Appendix E. Ecosystem and Socioeconomic Profile of the Bristol Bay Red King Crab Stock

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Executive Summary

National initiative and NPFMC recommendations suggest a high priority for conducting an ecosystem and socioeconomic profile (ESP) for the Bristol Bay red king crab (BBRKC) stock due to recent declines in abundance and poor recruitment. In addition, scores for stock prioritization, habitat prioritization, and data classification analysis were moderate to high. The BBRKC ESP follows the new standardized framework for evaluating ecosystem and socioeconomic considerations, and may be considered a proving ground for potential operational use in the main stock assessment.

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

Ecosystem Considerations

- Available physical indicators for 2020 show a return to near-average conditions in Bristol Bay. A relatively high positive Arctic Oscillation index in winter 2020 may suggest favorable conditions for BBRKC productivity.
- Persistently low levels of chlorophyll *a* and above-average wind stress in Bristol Bay in combination with substantial increases in juvenile sockeye salmon abundance in the past 5 years could be indicative of poor larval conditions.
- The degree of match or mismatch of first-feeding larval red king crab with preferred diatom prey may be critical for larval survival, and recent fluctuations in spring temperatures during embryo development could impact the synchrony between hatch timing and the spring bloom.
- 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.
- Current-year increases in corrosive bottom waters in Bristol Bay have the potential to impact shell formation, growth and survival of BBRKC.

Socioeconomic Considerations

- The numbers of vessels and processors active in the 2018/19 and 2019/20 BBRKC seasons dropped below the lower bounds of their long-term historical range during 2018 and 2019. Both metrics have been in a generally declining trend since the BBRKC fishery was substantially restructured and consolidated following rationalization.
- Ex-vessel price has remained above the long-term average since 2010, partially mitigating some income effects of declining BBRKC production, but the reduced level of participation and employment suggest that reduced economic performance of the BBRKC fishery may have negative distributional effects.
- While aggregate BBRKC ex-vessel value was at a historical low in 2019, BBRKC ex-vessel revenue share on average for active vessels was only moderately below average during 2019. The local quotient for BBRKC catch value of landings to Dutch Harbor also declined to a historical low in 2019.

Introduction

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

This ESP for Bristol Bay red king crab (hereafter referred to as BBRKC) follows a template for ESPs (Shotwell et al., *In Review*) and replaces the previous ecosystem considerations chapter in the 2011 Bering Sea and Aleutian Islands Crab SAFE document and the stock-specific report cards produced in recent years.

The ESP process consists of the following four steps:

1.) Evaluate national initiative and stock assessment classification scores (Lynch et al., 2018) along with regional research priorities to assess the priority and goals for conducting an ESP.

2.) Perform a metric assessment to identify potential vulnerabilities and bottlenecks throughout the life history of the stock and provide mechanisms to refine indicator selection.

3.) Select a suite of indicators that represent the critical processes identified in the metric assessment and monitor the indicators using statistical tests appropriate for the data availability of the stock.

4.) Generate the standardized ESP report following the guideline template and report ecosystem and socioeconomic considerations, data gaps, caveats, and future research priorities.

Justification

The national initiative stock and habitat prioritization scores for BBRKC are overall high primarily because the distribution of this stock depends greatly on habitat. There is also increasing model development for BBRKC, and the stock is highly vulnerability to the impacts of future ocean acidification. Furthermore, the BBRKC stock has been on a declining trend with subsequent lower total allowable catch in recent years, warranting the Crab Plan Team to request an evaluation of ecosystem factors. Current data availability as well as target data availability for five attributes of stock assessment model input data (i.e. catch, size composition, abundance, life history and ecosystem linkage) were classified for the BBRKC stock in order to identify data gaps and assess the priority for conducting an ESP. BBRKC is currently managed as a Tier 3 crab stock and as such, the new data classification scores characterize the stock as data-moderate with estimates of spawner/recruit relationships currently unavailable. Both current and target data availability attribute levels for the BBRKC stock size composition attribute were classified as a 3, which adequately supports a size-structured stock assessment. However, abundance, life history and ecosystem linkage attributes were highlighted as having gaps between current and target data availability. Research priorities for data classification include improvements in stock specific growth estimates and associated life history information, as well as understanding mechanisms for detecting productivity regimes in the population. These initiative scores and data classification levels suggest a high priority for conducting an ESP for BBRKC.

Data

Initially, information on BBRKC was gathered through a variety of national initiatives that were conducted by AFSC personnel. These include (but are not limited to) stock assessment prioritization, habitat assessment prioritization, climate vulnerability analysis, and stock assessment categorization. A form was submitted to stock assessment authors to gather results from all the initiatives in one location, thus serving as the initial starting point for developing the ESP metrics for groundfish and crab stocks in the BSAI and GOA fishery management plans (FMP).

Data used to generate ecosystem metrics and indicators for the BBRKC ESP were collected from a variety of laboratory studies, remote sensing databases, fisheries surveys, regional reports and fishery observer data collections (Table 1). Results from laboratory studies were specifically used to inform metrics and indicators relating to thermal tolerances, phenology and energetics across RKC life history stages. Larval indicator development utilized datasets from the NOAA Bering Arctic Subarctic Integrated Survey (BASIS) and blended satellite data products from NOAA, NASA and ESA. Data for late-juvenile through adult RKC stages were derived from the annual NOAA eastern Bering Sea bottom trawl survey and fishery observer data collected during the BBRKC fishery. Information on RKC habitat use was derived from essential fish habitat (EFH) model output and maps (Figure 3; Laman et al., 2017) as well as laboratory studies and collaborative RKC tagging efforts. Data from the NOAA Resource Ecology and Ecosystem Modeling (REEM) food habits database were used to determine species compositions of benthic predators on commercial crab species.

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

Metrics Assessment

National Metrics

The national initiative form data were summarized into a metric panel (Figure 1) that acts as a first pass ecosystem and socioeconomic synthesis. Metrics range from estimated values to qualitative scores of population dynamics, life history, or economic data for a given stock (see Shotwell et al., *In Review* for more details). To simplify interpretation, the metrics are rescaled by using a percentile rank for BBRKC relative to all other stocks in the groundfish and crab FMP's. Additionally, some metrics are reversed so that all metrics can be compared on a low to high scale between all stocks in the FMP. These adjustments allow for initial identification of vulnerable (percentile rank value is high) and resilient (percentile rank value is low) traits for BBRKC. Data quality estimates are also provided from the lead stock assessment author (0 or green shaded means no data to support answer, 4 or purple shaded means complete data), and if there are no data available for a particular metric then an "NA" will appear in the panel. The metric panel gives context for how BBRKC relate to other groundfish and crab stocks and highlights the potential vulnerabilities and data gaps for the stock. Threshold values identified from national initiatives (Methot, 2015, Morrison et al., 2015, NMFS, 2011) for select metrics are provided to highlight high levels of vulnerability for a given stock (Figure 1, red dots).

For BBRKC ecosystem metrics, latitude range, reproductive strategy, early life history survival, ocean acidification sensitivity, and habitat specificity indicate high vulnerability via the percentile method when compared to other Alaska groundfish and crab stocks. Additionally, maximum length, recruitment variability, population growth rate, depth range, bottom-up ecosystem value, fecundity, and maximum age were over the thresholds defined by national initiatives. Scores suggest that RKC are habitat specialists and reproductive success may be highly sensitive to specific environmental conditions due to aggregate mating behavior. Additionally, a relatively long larval duration, pelagic predation pressure, and specific habitat requirements following settlement indicate that early life history stages are a criticality in RKC life stages. Initial metric panel results indicate that stage-based information incorporating predation pressures, habitat dependence, ocean acidification and climatic conditions would be valuable for the stock and would assist with subsequent indicator development. For the three applicable socioeconomic metrics, values indicated fairly high commercial importance, indicating that RKC may be increasingly sensitive to targeted fishing.

BBRKC had numerous data gaps for ecosystem metrics including length- and age-based metrics, recruitment variability and natural mortality. Data quality was rated as medium to complete for all metrics with data available, although the prevalence of data gaps for important life history metrics highlight the need for additional research to better understand RKC life history processes.

Ecosystem Processes

Data evaluated over ontogenetic shifts (e.g., egg, larvae, juvenile, adult) may be helpful for identifying specific bottlenecks in productivity and relevant indicators for monitoring. As a first attempt to summarize important processes or potential bottlenecks across RKC life history stages, we include a detailed life history synthesis (Table 2a), an associated summary of relevant ecosystem processes (Table 2b), and a baseline life history conceptual model (Figure 2a). In the life history tables and conceptual model, abiotic and biotic processes were identified by each life stage from the literature, process studies and laboratory rearing experiments. Details on why these processes were highlighted, as well as the potential relationship between ecosystem processes and stock productivity are described below.

Red king crab molt, mate and extrude new egg clutches each spring, after which females brood fertilized eggs externally for up to a year (Stevens and Swiney, 2007). Embryo development is delayed in cold years (Chilton et al., 2010) and laboratory studies suggest that acidified conditions have significant effects on embryogenesis (Long et al., 2013). Following hatch, RKC larval development consists of four zoeal stages and one glaucothoe stage, after which larvae metamorphose and settle as stage C1 benthic juveniles. Zoea larvae feed primarily on diatoms; the chain-forming diatom *Thallasiosira nordenskioldii* is a particularly important larval food source due to its large size and high densities in natural populations (Paul et al., 1989). First-feeding larvae represent a critical bottleneck during development as previous research indicates that chances of survival are greatly reduced if larvae do not feed within 60 hours of hatching (Paul and Paul, 1980). Likewise, because the glaucothoe stage is a non-feeding stage, survival likely depends on nutrition acquired during zoeal stages. Laboratory rearing experiments reported optimal larval survival at 8°C (Nakanishi, 1987), although RKC zoeal stages appear to exhibit an ontogenetic change in thermal tolerance, and ZII larval survival is greatly reduced above 6°C (Shirley and Shirley, 1989). Although first-feeding success of RKC larvae is likely higher for earlier hatch dates coinciding with high densities of *Thallasiosira*, cooler water temperatures slow larval development rates and increase mortality due to both increased offshore transport and larval stage duration (Loher and Armstrong, 2000). Shirley and Shirley (1990) found that the length of the RKC larval period was inversely related to chlorophyll *a* concentrations, and that larval survival was inversely related to larval period length. Likewise, larval advection and dispersal relative to oceanographic conditions and the availability of suitable settlement habitat may be significant drivers of recruitment success in a given year (Daly et al., 2018).

During the early juvenile stages, successful settlement requires shallow, nearshore waters (<50m) and structurally complex habitats due to the reliance on crypsis to evade predation (Loher and Armstrong, 2000; Stevens, 2003). Survival in small juvenile RKC increases with the amount of physical structure in settlement habitats (Stoner, 2009; Pirtle et al., 2012), whereas larger juveniles are often associated with habitats composed of structural invertebrates that likely provide increased foraging opportunities (Pirtle and Stoner, 2010). These results suggest an ontogenetic shift in habitat requirements following the first year of benthic life as RKC juveniles rely less on high-relief habitat, and instead form large pods to evade predators. Juvenile RKC molt several times a year during early benthic instar stages and are especially vulnerable to groundfish predators such as Pacific cod while soft (Livingston, 1989). Overall, juvenile RKC appear to have a broad range of temperature tolerance, indicated by relatively high survival over the range of temperatures tested (2 to 12 °C) in a laboratory experiment (Stoner et al., 2010). This is likely advantageous during the juvenile stage when RKC utilize relatively shallow habitats more prone to temperature fluctuations.

Late juvenile and adult RKC are less reliant on complex substrate and, instead, temperatures appear to drive patterns in spatial distributions and migration timing. Northerly shifts in stock distribution are generally associated with both warmer temperatures and high Pacific Decadal Oscillation values during the summer (Loher and Armstrong, 2005; Zheng and Kruse, 2006), whereas fall distributions during the fishery tend to contract to the center of Bristol Bay during warm years (Zacher et al., 2018). Mature female RKC appear to avoid waters <2 °C (Chilton et al., 2010) and recent tagging efforts suggest that mature males tend to avoid warm waters >4 °C. Historic spawning grounds for RKC have been identified off the western end of the Alaska Peninsula in an area commonly referred to as "Cod Alley", although in recent years the area has been subject to intense fishing pressure (Dew, 2010). Essential fish habitat for red king crab remains poorly defined and very little is known about the potential effects of bottom trawling on RKC spatial distributions, spawning aggregations and habitat use.

Socioeconomic Processes

This section will be completed for the final submission

Indicators Assessment

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

Indicator Suite

Very few studies have effectively linked environmental variables or ecosystem conditions to recruitment of Bering Sea crab stocks, owing primarily to the highly variable nature of crab recruitment. Zheng and Kruse (2000) noted that strong year classes of RKC in the early 1970's corresponded with low temperatures. However, recruitment trends are not consistently explained by temperatures or decadal-scale environmental variability and weak relationships suggest that climatic conditions alone do not account for all the variability in year class strength. Groundfish predation has been hypothesized as a mechanism driving recruitment variability and previous studies indicate a strong negative relationship between Pacific cod biomass and red king crab recruitment (Zheng and Kruse, 2006; Betchol and Kruse, 2010). Large-scale indices of environmental variation including the Aleutian Low, Pacific Decadal Oscillation and Arctic Oscillation have also been linked to red king crab productivity (Loher and Armstrong, 2005; Zheng and Kruse, 2006; Szuwalski et al., *in review*) , although associated mechanisms remain unclear. In acknowledging the paucity of these mechanistic linkages, we generated a suite of ecosystem and socioeconomic indicators using stock vulnerabilities identified in the metric assessment (Figure 1) in addition to tested driver-response relationships from previously published studies (Table 2b). When selecting a suite of indicators for the BBRKC ESP, efforts were focused on developing spatially explicit indicators bounded by the BBRKC management area, which includes all waters north of the latitude of Cape Sarichef (54°36' N lat.), east of 168°00' W long., and south of the latitude of Cape Newenham (58°39' N lat.; ADF&G 2012). The following list of indicators is organized by process, and ecosystem indicators are grouped by RKC life history stage when applicable. Indicator title and a brief description are provided in Table 3a for ecosystem indicators and Table 3b for socioeconomic indicators with references, where possible, for more information.

Ecosystem Indicators:

1. Physical Indicators

- The EBS **cold pool index** (<2°C) is not only important in driving RKC distributions, but also in driving distributions of major predators of RKC. Pacific cod and several flatfish species typically avoid temperatures less than 1° C (Kotwicki and Lauth, 2013), suggesting that cold years when the cold pool extends into Bristol Bay may offer RKC a refuge from predation. The cold pool index was calculated as the fraction of the EBS BT survey area with bottom water less than 2°C on 1 July of each year from Bering10K ROMS model output hindcasts (Kearney et al., 2020).
- **Summer bottom temperatures** in Bristol Bay represent environmental conditions during the summer survey period and drive juvenile and adult RKC distributions (Loher and Armstrong, 2005), timing of the reproductive cycle (Chilton et al., 2010) and larval transport (Daly et al., 2018). Laboratory studies have also shown that temperature is a direct driver of growth, molt duration and feeding ration (Long et al., 2017: Stoner et al., 2013). Summer bottom temperatures were calculated as the average of June-July bottom temperatures within the BBRKC management boundary from ROMS model output (Kearney et al., 2020).
- The **Arctic Oscillation** is a large-scale mode of climate variability; increased red king crab recruitment has been associated with increases in the Arctic Oscillation (Szuwalski et al., *in review*). When the Arctic Oscillation is in its positive phase, strong winds circling the North Pole confine colder air across polar regions. The Arctic Oscillation indicator was determined as the average of Jan-March Arctic Oscillation deviations, developed by NOAA's Climate Prediction Center.
- A **Corrosivity Index** developed from Bering10K ROMS output was calculated as the percent of the BBRKC management area containing an average bottom aragonite saturation state of < 1 from Feb-April (D. Pilcher, *pers. commun.*, 2020; Pilcher et al., 2019). The corrosivity index represents potential acidified bottom water conditions in Bristol Bay, which would negatively affect RKC physiology. Reductions in RKC larval condition (Long et al., 2013), juvenile growth and survival (Long et al., 2013), and shell hardness (Coffey et al., 2017) have been documented in low pH conditions.
- **Spring bottom temperatures, wind stress** and **chlorophyll *a* biomass** indicators represent environmental conditions and food sources for RKC early life history stages. Temperature-mediated shifts in embryo development, hatch timing and larval duration could subsequently result in RKC larvae mismatches with prey resources, or increase the probability of advection away from favorable nursery grounds. First-feeding success of RKC larvae has also been linked to high diatom abundances, light winds and water column stability (Paul et al., 1989). Spring

bottom temperatures were calculated as the average of Feb-March bottom temperatures within the BBRKC management boundary from ROMS model output (Kearney et al., 2020). Wind stress was determined by averaging June ocean surface wind speeds from remote sensing data within the BBRKC management boundary (Zhang et al., 2006, NOAA/NESDIS, CoastWatch). Chlorophyll *a* biomass was calculated as the April-June average chlorophyll-a estimates from MODIS satellites within the Southern Inner Shelf of the Bering Sea (J. Nielsen, *pers. commun.*, 2020).

2. Biological Indicators

- Estimates of **juvenile sockeye salmon abundance** in the EBS and **Pacific cod biomass** in Bristol Bay represent major predators during the larval and juvenile to adult stages, respectively. Sockeye salmon abundance was estimated from NOAA Bering Arctic Subarctic Integrated Surveys in the EBS (E. Yasumiishi, *pers. commun*., 2020). Estimates of Pacific cod biomass were derived from the EBS bottom trawl survey catch data.
- Species included in the **benthic invertebrate biomass** indicator (i.e. brittle stars, sea stars, sea cucumber, bivalves, non-commercial crab species, shrimp and polychaetes) are important prey sources for BBRKC (Feder et al. 1980; Jewett and Feder, 1982).. Increases in invert biomass may suggest optimal foraging conditions for RKC, although increases in highly mobile benthic foragers such as hermit crabs and sea stars may, instead, may point towards increased competition for benthic resources. Biomass estimates were determined from the EBS bottom trawl survey catch data.
- A **BBRKC recruit biomass** index effectively tracks the number of males that will likely enter the fishery the following year. Small catches of these sub-legal RKC are often a reliable indicator of impending declines in mature male biomass. BBRKC recruit biomass (110-134 mm CL) was estimated from the EBS bottom trawl survey catch data (J. Richar, *pers. commun*., 2020).
- Spatial distribution indicators include summer **area occupied by mature male and female RKC**, as well as male **catch distance from shore** during the fishery. Areas occupied were determined as the minimum area containing 95% of the cumulative BBRKC CPUE from the EBS bottom trawl survey. Catch distance from shore was calculated using fishery observer data as the mean distance legal male RKC were caught from shore during the fishery (L. Zacher, *pers. commun*., 2020). In warm years, RKC tend to aggregate in the center of Bristol Bay (Zacher et al., 2018), which may have implications for the effectiveness of fixed closure areas and RKC bycatch during winter groundfish fisheries.

Socioeconomic Indicators:

1. Fishery Performance Indicators

- CPUE (mean no. of crabs per potlift): Fishing effort efficiency, as measured by estimated mean number of retained BBRKC per potlift.
- Total Potlifts: Fishing effort, as measured by estimated number of crab pots lifted by vessels during the BBRKC fishery.
- Vessels active in fishery: Annual count of crab vessels that delivered commercial landings of BBRKC to processors.
- BBRKC male bycatch biomass: Incidental bycatch biomass estimates of male BBRKC (tons) in trawl and fixed gear fisheries

2. Economic Indicators

- TAC Utilization (%): Percentage of the annual BBRKC TAC (GHL prior to 2005) that was harvested by active vessels, including deadloss discarded at landing.

- Ex-vessel value of BBRKC landings: Aggregate ex-vessel value of BBRKC landings (as adjusted by CFEC to account for post-season adjustments to ex-vessel settlements), summed over all ex-vessel sales reported.
- Ex-vessel price per pound: commercial value per unit (pound) of BBRKC landings (as adjusted by CFEC to account for post-season adjustments to ex-vessel settlements), measured as weighted average value over all ex-vessel sales reported. Ex-vessel prices, combined with vessel operating costs and other factors, determine the economic return to vessels per unit of catch and, considering the availability and expected returns from alternative fishing targets, are a direct driver of the level and intensity of fishing effort.
- BBRKC ex-vessel revenue share (% of total exvessel revenue): BBRKC ex-vessel revenue share as percentage of total calendar year ex-vessel revenue from all commercial landings in Alaska fisheries, mean value over all vessels active in BBRKC during the respective year. Revenue share provides an indicator of the relative income dependence of participating vessels on the BBRKC fishery, where changes in the fishery that reduce the returns from fishing (e.g., reductions in TAC and/or ex-vessel price) are offset by income produced from alternative fishing targets.

3. Community Indicators

- Processors active in fishery: Total number of crab processors that purchased landings of BBRKC from delivering vessels during the calendar year. This provides an indicator of the level of participation of buyers in the market for BBRKC landings.
- Processing Employment in BBRKC: Crab processing employment generated in BBRKC fishery as measured by total paid hours of labor input by processing employees, summed over all shore-based plants that processed BBRKC landings.
- Local Quotient of BBRKC landed catch in Dutch Harbor: Ex-vessel value share of BBRKC landings to Unalaska/Dutch Harbor, as percentage of total value of commercial landings to processors in the community from all commercial Alaska fisheries, as aggregate percentage over all landings during the respective year. Dutch Harbor is the principal port of landing for the BBRKC fishery, historically, representing between 43% and 58% of annual landings since 2005.

Indicator Analysis

We provide the list and time-series of indicators (Table 3, Figures 4-5) and then monitor the indicators using three stages of statistical tests that gradually increase in complexity depending on the stability of the indicator for monitoring the ecosystem or socioeconomic process and the data availability for the stock (Shotwell et al., *In Review*). At this time, we report the results of the first and second stage statistical tests of the indicator analysis for BBRKC. The third stage will require more indicator development and review of the ESP modeling applications.

Stage 1, Traffic Light Test:

The first stage of the indicator analysis is a simple assessment of the most recent year relative value and a traffic-light evaluation of the most current year where available (Table 3). Both measures are based on one standard deviation from the long-term mean of the time series. A symbol is provided if the most recent year of the time series is greater than (+), less than (-), or within (•) one standard deviation of the long-term mean for the time series. If the most recent year is also the current year then a color fill is provided for the traffic-light ranking based on whether the relative value creates conditions that are good (blue), average (white), or poor (red) for BBRKC (Caddy et al., 2015). The blue or red coloring does not always correspond to a greater than (+) or less than (-) relative value. In many cases the most current year was not available and this demonstrates significant data gaps for evaluating ecosystem and socioeconomic data for BBRKC.

Overall, BBRKC recruitment still remains well below average. EBS bottom trawl survey biomass estimates were not available for 2020, however the 2018 recruitment estimate was the lowest in the 40-year time series, following the lowest previously observed in 2017. Trends in physical ecosystem indicators suggest poor to fair environmental conditions during the past 5 years for the BBRKC stock. The cold pool extent in Bristol Bay was at an all-time low from 2018-2019 while average summer bottom temperatures have exceeded 4°C in three of the past five years. Environmental conditions in 2020 appear to have returned to near-average compared to the long-term mean, with a positive phase Arctic Oscillation coinciding with an increase in the cold pool extent and a nearly 2°C decline in summer bottom temperatures from 2019 to 2020. On the contrary, a nearly 3-fold increase in bottom water corrosivity in Bristol Bay from 2019 to 2020 suggests that over 50% of Bristol Bay bottom waters were below the aragonite saturation threshold ($\Omega arag < 1$) from February to April.

Spring bottom temperatures in 2020 averaged 0.37°C, which suggests that embryo development and hatching may have been delayed due to colder than average bottom temperatures. 2020 spring bottom temperatures were below 2006 and 2007 bottom temperatures when Chilton et al. (2010) noted that stations sampled in May had high numbers of mature female RKC still brooding embryos fertilized the previous season. These results suggest that in 2020, peak hatch timing may have been delayed until June, which could have implications for temporal synchrony between larval RKC and the spring bloom. Furthermore, chlorophyll *a* biomass estimates have remained below-average for the past five years and wind stress in Bristol Bay has been above-average during this time period. Together these conditions may be indicative of declines in diatom abundances and low larval encounter rates due to increased surface mixing. Record high juvenile sockeye salmon abundances since 2014 may be further indicative of increased predation and subsequent poor survival of RKC larval stages in the past 5 years.

Due to the 2020 cancellation of the EBS bottom trawl survey, current-year data are not available for Pacific cod and benthic invert biomass indicators. However, both indicators are on a downward trend and Pacific cod biomass has been below average since 2016 in Bristol Bay. Current year data was also unobtainable for spatial distribution indicators, though recent trends are consistent with documented shifts in spatial distributions during previous warm periods in Bristol Bay (Loher and Armstrong, 2005; Zacher et al., 2018). During warm years in 2018-2019, male RKC were located further from shore during the fishery, and both males and females occupied a larger area during the summer trawl survey in recent years.

Indicators reported for applicable socioeconomic metrics are derived from fishery-dependent sources that are typically available for the prior year or lagged by up to three years (as of the September-November assessment cycle for most Alaska-region FMP crab and groundfish stocks), and as such are limited to providing retrospective information. The metrics reported in Table 3b, therefore, are based on the most current available value of the respective data series, representing conditions in the BBRKC fishery during 2018 or 2019.

Fishery performance metrics related to aggregate fishing effort, including number of active vessels and total number of potlifts, were low relative to the long term averages, but were within the range of recent variation and exhibiting declining trends commensurate with lower TACs following the 2016/17 season. CPUE has declined since 2016, but was slightly below average during 2019.

Metrics for economic and community indicators were more generally negative for 2018-2019. Ex-vessel price remained relatively high over the most recent years, which may have partially mitigated some effects of decreased production, however, aggregate ex-vessel value reached a historical low during 2019, falling below 1 standard deviation of the long-term mean. BBR ex-vessel revenue share declined more modestly during 2019, possibly reflecting distribution of aggregate landings over fewer vessels, as well as a relatively brief BBRKC season allowing more time devoted to other fisheries. Processing employment generated by BBRKC, as measured in aggregate paid processing labor hours, also fell to a historical low. The local quotient of BBRKC catch value in Dutch Harbor fell to 7%, indicating that the decline in

BBRKC landing value was somewhat isolated to the fishery, with local landings from other fisheries maintaining value in 2019.

Stage 2, Importance Test:

Bayesian adaptive sampling (BAS) was used for the second stage statistical test to quantify the association between hypothesized predictors and BBRKC mature male biomass (MMB), and to assess the strength of support for each hypothesis. BAS explores model space, or the full range of candidate combinations of predictor variables, to calculate marginal inclusion probabilities for each predictor, model weights for each combination of predictors, and generate Bayesian model averaged predictions for outcomes (Clyde et al., 2011). In this second test, the full set of indicators is first winnowed to the predictors that could directly relate to MMB, and have consistent temporal scales. We then provide the mean relationship between each predictor variable and log MMB over time (Figure 6a), with error bars describing the uncertainty (1 standard deviation) in each estimated effect and the marginal inclusion probabilities for each predictor variable (Figure 6b). A higher probability indicates that the variable is a better candidate predictor of BBRKC MMB. The highest ranked predictor variables (> 0.50 inclusion probability) were: BBRKC recruit biomass, Pacific cod biomass, and the Arctic Oscillation. Unfortunately, due to the nature of the BAS model only being able to fit years with complete observations for each covariate, the final subset of covariates was quite small and creates a significant data gap. Despite this shortcoming, predictive performance of the BAS model appears to generally capture BBRKC MMB trends across the time series (Figure 6d).

Recommendations

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

Ecosystem Considerations

- Available physical indicators for 2020 show a return to near-average conditions in Bristol Bay. A relatively high positive Arctic Oscillation index in winter 2020 may suggest favorable conditions for BBRKC productivity.
- Persistently low levels of chlorophyll *a* and above-average wind stress in Bristol Bay in combination with substantial increases in juvenile sockeye salmon abundance in the past 5 years could be indicative of poor larval conditions.
- The degree of match or mismatch of first-feeding larval red king crab with preferred diatom prey may be critical for larval survival, and recent fluctuations in spring temperatures during embryo development could impact the synchrony between hatch timing and the spring bloom.
- 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.
- Current-year increases in corrosive bottom waters in Bristol Bay have the potential to impact shell formation, growth and survival of BBRKC.

Economic Considerations

- The numbers of vessels and processors active in the 2018/19 and 2019/20 BBRKC seasons dropped below the lower bounds of their long-term historical range during 2018 and 2019. Both metrics have been in a generally declining trend since the BBRKC fishery was substantially restructured and consolidated following rationalization.

- Ex-vessel price has remained above the long-term average since 2010, partially mitigating some income effects of declining BBRKC production, but the reduced level of participation and employment suggest that reduced economic performance of the BBRKC fishery may have negative distributional effects.
- While aggregate BBRKC ex-vessel value was at a historical low in 2019, BBRKC ex-vessel revenue share on average for active vessels was only moderately below average during 2019. The local quotient for BBRKC catch value of landings to Dutch Harbor also declined to a historical low in 2019.

Data Gaps and Future Research Priorities

Current year data gaps for ecosystem indicators due to the cancellation of the 2020 EBS bottom trawl survey emphasize the necessity of annual surveys for tracking impending ecosystem shifts and potential impacts to BBRKC. 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.

Given the dramatic increase in Bristol Bay sockeye salmon in recent years, we emphasize the importance of understanding predator-prey interactions and spatial overlap. Furthermore, additional groundfish stomach data outside of the summer survey time series would inform predation mortality during the molt when RKC are highly vulnerable. The prevalence of corrosive bottom waters in Bristol Bay also highlights the need for continued research to identify the potential impacts of ocean acidification on RKC physiology. Ongoing efforts to understand the relationship between aragonite saturation states and BBRCK distributions (E. Kennedy, *pers. commun*., 2020) will be particularly important if Bristol Bay continues to experience corrosive water conditions. 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 Bering Sea commercial crab stocks.

Socioeconomic indicators of community participation in the BBRKC fishery included in this report are limited to general metrics related to the processing sector (number of active processors, aggregate processing labor hours), and local quotient of landed value in Dutch Harbor. Extensive data resources are available to support development of a wide variety of useful community-related indicators, however, more comprehensive depiction of indicators at the level of individual communities within the ESP is currently constrained by the limited scope and intent of the document. AFSC is currently developing a dedicated annual report to accompany the Crab and Groundfish Economic SAFE reports, focused on providing comprehensive analysis and monitoring of community participation and engagement in groundfish and crab fisheries. The Annual Community Engagement and Participation Overview (ACEPO) will provide detailed, community-level metrics of fishery participation, including income and employment, and ownership of vessel, plant, permit and quota share assets. Development of methods and indices for effectively capturing these and other dimensions of management effects on communities is currently concentrated on producing the ACEPO report. It is expected that this will provide the basis for identifying reduced-form indicators of community effects that will be suitable for incorporation in future ESPs.

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[*]Superscript numbers refer to references in Tables 2a and 2b

Table 1. List of data sources used in the Bristol Bay red king crab (BBRKC) ESP evaluation. Please see the BBRKC SAFE document (Zheng et al., 2019), the NOAA EBS Trawl Survey: Results for Commercial Crab Species Technical Memo (Zacher et al., 2020) and the SAFE Economic Status Report (Garber-Yonts and Lee, 2019) for more details.

	Title	Description	Years	Extent
Ecosystem	RACE EBS Bottom Trawl Survey	Bottom trawl survey of groundfish and crab on standardized 376-station grid using an 83-112 Eastern otter trawl	1975-2019	EBS annual
	REEM Food Habits Database	Diet data for key groundfish species collected by the Resource Ecology and Ecosystem Modeling (REEM) Program on the EBS bottom trawl survey	1987-2019	EBS annual
	ADF&G Crab Observer program data	BBRKC catch and effort data reported by ADF&G statistical areas during the fall fishery	2000-2019	EBS annual
	Essential Fish Habitat Models	Habitat suitability MaxEnt models for describing essential fish habitat of groundfish and crab in Alaska, EFH 2017 Update	1970-2017	Alaska
	BASIS survey	Surface/midwater column community survey of forage fish and salmon stocks	2002-2018	EBS, biennial
	ROMS Model Output	High-resolution regional oceanographic model hindcasts from the Bering Sea Regional Ocean Modeling System (ROMS)	1970-2020	EBS variable
	NOAA Climate Model Output	Monthly large-scale climate indices constructed by the National Weather Service's Climate Prediction Center	1854-2020	North Pacific annual
	Satellite Data	Monthly wind stress and 8-day composite ocean color products from MODIS Aqua and MetOp ASCAP sensors (NOAA NCEI/NOAA NESDIS)	1988-2020	Global annual
Socioeconomic	ADF&G fish ticket database	Volume, value, and port of landing for Alaska crab and groundfish commercial landings; data processed and provided by Alaska Fisheries Information Network	1992-2019	Alaska
	ADF&G Crab Observer program data	BBRKC catch and effort data (number of active vessels, total pots lifted, and CPUE), sourced from ADF&G Annual Fishery Management Report	1980-2019	Alaska
	BSAI Crab Economic Data Report database	Crab processing employment; data processed and provided by Alaska Fisheries Information Network	1998-2018	Alaska

Table 2a: Ecological information by life history stage for Bristol Bay red king crab

Stage	Habitat & Distribution	Phenology	Age, Length, Growth	Energetics	Diet	Predators
Egg	Clutch of embryos brooded under the female's abdomen until hatching[7]	328-365 day embryo incubation, peak hatch in Feb[5]	Egg length 1.16mm[3]	Optimal: 3°C – 8°C[3]	Yolk	Nemertean worms and amphipods feed on egg clutches[6]
Larvae	Pelagic; nearshore along the Alaska Peninsula (40-70m depth)[9]	March-June, Hatch to C1 benthic stage: 130 d at 8°C[3]	1.1 – 2mm CL[2]	Optimal: 5°C – 10°C[2,3]	Phytoplankton-diatoms[4] (glaucothoe: non-feeding)	Planktivorous fish, salmon smolt[11]
Juvenile	Benthic; nearshore complex habitat- boulders, cobble, shell hash, structural invertebrates (<50m depth)[8, 14]	Peak settlement in July[8], 1 to 5-6 years duration for benthic instar stages	Mean size at settlement: 1.91 - 2.18mm CL[16,17]	No effect on survival of C1-C4 juveniles from 1.5°C to 12°C[18]	Sponges, diatoms, foraminifera, crustaceans, polychaetes, bryozoans[15]	Pacific cod[13], flatfish, crab[22]
Adult	Benthic: sand and mud bottoms (50-200m depth)[20, 21]	5-6+ years, Annual molt and mate Jan-June	For management, females >89 mm CL and males >119 mm CL are assumed to be mature[12]	Optimal: 2°C – 4°C[20]	Mollusks, echinoderms, polychaetes, crustaceans, hydroids, sea stars[19]	Pacific cod, halibut, skates[13,23] (primarily during the molt)

Table 2b. Key processes affecting survival by life history stage for Bristol Bay red king crab (BBRKC)

Stage	Processes Affecting Survival	Relationship to BBRKC
Egg	1. Temperature 2. CO_2 concentrations	Cold temperatures extend embryo development[(25)] while embryo mortality increases at temperatures above 8°C[(3)]. Exposure to increased $C0_2$ levels delays hatch time and reduces embryo condition[(24)]
Larvae	1. Spatial and temporal synchrony with spring bloom 2. Diatom abundance in spring/summer 3. Larval transport/retention onshore	RKC peak hatch coinciding with high abundances of *Thallasiosira* ssp. may increase larval survival[(4)]. Settlement success and benthic survival is likely related to oceanographic conditions that facilitate transport to suitable nearshore nurseries[(27)].
Juvenile	1. Availability of highly structured habitat 2. Predation	Complex nursery habitats promote the survival of benthic juvenile stages by providing refuge from predators[(14)]
Adult	1. Bottom temperature 2. Predation	Bottom temperatures are likely responsible for shifts in spatial distribution and migration timing[(28)]. After molting, adult RKC are highly vulnerable to groundfish predation.

Table 3a. First stage ecosystem indicator analysis for Bristol Bay red king crab (BBRKC), including indicator title and short description. The most recent year relative value (greater than (+), less than (-) or within 1 standard deviation (•) of long-term mean) of the time series is provided. Fill color is based on a traffic light evaluation for BBRKC of the current year conditions relative to 1 standard deviation of the longterm mean (white = average, blue = good, red = poor, no fill = no current year data).

Title	Description	Recent
Cold Pool Index	Fraction of the EBS BT survey area with bottom water less than 2°C on 1 July of each year from Bering10K ROMS model output hindcasts	•
Summer Bottom Temperature	Average of June-July bottom temperatures (° C) within the BBRKC management boundary from the Bering 10K ROMS model output hindcasts	•
Arctic Oscillation	Average of Jan-March Arctic Oscillation Index estimates; constructed by projecting daily 1000mb height anomalies poleward of 20°N onto the loading pattern of the Arctic Oscillation	+
Corrosivity Index	Percent of the BBRKC management area containing an average bottom aragonite saturation state of < 1 from Feb-April	+
Spring Bottom Temperature	Average of Feb-March bottom temperatures (° C) within the BBRKC management boundary from the Bering 10K ROMS model output hindcasts	•
Wind Stress	June ocean surface wind stress within the BBRKC management boundary. Product of NOAA blended winds and MetOp ASCAP sensors from multiple satellites	•
Chlorophyll-a Biomass	April-June average chlorophyll-a biomass within the Southern Inner Shelf of the Bering Sea; calculated with 8-day composite data from MODIS satellites	•
Juvenile sockeye salmon abundance	Estimated September juvenile sockeye salmon biomass from the Bering Arctic Subarctic Integrated Surveys in the EBS	+
Pacific cod biomass	Biomass (1,000t) of Pacific cod within the BBRKC management boundary on the EBS bottom trawl survey	-

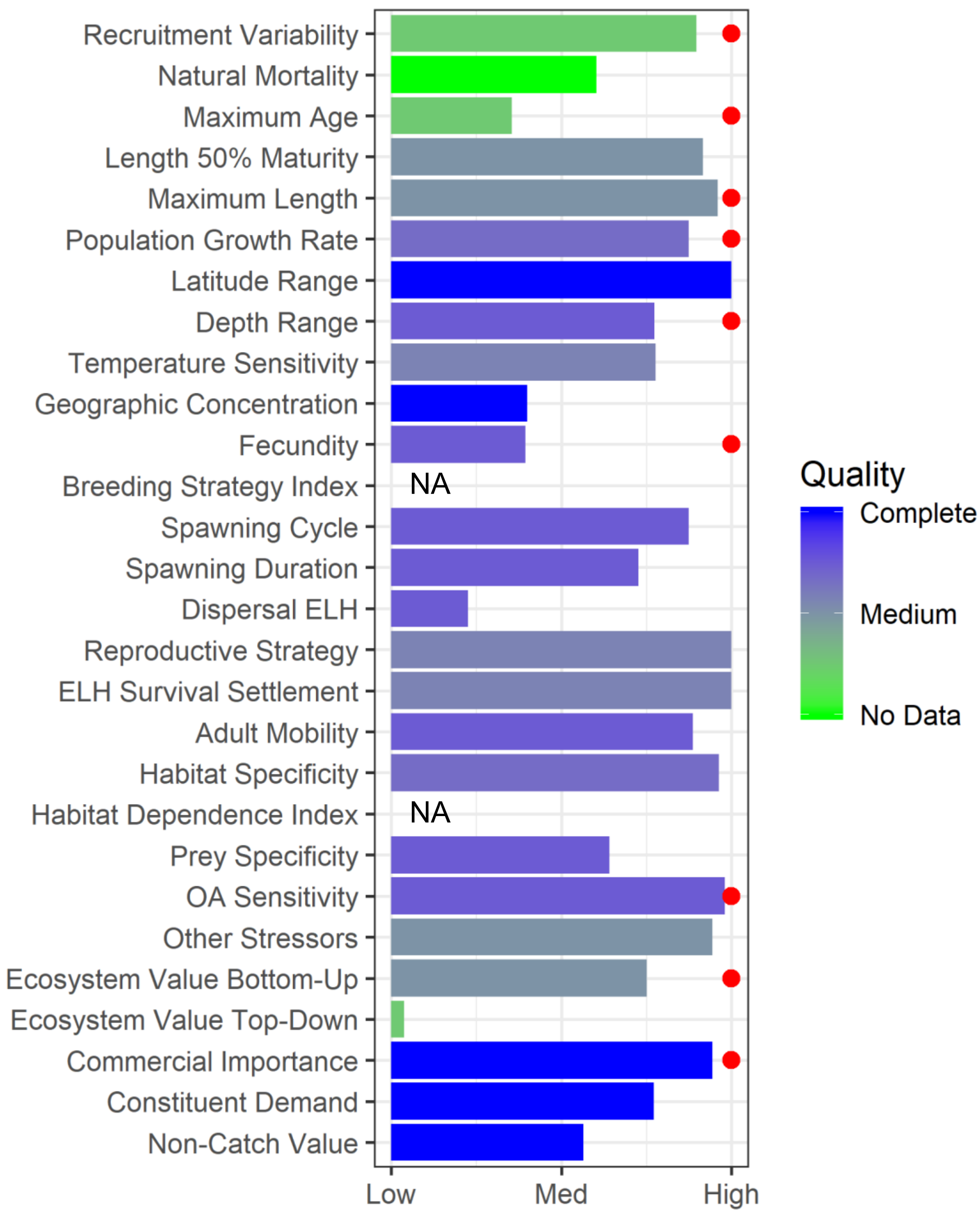
Table 3a (cont.). First stage ecosystem indicator analysis for Bristol Bay red king crab (BBRKC), including indicator title and short description. The most recent year relative value (greater than (+), less than (-) or within 1 standard deviation (•) of long-term mean) of the time series is provided. Fill color is based on a traffic light evaluation for BBRKC of the current year conditions relative to 1 standard deviation of the longterm mean (white = average, blue = good, red = poor, no fill = no current year data).

Title	Description	Recent
Benthic invertebrate biomass	Combined biomass (1,000t) of benthic invertebrates within the BBRKC management boundary on the EBS bottom trawl survey	●
BBRKC recruit biomass	Biomass of male red king crab (110-134 mm CL) from the EBS bottom trawl survey that will likely enter the fishery the following year.	-
BBRKC Catch Distance from Shore	Mean distance (km) legal male Bristol Bay red king crab were caught from shore in the autumn fishery (starting Oct. 15th) using observer data.	+
BBRKC mature male area occupied	The minimum area containing 95% of the cumulative CPUE for BBRKC mature males from the EBS bottom trawl survey	+
BBRKC mature female area occupied	The minimum area containing 95% of the cumulative CPUE for BBRKC mature females from the EBS bottom trawl survey	+

Table 3b. First stage socioeconomic indicator analysis for Bristol Bay red king crab (BBRKC), including indicator title and short description. The most recent year relative value (greater than (+), less than (-) or within 1 standard deviation (•) of long-term mean) of the time series is provided. Fill color is based on a traffic light evaluation for BBRKC of the current year conditions relative to 1 standard deviation of the longterm mean (white = average, blue = good, red = poor, no fill = no current year data).

Title	Description	Recent
CPUE	Fishing effort efficiency, as measured by estimated mean number of retained BBRKC per potlift	•
Vessels active in fishery	Annual count of crab vessels that delivered commercial landings of BBRKC to processors[2]	-
Total Potlifts	Fishing effort, as measured by estimated number of crab pots lifted by vessels during the BBRKC fishery	•
BBRKC Male Bycatch in Groundfish Fishery	Incidental bycatch biomass estimates of male BBRKC (tons) in trawl and fixed gear fisheries	•
TAC Utilization	Percentage of the annual BBRKC TAC (GHL prior to 2005) that was harvested by active vessels, including deadloss discarded at landing.	•
Ex-vessel value of BBRKC landings	Aggregate ex-vessel value of BBRKC landings (as adjusted by CFEC to account for post-season adjustments to ex-vessel settlements), summed over all ex-vessel sales reported.	-
Ex-vessel price per pound	Commercial value per unit (pound) of BBRKC landings (as adjusted by CFEC to account for post-season adjustments to ex-vessel settlements), measured as weighted average value over all ex-vessel sales reported.	•
BBRKC ex-vessel revenue share	BBRKC ex-vessel revenue share as percentage of total calendar year ex-vessel revenue from all commercial landings in Alaska fisheries, mean value over all vessels active in BBRKC during the respective year.	-
Processors active in fishery	Total number of crab processors that purchased landings of BBRKC from delivering vessels during the calendar year.	-
Processing Employment in BBRKC	Crab processing employment generated in BBRKC fishery as measured by total paid hours of labor input by processing employees, summed over all shore-based plants that processed BBRKC landings.	-
Local Quotient of BBRKC landed catch in Dutch Harbor	Ex-vessel value share of BBRKC landings to Unalaska/Dutch Harbor, as percentage of total value of commercial landings to processors in the community from all commercial Alaska fisheries, as aggregate percentage over all landings during the respective year.	-

Figure 1. Baseline metrics for Bristol Bay red king crab graded as a percentile rank over all groundfish and crab stocks in the FMP. Higher rank values indicate a vulnerability and color of the horizontal bar describes data quality of the metric (see Shotwell et al., *In Review*, for more details on the metric definitions). The red dot is a threshold value based on information collected from national initiatives.



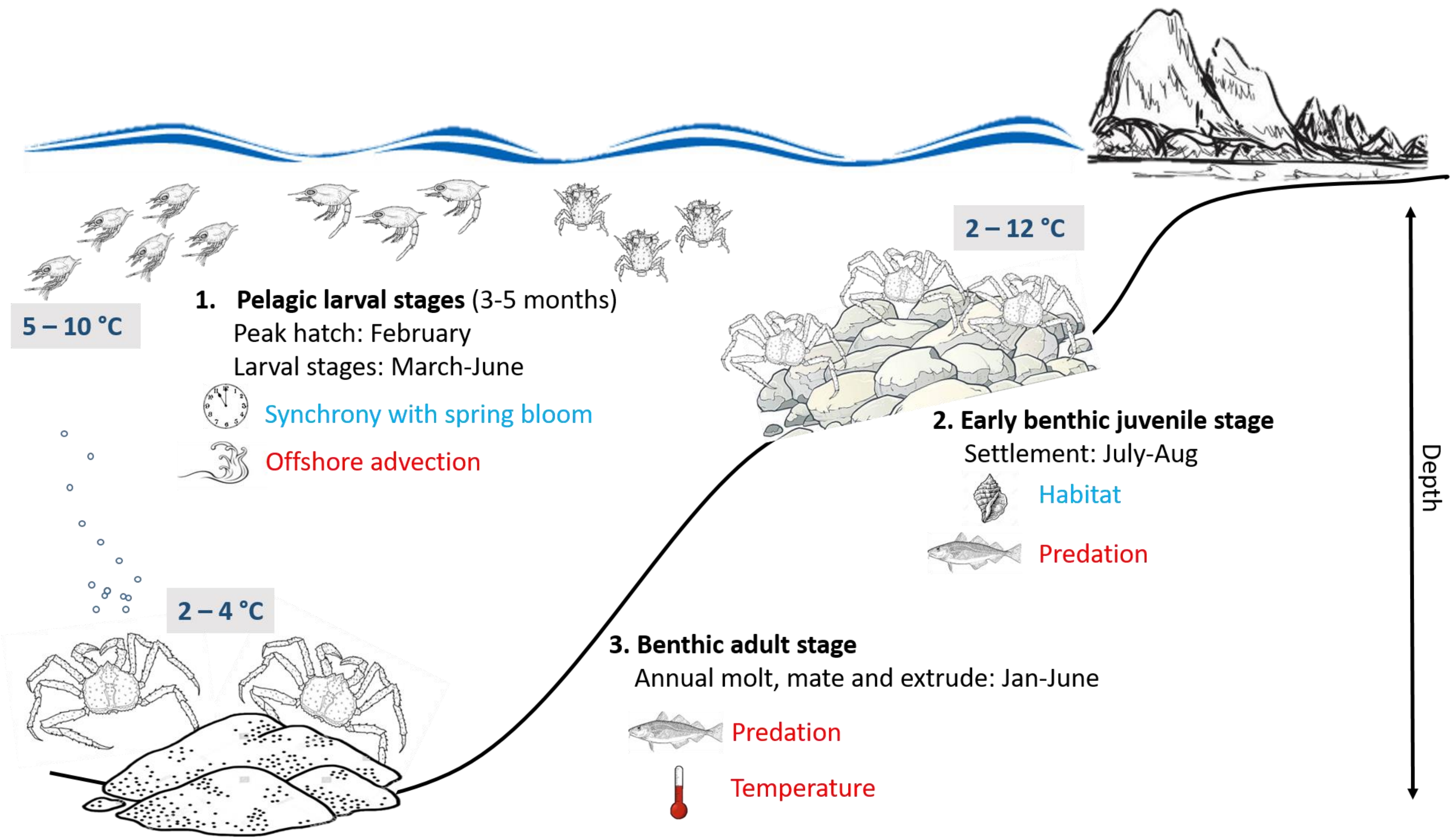


Figure 2a. Conceptual diagram of phenological information by life history stage for Bristol Bay red king crab and processes likely affecting survival in each stage. Thermal requirements by life history stage were determined from RKC laboratory studies.

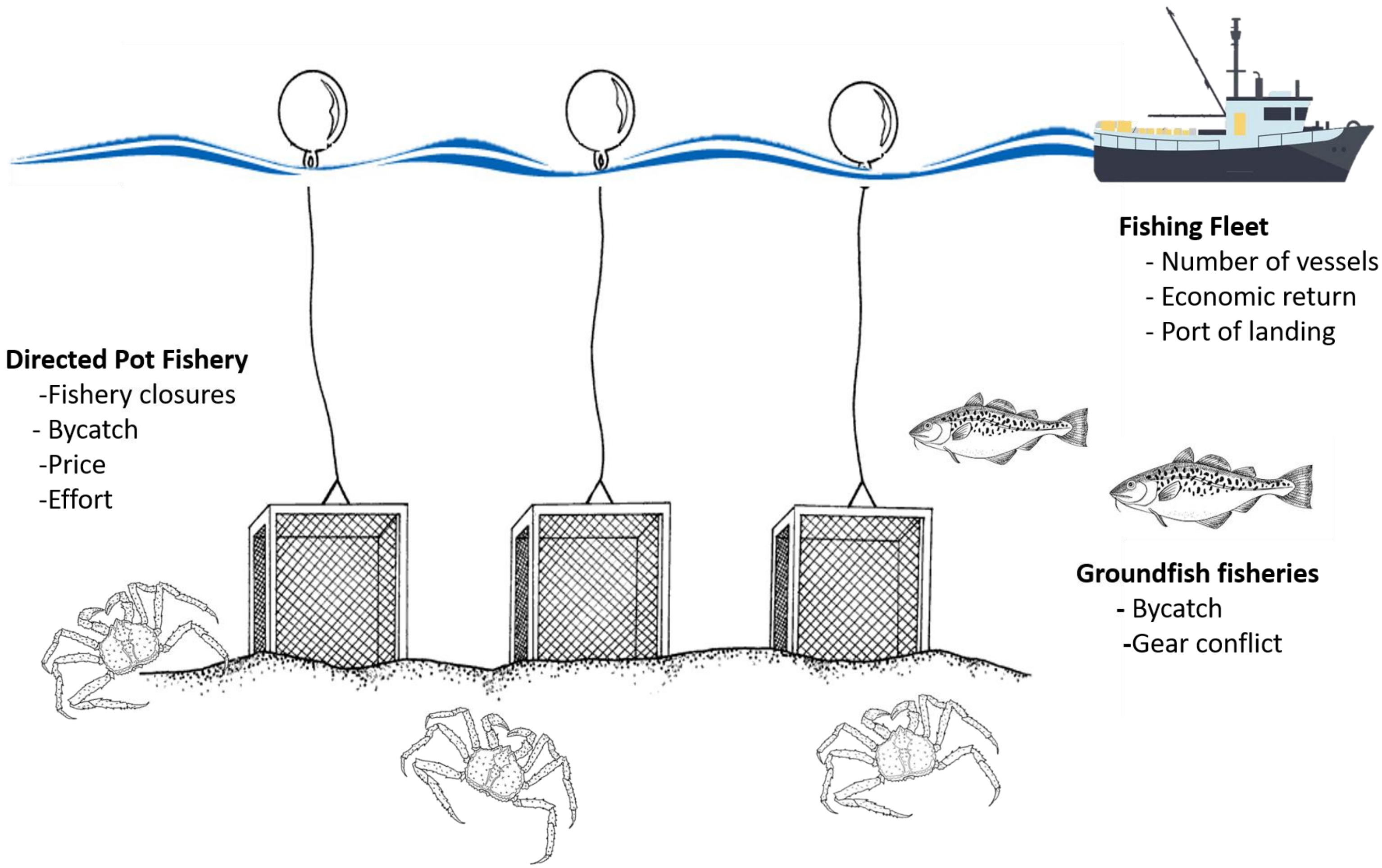


Figure 2b. Conceptual diagram of socioeconomic performance metrics that may identify dominant pressures on the Bristol Bay red king crab stock.

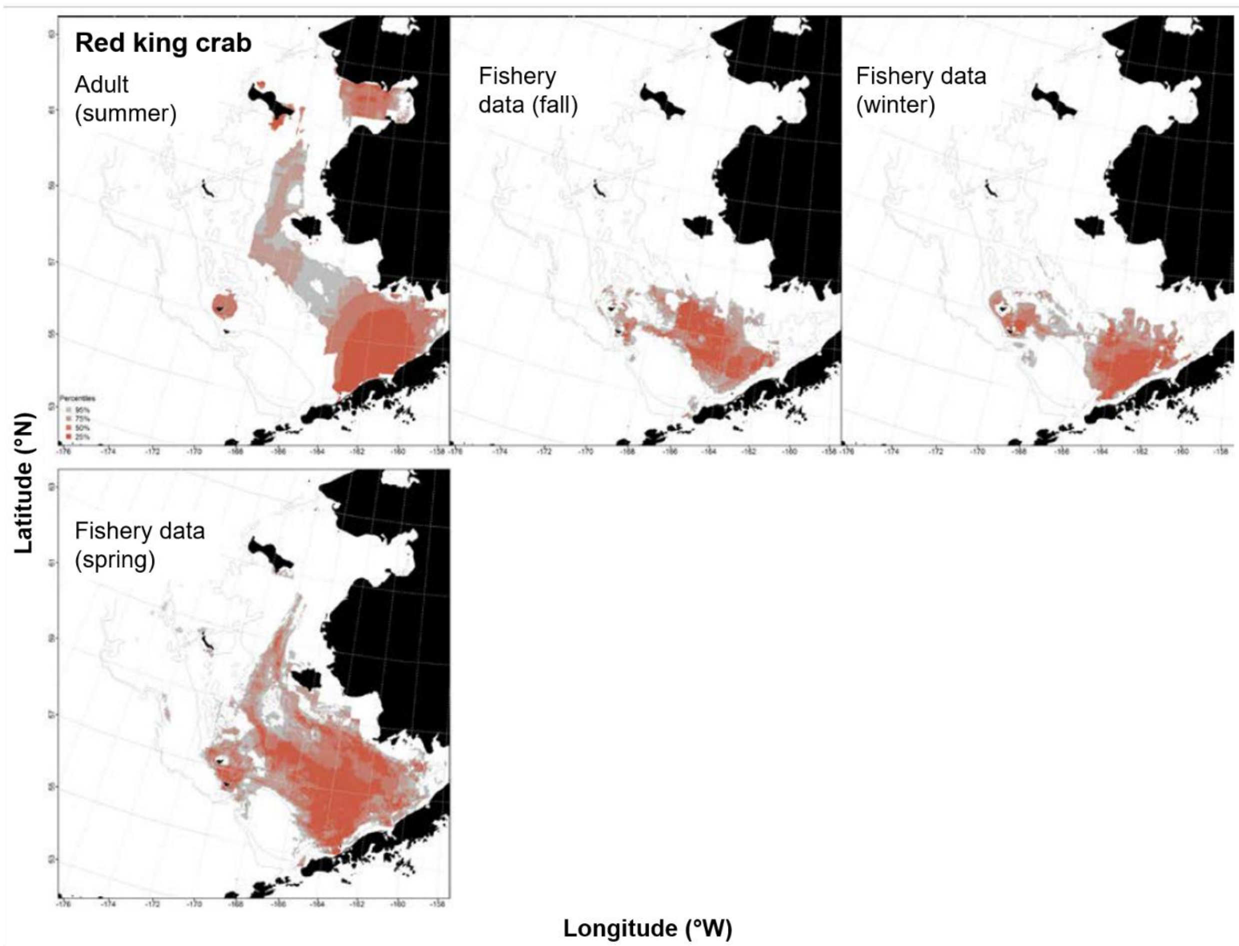


Figure 3. Essential fish habitat (EFH) predicted for red king crab (upper left panel) from RACE-GAP summertime bottom trawl surveys (1982-2014) and predicted from presence in commercial fishery catches (2003-2013) from fall, winter, and spring (remaining three panels) in the eastern Bering Sea. Figure modified from Laman et al., (2017).

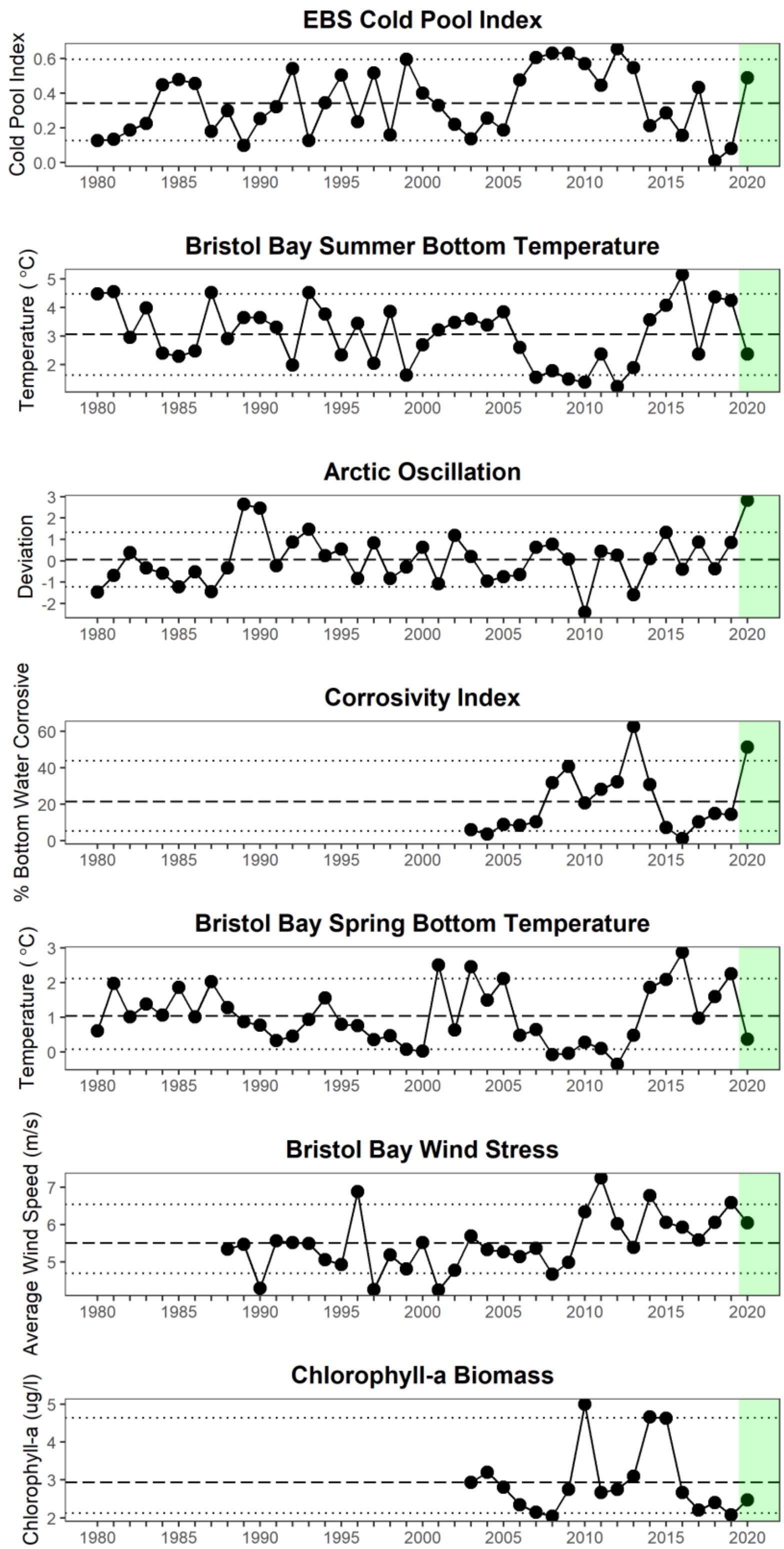


Figure 4. Selected ecosystem indicators for Bristol Bay red king crab with time series ranging from 1980 – 2020. Upper and lower dotted horizontal lines are 90th and 10th percentiles of time series. Dashed horizontal line is the mean of time series. Light green shaded area represents most recent year data for traffic light analysis.

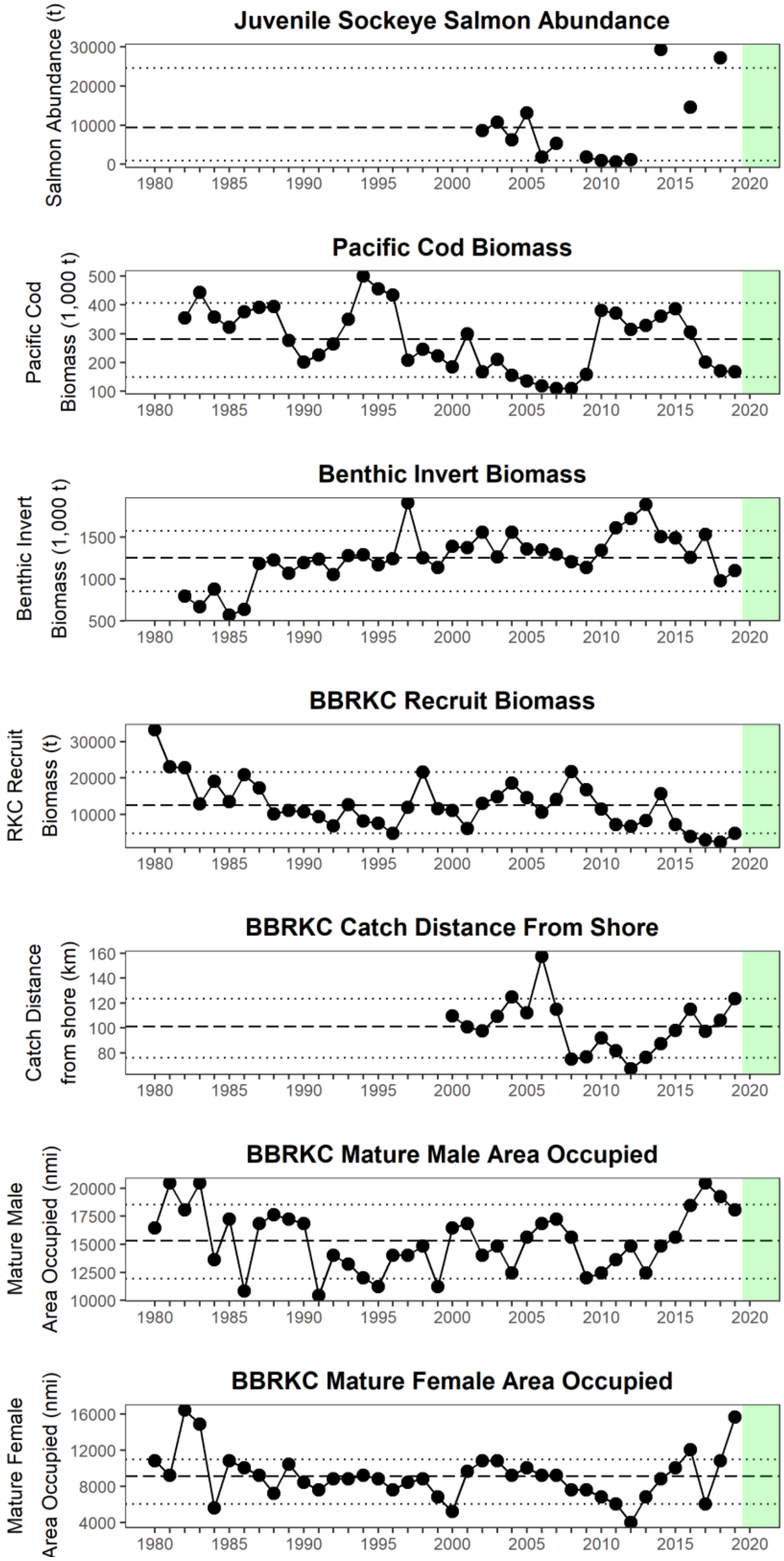


Figure 4 (cont.). Selected ecosystem indicators for Bristol Bay red king crab with time series ranging from 1980 – 2020. Upper and lower dotted horizontal lines are 90th and 10th percentiles of time series. Dashed horizontal line is the mean of time series. Light green shaded area represents most recent year data for traffic light analysis.

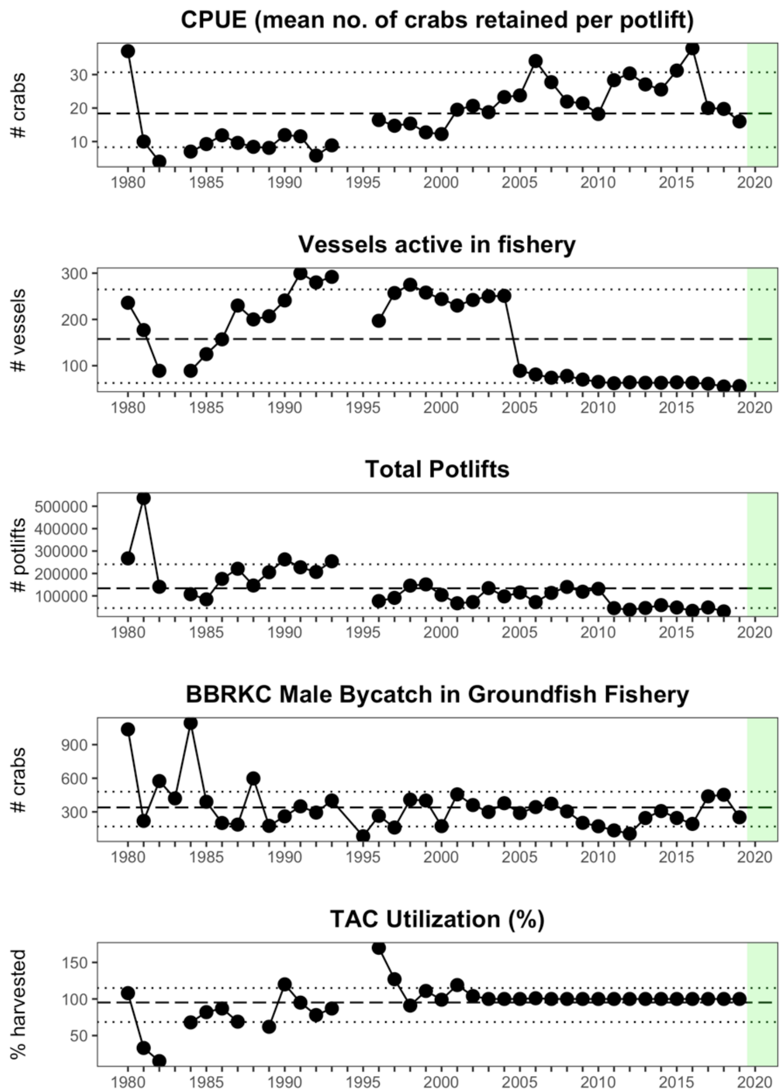


Figure 5. Selected socioeconomic indicators for Bristol Bay red king crab with time series ranging from 1980 – 2019. Upper and lower dotted horizontal lines are 90th and 10th percentiles of time series. Dashed horizontal line is the mean of time series. Light green shaded area represents most recent year data for traffic light analysis.

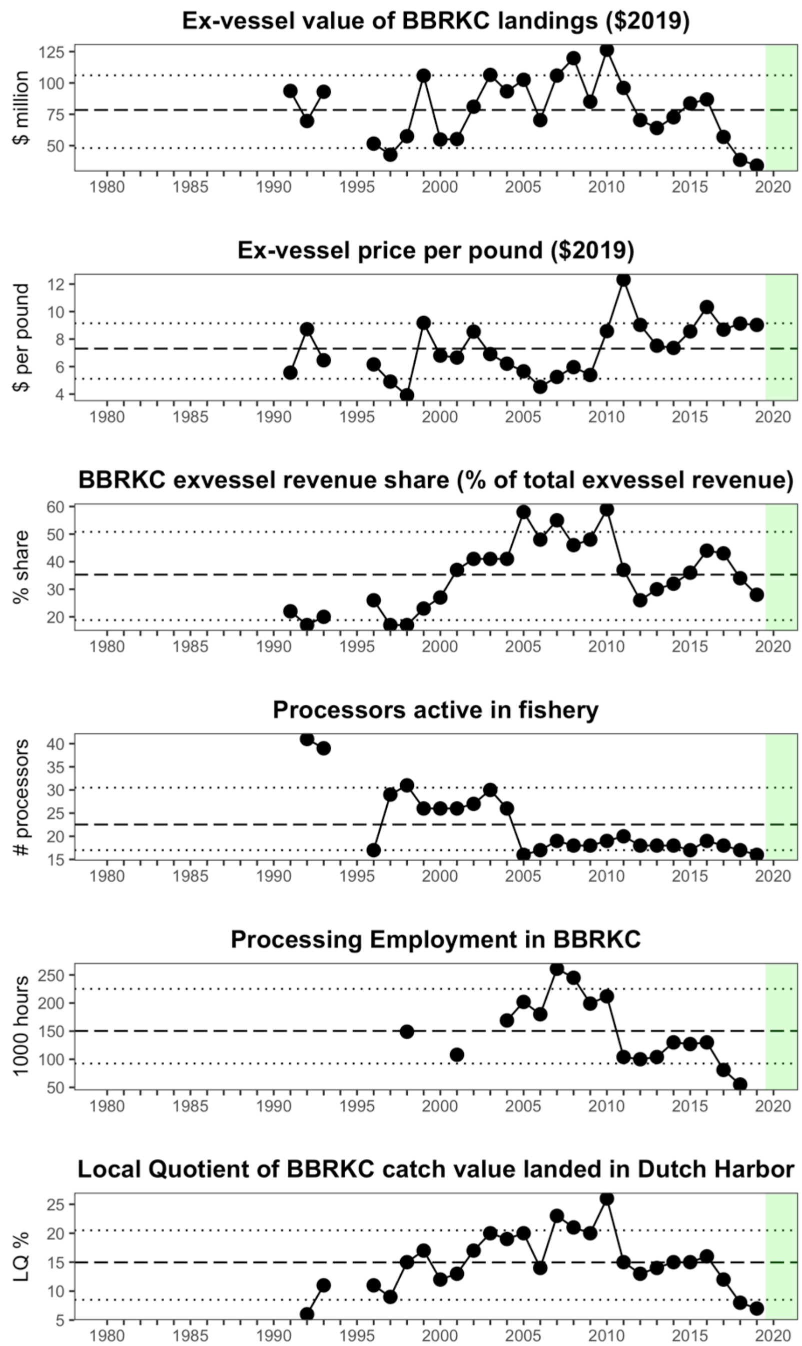


Figure 5. (cont.) Selected socioeconomic indicators for Bristol Bay red king crab with time series ranging from 1980 – 2019. Upper and lower dotted horizontal lines are 90th and 10th percentiles of time series. Dashed horizontal line is the mean of time series. Light green shaded area represents most recent year data for traffic light analysis.

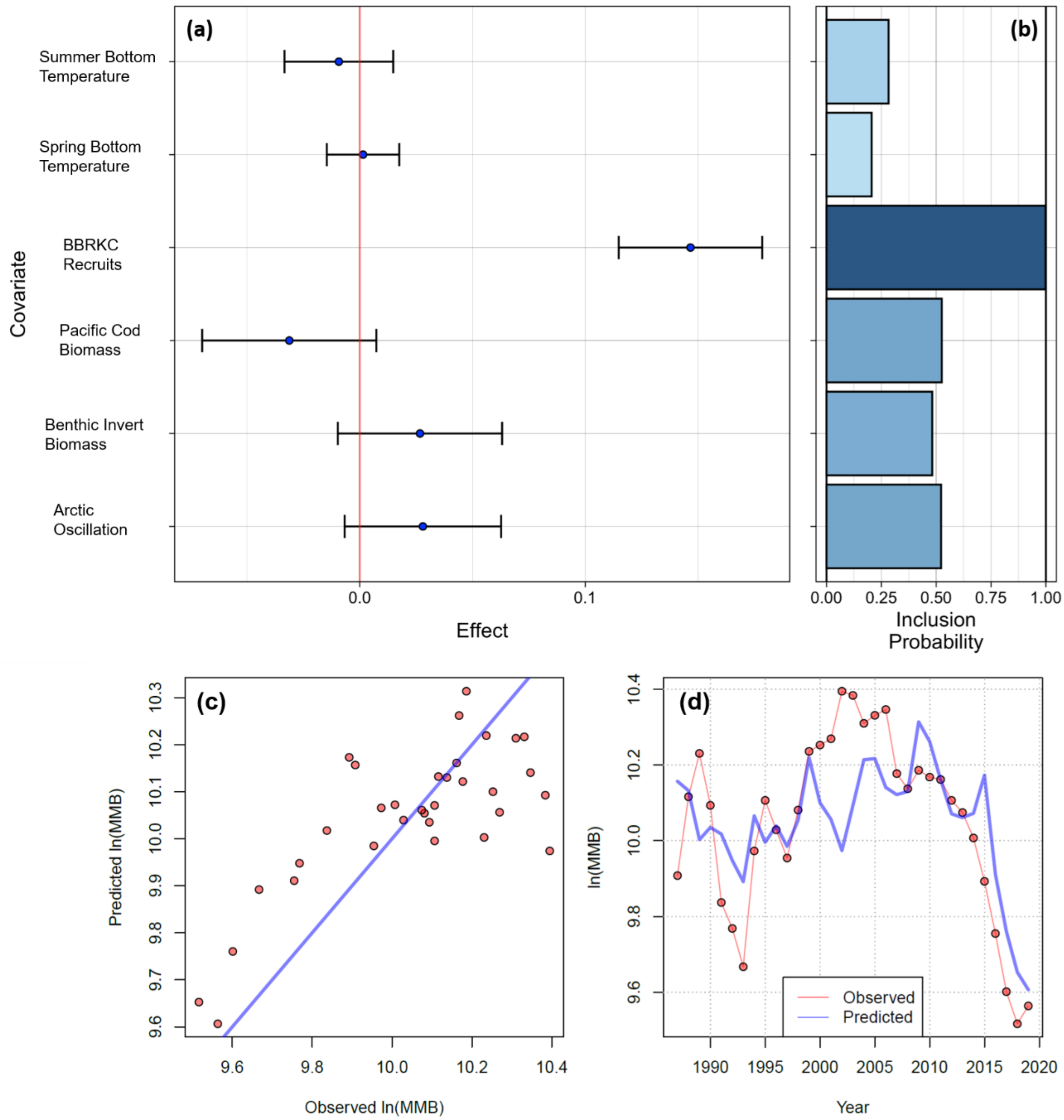


Figure 6. Bayesian adaptive sampling output showing the mean relationship and uncertainty (± 1 SD) with log-transformed Bristol Bay red king crab mature male biomass: a) the estimated effect and b) marginal inclusion probabilities for each predictor variable of the subsetted covariate ecosystem indicator dataset. Output also includes model c) predicted fit (1:1 line) and d) average fit across the MMB time series.