Appendix F. Ecosystem and Socioeconomic Profile of the Bristol Bay red king crab stock - Update

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Executive Summary

The Ecosystem and Socioeconomic Profile (ESP), is a standardized framework for compiling and evaluating relevant stock-specific ecosystem and socioeconomic indicators and communicating linkages and potential drivers of the stock within the stock assessment process (Shotwell et al., 2023). This update report provides supporting information for the Bristol Bay red king crab (BBRKC) ESP report card (Fedewa et al., 2025) and details the methodology and results from statistical analyses used to monitor current year status and trends of ecosystem and socioeconomic indicators. The BBRKC stock was evaluated at the intermediate indicator analysis stage using the Bayesian Adaptive Sampling (BAS) importance method. Highlights of the indicator assessment are summarized below as considerations that can be used for evaluating concerns in the main stock assessment or other management decisions.

Acceptable Biological Catch (ABC) Considerations:

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

Predictive Indicators:

- Elevated wind stress in Bristol Bay suggests poor feeding conditions for larval red king crab in 2025, and is predicted to result in a decline in BBRKC recruitment to the fishery in ~ 6 to 8 years due to poor larval survival.
- Bristol Bay red king crab have experienced a steady decline in bottom water pH in the past two decades, and pH declined to 7.94 in 2025. Continued declines in pH are predicted to result in a decline in BBRKC recruitment due to negative impacts on growth, shell hardening, and survival.

Contextual Indicators:

- While Bristol Bay was considerably warmer than the last four years, direct impacts on the stock are uncertain.
- The spatial extent of mature male distribution has expanded with warming bottom temperatures over the past 40 years, and the ratio of red king crab in the Northern District relative to Bristol Bay remains above the 42-year time series mean. In 2025, 60% of mature male BBRKC were located in trawl closure areas during the summer survey period, although northward stock distribution shifts and range expansion may limit the utility of these closure areas and static management boundaries.
- An increase in the proportion of mature females with empty clutches in 2025 suggests a potential reduction in reproductive potential of the stock, although the proportion of empty clutches remains small (< 4%) and indicates that the majority of mature females had completed the molt/mate cycle prior to sampling on the NOAA bottom trawl survey.

Fishery-Informed Indicators:

- Metrics of total effort in the fishery, total potlifts (11.5 thousand) and number of active vessels (34), were at or near historical lows during the 2024/25 fishery.
- Catch per unit effort (CPUE) of retained crab in the 2024/25 fishery increased to 29.6, well above the long term average, from a relatively average level of 20.5 during the previous (2023/24) season.
- Crab vessel captain observations on fishing conditions in the 2024/25 BBRKC fishery, as reported in the Alaska Bering Sea Crabbers (ABSC) Skipper Survey, are consistent with high fishery CPUE. The large majority (89%) of captains reported a greater than 10% increase in abundance of legal males relative to the previous open season, with 63% of respondents reporting

a 25% or greater increase. Regarding significant changes in fishing practices from the previous season, the majority (52%) of respondents indicated no significant change, with longer soak times being the second most common response (14%). Other than no change (44%), the most common reported reason for changing fishing practices was high CPUE (30%), followed by excessive sorting and discard (15%).
- Incidental catch of Bristol Bay red king crab in 2024 groundfish fisheries declined from the previous year to 90.9 thousand metric tons, the lowest level since 2012.

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 (Figure F.2a and Table F.1)
- Economic and community indicators reflect the critical importance of the BBRKC fishery to industry and community stakeholders. The unprecedented high ex-vessel price observed in the 2024/25 fishery (average $22.60/pound) demonstrates exceptionally strong market demand for the product of this fishery, generating substantial (though low by historical standards) ex-vessel value, despite the sharply constrained catch allocation, representing 71% of the total fishing revenue earned by the active BBRKC fleet during 2024 (compared to 39% between 2005 and 2019). With the fleet consolidating the limited TAC across 34 active vessels (compared to an average of 60 from 2015-2019) facilitated by quota leasing under the rationalization program, the crab industry continues to face continued financial stresses as a result of stock conditions and market volatility, with distributional and community effects stemming from idled vessels and reduced crew and processing employment.

Introduction/Background

An ESP was recommended for Bristol Bay red king crab (BBRKC) in 2019 and the ESP full report was created in 2020 (Fedewa et al., 2020). The ESP full report is provided as an appendix to the operational stock assessment and fishery evaluation or SAFE report for the BBRKC stock and is reviewed and evaluated at the same time as the operational stock assessment. The elements of an ESP full report include a justification supporting the ESP recommendation, description of data streams used in the ESP, comprehensive literature review, synthesis of ecosystem and socioeconomic processes, description of the selected indicator suite, statistical analysis of the indicators according to the data availability of the stock, summary conclusions, and a final section detailing data gaps and research priorities.

In years following full reports, an ESP update report may be created in conjunction with the full or updated SAFE report schedule. The ESP update includes mainly static elements in a short background to recap the ESP full report, reference the conceptual model, provide descriptions of the selected indicators used in the indicator analysis, and update the statistical analysis with new indicator data. 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 F.1). Please refer to the last full ESP document (Fedewa et al., 2020) for more details.

Indicator Assessment

Selected indicators for BBRKC 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 BBRKC, please refer to the previous ESP documents (Fedewa et al., 2020). Time series of these indicators are provided in Figure F.2a (ecosystem indicators) and Figure F.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 F.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 F.2).
- “Neutral”: Used in Table F.1 for any value within 1 standard deviation of the mean.
- “High” or “Low”: Used in Table F.1 if the value was more than 1 standard deviation above or below the mean (above or below the solid green lines in Figure F.2).

The ESP full report evaluates the indicator suite as a whole when the ESP is first created (Fedewa et al., 2020). 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 2025 suite include:

- Female BBRKC Reproductive Failure: This modified indicator replaces the Female BBRKC Reproductive Potential indicator, and calculates the proportion of mature females with empty clutches slightly different than the previously employed method.
- Chlorophyll *a* Concentration: Transitioned from the ESA GlobColour blended satellite product to the ESA OC-CCI blended satellite product.
- Spring pH: Previous estimates from Bering10K ROMS model hindcasts were transitioned to MOM6 hindcasts.

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

Removed indicators in the 2025 suite include:

- Summer Cold Pool Extent was removed to limit redundancy with Summer Bottom Temperature

Indicator Suite

Below we list 1) a short description of each indicator, including the data source and contributor, 2) the indicator lag assigned for ecosystem indicator analysis, as determined by the proposed mechanistic relationship between the stock and indicator (ecosystem indicators only), 3) factors driving indicator trends, and 4) potential implications of directional shifts in indicator trends for BBRKC.

Ecosystem Indicators:

Larval Indicators (Figure F.2a .a-d)

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
    - Lag assigned for ecosystem indicator analysis: 6 years
    - 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 BBRKC recruitment has been associated with positive values of the Arctic Oscillation (Szuwalski et al., 2021).
b. Summer Wind Stress: Summer wind stress (m/s) in Bristol Bay from NOAA/NCDC blended winds and Metop-A ASCAT satellite (NOAA/NESDIS, CoastWatch). Proposed sign of the relationship is negative. Contact: Dale Robinson
    - Lag assigned for ecosystem indicator analysis: 6 years
    - Factors influencing trends: Wind stress is affected by wind speed, the shape of wind waves and atmospheric stratification.
    - Implications: Higher wind stress suggests less suitable conditions for larval first-feeding success (Paul et al., 1989).
c. Chlorophyll *a* Concentration: April – June average chlorophyll *a* concentration in the Bristol Bay Red King Crab management district, calculated with the ESA OC-CCI blended satellite product. Proposed sign of the relationship is positive. Contact: Erin Fedewa
    - Lag assigned for ecosystem indicator analysis: 6 years
    - Factors influencing trends: Spring chlorophyll 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-a concentrations indicate less diatoms in the water column, which are a critical prey source for larval RKC (Paul et al., 1989).
d. Bristol Bay Sockeye Inshore Run Size: Annual inshore run size of Bristol Bay sockeye salmon (in millions of fish), calculated as the sum of catches in five terminal fishing districts, plus the escapement of sockeye to nine major river systems. The current year run size estimate is preliminary and subject to change until fish ticket numbers are finalized. Proposed sign of the relationship is negative. Contact: Curry Cunningham
    - Lag assigned for ecosystem indicator analysis: 6 years
    - Factors influencing trends: High sockeye salmon abundance in the Bering Sea has been linked to increased prey abundance and sea surface temperatures (Yasumiishi et al., 2024).
    - Implications: The recent high production stanza for sockeye salmon and record high run sizes suggest the potential for increased predation on larval red king crab in Bristol Bay.

Juvenile Indicators (Figure F.2a. e-g)

e. Spring pH: Spring (February – April 15) pH index of Bristol Bay bottom waters, estimated from MOM6 model hindcasts. Proposed sign of the relationship is positive. Contact: Darren Pilcher
    - Lag assigned for ecosystem indicator analysis: 4 years

- Factors influencing trends: The pH values on the inner and middle shelf of the Bering Sea are driven by freshwater runoff from river systems and bacterial respiration of sinking organic matter generated by phytoplankton productivity. Although drivers of interannual pH variability are poorly understood, declining pH values over the full time series are due to positive trends in the partial pressure of carbon dioxide in surface waters (Pilcher et al., 2019).
- Implications: Juvenile red king crab condition, growth, shell hardness and survival are negatively impacted by exposure to pH values below 7.8 (Long et al. 2013; Swiney et al., 2017), and ocean acidification may be a significant factor in the recruitment failure of BBRKC (Litzow et al., 2025).

f. Bottom Temperature: Average summer bottom temperature in Bristol Bay from the EBS bottom trawl survey. Proposed sign of the relationship is negative. Contact: Erin Fedewa
- Lag assigned for ecosystem indicator analysis: 2 years
- Factors influencing trends: Bottom temperatures in the Bering Sea are driven by winter sea ice extent and winds, and summer cold pool formation.
- Implications: While red king crab have a fairly wide thermal tolerance (Long and Daly 2017), colder temperatures drive shifts in ovigerous female distributions and delay embryonic development and hatching (Loher and Armstrong 2005).

g. Pacific Cod Predator Density: Summer Pacific cod density (kg/km²) estimated from EBS bottom trawl survey stations included in the BBRKC management district. Proposed sign of the relationship is negative. Contact: Erin Fedewa
- Lag assigned for ecosystem indicator analysis: 1 year
- Factors influencing trends: Pacific cod are a major predator of red king crab, and predation likely increases in the spring when crab are soft and molting.
- Implications: High Pacific cod density suggests increased predation pressure on BBRKC.

Adult Indicators (Figure F.2a. h-n)

h. Benthic Prey Density: Summer benthic invertebrate mean density (kg/km²), estimated from EBS bottom trawl survey stations included in BBRKC management district. Invertebrates are subset to include species observed in red king crab diet studies, and include brittle stars, sea stars, sea cucumber, bivalves, non-commercial crab species, shrimp and polychaetes.Proposed sign of the relationship is positive. Contact: Erin Fedewa
- Lag assigned for ecosystem indicator analysis: 1 year
- 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 suggests increased prey availability for BBRKC. However, the bottom trawl survey does not sample key prey items such as polychaetes and bivalves well, thus this indicator is a fairly coarse proxy for prey quantity.

i. BBRKC Mature Male Area Occupied: The minimum area containing 95% of the cumulative mature male red king crab CPUE in the BBRKC management district during the EBS summer bottom trawl survey. Proposed sign of the relationship is positive. Contact: Erin Fedewa
- Not included in ecosystem indicator analysis
- Factors influencing trends: Red king crab spatial distributional shifts have been associated with changes in bottom temperatures (Loher and Armstrong, 2005; Zacher et al., 2018).

- Implications: The range expansion of mature male red king crab during the past decade has been associated with a northward shift in centroids of abundance. Range expansion may suggest that mature males are tracking thermal habitat preferences in response to recent warming in the Bering Sea.

j. <u>BBRKC Mature Female Area Occupied:</u> The minimum area containing 95% of the cumulative mature female red king crab CPUE in the BBRKC management district during the EBS summer bottom trawl survey. Proposed sign of the relationship is positive. Contact: Erin Fedewa
    - Not included in ecosystem indicator analysis
    - Factors influencing trends: Northerly shifts in stock distribution are generally associated with both warmer temperatures and high Pacific Decadal Oscillation values during the summer, and mature female RKC appear to avoid waters < 2°C (Loher and Armstrong, 2005; Zheng and Kruse, 2006).
    - Implications: Spatial distribution shifts may result in more mature females inhabiting the Nearshore Bristol Bay Trawl Closure Area, although continued range contraction may raise concern for increased competition for resources.

k. <u>Fishery Catch Distance from Shore:</u> The mean distance legal male red king crab were caught from shore during the fishery, calculated using fishery observer data. During 2021 and 2022 fishery closures, mean distance from shore was estimated with satellite-tagged legal male red king crab, and calculated as the mean distance from shore for all tags east of 165°W. This boundary approximates the actual fishing grounds rather than the spatial allocation of tagging efforts. No directional relationship with the stock. Contact: Leah Zacher
    - Not included in ecosystem indicator analysis
    - Factors influencing trends: Red king crab during the fall fishery tend to aggregate in the center of Bristol Bay and the Red King Crab Savings Area in warm years, and disperse along the Alaska Peninsula in cold years (Zacher et al., 2018).
    - Implications: A spatial shift in fishing effort may be indicative of population-level distribution shifts from summer to fall. Distance from shore has implications for crab-fishing gear interactions, bycatch of crab, and unobserved mortality, most notably if BBRKC are found outside of protected areas.

l. <u>Female BBRKC Reproductive Failure:</u> The proportion of newshell mature female BBRKC with no eggs, empty egg cases, or dead eggs. Because cold temperatures delay the female molt/mate cycle, oldshell barren females are excluded under the assumption that they will likely molt and mate in the coming months after survey sampling is complete. Proposed sign of the relationship is negative. Contact: Erin Fedewa
    - Lag assigned for ecosystem indicator analysis: 7 years
    - Factors influencing trends: Female reproductive potential is a function of female size, clutch size, and sperm reserves (Gardner et al., 2024). An increased frequency of clutch failure may indicate sperm limitation, inability to locate a mate, or energetic limitations imposed on extrusion and fertilization.
    - Implications: An increase in the proportion of mature females with empty clutches suggests a reduction in reproductive potential of the stock. A > 30% proportion of mature females with empty clutches in the late 1970’s coincided with a stock collapse, suggesting that clutch failures should be continually monitored for under depressed population levels.

m. <u>Northern District:Bristol Bay RKC Ratio:</u> Calculated as the ratio of total red king crab abundance in the Northern District to total red king crab abundance in the Bristol Bay Management District. Proposed sign of the relationship is negative. Contact: Erin Fedewa
    - Not included in ecosystem indicator analysis

- Factors influencing trends: The Northern District to Bristol Bay District ratio may be driven by shifts in larval advection patterns, or exchange between the two districts due to seasonal migrations or directional movement. Preliminary results from tagging studies suggest that males tagged just above the management boundary move south into Bristol Bay in the fall, but don't rejoin the core Bristol Bay stock (L. Zacher, personal communication). Mature females tagged further north did not re-enter Bristol Bay during the study.
- Implications: A large increase in the abundance ratio between the two districts may coincide with northward range expansion of the Bristol Bay stock and movement outside of management boundaries during the summer survey period. Because red king crab in the Northern Unstratified District are not included in the BBRKC stock assessment, this indicator tracks a critical management concern.

n. <u>Proportion of Mature Males in Closure Areas:</u> The proportion (%) of total mature male abundance during the summer EBS bottom trawl survey located in year-round closure areas. Closure areas include the Red King Crab Savings Area, the Red King Crab Savings Subarea in subsequent calendar years following a BBRKC directed fishery closure, and the Nearshore Bristol Bay Trawl Closure Area (with the exception of the Togiak/Nearshore Bristol Bay Trawl Area). NMFS Reporting Area 516 was also excluded as a closure area since the area is only closed seasonally. Proposed sign of the relationship is positive. Contact: Erin Fedewa
   - Not included in ecosystem indicator analysis
   - Factors influencing trends: Proportion of the male population found in closure areas is influenced by interannual variability in stock distribution and spatial extent (likely temperature-mediated), although high catch stations can disproportionately impact the estimate in years when survey catch is patchy.
   - Implications: An increase in the proportion of mature males in closure areas suggests the potential for reduced bycatch of crab in groundfish fisheries, and a potential reduction in interactions with fishing gear during the summer period. However, directional movement of males in the fall and winter when groundfish fishing intensity increases highlights the limited scope of this indicator for drawing inference on bycatch and unobserved mortality.

Socioeconomic Indicators:

<u>Fishery Informed Indicators (Figure F.2b. a-g)</u>

a. <u>Number of Active Vessels:</u> Annual number of active vessels in the BBRKC fishery to represent the level of fishing effort assigned to the fishery. Contacts: Jean Lee and Brian Garber-Yonts
   - 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 BBRKC fleet is driven by the TAC in BBRKC, EBS snow crab, and increasingly, Tanner crab, with crab harvest quota leasing facilitating adjustment of the fleet to achieve efficient deployment of harvesting capacity, although 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. <u>Fishery CPUE:</u> Annual catch-per-unit-effort (CPUE), expressed as mean number of crabs per potlift, in the BBRKC fishery to represent relative efficiency of fishing effort. The cost recovery fishery is not included. Contact: Ben Daly

- Factors influencing trends: Annual fishery CPUE can vary based on a suite of factors including total fishery potlifts, BBRKC abundance, pot gear soak time, pot gear configuration, bait. weather/tides, 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. <u>Fishery Total Potlifts:</u> Annual total potlifts in the BBRKC fishery. The cost recovery fishery is not included. Contact: Ben Daly
   - 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. <u>Annual Incidental Catch:</u> Annual estimates of incidental catch biomass estimates of BBRKC (tons) in federally-managed EBS groundfish fisheries. Contact: Brian Garber-Yonts and Jean Lee
   - Factors influencing trends: Incidental catch of BBRKC in groundfish fisheries occurs primarily in non-pelagic flatfish trawl fisheries and is influenced by the magnitude, temporal and spatial distribution of groundfish fisheries, depth fished (particularly for mature and immature female BBRKC), gear and other aspects of flatfish harvesting effort, as well as the size distribution, abundance, spatial, and temporal distribution of the BBRKC stock (Ryznar and Litzow, 2024).
   - Implications: Rapid changes of incidental catch may imply shifting distribution of the BBRKC population into non-preferred habitat, which could increase competition and predation. Additionally, an increase in incidental catch could be viewed as an early indicator of large year classes of BBRKC or confirmatory of previously estimated year classes.

e. <u>Alaska Bering Sea Crabbers (ABSC) Skipper Survey Perceived Abundance:</u> 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 legal males during the 2024 fishery relative to the last BBRKC 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

f. <u>Alaska Bering Sea Crabbers (ABSC) Skipper Survey Changes in Fishing Practices:</u> 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 2024 fishery relative to the last BBRKC 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

g. 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 2024 fishery relative to the last BBRKC 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 F.2b. h-j)

h. Ex-vessel Value: Annual ex-vessel value of the BBRKC fishery landings represents gross economic returns to the harvest sector, as a principal driver of fishery behavior. Contact: Brian Garber-Yonts and Jean Lee
   - Factors influencing trends: Ex-vessel revenue increased in the fishery due to a 31% increase in average ex-vessel price to an unprecedented $22.60/pound, more than twice the post-2005 average.
   - Implications: Although at the lower margin of the central range of variation about the long-term average, the fishery generated significant income for the harvest sector despite the historically low TAC level.

i. Ex-vessel Price: Annual red king 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 and Jean Lee
   - Factors influencing trends: Ex-vessel price for BBRKC is influenced by productivity of global crab stocks, market supply, and consumer demand, as mediated by varying conditions of international trade, including tariffs and embargoes. Domestic and overseas market demand for premium seafood products, including king crab, has surged over the last several years, with king crab prices continuing the trend despite Russian production reaching a record high in 2024, exported primarily to Asia due to import embargoes in the US and Europe (FAO, 2025a; 2025b).
   - Implications: Among broader implications for the fishery, increasing import tariffs and expected decline in Russian production of king crab in the next year have the potential to push ex-vessel price higher during the 2025/26 fishery, potentially drawing a larger fleet to participate in the event of a fishery opening.

j. Ex-vessel Revenue Share: Annual red king crab ex-vessel revenue share, expressed as vessel-average proportion of annual gross landings revenue earned from the BBRKC fishery. Contact: Brian Garber-Yonts and Jean Lee
   - Factors influencing trends: The share of active BBRKC vessels' total annual landings revenue, in aggregate, across all fisheries generated by the BBRKC fishery, is determined by the ex-vessel prices and production volumes across the portfolio of fishing targets. With limited alternative crab and non-crab fishing targets available to Bering Sea crab vessels, and the consistently high price premium for king crab generally, and BBRKC in particular, differences in the BBRKC TAC have a disproportionately large effect on revenue share.
   - Implications: The high level of this indicator demonstrates the high level of dependence on the BBRKC fishery. Whereas variation in ex-vessel price and revenue have implications for income for crab quota holders as well as active vessels, implications of

the level of, and interannual variation in, revenue share are primarily limited to the active fleet, its owners and crew members.

Indicator Analysis

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

We evaluated the ecosystem indicators 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). These regression techniques estimate predictive performance for the parameter of interest and are run separate from the stock assessment model. They provide the direction, magnitude, uncertainty of the effect, and an estimate of inclusion probability. The advanced stage is used for providing visibility on current research ecosystem models and may be used for testing a research ecosystem linked stock assessment model where output can be compared with the current operational stock assessment model to understand information on retrospective patterns, prediction performance, and comparisons to model outputs.

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

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

Ecosystem Indicator Analysis

The BBRKC stock is data-rich with an associated size-structured stock assessment 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 in an effort to communicate only the most relevant ecosystem considerations for setting biological reference points for the current year.

Bayesian adaptive sampling (BAS) was used as an intermediate stage indicator analysis to quantify the strength and direction of association between ecosystem indicators and BBRKC recruitment. BAS explores model space, or the full range of candidate combinations of predictor variables, to calculate marginal inclusion probabilities for each predictor, model weights for each combination of predictors, and generate Bayesian model averaged predictions for outcomes (Clyde et al., 2011). BBRKC recruitment, our population process of interest, was calculated using the EBS bottom trawl survey abundance of male "pre-recruit" red king crab (≥ 95mm carapace length and ≤ 120mm carapace length) under the assumption that this size class represents individuals that are one molt away from recruiting to the fishery, and approximately 6 - 7.9 years post-settlement (Loher et al., 2001).

Prior to running BAS, the full suite of 14 ecosystem indicators was winnowed to the predictors that directly relate to recruitment. We eliminated the following indicators, as they are not hypothesized to drive BBRKC recruitment and instead, provide contextual information about the stock or a relevant management concern: 1) proportion of mature males in closure areas, 2) fishery catch distance from shore, 3) mature female area occupied, 4) mature male area occupied, and 5) Northern District to Bristol Bay red king crab ratio. We further restricted potential covariates to those that provided the longest model run, and through the most recent estimate of recruitment when possible. Given the short time series length for chlorophyll-*a* concentration relative to other ecosystem indicators once lags were applied (n = 22 years, 2004-2025), it was dropped from the final BAS model to allow for the longest model run possible.

Ecosystem indicator lags were assigned to the remaining indicator suite based on hypothesized mechanistic linkages between the proposed life history stage and the indicator, as well as targeted size ranges that the indicators are hypothesized to have the greatest impact on. Preliminary sensitivity analyses indicate that BAS results are fairly robust to +/- 1 year lags, although the inability to accurately age crab results in difficulties assigning lags with high confidence. Pre-recruit male BBRKC were assumed to be 6 - 7 years old, therefore larval indicators were assigned a lag of 6 years. Female BBRKC crab reproductive failure was lagged an additional year beyond the 6-year larval lag, assuming a 12 month embryo development period. Bottom temperature and pH are assumed to affect growth and survival of juvenile stages, and were assigned lags of 2 and 4 years, respectively. One year lags were assigned to benthic prey density and Pacific cod predator density assuming impacts to survival the year following poor feeding conditions and high predation pressure.

Prior to running the model, we also tested for any highly correlated indicators ($r \geq 0.6$) with the understanding that high correlations among predictors may "dilute" inclusion probabilities and render them less useful as a posterior summary of variable importance. No indicators in the BBRKC ecosystem indicator suite were excluded due to collinearity. This resulted in a final suite of 8 predictors: pH, bottom temperature, female reproductive failure, Pacific cod density, Arctic Oscillation, sockeye salmon run size, benthic prey density and wind stress (Figure F.4). Because missing data are dropped from BAS model runs, 34 years were dropped due to incomplete observations, and resulted in a model run from 1997 - 2025 after lags were applied. NAs due to the cancellation of the 2020 EBS bottom trawl survey were especially problematic, and resulted in 2020 - 2022 being dropped from the analysis after lagging indicators.

We identified two ecosystem indicators that quantitatively predicted BBRKC recruitment, while remaining indicators demonstrated poor predictive performance (Figure F.5). The highest ranked predictor variable, pH, had credible intervals that could be distinguished from zero, a positive effect (-0.22; Figure F.6a), and a relatively high inclusion probability (0.75; Figure F.6b). The second highest ranked predictor, wind stress, had credible intervals that could be distinguished from zero, a negative effect (-0.17; Figure F.6a), and an inclusion probability > 0.5 (0.65: Figure F.6b). This evidence for a negative effect is consistent with the hypothesis that increased wind stress reduces BBRKC larvae-diatom prey encounter rates and negatively impacts survival to recruitment. The final model explained a moderate amount of variation in BBRKC recruitment ($R^2 = 0.39$), however we note that large credible intervals suggest a large degree of uncertainty in the estimated effect sizes**.** Model predicted fit (Figure F.6c) and average predicted fit across the recruitment time series subset (1997 - 2025; Figure F.6d) indicate that wind stress and pH do a fair job at capturing general patterns in BBRKC recruitment, but fail to predict the magnitude of interannual variation in recruitment. Remaining indicators were categorized as contextual (mature male area occupied, mature female area occupied, fishery catch distance from shore, female reproductive failure, proportion of mature males in closure areas, Northern District to Bristol Bay red king crab ratio) and monitoring (benthic prey density, Pacific cod predator density, bottom temperature, Arctic Oscillation index, sockeye salmon inshore run size, chlorophyll-*a* concentration) using the criteria listed above.

We also summarize recent indicator trends and provide management considerations by providing a five year status table of the indicators organized into predictive, contextual, or monitoring categories (Table F.1a). Indicator status is evaluated based on being greater than ("high"), less than ("low"), or within ("neutral") one standard deviation of the long term mean. Potential concerns for the health or status of the stock are identified using predictive relationships (predictive ecosystem indicators) or proposed mechanistic relationships (contextual ecosystem indicators) with the stock, and are communicated as a sign and associated color relative to the indicator value and directional indicator-stock relationship. The sign of the relationship for predictive indicators is based on the importance method results, while the sign for contextual or monitoring indicators is based on the conceptual model and hypothesized relationship with the stock (Figure F.1). The color of the status cell (also referred to as the "traffic light") is related to the sign of the indicator and the status. If a high value of an indicator generates good conditions for the stock and is also greater than one standard deviation above the mean, then that table cell is colored blue. If a high value generates poor conditions for the stock and is greater than one standard deviation above the mean, then that table cell is colored red. All values less than or equal to one standard deviation from the long-term mean are average and there is no assigned color. Also, if the sign of the relationship between an ecosystem indicator and the stock is unclear, no relationship is assigned.

Overall, results from the traffic light table (Table F.1a) indicate that wind stress in 2025 was high relative to the long-term mean, while pH continued to decline in 2025. These current-year estimates represent potential red flags for the stock, and are predicted to result in a recruitment decline in BBRKC in the future (4-7 years). All contextual indicators with 2025 updates remained within one standard deviation of their long-term mean. The Executive Summary at the beginning of this document provides a summary 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 BBRKC fishery: 4 fishery-informed indicators derived from NMFS/ADFG in-season management monitoring systems, 3 selected from the Alaska Bering Sea Crabbers (ABSC) Bristol Bay Red King Crab Skipper Survey, and 3 economic indicators drawn from mandatory economic reporting systems (ADFG's Commercial Operators Annual Reports). All socioeconomic indicators are produced from observations captured during or after completion of the fishery and are not available for the 2025 calendar year. Indicators derived from agency monitoring and reporting systems use time series of historical data through the most recent (2024/25) BBRKC fishery, which occurred during the final months of 2024, 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 2024 survey, which elicited single period comparisons between the 2024/25 fishery and the most recent previous fishery (ABSC, 2024). Inclusion of these indicators is primarily aimed at informing ABC determinations, and is intended as a provisional mechanism for incorporating an alternative source of fishery-dependent data on fleet behavior and observations of abundance, age, sex, and other conditions of the catch for consideration of authors and reviewers of the assessment. 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. Additional indicators, including synthesis of survey time series (n = 3, as of 2024) may be developed for future ESPs pending CPT and SSC evaluation of the initial selection of indicators and, more generally, of recommendations regarding use of the ABSC Skipper Survey as a candidate data source of fishery-informed indicators for use in crab ESPs.

Collectively, the 7 fishery-informed indicators indicated that the most recent fishery represented levels of fishing effort (number of active vessels and total potlifts) more than 1 SD below the long term average, high CPUE (greater than 1 SD above the long-term mean of the time series), and high crab skipper perception of abundance of legal males (relative to the previous season), neutral crab perceptions of changes in fishing behavior and drivers thereof, and neutral status of incidental catch in groundfish fisheries relative to the long term mean (Table F.1b).

At 34 active vessels, the fleet increased by 3 from the 2023/24 season, but it sharply contracted relative to the average of 56 over the five years prior to the closure for the 2021/22 season. Quota royalty income likely mitigates some financial impact of non-entry for vessel owners that have substantial crab quota share holdings, however, idling of a significant segment of the fleet has distributional effects within the harvest sector, including for crew members and associated communities, and over time may have structural implications for the fleet itself and the crab harvest sector generally.

Economic indicators, which in the context of the ESP are exclusively intended to inform TAC deliberations, reinforce other information demonstrating the continuing extreme economic conditions of the fishery. Ex-vessel price and ex-vessel revenue share indicators reached unprecedented high levels - multiple standard deviations above their respective long-term mean values, during the 2024/25 fishery. Ex-vessel revenue increased from $36.8 million 2023 to $52 million in 2024 due to the unprecedentedly high ex-vessel price, low by historical standards but approaching the lower bound of the 1 SD range about the long-term average. The US historically being a net importer of king crab, and the limited supply of king crab from the US and overseas fisheries, combined with the relatively insulated market demand for premium seafood products from general economic trends affecting more commodity-oriented seafood products, suggests that the ex-vessel price of BBRKC is likely to remain high through the 2025/26 season.

The Executive Summary at the beginning of this document provides a summary and interpretation of fishery-informed and economic indicator trends that can be used to inform ABC and TAC decisions. For this BBRKC ESP update, a more limited set of socioeconomic indicators is reported than for previous iterations, and compared to the full ESP produced for the 2025/25 Tanner crab assessment. Given resource limitations, a more inclusive set of socioeconomic indicators in crab ESPs (both full ESPs and update versions) awaits general guidance from the SSC and Council regarding priorities for ESP/socioeconomic indicators to inform TAC setting.

Conclusion

The BBRKC 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., 2020). Fourteen ecosystem and eleven socioeconomic indicators were identified to monitor for BBRKC. Because BBRKC 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. This information can be used for evaluating concerns in the main stock assessment or other management decisions and we organize the results by acceptable biological catch (ABC) and total allowable catch (TAC) considerations. Indicators that can inform ABC and risk tables include predictive, contextual, or fishery-informed indicators. Indicators that can inform TAC include all ABC indicators as well as economic and community indicators.

Wind stress and pH predictive indicators suggest the potential for poor larval feeding conditions and reduced juvenile survival in 2025, and poor recruitment to the fishery in ~4-7 years as a result. Contextual indicators highlight increased spatial extent of mature males relative to static management boundaries, an increase in the proportion of mature females with empty clutches, and overall warm conditions in Bristol Bay this summer, although all current-year estimates were within 1 SD of time series means. Fishery-informed indicators suggest that despite historically low levels of fishing effort during the 2024/25 season, efficiency of effort was high. Economic indicators emphasize the ongoing extreme economic state of the BBRKC fishery due to low TACs, following recent closures in the BBRKC and other BSAI crab fisheries, mitigated to some degree, and in limited respects, by the historic high market values for king crab product. Overall, socioeconomic indicators are generally consistent with stable or mildly improving stock condition relative to the recent history of low population density.

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Tables

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

Indicator category	Indicator	2021 Status	2022 Status	2023 Status	2024 Status	2025 Status
Predictive	Spring pH	**low**	**low**	**low**	**low**	**low**
	Summer Wind Stress	**high**	neutral	neutral	neutral	**high**
Contextual	BBRKC Mature Male Area Occupied	neutral	neutral	neutral	*high*	neutral
	BBRKC Mature Female Area Occupied	*high*	neutral	neutral	neutral	neutral
	Fishery Catch Distance from Shore	neutral	neutral	neutral	neutral	NA
	Female BBRKC Reproductive Failure	**high**	neutral	neutral	neutral	neutral
	Northern District: Bristol Bay RKC Ratio	**high**	**high**	**high**	**high**	neutral
	Proportion of Mature Males in Closure Areas	neutral	neutral	*high*	neutral	neutral
Monitoring	Arctic Oscillation Index	neutral	neutral	neutral	neutral	neutral
	Chlorophyll *a* Concentration	neutral	neutral	*high*	neutral	*high*
	Bristol Bay Sockeye Inshore Run Size	**high**	**high**	neutral	neutral	**high**
	Bottom Temperature	neutral	neutral	neutral	neutral	neutral
	Pacific Cod Predator Density	neutral	neutral	neutral	neutral	neutral
	Benthic Prey Density	neutral	*high*	neutral	neutral	neutral

Table F.1b: First stage socioeconomic indicator analysis for BBRKC, including indicator title and the indicator status of the last five years. The indicator status is designated with text, (greater than = "high", less than = "low", or within 1 standard deviation = "neutral" of the long-term mean). A gray fill and text = "NA" will appear if there were no data for that year. A red color indicates a fishery closure and the text = "Closed" will appear. Note that the year heading references calendar year; the BBRKC fishery is prosecuted Oct-Dec, such that the calendar year corresponds to the first period of the crab season-year; the most recent BBRKC fishery occurred during the 2024/25 crab season.

Indicator category	**Indicator**	**2020 Status**	**2021 Status**	**2022 Status**	**2023 Status**	**2024 Status**
Fishery-Informed	Number of Active Vessels	neutral	Closed	Closed	low	low
	Fishery CPUE	neutral	Closed	Closed	neutral	high
	Fishery Total Potlifts	neutral	Closed	Closed	low	low
	Annual Incidental Catch	neutral	neutral	neutral	neutral	neutral
	ABSC Skipper Survey: Perceived Abundance	NA	Closed	Closed	neutral	high
	ABSC Skipper Survey: Changes in Fishing Practices	NA	Closed	Closed	high	neutral
	ABSC Skipper Survey: Principal Driver of Changes	NA	Closed	Closed	high	neutral
Economic	Ex-vessel Value	low	Closed	Closed	low	low
	Ex-vessel Price	high	Closed	Closed	high	high
	Ex-vessel Revenue Share	neutral	Closed	Closed	high	high

Figures

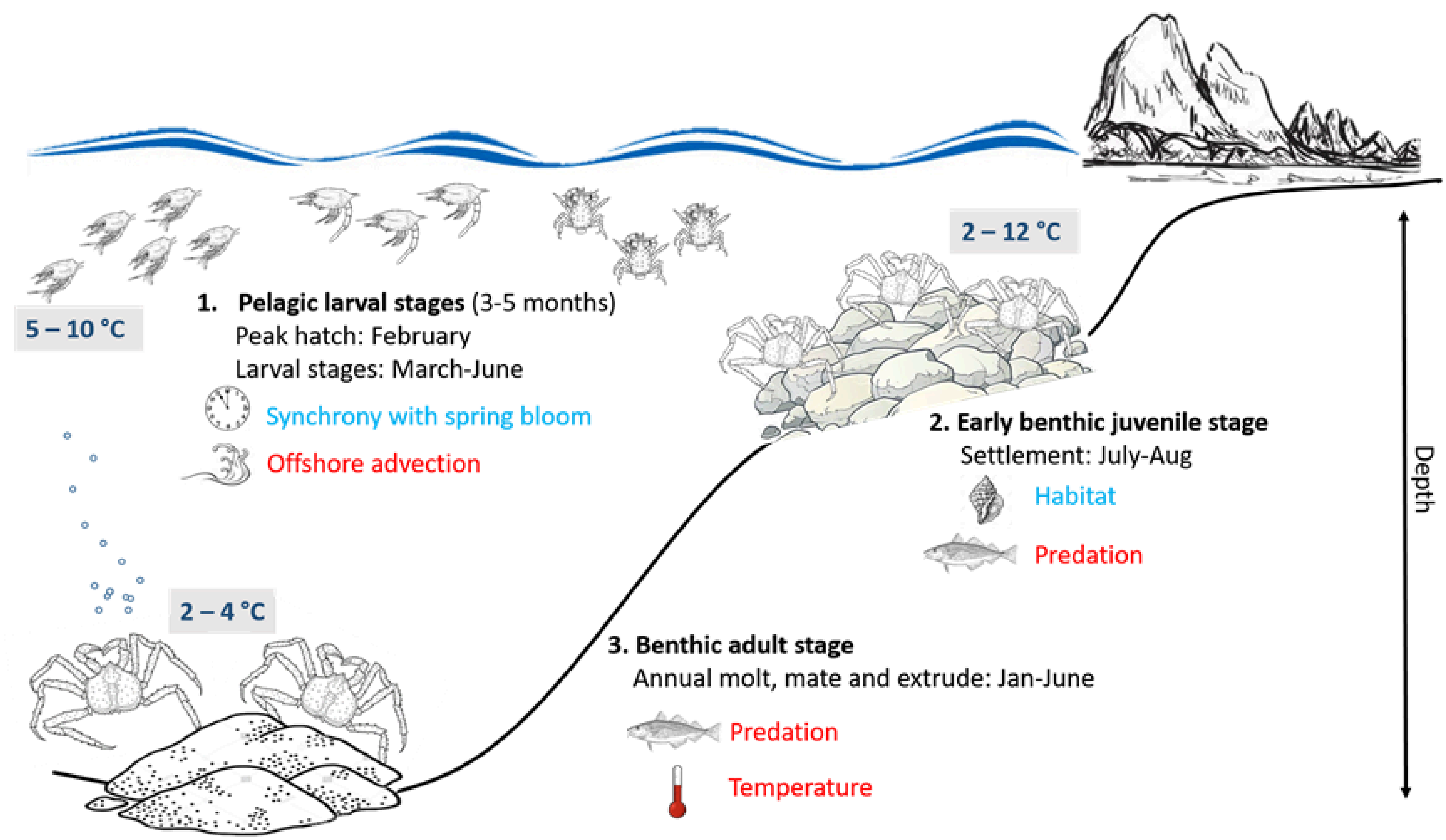

Figure F.1: Life history conceptual model for BBRKC summarizing ecological information and key ecosystem processes affecting survival by life history stage. Red text indicates that increases in the process negatively affect survival of the stock, while blue text means that increases in the process positively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

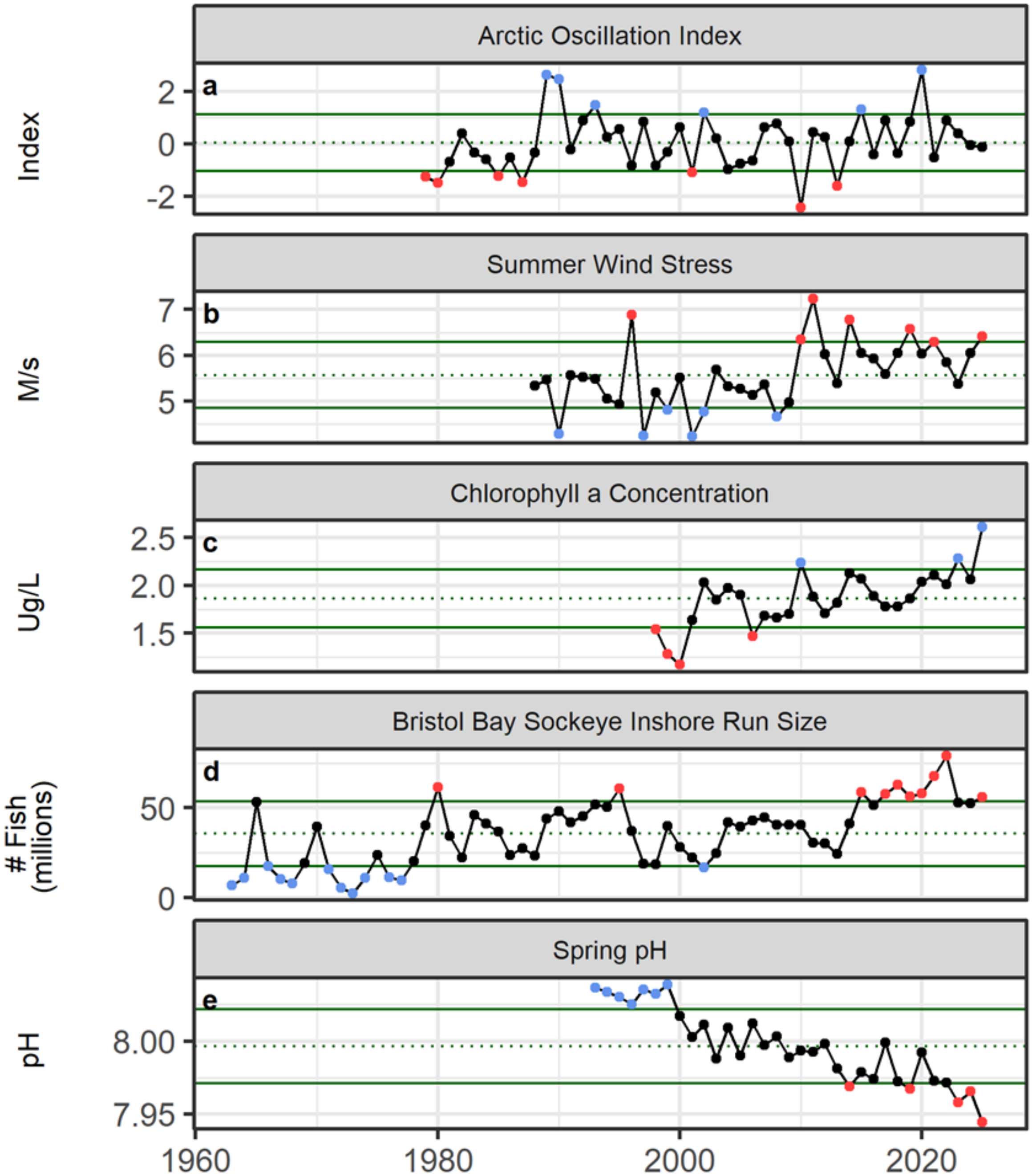

Figure F.2a: Selected ecosystem indicators for BBRKC with time series ranging from 1963 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

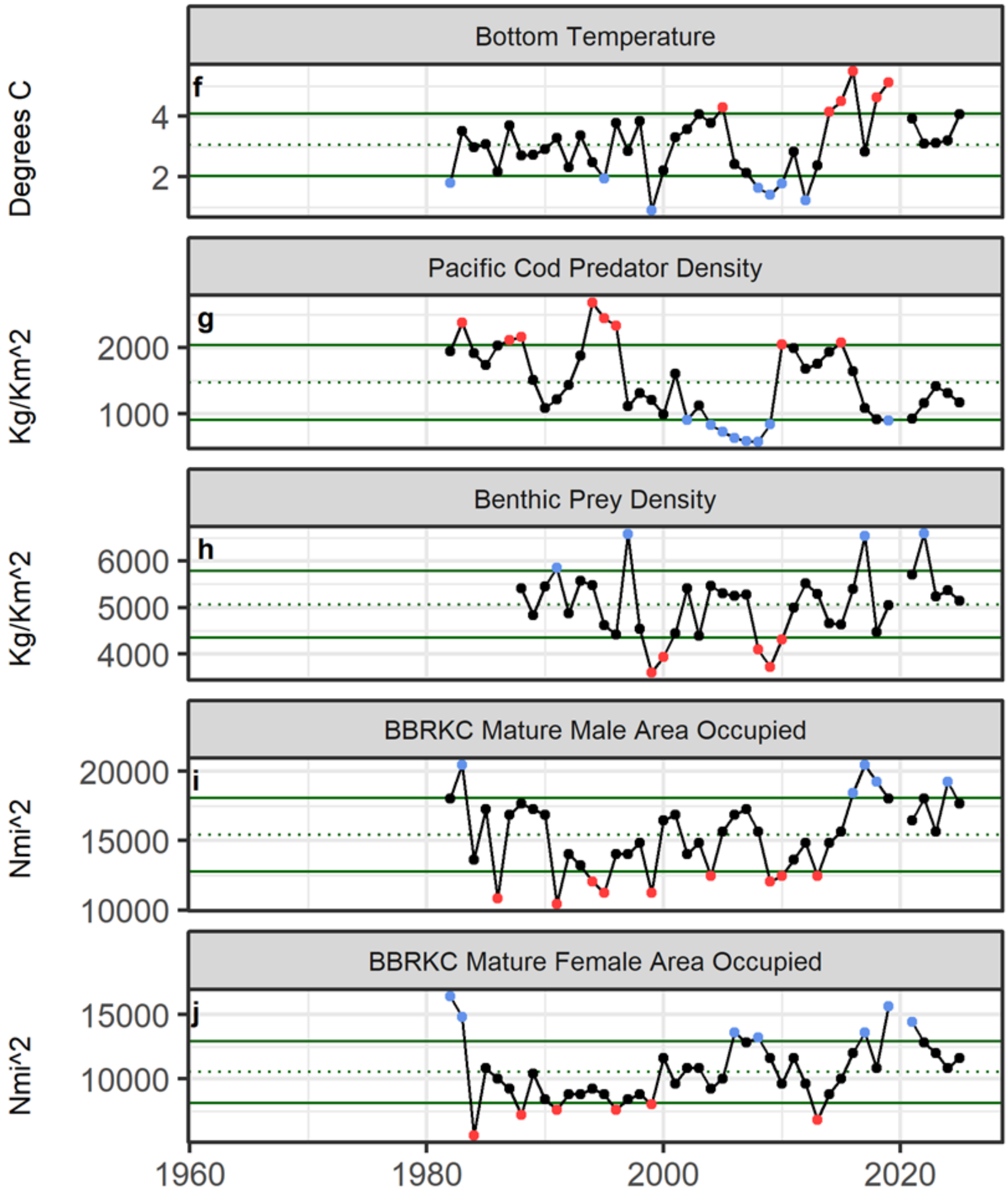

Figure F.2a (cont.): Selected ecosystem indicators for BBRKC with time series ranging from 1963 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

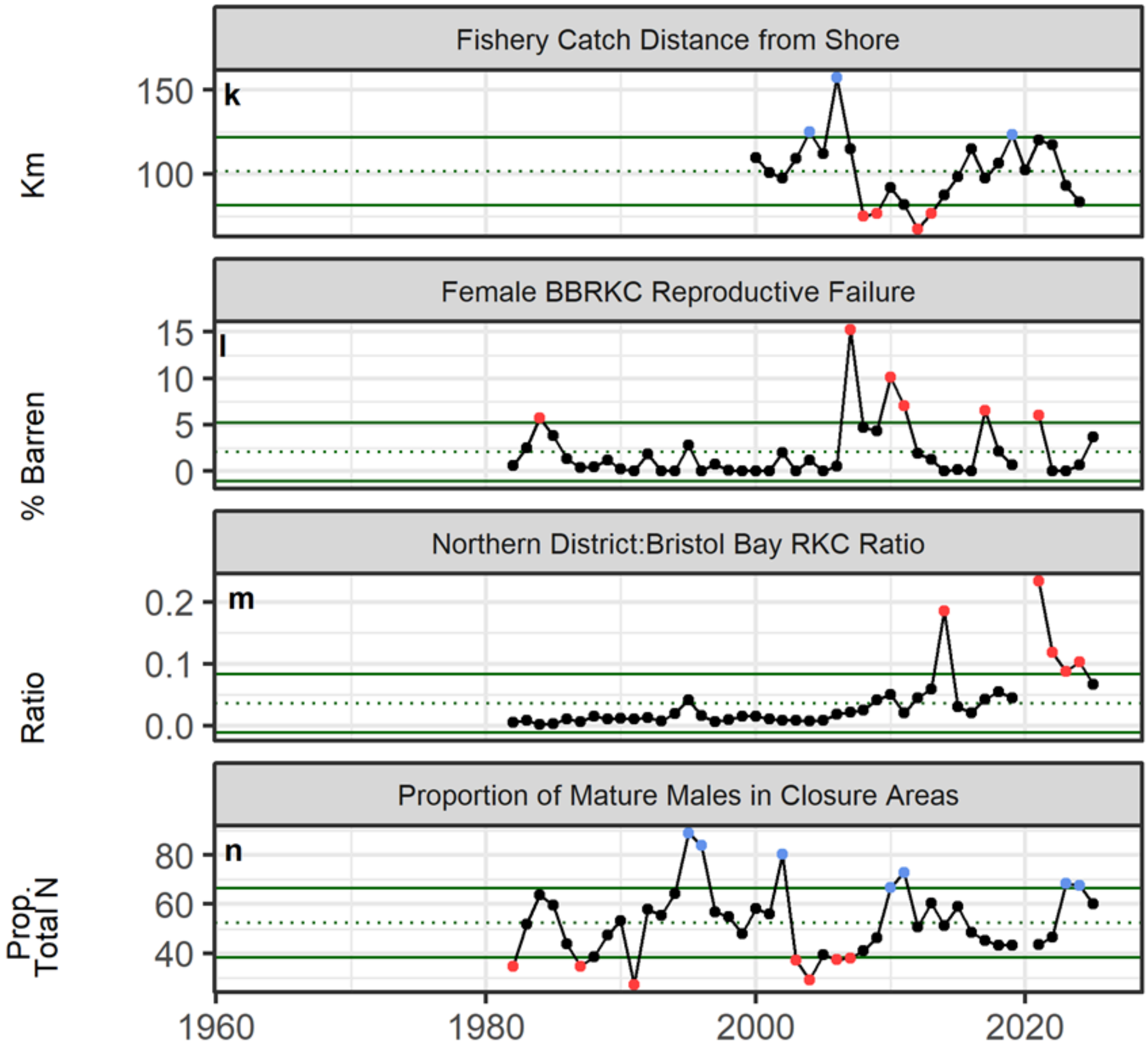

Figure F.2a (cont.): Selected ecosystem indicators for BBRKC with time series ranging from 1963 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

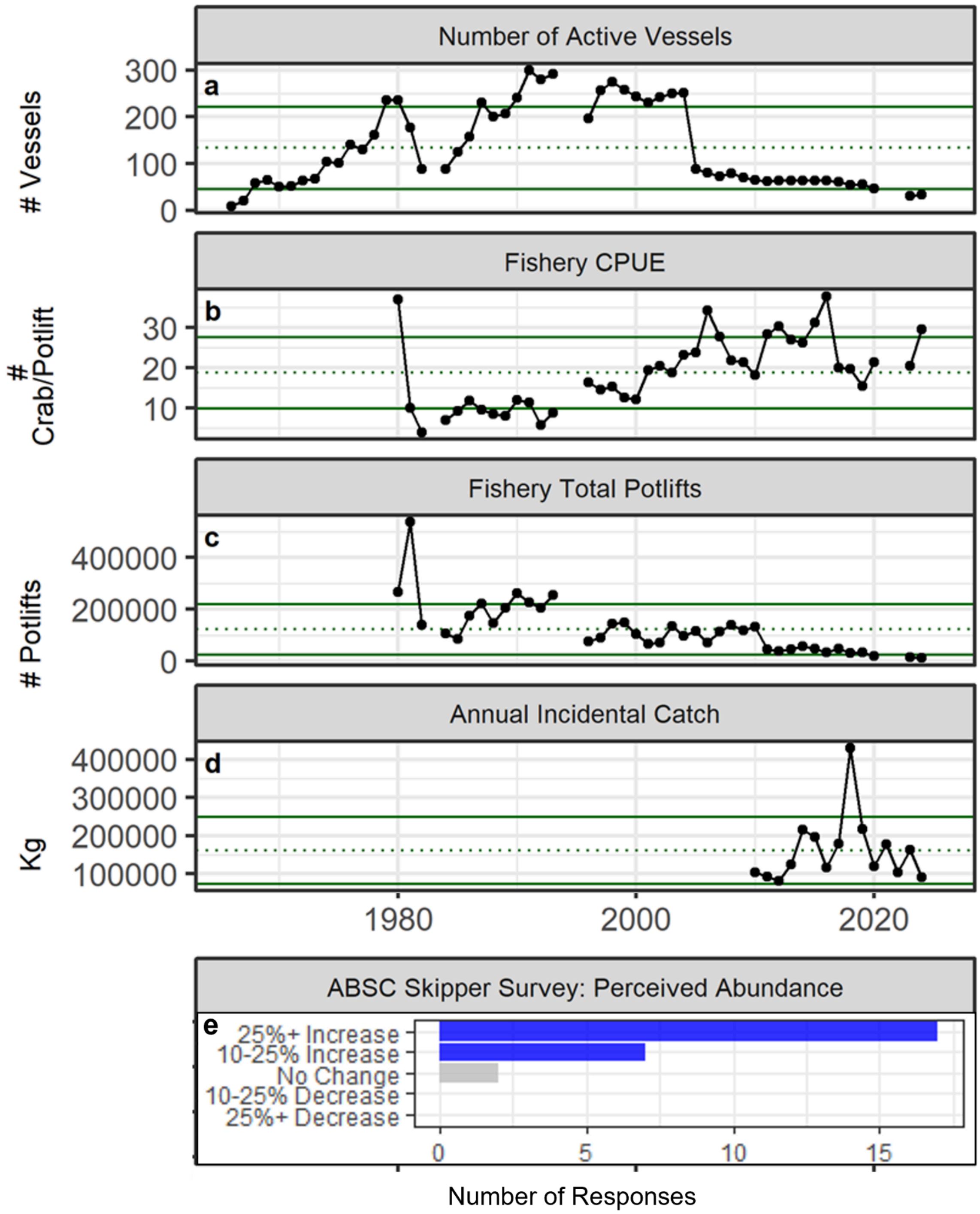

Figure F.2b: Selected socioeconomic indicators for BBRKC with time series ranging from 1966 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

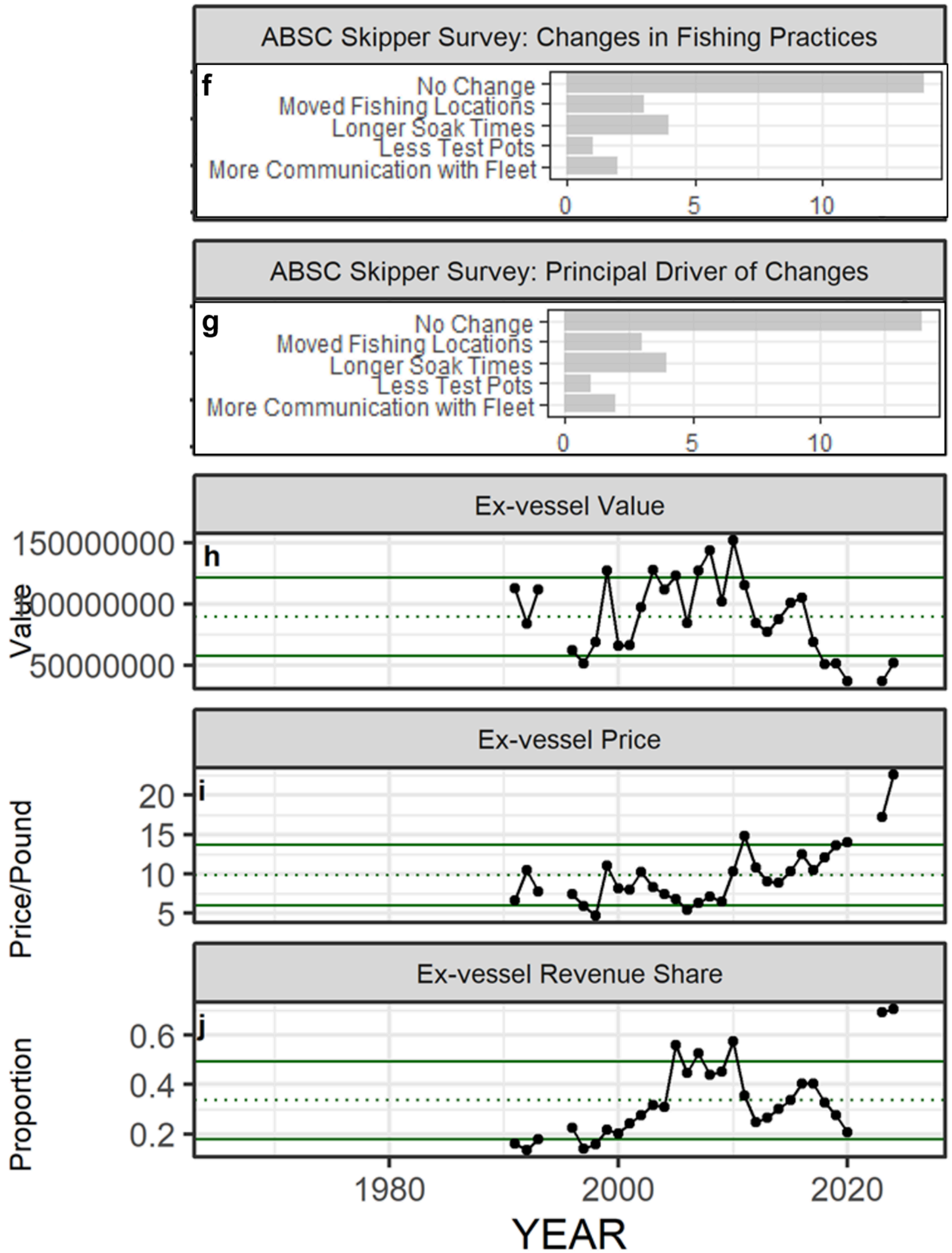

Figure F.2b (cont.): Selected socioeconomic indicators for BBRKC with time series ranging from 1966 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

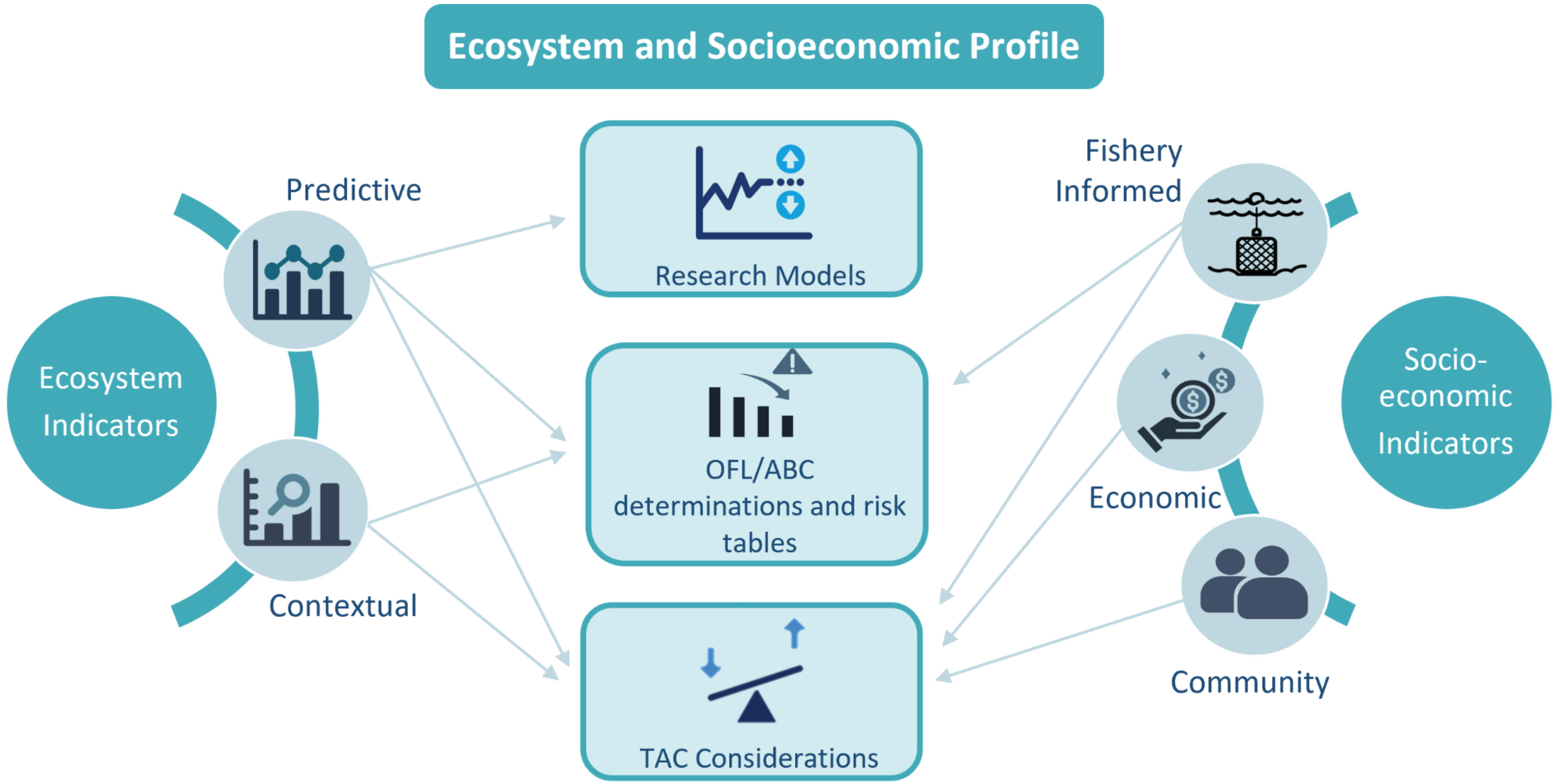

Figure F.3: Schematic of decision pathways for ecosystem and socioeconomic indicators

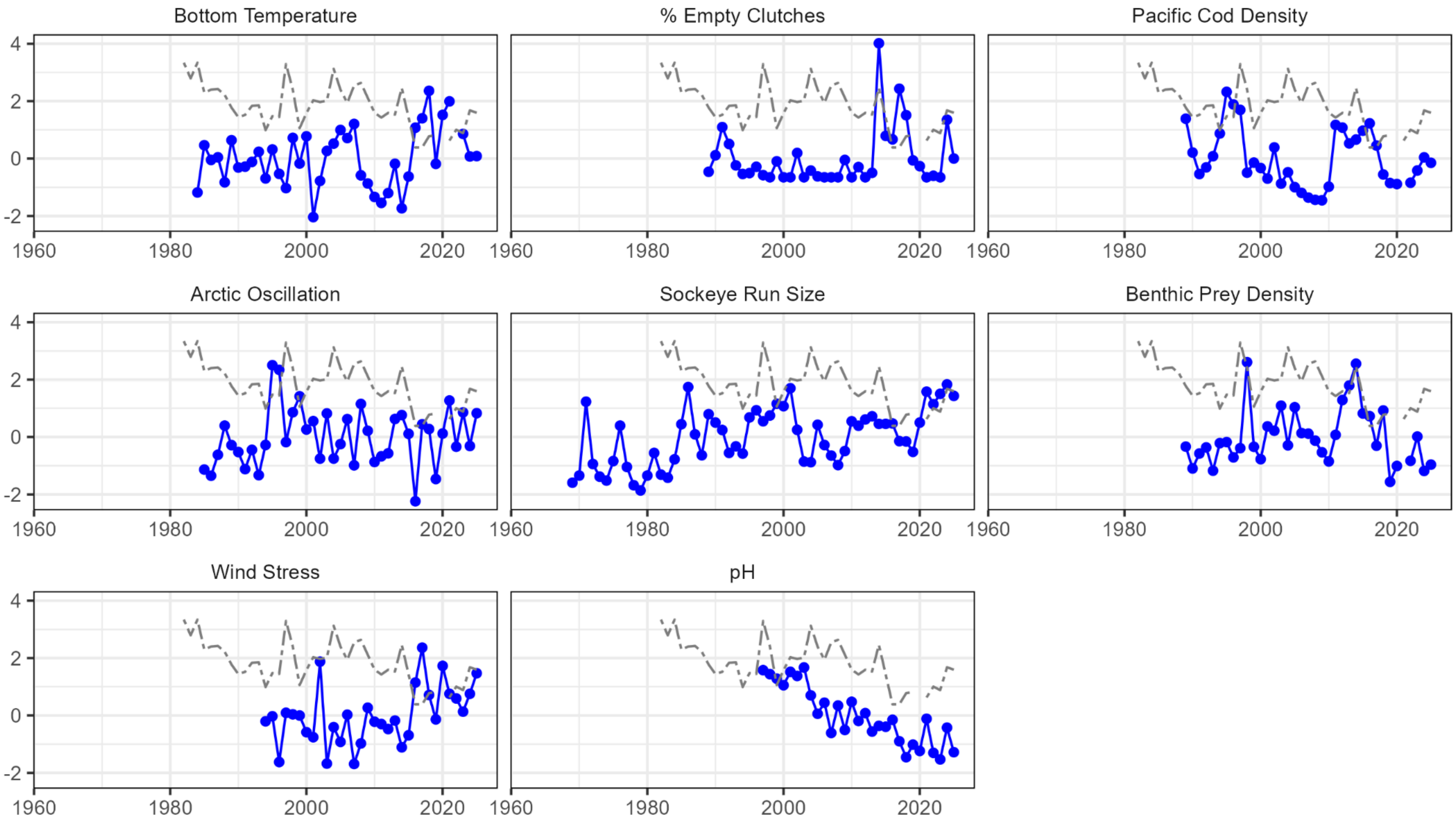

Figure F.4: Standardized ecosystem indicators (blue lines) tested in the final Bayesian Adaptive Sampling Model. The grey line on each facet is the response variable, log-transformed BBRKC recruitment (survey abundance of 95 - 120mm males).

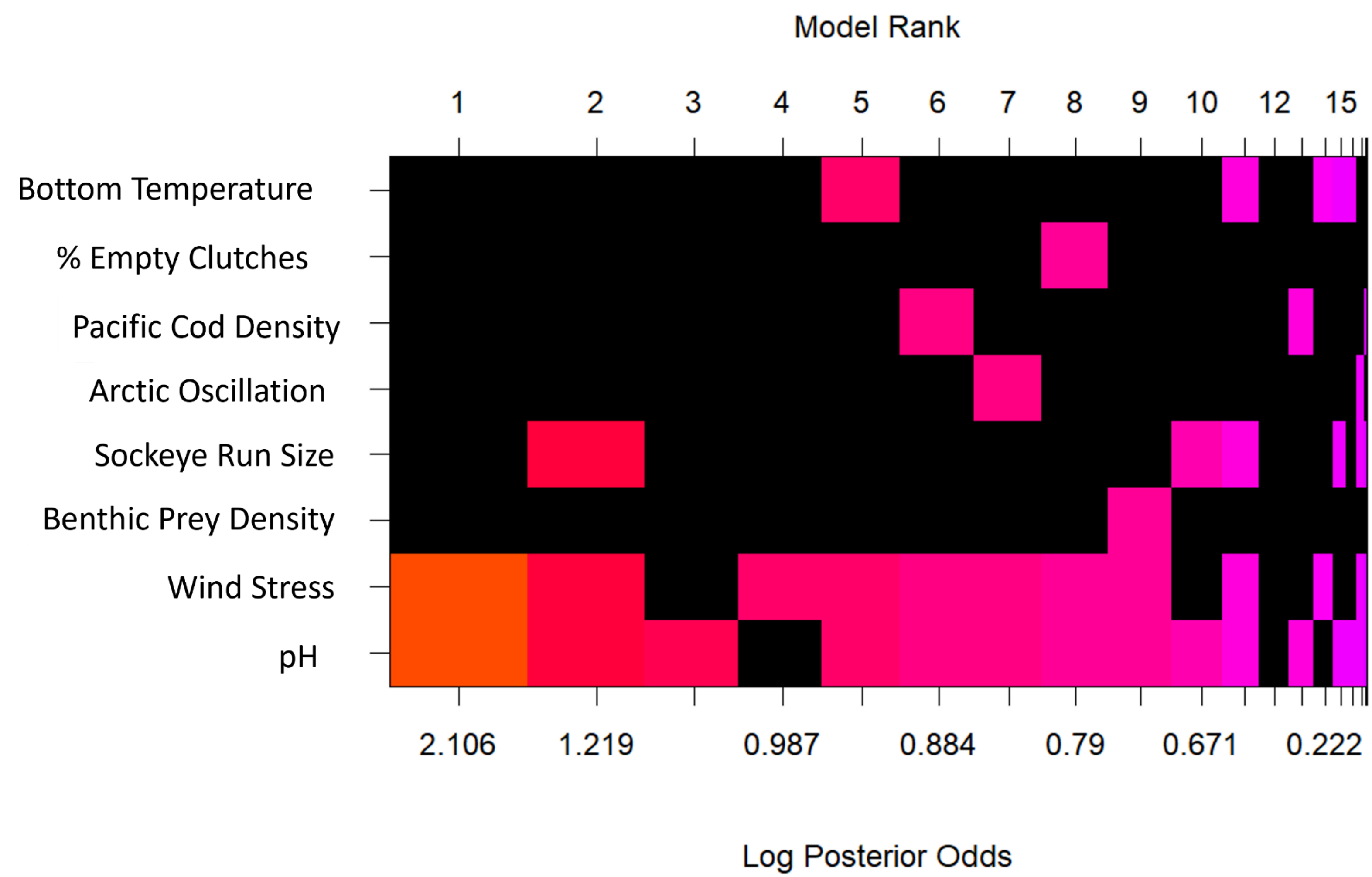

Figure F.5: Visualization of model space of the top models tested with Bayesian Adaptive Sampling. Models are sorted by their posterior probability from best at the left to worst at the right with the rank on the top x-axis, and each column represents one of the tested models.

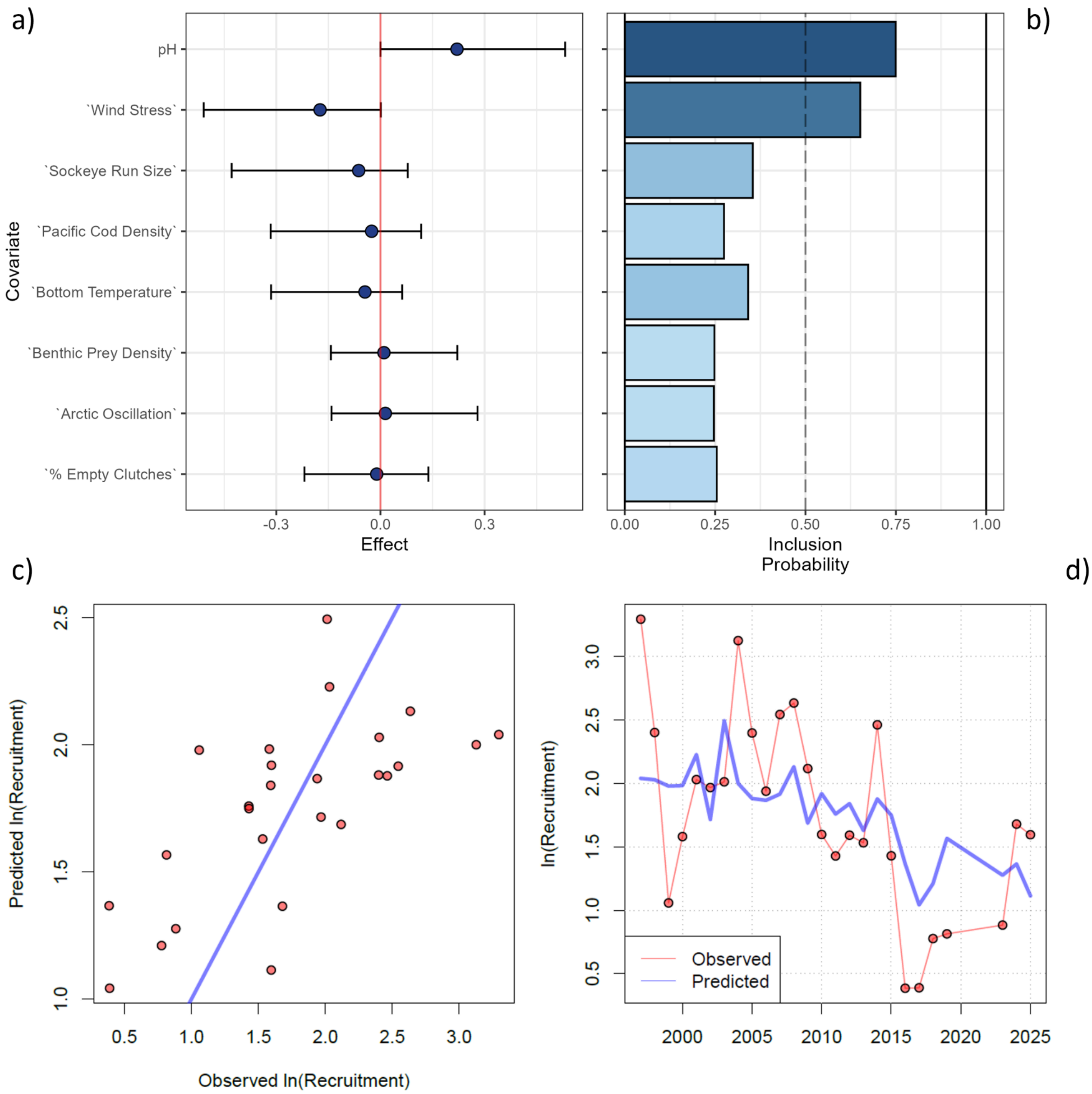

Figure F.6: Bayesian adaptive sampling output showing the mean relationship and uncertainty (± 1 SD) with log-transformed BBRKC recruitment (survey abundance of 95 - 120mm males). a) The estimated effect and b) the marginal inclusion probabilities for each predictor variable of the subsetted covariate ecosystem indicator dataset. Output also includes c) model predicted fit (1:1 line) and d) average fit across the abbreviated recruitment time series (1997-2025).