Appendix A. Ecosystem and Socioeconomic Profile of the eastern Bering Sea snow crab stock - Update

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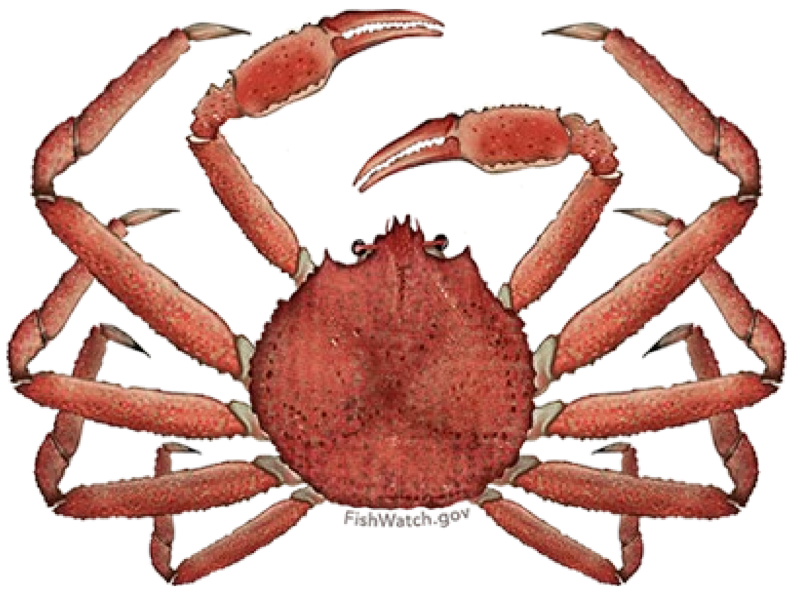

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Table of Contents

Executive Summary

The Ecosystem and Socioeconomic Profile (ESP), is a standardized framework for compiling and evaluating relevant stock-specific ecosystem and socioeconomic indicators and communicating linkages and potential drivers of the stock within the stock assessment process (Shotwell et al., 2023). This update report provides supporting information for the eastern Bering Sea (EBS) snow crab ESP report card (Fedewa et al., 2026) and details the methodology and results from statistical analyses used to monitor current year status and trends of ecosystem and socioeconomic indicators. The EBS snow crab stock was evaluated at the intermediate indicator analysis stage using Dynamic Structural Equation Modeling (DSEM). Highlights of the indicator assessment are summarized below as considerations that can be used for evaluating concerns in the main stock assessment or other management decisions.

Acceptable Biological Catch (ABC) Considerations:

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

Predictive Indicators:

- **Juvenile snow crab energetic condition** rebounded following the population collapse and remains elevated in 2026, suggesting high survival into 2027 due to elevated energetic stores.
- **Juvenile snow crab occupied temperatures** were < 0°C in 2026, indicating conditions suitable for high survival, recruitment and stock recovery.
- **Spring sea ice extent** increased substantially in 2026 and is above the time series mean. High sea ice coverage promotes greater flux of primary production to the benthos and supports elevated energetic condition in juvenile snow crab.
- **The spatial extent of bottom waters ≤ 0°C** was near average in 2026, suggesting optimal availability of cold-water habitat for highly stenothermic juvenile snow crab.

Contextual Indicators:

- Record-high mature female abundance in 2026 resulted in a strongly female-skewed operational sex ratio (85 mature females for one >95mm large male), although only ~3% of mature females with empty clutches suggests high reproductive potential despite depressed abundances of large male snow crab.
- Bitter crab disease and Pacific cod predation indicators that represent proximate mechanisms for increased mortality of juvenile snow crab remained below average in 2026.
- Mature male snow crab center of abundance and area occupied remain near average in 2026 despite relatively cold summer temperatures.
- The male size at 50% maturity remains near average in 2026, although this indicator has been trending down for the past three decades. Mature female size at 50% maturity declined in 2026 following several cohorts of large, mature females observed in 2024 and 2025.

Fishery-Informed Indicators:

- Catch per unit effort (CPUE) of retained crab in the 2025/26 fishery declined relative to the prior 2024/25 season (219 crab/potlift to 147 crab/potlift) and remains below the long-term average.
- Total effort in the fishery, as measured by number of active vessels (36) and total potlifts (83.4 thousand), increased relative to the previous year fishery but remains below the post-rationalization average.
- Incidental catch of snow crab in BSAI groundfish fisheries in 2026 increased slightly from the previous year but was near the lower bound of the historical range and below the average of the previous five years.

- The center of distribution of fishing activity in the 2025/26 fishery shifted substantially to the SE relative to 2024/25. This is consistent with ~60% of skippers in the Alaska Bering Sea Crabbers (ABSC) Skipper Survey noting that they fished further south and/or changed fishing locations more frequently. Skippers reported that this behavioral change was primarily due to weather and sea ice, but many skippers also noted heavy sorting of small males and females as a motivator.
- Skipper survey responses varied when asked what drove the location of their fishing this season but included fuel consideration during a low TAC year and finding the closest grounds with decent catch.
- ~50% of skippers reported a >10% increase in perceived abundance of industry-preferred males relative to the previous open season, and 47% of skippers noted slightly more to a lot more hybrid crab than the previous season.

Total Allowable Catch (TAC) Considerations:

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

- Predictive, contextual and fishery-informed ABC considerations above can also be used to inform TAC considerations within the purview of the State TAC setting process. Ecosystem indicators in the monitoring category may also be relevant to TAC considerations but are not interpreted here (Figure A.2a and Table A.1).
- Economic indicators from the 2025/26 fishery are not yet available but will be updated prior to the October NPFMC meeting.

Introduction/Background

An ESP was recommended for EBS snow crab in 2021 and the ESP full report was created in 2022 (Fedewa et al., 2022). In years following full reports, an ESP update report may be created in conjunction with the full or updated SAFE report schedule. The ESP update provides descriptions of all indicators developed for the ESP and results from a statistical indicator analysis completed with current year indicator data. Any necessary changes to the indicator suite such as newly available indicators, modifications due to data changes, or removals can also be catalogued. The intent of an ESP update report is to provide results of new data since the last ESP full report. It is not a full re-evaluation of the indicator selection or analysis choices. If a full re-evaluation is recommended, a subsequent ESP full report can be scheduled depending on regional prioritization.

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

Ecosystem and Socioeconomic Processes

We summarize important processes that may be helpful for identifying productivity bottlenecks and dominant pressures on the stock with a conceptual model detailing ecosystem processes by life history stage (Figure A.1). Please refer to the last full ESP document (Fedewa et al., 2022) for more details.

Indicator Assessment

Selected indicators for EBS snow crab are organized into categories: three for ecosystem indicators (larval, juvenile, and adult) and three for socioeconomic indicators (fishery-informed, economic, and community). For detailed information regarding these ecosystem and socioeconomic indicators and the proposed mechanistic linkages for EBS snow crab, please refer to the previous ESP documents (Fedewa et al., 2022). Time series of these indicators are provided in Figure A.2a (ecosystem indicators) and Figure A.2b (socioeconomic indicators).

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

- "Average": Used if the value in the time series is near the long-term mean (dotted green line in Figure A.2).
- "Above average" or "Below average": Used if the value is above or below the mean but was within 1 standard deviation of the mean (in between solid green lines in Figure A.2).
- "Neutral": Used in Table A.1 for any value within 1 standard deviation of the mean.
- "High" or "Low": Used in Table A.1 if the value was more than 1 standard deviation above or below the mean (above or below the solid green lines in Figure A.2).

The ESP full report evaluates the indicator suite when the ESP is first created (Fedewa et al., 2022). The ESP update report maintains all these indicators but may require some modifications each year to ensure delivery of the best scientific information available. Changes this year are documented below.

Modified indicators in the suite include:

- Male Snow Crab Size at Maturity: Transitioned from design-based estimates to model-based estimates using a spatiotemporal generalized linear mixed effects model in sdmTMB

- Female Snow Crab Size at Maturity: Transitioned from design-based estimates to model-based estimates using a spatiotemporal generalized linear mixed effects model in sdmTMB

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

Indicator Suite

Below we list 1) a short description of each indicator, including the data source and contributor, 2) factors driving indicator trends, and 3) potential implications of indicator trends for EBS snow crab.

Ecosystem Indicators:

Larval Indicators (Figure A.2a. a-b)

a. Arctic Oscillation Index: January - March Arctic Oscillation index from the NOAA National Climate Data Center. Proposed sign of the relationship is negative. Contact: Erin Fedewa.
    - Factors influencing trends: The Arctic Oscillation is a measure of the relative strength of low pressure over the Arctic and is defined by surface atmospheric weather patterns.
    - Implications: Poor snow crab recruitment has been associated with positive values of the Arctic Oscillation (Szuwalski et al., 2021).

b. Chlorophyll-*a* Concentration: Mean April – June average chlorophyll *a* concentration on the north-middle shelf of the EBS (BSIERP regions 9 and 5), calculated with the ESA OC-CCI blended satellite product. Proposed sign of the relationship is positive. Contact: Matt Callahan.
    - Factors influencing trends: Spring chlorophyll-*a* concentration is directly influenced by the timing and magnitude of the spring bloom and strongly impacts the amount of energy that is transferred through trophic pathways in the Bering Sea.
    - Implications: Low chlorophyll concentrations and subsequently less diatoms in the water column may drive increased larval mortality due to less favorable feeding conditions

(Incze et al., 1987). A reduction in diatoms would also suggest less production reaching the seafloor, which may negatively impact juvenile snow crab lipid storage and energetic condition (Copeman et al., 2021).

Juvenile Indicators (Figure A.2a. c-h)

c. Cold Pool Spatial Extent (≤ 0°C): The total area (nmi²) of all EBS bottom trawl survey stations with bottom temperatures ≤ 0°C. Proposed sign of the relationship is positive. Contact: Erin Fedewa.
   - Factors influencing trends: The spatial extent of bottom waters ≤ 0°C is driven by winter sea ice extent and winds.
   - Implications: The EBS snow crab population collapse was attributed to warming and sea ice loss during the 2018-2019 marine heatwave (Szuwalski et al., 2023; Litzow et al., 2024), and cold-water habitat ≤ 0°C is critical for supporting high snow crab densities, energetic condition and survival in rebuilding towards a pre-collapse state (Fedewa et al., 2025).

d. Juvenile Snow Crab Temperature of Occupancy: Mean bottom temperature weighted by immature snow crab CPUE during the EBS summer bottom trawl survey, representing the realized thermal niche of juvenile snow crab. Proposed sign of the relationship is negative. Contact: Erin Fedewa.
   - Factors influencing trends: Temperatures occupied by juvenile snow crab are directly influenced by bottom temperatures in the Bering Sea and thermal preferences of stenothermic juveniles. Realized thermal niches are also influenced by species interactions.
   - Implications: Occupied temperatures < 0°C are critical for supporting high snow crab density and elevated energetic reserves (Fedewa et al., 2025). Occupied temperatures > 2°C have been suggested as an upper temperature threshold for juvenile snow crab (Murphy 2020). Marine heatwaves and the resulting loss of climate refugia are expected to increase temperatures occupied by juvenile snow crab beyond thermal preferences.

e. Spring Sea Ice Extent: March-April average winter sea ice concentration in the EBS and NBS bottom trawl survey area from the ERA5 reanalysis dataset. Concentration values represent the percentage of the Bering Sea covered by sea ice, with values below 15% considered ice-free. Proposed sign of the relationship is positive. Contact: Erin Fedewa.
   - Factors influencing trends: Winter sea ice in the Bering Sea is driven by atmospheric CO_2, ocean heat transport and winds.
   - Implications: Low levels of sea ice have been associated with dampened productivity of snow crab (Mullowney et al., 2023).

f. Juvenile Snow Crab Disease Prevalence: Prevalence (%) of immature snow crab showing visual symptoms of bitter crab disease during the summer EBS bottom trawl survey, calculated as the abundance of visually positive immature crab divided by total immature abundance. Proposed sign of the relationship is negative. Contact: Erin Fedewa.
   - Factors influencing trends: Bitter crab disease tends to occur at stations with high population density of small, new shell crab, and 2 - 4°C bottom temperatures (Balstad et al., 2024). However, visual detection methods substantially underestimate disease prevalence, and infections detected with sensitive PCR assays at disease monitoring sites indicate that prevalence levels are much higher than reported here (Fedewa et al., 2025).
   - Implications: Because bitter crab disease is assumed fatal and primarily affects small crab, increases in visual disease prevalence are expected to negatively impact survival

and recruitment success. Disease monitoring is critical when large cohorts enter the population because an increased proportion of small snow crab in the system could lead to higher disease prevalence and mortality.

g. Juvenile Snow Crab Energetic Condition: Summer snow crab juvenile energetic condition is estimated from water content in the hepatopancreas (% dry weight) sampled from snow crab on the EBS bottom trawl survey. Proposed sign of the relationship is positive. Contacts: Erin Fedewa and Louise Copeman.
    - Factors influencing trends: Dramatic declines in energetic condition during the 2018-2019 snow crab population collapse were driven by warming during a marine heatwave and high snow crab population density (Fedewa et al., 2025). Declines in lipid storage in juvenile snow crab have also been linked to warmer temperatures and reduced food quality in the Bering Sea (Copeman et al., 2021).
    - Implications: Increased energetic condition suggests favorable conditions for high survival and recruitment, whereas energetic condition that falls below a laboratory-derived threshold of 22.6% has been attributed to starvation-induced mortality (Copeman et al., in prep).

h. Pacific Cod Consumption: The daily summer consumption of snow crab (mt/day) by Pacific cod in the EBS, estimated from Pacific cod diet compositions, EBS trawl survey CPUE, and temperature adjusted length-specific maximum consumption rates. Pacific cod consumption estimates include unidentified *Chionocetes* sp. as well as identified *C. opilio* from stomach contents. Unidentified crab were extrapolated to *C. opilio* based on identified *C. bairdi* and *C. opilio* proportions by cod size and stratum. Proposed sign of the relationship is negative. Contact: Kerim Aydin.
    - Factors influencing trends: Consumption rates are driven by Pacific cod abundance, juvenile snow crab abundance, the spatial extent of the cold pool, and the spatial overlap between Pacific cod and snow crab (Reum et al., 2025).
    - Implications: High consumption rates indicate increased top-down predation pressure, and the potential for reduced recruitment of juvenile snow crab.

Adult Indicators (Figure A.2a. i-o)

i. Benthic Prey Density: Summer benthic invertebrate density (kg/km^2), estimated from EBS bottom trawl survey stations included in the upper 75th percentile of snow crab CPUE within each year. Invertebrates are subset to include species observed in snow crab diet studies, and include brittle stars, sea stars, sea cucumbers, bivalves, non-commercial crab species, shrimp and polychaetes. Proposed sign of the relationship is positive. Contact: Erin Fedewa.
    - Factors influencing trends: Environmental factors such as bottom temperature, primary production and ice cover likely affect spatiotemporal variation in epibenthic invertebrates, but the dynamics remain poorly understood (Yeung and McConnaughey, 2006).
    - Implications: High benthic invertebrate density may suggest increased prey availability for juvenile and adult snow crab. However, the bottom trawl survey does not sample key prey items such as polychaetes and bivalves well, thus this indicator is a coarse proxy for prey quantity.

j. Male Snow Crab Size at 50% Maturity: Carapace width (mm) at 50% probability of having undergone terminal molt to maturity. Male size at maturity is derived from abundance-weighted maturity-at-size ogives and calculated as the size at which the probability of maturity first crosses 50% each year. Maturity ogives are estimated from spatiotemporal generalized linear mixed effects models in sdmTMB for newshell males only. Proposed sign of the relationship is positive. Contact: Emily Ryznar

- Factors influencing trends: Declining trends in male size at 50% maturity have been linked to cohort size, which negatively impacts size at maturity, and the abundance of large males, which has a positive effect due to mate competition (Murphy 2021; Mullowney and Baker, 2021, Ryznar et al., in review).
- Implications: The potential for sperm limitation in populations depleted of large mature male snow crab may decrease reproductive potential of the stock (Baker et al., 2022). In addition, declining size at maturity creates a negative feedback loop where high exploitation rates on large males reduces their abundance, which in turn alters the maturity schedules of the remaining population, resulting in less large males and a decline in the stock's overall reproductive potential (Ryznar et al., in review).

k. Female Snow Crab Size at 50% Maturity: Carapace width (mm) at 50% probability of having undergone terminal molt to maturity. Female size at maturity is derived from abundance-weighted maturity-at-size ogives and calculated as the size at which the probability of maturity first crosses 50% each year. Maturity ogives are estimated from spatiotemporal generalized linear mixed effects models in sdmTMB for newshell females only. Proposed sign of the relationship is positive. Contact: Emily Ryznar
   a. Factors influencing trends: Female snow crab size at 50% maturity is primarily driven by competitive effects from mature female abundance, which decreases size at maturity, while the incidence of large, immature females is influenced by both mate limitation and nonlinear temperature effects (Orensanz et al., 2007; Murphy 2021; Ryznar et al., in review).
   b. Implications: Because fecundity increases with female size, directional downward shifts in size at maturity could decrease reproductive potential.

l. Mature Male Snow Crab Area Occupied: The minimum area containing 95% of the cumulative mature male snow crab CPUE during the EBS summer bottom trawl survey. Proposed sign of the relationship is positive. Contact: Erin Fedewa.
   a. Factors influencing trends: The spatial extent of snow crab in the EBS contracts in response to warmer bottom temperatures and a smaller cold pool extent (Fedewa et al., 2021). Spatial extent is also influenced by snow crab abundance due to density dependent range contraction (Murphy et al., 2010).
   b. Implications: Declines in the spatial extent of mature male snow crab can result in density-dependent prey limitation and starvation-induced mortality, which are exacerbated in warm temperatures due to increased metabolic demand (Szuwalski et al., 2023). Dramatic declines in the spatial extent of mature males preceded the 2019-2021 population collapse, emphasizing the importance of this indicator as a potential red flag.

m. Mature Male Snow Crab Center of Abundance: CPUE-weighted average latitude of the mature male snow crab stock during the EBS summer bottom trawl survey. Proposed sign of the relationship is positive. Contact: Erin Fedewa.
   a. Factors influencing trends: Historically, centroids of abundance have tracked bottom temperatures, and were further south with colder temperatures (Orensanz et al., 2005).
   b. Implications: Northward shifts in centroids of abundance under warming are expected to be a positive sign for stock health as snow crab track preferred cold-water refuge

northward. However, this may have implications for availability to the snow crab fishery and NOAA bottom trawl survey.

n. Female Snow Crab Reproductive Failure: The proportion of hardshell mature female snow crab with no eggs, empty egg cases, or dead eggs. Hardshell crab are designated as code "2" to "5" from the EBS bottom trawl survey shell condition indices. Proposed sign of the relationship is negative. Contact: Erin Fedewa.
    a. Factors influencing trends: Female reproductive failure is driven by the inability to find a mate, and/or utilize stored sperm reserves to fertilize egg clutches (Webb et al., 2016; Murphy et al., 2017). An increased frequency of clutch failure may indicate sperm limitation, or energetic limitations imposed on extrusion and fertilization. Barren clutches can also be attributed to senescence, suggesting that a mature female population composed of old-shell females (primarily shell condition 5) may drive year to year trends in the proportion of empty clutches.
    b. Implications: A low proportion of mature females with empty clutches indicates high reproductive potential and suggests that the majority of females were able to find mates or utilize stored sperm during the mating season.

o. Snow Crab Operational Sex Ratio: The ratio of mature female to large male (> 95 mm CW) snow crab abundance in the EBS. The proposed sign of the relationship is negative. Contact: Erin Fedewa.
    a. Factors influencing trends: The operational sex ratio is directly influenced by the relative abundances of large males and mature females. Non-synchronous shifts in abundance between the two sexes, or a male population dominated by small mature males are two mechanisms for a skewed operational sex ratio.
    b. Implications: A female-biased operational sex ratio suggests the possibility for sperm limitation (Baker et al., 2022), however, a high proportion of full clutches in mature females indicates that female sperm reserves are likely sufficient for egg production. A female-biased sex ratio could also result in increased interspecies mating and hybridization due to snow crab mate limitation.

Socioeconomic Indicators:

Fishery Informed Indicators (Figure A.2b. a-h)

a. Number of Active Vessels: Annual number of active vessels in the snow crab fishery to represent the level of fishing effort assigned to the fishery, reported by crab year. Contact: Ethan Nichols.
    - Factors influencing trends: BSAI crab fishing vessels are highly specialized for the fishery and have a limited portfolio of non-crab fishing targets. Variation in the size of the EBS snow crab fleet is driven by the TACs in the EBS snow crab, BBRKC and, increasingly, Tanner crab fisheries, with crab harvest quota leasing facilitating adjustment of the fleet to achieve efficient deployment of harvesting capacity. Anecdotal evidence suggests some vessels may temporarily operate at a loss in order to retain crew and access to quota lease contracts.
    - Implications: Variation in the size and composition of the active fleet may have implications for overall fleet behavior, including intervessel coordination and search efficiency.

b. Fishery CPUE: Annual catch-per-unit-effort (CPUE) reported by crab year, expressed as total number of crabs per potlift, in the snow crab fishery to represent relative efficiency of fishing effort. Discerning directed and incidental catch before 2005 is not possible at this time, but the rate of incidental catch is assumed to be low. These data should be interpreted as total (directed + incidental) CPUE 1900 - 2004 and directed CPUE 2005 - present. Contact: Tyler Jackson.

- Factors influencing trends: Annual fishery CPUE can vary based on a suite of factors including total fishery potlifts, EBS snow crab abundance, pot gear soak time, pot gear configuration, bait. weather/tides/sea ice, and fleet dynamics.
- Implications: Changes in CPUE can be used to interpret shifts in relative stock abundance and/or distribution, inform management decisions, and explain timing and distribution of fishing effort.

c. Fishery Total Potlifts: Annual directed potlifts in the snow crab fishery to represent the level of fishing effort expended by the active fleet, reported by crab year. Contact: Tyler Jackson.

- Factors influencing trends: Annual fishery total potlifts can vary based on a suite of factors including number of active vessels, TAC size, CPUE, weather/tides, distance to fishing grounds, and fleet dynamics.
- Implications: Changes in total potlifts represent the level of fishing effort expended by the active fleet

d. Centroid of Fishery: Center of gravity, expressed in latitude, as an index of spatial distribution for the snow crab fishery to monitor spatial shifts in fishery behavior, reported by crab year. Contact: Tyler Jackson.

- Factors influencing trends: Influenced by a combination of factors that affect industry decision makings including crab distribution, number of pots available, amount of quota (post 2005), CPUE, fuel price, distance from port, gear distribution, etc.
- Implications: Spatial shifts in fishing effort away from historical fishing grounds may impact coastal communities, processors and the fleet (e.g. longer/costlier trips).

e. Annual Incidental Catch: Annual incidental catch of snow crab in EBS groundfish fisheries. Contact: Ethan Nichols.

- Factors influencing trends: Incidental catch of snow crab in groundfish fisheries occurs in non-pelagic trawl and fixed-gear groundfish fisheries and is influenced by annual variations in the spatial and temporal overlap of the groundfish fisheries with snow crab abundance and distribution.
- Implications: Rapid shifts in incidental catch rates of snow crab may reflect changes in population distribution, including movement into areas that provide less favorable conditions and may expose individuals to greater competition or predation. Higher incidental snow crab catch rates may also serve as an early signal of strong recruitment or provide additional support for previously identified year classes.

f. Alaska Bering Sea Crabbers (ABSC) Skipper Survey Perceived Abundance: Responses from a single question in the ABSC Skipper Survey, disseminated to all skippers following the completion of the most recent fishery. Skippers were asked to rank perceived abundance of industry preferred male snow crab during the 2025/26 fishery relative to the last snow crab season. Open-ended "other" response choice was not included. Contact: Cory Lescher.

- Factors influencing trends: Perceived abundance can vary based on a suite of factors including fishing location, soak time and skipper skill and experience.
- Implications: Changes in perceived abundance often help to explain skipper adaptation strategies and can be used as a relative measure of stock status.

g. Alaska Bering Sea Crabbers (ABSC) Skipper Survey Changes in Fishing Practices: Responses from a single question in the ABSC Skipper Survey, disseminated to all skippers following the completion of the most recent fishery. Skippers were asked to select the most significant change they made in fishing practices during the 2025/26 fishery relative to the last snow crab season. Open-ended "other" response choice was not included. Contact: Cory Lescher.
   - Factors influencing trends: Changes in fisher behavior can be driven by factors such as increased bycatch, low CPUE, shifts in stock abundance and/or distribution, operating cost, and experience and knowledge.
   - Implications: Changes in fishing practices can be used to interpret trends in fishery performance metrics and the health of the stock.

h. Alaska Bering Sea Crabbers (ABSC) Skipper Survey Principal Driver of Changes: Responses from a single question in the ABSC Skipper Survey, disseminated to all skippers following the completion of the most recent fishery. Skippers were asked to select their main reason for any change in fishing practices during the 2025/26 fishery relative to the last snow crab season. Open-ended "other" response choice was not included. Contact: Cory Lescher.
   - Factors influencing trends: Motivation for changes in fisher behavior can be driven by bycatch and fishery regulations, TAC allocation and CPUE.
   - Implications: Understanding the motivation for changes in fishing practices can assist fishery managers in developing more effective management strategies.

Economic Indicators (Figure A.2b. i-k)

Economic data relevant to the most recent fishery are not yet available but will be included in this document prior to the October NPFMC meeting.

i. Ex-vessel Value: Annual snow crab ex-vessel value of the snow crab fishery landings represents gross economic returns to the harvest sector, as a principal driver of fishery behavior. Contact: Brian Garber-Yonts.
   - Factors influencing trends: TBD
   - Implications: TBD

j. Ex-vessel Price: Annual snow crab ex-vessel price per pound represents per-unit economic returns to the harvest sector, as a principal driver of fishery behavior. Contact: Brian Garber-Yonts.
   - Factors influencing trends: TBD
   - Implications: TBD

k. Ex-vessel Revenue Share: 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.
   - Factors influencing trends: TBD
   - Implications: TBD

Indicator Analysis

Ecosystem and socioeconomic indicators are monitored through distinct workflows, depending on the management decisions they are intended to inform (Figure A.3). Ecosystem indicators generally inform the acceptable biological catch (ABC) and can either be incorporated directly into the model through predictive or causal inference, or indirectly through contextual avenues such as risk tables (Dorn and Zador, 2020). Socioeconomic indicators related to the performance or behavior of the fishery can also inform the ABC both directly by informing time-varying fishery selectivity and indirectly through context in the risk table. Other socioeconomic indicators such as those related to the economics of the fishery or the communities that are supported by the fishery impact decisions further downstream of the stock assessment process and generally are used in decisions related to setting total allowable catch (TAC). Additionally, all indicators selected for monitoring in the ESP may inform TAC deliberations.

We evaluated the ecosystem indicators through a series of stages using statistical tests that increase in complexity depending on the data availability of the stock (Shotwell et al., 2023). The beginning stage is a relatively simple evaluation by traffic light scoring. This evaluates the indicator value from each year relative to the mean of the whole time series and includes the proposed sign of the overall relationship between the indicator and the stock health. The intermediate stage uses importance methods related to a stock assessment parameter of interest (e.g., recruitment, growth, catchability) to estimate predictive performance of indicators. The advanced stage may be used for testing a research ecosystem linked stock assessment model where output can be compared with the current operational stock assessment model.

We evaluated the socioeconomic indicators using only the beginning stage statistical tests and did not assign a proposed relationship between the indicator and stock, as the role of socioeconomic indicators in the stock assessment process is currently being evaluated by the North Pacific Fishery Management Council (NPFMC or Council, December 2023, 2024 memorandum).

Ecosystem Indicator Analysis Methods

The EBS snow crab stock is data-rich with an associated size-structured model (Generalized Model for Assessing Crustacean Stocks or GMACS); therefore, the ecosystem indicators were evaluated using intermediate indicator analysis stage methods. Results from this intermediate stage analysis are used to categorize ecosystem indicators as a) predictive indicators that demonstrate a robust quantitative relationship with the population process of interest, b) contextual indicators that provide anticipatory information to inform a management concern or highlight a potential red flag related directly to the status or health of the stock, but lack predictive skill, or c) monitoring indicators that do not demonstrate quantitative links to population processes, nor provide information that is immediately relevant to the stock and/or fishery managers. The intent of this indicator categorization is to succinctly communicate potential red flags for the stock based on current-year indicator trends and stock-indicator relationships, while providing a mechanism to down-weight indicators that don't quantitatively inform population processes. Monitoring indicators are reported in this document and will continue to be evaluated annually, but we limit our interpretation and synthesis to predictive and contextual indicators only to communicate only the most relevant ecosystem considerations for setting biological reference points for the current year.

Dynamic Structural Equation Models (DSEMs; Thorson et al., 2024) were used to evaluate hypothesized causal relationships between ecosystem indicators and snow crab recruitment. From the full suite of 15 ecosystem indicators, we excluded six indicators that were considered contextual rather than direct drivers of recruitment: operational sex ratio, male size at maturity, female size at maturity, mature male area occupied, mature male center of abundance, and female reproductive failure. This resulted in nine indicators available for DSEM analysis (Figure A.4). All indicators were updated with current-year values, except Pacific cod consumption (current-year data pending due to processing time required for stomach content analysis following the annual EBS bottom trawl survey). Snow crab recruitment was defined as the abundance of immature male snow crab (40–50 mm CW) from the EBS bottom trawl survey time series (1988–2026).

We developed directed acyclic graphs (DAGs) representing hypothesized causal pathways through which ecosystem conditions could affect recruitment via enhanced survival or increased mortality. Pathways included climate forcing, larval food availability, juvenile food availability, cold-water habitat, disease, and predation (Figure A.5). Separate DSEMs were fitted for each hypothesized causal pathway. Because snow crab cannot be aged directly and survey abundance estimates may contain multiple pseudocohorts, lag structures were specified a priori based on hypothesized life-history mechanisms and the size range expected to be most influenced by each indicator. 40-50mm immature snow crab are estimated to be approximately 4.5–5.7 years post-settlement (Sainte-Marie et al., 1995); therefore, chlorophyll-*a* was assigned a four-year lag to represent larval food availability. Indicators representing juvenile prey resources, mortality processes, and thermal conditions were assigned lags of 0–1 years to reflect their hypothesized effects on survival during the juvenile period.

DSEMs were fitted using the *dsem* R package (Thorson et al., 2024). Ecosystem predictors were modeled with first-order autoregressive processes, and process errors were assumed to follow a multivariate normal distribution. Observation error was fixed, all variables were standardized, and recruitment was log-transformed prior to analysis. To evaluate the relative support for ecosystem-driven recruitment dynamics, we compared each causal DSEM with two null base recruitment models containing no ecosystem predictors: an independent and identically distributed (IID) recruitment model and a recruitment model with first-order autoregressive (AR1) dynamics.

Ecosystem Indicator Analysis Results

Overall, we found no support for hypothesized causal effects of larval food availability, disease, or predation on snow crab recruitment. In contrast, results supported direct and indirect effects of climate forcing and cold-water habitat availability on recruitment. Sea ice extent had a positive direct effect on snow crab recruitment (causal estimate = 0.31 ± 0.14, P = 0.02; Figure A.5). Cold pool extent had an indirect negative effect on recruitment through temperatures occupied by juvenile snow crab, with reduced cold pool extent increasing temperatures occupied by juvenile snow crab (−0.78 ± 0.10, $P < 0.001$), which in turn negatively affected recruitment (−0.35 ± 0.14, $P = 0.01$). The juvenile food availability model also supported an indirect positive effect of sea ice extent on recruitment through juvenile energetic condition. Sea ice extent was positively associated with energetic condition (0.30 ± 0.12, $P = 0.01$), which had a strong positive effect on recruitment (1.1 ± 0.29, $P < 0.001$). Including these sea ice and energetic-condition pathways reduced estimated recruitment variance by 71% relative to the null IID model (Figure A.6). However, the strong effect of energetic condition was largely driven by a single observation in 2019, which coincided with heatwave and collapse conditions, and may not represent a generalizable relationship across the historical period.

Overall, all DSEM models tested showed acceptable diagnostics, with small gradients and invertible Hessian matrices. We also present model fits and residual diagnostics for the climate forcing, cold water habitat availability and juvenile food availability models that demonstrated statistically significant causal pathways (Figures A.7 – A.9). DHARMa diagnostics for all three models indicated no significant deviation from the expected residual distribution, no evidence of overdispersion, and no evidence of excess outliers. However, the significant quantile test indicated systematic variation in residuals across the range of predicted values, suggesting potential model misspecification, such as unmodeled nonlinearity or other systematic structure that will continue to be explored further. Additional diagnostics (e.g. self-test simulations, retrospective skill testing, Leave-Future-Out cross validation) are still in development pending NPFMC guidance, and will be included in future versions of this document.

Following the indicator analysis, we categorized the full suite of ecosystem indicators as predictive (sea ice extent, cold pool extent, juvenile snow crab energetic condition and juvenile snow crab temperatures occupied), contextual (disease prevalence, Pacific cod consumption, male snow crab size at maturity, male snow crab area occupied, male snow crab center of abundance, female snow crab reproductive failure and snow crab operational sex ratio) or monitoring (Arctic oscillation index, chlorophyll-a concentration, benthic prey density and female snow crab size at maturity) based on the criteria above and DSEM indicator analysis results. We then summarized recent indicator trends in a five-year status table (Table A.1a), with indicator status classified as high, low, or neutral based on whether values are more than one standard deviation above, below, or within the long-term mean. For predictive and contextual indicators, potential concerns for stock status are identified based on the direction of the indicator–stock relationship. Relationships for predictive indicators are based on importance analyses, whereas contextual and monitoring relationships are based on the conceptual model and hypothesized mechanisms (Figure A.1). Status is shown using a "traffic light" system: blue indicates a high indicator value associated with favorable stock conditions, red indicates a high value associated with unfavorable conditions, and neutral values are uncolored. No relationship is assigned when the direction of an indicator–stock relationship is unclear.

In addition, the Executive Summary at the beginning of this document provides a concise overview of predictive and contextual indicator trends, and an interpretation of results from the intermediate stage indicator analysis that can be used to inform ABC and TAC decisions.

Socioeconomic Indicator Analysis

We present 11 socioeconomic indicators that depict a historical time series of key socioeconomic information for the snow crab fishery: 5 fishery-informed indicators derived from NMFS/ADFG in-season management monitoring systems, 3 selected from the Alaska Bering Sea Crabbers (ABSC) EBS Snow Crab Skipper Survey, and 3 economic indicators drawn from mandatory economic reporting systems (to be updated prior to the October Council meeting). Indicators derived from agency monitoring and reporting systems use time series of historical data through the most recent (2025/26) snow crab fishery, and are used to assess current status of the fishery relative to long-term trends

Indicators from the ABSC Skipper Survey represent a synthesis of responses to the 2025/26 survey, which elicited single period comparisons between the most recent fishery and the fishery the year prior. Inclusion of these indicators is primarily intended as a provisional mechanism for incorporating fishery-dependent data on fleet behavior and catch observations into ABC buffer considerations. The initial selection of three questions from the survey as indicators focuses on skippers' perception of the abundance of legal males and perceived changes and drivers of fishing behavior. These are drawn from a total of 9 recurring questions, which also encompass questions regarding the abundance and explanatory factors for encounters with sublegal males and females, and shell condition of legal males, as well as additional questions relevant to pertinent management concerns. Because snow-Tanner hybrid crab can be landed legally as snow crab and hybrid abundance on the summer bottom trawl survey increased dramatically in 2025, we also included a Skipper Survey response on the perceived abundance of hybrids.

The Executive Summary at the beginning of this document provides a summary and interpretation of fishery-informed indicator trends that can be used to inform ABC decisions.

Conclusion

The EBS snow crab ESP follows the standardized framework for evaluating the various ecosystem and socioeconomic considerations for this stock (Shotwell et al., 2023). The conceptual model provides a reference for the comprehensive literature review and associated tables of the ESP full report (Fedewa et al., 2022). Fifteen ecosystem indicators and 11 socioeconomic indicators were identified to monitor and analyze for EBS snow crab. Because EBS snow crab is a data-rich stock with an annual fishery-independent survey to assess population status, ecosystem indicators were evaluated using intermediate indicator analysis stage methods. We provide several overarching takeaways from the indicator assessment results, which can be used for evaluating concerns in the main stock assessment or management decisions related to acceptable biological catch (ABC) and total allowable catch (TAC) considerations. Indicators that can inform ABC and risk tables include predictive, contextual, or fishery-informed indicators. Indicators that can inform TAC include all ABC indicators as well as economic and community indicators.

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Literature Cited

Baker, K. D., Mullowney, D. R. J., and Sainte-Marie, B. 2022. Large males matter: Low sperm reserves in female snow crab (*Chionoecetes opilio*) off Newfoundland, Canada. Fisheries Research, 253:13.

Balstad, L. J., Fedewa, E. J., and Szuwalski, C. S. 2024. Drivers of bitter crab disease occurrence in eastern Bering Sea snow crab (*Chionoecetes opilio*). ICES Journal of Marine Science.

Copeman, L. A., Ryer, C. H., Eisner, L. B., Nielsen, J. M., Spencer, M. L., Iseri, P. J., and Ottmar, M. L. 2021. Decreased lipid storage in juvenile Bering Sea crabs (*Chionoecetes* spp.) in a warm (2014) compared to a cold (2012) year on the southeastern Bering Sea. Polar Biology, 44: 1883-1901.

Dorn, M. W. and S. G. Zador. 2020. A risk table to address concerns external to stock assessments when developing fisheries harvest recommendations. Ecosys. Health and Sustainability. 6(1):1-11.

Fedewa, E. J., Jackson, T. M., Richar, J. I., Gardner, J. L., and Litzow, M. A. 2020. Recent shifts in northern Bering Sea snow crab (*Chionoecetes opilio*) size structure and the potential role of climate-mediated range contraction. Deep Sea Research Part II: Topical Studies in Oceanography: 104878.

Fedewa, E., B. Garber-Yonts, and K. Shotwell. 2022. Appendix G. Ecosystem and Socioeconomic Profile of the eastern Bering Sea snow crab stock. *In*: Szuwalski 2022. An Assessment for eastern Bering Sea snow crab. North Pacific Fishery Management Council, Anchorage, AK. Available from https://akesp.psmfc.org.

Fedewa E.F., Jensen P.C., Small H.J., Litzow M.A., Malick M.J., Zacher L.S., Long W.C., Kotwicki S. 2025. Bitter crab disease dynamics in eastern Bering Sea Tanner and snow crab: an underestimated and emergent stressor. Fisheries Research, 283: 107307.

Fedewa, E., Shotwell, K., and Garber-Yonts, B. 2025. Appendix A. Ecosystem and Socioeconomic Profile of the eastern Bering Sea snow crab stock - Report Card. *In*: Szuwalski 2025. An Assessment for eastern Bering Sea snow crab. North Pacific Fishery Management Council, Anchorage, AK. Available from https://www.npfmc.org/about-the-council/plan-teams/bsai-crab-planning-team/.

Fedewa, E.F., Copeman, L.A., Litzow, M.A. 2025. Energetic limitations and mass mortality of Bering Sea snow crab: Interacting effects of warming and density on collapse and recovery. Canadian Journal of Fisheries and Aquatic Sciences. 82: 1-14.

Incze, L. S., Armstrong, D. A., and Smith, S. L. 1987. Abundance of larval Tanner crabs (*Chionoecetes* spp.) in relation to adult females and regional oceanography of the southeastern Bering Sea. Canadian Journal of Fisheries and Aquatic Sciences, 44: 1143-1156.

Incze, L. S., Armstrong, D. A., and Wencker, D. L. 1982. Rates of development and growth of larvae of *Chionoecetes bairdi* and *C. opilio* in the southeastern Bering Sea. *In* Proceedings of the International Symposium on the Genus *Chionoecetes*, 3rd edn, pp. 191-218. Ed. by A. J. Paul, F. Gaffney, D. Haapa, J. Reeves, R. Baglin, and S. K. Davis. Alaska Sea Grant College Program, University of Alaska Fairbanks, Anchorage, AK.

Litzow, M. A., Fedewa, E. J., Malick, M. J., Connors, B. M., Eisner, L., Kimmel, D. G., Kristiansen, T., Nielsen, J.M., Ryznar, E.R. 2024. Human-induced borealization leads to the collapse of Bering Sea snow crab. Nature Climate Change.

Mullowney, D. R. J., and Baker, K. D. 2021. Size-at-maturity shift in a male-only fishery: factors affecting molt-type outcomes in Newfoundland and Labrador snow crab (*Chionoecetes opilio*). ICES Journal of Marine Science, 78: 516-533.

Mullowney DRJ, Baker KD, Szuwalski CS, Boudreau SA, Cyr F, et al. 2023. Sub-Arctic no more: Short- and long-term global-scale prospects for snow crab (*Chionoecetes opilio*) under global warming. PLOS Climate 2(10).

Murphy, J. T., Hallowed, A. B., and Anderson, J. J. 2010. Snow crab spatial distributions: Examination of density-dependent and independent processes. In Biology and Management of Exploited Crab Populations under Climate Change, 25th edn, pp. 49-79. Ed. by G. H. Kruse, G. L. Eckert, R. J. Foy, R. N. Lipcius, B. Sainte-Marie, D. L. Stram, and D. Woodby. Alaska Sea Grant College Program, University of Alaska Fairbanks, Anchorage, AK.

Murphy, J. T., Rugolo, L. J., and Turnock, B. J. 2017. Integrating demographic and environmental variables to calculate an egg production index for the Eastern Bering Sea snow crab (*Chionoecetes opilio*). Fisheries Research, 193: 143-157.

Murphy, J. T. 2020. Climate change, interspecific competition, and poleward vs. depth distribution shifts: Spatial analyses of the eastern Bering Sea snow and Tanner crab (*Chionoecetes opilio* and *C. bairdi*). Fisheries Research, 223: 105417.

Murphy, J. T. 2021. Temporal and spatial variability in size-at-maturity for the eastern Bering Sea snow and Tanner crab (*Chionoecetes opilio* and *C. bairdi*). Fisheries Research, 234: 105761.

Orensanz, J., Ernst, B., Armstrong, D., Stabeno, P., and Livingston, P. 2005. Contraction of the geographic range of distribution of snow crab (*Chionoecetes opilio*) in the Eastern Bering Sea: An environmental ratchet? Reports of California Cooperative Oceanic Fisheries Investigations, 45: 65-79.

Orensanz, J.M., Ernst, B., Armstrong, D.A. 2007. Variation of Female Size and Stage at Maturity in Snow Crab (*Chionoecetes Opilio*) (Brachyura: Majidae) from the Eastern Bering Sea. Journal of Crustacean Biology 27: 576–591.

Reum, J.C., Thorson, J.T., Fedewa, E.F. 2026. Joint spatiotemporal models for the estimation of prey consumption and predator-prey overlap: Dynamics of Pacific cod predation on snow and Tanner crab in the eastern Bering Sea. Fisheries Oceanography. 3: 370-385.

Ryznar, E.R., Fedewa, E.J., Litzow, M.S. In review. Changing size at maturity in Bering Sea snow crab: the role of mate availability and competition. ICES Journal of Marine Science.

Sainte-Marie, B., Raymond, S., and Brêthes, J. 1995. Growth and maturation of the benthic stages of male snow crab, *Chionoecetes opilio* (Brachyura: Majidae). *Canadian Journal of Fisheries and Aquatic Sciences*. 52(5): 903-924.

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

Szuwalski, C., Cheng, W., Foy, R., Hermann, A. J., Hollowed, A., Holsman, K., Lee, J., et al. 2021. Climate change and the future productivity and distribution of crab in the Bering Sea. ICES Journal of Marine Science, 78: 502-515.

Szuwalski, C. S., Aydin, K., Fedewa, E. J., Garber-Yonts, B., and Litzow, M. A. 2023. The collapse of eastern Bering Sea snow crab. Science, 382: 306-310.

Thorson, J. T., Andrews, A. G., III, Essington, T. E., & Large, S. I. 2024. Dynamic structural equation models synthesize ecosystem dynamics constrained by ecological mechanisms. *Methods in Ecology and Evolution*, 15(4), 744–755.

Webb, J. B., Slater, L. M., Eckert, G. L., and Kruse, G. H. 2016. The contribution of fecundity and embryo quality to reproductive potential of eastern Bering Sea snow crab (*Chionoecetes opilio*). Canadian Journal of Fisheries and Aquatic Sciences, 73: 1800-1814.

Yeung C, McConnaughey RA. 2006. Community structure of eastern Bering Sea epibenthic invertebrates from summer bottom-trawl surveys 1982 to 2002. Mar Ecol Prog Ser 318:47-63.

Tables

Table A.1a: First stage ecosystem indicator analysis for EBS 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 the long-term mean). Fill color of the cell is based on the proposed sign of the overall relationship between the indicator and the stock (blue or italicized text = good conditions for the stock, red or bold text = poor conditions, white = average conditions). A gray fill and text = "NA" will appear if there were no data for that year.

Indicator category	Indicator	2022 Status	2023 Status	2024 Status	2025 Status	2026 Status
Predictive	Spring Sea Ice Extent	neutral	neutral	neutral	neutral	*high*
	Cold Pool Extent (≤ 0°C)	neutral	neutral	neutral	neutral	neutral
	Juvenile Snow Crab Energetic Condition	neutral	neutral	neutral	neutral	neutral
	Juvenile Snow Crab Temperature of Occupancy	neutral	neutral	neutral	neutral	neutral
Contextual	Juvenile Snow Crab Disease Prevalence	neutral	neutral	neutral	neutral	neutral
	Pacific Cod Consumption	neutral	neutral	neutral	neutral	NA
	Male Snow Crab Size at Maturity	neutral	neutral	neutral	**low**	neutral
	Mature Male Snow Crab Area Occupied	neutral	neutral	**low**	**low**	neutral
	Mature Male Snow Crab Center of Abundance	*high*	*high*	neutral	neutral	neutral
	Female Snow Crab Reproductive Failure	**high**	neutral	neutral	*low*	neutral
	Snow Crab Operational Sex Ratio	neutral	neutral	neutral	**high**	**high**
Monitoring	Arctic Oscillation Index	neutral	neutral	neutral	neutral	neutral
	Chlorophyll a Concentration	*high*	neutral	neutral	*high*	neutral
	Benthic Prey Density	neutral	**low**	neutral	*high*	*high*
	Female Snow Crab Size at Maturity	neutral	neutral	*high*	*high*	neutral

Table A.1b: First stage socioeconomic indicator analysis for EBS 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). A gray fill and text = “NA” will appear if there were no data for that year. A red color indicates a fishery closure and the text = “Closed” will appear. Note that the year heading references calendar year; the EBS snow crab fishery is prosecuted Jan-May, such that the calendar year corresponds to the second period of the crab season-year; the most recent snow crab fishery occurred during the 2025/26 crab season. ABSC Skipper Survey indicator status is reported for the most recent crab season only.

Indicator category	**Indicator**	**2022 Status**	**2023 Status**	**2024 Status**	**2025 Status**	**2026 Status**
Fishery Informed	Number of Active Vessels	low	NA	NA	low	low
	Fishery CPUE	NA	NA	neutral	neutral	neutral
	Fishery Total Potlifts	NA	NA	neutral	neutral	neutral
	Centroid of Fishery	NA	NA	high	neutral	neutral
	Annual Incidental Catch	neutral	neutral	neutral	neutral	neutral
	ABSC Skipper Survey: Perceived Abundance	NA	NA	NA	NA	high
	ABSC Skipper Survey: Changes in Fishing Practices	NA	NA	NA	NA	high
	ABSC Skipper Survey: Principal Driver of Changes	NA	NA	NA	NA	high
Economic	Ex-vessel Value	low	NA	NA	NA	NA
	Ex-vessel Price	high	NA	NA	NA	NA
	Ex-vessel Revenue Share	neutral	NA	NA	NA	NA

Figures

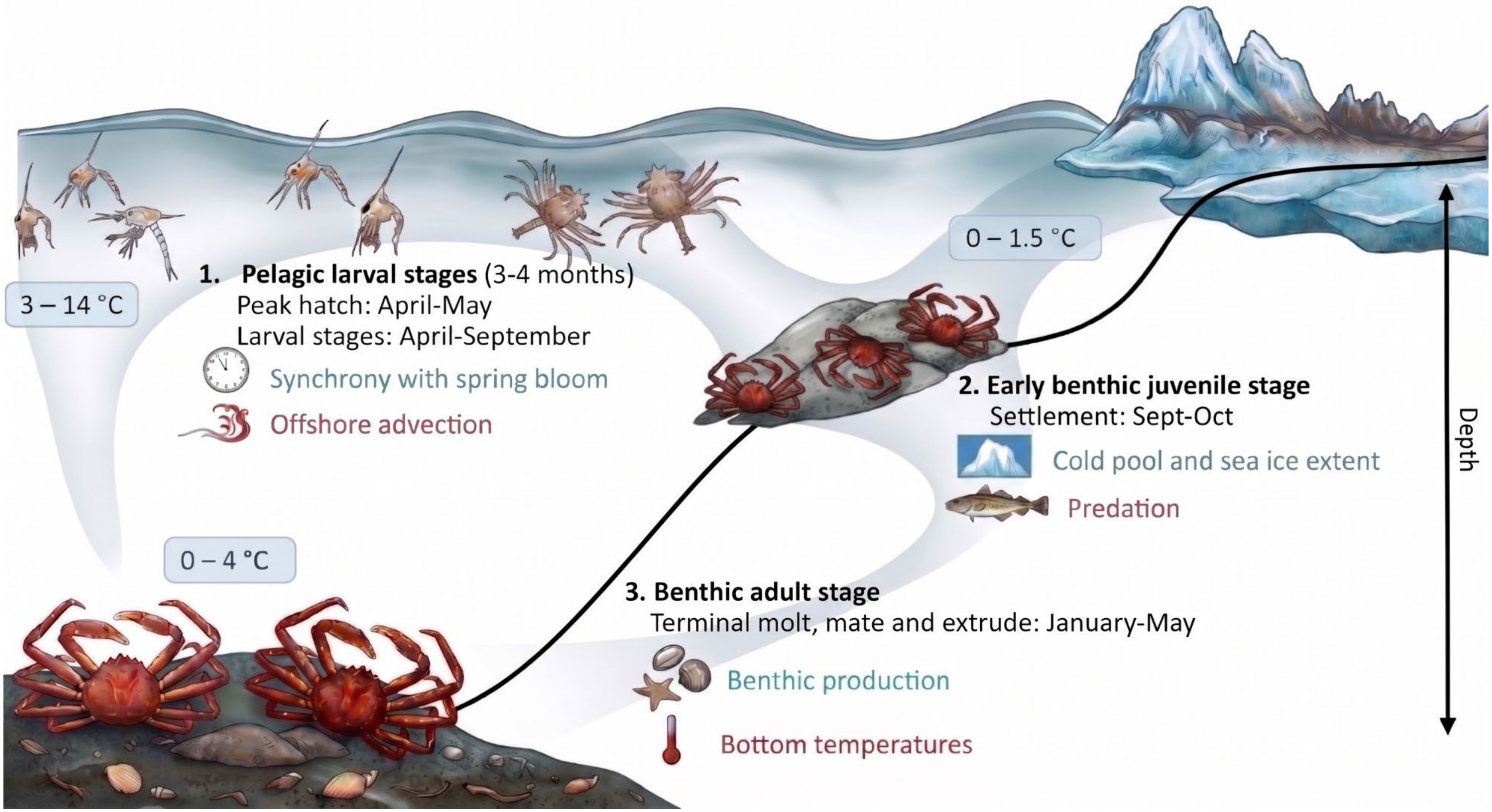


Figure A.1: Life history conceptual model for EBS snow crab summarizing ecological information and key ecosystem processes affecting survival by life history stage. Red text indicates that increases in the process negatively affect survival of the stock, while blue text means that increases in the process positively affect survival.

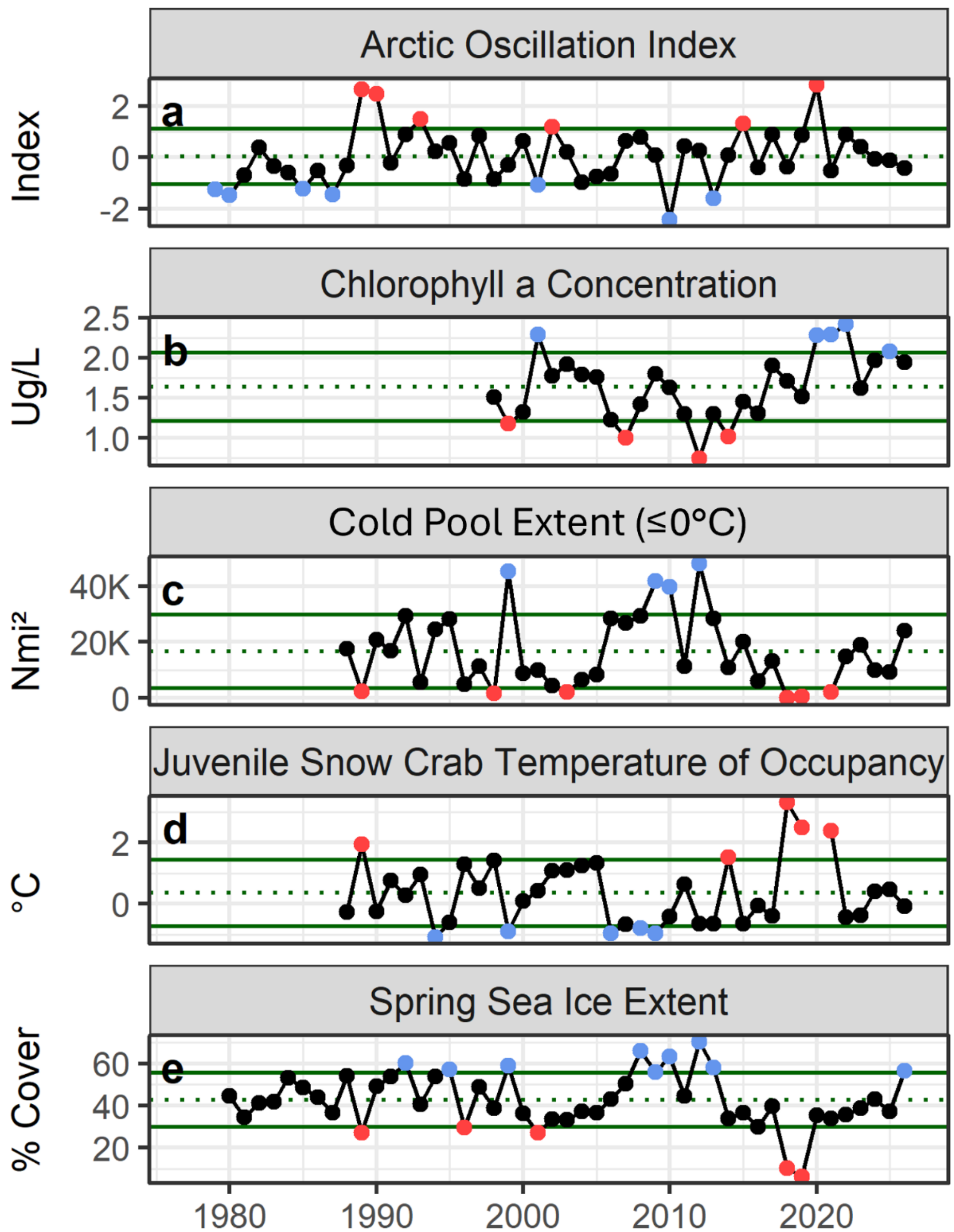


Figure A.2a: Selected ecosystem indicators for EBS snow crab with time series ranging from 1975 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

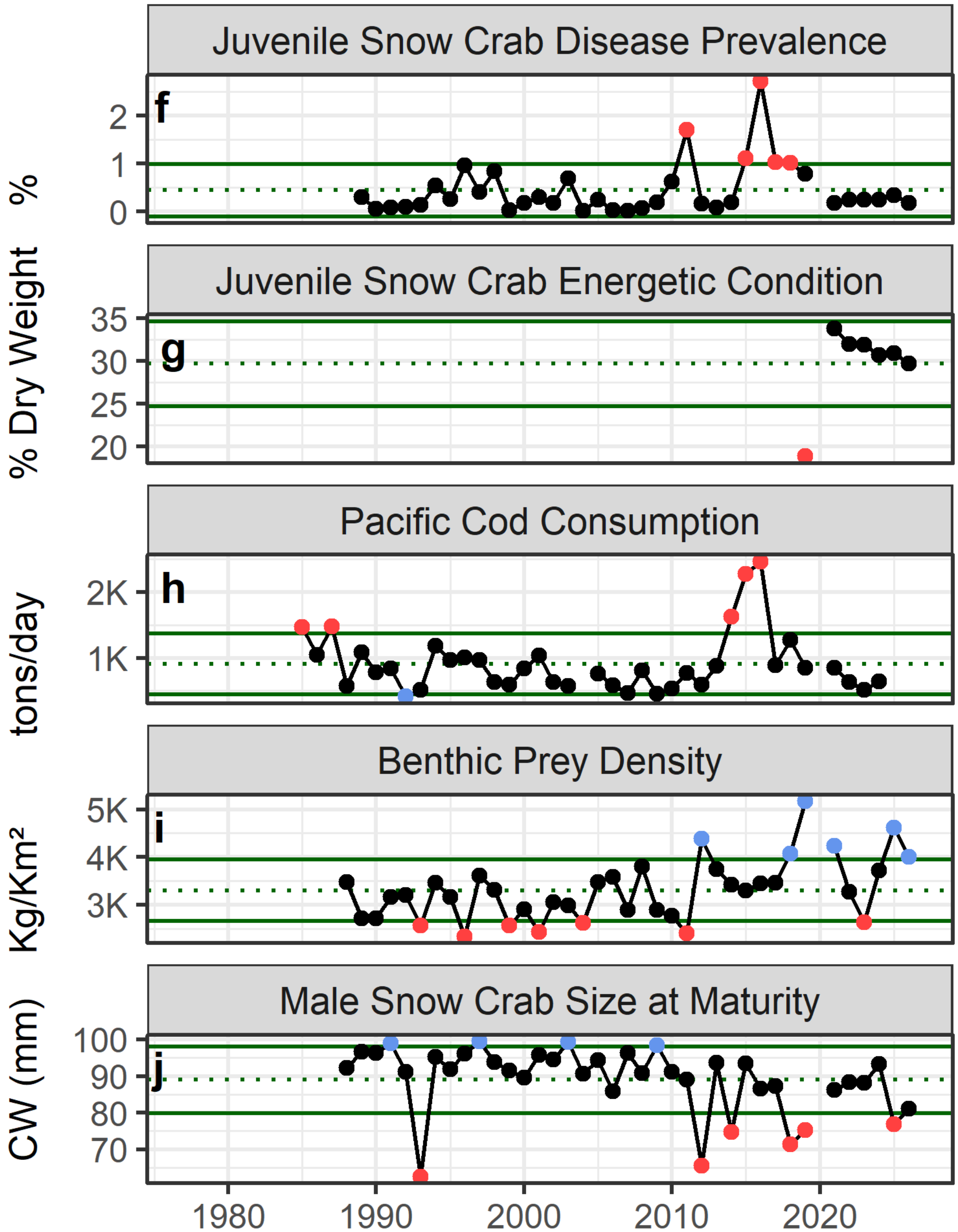


Figure A.2a (cont.): Selected ecosystem indicators for EBS snow crab with time series ranging from 1975 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

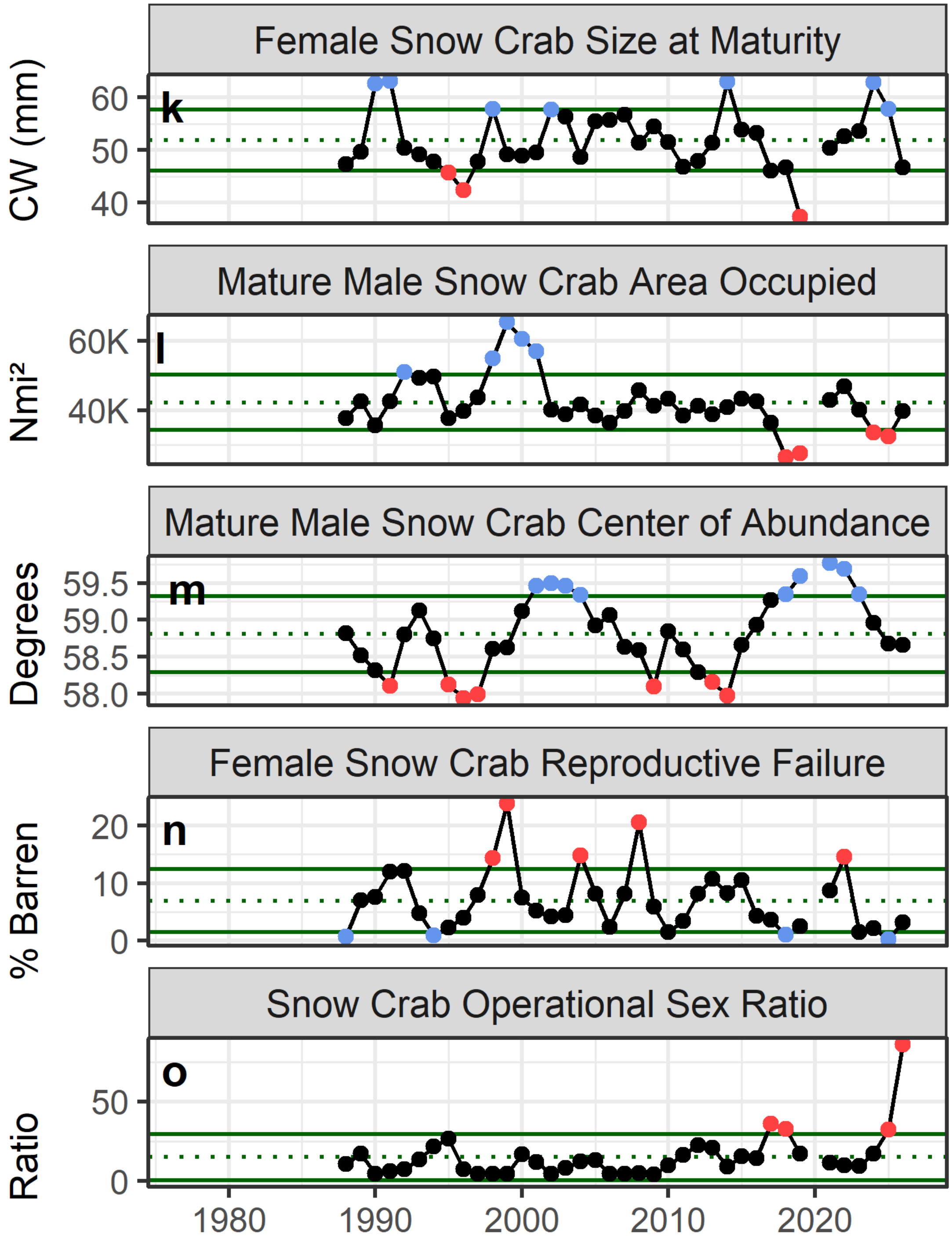


Figure A.2a (cont.): Selected ecosystem indicators for EBS snow crab with time series ranging from 1975 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

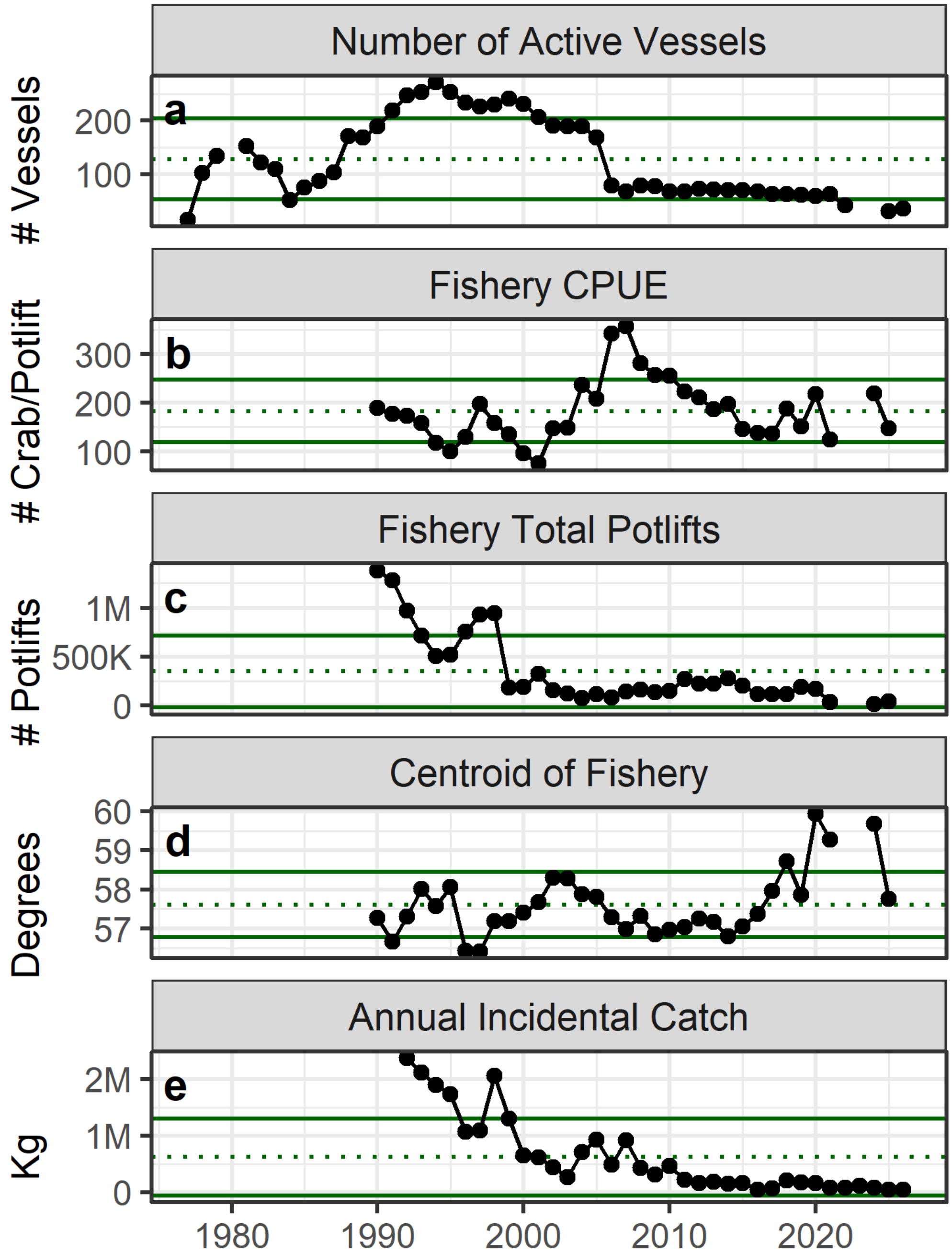


Figure A.2b: Selected socioeconomic indicators for EBS snow crab with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

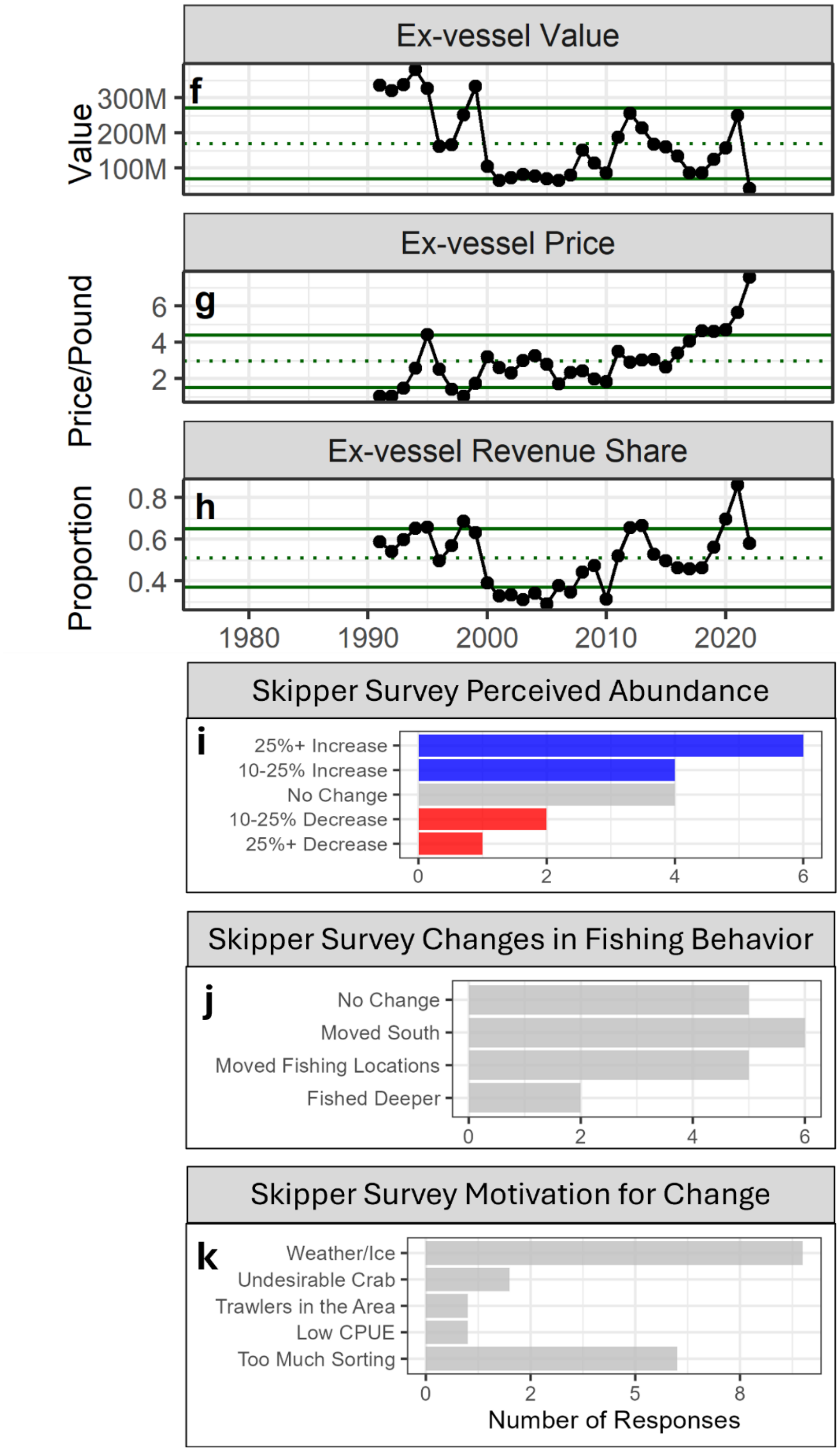


Figure A.2b (cont.): Selected socioeconomic indicators for EBS snow crab with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

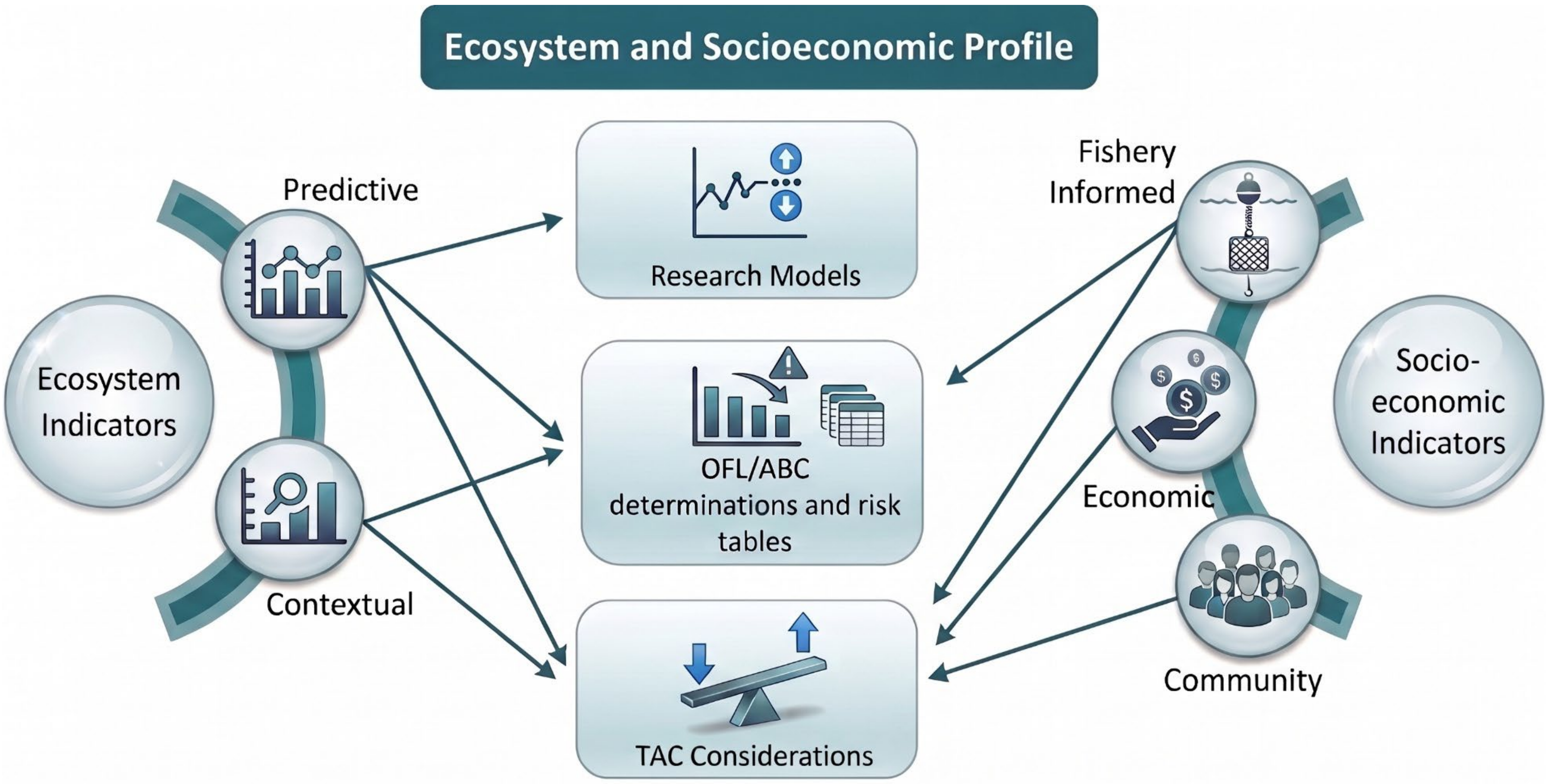


Figure A.3: Schematic of decision pathways for ecosystem and socioeconomic indicators.

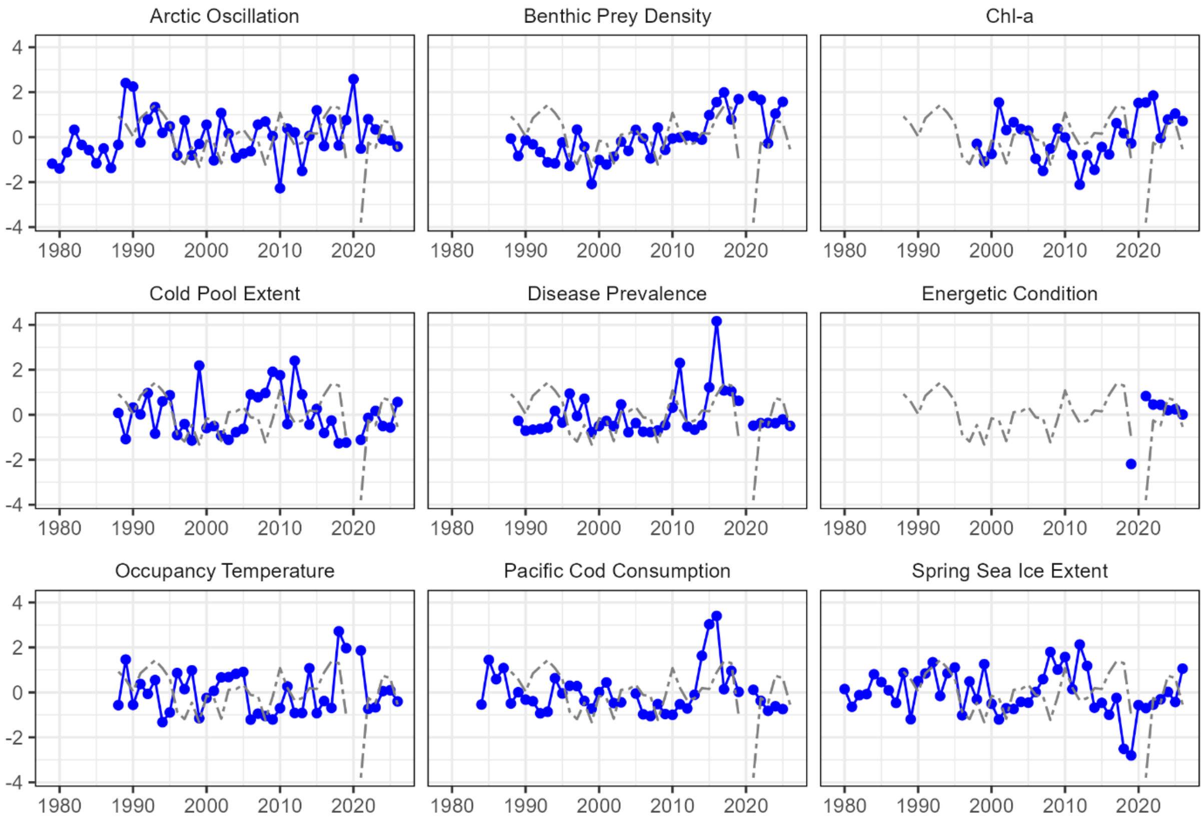


Figure A.4: Dynamic Structural Equation Modeling response and predictor variables. a) Response variable, log-transformed snow crab recruitment (survey abundance of 40-50 mm immature males), and b) standardized ecosystem indicators tested in the final DSEM model.

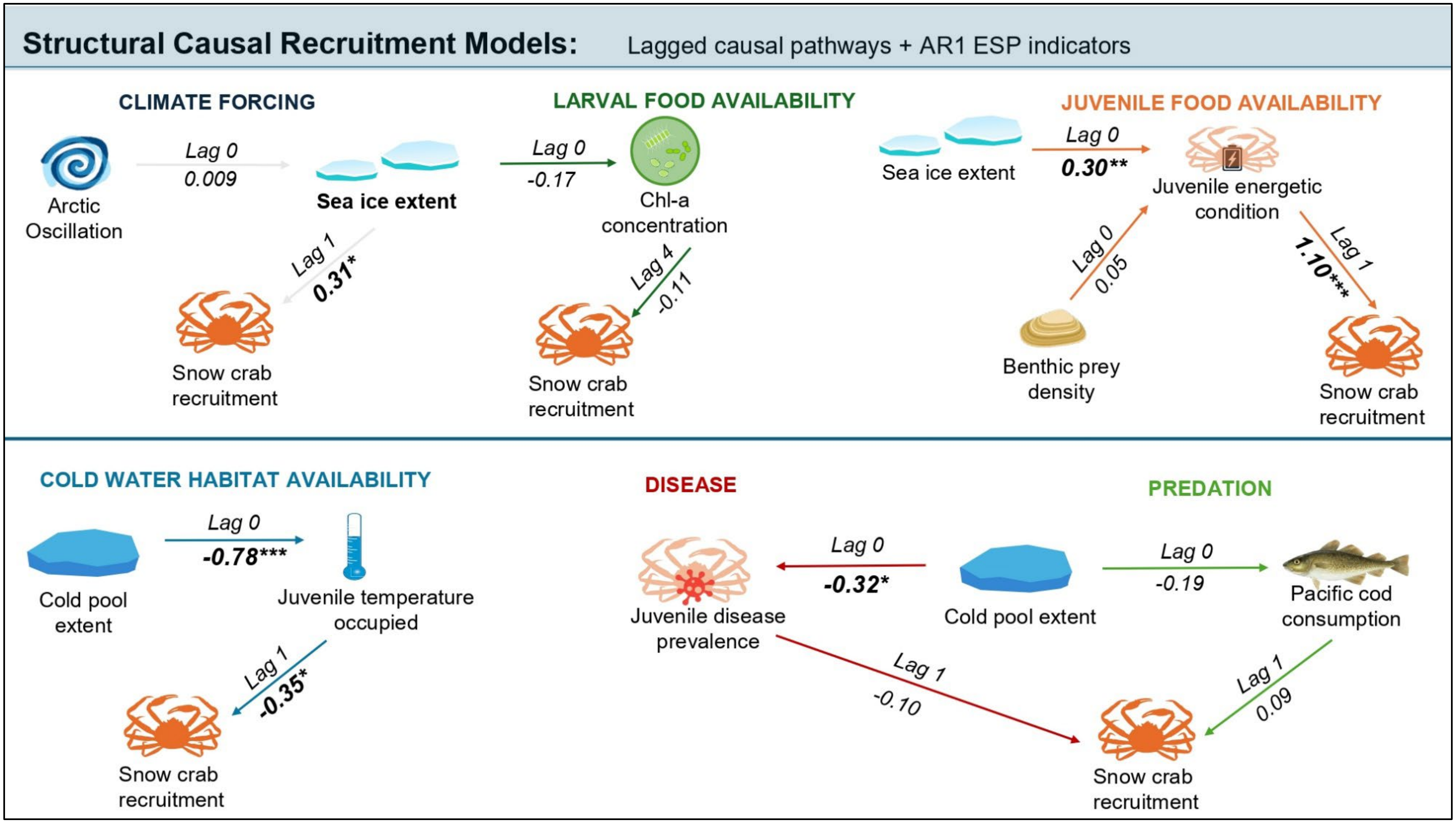


Figure A.5: Dynamic Structural Equation Models (DSEMs) explaining snow crab recruitment. Each directed acyclic graph (DAG) represents a separate DSEM and depicts the causal hypotheses tested, the lag structure specified for each causal pathway, and the resulting causal effect estimates (± SE). Bold coefficients indicate a P value < 0.05 from a two-sided Wald test. *P < 0.05; **P < 0.01; ***P < 0.001.

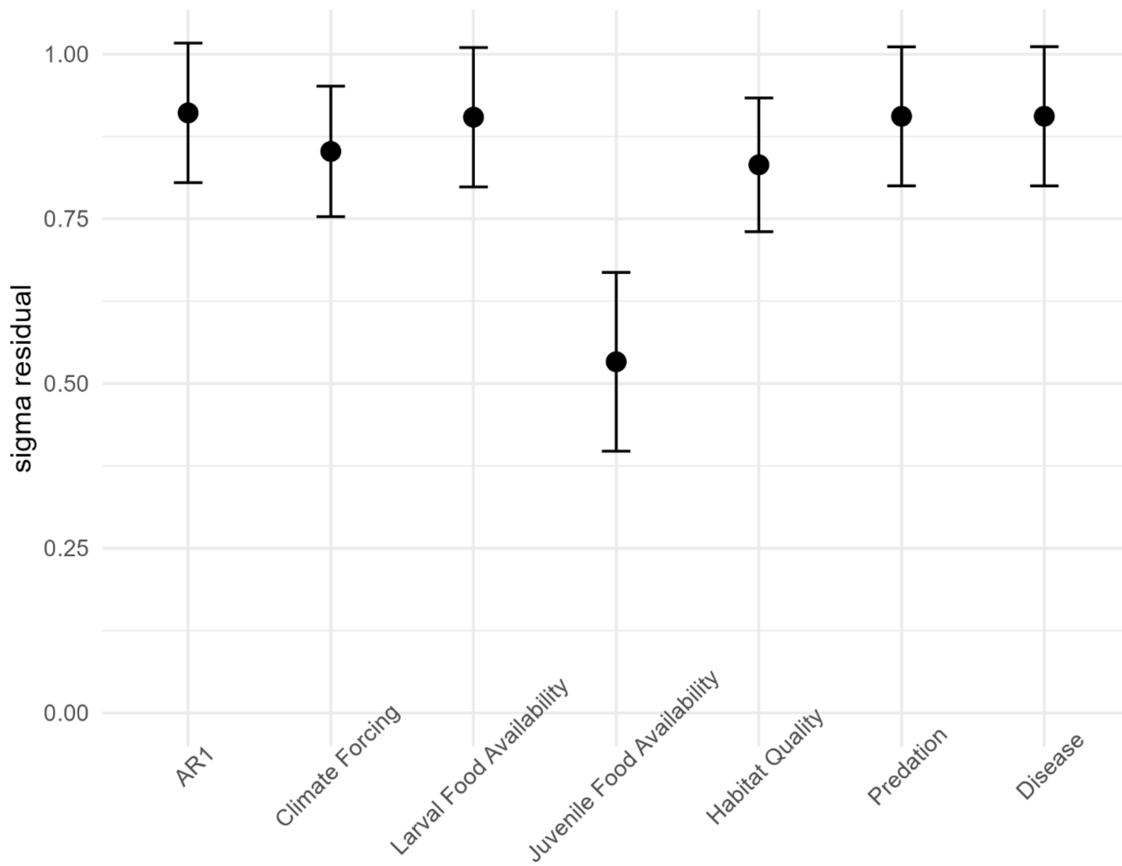


Figure A.6: Estimated recruitment process-error standard deviation (σ) across dynamic structural equation models (DSEMs). Points represent model estimates of recruitment process error, with error bars showing ±1 SE, for the independent and identically distributed (IID), autoregressive (AR1), and causal DSEMs representing climate forcing, larval food availability, juvenile food availability, habitat quality, predation, and disease causal hypotheses. Differences in σ indicate the relative amount of unexplained recruitment variability remaining under each model formulation.

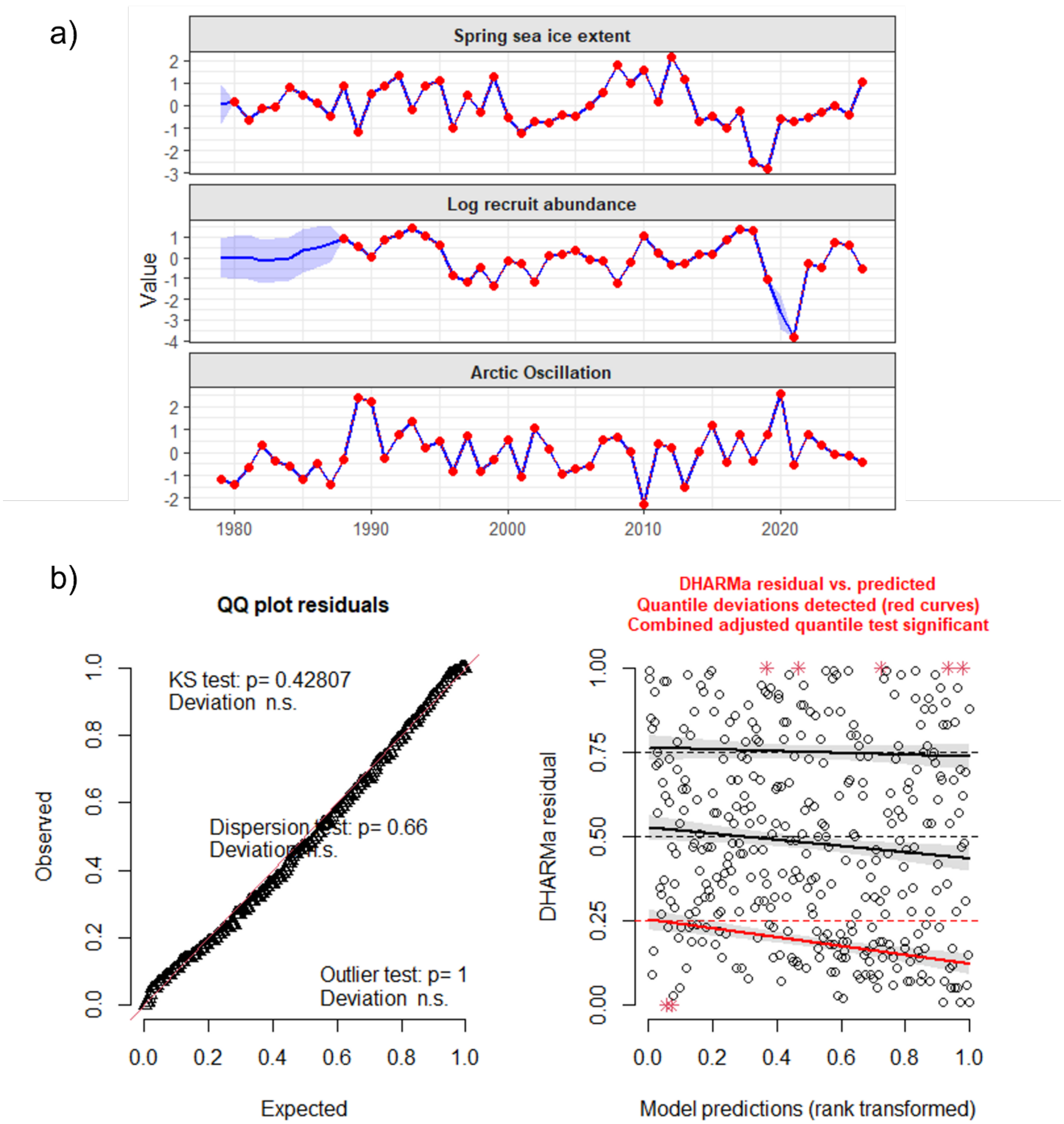


Figure A.7: Results from the Climate Forcing DSEM model. (A) Observed values (red points) and model-estimated latent states (blue lines ±1 SE). (B) Diagnostic plots of leave-one-out (LOO) residuals for the Climate Forcing DSEM, generated using DHARMa.

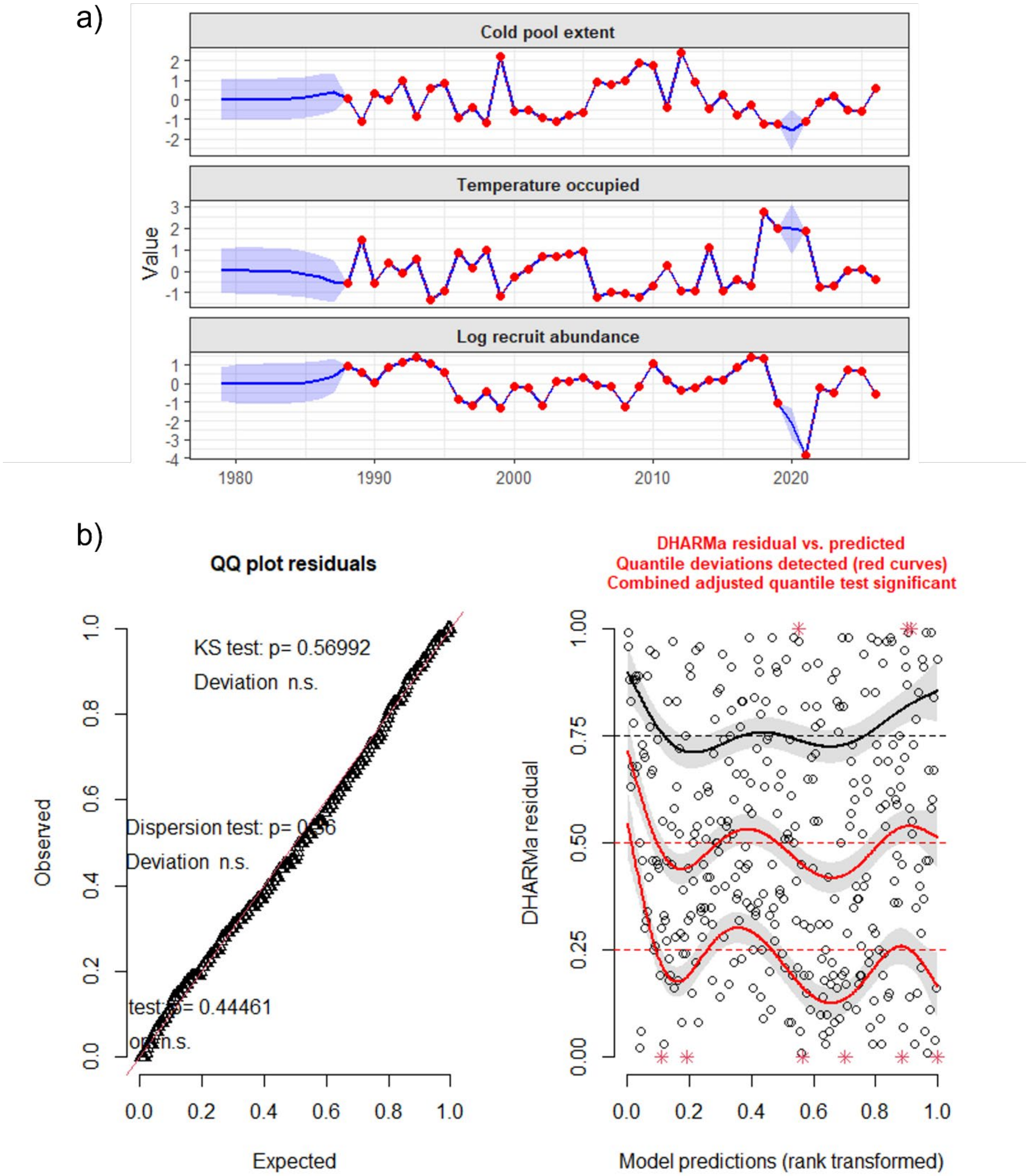
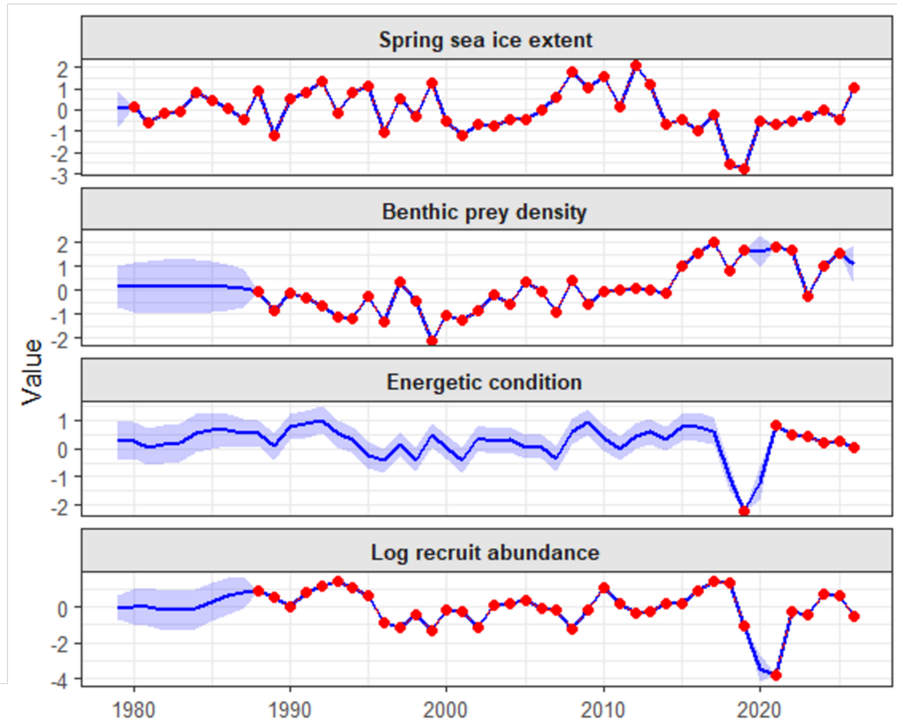


Figure A.8: Results from the Cold-Water Habitat Availability DSEM model. (A) Observed values (red points) and model-estimated latent states (blue lines ±1 SE). (B) Diagnostic plots of leave-one-out (LOO) residuals for the Cold-Water Habitat Availability DSEM, generated using DHARMa.

a)



b)

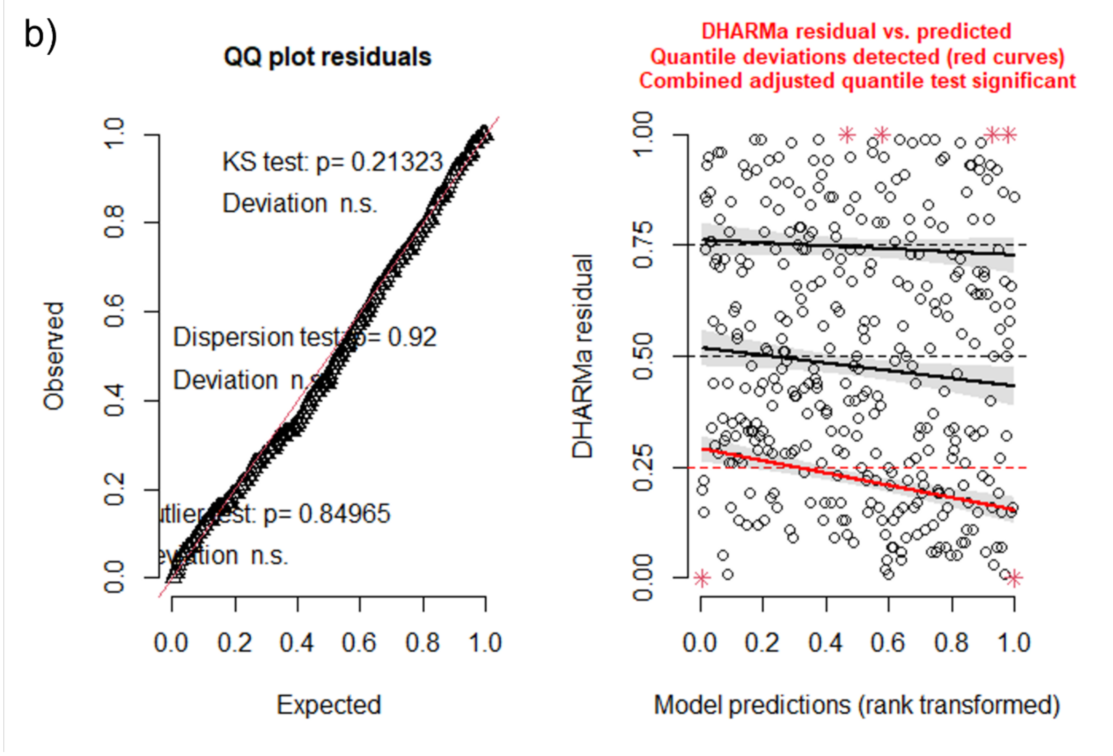


Figure A.9: Results from the Juvenile Food Availability DSEM model. (A) Observed values (red points) and model-estimated latent states (blue lines ±1 SE). (B) Diagnostic plots of leave-one-out (LOO) residuals for the Juvenile Food Availability DSEM, generated using DHARMa.