Appendix C. Ecosystem and Socioeconomic Profile of the Bristol Bay Red King Crab stock - Report Card

Erin Fedewa, Kalei Shotwell, and Brian Garber-Yonts

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With Contributions from:

Matt Callahan, Curry Cunningham, Ben Daly, Shannon Hennessey, Jean Lee, Cory Lescher, Jens Nielsen, Katie Palof, Darren Pilcher, Dale Robinson, Emily Ryznar, Abigail Tyrell, and Leah Zacher

Current Year Update

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

Please refer to the last full ESP and most recent report card documents (Fedewa et al., 2020, Fedewa et al., 2023) which are available as an appendix within the Bristol Bay red king crab (BBRKC) stock assessment and fishery evaluation or SAFE reports for further information regarding the ecosystem and socioeconomic linkages for this stock.

Management Considerations

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

- Bottom water pH in Bristol Bay increased in 2024, although red king crab have experienced a steady decline in bottom water pH in the past two decades. Continued declines to pH levels of 7.8 could negatively affect juvenile red king crab growth, shell hardening and survival.
- A continued high period of Bristol Bay sockeye salmon production and low chlorophyll *a* concentration suggest poor larval feeding conditions and survival to settlement.
- The increased spatial extent of mature male red king crab and high ratio of Northern District to Bristol Bay District red king crab since 2021 are indicative of a northward range expansion and summer movement outside of management boundaries. In 2024, 68% of mature males were located in closure areas during the summer survey period, although spatial distribution shifts may limit the utility of these closure areas.
- An increase in the proportion of mature females with empty clutches in 2024 suggests a reduction in reproductive potential of the stock. Although empty clutch proportion remains small (~4%), clutch failures should continually be monitored under depressed population levels.
- Following closures during the two previous seasons, the BBRKC fishery was opened to targeted fishing for the 2023/24 season, contemporaneously with the second consecutive closure of the EBS snow crab fishery.
- The consolidation of the active fleet to 31 active vessels participating in the 2023/24 BBRKC fishery is directionally consistent with efficiency-driven adjustment in fleet capacity, but economic incentives and financial considerations faced by crab industry participants during the current period of uncertainty associated with crab stock declines are complex.
- Although not adequately captured within the limited range of socioeconomic indicators reported in the ESP to date, the unprecedented and ongoing economic and social pressures on the crab industry and stakeholder communities associated with the decline of BSAI crab fisheries, encompass a broad array of critical management considerations and require improved data and analyses to inform management.
- Incidental catch of BBRKC in EBS groundfish fisheries remained near or below the time-series average for the 2020-2023 period.

Modeling Considerations

The following are the summary results from the most recent intermediate and advanced stage monitoring analyses for BBRKC (Fedewa et al., 2023):

- The highest ranked predictor variables (> 0.5 inclusion probability) in the intermediate stage monitoring analysis were: 1) Pacific cod density, 2) cold pool extent, and 3) benthic invertebrate

density. Due to concerns with non-stationarity in longer ecosystem time series, indicator importance tests in future BBRKC ESP updates will explore additional statistical methods.
- The advanced stage indicator analysis provides updates on developing research ecosystem linked models that are not yet included as a model alternative in the main stock assessment. We have not received updates on new research ecosystem linked models for BBRKC at this time.

Assessment

Ecosystem and Socioeconomic Processes

We summarize important processes that may be helpful for identifying productivity bottlenecks and dominant pressures on the stock in conceptual models detailing 1) ecosystem processes by BBRKC life history stage (Figure 1a) and 2) socioeconomic performance metrics (Figure 1b). Please refer to the last full ESP document (Fedewa et al., 2020) for more details.

Indicator Suite

The following list of indicators for BBRKC is organized by categories: three for ecosystem indicators (larval, juvenile, and adult) and three for socioeconomic indicators (fishery performance, economic, and community). The indicator name and short description are provided in the heading. We also include the anticipated sign of the proposed relationship between the indicator and the stock population dynamics where relevant. Following the indicator heading is a series of bullets that include information on the contact for the indicator, status and trends for the current year, factors influencing those trends, and implications for fishery management. This format follows the Ecosystem Status Reports. We use the following nomenclature when describing these indicators:

- If the value in the time series is at the long-term mean of the time series (or the mean), we use the term “average” (dotted green line in Figure 2).
- If the value is above/below the mean but below/above 1 standard deviation of the mean (solid green line in Figure 2) we use the terms “above average” or “below average”.
- Any value within 1 standard deviation of the mean is considered “neutral” in Table 1.
- If the value is above/below 1 standard deviation of the mean (solid green line in Figure 2) we use the term “high” or “low”.

We concentrate on updates since the last ESP report card (Fedewa et al., 2023). Please refer to the last full ESP document for detailed information regarding these ecosystem and socioeconomic indicator descriptions and proposed mechanistic linkages for this stock (Fedewa et al., 2020). Time series of the ecosystem and socioeconomic indicators are provided in Figure 2a and Figure 2b, respectively.

New indicators in 2024 include: 1) the ratio of Northern District to Bristol Bay District red king crab, 2) mature female reproductive potential, and 3) the proportion of mature male red king crab located in Bristol Bay closure areas during the summer survey period. In addition, the previously reported juvenile sockeye salmon abundance indicator (AFSC BASIS survey) has been discontinued and replaced with the annual inshore run size of Bristol Bay sockeye salmon.

Ecosystem Indicators:

1. Larval Indicators (Figure 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 and the time series is lagged five years for intermediate stage indicator analysis

- Contact: Erin Fedewa
- Status and trends: The Arctic Oscillation was in a neutral state in winter 2024.
- 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), suggesting that stock productivity won't be directionally influenced by a neutral Arctic Oscillation.

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 and the time series is lagged seven years for intermediate stage indicator analysis.
    - Contact: Dale Robinson
    - Status and trends: Wind stress in Bristol Bay increased in 2024 and is above the 37-year mean.
    - 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.

c. Chlorophyll *a* Concentration: April – June average chlorophyll *a* concentration in the Bristol Bay Red King Crab managment district, calculated with the ESA GlobColour blended satellite product (4km resolution, 8 day composite data). Proposed sign of the relationship is positive and the time series is lagged seven years for intermediate stage indicator analysis.
    - Contact: Erin Fedewa
    - Status and trends: Chlorophyll *a* concentration increased in 2024 following the time series low in 2023, although still remains well below the 27-year mean.
    - 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 2024 run size estimate is preliminary and subject to change until fish ticket numbers are finalized. Proposed sign of the relationship is negative and the time series is lagged five years for intermediate stage indicator analysis.
    - Contact: Curry Cunningham
    - Status and trends: The preliminary 2024 estimate of 53.5 million sockeye salmon is a slight decline from 2023, but still well above the 1963-2023 average.
    - Factors influencing trends: Increases in sockeye salmon abundance in the Bering Sea have been associated with increased prey abundance and a nonlinear relationship with sea surface temperature (Yasumiishi et al., 2024).
    - Implications: The recent high production stanza for sockeye salmon and record high run sizes observed in 2021-2022 suggest the potential for increased predation on larval red king crab in Bristol Bay.

2. Juvenile Indicators (Figure 2a.e-h)

e. Spring pH: Spring (February – April 15) pH index of Bristol Bay bottom waters, estimated from Bering10K ROMS model hindcasts. Proposed sign of the relationship is positive and the time series is lagged 6 years for intermediate stage indicator analysis.
    - Contact: Darren Pilcher
    - Status and trends: Bottom water pH values in Bristol Bay increased to 7.95 in 2024, following the lowest pH value in the 55-year time series in 2023. Overall, model hindcasts indicate a declining trend in pH since the start of the time series in 1970.
    - 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: An increase in the pH of bottom waters in 2024 and pH values above 7.8 suggest that red king crab condition, growth, shell hardness and survival were not negatively impacted by ocean acidification. The increase in pH may be associated with a less pronounced spring bloom in 2023 and 2024.

f. Summer Bottom Temperature: Average summer bottom temperature in Bristol Bay from the EBS bottom trawl survey. Proposed sign of the relationship is negative and the time series is lagged 6 years.
    - Contact: Erin Fedewa
    - Status and trends: The mean bottom temperature in Bristol Bay increased to 3.2°C in 2024, and conditions are near-average relative to the 45-year mean.
    - Factors influencing trends: Bottom temperatures in the Bering Sea are driven by winter sea ice extent and winds, and summer cold pool formation.
    - Implications: Despite a slight increase in Bristol Bay bottom temperature in 2024, temperatures are still within the preferred thermal range of larval, juvenile and adult red king crab.

g. Summer Cold Pool Spatial Extent: Calculated as the total area (nmi^2) of EBS bottom trawl survey stations within the BBRKC management district with bottom temperatures < 2°C. Proposed sign of the relationship is positive and the time series is lagged two years for intermediate stage indicator analysis.
    - Contact: Erin Fedewa
    - Status and trends: There was a small cold pool in Bristol Bay, although the spatial extent was much smaller than that of the cold pools in 2022 and 2023. The 2024 estimate was well below the 45-year mean.
    - Factors influencing trends: The spatial extent of the cold pool is determined by winter sea ice extent and winds. The cold pool drives the spatial distribution of many crab and groundfish species in the Bering Sea.
    - Implications: A reduction in the spatial extent of the cold pool in 2024 suggests increased spatial overlap between red king crab and groundfish predators such as Pacific cod that tend to avoid waters < 2°C.

h. Summer Pacific Cod Density: Summer Pacific cod density (kg/km^2) estimated from EBS bottom trawl survey stations included in the BBRKC management district. Proposed sign of the relationship is negative and the time series is lagged one year for intermediate stage indicator analysis.
    - Contact: Erin Fedewa

- Status and trends: Pacific cod density decreased slightly from 2023 to 2024 in Bristol Bay, and the 2024 estimate is just below the 37-year mean.
- Factors influencing trends: Pacific cod are a major predator of red king crab, and consumption rates increase in the spring when crab are soft and molting. The 2018 heat wave in the Bering Sea resulted in a northward range expansion of Pacific cod into the Northern Bering Sea for summer feeding migrations (Spies et al., 2020).
- Implications: A small decline in Pacific cod density in 2024 suggests reduced predation pressure on BBRKC, although a below-average cold pool extent in Bristol Bay may increase spatial overlap between Pacific cod and red king crab.

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

i. Summer Benthic Invertebrate 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 and the time series is lagged one year for intermediate stage indicator analysis.
    - Contact: Erin Fedewa
    - Status and trends: Benthic invertebrate density increased slightly from 2023 to 2024, and the 2024 estimate is below the 37-year mean.
    - 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: Below average benthic invertebrate density in recent years indicates decreased prey availability for red king crab, although the small increase in 2024 increase suggests positive implications for the stock.

j. Summer Mature Male BBRKC 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
    - Status and trends: The spatial extent of mature male BBRKC increased from 2023 to 2024. The 2024 area occupied by mature males is well above the 45-year mean, and is one of the largest estimates in the time series.
    - 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.

k. Summer Mature Female BBRKC Area Occupied: 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
    - Status and trends: The spatial extent of mature female BBRKC has been declining since 2019 despite increases in mature female abundance in 2023 and 2024. The 2024 area occupied estimate is at the 45-year mean.

- 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: The contraction of mature female summer distribution in recent years has been attributed to high survey catches north of Port Moller and an overall southeast shift in centroids of abundance since 2019. Although these spatial distribution shifts have resulted in more mature females inhabiting the Nearshore Bristol Bay Trawl Closure Area, continued range contraction may raise concern for increased competition for resources.

l. Annual Fishery Catch Distance from Shore: 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. Proposed sign of the relationship is positive.
    - Contact: Leah Zacher
    - Status and trends: The legal male red king crab catch during the 2023 fishery was closer to shore than all BBRKC fisheries since 2014. The 2023 estimate is below the 24-year average.
    - Factors influencing trends: Red king crab 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 in 2023 is associated with fewer legal males caught west of the Red King Crab Savings Area, and may be linked to temperature-driven inshore movement of males.

m. Summer BBRKC Female Reproductive Potential: The proportion (%) of shell condition 1 and 2 mature female red king crab caught on the summer EBS bottom trawl survey with empty clutches. Because cold temperatures can delay the molt-mate cycle and newshell mature females may still be extruding clutches at the time of sampling, the years in which a resampling was conducted in Bristol Bay utilized only mature female data from the resampling event. Proposed sign of the relationship is negative.
    - Contact: Erin Fedewa
    - Status and trends: In 2024, approximately 4% of mature females sampled on the EBS bottom trawl survey had empty clutches, and the estimate was the highest proportion empty in over a decade.
    - Factors influencing trends: Female reproductive potential is a function of female size, clutch size, and sperm reserves. Increases in the proportion of mature females with empty clutches suggest that females were unable to find a mate.
    - Implications: An increase in the proportion of mature females with empty clutches suggests a reduction in reproductive potential of the stock in 2024. A > 30% proportion of mature females with empty clutches in the late 1970's coincided with a stock collapse, suggesting that while the current mature female population is well below this threshold, clutch failures should be continually monitored for under depressed population levels.

n. Summer BBRKC Northern District Ratio: 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

- Status and trends: The ratio of Northern District red king crab abundance to Bristol Bay red king crab abundance increased slightly in 2024 to 0.12. The ratio has remained well above the 43-year time series mean since 2021.
- 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. 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. Mature females tagged further north did not re-enter Bristol Bay during the study.
- Implications: Abundance of red king crab in the Northern District remains very small relative to the Bristol Bay population, but a large increase in the abundance ratio between the two districts in 2021, and a ratio > 0.1 from 2022 - 2024 are consistent with a northward range expansion of the Bristol Bay stock and summer movement outside of management boundaries.

o. Summer BBRKC Protected Area Proportion: The proportion (%) of total mature male model-based 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: Shannon Hennessey and Emily Ryznar
- Status and trends: In 2024, approximately 68% of the mature male population was located in closed areas during the summer survey period. This estimate is well-above the 45-year time series mean after a stanza from 2016 – 2021 when less than 50% of the mature male population was located in closed areas.
- 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: A recent 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: (all monetary values are inflation-adjusted to $2023 value)

<u>1. Fishery Performance Indicators (Figure 2b.a-d)</u>

a. Number of Active Vessels BBRKC Fishery: Annual number of active vessels in the Bristol Bay red king crab fishery
- Contact: Brian Garber-Yonts
- Status and trends: The number of vessels active in the 2023/24 fishery declined to 31, substantially fewer than participated in the fishery during the most recent years before the closures for the 2021/22 and 2022/23 seasons.
- Factors influencing trends: The consolidation from 47 active vessels during 2020 to 31 in in 2023, relative to the 19% reduction in TAC between the two seasons, likely reflects the importance of the snow crab fishery in vessel owners' decisions to enter the

BSAI crab fisheries in a given year. It may also indicate, to some degree, a more persistent consolidation of the BSAI crab fleet as a result of financial pressures on vessel owners associated with recent crab fishery closures.

- Implications: TBD

b. Annual CPUE BBRKC Fishery: Annual catch-per-unit-effort (CPUE), expressed as mean number of legal crabs per potlift, in the BBRKC fishery, representing relative efficiency of fishing effort. The cost recovery fishery is not included.
    - Contact: Ben Daly
    - Status and trends: The BBRKC fishery CPUE declined slightly in 2023 following two years of fishery closures. Annual CPUE in 2023 was at the 30-year average of 20.54 legal crab per potlift.
    - Factors influencing trends: TBD
    - Implications: TBD
c. Total Potlifts BBRKC Fishery: Annual total potlifts in the BBRKC directed fishery, representing the level of fishing effort expended by the active fleet. The cost recovery fishery is not included.
    - Contact: Ben Daly
    - Status and trends: Total potlifts declined slightly in 2023 following two years of fishery closures, and remain well below the 30-year average.
    - Factors influencing trends: TBD
    - Implications: TBD
d. Annual Incidental Catch: Annual estimates of incidental catch biomass estimates of Bristol Bay red king crab (tons) in federally-managed EBS groundfish fisheries
    - Contact: Brian Garber-Yonts
    - Status and trends: Incidental catch of BBRKC during 2023 groundfish fisheries matched the time-series average, with the previous three years being at or below average following a time-series high in 2019.
    - Factors influencing trends: TBD
    - Implications: TBD

<u>2. Economic Indicators (Figure 2b.e-h)</u>

e. TAC Utilization: Percentage of annual Bristol Bay red king crab total allowable catch that was harvested by active vessels
    - Contact: Brian Garber-Yonts
    - Status and trends: Consistent with previous BBRKC seasons since rationalization, the utilization of the TAC exceeded 99% in 2023.
    - Factors influencing trends: TBD
    - Implications: TBD
f. Ex-vessel Value: Annual red king crab ex-vessel value of the Bristol Bay red king crab fishery landings ($2023)
    - Contact: Brian Garber-Yonts
    - Status and trends: Ex-vessel value declined slightly from 2020, the most recent year the fishery was open to targeted fishing. This represented the lowest value in the time-series history and the fourth consecutive open season that ex-vessel value was below the 1-sd bound of the time-series range of variation.
    - Factors influencing trends: The trend of declining and extreme low ex-vessel value over the most recent five open BBRKC seasons coincided with upward-trending, and historically high ex-vessel price, which culminated in an unprecedented extreme high

value in 2023. The price trend partially offset the effect of the sharp downward trend in production volume since 2016 on gross earnings over the period.
    - Implications: TBD

g. Ex-vessel Price: Annual red king crab ex-vessel price per pound of the Bristol Bay red king crab fishery ($2023)
    - Contact: Brian Garber-Yonts
    - Status and trends: Ex-vessel price reached $16.68 per pound on average during 2023, an all-time high for the fishery.
    - Factors influencing trends: TBD
    - Implications: TBD

h. Ex-vessel Revenue Share: Annual ex-vessel revenue share, expressed as aggregate ex-vessel value of the Bristol Bay red king crab fishery as a percent of total ex-vessel value of landings from all fisheries produced by vessels active in the Bristol Bay red king crab fishery
    - Contact: Brian Garber-Yonts
    - Status and trends: Ex-vessel revenue share reached an all time high of 69% during 2023, nearly three standard deviations above the long-term average.
    - Factors influencing trends: The extreme high value of the ex-vessel revenue share metric for the 2023 Bristol Bay fishery is augmented by the historical high 2023 ex-vessel price, but principally reflects the contemporaneous closure of the snow crab fishery and limited availability of other fishing targets for the BSAI crab fleet.
    - Implications: TBD

3. Community Indicators

i. Alaska Bering Sea Crabbers (ABSC) Skipper Survey, distributed to captains following the most recent BBRKC crab season. Although not yet an established time series, the questionnaire is designed to extract both qualitative and quantitative information on perceived abundance, fisher behavior and gear performance.
    - Contact: Cory Lescher
    - Status and trends: Results indicated that 61% of the skippers that participated in the survey changed their fishing behavior this season by using longer soak times to reduce sorting of sub-legal males and females, increase CPUE of legal males, and reduce bycatch. The majority of skippers noted seeing an increase in Pacific cod in pots. Anecdotal comments indicated that mature females were further east of fishing grounds, and skippers collectively attempted to move off female hot spots by increasing communication between vessels.
    - Factors influencing trends: 42% of skippers that fished the 2023-2024 BBRKC fishery responded to the survey. Varied responses to survey questions on perceived abundance may be dependent on locations fished, and skipper experience and skill
    - Implications: Local knowledge from fishermen provides important context for interpreting shifts in fishery performance indicators

Indicator Monitoring Analysis

There are up to three stages (beginning, intermediate, and advanced) of statistical analyses for monitoring the indicator suite listed in the previous section. The beginning stage is a relatively simple evaluation by traffic light scoring. This evaluates the current year trends relative to the mean of the whole time series, and provides a historical perspective on the utility of the whole indicator suite. The intermediate stage uses importance methods related to a stock assessment variable of interest (e.g., recruitment, growth,

catchability). These regression techniques provide a simple predictive performance for the variable of interest and are run separate from the stock assessment model. They provide the direction, magnitude, uncertainty of the effect, and an estimate of inclusion probability. The advanced stage is used for 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.

Beginning Stage: Traffic Light Test

We use a simple scoring calculation for this beginning stage traffic light evaluation on the indicators listed in the Indicator Suite section. Please refer to the last full ESP document (Fedewa et al., 2020) for more details on the simple scoring calculation. The scores are summed by the ecosystem or socioeconomic indicator categories and divided by the total number of indicators available in that category for a given year. The scores over time allow for comparison of the indicator performance and the history of stock productivity (Figure 3). We also provide five year indicator status tables with a color (ecosystem indicators only) for the relationship with the stock (Tables 1a,b). Socioeconomic indicators representing the target fishery are reported by calendar year through 2022, the last year that the fishery was open. Incidental catch is reported for the most recent full calendar year.

Overall, the ecosystem indicators score in 2024 increased from 2023 but remained below average (Figure 3, top panel). By category from 2023 to 2024, the larval and juvenile indicators remained below average and the adult indicators increased to above average. The BBRKC fishery reopened this year following a two-year closure for the 2021/22 and 2022/23 seasons. We, therefore, compare the most recent socioeconomic indicators with the year prior to the fishery closures. Overall, socioeconomic indicators in 2023 remain below average but increased from 2020 (Figure 3, bottom panel). By category from 2020 to 2023, fishery performance indicators remain below average, while economic indicators increase from average to above average.

Due to fishery closures in 2021 and 2022, social and economic indicator information is extremely limited for most recent years. However, we note that these missing data should, instead, emphasize the economic hardships being faced by the BBRKC crab harvesters and processors during these closure periods.

Intermediate Stage: Importance Test

Bayesian adaptive sampling (BAS) was used to quantify the association between hypothesized ecosystem predictors and BBRKC recruitment (survey abundance of immature male BBRKC, 95 – 120mm), and to assess the strength of support for each hypothesis (Fedewa et al., 2023). We provide the mean relationship between each predictor variable and BBRKC recruitment over time (Figure 4a), with error bars describing the uncertainty (95% confidence intervals) in each estimated effect and the marginal inclusion probabilities for each predictor variable (Figure 4b). Results from this analysis may assist with evaluation of the updated indicator suite for use in the risk table. A higher probability indicates that the variable is a better candidate predictor of BBRKC recruitment.

The highest ranked predictor variables based on the most recent BAS analysis were 1) Pacific cod biomass, 2) cold pool spatial extent, and 3) benthic invertebrate biomass. The direction of these effects were consistent with hypothesized directional relationships identified in peer-reviewed literature. Intermediate stage indicator importance tests in future ESP report cards will explore additional statistical techniques to address potential nonstationarity and missing observations.

Advanced Stage: Research Model Test

At this time, we do not have any ecosystem research models to report for BBRKC.

Data Gaps and Future Research Priorities

Low stock recruitment in the past decade warrants building a better understanding of early life history processes to identify critical bottlenecks that will support the development of meaningful larval indicators. Future laboratory and field research should, for example, better resolve the range of optimal environmental conditions for embryo survival and successful settlement in juvenile nursery areas. Evaluating RKC phenology relative to spring bloom timing may be useful for predicting larval condition and subsequent survival to settlement. Additionally, evaluating larval drift patterns and identifying essential fish habitat for benthic juvenile RKC may support the development of a larval retention or settlement success indicator. Likewise, the dramatic increase in Bristol Bay sockeye salmon coinciding with declines in BBRKC recruitment in recent years emphasizes the importance of understanding predator-prey interactions and spatiotemporal overlap of major pelagic predators with BBRKC larval stages.

Potential climate-driven shifts in BBRKC spatial distributions also underscore the importance of assessing fishery interactions with trawl and pot gear relative to BBRKC migration patterns, molt-mate timing and spawning habitat. Future efforts should aim to develop spatial maps identifying fishery interaction hotspots for BBRKC by month and across years, and to develop stock and life history-specific vulnerability assessments of fishing effects. Overall, we highlight the continued importance of developing a mechanistic understanding of driver-response relationships to facilitate the inclusion of informative ecosystem indicators for BBRKC.

We plan to further evaluate the information provided in the Economic SAFE and ACEPO report to determine what socioeconomic indicators could be provided in the ESP that are not redundant with those reports and related directly to stock health. Additional consideration of the timing of the economic and community reports, which are delayed by 1-2 years (depending on the data source) from the annual stock assessment cycle, should also be undertaken. We emphasize the importance of developing community indicators that effectively communicate the economic hardships currently being faced by industry under multiple Bering Sea crab fishery closures. The Scientific and Statistical Committee (SSC) recently recommended that local knowledge, traditional knowledge, and subsistence information may be helpful for understanding recent fluctuations in stock health, shifts in stock distributions, or changes in fishing behavior.

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Tables

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

Indicator category	Indicator	2020 Status	2021 Status	2022 Status	2023 Status	2024 Status
Larval	Arctic Oscillation Index	*high*	neutral	neutral	neutral	neutral
	Summer Wind Stress	neutral	**high**	neutral	neutral	neutral
	Spring Chlorophyll *a* Concentration	neutral	neutral	**low**	**low**	**low**
	Bristol Bay Sockeye Inshore Run Size	**high**	**high**	**high**	neutral	neutral
Juvenile	Spring pH	**low**	**low**	**low**	**low**	**low**
	Summer Bottom Temperature	NA	neutral	neutral	neutral	neutral
	Summer Cold Pool Extent	NA	**low**	neutral	neutral	neutral
	Summer Pacific Cod Density	NA	neutral	neutral	neutral	neutral
Adult	Summer Benthic Invertebrate Density	NA	neutral	neutral	**low**	neutral
	Summer Red King Crab Male Area Occupied	NA	neutral	neutral	neutral	*high*
	Summer Red King Crab Female Area Occupied	NA	*high*	neutral	neutral	neutral
	Annual Fishery Catch Distance from Shore	neutral	neutral	neutral	neutral	NA
	Summer BBRKC Female Reproductive Potential	NA	neutral	neutral	neutral	neutral
	Summer BBRKC Northern District Ratio	NA	**high**	**high**	neutral	**high**
	Summer BBRKC Protected Area Proportion	NA	neutral	neutral	*high*	*high*

Table 1b. First stage socioeconomic indicator analysis for BBRKC, including indicator title and the indicator status of the last five available years. The indicator status is designated with text, (greater than = "high", less than = "low", or within 1 standard deviation = "neutral" of time series mean). A gray fill and text = "NA" will appear if there were no data for that year. A red color indicates a fishery closure and the text = "Closed" will appear.

Indicator category	Indicator	2019 Status	2020 Status	2021 Status	2022 Status	2023 Status
Fishery Performance	Number of Active Vessels BBRKC Fishery	neutral	low	**Closed**	**Closed**	low
	Annual CPUE BBRKC Fishery	neutral	neutral	**Closed**	**Closed**	neutral
	Annual Total Potlifts BBRKC Fishery	neutral	low	**Closed**	**Closed**	low
	Annual Incidental Catch	neutral	neutral	neutral	neutral	neutral
Economic	Annual TAC Utilization BBRKC Fishery	neutral	neutral	**Closed**	**Closed**	neutral
	Annual Ex-vessel Value BBRKC Fishery	low	low	**Closed**	**Closed**	low
	Annual Ex-vessel Price BBRKC Fishery	high	high	**Closed**	**Closed**	high
	Annual Ex-vessel Revenue Share BBRKC Fishery	neutral	neutral	**Closed**	**Closed**	high

Figures

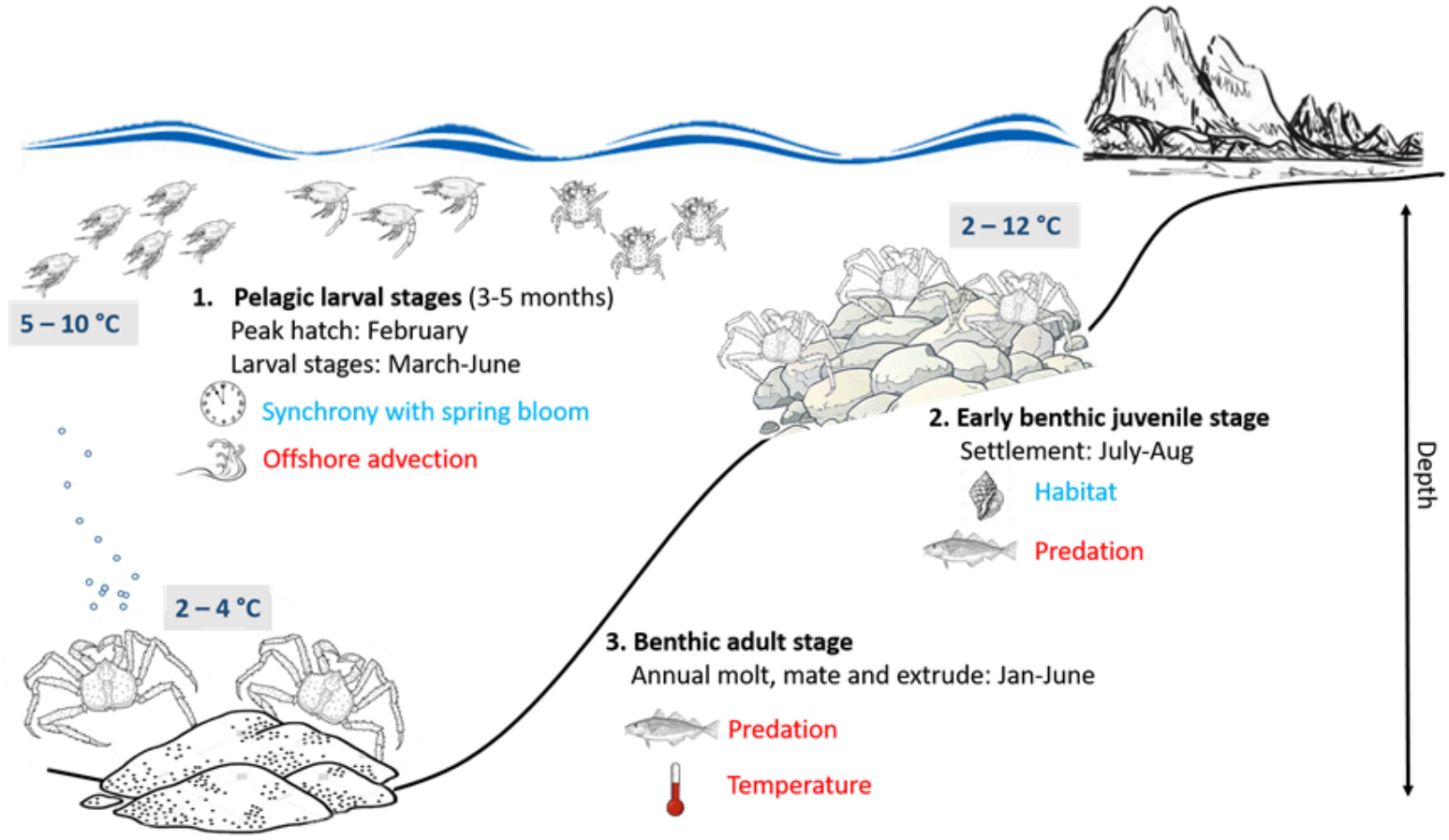

Figure 1a: Life history conceptual model for BBRKC summarizing ecological information and key ecosystem processes affecting survival by life history stage. Thermal requirements by life history stage were determined from RKC laboratory studies. Red text means increases in process negatively affect survival, while blue text means increases in process positively affect survival.

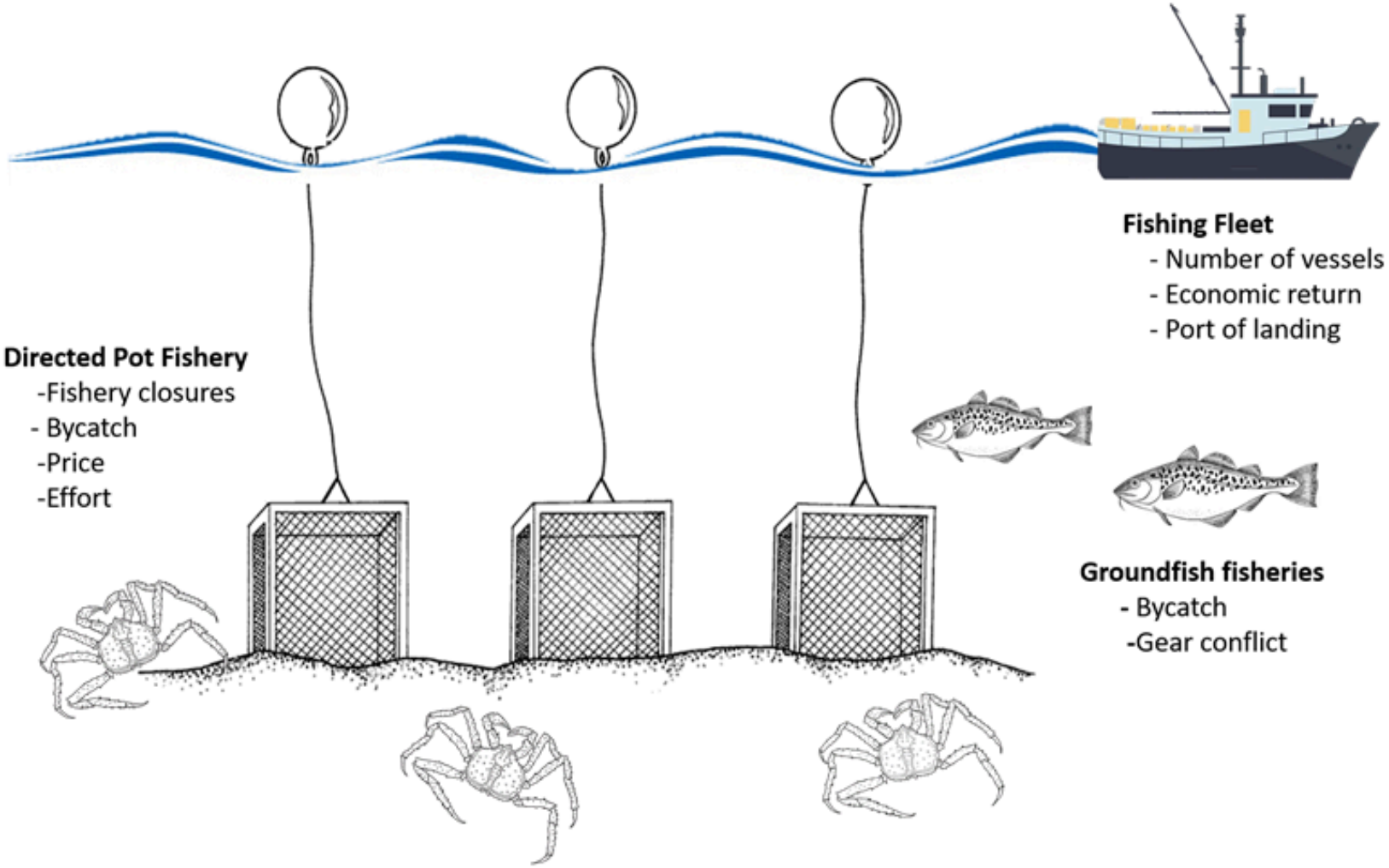

Figure 1b: Conceptual model of socioeconomic performance metrics for BBRKC that may identify dominant pressures on the Bristol Bay red king crab stock.

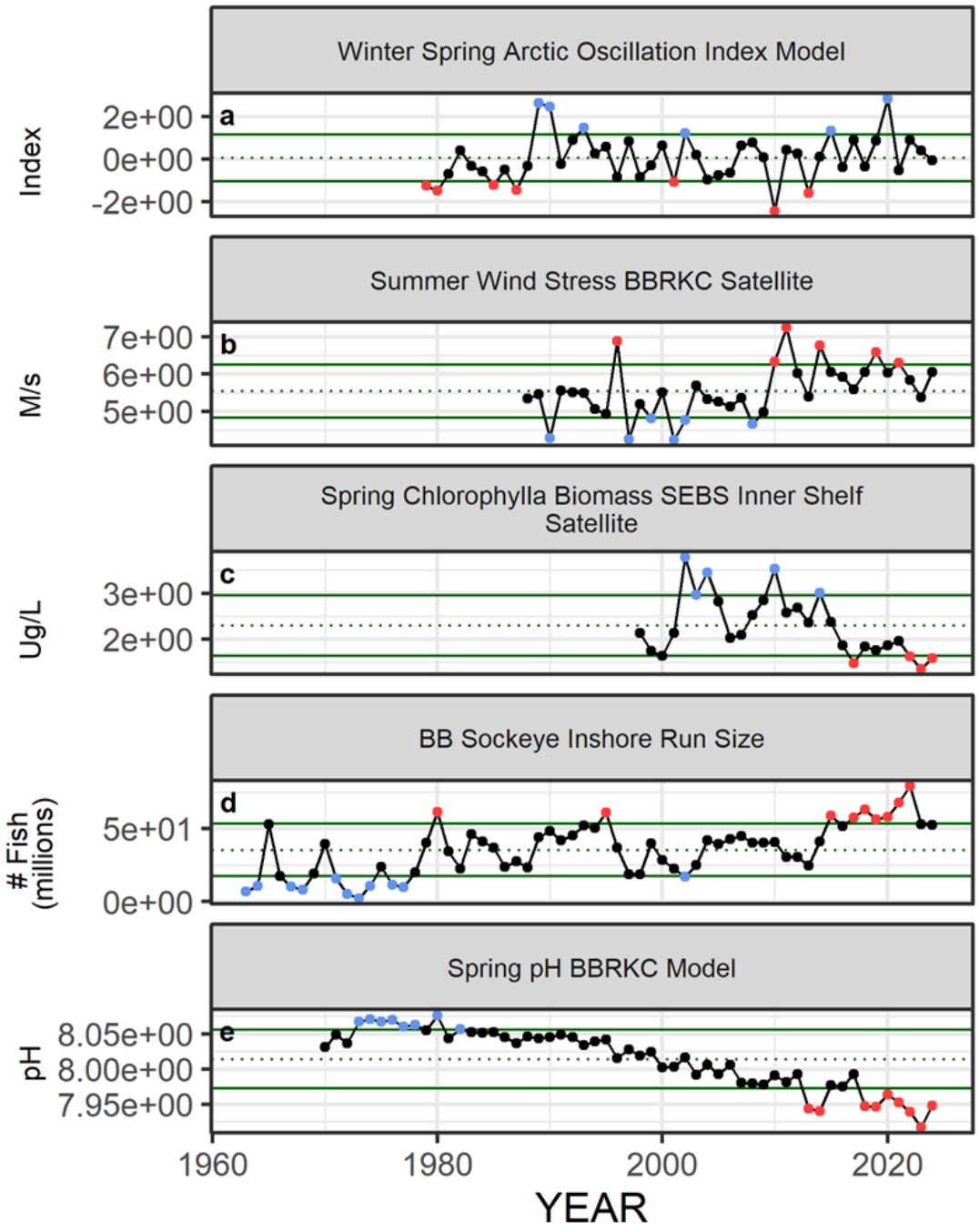

Figure 2a. Selected ecosystem indicators for snow crab with time series ranging from 1970 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. Dots in the time series are colored if above or below 1 standard deviation of the time series mean and the color represents the proposed relationship for stock (blue for good conditions, red for poor conditions), black circle for neutral. If "NA" then a gap will appear in the time series.

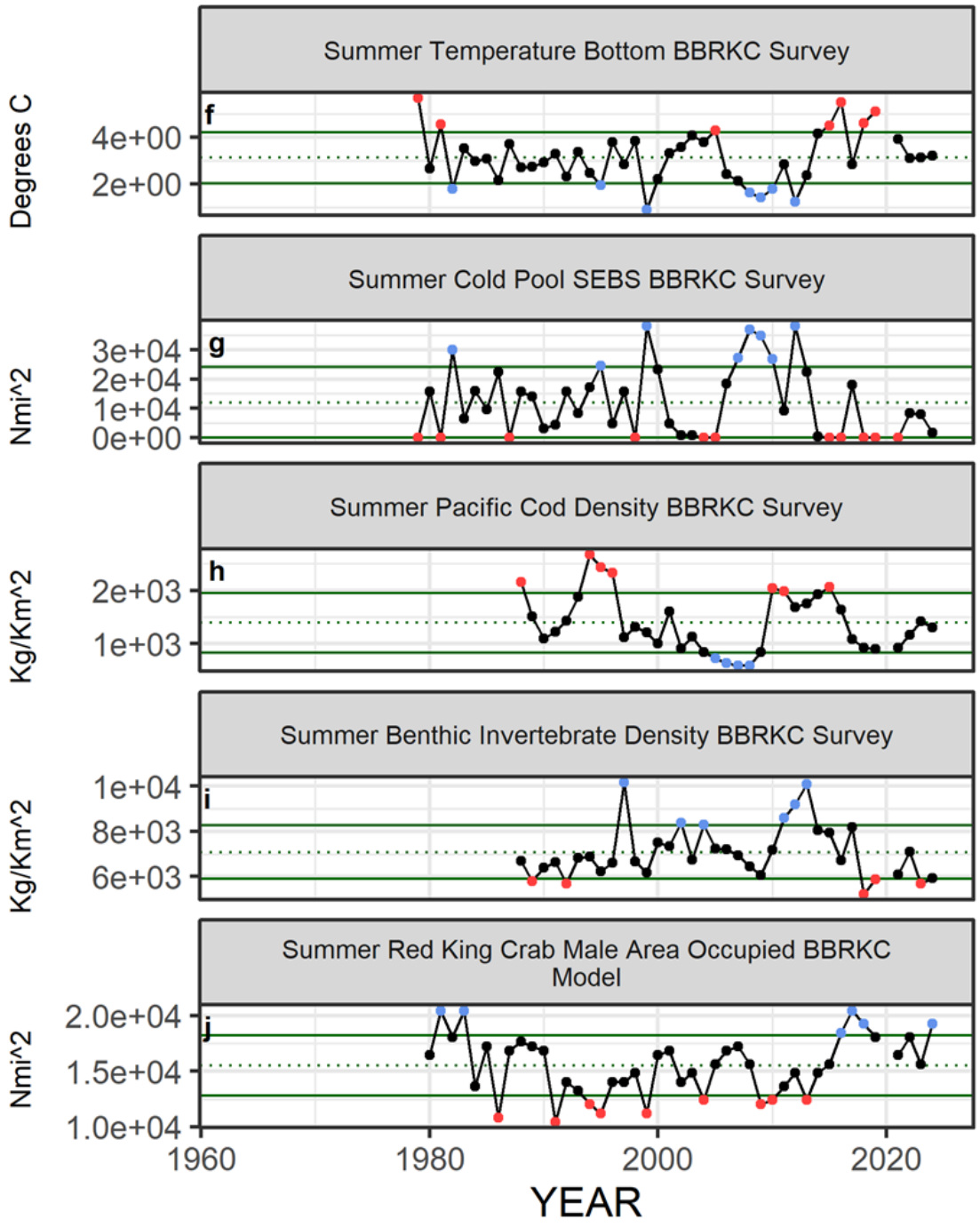

Figure 2a (cont.). Selected ecosystem indicators for snow crab with time series ranging from 1970 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. Dots in the time series are colored if above or below 1 standard deviation of the time series mean and the color represents the proposed relationship for stock (blue for good conditions, red for poor conditions), black circle for neutral. If "NA" then a gap will appear in the time series.

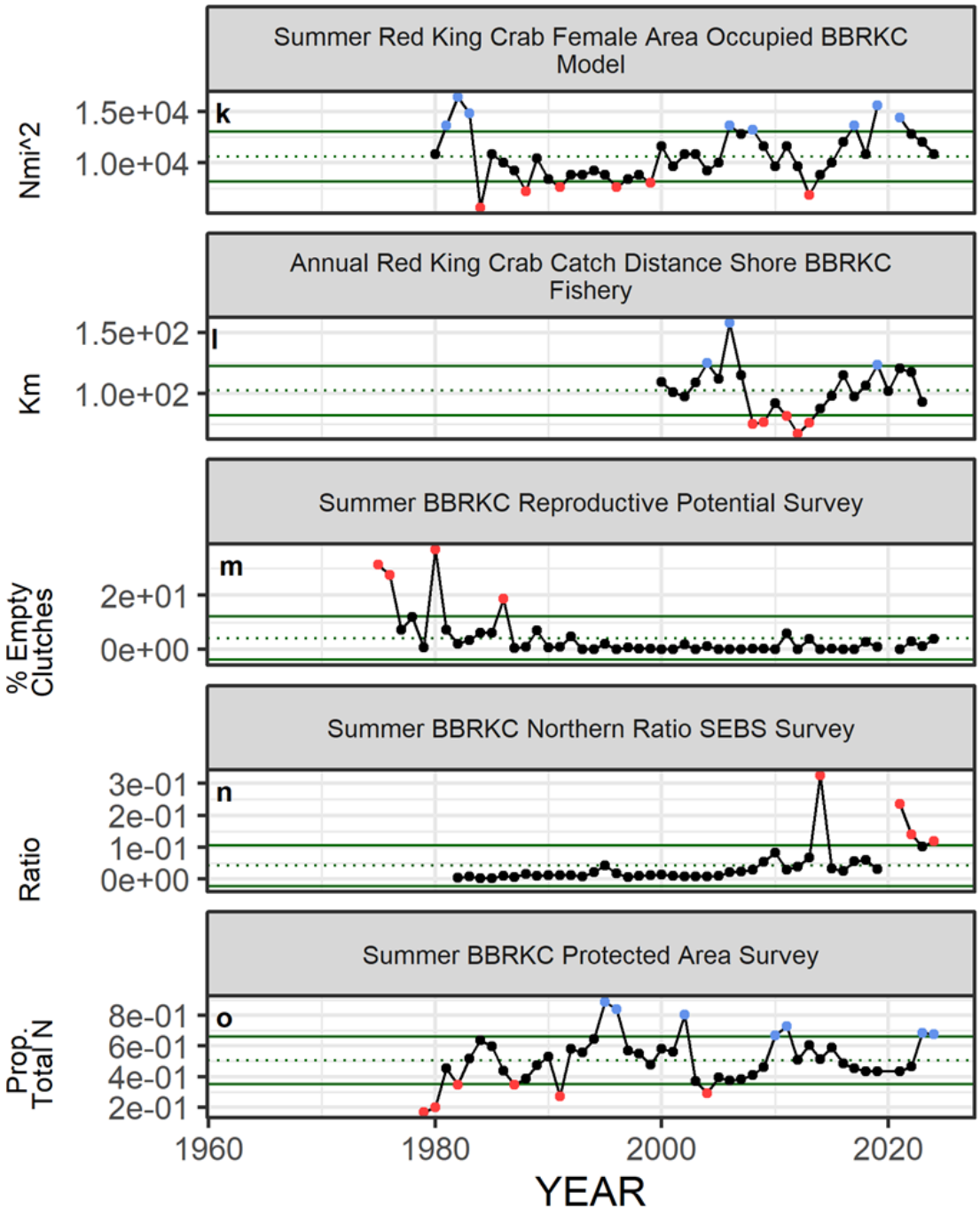

Figure 2a (cont.). Selected ecosystem indicators for snow crab with time series ranging from 1970 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. Dots in the time series are colored if above or below 1 standard deviation of the time series mean and the color represents the proposed relationship for stock (blue for good conditions, red for poor conditions), black circle for neutral. If "NA" then a gap will appear in the time series.

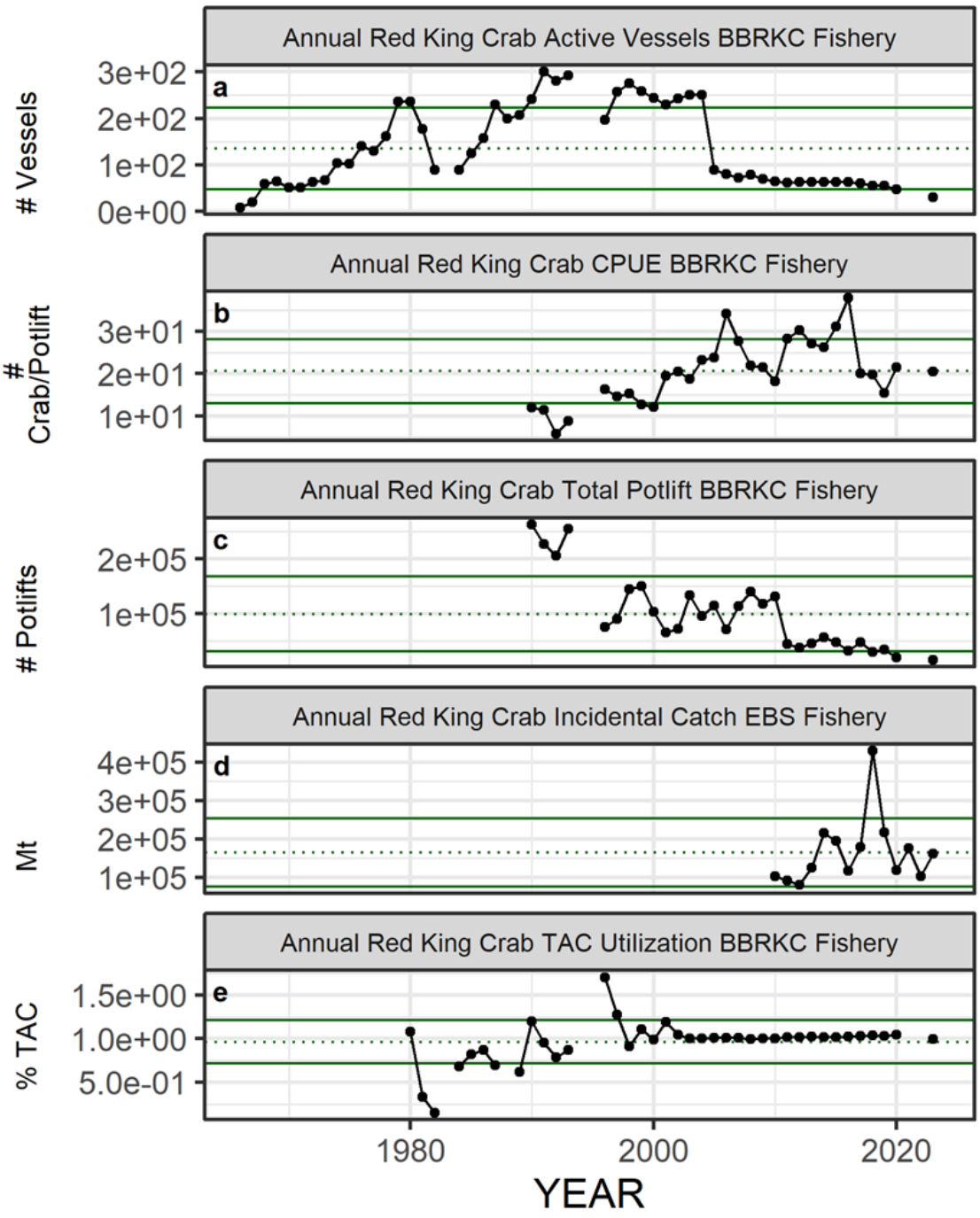

Figure 2b. Selected socioeconomic indicators for snow crab with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. If "NA" then a gap will appear in the time series.

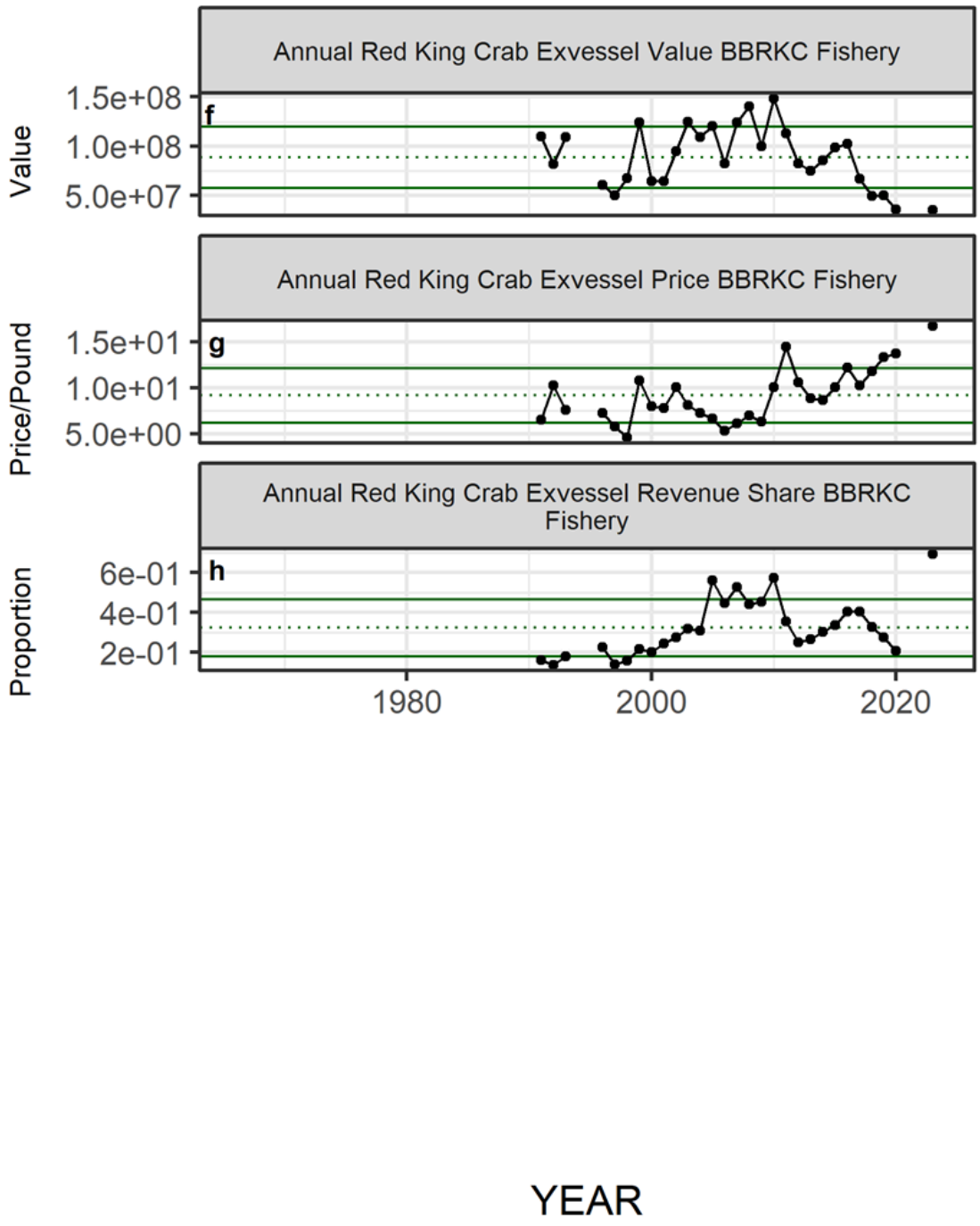

Figure 2b (cont.). Selected socioeconomic indicators for snow crab with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. If "NA" then a gap will appear in the time series.

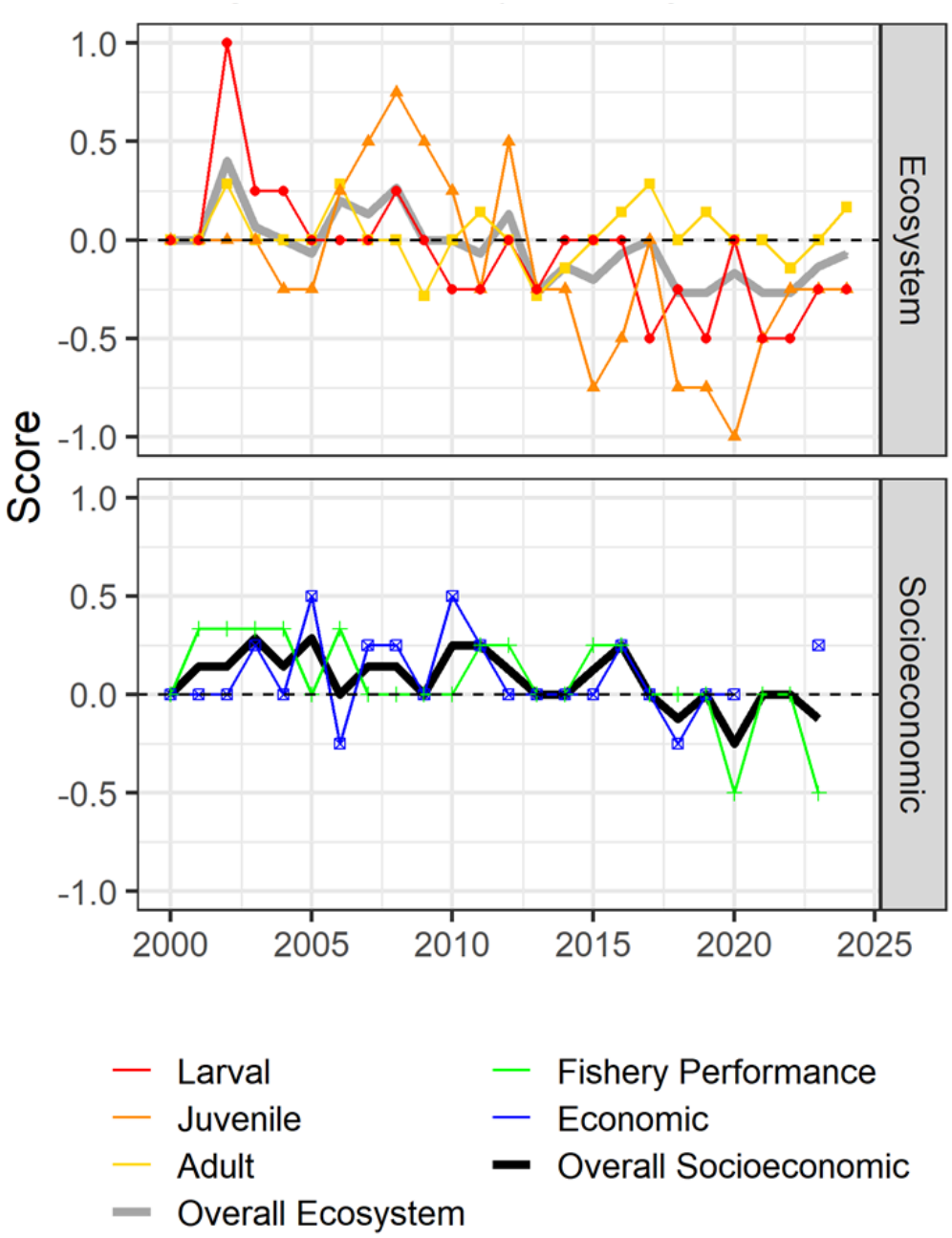

Figure 3: Simple summary traffic light score by category and overall for ecosystem and socioeconomic indicators from 2000 to present.

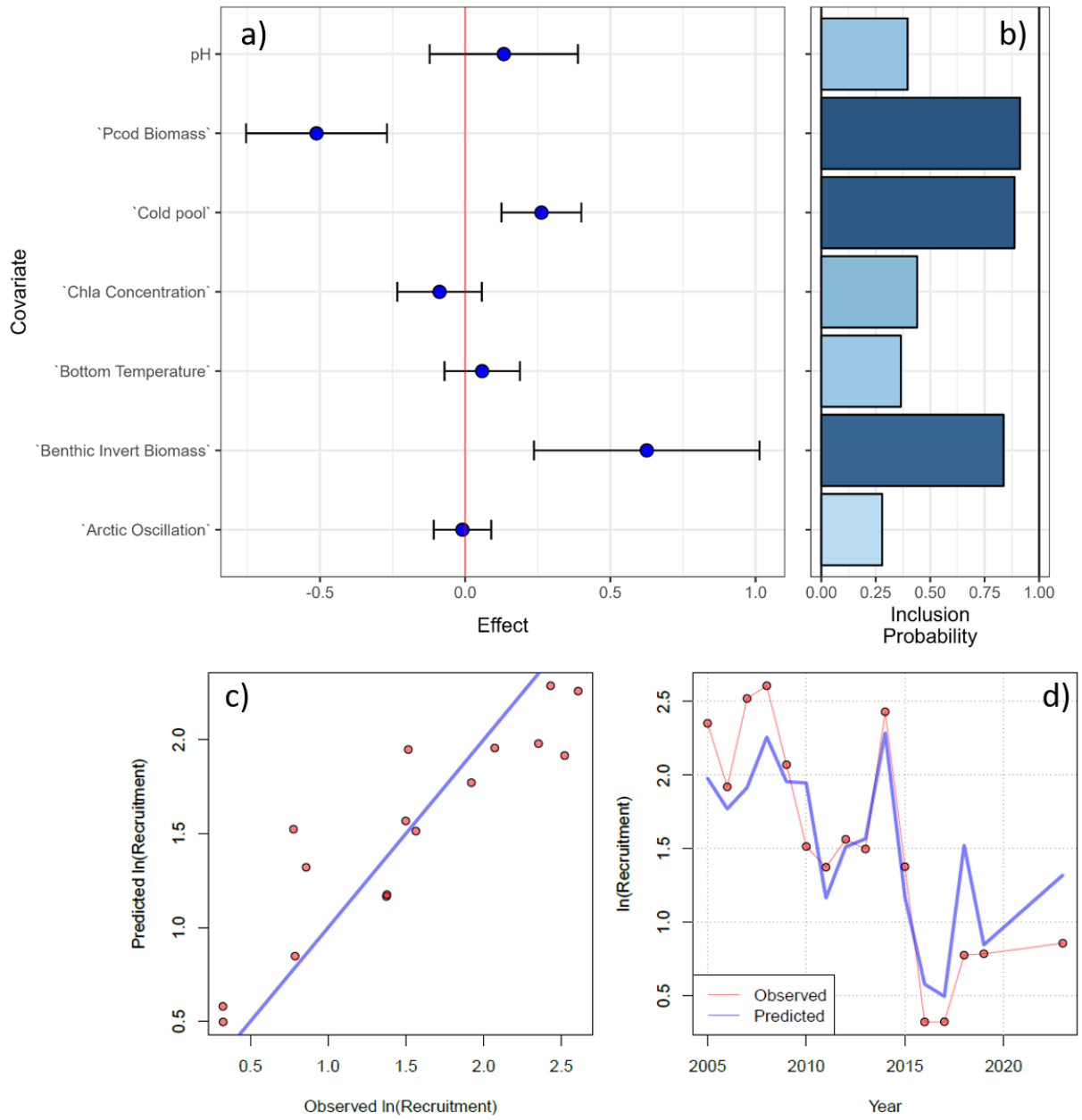

Figure 4. Bayesian adaptive sampling output showing the mean relationship and uncertainty (± 1 SD) with log-transformed Bristol Bay red king crab recruitment (male survey abundance 95 – 120mm): a) the estimated effect and b) marginal inclusion probabilities for each predictor variable of the subsetted covariate ecosystem indicator dataset. Output also includes model c) predicted fit (1:1 line) and d) average fit across the abbreviated recruitment time series (2005 – 2021).