and summer sea surface temperature index could be used directly to help explain the variability in recruitment deviations and predict pending recruitment events for EBS Pacific cod. Also, the sea ice extent during the ice retreat period, or simply the center of gravity northings from the VAST model, could be used as covariates if future spatial models were developed for this stock.

Data Gaps and Future Research Priorities

While the metric and indicator assessments provide a relevant set of proxy indicators for evaluation at this time, there are certainly areas for improvement. Gaps in indicator time series cause issues with updating the ESP and can lead to difficulty in identifying impending shifts in the ecosystem that may impact the EBS Pacific cod population. Development of high-resolution remote sensing (e.g., regional surface temperature, transport estimates, primary production estimates) or climate model indicators (e.g., bottom temperature, nutrient-phytoplankton-zooplankton variables) would assist with the current multi-year data gap for several indicators if they sufficiently capture the main trends of the survey data and are consistently and reliably available.

Refinements or updates to current indicators may also be helpful. More specific phytoplankton indicators tuned to the spatial and temporal distribution of EBS Pacific cod larvae as well as phytoplankton community structure information (e.g., hyperspectral information for size fractionation) could be more useful for understanding Pacific cod larval fluctuations. Current estimates of zooplankton biomass are only available at smaller spatial scales and regional to gulf-wide estimates of zooplankton biomass as well as offshore to nearshore monitoring of Pacific cod larvae and zooplankton are needed to elucidate prey trends at the spatial scales relevant to fisheries management. The AFSC continues investigating environmental regulation of first year of life processes in Pacific cod to better understand the interrelationship between processes occurring during pre-settlement (spawning/larvae), settlement (summer growth) and post-settlement (first overwintering) phases. Work is underway to develop a spawning habitat index for Pacific cod, analogous to that for the Gulf of Alaska, based on refined bottom temperature measurements and ROMS model output. This research will characterize spatial and temporal changes in spawning habitat in the EBS and its importance for larval phenology, advection, and survival. Transport processes and connectivity between larval and juvenile nursery areas will continue to be an important area of research as the Regional Oceanographic Model (ROMS) for the Bering Sea is updated.

We currently lack an indicator of predation on YOY Pacific cod during their first autumn and winter, during a period when predation mortality is thought to be significant. Sampling of predator diets in fall and winter would help to fill this gap. The EBS CEATTLE model might also allow for a gap-free index of age-1 predation mortality and bioenergetics indices for EBS Pacific cod (e.g., annual ration, consumption). Additionally, evaluating condition and energy density of juvenile and adult Pacific cod samples at the outer edge of the population may be useful for understanding the impacts of shifting spatial statistics such as center of gravity and area occupied. Information is available from the northern Bering Sea bottom trawl survey and the AFSC longline survey that could be used for evaluating the northern and western edge of the EBS Pacific cod population. The North Pacific Research Board has funded an integrated ecosystem research program in the Arctic that may also be helpful for evaluating the northern edge of the EBS Pacific cod population.

We plan to evaluate the information provided in the Economic SAFE and ACEPO report to determine what socioeconomic indicators could be provided in the ESP that are not redundant with those reports and related directly to stock health. This may result in a transition of indicators currently reported in this ESP to a different series of socioeconomic indicators in future ESPs and may include a shift in focus from engagement to dependency. Additional considerations should be given regarding the timing of the economic and community reports that are delayed by 1-2 years depending on the data source from the annual stock assessment cycle. The Scientific and Statistical Committee (SSC) recently recommended that local knowledge, traditional knowledge, and subsistence information may be helpful for understanding recent fluctuations in stock health, shifts in stock distributions, or changes in size or condition of species in the fishery. We could include this information as supportive evidence and perspective on many indicators monitored within the ESP.

As indicators are improved or updated, they may replace those in the current set of indicators to allow for refinement of the BAS model and potential evaluation of performance and risk within the operational stock assessment model. 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 indicators (RFI) for the EBS Pacific cod ESP will include these data gaps and research priorities along with a list of potential new indicators that could be developed for the next full ESP assessment.

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Tables

Table 2.2.1a. Bering Sea & Aleutian Islands Pacific cod catch and ex-vessel data. Total and retained catch (thousand metric tons), number of vessel, catcher/processor (CP) hook-and-line (H&L) share of catch, CP trawl share of catch, Shoreside retained catch (thousand metric tons), shoreside number of vessel, shoreside pot gear share of catch, shoreside trawl share of catch, shoreside ex-vessel value and price (million US$), and fixed gear to trawl price premium (US$ per pound); 2012-2016 average and 2017-2021.

	2012-2016 Average	2017	2018	2019	2020	2021
Total catch K mt	250.66	253	220.3	198	169.9	135.7
Retained catch K mt	246.28	250.07	218.01	195.93	167.39	132.04
Vessels #	164	173	193	196	189	146
CP H&L share of BSAI catch	51.02%	49.7%	46.27%	45.21%	43.95%	44.64%
CP trawl share of BSAI catch	15.22%	12.77%	13.91%	13.04%	13.18%	13.73%
Shoreside retained catch K mt	76.04	87.97	82.48	77.53	68.34	52.64
Shoreside catcher vessels #	113.6	128	144	149	151	115
CV pot gear share of BSAI catch	12.78%	17.26%	19.38%	21.98%	21.4%	23.12%
CV trawl share of BSAI catch	17.7%	17.88%	18.03%	16.98%	18.86%	16.61%
Shoreside ex-vessel value M $	$41.96	$53.98	$65	$62.26	$53.43	$39.32
Shoreside ex-vessel price lb $	$0.27	$0.32	$0.4	$0.42	$0.39	$0.37
Shoreside fixed gear ex-vessel price premium	$0.02	$0.05	$0.07	$0.11	$0.1	$0.04

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 2.2.1b. Bering Sea & Aleutian Islands 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); At-sea share of value and at-sea shoreside price difference (US$ per pound); 2012-2016 average and 2017-2021.

	2012-2016 Average	2017	2018	2019	2020	2021
All Products volume K mt	122.95	119.54	107.41	94.97	77.62	62.86
All Products value M $	$358.12	$434.67	$458.84	$346.52	$265.77	$236.67
All Products price lb $	$1.32	$1.65	$1.94	$1.66	$1.55	$1.71
Fillets volume K mt	8.06	10.01	10.36	8.02	7.51	5.61
Fillets value share	14.65%	18.8%	20.53%	19.98%	23.25%	22.43%
Fillets price lb $	$2.95	$3.7	$4.12	$3.91	$3.73	$4.29
Head & Gut volume K mt	100.41	92.38	79.04	70.25	55.04	45.96
Head & Gut value share	78.3%	73.71%	70.73%	71.53%	65.97%	68.53%
Head & Gut price lb $	$1.27	$1.57	$1.86	$1.6	$1.44	$1.6
At-sea value share	70.91%	69.72%	63.54%	66.96%	63.82%	65.49%
At-sea price premium ($/lb)	-$0.134	-$0.33	-$0.51	-$0.36	-$0.48	-$0.34

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 2.2.1c. 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 for head and gut (H&G), fillets, China, Japan, and Europe; 2012-2016 average and 2017-2021.

	2012-2016 Average	2017	2018	2019	2020	2021
Global cod catch K mt	1763.16	1760.31	1636.16	1565.77	1483.09	-
U.S. P. cod share of global catch	21.3%	21.2%	18.2%	17.2%	15.2%	-
Europe Share of global catch	75.1%	75.9%	78.3%	78.5%	80.3%	-
Pacific cod share of U.S. catch	99.6%	99.8%	99.9%	99.8%	99.7%	-
U.S. cod consumption K mt (est.)	107.83	118.56	113.62	106.28	103.36	107.08
Share of U.S. cod not exported	29.4%	32.5%	35.5%	36.8%	45%	53.1%
Export volume K mt	107.74	92.79	73.14	65.1	44.48	32.52
Export value M US$	$326.55	$295.5	$253.37	$217.88	$139.4	$101.68
Export price lb US$	$1.37	$1.44	$1.57	$1.52	$1.42	$1.42
Frozen (H&G) volume share	89.49%	93.6%	90.95%	92.31%	92.32%	89.44%
Frozen (H&G) value share	88.19%	92.15%	90.42%	90.71%	89.83%	84.21%
Fillets volume share	4.34%	4.12%	4.97%	4.68%	5.86%	8.73%
Fillets value share	5.78%	5.33%	5.69%	5.84%	7.38%	12.93%
China volume share	51.63%	52.4%	47.55%	41.52%	39.52%	31.36%
China value share	49.01%	49.67%	46.46%	40.21%	37.35%	28.38%
Japan volume share	14.57%	16.09%	15.06%	11.86%	13.04%	10.99%
Japan value share	15.1%	18.36%	16.67%	12.97%	13.89%	11.78%
Europe* volume share	21.05%	17.35%	15.95%	21.6%	20.13%	11.53%
Europe* value share	22.65%	17.73%	17.67%	23.12%	20.69%	10.95%

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.
*Europe refers to: Austria, Belgium, Denmark, France, Germany, Greece, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and United Kingdom
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 2.2.2a. Beginning stage ecosystem indicator analysis for EBS Pacific cod, including indicator title and the indicator status of the last five available years. The indicator status is designated with text, (greater than = "high", less than = "low", or within 1 standard deviation = "neutral" of the time series 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	2018 Status	2019 Status	2020 Status	2021 Status	2022 Status
Physical	Winter Spring North Pacific Index Model	*high*	neutral	*high*	neutral	neutral
	Winter Sea Ice Advance BS Satellite	**low**	**low**	neutral	neutral	neutral
	Spring Sea Ice Retreat BS Satellite	**low**	**low**	neutral	neutral	neutral
	Spring Summer Temperature Surface SEBS Satellite	**high**	**high**	**high**	neutral	neutral
	Summer Temperature Bottom SEBS Model	**high**	**high**	neutral	neutral	neutral
Lower Trophic	Spring Chlorophyll a Peak SEBS Satellite	*high*	**low**	neutral	neutral	neutral
	Summer Euphausiid Abundance EBS Survey	neutral	NA	NA	NA	neutral
Upper Trophic	Summer Pacific Cod Condition Juvenile EBS Survey	neutral	neutral	NA	neutral	neutral
	Summer Pacific Cod Condition Adult EBS Survey	neutral	neutral	NA	neutral	neutral
	Summer Pacific Cod Center Gravity East EBS Model	**low**	*high*	NA	neutral	neutral
	Summer Pacific Cod Center Gravity North EBS Model	**high**	**high**	NA	**high**	neutral
	Summer Pacific Cod Area Occupied EBS Model	neutral	neutral	NA	neutral	neutral
	Annual Arrowtooth Biomass EBS Model	neutral	**high**	**high**	**high**	NA

Table 2.2.2b. Beginning stage socioeconomic indicator analysis for EBS Pacific cod, including indicator title and the indicator status of the last five available years. The indicator status is designated with text, (greater than = “high”, less than = “low”, or within 1 standard deviation = “neutral” of time series mean). A gray fill and text = “NA” will appear if there were no data for that year.

Indicator category	Indicator	2018 Status	2019 Status	2020 Status	2021 Status	2022 Status
Economic	Annual Pacific Cod Real Exvessel Value EBS Fishery	high	neutral	neutral	low	NA
	Annual Pacific Cod Real Exvessel Price EBS Fishery	neutral	neutral	neutral	neutral	NA
	Annual Pacific Cod Real Revenue Per Unit Effort EBS Fishery	high	high	neutral	neutral	NA
Community	Annual Pacific Cod RQ Harvesting Revenue Dutch Harbor Fishery	neutral	neutral	NA	NA	NA
	Annual Pacific Cod RQ Processing Revenue Dutch Harbor Fishery	neutral	low	NA	NA	NA

Figures

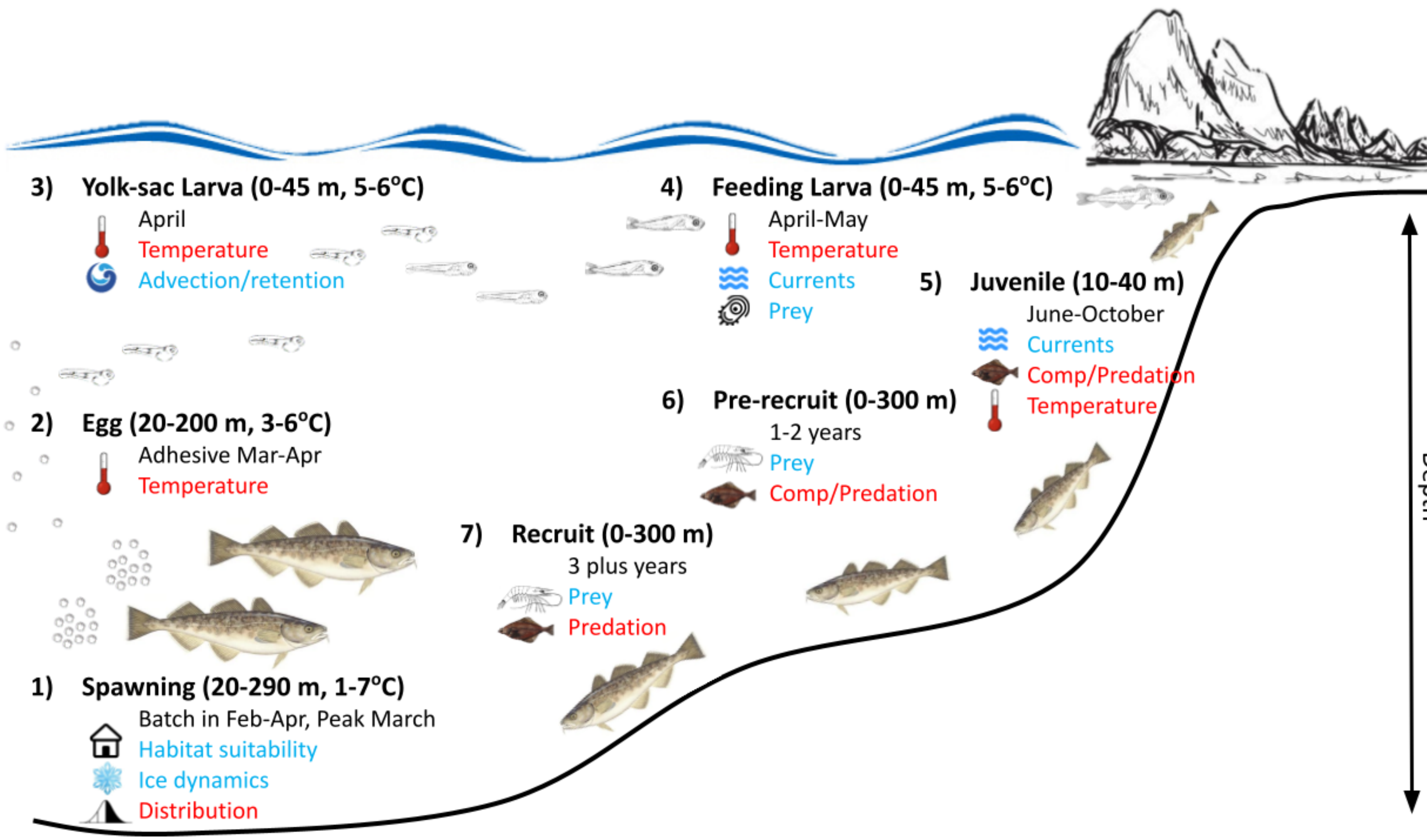

Figure 2.2.1: Life history conceptual model for EBS Pacific cod summarizing ecological information and key ecosystem processes affecting survival by life history stage. Red text means increases in the process negatively affect survival, while blue text means increases in the process positively affect survival.

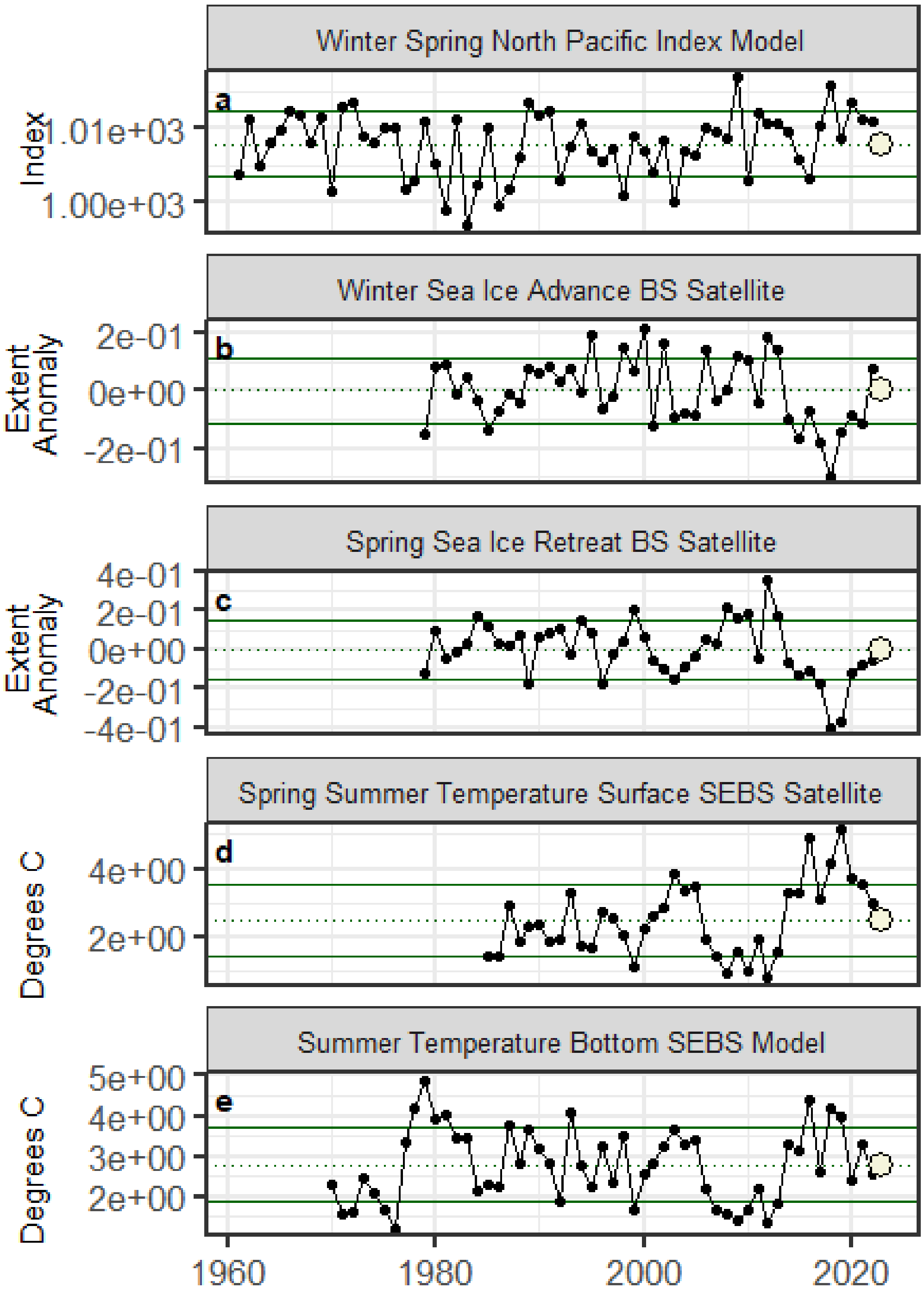

Figure 2.2.2a. Selected ecosystem indicators for EBS Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. A symbol appears when current year data are available and follows the traffic light status table designations (triangle direction represents if above or below 1 standard deviation of the time series mean, color represents proposed relationship for stock with blue for good conditions, red for poor conditions, and a white circle is neutral).

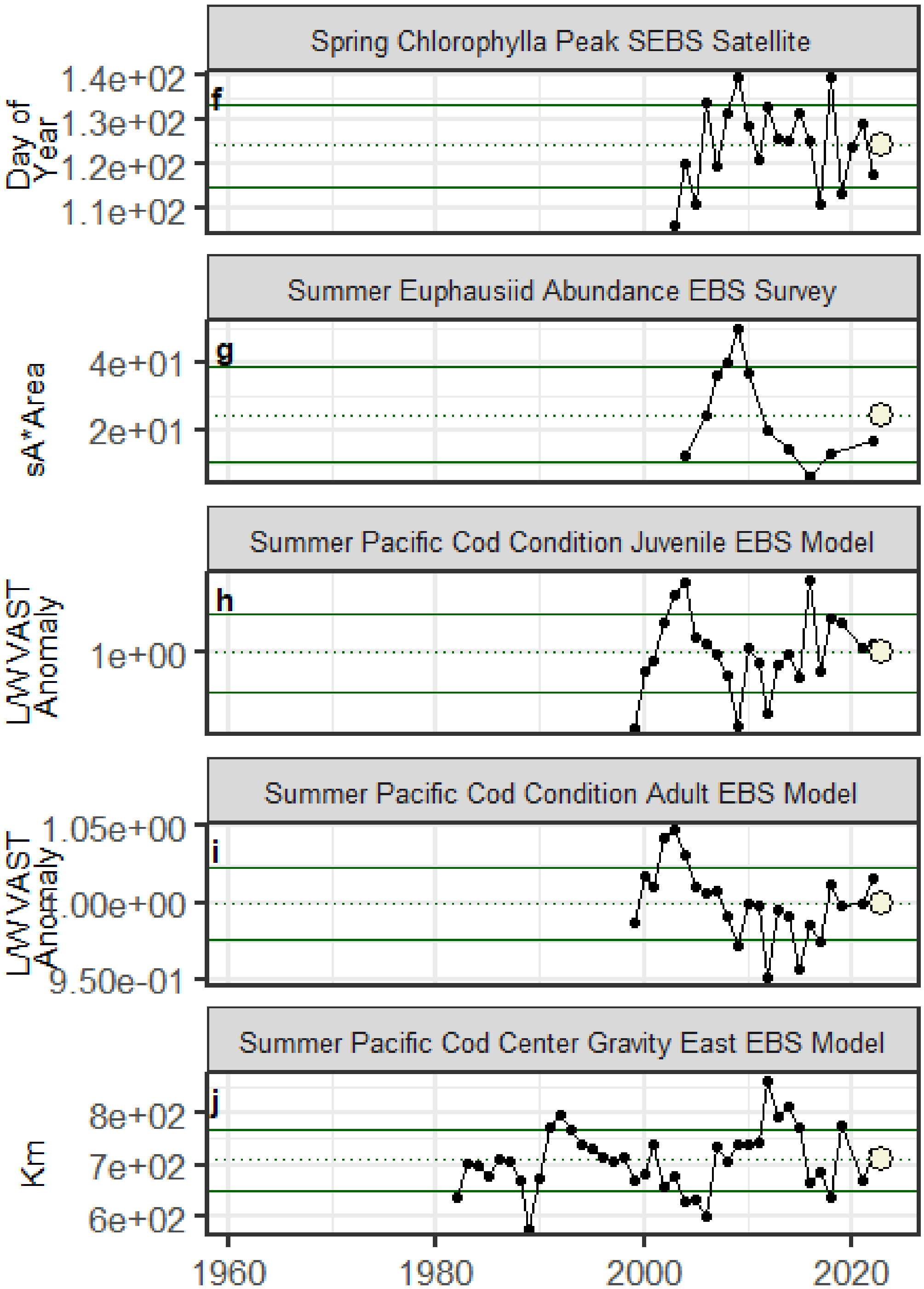

Figure 2.2.2a (cont.). Selected ecosystem indicators for EBS Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. A symbol appears when current year data are available and follows the traffic light status table designations (triangle direction represents if above or below 1 standard deviation of the time series mean, color represents proposed relationship for stock with blue for good conditions, red for poor conditions, and a white circle is neutral).

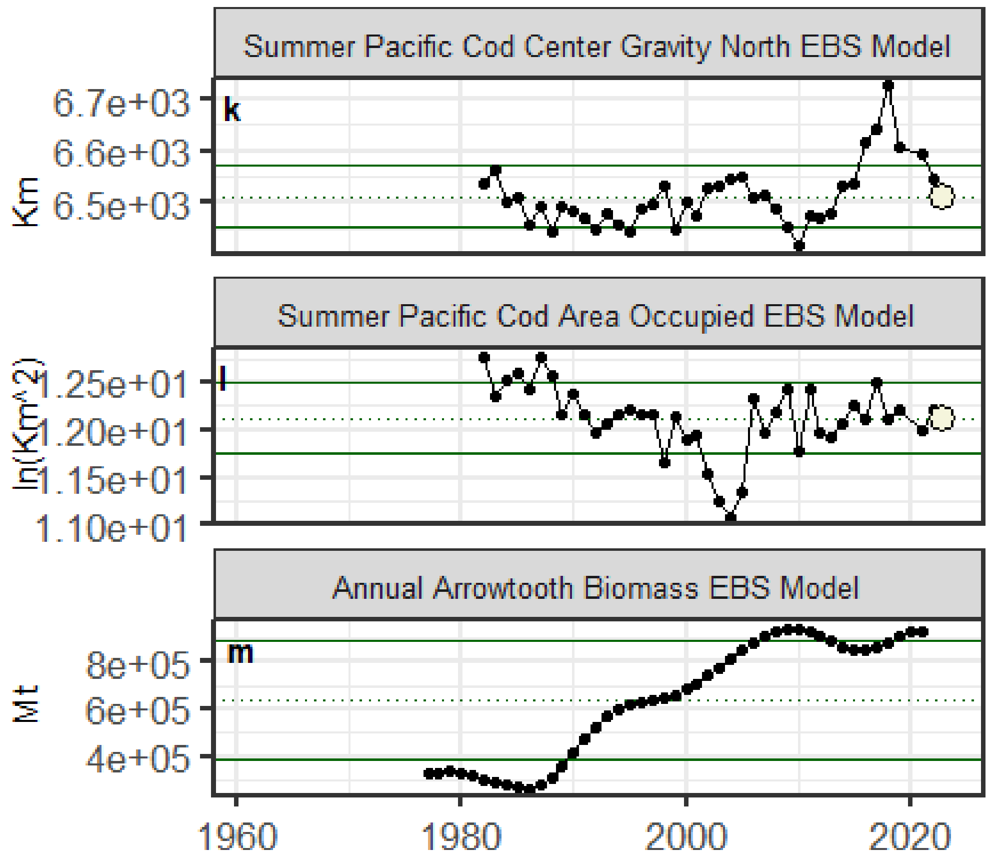

Figure 2.2.2a (cont.). Selected ecosystem indicators for EBS Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. A symbol appears when current year data are available and follows the traffic light status table designations (triangle direction represents if above or below 1 standard deviation of the time series mean, color represents proposed relationship for stock with blue for good conditions, red for poor conditions, and a white circle is neutral).

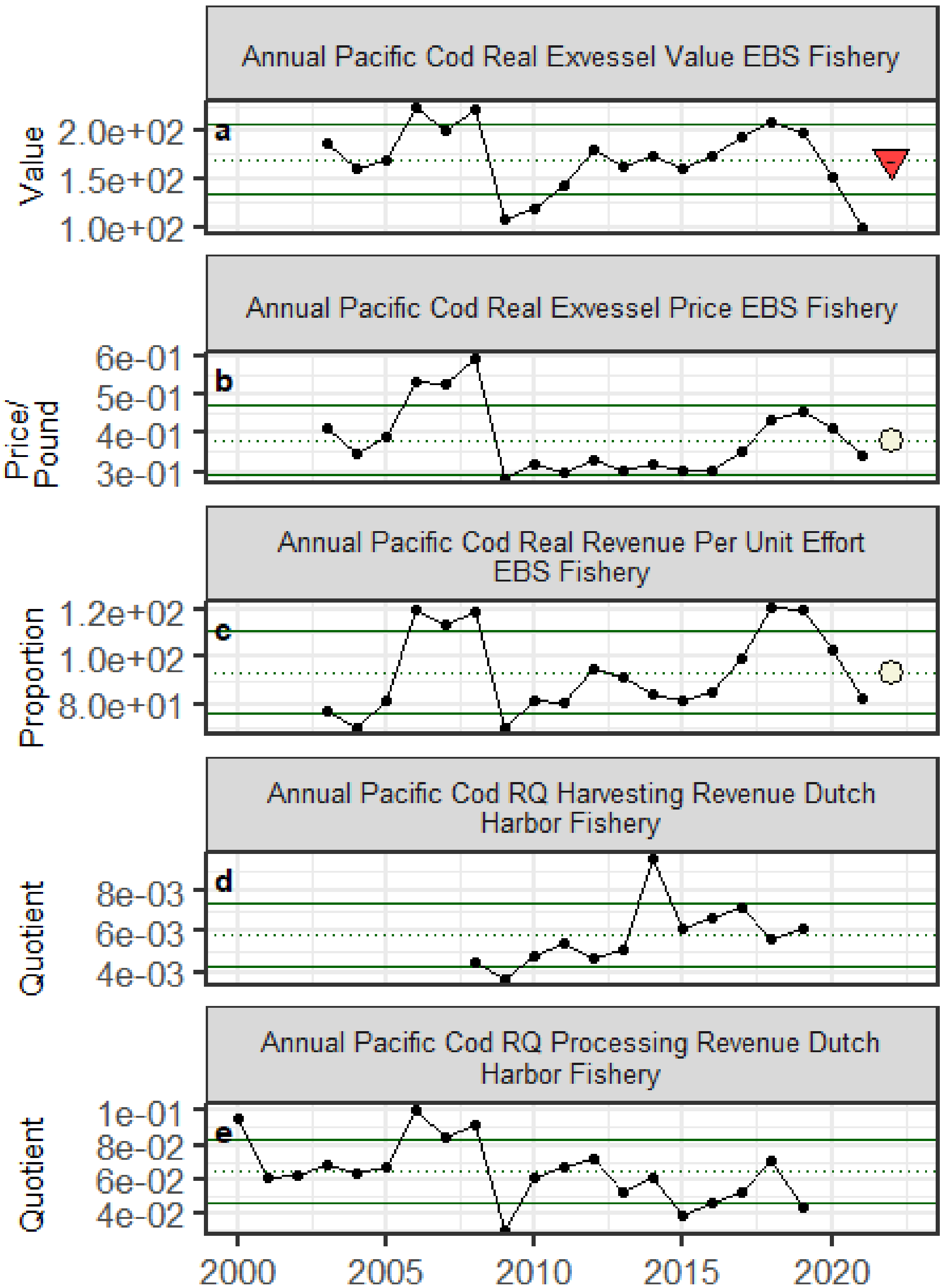

Figure 2.2.2b. Selected socioeconomic indicators for EBS Pacific cod with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. A symbol appears when current year data are available and follows the traffic light status table designations (triangle direction represents if above or below 1 standard deviation of the time series mean, color only designates above (blue) or below (red) one standard deviation of the time series mean, no implied relationship with the stock).

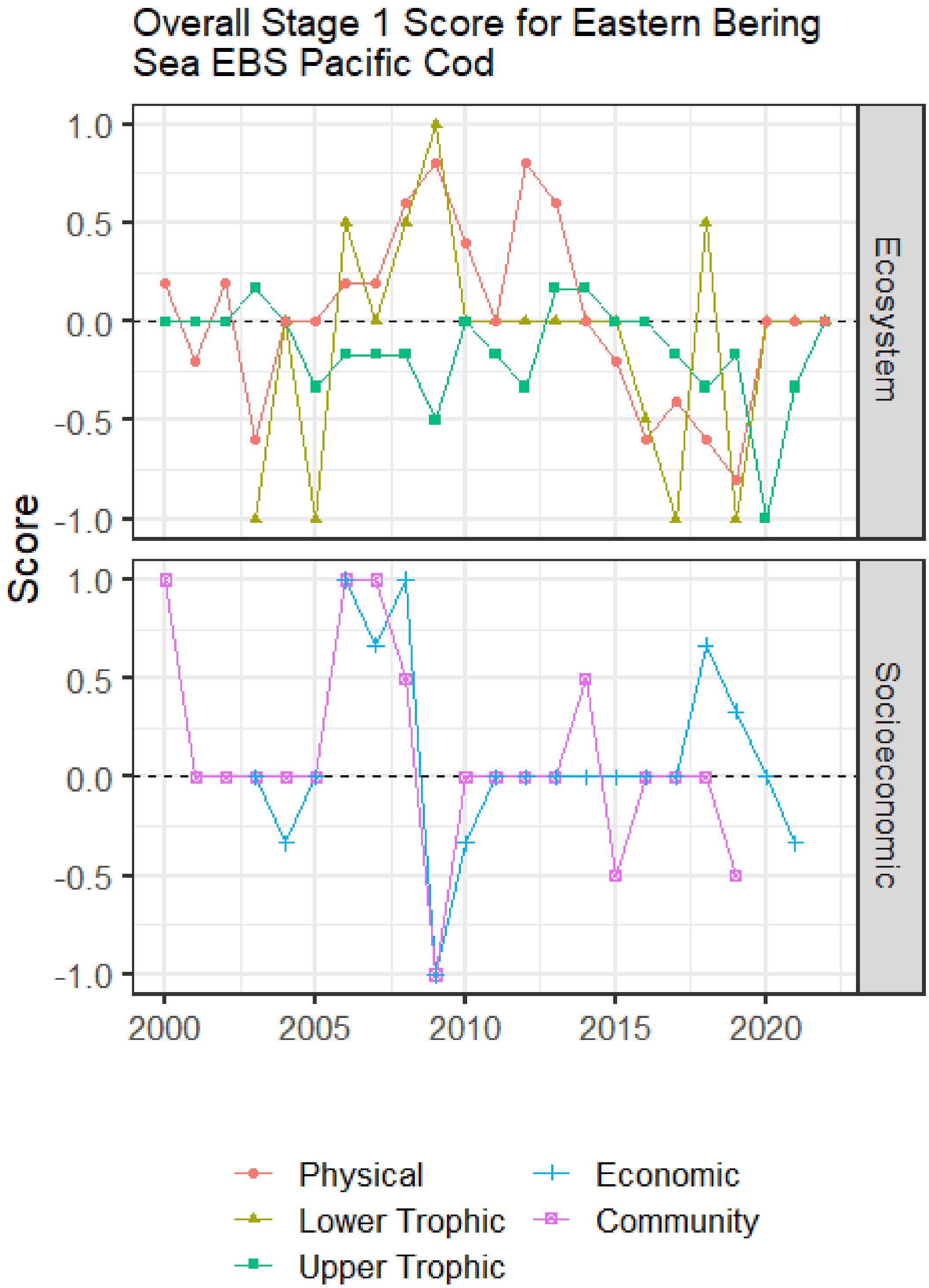

Figure 2.2.3: Simple summary traffic light score by category for ecosystem and socioeconomic indicators from 2000 to present.

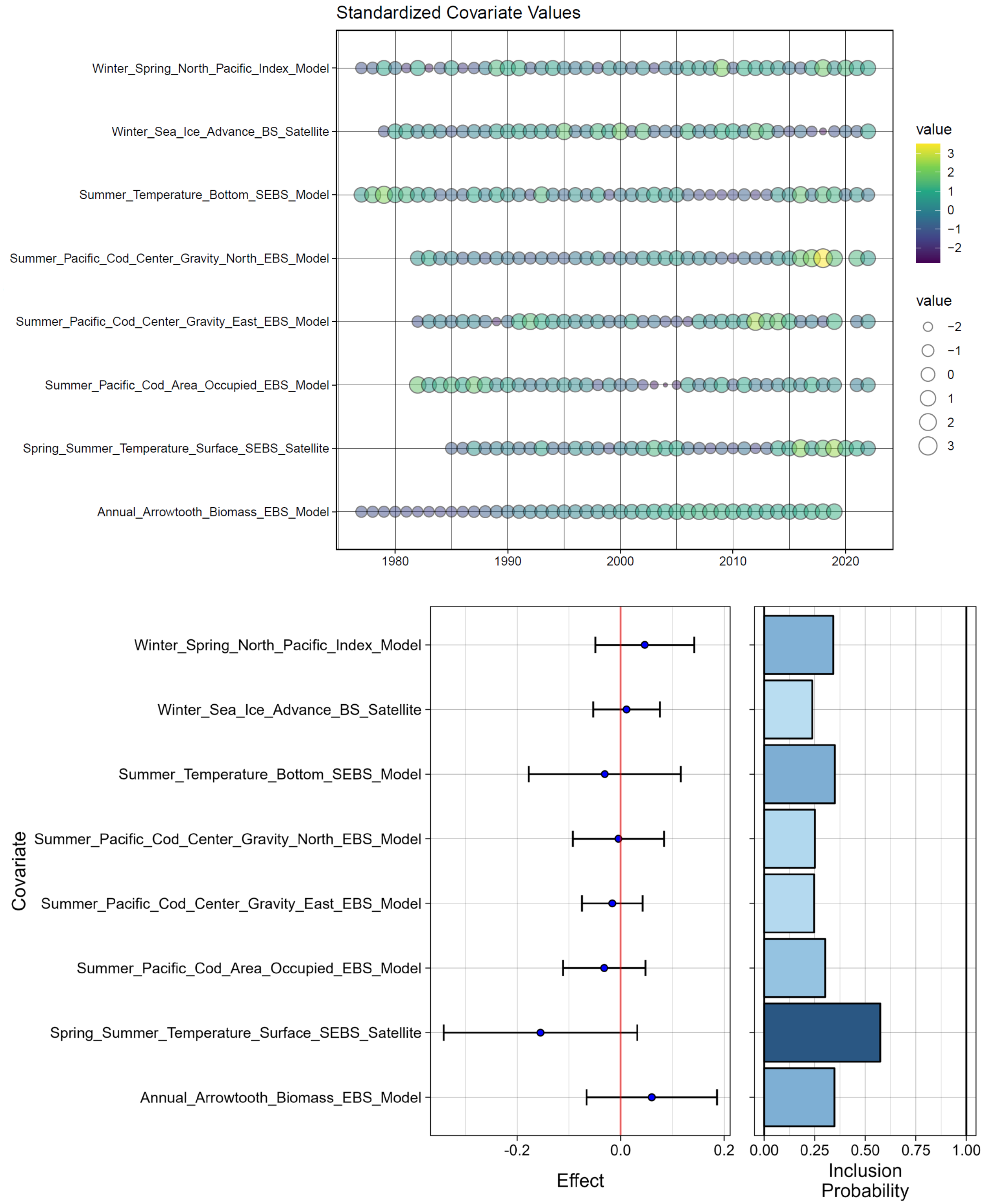

Figure 2.2.4: Bayesian adaptive sampling output showing (top graph) standardized covariates and (bottom graph) the mean relationship and uncertainty (95% confidence intervals) with log EBS Pacific cod recruitment, in each estimated effect (left bottom graph), and marginal inclusion probabilities (right bottom graph) for each predictor variable of the subsetted covariate set.