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

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Recommendation

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

Please refer to the last full ESP document for further information regarding the ecosystem and socioeconomic linkages for this stock (Fedewa et al., 2020, available within the Bristol Bay red king crab SAFE, Appendix E, pp. 172-204: https://meetings.npfmc.org/CommentReview/DownloadFile?p=06e93325-0336-4947-a2b9-cbf7b5db9bc8.pdf&fileName=C1%202%20BBRKC%20SAFE.pdf).

Management Considerations

- Above-average wind stress and persistently low levels of chlorophyll-*a* in Bristol Bay in combination with substantial increases in juvenile sockeye salmon abundance in the past 5 years could be indicative of poor larval feeding conditions and increased predation on early life stages.
- A greater than 10% ratio of eyed to uneyed clutches in mature female red king crab in June during the 2021 AFSC EBS bottom trawl survey indicates that reproductive cycles were delayed due to relatively cold spring bottom temperatures in Bristol Bay. Delayed spring hatching of red king crab embryos in 2021 relative to mid-May peak bloom timing may have impacted the spatiotemporal overlap between first-feeding larvae and preferred diatom prey.
- The cold pool did not extend into Bristol Bay in summer 2021 and bottom water temperatures were above the long-term average, suggesting optimal conditions for embryo development and potentially greater larval retention within Bristol Bay. Summer bottom temperatures were well-within the thermal range of juvenile and adult red king crab.
- Red king crab have experienced a steady decline in bottom water pH in the past 5 years. Continued declines to threshold pH levels of 7.8 could negatively affect juvenile red king crab growth, shell hardening and survival.
- BBRKC recruitment remains well below the long-term average. Concurrent declines in Pacific cod and benthic invertebrate biomass in the past 5 years coinciding with above-average bottom temperatures and a reduced cold pool may suggest bottom-up climate forcing on Bristol Bay benthic communities.
- Spatial extent of mature female red king crab in Bristol Bay was above average in 2021 despite declines in abundance. The relatively large spatial footprint of mature females in 2021 is likely attributed to high catches of red king crab in the northwesternmost station of the Bristol Bay management area during the AFSC EBS bottom trawl survey. Northwest shifts in stock distribution may limit the effectiveness of central Bristol Bay trawl closure areas designated to protect red king crab.

Modeling Considerations

Bayesian adaptive sampling (BAS) was utilized for the intermediate stage statistical importance testing in the last full ESP (Fedewa et al., 2020) to quantify the association between hypothesized predictors and BBRKC mature male biomass. The highest ranked predictor variables (> 0.50 inclusion probability) resulting from the analysis were: BBRKC recruit biomass, Pacific cod biomass, and the Arctic Oscillation. Due to concerns with autocorrelation in model-based estimates of mature male biomass (A. Punt, *pers. commun.*, 2020), indicator importance tests in future BBRKC ESP updates will use survey biomass estimates as a response variable. 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 RKC life history stage (Figure 1a) and 2) socioeconomic performance metrics (Figure 1b). The ecosystem conceptual model highlights abiotic and biotic processes identified by each life stage from the literature, process studies and laboratory rearing experiments. During early larval stages, RKC survival is dependent on spatiotemporal overlap with high densities of diatoms (Paul et al., 1989; Paul and Paul, 1980), optimal environmental conditions for development (Nakanishi, 1987) and dispersal to suitable settlement habitat (Daly et al., 2018). Specific habitat requirements for juvenile RKC include physical structure and high relief to both evade predators (Stoner, 2009; Pirtle et al., 2012) and provide increased foraging opportunities (Pirtle and Stoner, 2010). Late juvenile and adult RKC are less reliant on complex structure, and instead, spatial distributions and migration timing are driven by bottom temperatures (Loher and Armstrong, 2005; Zheng and Kruse, 2006; Zacher et al., 2018).

The socioeconomic conceptual model highlights fishery performance indicators, which represent processes most directly involved in prosecution of the BBRKC fishery, and thus have the potential to differentially affect the condition of the stock depending on how they influence the timing, spatial distribution, selectivity, and other aspects of fishing pressure. Implementation of the Crab Rationalization Program and the allocation of tradable crab harvest quota shares resulted in rapid consolidation of the BBRKC fleet and changed the timing of the fishery from short derby seasons to more extended seasons. These and other institutional changes continue to influence the geographic and inter-sectoral distribution of benefits produced by the BBRKC fleet.

Indicator Suite

The following list of indicators for BBRKC is organized by categories: three for ecosystem indicators (physical, lower trophic, and upper trophic) and two for socioeconomic indicators (fishery performance, economic). Full details on the indicators listed, including a description and proposed mechanistic linkages, are available in the last full ESP (Fedewa et al., 2020). Here, we only include the indicator title and associated contributor contact. Indicators are updated with current-year data whenever possible. Time series of the ecosystem and socioeconomic indicators are provided in Figure 2a-2b and Figure 3, respectively. Please note, we are not including the ROMS spring bottom temperature indicator at this time as more seasonal skill testing is necessary before use in a stock assessment context. A ROMS ocean acidification indicator was updated with current-year data, however the whole time series is presented as pH values instead of aragonite saturation states to simplify interpretation. In addition, Bristol Bay summer bottom temperature and cold pool extent indicators were developed for the 2021 BBRKC report card using EBS bottom trawl survey temperature data, whereas in the last full BBRKC ESP, these respective indicators were developed from Bering 10K ROMS model hindcasts due to the cancellation of the 2020 EBS bottom trawl survey. Next year we plan to evaluate potential ocean model indicators within the criteria outlined in the Bristol Bay red king crab request for indicators. Five socioeconomic indicators have been discontinued due to concerns over redundancy with the stock assessment model and in an effort to emphasize those indicators that are most closely associated with the health and condition of the stock.

The five discontinued indicators are the following: annual incidental catch of Bristol Bay red king crab in eastern Bering Sea trawl and fixed gear fisheries, which is explicitly included in the assessment model; TAC utilization in the Bristol Bay red king crab fishery, which has not deviated from 100% utilization since prior to rationalization; and three community-focused indicators - annual active processors in the Bristol Bay red king crab fishery, annual processing employment in the Bristol Bay red king crab fishery, and annual local quotient of Bristol Bay red king crab landed catch in Dutch Harbor - which are not directly associated with the condition of the stock and are thus not directly relevant to ABC or TAC decision-making. Detailed community information for BSAI crab fisheries, including the above indicators, are available in the Annual Community Engagement and Participation Overview (ACEPO) report (Wise et al., 2021).

Ecosystem Indicators:

1. Physical Indicators
    - Summer cold pool extent (nmi) in Bristol Bay from the AFSC eastern Bering Sea bottom trawl survey (contact: E. Fedewa)
    - Summer bottom temperatures in Bristol Bay from the AFSC eastern Bering Sea bottom trawl survey (contact: E. Fedewa)
    - Winter-spring Arctic Oscillation index (NOAA National Climate Data Center)
    - Spring pH index in Bristol Bay from the Bering10K ROMS model (Pilcher et al., 2019) (contact: D. Pilcher)
    - Summer wind stress (m/s) in Bristol Bay from NOAA/NCDC blended winds and Metop-A ASCAT satellite (Zhang et al., 2006, NOAA/NESDIS, CoastWatch) (contact: K. Shotwell)
    - Spring chlorophyll-*a* biomass in Bristol Bay from MODIS satellites (contact: J. Nielsen)
2. Lower Trophic Indicators
    - None at this time
3. Upper Trophic Indicators
    - September juvenile sockeye salmon abundance in the EBS from the AFSC Bering Arctic Subarctic Integrated Survey (contact: E. Yasumiishi)
    - Summer Pacific cod biomass in Bristol Bay from the AFSC eastern Bering Sea bottom trawl survey (contact: E. Fedewa)
    - Summer benthic invertebrate biomass in Bristol Bay from the AFSC eastern Bering Sea bottom trawl survey (contact: E. Fedewa)
    - Annual red king crab recruit biomass (110-134 mm CL) in Bristol Bay from the AFSC eastern Bering Sea bottom trawl survey (contact: J. Richar).
    - Summer mature male red king crab area occupied in Bristol Bay from the AFSC eastern Bering Sea bottom trawl survey (contact: E. Fedewa)
    - Summer mature female red king crab area occupied in Bristol Bay from the AFSC eastern Bering Sea bottom trawl survey (contact: E. Fedewa)
    - Annual male red king crab catch distance from shore in Bristol Bay during the fishery (contact: L. Zacher).

Socioeconomic Indicators:

1.) Fishery Performance Indicators
    - Annual catch-per-unit-effort (CPUE) (expressed as mean number of crabs per potlift) in the Bristol Bay red king crab fishery
    - Annual total potlifts in the Bristol Bay red king crab fishery
    - Annual number of active vessels in the Bristol Bay red king crab fishery

2.) Economic Indicators
    - Annual red king crab ex-vessel value of the Bristol Bay red king crab fishery landings
    - Annual red king crab ex-vessel price per pound of the Bristol Bay red king crab fishery
    - Annual red king crab ex-vessel revenue share (expressed as percent of total ex-vessel revenue) of the Bristol Bay red king crab fishery
3.) Community Indicators
    - None at this time

Indicator Monitoring Analysis

We provide an update to the list and time-series of ecosystem and socioeconomic indicators (Figures 2a-2b and 3) and then report the results of the first stage statistical test for the ecosystem indicator analysis with the inclusion of current-year data (Table 1). We plan to update the second stage indicator analysis in 2022. At this time, socioeconomic indicators are not yet available for 2021 and time series are presented through 2020 (Figure 3, Table 2).

Beginning Stage: Traffic Light Test

Overall, trends in physical ecosystem indicators suggest poor larval environmental conditions during the past 5 years for the BBRKC stock. Relatively cold spring water temperatures in 2020 (full ESP: Fedewa et al., 2020) and 2021 in addition to above-average wind stress and below-average chlorophyll *a* biomass for the past 5 years suggest BBRKC hatch-spring bloom spatiotemporal mismatches, declines in preferred larval prey and low larval encounter rates due to increased surface mixing. Record high juvenile sockeye salmon abundances in Bristol Bay since 2014 may be further indicative of increased predation and subsequent poor survival of RKC larval stages, although most recent sockeye salmon abundance estimates are not available due to AFSC survey cancellations. Bristol Bay summer bottom temperatures in 2021 were ~1°C colder than 2018-2019 temperatures, although the cold pool did not extend into Bristol Bay in 2021. The pH of bottom waters in Bristol Bay has been on a steady decline since 2016.

Current-year values for upper trophic level Pacific cod and benthic invertebrate indicators are not yet available following the conclusion of the 2021 EBS bottom trawl survey. However, both indicators are on a downward trend and Pacific cod biomass has been below average since 2016 in Bristol Bay. BBRKC recruitment still remains well below average as well. Spatial extent of mature female red king crab remains well above average while male spatial extent declined in 2021. During warm years from 2018-2019, male RKC were located further from shore during the fishery whereas catch distance from shore declined to near-average during the 2019-2020 fishing season.

Trends in fishery performance and economic indicators correspond to ongoing decline in TACs issued in the BBRKC fishery since 2014. Effort in the fishery, as indicated by the number of active vessels and total number of potlifts, both of which continued the downward trends observed in recent years, and reached the lowest points on record during the 2020-2021 fishing season, while CPUE increased somewhat relative to the previous three seasons, but remained at a relative low compared to the post-rationalization period overall. Ex-vessel price declined slightly for the 2020-2021 season, but remained relatively high compared to the post-rationalization period overall. Consistent with substantial declines in TACs since 2016-2017, gross ex-vessel revenue aggregated over all landings, and the percentage share of total annual landings revenue represented by BBRKC landings for those vessels active in the fishery during 2020-2021 continued the sharp declining trend observed over the recent period, with both reaching historical lows and aggregate revenue reaching the lowest level on record.

Data Gaps and Future Research Priorities

Environmental conditions are rapidly changing in the eastern Bering Sea and continued research is needed to identify temperature thresholds and characterize responses across BBRKC life stages to changes in bottom temperatures. Specifically, future laboratory and field research should focus on clarifying the range of optimal temperatures for embryo survival and successful settlement in juvenile nursery areas. In addition, potential climate-driven shifts in phenology and spatial distribution underscore the importance of assessing fishery interactions with trawl and pot gear relative to BBRKC migration patterns, molt-mate timing and spawning habitat.

Given the dramatic increase in Bristol Bay sockeye salmon coinciding with declines in BBRKC recruitment in recent years, we emphasize the importance of understanding predator-prey interactions and spatiotemporal overlap of major pelagic predators with BBRKC larval stages. Juvenile salmon diet studies conducted from 1984-1992 (Farley 2001, *unpublished data*) reported that juvenile sockeye salmon consumption of red king crab zoea exceeded 45% in several years, suggesting potential links between salmon predation and BBRKC recruitment. In more recent years, the Bering-Aleutian Salmon International Survey has taken place in late-September following peak settlement of BBRKC and there appears to be no ongoing efforts to characterize diets of juvenile sockeye salmon in summer months when BBRKC are likely important prey items. Furthermore, additional groundfish stomach data outside of the summer survey time series would inform predation mortality during the molt when RKC are highly vulnerable.

Low stock recruitment in the past decade also warrants a better understanding of early life history processes and bottlenecks to aid in developing meaningful larval indicators as early warning signs. 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. Overall, we highlight the continued importance of developing a mechanistic understanding of driver-response relationships to facilitate the inclusion of ecosystem indicators in future management strategies for BBRKC.

BBRKC ESP developments for 2022 include: 1) addressing the Crab Plan Team the NPFMC Scientific and Statistical Committee's 2020 recommendations (e.g. improving interpretability of indicator plots to emphasize lags and directional effects on the stock, considering nonlinear responses of BBRKC, assessing proposed indicators for potential redundancy), 2) updating the second stage indicator analysis, 3) producing a Request for Indicators in January 2022 to highlight data gaps and propose new indicator contributions, and 4) updating ecosystem and socioeconomic indicators and considerations prior to the 2022 Crab Plan Team meeting to inform BBRKC management.

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Tables

Table 1. First stage ecosystem indicator analysis for Bristol Bay red king crab (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 long-term mean). Fill color of the cell is based on the sign of the anticipated relationship between the indicator and BBRKC (blue = good conditions for BBRKC, red = poor conditions, white = average conditions). A gray fill and text = “missing” will appear if there were no data for that year.

Indicator	2017 Status	2018 Status	2019 Status	2020 Status	2021 Status
Summer Cold Pool BBRKC Survey	neutral	low	low	missing	low
Summer Temperature Bottom BBRKC Survey	neutral	high	high	missing	neutral
Winter Spring Arctic Oscillation Index Model	neutral	neutral	neutral	high	neutral
Spring pH Index BBRKC Model	neutral	neutral	neutral	low	low
Summer Wind Stress BBRKC Satellite	neutral	neutral	high	neutral	high
Spring Chlorophylla Biomass SEBS Inner Shelf Satellite	low	neutral	neutral	neutral	neutral
Summer Sockeye Salmon Abundance EBS Survey	missing	high	missing	missing	missing
Summer Pacific Cod Biomass BBRKC Survey	neutral	low	low	missing	missing
Summer Benthic Invertebrate Biomass BBRKC Survey	neutral	neutral	neutral	missing	missing
Annual Red King Crab Recruit Biomass BBRKC Model	low	low	low	missing	low
Summer Red King Crab Area Occupied Male BBRKC Survey	high	high	high	missing	neutral
Summer Red King Crab Area Occupied Female BBRKC Survey	high	neutral	high	missing	high
Annual Red King Crab Catch Distance Shore BBRKC Fishery	neutral	neutral	high	neutral	missing

Table 2. First stage socioeconomic indicator analysis for Bristol Bay red king crab (BBRKC), including indicator title and the indicator status for the years 2016-2020. The indicator status is designated with text, (greater than = "high", less than = "low", or within 1 standard deviation = "neutral" of long-term mean). Fill color of the cell is based on the indicator status text (blue = high value, red = low value, white = average value) and does not assign an anticipated relationship between the indicator and BBRKC. A gray fill and text = "missing" will appear if there were no data for that year.

Indicator	2016 Status	2017 Status	2018 Status	2019 Status	2020 Status
Annual Red King Crab Active Vessels BBRKC Fishery	low	low	low	low	low
Annual Red King Crab Total Potlift BBRKC Fishery	neutral	neutral	neutral	neutral	low
Annual Red King Crab Potlift CPUE BBRKC Fishery	high	neutral	neutral	neutral	neutral
Annual Red King Crab Exvessel Price BBRKC Fishery	high	neutral	neutral	neutral	neutral
Annual Red King Crab Exvessel Revenue Share BBRKC Fishery	neutral	neutral	neutral	neutral	low
Annual Red King Crab Exvessel Value BBRKC Fishery	neutral	neutral	low	low	low

Figures

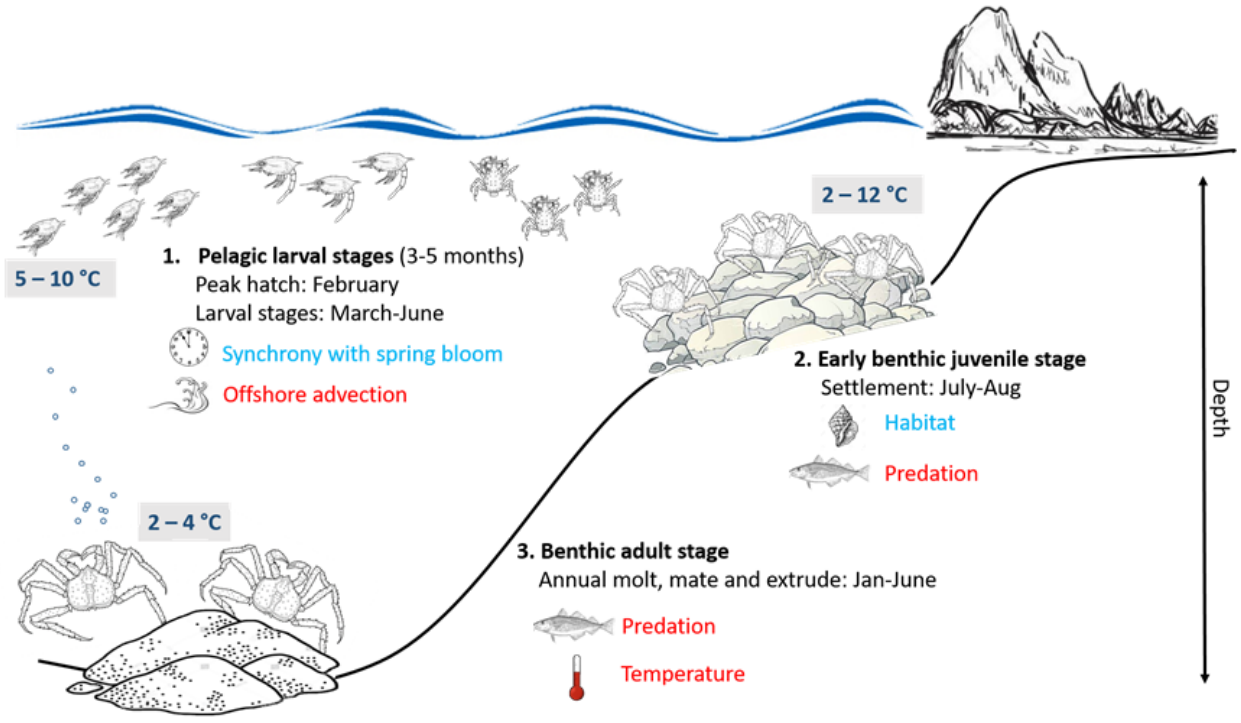

Figure 1a. Conceptual diagram of phenological information by life history stage for Bristol Bay red king crab and processes likely affecting survival in each stage. Thermal requirements by life history stage were determined from RKC laboratory studies.

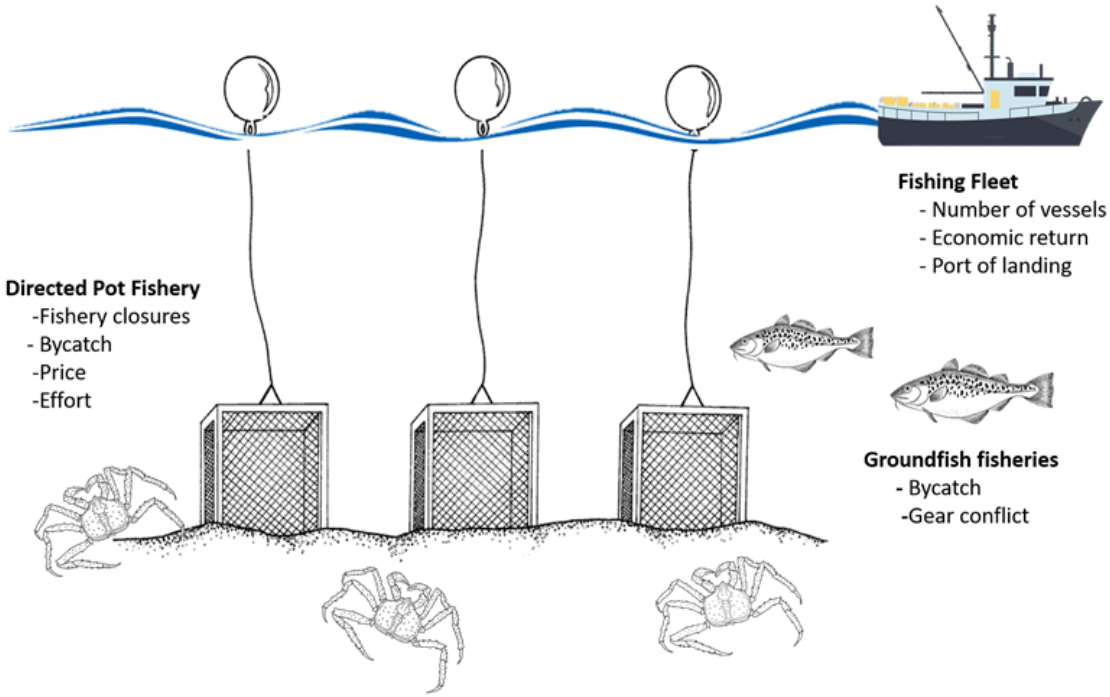

Figure 1b. Conceptual diagram of socioeconomic performance metrics that may identify dominant pressures on the Bristol Bay red king crab stock.

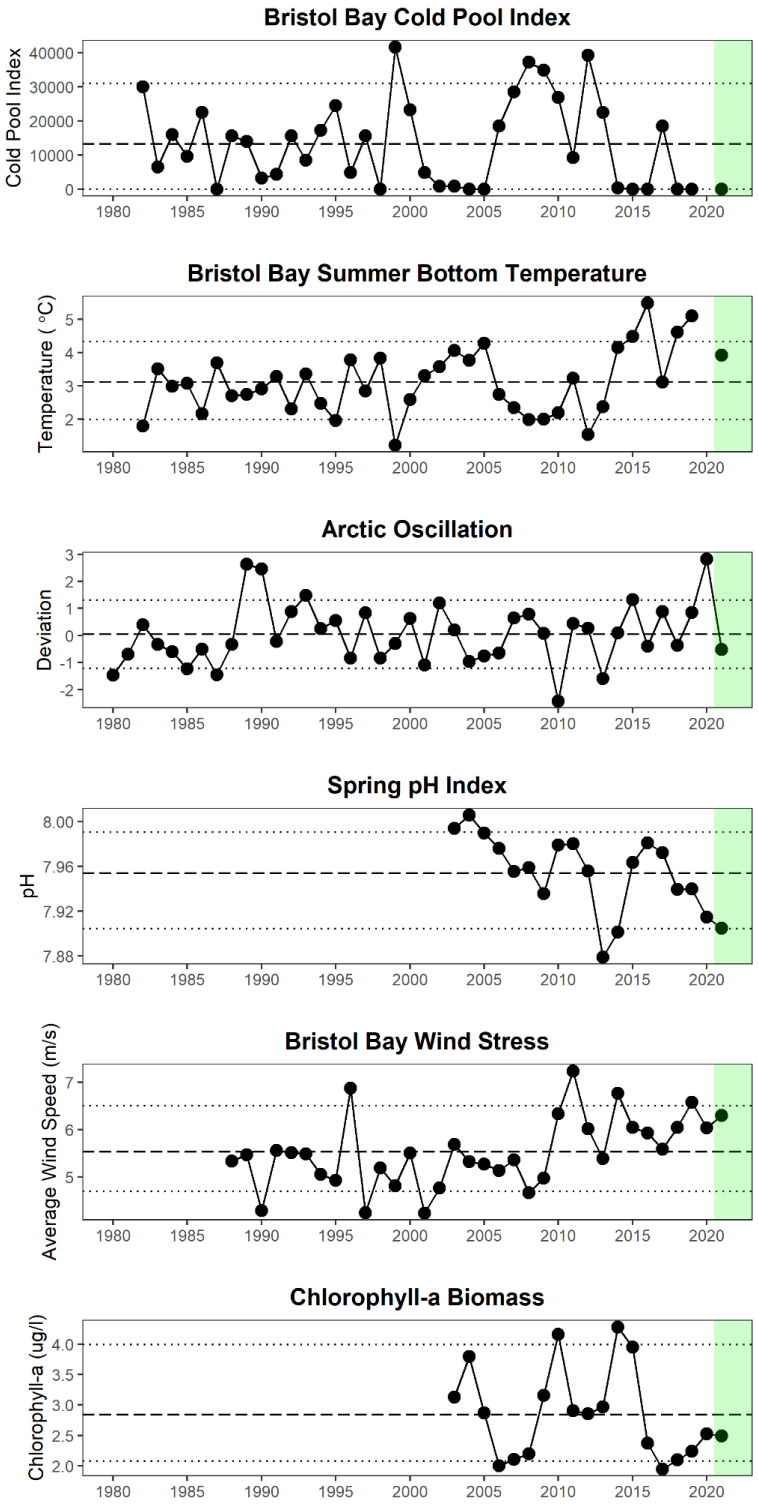

Figure 2a. Selected physical indicators for Bristol Bay red king crab with time series ranging from 1980 – 2021. Upper and lower dotted horizontal lines are 90th and 10th percentiles of time series. Dashed horizontal line is the mean of time series. Light green shaded area represents most recent year data.

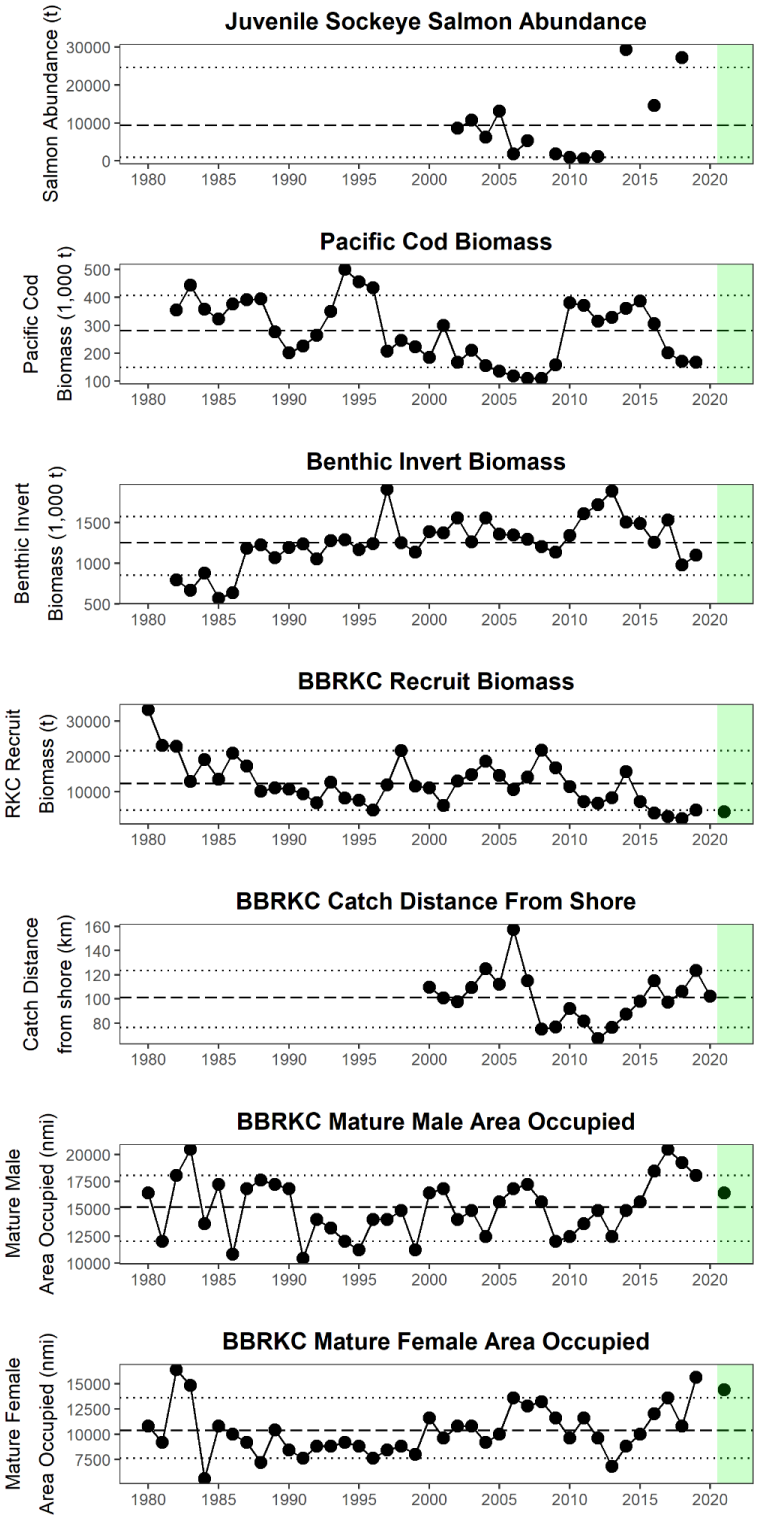

Figure 2b. Selected upper trophic indicators for Bristol Bay red king crab with time series ranging from 1980 – 2021.

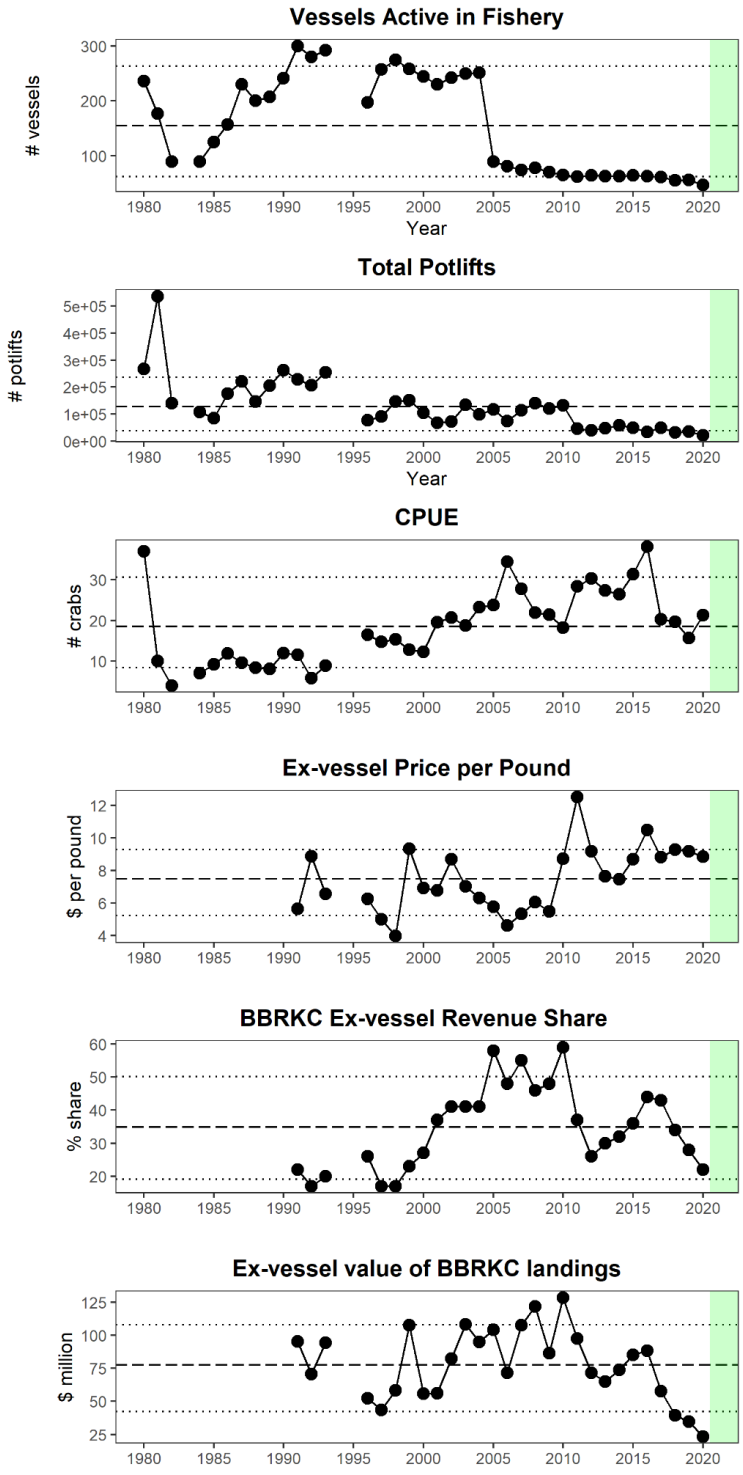

Figure 3. Selected socioeconomic indicators for Bristol Bay red king crab with time series ranging from 1980 – 2020. Upper and lower dotted horizontal lines are 90th and 10th percentiles of time series. Dashed horizontal line is the mean of time series. Light green shaded area represents most recent year data.