# Appendix xx. Ecosystem and Socioeconomic Profile of the snow crab stock in the Eastern Bering Sea

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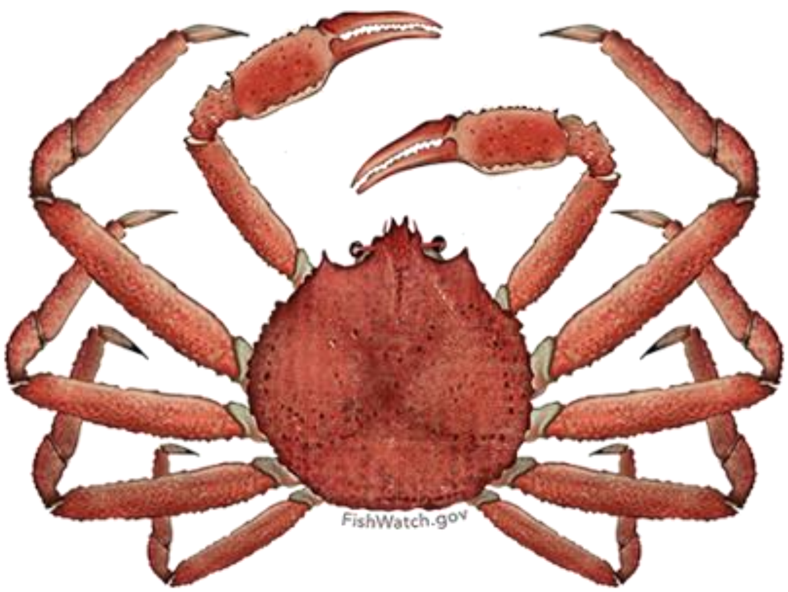


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# Executive Summary

National initiatives and North Pacific Fishery Management Council (NPFMC) recommendations suggest a high priority for conducting an ecosystem and socioeconomic profile (ESP) for the eastern Bering Sea (EBS) snow crab stock. In addition, annual guidelines for the Alaska Fisheries Science Center (AFSC) support research that improves our understanding of environmental and climate forcing of ecosystem processes with a focus on variables that can provide direct input into or improve stock assessment and management. The EBS snow crab ESP follows the new standardized framework for evaluating ecosystem and socioeconomic considerations for EBS snow crab, and may be considered a proving ground for potential use in the main stock assessment.

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

## Management Considerations

The following are the summary considerations from the current updates to the ecosystem and socioeconomic indicators evaluated for EBS snow crab:

- While the Arctic Oscillation index returned to a negative phase in 2021 following the highest Arctic Oscillation index in history, the spatial extent of the cold pool remains well-below average and likely represents the loss of suitable cold-water habitat for snow crab.
- Temperatures occupied by juvenile snow crab were above-average in 2021 and approached a proposed maximum temperature threshold of 2°C.
- Following a dramatic increase in the prevalence of bitter crab syndrome and Pacific cod predation in 2016, disease prevalence has continued to decline in 2021. Pacific cod consumption rates were not yet available for 2021.
- The average center of distribution of male snow crab in 2021 was the most northerly in the 33-year timeseries, indicative of a large-scale distribution shift from historic mid-shelf habitats.
- Size of male snow crab at 50% probability of maturation declined dramatically in 2021, reaching an all-time low.
- Reflecting the reduced 2021/22 EBS snow crab TAC, vessel participation in the EBS snow crab fishery declined to 37 in 2022, the lowest level since 1977 and approximately 60% of the fleet size over the previous five years.

## Modeling Considerations

The following are the summary considerations from the intermediate and advanced stage monitoring analyses for EBS snow crab:

- The highest ranked predictor for the recruitment regression model was juvenile snow crab disease prevalence, although marginal inclusion probabilities were < 0.5 for all predictors.

- Overall, intermediate stage monitoring analyses explained very little variation in snow crab recruitment. Future efforts should assess alternative metrics for recruitment and refine covariates and lags.

## Responses to SSC and Plan Team Comments on ESPs in General

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

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

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

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

We have also initiated a new document called the request for indicators or RFI to initiate the ESP process once an ESP is recommended for a stock. The RFI begins with a summary of the dominant ecosystem and socioeconomic processes influencing the stock and then provides the requested list of potential indicators representing those dominant pressures. Instructions for how to contribute an indicator in response to the stock request are included along with details on the indicator review process and associated guideline criteria, the role and responsibilities of ESP teams and contributors, and use and acknowledgement of the indicator if selected for the ESP. The standardized structure of the RFIs and the included guideline criteria will help with vetting indicators and assist with the review of indicators by the ESP teams. A RFI was created for EBS snow crab in September 2021 and presented to the Crab Plan Team for review in September 2021 and in January 2022. We plan to update this RFI with information from the “Data Gaps and Research Priorities” section for the next ESP cycle in 2023.

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

Community indicators are currently available in the Annual Community and Participation Overview (ACEPO) report (Wise et al., 2021), which presents social and economic information for communities that are substantially engaged in and/or dependent on the commercial groundfish and crab fisheries in Alaska, as well as in the annual Crab Economic SAFE. Moving forward, we plan to concentrate development of socioeconomic indicators in the ESP that are most directly associated with the condition or health of the stock and the conduct of the fishery, and therefore have the most direct bearing on the scope of stock assessment development and harvest specification decision processes that are the focus of ESP documents. Pending additional guidance, including clearer conceptual linkage of specific community-related indicators to factors within the scope of the ESP process, efforts toward more effective and timely monitoring and reporting of community engagement and dependency indicators to inform the Council regarding broader fishery science and management issues will be directed toward development of the ACEPO, Economic SAFE and other information products.

### Responses to SSC and Plan Team Comments Specific to this ESP

"The SSC noted the relatively strong correlations for snow crab and BBRKC with the Arctic Oscillation, and suggests this could be further explored to determine the mechanism. The SSC requests that the CPT or the crab assessment authors examine recruitment estimates across crab stocks to see if they share a common underlying pattern. The SSC recommends that an Ecosystem and Socioeconomic Profile (ESP) be developed for EBS snow crab as time allows that carefully considers what indicators directly affect this stock" (SSC, October 2020, pg. 16)

We have developed this full ESP for EBS snow crab following the standardized ESP template detailed in (Shotwell et al., *In Review*) as recommended by the SSC.

# Introduction

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

This ESP for EBS snow crab (*Chionoecetes opilio*) follows the template for ESPs (Shotwell et al., *In Review*) and replaces the previous ecosystem considerations section in the main EBS snow crab stock assessment and fishery evaluation (SAFE) report. Information from the original ecosystem considerations section may be found in Szuwalski (2021).

The ESP process consists of the following four steps:

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

### Justification

National initiatives and NPFMC recommendations support conducting an ESP for the EBS snow crab stock. The high commercial importance and constituent demand of the stock and habitat dependence throughout the life cycle created a high score for both stock assessment and habitat assessment prioritization (Methot, 2015; McConnaughey et al., 2017). The vulnerability scores were low to moderate based on productivity, susceptibility (Patrick et al., 2010), and high sensitivity with low exposure based on future climate exposure (Spencer et al., 2019). The new data classification scores for EBS snow crab suggest a data-moderate stock with high quality data for catch and abundance, and moderate quality data for size/age composition, life history categories, and ecosystem linkages (Lynch et al., 2018). These initiative scores and data classification levels suggest a moderate to high priority for conducting an ESP for EBS snow crab. Additionally, AFSC research priorities support studies that improve our understanding of environmental and climate forcing of ecosystem processes with focus on variables that provide direct input into stock assessment and management. Finally the Crab Plan Team and SSC have requested an ESP be conducted for EBS snow crab as time allows to consider what indicators directly affect the EBS snow crab stock.

### Data

Initially, information on EBS snow crab was gathered through a variety of national initiatives that were conducted by AFSC personnel in 2015 and 2016. These include (but are not limited to) stock assessment prioritization, habitat assessment prioritization, climate vulnerability analysis, and stock assessment categorization. Data derived from this effort served as the initial starting point for developing the ESP metrics for stocks in the Bering Sea and Aleutian Islands (BSAI) and Gulf of Alaska (GOA) groundfish fishery management plans (FMP) and the BSAI king and tanner crab FMP. Please see Shotwell et al., *In Review*, for more details.

Data used to generate ecosystem metrics and indicators for the EBS snow crab ESP were collected from a variety of laboratory studies, remote sensing databases, fisheries surveys, regional reports and fishery observer data collections (Table 1). Results from laboratory studies were specifically used to inform metrics and indicators relating to thermal tolerances, phenology and energetics across EBS snow crab life history stages (Table 2a). Larval indicator development utilized blended satellite data products from NOAA, NASA and ESA. Data for late-juvenile through adult EBS snow crab stages were derived from the annual NOAA eastern Bering Sea bottom trawl survey and fishery observer data collected during the EBS snow crab fishery. Data from the NOAA Resource Ecology and Ecosystem Modeling (REEM) food habits database were used to determine Pacific cod consumption rates.

Data used to generate socioeconomic metrics and indicators were derived from fishery-dependent sources, including commercial landings data for EBS snow crab collected in ADFG fish tickets and the BSAI Crab Economic Data Report (EDR) database (both sourced from AKFIN), and effort statistics reported in the most recent ADFG Annual Management Report for BSAI shellfish fisheries estimated from ADF&G Crab Observer program data (Leon et al. 2017).

## Metrics Assessment

We first provide the analysis of the national initiative data used to generate the baseline metrics for this second step of the ESP process and then provide more specific analyses on relevant ecosystem and/or socioeconomic processes. Metrics are quantitative stock-specific measures that identify vulnerability or resilience of the stock with respect to biological or socioeconomic processes. Where possible, evaluating these metrics by life history stage can highlight potential bottlenecks and improve mechanistic understanding of ecosystem or socioeconomic pressures on the stock.

### National Metrics

The national initiative data were summarized into a metric panel (Figure 1) that acts as a first pass ecosystem and socioeconomic synthesis. Metrics ranged from estimated values to qualitative scores of population dynamics, life history, or economic data for a given stock (see Shotwell et al., *In Review* for more details). To simplify interpretation, the metrics were rescaled by using a percentile rank for EBS snow crab relative to all other stocks in the groundfish and crab FMPs. Additionally, some metrics were inverted so that all metrics could be compared on a low to high scale between all stocks in the FMPs. These adjustments allowed for initial identification of vulnerable (percentile rank value is high) and resilient (percentile rank value is low) traits for EBS snow crab. Data quality estimates were also provided from the lead stock assessment author (0 or green shaded means no data to support answer, 4 or purple shaded means complete data), and if there were no data available for a particular metric then an "NA" would appear in the panel. EBS snow crab did have a few data gaps for the metric panel namely mean trophic level, growth rate, and recruitment variability as these categories were not well understood for crab stocks. Data quality ranged from no data to good for the remaining metrics. The metric panel gives context for how EBS snow crab relate to other groundfish and crab stocks in the FMPs and highlights the potential vulnerabilities for the EBS snow crab stock.

The 80$^{th}$ and 90$^{th}$ percentile rank areas are provided to highlight metrics indicating a high level of vulnerability for EBS snow crab (Figure 1). Spawning cycle and fecundity fell within the 80$^{th}$ percentile rank when compared to other stocks in the groundfish and crab FMPs. Latitude range, ocean acidification sensitivity, commercial importance, habitat dependence, early life history survival and settlement, complexity in reproductive strategy, spawning duration, and temperature sensitivity all fell within the 90$^{th}$ percentile rank. EBS snow crab were relatively resilient for breeding strategy, geographic concentration, maximum length, length at 50% maturity, predation stressors, prey specificity, and dispersal during early life history.

## Ecosystem Processes

Data evaluated over ontogenetic shifts (e.g., embryo, larvae, juvenile, adult) may be helpful for identifying specific bottlenecks in productivity and relevant indicators for monitoring. As a first attempt, we summarized important ecosystem processes or potential bottlenecks across snow crab life history stages from the literature, process studies and laboratory rearing experiments (Table 2) and created a summary conceptual model of this information (Figure 2). Details on why these processes were highlighted, as well as the potential relationship between ecosystem processes and stock productivity are described below.

After molting to maturity, female snow crab mate and extrude new egg clutches each spring, which remain attached to pleopods on the female’s abdomen for a full year prior to hatching (Watson, 1970). Fecundity is positively correlated with female size, and primiparous females have a lower fecundity than multiparous females (Sainte-Marie, 1993). The optimal range for embryo development is 0 to 3°C, although laboratory studies indicate that incubation temperatures below 0°C can trigger diapause or a biennial reproduction cycle (Webb et al., 2007). Peak hatching of snow crab larvae occurs in April (Armstrong et al., 1981) and phyto-detritus may act as a chemical cue for larval release (Starr et al., 1994). Larval duration for each of the two zoeal stages is approximately 30 days (Incze et al., 1982). A longer larval stage associated with cooler temperatures may leave larvae more vulnerable to pelagic predators for a prolonged period. Furthermore, historical larval year-class failures have coincided with low zooplankton abundance over the middle shelf and low water column stability, suggesting that increased larval mortality is related to less favorable feeding conditions (Incze et al., 1987) and mismatches between larval release and the spring bloom (Somerton 1982). Likewise, laboratory studies suggest that relatively high prey densities are required for successful feeding in snow crab zoeae (Paul et al., 1979). Major predators of larval snow crab include yellowfin sole (Armstrong et al., 1980), walleye pollock, jellyfish and juvenile salmon (Kruse et al., 2007).

Snow crab larvae settle from late August to the end of October (Conan et al., 1992). Early benthic instars are cryptic and concentrate in shallow, cold water habitats (Lovrish et al., 1995; Murphy et al., 2010). Previous laboratory studies have shown that adequate energetic stores are prerequisites for molting, growth, and survival in snow crab early life history stages (e.g. Lovrich and Ouellet, 1994), indicating that variability in energetic reserves could represent a potential recruitment bottleneck in snow crab. Both settlement intensity and early benthic survival are likely critical determinants of year-class strength in snow crab (Sainte-Marie et al., 1996), and successful advection to areas of suitable temperature and muddy substrate are thought to be critical criteria for juvenile survival (Dionne et al., 2003). Density-dependence may also play a regulatory role due to high rates of cannibalism (Lovrich and Sainte-Marie 1997) and potential prey resource limitation in juvenile nurseries. Previous studies have shown that Pacific cod, sculpin, skates and halibut are major predators of juvenile snow crab (Livingston et al., 1993; Livingston and deReynier, 1996; Lang et al., 2003) and the cold pool may provide refuge from predators like Pacific cod that avoid waters less than 2°C (Ciannelli and Bailey, 2005). Juvenile snow crab are especially vulnerable to predation and cannibalism during and immediately following molting.

Spatial patterns in juvenile and adult snow crab distribution are determined largely by ontogenetic migrations linked to size- and sex-specific thermal requirements. Immature snow crab concentrate in colder, shallow waters of the NBS and EBS middle shelves, and have historically avoided thermal habitats >2°C (Kolts et al., 2015; Murphy, 2020). Likewise, primiparous female snow crab appear to track near-bottom temperature during a northeast to southwest ontogenetic migration to warmer waters near the shelf break (Ernst et al., 2005; Parada et al., 2010). Shifts in centers of distribution of mature female snow crab relative to prevailing currents may affect larval supply to nursery areas (Zheng and Kruse, 2006) and thermal occupancy patterns of snow crab depend on the availability of cold water habitat (Fedewa et al., 2020). While 2°C may represent a critical temperature threshold for immature snow crab (Murphy, 2020), negative effects on metabolic processes are not apparent in mature snow crab until temperatures exceed 7°C (Foyle et al., 1989). Temperature also influences molt timing (Dutil et al., 2010), growth rates (Yamamoto et al., 2015), energy stores (Hardy et al., 2000), and body condition (Dutil et al., 2010) of snow crab in the laboratory.

### Socioeconomic Processes

As described below, the set of socioeconomic indicators proposed in this ESP are categorized as Fishery Performance and Economic Performance indicators. Fishery Performance indicators are intended to represent processes most directly involved in prosecution of the EBS snow crab fishery, and thus have the potential to differentially affect the condition of the stock depending on how they influence the timing, spatial distribution, selectivity, and other aspects of fishing pressure. Economic Performance indicators are intended to capture observable dimensions of key economic drivers of fishery performance and fleet behavior. Notwithstanding these categorical distinctions, the social and economic processes that affect ¬-- and are affected by -- the condition of the stock are complex and interrelated at different time scales. While the complex of reciprocal linkages between condition of the EBS snow crab stock and fishery and economic performance-related processes may be hypothesized in principal, no conceptual model currently exists that is adequate to support practical predictive application of socioeconomic indicators comparable to that of ecosystem indicators for informing the snow crab assessment. A further distinction of most observable socioeconomic processes from ecosystem processes associated with the EBS snow crab fishery is that data collection and monitoring of many aspects of socioeconomic processes is conducted during or following the fishing season, such that the most recent available data point may be lagged by up to two years behind the current assessment, and as such, cannot be captured in indicators that provide advance information for use in informing the current stock assessment. As such, in the context of the ESP, available time series of socioeconomic indicators are largely limited to providing a general frame of reference regarding socioeconomic factors associated with historic fishery management, to inform interpretation of historic patterns observed in other data series captured in the assessment and, potentially, stimulating research on linkages between socioeconomic processes and stock condition.

Socioeconomic processes associated with fisheries are strongly influenced by the institutional structures of fishery management, which develop over time and include both measures undertaken in the course of in-season management, as well as comprehensive changes in management and industry structures that induce complex, multidimensional change affecting numerous social and economic processes.

Implementation of the Crab Rationalization (CR) Program, including the shift from GHL to TAC management (effectively controlling harvest overages) beginning in 2005 is an example of the latter, and arguably represents a regime shift in management and economic structure of the fishery (a full summary of the management history of the EBS snow crab fishery is beyond the scope of the ESP; see NPFMC, 2017 and Nichols, et al., 2021). Among other changes, the CR program resulted in rapid consolidation of the EBS snow crab fleet, from a high of 272 vessels in 1994 to 78 during the first year of the CR program. Allocation of tradable crab harvest quota shares, with leasing of annual harvest quota, facilitated fleet consolidation and improved operational and economic efficiency of the fleet, changing the timing of the fishery from short derby seasons to more extended seasons, and inducing extensive and ongoing changes in harvest sector ownership, employment, and income. Crab processing sector provisions of the CR program include allocation of transferable processing quota shares (PQS), leasing of annual processing quota and custom-processing arrangements that enable PQS holders that do not operate a processing plant to purchase IFQ crab landings and direct them to a processing plant for custom processing, and community protection measures, including regional designation on harvest quota, requiring associated catch to be landed to ports within a specified region. While these and other elements of CR program design facilitated similar operational and economic efficiencies in the harvest sector, with more limited consolidation of processing capacity to somewhat fewer locations, and fewer plants in some ports, they have also limited some economic adjustments that would likely have occurred in their absence. Most notably, North regional designation of a large fraction of EBS snow crab IFQ has likely maintained a larger proportion of landings to St. Paul Island than would have occurred otherwise. St. Paul Island has historically and to-date received the largest share of EBS snow crab landings, with Akutan, King Cove, and Unalaska/Dutch Harbor representing the other principal landing ports for EBS landings historically and to-date. See the Council's 10-Year Program Review for the CR Program for detailed description and analysis of program structure and management (Council, 2017).

These and other institutional changes continue to influence the geographic and inter-sectoral distribution of benefits produced by the EBS snow crab fishery, both through direct ownership and labor income in the EBS snow crab harvest and processing sectors, and indirect social and economic effects on fishery-dependent communities throughout Alaska and greater Pacific Northwest region. The full range of available metrics reflecting fishery, economic, and social processes cannot be captured within the scope of the ESP framework. A more comprehensive suite of metrics and indicators intended to inform Bering Sea crab fishery management, including annual harvest specifications as well as consideration of management measures addressing distributional issues or mitigation of social and economic effects of stock declines, low TAC levels and fishery closures, are provided in the annual Crab Economic SAFE and ACEPO reports.

# Indicators Assessment

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

## Indicator Suite

*Ecosystem Indicators*

Physical Indicators (Figure 3a.a-c)

a.) Anomalies of average daily sea-ice extent relative to 1978-2010 mean computed over ice-retreat season of March through May (contact: Muyin Wang)
b.) The areal extent of EBS bottom trawl survey stations with bottom temperatures < 2ºC (contact: Erin Fedewa)
c.) Winter-spring Arctic Oscillation index from the NOAA National Climate Data Center (contact: Erin Fedewa)

Lower Trophic Indicators (Figure 3a.d-e)

d.) Derived chlorophyll a concentration during spring and summer season (April, May, June) in the northern middle southeastern Bering Sea from the MODIS satellite (contact: Jens Nielsen)
e.) Benthic invertebrate biomass was determined from the EBS bottom trawl survey catch data for southeastern Bering Sea and includes brittle stars, sea stars, sea cucumber, bivalves, non-commercial crab species, shrimp and polychaetes. (contact: Erin Fedewa)

Upper Trophic Indicators (Figure 3a.f-k)

f.) Mean carapace width of male snow crab at 50% probability of maturation, as determined from maturity curves developed from EBS bottom trawl survey data (contact: Jon Richar)
g.) The daily summer consumption of snow crab by Pacific cod in the EBS, estimated from Pacific cod diet compositions, EBS trawl survey CPUE, and temperature adjusted length-specific maximum consumption rates (contact: Kerim Aydin)
h.) Mean bottom temperature weighted by immature female snow crab CPUE at each station of the EBS summer bottom trawl survey (contact: Erin Fedewa)
i.) Prevalence of immature snow crab showing visual evidence of Bitter Crab Syndrome during the summer EBS bottom trawl survey (contact: Erin Fedewa)
j.) Area occupied, calculated as the minimum area containing 95% of the cumulative male snow crab CPUE during the EBS summer bottom trawl survey (contact: Erin Fedewa)
k.) CPUE-weighted average latitude of the male snow crab stock during the EBS summer bottom trawl survey (contact: Erin Fedewa)

*Socioeconomic Indicators*

Fishery Performance Indicators (Figure 3b.a-e)

a.) Annual number of active vessels in the snow crab fishery, representing the level of fishing effort assigned to the fishery (contact: Brian Garber-Yonts)
b.) Annual catch-per-unit-effort (CPUE), expressed as mean number of crabs per potlift, in the snow crab fishery, representing relative efficiency of fishing effort (contact: Kalei Shotwell)
c.) Center of gravity, expressed in latitude, as an index of spatial distribution for the snow crab fishery to monitor spatial shifts in fishery behavior (contact: Kalei Shotwell)
d.) Annual incidental catch of snow crab in EBS groundfish fisheries (contact: Brian Garber-Yonts)
e.) Annual total potlifts in the snow crab fishery, representing the level of fishing effort expended by the active fleet (contact: Kalei Shotwell)

Economic Indicators (Figure 3b.f-h)

f.) Annual snow crab ex-vessel price per pound, representing per-unit gross economic returns to the harvest sector, as a principal driver of fishery behavior (contact: Brian Garber-Yonts)

g.) Annual snow crab ex-vessel revenue share, expressed as vessel-average proportion of annual gross landings revenue earned from the EBS snow crab fishery (contact: Brian Garber-Yonts)
h.) Annual snow crab ex-vessel value of the snow crab fishery landings, representing gross economic returns to the harvest sector, as a principal driver of fishery behavior (contact: Brian Garber-Yonts)

## 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. These analyses gradually increase in complexity depending on the stability of the indicator for monitoring the ecosystem or socioeconomic process and the data availability for the stock (Shotwell et al., *In Review*). The beginning stage is a relatively simple score based on 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.

At this time, we report the results of the beginning and intermediate stages of the indicator monitoring analysis for EBS snow crab and a review of current ecosystem linked modeling developments for the advanced stage.

*Beginning Stage: Simple Score*

We use a simple scoring calculation for the beginning stage 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 (Figure 2) is also assigned to the indicator where possible for ecosystem indicators only. 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. We provide the category scores for the past twenty years as the majority of indicators were available throughout this time period (Figure 4). The scores over time allow for comparison of the indicator performance and the history of stock productivity. We also provide five year indicator status tables with a color or text code for the relationship with the stock (Table 3) and evaluate the current year status in the historical indicator time series graphic (Figure 3) for each ecosystem and socioeconomic indicator.

We evaluate the list of ecosystem indicators to understand the pressures on the EBS snow crab stock regarding recruitment, stock productivity, and stock health. We start with the physical indicators and proceed through the increasing trophic levels, fishery performance, and economic indicators as listed above. Following the 2019-2020 highest Arctic Oscillation index in history (Zhang et al., 2021), the winter-spring Arctic Oscillation index returned to near-normal in 2021. Poor snow crab recruitment has been associated with positive values of the Arctic Oscillation (Szuwalski et al., 2021), suggesting that large-scale weather and climate anomalies in 2019/2020 could have impacted stock productivity. Likewise, the summer cold pool extent has remained well-below average. Although 2021 spring sea ice extent estimates were not yet available, 2018 and 2019 sea ice extent reached an all-time low.

Lower trophic level indicators include chlorophyll-*a* biomass and benthic invertebrate biomass, both of which represent potential prey resources for pelagic and benthic snow crab stages. While chlorophyll-*a* biomass was near-average in 2021, benthic invertebrate biomass increased due to large catches of purple-orange sea stars. For the upper trophic level indicators, male snow crab area occupied and juvenile disease prevalence remained near-average in 2021. The male snow crab center of distribution shifted north, potentially indicating temperature-driven distributional shifts, or contraction of north-to-south ontogenetic migrations driven by thermal preferences (Orensanz et al., 2004). Likewise, temperatures occupied by immature snow crab were well-above average in 2021, suggesting that cold-water habitat critical for evading groundfish predators was likely unavailable to juveniles. Male size at 50% probability of maturation declined dramatically in 2021 which may be indicative of population-level shifts in the average size at maturity.

Calendar year 2020 is the most recent year for which data is available for six of the eight socioeconomic indicators, and two of the fishery performance indicators, count of active EBS snow crab vessels and incidental catch in EBS groundfish fisheries, are available for 2021 and are produced for 2022 to-date. Incidental catch has remained substantially below the historical average, while remaining within one standard deviation, since 2008; although scoring qualitatively neutral for 2021 (the most recent value measured for the full calendar year), this indicator approached the lowest value for the entire time series. The active snow crab fleet during 2022 (noting that the fishery is ongoing as of preparation of this draft report) declined to 37 vessels, the lowest level since 1977 at the beginning of the time series, and approximately 60% of the number of vessels participating during the previous five years. The latitude of the center of gravity of the 2020 fishery shifted to the northwestern extent of the EBS, approaching the boundary of the U.S. EEZ, exceeding three standard deviations above the historical mean. CPUE and total potlifts were within the normal range relative to recent and historical values.

Economic performance indicators ex-vessel price and ex-vessel revenue share reached high values during 2020, exceeding one standard deviation above the historical mean. Ex-vessel price reached historically high values from 2018 through 2020, largely reflecting market conditions preceding the covid-19 pandemic. Wholesale price data from 2020 (Crab Economic SAFE) and subsequent market trends indicate ex-vessel price for snow crab during 2021 and 2022 will substantially exceed the hisrorical range of variation for this indicator. EBS snow crab ex-vessel revenue share for vessels participating in the fishery during calendar year 2020 reached the highest value to date, largely reflecting the reduced TAC in the Bristol Bay red king crab fishery during 2020 (which is the principal target and revenue source in addition to snow crab for most vessels participating in the snow crab fishery) and reduced red king crab gross revenues at the average vessel level, and more generally, the lack of alternate target fisheries available to crab vessels.

*Intermediate Stage: Importance Analysis*

Bayesian adaptive sampling (BAS) was used for the intermediate stage statistical analysis to quantify the association between hypothesized predictors and EBS snow crab recruitment and to assess the strength of support for each hypothesis. BAS explores model space, or the full range of candidate combinations of predictor variables, to calculate marginal inclusion probabilities for each predictor, model weights for each combination of predictors, and generate Bayesian model averaged predictions for outcomes (Clyde et al., 2011). In this intermediate analysis, the full set of indicators is first winnowed to the predictors that could directly relate to recruitment and highly correlated covariates are removed (Figure 5). 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. This results in a model run from 1989 through 2021 (excluding 2008 and 2020) for EBS snow crab. We then provide the mean relationship between each predictor variable and log EBS snow crab recruitment over time (Figure 5, 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 5, right side). A higher probability indicates that the variable is a better candidate predictor of EBS snow crab recruitment. The highest ranked predictor variable based on this process was juvenile snow crab disease prevalence, although all marginal inclusion probabilities were < 0.5 and the model had very little explanatory power (Figure 5).

The BAS method requires observations of all predictor variables in order to fit a given data point. This method estimates the inclusion probability for each predictor, generally by looking at the relative likelihood of all model combinations (subsets of predictors). If the value of one predictor is missing in a given year, all likelihood comparisons cannot be computed. When the model is run, only the subset of observations with complete predictor and response time series are fit. It is possible to effectively trick the model into fitting all years by specifying a 0 (the long-term average in z-score space) for missing predictor values. However, this may bias inclusion probabilities for time series that have more zeros and result in those time series exhibiting low inclusion probability, independent of the strength of the true relationship. Due to this consideration of bias, we only fit years with complete observations for each covariate at the longest possible time frame. This resulted in a smaller final subset of covariates. We plan to explore alternate model runs to potentially include more covariates in the future.

*Advanced Stage: Research Model*

New research models are currently being explored to assess potential mechanisms for increased mortality (e.g. bitter crab syndrome, cod predation, cannibalism) in 2019-2020.

# Conclusion

The EBS snow crab ESP follows the standardized framework for evaluating the various ecosystem and socioeconomic considerations for this stock (Shotwell et al., *In Review*). Given the metric and indicator assessment we provide the following summary for ecosystem and socioeconomic indicators:

## Ecosystem Indicators

In summary, ecosystem indicators highlight the potential loss of cold-water habitat available to snow crab, as evidenced by record-low cold pool extent and dramatic increases in temperatures occupied by immature snow crab in recent years. 2020 marked the highest Arctic Oscillation in history, which has been associated with poor snow crab recruitment. Declines in sea ice extent also pose negative consequences for spring cold pool formation, carbon flux to the benthos and spatiotemporal mismatches with snow crab larvae and spring blooms. Pacific cod consumption and bitter crab syndrome prevalence reached all-time highs in 2016 and may have been attributed to 2019-2020 mortality events, although both indices returned to near-average in 2021. Northerly shifts in male snow crab centers of distribution in 2021 coincided with a large-scale snow crab population decline.

## Socioeconomic Indicators

The most recently available time series of fishery and economic performance indicators for the EBS snow crab fishery largely predate the historically low TAC set for the 2021/22 season. High ex-vessel price during 2020, and likely historically high values during 2021 and 2022, as well as the substantial contraction of the fleet and consolidation of harvest quota indicated for the ongoing 2022 snow crab fishery, will partially mitigate some economic impacts on the crab harvest sector resulting from the historically low 2021/22 snow crab TAC, however, these factors are offset by increased operational costs due to the shift of fishing activity to more remote grounds and exogenous increase in fuel prices and other input costs associated with broader market trends during 2021 and 2022.

### Data Gaps and Future Research Priorities

Future research should support the development of indicators that quantify snow crab physiological and biological responses to rapidly changing ecosystem conditions in the Bering Sea. Recent, dramatic population declines emphasize the importance of understanding proximate causes and mechanisms for mortality including predator-prey interactions, disease dynamics, shifts in benthic production, and responses to thermal stress.

Refinements or updates to existing indicators may also be warranted given the limited inference resulting from stage 2 modeling efforts. Spatial scales for physical and lower trophic level indicators may need to be refined to overlap with spatial distributions across ontogeny. The development of Essential Fish Habitat maps for snow crab by life history stage would provide spatial bounds to subset physical and lower trophic level datasets. Furthermore, replacing chlorophyll-*a* biomass estimates with size fractionation data might better clarify the role of diatoms in enhancing larval survival.

The limited scope and timeliness of socioeconomic indicators reported in the ESP provide little information regarding the economic stresses on the harvest and processing sectors of the Bering Sea crab fisheries and associated communities resulting from the recent declines in the two principal Bering Sea crab fisheries. These stresses, if persistent, have the potential to induce substantial structural changes in crab harvest and processing industries, as well as management changes intended to mitigate adverse social and economic effects, ultimately inducing systematic operational changes in the behavior of snow crab fishing vessels. Lacking a conceptual framework for capturing linkages between social and economic drivers, fishing behavior, and condition of the crab stock, it is difficult to conceive how any suite of socioeconomic indicators in the context of the ESP may meaningfully inform the snow crab stock assessment or harvest specification process. Research in spatial aspects of the EBS snow crab fishery with direct relation to the stock assessment may provide the basis for further development of relevant and informative socioeconomic indicators for use in the ESP. As well, improving the timeliness of socioeconomic indicators should be explored, including use of models for nowcast/forecast of time series, and or alternate or proxy measures that track key socioeconomic indicators.

# 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 also thank the Crab Plan Team and SSC for their helpful insight on the development of this report and future reports.

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Note: full citations for referenced sources will be included for the final September, 2022 draft of the ESP.

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# Tables

Table 1: List of data sources used in the ESP evaluation. Please see the main EBS snow crab SAFE document, the Ecosystem Considerations Report (Siddon, 2021) and the Economic Status Report (Garber-Yonts *et al.*, 2021) for more details.

| Title | Description | Years | Extent |
|---|---|---|---|
| AFSC Bottom Trawl Survey | Bottom trawl survey of groundfish in June through August, eastern Bering Sea using Poly Nor'Eastern trawl on stratified random sample grid, catch per unit of effort in metric tons | 1982 – present | Gulf of Alaska annual |
| REEM Diet Database | Food habits data and associated analyses collected by the Resource Ecology and Ecosystem Modeling (REEM) Program, AFSC on multiple platforms | 1990 – present | Gulf of Alaska annual |
| MODIS | 4 km MODIS ocean color data aggregated 8-day composites. | 2003-present | Global |
| NOAA National Climate Data Center | Monthly large-scale climate indices constructed by the National Weather Service's Climate Prediction Center | 1950-present | North Pacific annual |
| ADF&G Crab Observer program data | Snow crab catch and effort data (number of active vessels, total pots lifted, and CPUE), sourced from ADF&G Annual Fishery Management Report | 1980-2019 | Alaska |
| ADF&G fish ticket database | Volume, value, and port of landing for Alaska crab and groundfish commercial landings; data processed and provided by Alaska Fisheries Information Network | 1992-2019 | Alaska |

Table 2a: Ecological information by life history stage for EBS snow crab.

| Stage | Habitat & Distribution | Phenology | Age, Length, Growth | Energetics | Diet | Predators/Competitors |
|---|---|---|---|---|---|---|
| **Egg** | Clutch of embryos brooded under the female's abdomen until hatching | 240 days at 6°C to 353 days at -1°C; cold temperatures trigger a 2-year reproductive cycle(1) | Egg diameter: 644.4-772.1 µm(2) | Optimal: 0°C – 3°C(3) | Yolk | Nemertean worms and amphipods feed on egg clutches |
| **Larvae** | Pelagic; concentrated in the upper 20m over the middle shelf(4) | April-June hatch | Mean carapace length: 1.25mm | Optimal: 6.9°C – 9.1°C(5) | Diatoms, small copepods | Jellyfish, juvenile pollock and Pacific salmon |
| **Juvenile** | Benthic; found in mud and gravel habitat in 1°C bottom temperatures (50-100m depth) | Peak settlement in October, later benthic stages molt annually in the spring | 10-12 benthic instar stages until final molt to maturity(6) | Growth indices highest at 5°C(7) | Crustaceans, bivalves, polychaetes(8) | Pacific cod, flatfish, sculpins, crab(9) |
| **Adult** | Benthic: sand and mud bottoms (70-200m depth) | 6-7+ years, migration to shallow waters in spring to mate | Average size range at terminal molt: females 47-59 mm CW, males 73-101mm CW(10) | Growth is optimum at 4°C(11) | Polychaetes, crustaceans, echinoderms, mollusks(12) | Pacific cod, halibut, skates(13) |

Note: Subscripts in table correspond to the following citations in sequential order 1. Webb et al., 2006, 2. Moriyasu and Lanteigne, 1998, 3. Webb et al., 2007, 4. Armstrong et al., 1981, 5. Yamamoto et al., 2017, 6. Sainte-Marie et al., 1995, 7. Yamamoto et al., 2015, 8. Kolts et al., 2013, 9. Lang et al., 2003, 10. Murphy 2021, 11. Foyle et al., 1989, 12. Divine et al., 2017, 13. Livingston et al., 1993

Table 2b. Key processes affecting survival by life history stage for EBS snow crab.

| Stage | Processes Affecting Survival | Relationship to EBS snow crab |
|---|---|---|
| **Egg** | 1. Temperature | Temperature direct affects the duration of incubation(1) |
| **Larvae** | 1. Synchrony with spring bloom<br>2. Offshore advection | Larval growth and survival is dependent on high concentrations of diatoms(2). Advection to areas overlying suitable bottom temperatures and substrate likely improves larval survival(3) |
| **Juvenile** | 1. Cold pool and sea ice extent<br>2. Predation | Pacific cod predation is a major source of immature snow crab mortality and the cold pool provides predator refuge for juvenile snow crab(4) |
| **Adult** | 1. Benthic production<br>2. Temperature | Food availability may drive patterns in growth, energetic condition and survival of snow crab. Shifts in the spatial extent of snow crab are driven by bottom temperatures and cold pool dynamics in the EBS(5) |

Note: Subscripts in table correspond to the following citations in sequential order 1. Webb et al., 2007, 2. Paul et al., 1979, 3. Parada et al., 2010, 4. Livingston, 1989, 5. Fedewa et al., 2020

Table 3a: First stage ecosystem indicator analysis for snow crab, including indicator title and the indicator status of the last five years. The indicator status is designated with text, (greater than = "high", less than = "low", or within 1 standard deviation = "neutral" of long-term mean). Fill color of the cell is based on the sign of the anticipated relationship between the indicator and sablefish (blue = good conditions for sablefish, red = poor conditions, white = average conditions). A gray fill and text = "missing" will appear if there were no data for that year.

| Indicator category | Indicator | 2018 Status | 2019 Status | 2020 Status | 2021 Status |
|---|---|---|---|---|---|
| Physical | Winter Spring Arctic Oscillation Index Model | neutral | neutral | **high** | neutral |
| Lower Trophic | AMJ Chlorophylla Biomass SEBS Satellite | neutral | neutral | *high* | neutral |
| Upper Trophic | Annual Snow Crab Male Size Maturity | **low** | neutral | NA | **low** |
| Physical | Spring Sea Ice Retreat BS Satellite | **low** | **low** | neutral | NA |
| Lower Trophic | Summer Benthic Invertebrate Biomass SEBS Survey | neutral | neutral | NA | *high* |
| Physical | Summer Cold Pool SEBS Survey | **low** | **low** | NA | **low** |
| Upper Trophic | Summer Snow Crab Consumption Pacific cod Model | **high** | neutral | NA | NA |
| | Summer Snow Crab Female Juvenile Temperature Occupancy | **high** | neutral | NA | **high** |
| | Summer Snow Crab Juvenile Disease Prevalence | neutral | neutral | NA | neutral |
| | Summer Snow Crab Male Area Occupied SEBS Survey | neutral | **low** | NA | neutral |
| | Summer Snow Crab Male Center Distribution SEBS Survey | neutral | neutral | NA | *high* |

Table 3b: First stage socioeconomic indicator analysis for snow crab, including indicator title and the indicator status of the last five years. The indicator status is designated with text, (greater than = "high", less than = "low", or within 1 standard deviation = "neutral" of long-term mean). Fill color of the cell is based on the sign of the anticipated relationship between the indicator and sablefish (blue = good conditions for sablefish, red = poor conditions, white = average conditions). A gray fill and text = "missing" will appear if there were no data for that year.

| Indicator category | Indicator | 2018 Status | 2019 Status | 2020 Status | 2021 Status | 2022 Status |
|---|---|---|---|---|---|---|
| Fishery Performance | Annual Snow Crab Active Vessels EBS Fishery | neutral | neutral | neutral | neutral | low |
| | Annual Snow Crab CPUE Fishery | neutral | neutral | neutral | NA | NA |
| | Annual Snow Crab Center Distribution EBS Fishery | high | neutral | high | NA | NA |
| Economic | Annual Snow Crab Exvessel Price EBS Fishery | high | high | high | NA | NA |
| | Annual Snow Crab Exvessel Revenue Share EBS Fishery | neutral | neutral | high | NA | NA |
| | Annual Snow Crab Exvessel Value EBS Fishery | neutral | neutral | neutral | NA | NA |
| Fishery Performance | Annual Snow Crab Incidental Catch EBS Fishery | neutral | neutral | neutral | neutral | neutral |
| | Annual Snow Crab Potlift Fishery | neutral | neutral | neutral | NA | NA |

# Figures

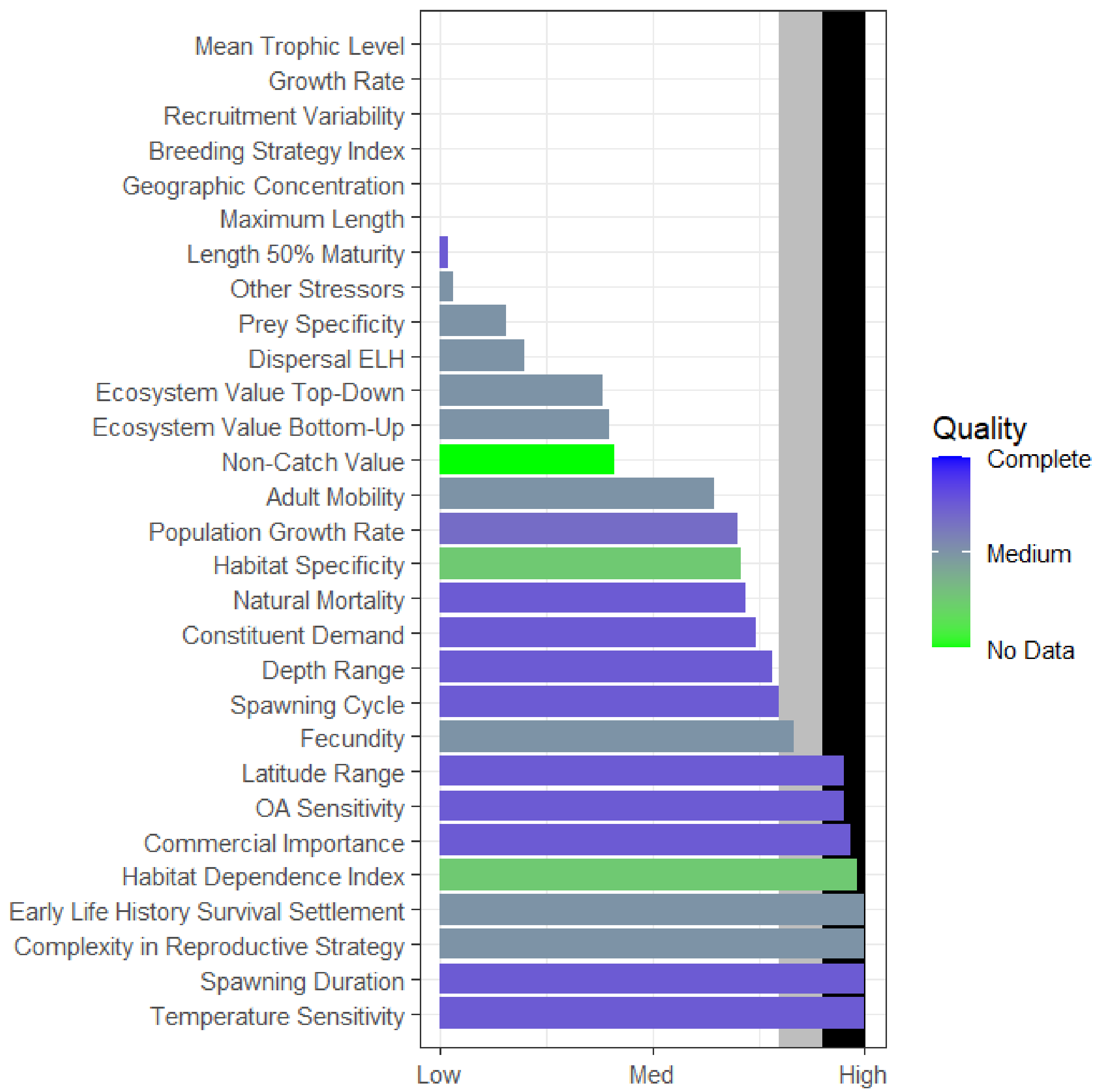


Figure 1: Baseline metrics for EBS snow crab graded as percentile rank over all groundfish and crab in the FMPs. Gray and black vertical bars indicate 80$^{th}$ and 90$^{th}$ percentile over all stocks. Higher rank values indicate a vulnerability and color of the horizontal bar describes data quality of the metric (see Shotwell et al., *In Review*, for more details on the metric definitions and thresholds).

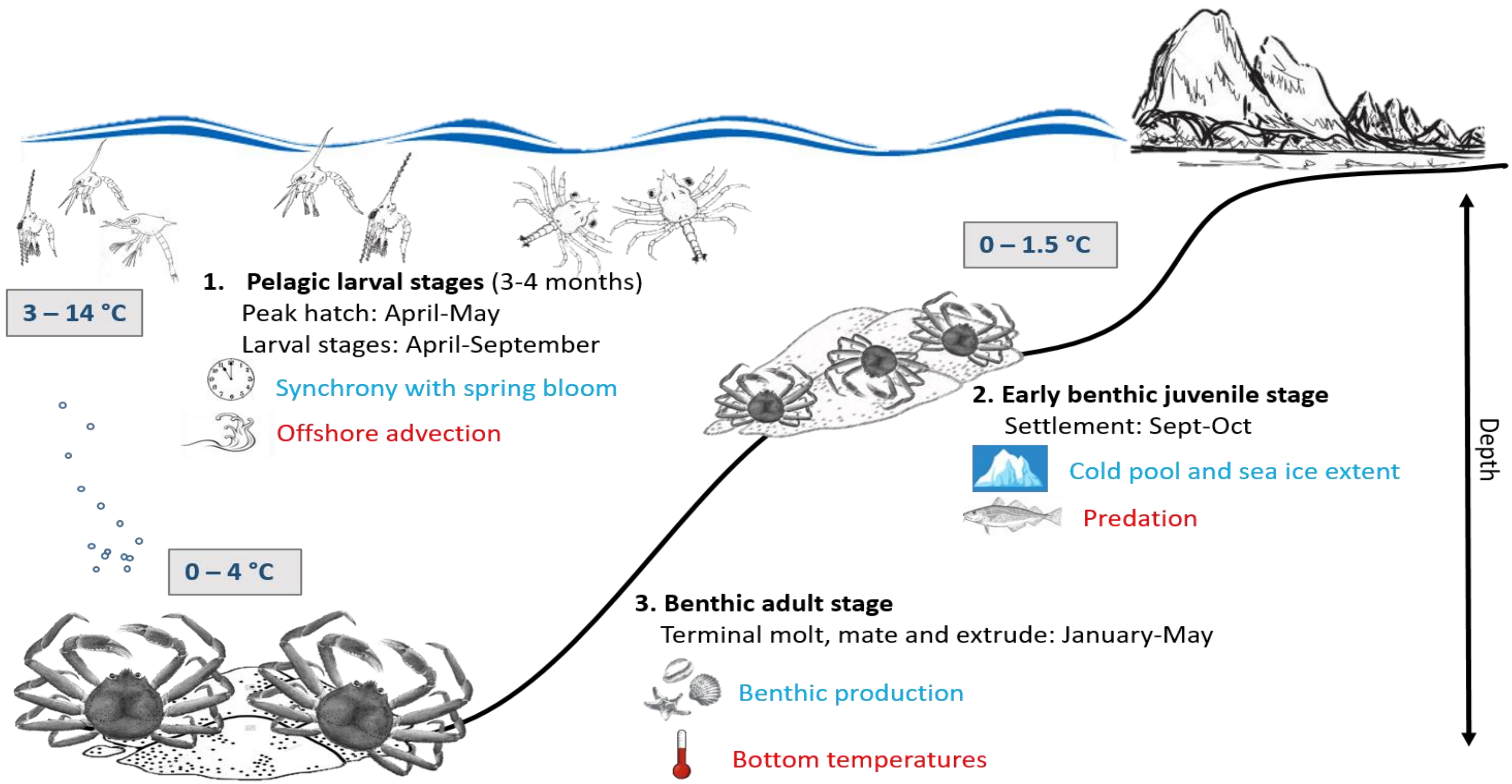


Figure 2. Life history conceptual model for EBS snow crab summarizing ecological information and key ecosystem processes affecting survival by life history stage. Red text means increases in process negatively affect survival, while blue text means increases in process positively affect survival.

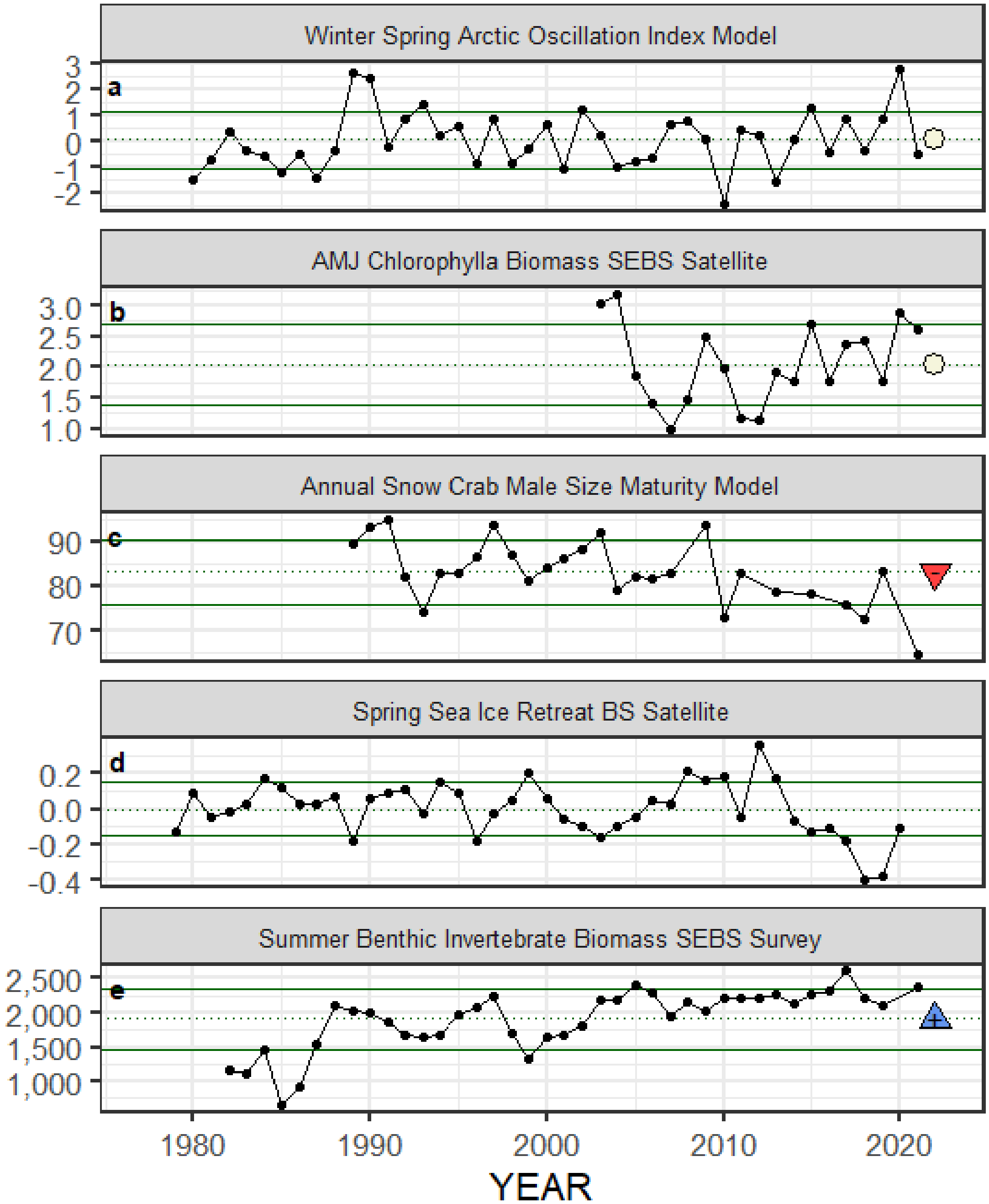


Figure 3a. Selected ecosystem indicators for EBS snow crab with time series ranging from1977– present. Upper and lower solid green horizontal lines are one standard deviation from the long-term mean of time series. Dotted green horizontal line is the mean of the time series. Symbols follow the simple scoring status table for the current year.

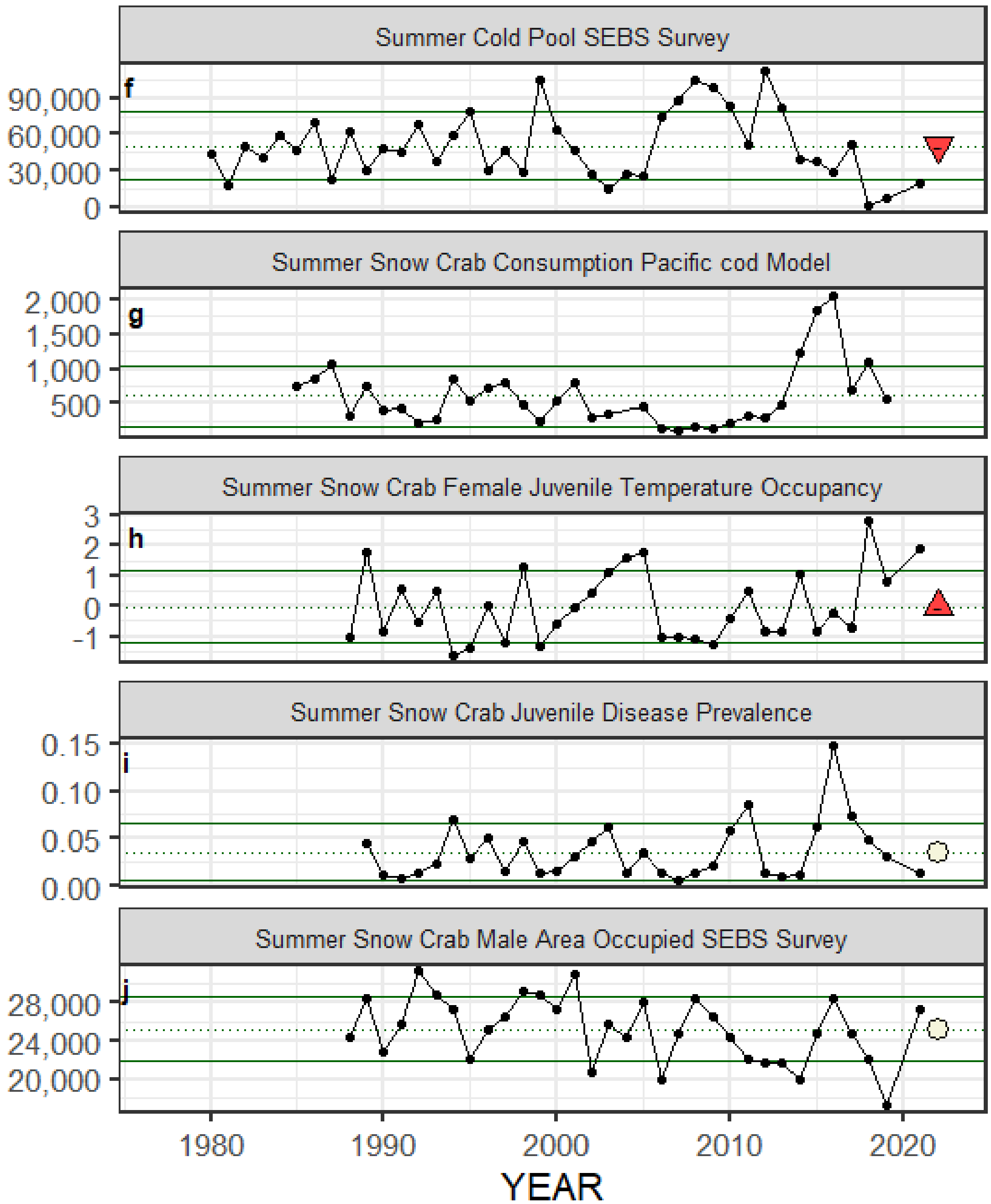


Figure 3a (cont.). Selected ecosystem indicators for EBS snow crab with time series ranging from1977–present. Upper and lower solid green horizontal lines are one standard deviation from the long-term mean of time series. Dotted green horizontal line is the mean of the time series. Symbols follow the simple scoring status table for the current year.

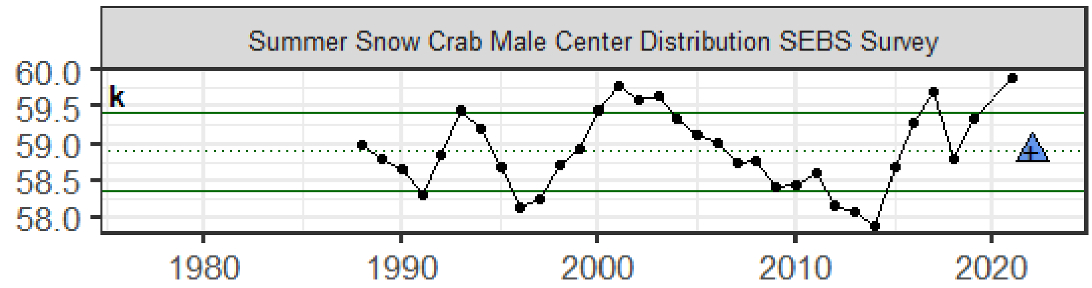


Figure 3a (cont.). Selected ecosystem indicators for EBS snow crab with time series ranging from1977–present. Upper and lower solid green horizontal lines are one standard deviation from the long-term mean of time series. Dotted green horizontal line is the mean of the time series. Symbols follow the simple scoring status table for the current year.

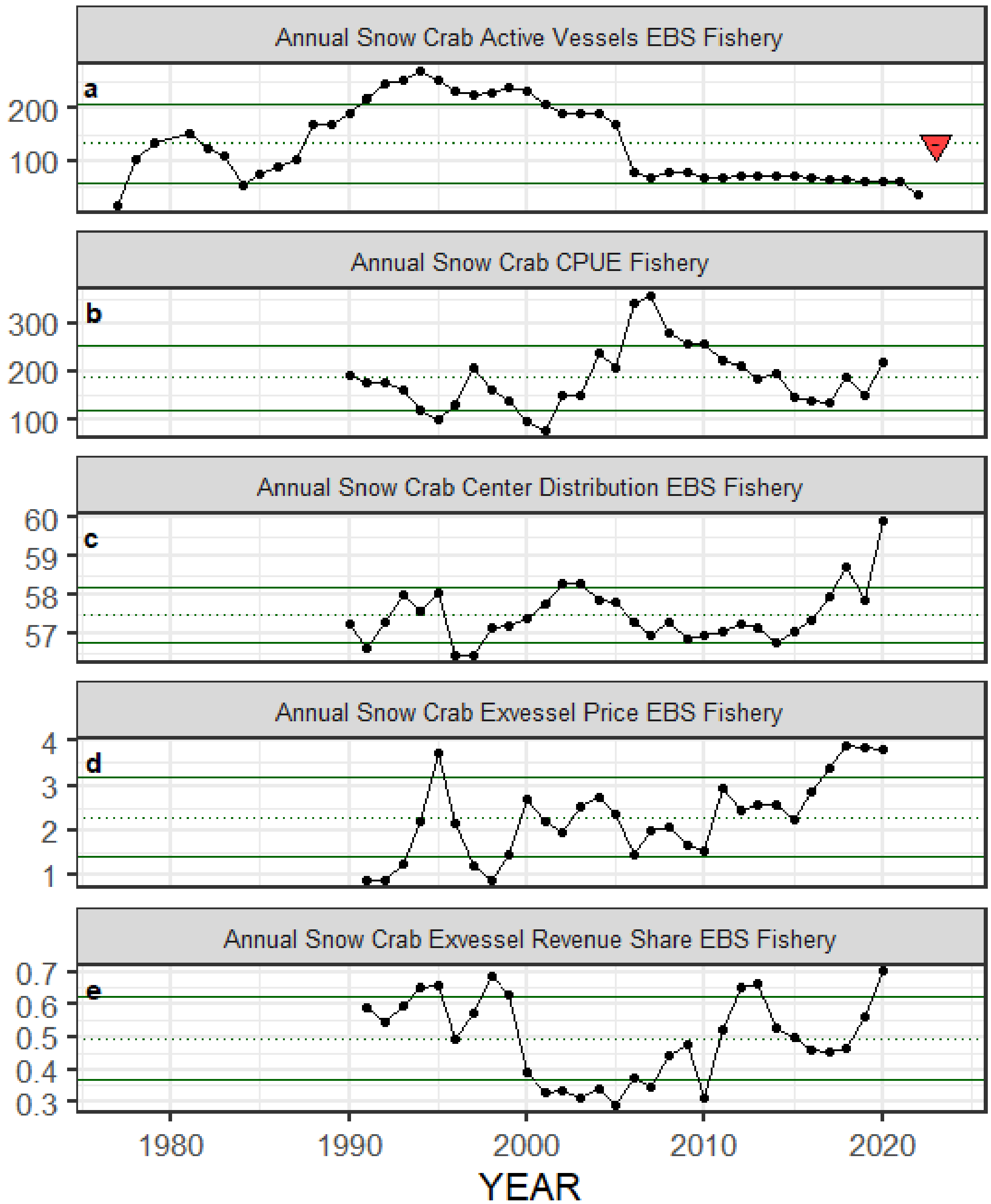


Figure 3b. Selected ecosystem indicators for EBS snow crab with time series ranging from1977– present. Upper and lower solid green horizontal lines are one standard deviation from the long-term mean of time series. Dotted green horizontal line is the mean of the time series. Symbols follow the simple scoring status table for the current year.

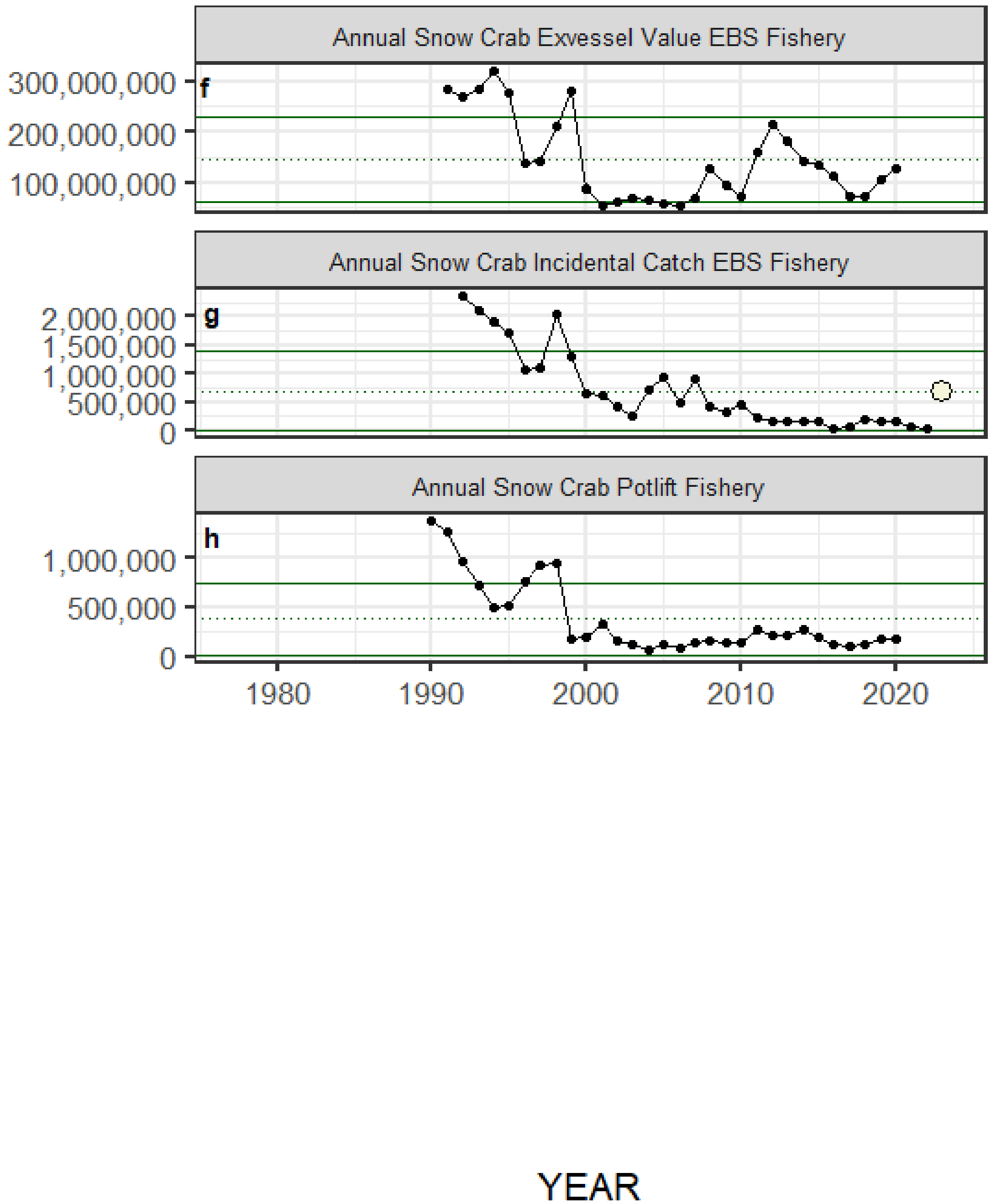


Figure 3 (cont.). Selected ecosystem indicators for EBS snow crab with time series ranging from1977–present. Upper and lower solid green horizontal lines are one standard deviation from the long-term mean of time series. Dotted green horizontal line is the mean of the time series. Symbols follow the simple scoring status table for the current year.

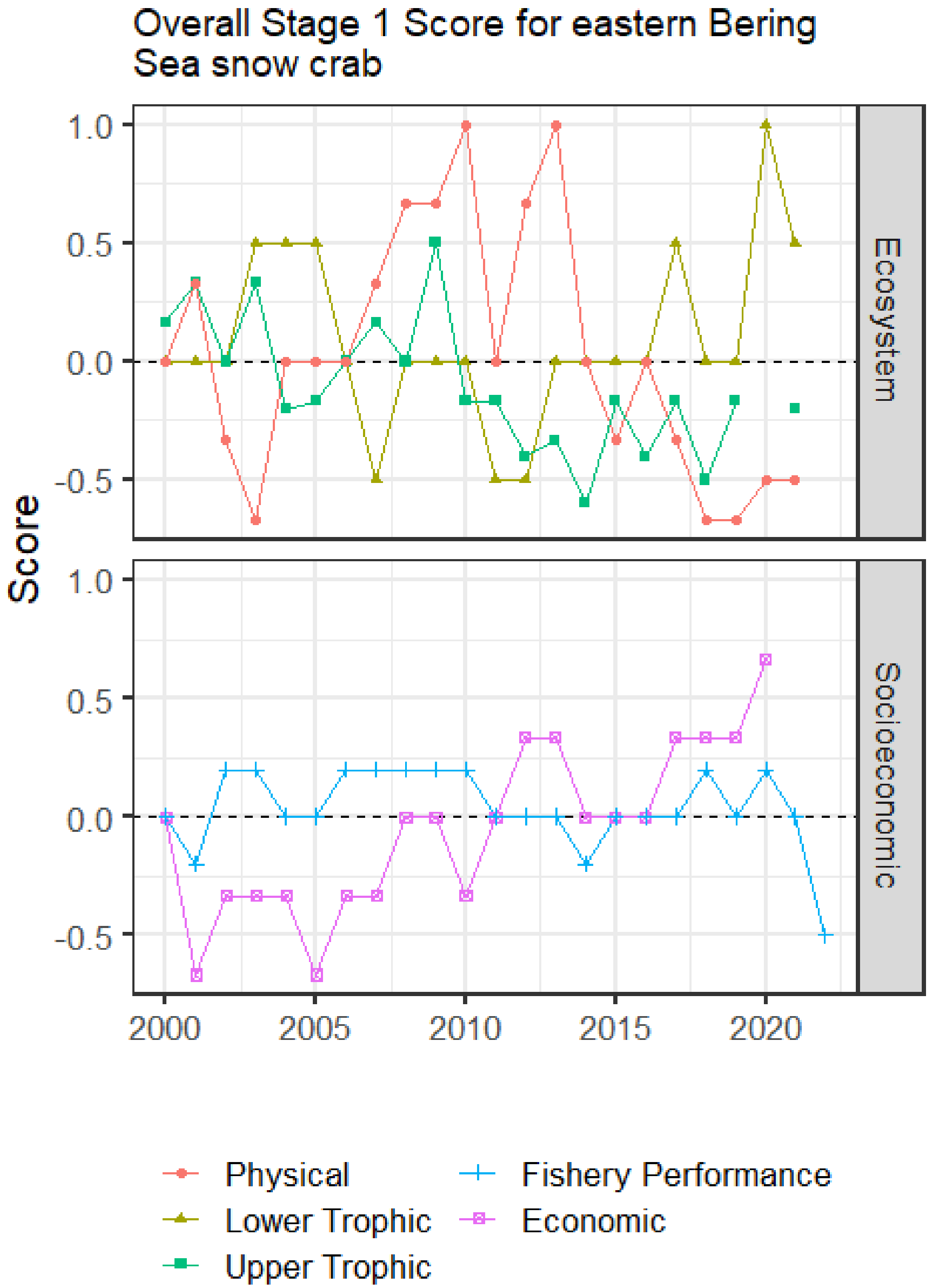


Figure 4. Simple score from Beginning Stage indicator analysis for ecosystem and socioeconomic categories from 2000 to present.

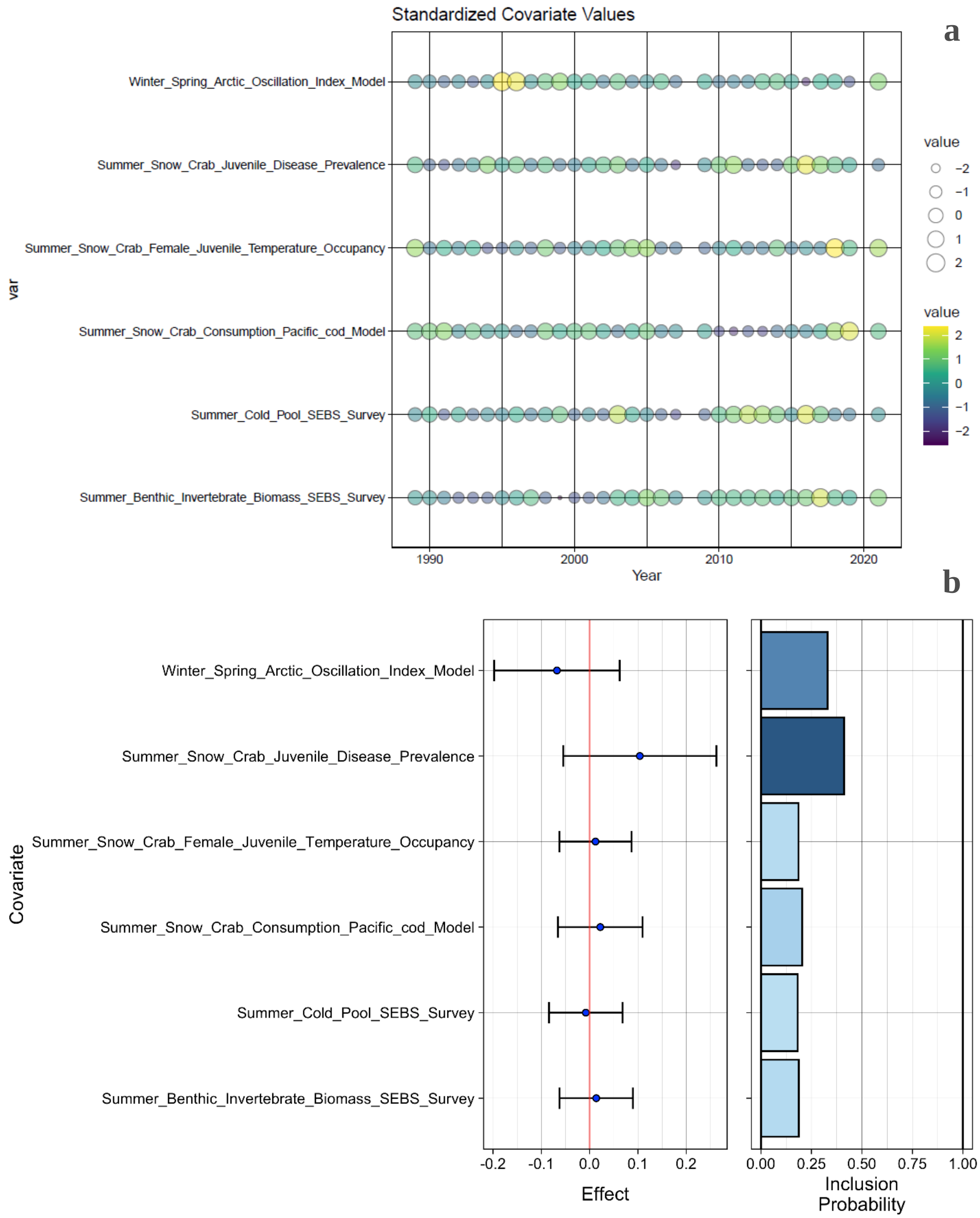


Figure 5. Bayesian adaptive sampling output showing (a) standardized covariates prior to subsetting and (b) the mean relationship and uncertainty (95% confidence intervals) with log EBS snow crab recruitment, in each estimated effect (left bottom graph), and marginal inclusion probabilities (right bottom graph) for each predictor variable of the subsetted covariate set.