Appendix 1xx. Ecosystem and Socioeconomic Profile of the Walleye Pollock stock in the Gulf of Alaska

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Executive Summary

National initiative scoring and AFSC research priorities suggest a high priority for conducting an ecosystem and socioeconomic profile (ESP) for Gulf of Alaska (GOA) walleye pollock. Annual guidelines for the AFSC support research that improves our understanding of environmental and climate forcing of ecosystem processes with a focus on variables that can provide direct input into or improve stock assessment and management. The GOA pollock ESP follows the new standardized framework for evaluating ecosystem and socioeconomic considerations for GOA pollock and may be considered a proving ground for potential use in the main stock assessment.

We use information from a variety of data streams available for the GOA pollock stock and present results of applying the ESP process through a metric and subsequent indicator assessment. Analysis of the ecosystem and socioeconomic processes for GOA pollock 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.

NOTE: the following considerations are preliminary and may change when the final 2019 data are provided for this ESP.

Ecosystem Considerations (Draft: will be updated in final SAFE)

- An ontogenetic habitat shift occurs between the early juvenile and late juvenile stages with progression from WGOA hotspot areas to a fairly wide distribution along the continental shelf.
- Batch spawning may mitigate vulnerability in terms of synchrony with optimal levels of larval prey, but spawn timing and duration are impacted by both spawner age structure and temperature.
- The degree of match or mismatch of first-feeding larval pollock with prey may be critical for larval survival with cold years enhancing synchrony with optimal prey conditions
- Juvenile pollock are sensitive to variations in foraging conditions, and spatial distribution may play a role in encounter of optimal prey such as euphausiids.
- Available indicators for 2019 show a return to “heat wave” conditions in the Gulf of Alaska.
- Early indicators of 2019 year-class strength suggest a weak year class, following apparent average or above-average year-classes in 2017 and 2018.
- Summer euphausiid abundance in the WGOA has been on a declining trend since 2011, and euphausiids have made up an unusually small percent of diets in juvenile pollock since 2013.
- Body condition of juvenile and adult pollock has been below average since 2015 when the 2012 year-class entered the survey and fishery.
- The prey availability for the 2018 year-class seem similar to that of the 2012 year-class, and may result in smaller size at age and poor condition when it enters the fishery.

Socioeconomic Considerations (Draft: will be updated in final SAFE)

- Fishery CPUE indicators have been above average since 2016 which is consistent with high stock levels in recent years.
- There was a precipitous drop in roe per-unit-catch in 2016 and 2017 that rebounded in 2018 which may be related to the poor body condition of adult pollock since 2015.
- The percent of revenue in Kodiak from GOA pollock reached a high in 2018, which along with other data could suggest a high level of reliance on the GOA pollock fishery by Kodiak residents.

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 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 (Sigler et al., 2017; 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 Gulf of Alaska (GOA) walleye pollock (*Gadus chalcogrammus*, hereafter referred to as pollock) follows a template for ESPs (Shotwell et al., *In Review*) and replaces the previous ecosystem considerations section in the main pollock stock assessment. Information from the original ecosystem considerations section may be found in Dorn et al. (2018).

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 prioritization scores for GOA pollock are overall high due to the high commercial importance of this stock and differential growth rates of pollock larvae and juveniles in different habitat in the GOA (Hollowed et al., 2016; McConnaughey et al., 2017). The vulnerability scores were in the moderate range of all groundfish scores based on productivity and susceptibility (Ormseth and Spencer, 2011), and in the low range for sensitivity to future climate exposure (P. Spencer, AFSC, *pers. commun.*). The new data classification scores (Lynch et al., 2018) for western/central GOA pollock suggest a data-rich stock with high quality data over the categories of catch, size/age composition, abundance, and life history and a priority for improving the use of ecosystem linkages in the stock assessment. These initiative scores and data classification levels suggest a high priority for conducting an ESP for the western/central portion of the GOA pollock stock, particularly given the high level of current life history data and the high potential data for exploring ecosystem linkages. GOA pollock interact strongly with other ecosystem components and incorporating those interactions is likely to be important to stock dynamics, model configuration, and management decisions.

Data

Initial information on GOA pollock was gathered through a variety of national initiatives that were conducted by AFSC personnel in 2015 and 2016. These include (but were not limited to) stock assessment prioritization, habitat assessment prioritization, climate vulnerability analysis, and stock assessment classification. Data from an earlier productivity susceptibility analysis conducted for all groundfish stocks in Alaska were also included (Ormseth and Spencer, 2011). Data derived from this effort serve as the initial starting point for developing the ESP metrics for stocks in the BSAI and GOA groundfish fishery management plans (FMP). Please see Shotwell et al., *In Review*, for more details.

Supplementary data were also collected from the literature and a variety of process studies, surveys, laboratory analyses, accounting systems, and regional reports (Table 1). Information for the first year of life was derived from ecosystem surveys and laboratory analyses run by multiple programs and divisions at the AFSC (e.g., Ecosystems and Fisheries Oceanography Coordinated Investigations (EcoFOCI), Recruitment Processes Alliance (RPA), Fisheries Behavioral Ecology (FBE) program, Resource Assessment and Conservation Engineering (RACE) Division, Resource Ecology and Fisheries Management (REFM) Division, Auke Bay Laboratory (ABL) Division) and by the Alaska Maritime National Wildlife Refuge (AMNWR), and GulfWatch Alaska (GWA). Data for early stage juveniles (less than 250 mm) through adult (greater than 410 mm) were consistently available from AMNWR, AFSC Midwater Assessment and Conservation Engineering (MACE) acoustic survey, the AFSC bottom trawl survey, and the North Pacific Observer Program administered by the Fisheries Monitoring and Analysis (FMA) division.

Data from Ecosystem Status Report (ESR) contributions were provided through personal communication with the contact author of the contribution (e.g., Rogers et al., 2019). Essential fish habitat (EFH) model output and maps were provided by personal communication with the editors of the EFH update (e.g., Rooney et al., 2018). High resolution regional ocean modeling system (ROMS) and nutrient-phytoplankton-zooplankton (NPZ) data were provided through personal communication with authors of various publications (e.g., Laman et al., 2017, Gibson et al., *In Press*) that use these data.

The majority of GOA pollock economic value data were compiled and provided by the Alaska Fisheries Information Network (AKFIN). GOA pollock ex-vessel data were derived from the NMFS Alaska Region Blend and Catch Accounting System, and the ADFG Commercial Operators Annual Reports (COAR). GOA pollock first-wholesale data were from the NMFS Alaska Region Blend and Catch Accounting System, the NMFS Alaska Region At-sea Production Reports, and the ADF&G Commercial Operators Annual Reports (COAR). Global catch statistics were found online at FAO Fisheries & Aquaculture Department of Statistics (http://www.fao.org/fishery/statistics/en).

Metrics Assessment

We first provide the analysis of the national initiative data used to generate the baseline metrics for this second step of the ESP process and then provide more specific analyses on relevant ecosystem and/or socioeconomic processes. Metrics are quantitative stock-specific measures that identify vulnerability or resilience of the stock with respect to biological or socioeconomic processes. Where possible, evaluating these metrics by life history stage can highlight potential bottlenecks and lead to mechanistic understanding of ecosystem or socioeconomic pressures on the stock.

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 GOA pollock relative to all other stocks in the groundfish FMP. Additionally, some metrics are inverted 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 GOA pollock. 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. GOA pollock only had one data gap for the recreational index information. The data quality was rated as good to complete for nearly all metrics except transformation size, subsistence index, and non-catch value. The metric panel gives context for how GOA pollock relate to other groundfish stocks in the FMP and highlights the potential vulnerabilities for the GOA pollock stock.

The 80th and 90th percentile rank areas are provided to highlight metrics that cross into these zones indicating a high level of vulnerability for GOA pollock (Figure 1, yellow and red shaded area). For ecosystem metrics, recruitment variability and predator stressors fell within the 90th percentile rank of vulnerability. Habitat dependence and bottom-up ecosystem value fell within the 80th percentile rank when compared to other stocks in the groundfish FMP. For socioeconomic metrics, commercial value fell within the 90th percentile rank and constituent demand fell within the 80th percentile rank. GOA pollock were relatively resilient for adult growth rate, age at 50% maturity, mean age, breeding strategy, dispersal in early life, adult mobility, habitat specificity, and habitat vulnerability.

Recruitment variability (standard deviation of log recruitment) for the GOA pollock stock is above the value of 0.9 which is considered very high recruitment variability (Lynch et al., 2018) and habitat dependence of larvae and juveniles make GOA pollock particularly vulnerable during early life history stages. Predation pressures on adult GOA pollock are high due to their key role in the ecosystem as a major dietary component for a broad range of predators. GOA pollock is in the top 10% of the most highly valued Alaska groundfish stocks relative to other Alaska groundfish stocks. The high value also explains the high constituent demand for excellence in the stock assessment. These initial results suggest that additional evaluation of ecosystem and socioeconomic processes would be valuable for GOA pollock and assist with subsequent indicator development.

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. The first year of life for pollock is characterized by high mortality, where eggs, larvae, and juveniles must survive a series of transitions among habitats and life stages (Duffy-Anderson, et al. 2016). We evaluate the life history stages of GOA pollock along four organizational categories of 1) distribution, 2) timing, 3) condition, and 4) trophic interactions to gain mechanistic understanding of influential ecosystem processes. We include a detailed life history synthesis (Table 2a), an associated summary of relevant ecosystem processes (Table 2b), four life history graphics along the organizational categories (Figure 2-5, reproduced from Shotwell et al., *In Review* and Gaichas et al., 2015), and provide supportive information from the literature, surveys, process studies, laboratory analyses, and modeling applications.

A suite of habitat variables can be used to predict the distribution of the stock by life history stage and determine the preferred properties of suitable habitat. The recent EFH update for Alaska groundfish included models and maps of habitat suitability distributions by stage and species (Rooney et al., 2018; Pirtle et al., *In Press*). We collected model output on the depth ranges, percent contribution of predictor variables, sign of directional deviation from the mean predictor value, and associated maps for the larval (hatch-25 mm), early juvenile (<40 mm), late juvenile (>=40 mm & < 250 mm), and adult stages (>= 255 mm) of GOA pollock (Figure 2). Once hatched, larvae will move to the upper 50 m (Kendall et al., 1994) and are widely distributed along the GOA shelf but are most abundant in Shelikof Strait with other hot spots on the northeast side of the Kodiak Archipelago and proximal to the Shumagin Islands (Doyle and Mier, 2016). Early stages of pollock are generally much less abundant in the eastern GOA relative to the western GOA but there is a fair degree of annual variability in the eastern GOA (Siddon et al., 2016). Early juveniles are semi-demersal in nearshore areas as well as occurring in the upper 40 m (Bailey et al., 1989). The use of the nearshore zone by juvenile pollock seems especially transitory and this habitat may serve as stable refuge from adverse offshore conditions (O. Ormseth, *pers. comm.*). A clear ontogenetic habitat shift occurs between the larval to early juvenile stage and late juvenile to adult stages with progression from the hotspot areas in the western GOA to a fairly wide distribution along the continental shelf (Figure 2 b-d). The preferred habitat seems to switch from a reliance on a particular thermal environment during larval and early juvenile stages (Figure 2e, 2j) to low-gradient, low lying areas such as channels, gullies, and flats that are not rocky and within 20-300 m depth (Figure 2k, 2h) during late juvenile and adult stages (Pirtle et al., *In Press*).

The timing or phenology of the pre-adult life stages (Table 2a) can be examined seasonally to understand match or mismatch with both physical and biological properties of the ecosystem (Figure 3). We synthesized data on the egg, larval, early juvenile and late juvenile life stages (Table 2a) and restricted to the core sampling area (western GOA only) for consistency across years for the egg and larval data. Physical and biological seasonal climatologies were derived from ROMS/NPZ model output used in an individual based model and the EFH update (Laman et al., 2017; Rooney et al., 2018, Gibson et al., *In Press*). During the early spring, GOA pollock aggregate to spawn in high densities in the GOA, with females releasing 10-20 batches of eggs over a period of weeks (Hinckley, 1990). This species is a batch spawner, with spawning duration varying from 17 to 57 days in duration (Doyle and Mier, 2016; Rogers and Dougherty, 2018). This batch spawning is considered a “bet hedging” strategy that may mitigate vulnerability in terms of synchrony with optimal levels of larval prey (Doyle and Mier, 2016). In the Shelikof region, most spawning occurs from late March to early May, although spawn timing and duration are impacted by both spawner age structure and sea surface temperature (Rogers and Dougherty, 2018). Pollock eggs are pelagic and vulnerable to physical processes that influence transport and buoyancy, which may result in the eggs sinking to the seafloor (M. Wilson, *pers. comm.*) as well as being vulnerable to invertebrate predators in the plankton (Brodeur et al., 1996). Larvae hatch from the eggs after incubating for approximately 14 days at about 3 mm in length (Blood et al. 1994). Peak abundance of newly hatched larvae (less than 5 mm) corresponds to an increase in water temperature but prior to the peak spring zooplankton bloom (Doyle and Mier, 2016). Once feeding is initiated after yolk-sac absorption, larval pollock predominantly feed on copepod nauplii (Kendall et al., 1987; Strasburger et al. 2014), and may be susceptible to food-limited growth and subsequent increased predation mortality (Canino et al., 1991). The degree of match or mismatch of first-feeding larval pollock with zooplankton prey production may thus be critical for larval survival (Figure 3) with cold years (late winter-early spring) potentially enhancing larval synchrony with optimal prey conditions. At 25 mm standard length, which corresponds to an age greater than 60 days, GOA pollock undergo juvenile transformation (Kendall et al., 1984; Brown et al., 2001). Juveniles are ubiquitous in the epipelagic zone of shelf, slope, and basin waters in the eastern and western GOA in summer and fall, which corresponds to the onset of the fall bloom (Figure 3).

Information on body composition, percent lipid and percent protein by size, can be used to understand shifts in energy allocation through the different life history stages (Figure 4). Throughout their life history, there was no trend in the data suggesting that GOA pollock have a fairly stable lipid and protein content. This stability implies an energy allocation strategy toward increasing growth rather than toward energy storage. However, there may be a potential bottleneck just prior to overwintering (termed the “settlement stage”, but pollock do not really settle) as there was an observed increase in the variability of the percent lipid. Overwintering during the first year of life may incur an energetic cost that results in a change in body condition with reduced lipid content. In the Bering Sea, high lipid storage prior to the first winter has been associated with stronger year-classes for pollock (Heintz et al., 2013). Young fish with greater energy stores may be less susceptible to predation during their first winter. There may be an additional gain to the higher energy stores to mitigate high variability in maturation schedule, spawn timing, and spawning duration.

Pollock trophic interactions occur primarily in the pelagic pathway in the food web, which leads from phytoplankton through various categories of zooplankton to planktivorous fishes such as capelin and sandlance (Dorn et al., 2018). The primary prey of juvenile and adult pollock are euphausiids, but pollock also consume shrimp, which are more associated with the benthic pathway, and make up approximately 18% of age 2+ pollock diet. All ages of GOA pollock are primarily zooplanktivorous during the summer growing season (>80% by weight zooplankton in diets for juveniles and adults; Figure 5). While there is an ontogenetic shift in diet from copepods to larger zooplankton (primarily euphausiids) and fishes, cannibalism is not as prevalent in the Gulf of Alaska (5%) as in the Eastern Bering Sea (40%) for adult pollock, and consumption of fishes is low even for large pollock (Yang and Nelson, 2000, Gaichas et al., 2015)). During mid- to late-summer, juvenile GOA pollock shift from a diet consisting of primarily copepods to one dominated by euphausiids (Wilson et al., 2011, 2013). Consumption of euphausiids has been associated with improved growth and body condition in the western GOA (Wilson et al., 2013). Fatty acid and stable isotope analysis of GOA pollock juvenile diets in the nearshore areas revealed a high level of geographic (habitat variability), seasonal, and interannual variability but a general ontogenetic trend was apparent with summer fish relying more heavily on calanoid copepods and autumn fish having a more diverse diet including benthic invertebrates, copepods, pteropods, and diatoms (Budge et al., *In Press*; Wang et al., *In Press*). This may suggest pollock in these nearshore areas do not have access to the high quality euphausiid prey of the offshore areas and must rely on a more diverse diet. In 2014 through 2015, poor body condition of juvenile pollock was associated with poor prey quality and increased metabolic demands due to warm temperatures during the marine heatwave (Rogers et al., *In Prep.*; J. Moss *pers. comm.*). Juvenile pollock are more sensitive to variations in foraging conditions than Pacific cod (Doyle and Mier, 2016), suggesting that environmental variability in prey availability is likely an important factor influencing juvenile GOA pollock.

The GOA community composition has undergone large shifts over the past several decades, likely in response to warming temperatures, which has notable impacts on trophic stability of the GOA (Barnes et al., *In Review*). When the demersal community shifts from one dominated by forage species like pollock to one dominated by top-level predators the likely pressures on pollock recruitment shift from environmental effects on larvae to predation control on juveniles (Baily et al., 2000). Food web models identify predation mortality as an important mechanism for changes in pollock biomass and show that the top five predators (excluding fisheries) on adult pollock (>20 cm) by relative importance are arrowtooth flounder (*Atheresthes stomias*), Pacific halibut (*Hippoglossus stenolepis*), Pacific cod (*Gadus macrocephalus*), Steller sea lion (*Eumetopias jubatus*, SSL), and sablefish (*Anoplopoma fimbria*) (Figure 5, Barnes et al., *In Review*, Gaichas et al., 2015). These predators account for over 80% of total mortality for GOA pollock and synchronous consumption dynamics of these predators suggest strong top-down control over GOA pollock (Barnes et al., *In Review*). For juvenile pollock (< 20 cm), arrowtooth flounder account for almost 50% of total mortality, followed by adult pollock (15%) and seabirds (10%) (Dorn et al., 2018). All major predators show some diet specialization, and none depend on pollock for more than 50% of their total consumption. Pacific halibut is most dependent on pollock (48%), followed by SSL (39%), then arrowtooth flounder (24% for juvenile and adult pollock combined), and lastly Pacific cod (18%). It is important to note that although arrowtooth flounder is the largest single source of mortality for both juvenile and adult pollock (Figure 5a,c), they depend less on pollock in their diets than do other pollock predators (Dorn et al., 2018).

Socioeconomic Processes

The GOA pollock fishery is managed as a limited entry open access fishery. Total allowable catch is annually allocated spatially based on biomass to the inshore fleet of catcher vessels using trawl gear that deliver to inshore processors in the Central and Western Gulf of Alaska. The value of pollock deliveries by vessels to inshore processors (shoreside ex-vessel value) increased 20% in 2018 from 2017 to $42.2 million, the average for the previous 5 years $38.8 million (real 2018 USD). This increase was the net effect of a 15% decrease in retained catch to 158 thousand t and a 41% increase in the ex-vessel price to $0.123 per pound (Tables 3a). The number of vessels fishing for pollock increased from 65 in 2017 to 71 in 2018. The increase ex-vessel price in 2018 coincided with increased first-wholesale prices for head-and-gut (H&G) prices and fillet products, which represent slightly less than two-thirds of annual production (Tables 3b). While year-over year prices for pollock H&G and fillets increased, the value of both products remained lower than levels observed in 2011-2016. First-wholesale value was $105 million in 2018 (8% increase) and production of pollock products was 69 thousand t (12% decrease) (Table 3b). The average first-wholesale price of pollock products increased 16% to $0.69 per pound (Table 3b). The GOA pollock fishery is subject to prohibited species catch (PSC) restrictions, in particular of Chinook salmon. These restrictions have resulted in periodic closures of the fishery in the past. In December 2016 the NPFMC decided to postpone work on bycatch management for the GOA groundfish trawl fisheries indefinitely.

Pollock is a global commodity with prices determined in the global market. GOA represents roughly 2%-5% of the global pollock catch volume (Table 3c). In the GOA, the primary products are H&G, surimi, fillets, and roe, each have typically accounted for approximately 35%, 25%, 30%, and 10% of first-wholesale value in recent years, respectively (Table 3b). H&G product is primarily exported to China and reprocessed for global markets and competes with the Russian supply of pollock. The majority of fillets produced are pin-bone-out (PBO) primarily destined for domestic and European markets. Approximately 30% of the fillets produced in Alaska are estimated to remain in the domestic market, which accounts for roughly 45% of domestic pollock fillet consumption (AFSC, 2016). Roe is a high-priced product destined primarily for Asian markets. GOA pollock fisheries became certified by the Marine Stewardship Council (MSC) in 2005, an NGO based third-party sustainability certification, which some buyers in the U.S. and Europe seek. Pollock also obtained the Responsible Fisheries Management certification in 2011. Pollock more broadly competes with other whitefish that, to varying degrees, can serve as substitutes depending on the product. In 2015, the official U.S. market name changed from “Alaska pollock” to “pollock”. Previously all pollock was called “Alaska pollock” and it was not possible to determine origin of the product. The market name change enabled U.S. retailers to differentiate between pollock caught in Alaska and Russia.

The ports at Kodiak and Sand Point account for about 80% and about 12%, respectively, of the GOA delivered pollock volume. A comparatively smaller share of GOA caught pollock is also delivered to King Cove. The communities of Kodiak are highly involved in both commercial processing and harvesting of groundfish. Fisheries taxes account for 13% of the local tax revenue. Pollock accounted for 16% of Kodiak’s 2013-2017 average ex-vessel value and the remainder of its ex-vessel value comes from a number of other fisheries. Kodiak is dependent upon commercial fisheries, as commercial fishing, processing, and service is a major industry contributing to the local community.

One indication of Kodiak’s engagement in processing activities for the GOA pollock fishery is calculating the portion of the total GOA pollock fishery landed in Kodiak as well as the percentage of the total revenue Kodiak gets from the GOA pollock fishery (Figure 6a). Overall, there has been an increase in the percentage of the fishery landed in Kodiak between 2000 and 2014 from 67% to 87% (Figure 6a, blue bars). After reaching a peak of 87% in 2014, the portion of the GOA pollock landed in Kodiak declined slightly to 80% and then dropped steeply to 62% in 2016 before turning upward. In 2018, 76% of GOA pollock was landed in Kodiak. The percentage of landings revenue in Kodiak that can be attributed to GOA pollock shows some fluctuation (Figure 6a, orange bars), dipping to 6.3% in 2007 before climbing slightly. The years with the highest percentages of revenues are 2014 and 2018 (24% and 29%, respectively). In 2018, there was a jump in the portion of revenue from GOA pollock (from 16% in 2017 to 29% in 2018, Figure 6a, orange bars).

In order to explore Kodiak’s engagement in harvesting activities for GOA pollock, we examined the associated value of GOA pollock harvested by vessels owned by Kodiak residents from 2000 to 2018 (Figure 6b, yellow line). The number of Kodiak vessels participating in the GOA pollock fishery decreased from 21 vessels in 2000 to 11 in 2007 (a decline of 48%). Since then, the number of vessels has increased; however, more research is required to understand the circumstances for these changes. In 2018, Kodiak residents owned 20 vessels involved in GOA Pollock harvesting. The average value of harvest per vessel owned by Kodiak residents fluctuated from a low of $128 thousand in 2002 to $228 thousand in

2009 (Figure 6b, blue bars). In 2010, the value then increased considerably to $479 thousand and continued to rise until sharply dropping in 2016, when there was a 35 % decrease. In 2018 the average value of GOA pollock harvested per vessel was $742 (Figure 6b, blue bars).

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. In this indicator assessment a time-series suite is first created that represent the critical processes identified by the metric assessment. These indicators must be useful for stock assessment in that they are regularly updated, reliable, consistent, and long-term. The indicator suite is then monitored in a series of stages that are statistical tests that gradually increase in complexity depending on the data availability of the stock (Shotwell et al., *In Review*).

Indicator Suite

Studies into the survival of early life stages and recruitment of GOA Pollock have identified important processes, which have in turn informed recruitment forecasting models incorporating a range of indicators. These models have included variables reflecting environmental conditions preceding or during the first few months of life, such as thermal conditions, advection, and wind mixing, and biological variables like predator biomass. For many years, a recruitment forecast model was included in the SAFE document for GOA pollock based on environmental data and larval counts (e.g. Dorn et al., 2007). The environmental indicators included winter-spring precipitation as a proxy for eddies or instabilities in the spring (hypothesized positive effect through concentration of prey; Bailey et al. 2005), winter wind mixing (strong mixing in winter is favorable due to increased nutrient mixing and spring blooms), spring wind mixing (weak mixing in spring is favorable for first-feeding larvae; Bailey and Macklin, 1994), and advection (weak or average transport in spring is favorable for retention of larvae in nursery habitats). Notably, the forecast model did not include any thermal indicators, although many studies have looked at the effect of thermal conditions on larval survival and recruitment. For instance, early studies found a positive relationship between springtime temperatures and larval pollock survival, with cold springs corresponding to lower rates of larval survival, especially during the first week post-hatch (Bailey et al., 1996). This was hypothesized to be related to the timing of microzooplankton production, particularly of copepod nauplii, which are a primary prey item of first-feeding larvae (Bailey et al. 1995). A subsequent time-series analysis found no apparent effect of spring temperatures on larval abundance (Doyle et al., 2009), although winter (January) temperatures were negatively associated with larval abundance. Another study found recruitment (as estimated in the assessment model) was negatively related to springtime temperatures (A'mar et al., 2009), but positively related to summer temperatures. Current work (Rogers, *in prep*) suggests no consistent relationship between temperature and stage-specific survival rates of GOA pollock during their first year, emphasizing that temperature is only one of many factors, often interacting, that regulate survival and recruitment in this species.

Some models have also included SSB, larval abundance, or age-0 abundance, together with subsequent environmental conditions and/or density-dependence, to predict recruitment. For instance, Bailey et al., 2012 developed a recruitment forecasting model based on larval rough counts, wind speed in May, an interaction between the biomass of arrowtooth flounder and temperature, and an autocorrelation term to capture the empirical 5-year cycle in recruitment. Notably, the estimated environmental effects were often non-linear and sometimes included thresholds. Brodeur and Ware (1995) provided evidence that biomass of zooplankton in the center of the Alaska Gyre was twice as high in the 1980s than in the 1950s and 1960s, consistent with a shift to positive values of the PDO since 1977. The percentage of zooplankton in the diets of pollock is relatively constant throughout the 1990s (Dorn et al., 2018). While indices of stomach fullness exist for these survey years, a more detailed bioenergetics modeling approach would be required to examine if feeding and growth conditions have changed over time, especially given the fluctuations in GOA water temperature in recent years, as water temperature has a considerable effect on digestion and other energetic rates.

We generated a suite of ecosystem and socioeconomic indicators using the mechanisms and tested relationships listed above by previous studies and the relevant ecosystem processes identified in the metric assessment (Table 2b). The following list of indicators is organized by trophic level similarly to the ecosystem status reports (Zador and Yasumiishi, 2018) and by GOA pollock life history stage. Indicator title and a brief description are provided in Table 4a for ecosystem indicators and 4b for socioeconomic indicators with references, where possible, for more information.

Ecosystem Indicators:

- Annual marine heatwave index is calculated from daily sea surface temperatures for 1981 through August 2019 from the NOAA High-resolution Blended Analysis Data for the central GOA (< 300 m). Daily mean sea surface temperature data were processed to obtain the marine heatwave cumulative intensity (MHWCI) (Hobday et al., 2016) value where we defined a heat wave as 5 days or more with daily mean sea surface temperatures greater than the 90th percentile of the January 1983 through December 2012 time series (Zador and Yasumiishi, 2018).
- Summer bottom temperatures were obtained by averaging the haul-specific bottom temperature (degrees Celsius) collected on the AFSC bottom trawl survey over all hauls from 1984 to present. Data are available triennial since 1984 and biennial since 2000 and can be accessed from the Alaska Fisheries Information Network (AKFIN).
- Spring small copepods for larvae and summer large copepods for young-of-the-year (YOY) GOA pollock were summarized as mean abundance for the core sampling area in Shelikof Strait of the EcoFOCI spring and summer surveys. The most recent survey year is represented by a rapid zooplankton assessment to provide a preliminary estimate of zooplankton abundance and community structure (Kimmel et al., 2019).
- Summer euphausiid abundance is represented as the acoustic backscatter per unit area (sA at 120 kHz, m2 nmi-2) classified as euphausiids and integrated over the water column and then across the surveyed area to produce an annual estimate of acoustic abundance (sA * area, proportional to the total abundance of euphausiids). The index is for the Kodiak core survey area available for variable years historically and biennially since 2013 (Ressler et al., 2019).
- Parakeet auklet reproductive success is measured at Chowiet Island during variable years since 1998. Reproductive success is defined as the proportion of nest sites with fledged chicks from the total nest sites that had eggs laid. This species is a diving plankton-feeder, like pollock, and reproductive success may be indicative of prey field in a central area to the GOA pollock population. Data are collected by the Alaska Maritime National Wildlife Refuge staff, U.S. Fish and Wildlife Service (Higgins et al., 2018).
- Spring pollock larvae and summer pollock YOY catch-per-unit-of-effort (CPUE) were summarized as mean abundance for the core sampling area in Shelikof Strait of the EcoFOCI spring and summer surveys. The most recent survey year is represented by a rapid ichthyoplankton assessment to provide a preliminary estimate of pollock CPUE (Rogers et al., 2019).
- Summer pollock condition for YOY were provided from samples taken in the EcoFOCI midwater trawl survey. Body condition was measured as residuals from a weight-length regression model. Fish with positive residuals are considered “fatter” with greater energetic reserves to survive life stage transitions such as first overwinter survival (Rogers et al., 2019).
- Summer pollock CPUE of YOY was estimated using the AFSC Kodiak beach seine survey available from 2006-present that targets summer YOY gadids (Pacific cod, pollock and saffron cod) at 16 fixed-site nearshore regions of Kodiak from mid-July through late August. Sites are sampled using a 36-m demersal beach seine deployed from a boat and pulled to shore by two people standing a fixed distance apart on shore. Maximum depth varies between 2 and 4 m

among seine sites, and sites consist of eelgrass or sand-small cobble. Juvenile gadids from each seine haul are counted and measured (mm TL, Laurel et al., 2007).

- Pollock relative biomass of YOY is measured from screening burrows of tufted puffins at Aiktak Island annually since 1991. This species is a diving fish-feeder and estimates of pollock relative biomass from feeding samples may be indicative of pollock densities near the western edge of the pollock population. Data are collected by the Alaska Maritime National Wildlife Refuge staff, U.S. Fish and Wildlife Service (Youngren et al., 2019).
- Summer pollock predation mortality for age-1 was quantified in the area encompassed by the GOA pollock stock assessment for 1990 to 2015. The predation index included estimates of total predator biomass from recent stock assessments, relative predator densities modeled from survey catch data (collected by RACE and the International Pacific Halibut Commission), mean annual rations obtained from bioenergetics models, and age-specific proportions of pollock consumed (as estimated from food habits data collected by REEM). The predation index accounted for annual variation in consumption by five major groundfish species: arrowtooth flounder, Pacific cod, Pacific halibut, sablefish, and pollock conspecifics (Barnes et al., *In Review*).
- Summer pollock proportion-by-weight of euphausiids in the diets of juvenile (10-25 cm, likely age-1) GOA pollock collected on summer bottom-trawl surveys (K. Aydin, *pers. commun.*).
- Fall pollock condition for adults was estimated from length-weight data from the fishery sampled by observers (1989-2018). A log length-weight regression was fitted and then the residuals from the regression were averaged by year. Data only for the months of August, September, and October were used to measure condition at the end of production year. The length-weight regression included a slope term for month, and this term increased slightly in value from August to October, indicating that condition improved during these months (M. Dorn, *pers. commun.*)
- Winter pollock condition for adults was estimated from length-weight data from the late winter acoustic surveys of pre-spawning pollock in the GOA. Most of the sampling occurred in Shelikof Strait, but data from outside Shelikof Strait were not excluded. A log length-weight regression was fitted and then the residuals from the regression were averaged by year. Fish in spawning or post-spawning condition were excluded, and the analysis was limited to fish greater or equal to 35 cm to exclude the age-1 and age-2 pollock. Estimates were produced for 1986-2019, excluding 1999, 2001, and 2011 (M. Dorn, *pers. commun.*).
- Summer pollock center of gravity and area occupied were estimated by fitting a spatio-temporal delta-generalized linear mixed model using standard settings for an "index standardization" model (Thorson 2019), implemented using the package VAST (Thorson and Barnett 2017) in the R statistical environment (R Core Team 2017). This configuration includes spatial and spatio-temporal variation in two linear predictors of a Poisson-link delta model (Thorson 2018), using a lognormal distribution for residual variation in positive catch rates. We specified a model with 250 "knots" while using the "fine_scale=TRUE" feature to conduct bilinear interpolation from the location of knots to the location of extrapolation-grid cells (Figure 7). For extrapolation-grid, we used the standard "Gulf of Alaska" grid which covers the spatial domain from which the bottom trawl survey randomizes sampling stations. We then restricted this extrapolation-grid to cells West of -140˚W; knots where distributed proportional to the spatial distribution of extrapolation-grid cells within this spatial domain. We then calculated center of gravity as the biomass-weighted average of the location of extrapolation-grid cells in northings or eastings (Thorson et al. 2016a) when projecting Latitude/Longitude to UTM coordinates within UTM zone 5. We also calculated effective area occupied as the area required to contain the population at its average biomass (Thorson et al. 2016b).
- Arrowtooth flounder total biomass (metric tons) from the most recent stock assessment model (Spies et al., 2017).
- Steller sea lion non-pup estimates were developed using the R package agTrend model within the bounds of the GOA. As a predator of pollock, an index of adult counts may be indicative of the

relative biomass GOA pollock. This region includes the GOA portion of the western Distinct Population Segment (known as the west, central and east GOA)

Socioeconomic Indicators:

- Winter-spring and summer-fall pollock CPUE (catch of pollock in tons/hour) was estimated from fishery observer data. Data were filtered to exclude catches less than 80% pollock, and gears other than pelagic gear. Only tows with a performance code of "no problem" were used. The geometric mean CPUE was calculated by taking the log of the CPUE and then exponentiating. Mean CPUE was calculated for the first trimester (Jan-April), and the third trimester (Aug-Dec, mostly Aug.-Oct.).
- Annual real Ex-vessel price per pound was calculated from 2003-2018 (2018 USD). Ex-vessel prices are revenue per pound of retained pollock delivered to processors. Prices influence the incentive to harvest fish as an increase in the price of fish increases the returns to fishing. Many other factors can influence the returns and the incentive to harvest including costs, activity in other fisheries in which harvesters may participate. The ex-vessel price metric has been inflation adjusted to 2018 USD to account for general trends in prices over time (B. Fissel, *pers., commun.*).
- Annual pollock roe per-unit-catch was calculated from 2003-2018. Production of roe per-unit catch is potentially indicative of the fecundity of the stock. As a high priced pollock product, processors and harvesters have an incentive to maximize the production of roe subject to harvest controls. A number of other factors besides fecundity can potentially influence the relative share of roe to retained catch including roe prices and the timing of harvest. This metric is constructed as 1000*(roe production)/(retained catch) (B. Fissel, *pers., commun.*).
- Annual percentage of the total revenue that Kodiak receives from the GOA pollock fishery from 2000 to 2018, also known as the local quotient was calculated to estimate community engagement. (S. Wise, *pers. commun.*).

Indicator Monitoring Analysis

We provide the list and time-series of indicators (Table 4, Figure 8) 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 monitoring analysis for GOA pollock. 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 4). 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 (yellow), or poor (red) for GOA pollock (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 GOA pollock.

The last major year class of GOA pollock was the 2012 year-class. The CPUE of larvae and YOY in the spring and summer offshore EcoFOCI surveys was unknown for 2012 as was the condition, but were all high in the following survey year (2013). The nearshore Kodiak survey showed above average abundance of YOY in 2012. Additionally, relative biomass of pollock in tufted puffin diet was the highest in the time series near the western edge of the population (Aiktak). Small copepods were likely abundant when they entered the system as YOY but large copepods were low and euphausiids were average to low and on a downward trend in the age-1 diet. A major heatwave impacted the GOA ecosystem starting in 2014, likely influencing the early maturation of the 2012 year-class. This year-class was subsequently in poor condition when they recruited to the fall fishery in 2015 and in the following 2016 winter acoustic survey. Historically, there is considerable year-to-year variability in the condition indices. But generally, condition in the fall fishery was high from 1989 to 1995, was low during 1996 to 2004, tending high since around 2005, but strongly negative in 2015 and 2016. Since 2016, there has been a rebound in the anomalies, but the indicator still remains below average. For the winter acoustic survey, there is a gradual increasing trend in condition with year-to-year variability from 1986 to 2008, followed by a decline. The 2016 and 2017 annual anomalies were strongly negative, followed by an increase in 2018, but the 2018 anomaly still remained negative. Since 2001, there is a good correlation between condition in the late-season fall fishery and condition in the winter acoustic Shelikof Strait samples in the following year. This suggests that these indicators are measuring something real about the pollock stock and are not due to sampling variability.

The overall spatial distribution of the 2012 year-class was also spread out substantially from previous years and more toward the east (area occupied is high with eastward shift in the center of gravity), so some of the pollock population may potentially be moving out of preferred habitat. A historical analysis on pollock distribution in the GOA found dispersion of the pollock stock up until 1996, which may be consistent with increasing trend in effective area occupied (Shima et al., 2002). In the spatial-temporal model results, total biomass has decreased, while effective-area has been stable or slightly increasing. The decrease in total biomass has been associated with decreased density within the range and a slight increase in range.

Main predator biomass has been decreasing and/or stable for the most recent years. Fishery CPUE was high at the beginning of the time series, declined, and then increased toward the end of the time series. Fishery CPUE remained relatively high during the first trimester of 2019. Higher fishery performance CPUE in the 1st trimester implies that the pollock were very concentrated, likely in pre-spawning aggregations, so catch rates were higher and roe may be in better condition. CPUE for the 1st and 3rd trimesters compared to model estimates of exploitable biomass track the estimated exploitable biomass from the assessment model reasonably well. CPUE in the fishery and in local communities (Kodiak) have been trending upwards but there is a decreasing trend in ex-vessel price and roe per unit catch during recent years consistent with the lower adult condition in the fall fishery and winter acoustic survey.

For the current year, we are again entering another major heat wave in the GOA and the average 2017 and potentially large 2018 year-class will likely experience similar feeding conditions to the 2012 year-class. Anomalously warm sea surface temperatures and a weak-moderate El Nino were predicted through winter 2018/19 and have continued through summer 2019. The current heat wave may negatively impact YOY pollock during a time when they are growing to a size that promotes over winter survival. Also, warm conditions tend to be associated with zooplankton communities that are dominated by less lipid rich species. The CPUE of larvae and YOY was above average for the 2017 year-class, unknown for the 2018 year-class, and poor for 2019 in the offshore surveys. The condition for the 2017 YOY was below average. The nearshore surveys in Kodiak showed very high abundance in both 2017 and 2018, and poor abundance in 2019. Relative biomass of pollock in tufted puffin diet was below average in 2017 and slightly above average in 2018. Small copepods in spring were above average in 2017, unknown in 2018 and likely below average in 2019, while large copepods in summer were very low in 2017 and unknown in 2018. Euphausiids were very low in 2017 and reproductive success of auklets (primarily planktivores) in the Chowiet is decreasing. The percent euphausiids in the diet of juvenile pollock in 2017 was the lowest in the time series.

For the indicators available in the current year, the traffic light analysis shows mostly poor conditions for YOY GOA pollock with a one stable indicator for small prey (Table 4a) and one good indicator for the winter/spring CPUE in the fishery (Table 4b). **NOTE:** Some of the 2019 summer updates are from personal communications and we will be updating these values for the final document in November.

Stage 2, Regression Test:

Bayesian adaptive sampling (BAS) was used for the second stage statistical test to quantify the association between hypothesized predictors and GOA pollock recruitment 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 recruitment (Figure 9a). We then provide the mean relationship between each predictor variable and log GOA pollock recruitment over time (Figure 9b, left side), with error bars describing the uncertainty (1 standard deviation) in each estimated effect and the marginal inclusion probabilities for each predictor variable (Figure 9b, right side). A higher probability indicates that the variable is a better candidate predictor of GOA pollock recruitment. The highest ranked predictor variables based on this process were the annual heatwave, the fall pollock condition of adults in the fishery, and the arrowtooth flounder biomass index (Figure 9). 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.

Stage 3, Modeling Test (NOTE: future application):

In the future, highly ranked predictor variables could be evaluated in the third stage statistical test, which is a modeling application that analyzes predictor performance and estimates risk probabilities within the operational stock assessment model. A new multi-species statistical catch-at-age assessment model (known as CEATTLE; Climate- Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics; Holsman, Ianelli, Aydin, Punt, & Moffitt, 2015) has recently been developed for understanding trends in age 1 total mortality for walleye pollock, Pacific cod, and arrowtooth flounder from the GOA (Adams et al., 2019). Total mortality rates are based on residual mortality inputs (M1), model estimates of annual predation mortality (M2), and fishing mortality (F). CEATTLE has been modified for the GOA and implemented in Template Model Builder (Kristensen, Nielsen, Berg, Skaug, & Bell, 2015) to allow for the fitting of multiple sources of data, time-varying selectivity, time-varying catchability, and random effects. The model is based, in part, on the parameterization and data used for the most recent stock assessment model of each species (Barbeaux et al., 2018; Dorn, Aydin, Jones, Palsson, & Spalinger, 2018; Spies & Palsson, 2018). The model is fit to data from five fisheries and seven surveys, including both age and length composition assumed to come from a multinomial distribution. Model estimates of M2 are empirically driven by bioenergetics based consumption information and diet data from the GOA to inform predator-prey suitability. The model was fit to data from 1977 to 2018.

Once the GOA CEATTLE model is more developed and published, the age 1 mortality index could provide a gap free estimate of predation mortality that could be tested in the operational stock assessment model. Additionally, the heatwave and condition indicators could be used directly to help explain the variability in recruitment deviations and predict pending recruitment events for GOA pollock.

Recommendations

The GOA pollock 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 (Draft: to be updated in final draft)

- An ontogenetic habitat shift occurs between the early juvenile and late juvenile stages with progression from WGOA hotspot areas to a fairly wide distribution along the continental shelf.

- Batch spawning may mitigate vulnerability in terms of synchrony with optimal levels of larval prey, but spawn timing and duration are impacted by both spawner age structure and temperature.
- The degree of match or mismatch of first-feeding larval pollock with prey may be critical for larval survival with cold years enhancing synchrony with optimal prey conditions
- Juvenile pollock are sensitive to variations in foraging conditions, and spatial distribution may play a role in encounter of optimal prey such as euphausiids.
- Available indicators for 2019 show a return to “heat wave” conditions in the Gulf of Alaska.
- Early indicators of 2019 year-class strength suggest a weak year class, following apparent average or above-average year-classes in 2017 and 2018.
- Summer euphausiid abundance in the WGOA has been on a declining trend since 2011, and euphausiids have made up an unusually small percent of diets in juvenile pollock since 2013.
- Body condition of juvenile and adult pollock has been below average since 2015 when the 2012 year-class entered the survey and fishery.
- The prey conditions for the 2018 year-class seem similar to that of the 2012 year-class, and may result in downstream poor condition when it reaches the fishery.

Socioeconomic Considerations (Draft: to be updated in final draft)

- Fishery CPUE indicators have been above average since 2016 which is consistent with high stock levels in recent years.
- There was a precipitous drop in roe per-unit-catch in 2016 and 2017 that rebounded in 2018 which may be related to the poor body condition of adult pollock since 2015.
- The percent of revenue in Kodiak from GOA pollock reached a high in 2018, which along with other data could suggest a level of reliance on the GOA pollock fishery by Kodiak residents.

Data Gaps and Future Research Priorities

While the metric and indicator assessments provide a relevant set of proxy indicators for evaluation at this time, there are certainly areas for improvement. The majority of indicators collected for GOA pollock have a fair number of gaps due to the biennial nature of survey sampling in the GOA. This causes issues with updating the ESP and the ecosystem considerations during off-cycle years and can lead to difficulty in identifying impending shifts in the ecosystem that may impact the GOA pollock population. Development of high-resolution remote sensing (e.g., regional surface temperature, transport estimates, primary production estimates) or climate model indicators (e.g., bottom temperature, NPZ variables) would assist with the current multi-year data gap for several indicators if they sufficiently capture the main trends of the survey data and are consistently and reliably available. Additional refinement on the GOA CEATTLE model might also allow for gap-free index of predation mortality for GOA pollock. An updated set of indicators may then be used in the third stage modeling application that evaluates performance and risk within the operational stock assessment model.

It may also be important in the near future to considering the potential impacts of other GOA pollock predators that may be on the rise (e.g., sablefish). Several recent large year-classes are estimated for the sablefish stock and this stock has potential overlap as both a competitor with (juveniles eat euphausiids) and predator of GOA pollock. Additionally, evaluating condition and energy density of pollock samples at the outer edge of the population may be useful for understanding the impacts of shifting spatial statistics such as center of gravity and area occupied. Information is available from the GulfWatch Alaska program that could be helpful for evaluating the eastern edge of the GOA pollock population.

In the future, a partial ESP may be requested as an update to the full ESP report provided here when no new information except indicator updates are available. A simplified one-page template (Figure 10, **NOTE**: to be finished in final draft) may be useful for evaluating the ESP considerations during a partial update year.

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Table 1: List of data sources used in the ESP evaluation. Please see the main GOA pollock SAFE document, the Ecosystem Considerations Report (Zador and Yasumiishi, 2018) and the Economic Status Report (Fissel et al., 2018) for more details.

Title	Description	Years	Extent
EcoFOCI Spring Survey	Shelf larval survey in May-early June in Kodiak to Unimak Pass using oblique 60 cm bongo tows, fixed-station grid, catch per unit effort in numbers per 10 m^2	1978 – present	Western GOA annual, biennial
FBE Summer Survey	Age-0 gadid survey in mid-July through late August on 16 fixed-site stations, northeast Kodiak Island using 36-m demersal beach seine, gadids count, length in mm	2006 – present	Kodiak annual
EcoFOCI Late Summer Survey	Midwater trawl survey of groundfish and forage fish from August-September using Stauffer trawl and bongo tows from Kodiak to Unimak Pass, fixed-station grid	2000 – present	Western GOA biennial
RACE Bottom Trawl Survey	Bottom trawl survey of groundfish in June through August, Gulf of Alaska using Poly Nor'Eastern trawl on stratified random sample grid, catch per unit of effort in mt	1984 – present	GOA tri-, biennial
Seabird Surveys	Ecological monitoring for status and trend of suite of seabird species conducted by Alaska Maritime National Wildlife Refuge (AMNWR) at eight sites throughout Alaska	1991-present	Alaska variable
MACE Acoustic Survey	Mid-water acoustic survey in March in Shelikof Strait for pre-spawning pollock and again in summer for age 1 pollock	1981 - present	GOA annual, biennial
Climate Model Output	Daily sea surface temperatures from the NOAA High-resolution Blended Analysis Data	1977 - present	Central GOA
ROMS/NPZ Model Output	Coupled hydrographic Regional Ocean Modeling System and lower tropic Nutrient-Phytoplankton-Zooplankton dynamics model	1996-2013	Alaska variable
Essential Fish Habitat Models	Habitat suitability MaxEnt models for describing essential fish habitat of groundfish and crab in Alaska, EFH 2016 Update	1970-2016	Alaska
REEM Diet Database	Food habits data collected by the Resource Ecology and Ecosystem Modeling (REEM) Program, AFSC on multiple platforms	1990 – present	GOA biennial
FMA Observer Database	Observer sample database maintained by Fisheries Monitoring and Analysis Division	1988-present	Alaska annual
NMFS Alaska Regional Office	Catch, economics, and social values for fishing industry, data processed and provided by Alaska Fisheries Information Network	1992-2018	Alaska annual
Reports & Online	ADFG Commercial Operators Annual Reports, AKRO At-sea Production Reports, Shoreside Production Reports, FAO Fisheries & Aquaculture Department of Statistics	2011-2018	Alaska, U.S., Global annual

Table 2a: Ecological information by life history stage for GOA pollock.

Stage		Habitat & Distribution	Phenology	Age, Length, Growth	Energetics	Diet	Predators/Competitors
Adult	**Recruit**	Shelf (0-300 m)	Recruit to survey and fishery ~age 1, length 5-16 cm(19)	Max: 31yrs(AFSC), 105♀/92♂ cm(AFSC) Average: 10 yrs (19) L_inf=65.2cm, K= 0.3 (19)		Euphausiids, shrimp, copepods, juvenile pollock (<1 %) (19)	Arrowtooth flounder, halibut, Pacific cod, steller sea lions, sablefish, shelf pelagic/benthic groundfish, fisheries (17,19)
	Spawning	Shelf (150-300 m, x̄ 200 m), Shelikof Strait/Valley (5,9,*11)	February-May, peak mid-March, 13 wks (1,20,25)	1st mature: 3-4 yr (11), 50%: 4.9 yr/44cm (19), ↑ size 50% to 48 since 2008 (19)	Oviparous, high fecundity (385-$662\cdot10^3$) eggs (11), 1.1-7.2 °C at depth(11)	Euphausiids, shrimp, copepods, juvenile pollock (<1 %) (19)	Arrowtooth flounder, halibut, Pacific cod, steller sea lions, sablefish, shelf pelagic/benthic groundfish, fisheries (17,19)
Offshore to Nearshore Pelagic	**Egg**	Pelagic; shelf (0-200 m, x̄ 150-200 m), Shelikof St/Valley, canyons (2,5,6,8-11)	mid-March-April, ~2 wks (10,11,20,25-26)	Egg size: 1.2-1.77 mm (20, RACE)	5.0-5.5°C at 150-250 m depth (10,11)	Yolk (RACE)	Invertebrates, detritivores, pelagic fishes (23,24)
	Yolk-sac Larvae	Pelagic; shelf and coastal areas (0-200 m, primarily upper 50 m), Shelikof St (2,3,5,6-8,10,11)	April (5), peak end April, 1 wk (20,25-26)	3-5 mm SL (2,3,5,6,8,10,11), growth rate 0.12-0.25 $\text{mm}\cdot\text{day}^{-1}$(11)	Preferred, 31.5-32.2 ppt, 3.6-7.0 °C (8,10)	Yolk (RACE)	Planktonic predators (zooplankton, birds, fishes), larval groundfishes (5,6,8)
	Feeding Larvae	Pelagic; shelf and coastal areas (0-200 m, primarily upper 50 m), Shelikof St (2,3,5,6-8,10,11)	May-July(5), peak May, 4-5 wks (22,25-26)	30-40 mm SL at transformation (RACE), growth rate 0.12-0.25 $\text{mm}\cdot\text{day}^{-1}$(11)	Preferred salinity=31.5-32.2, temperature=3.6-7.0 °C (8,10)	Copepod eggs & nauplii, copepodites (8)	Planktonic predators (zooplankton, birds, fishes), Pollock (17), larval groundfishes (5,6,8)
	Juvenile	Semi-demersal; shelf, coastal areas, bays, fjords, inlets (20-30 m and >30 m with age), mixed substrate (1,3,4,18)	Aug-Mar (1+ yr); 8-24 wks (25,26)	25-40 mm FL (offshore) (5); >40 mm SL (nearshore) (5); growth sensitive to diet, competition	Energy density ↑ with length, > over slope, spatial shifts due to +/- *C. marshallae*	Copepods, euphausiids (16)	Arrowtooth flounder, sablefish, cod, pollock (17), juvenile groundfish, macroalgae (12,18), macroinvertebrates (18)
	Pre-Recruit	Semi-demersal; shelf, coastal areas, bays, fjords, inlets, mixed substrate, mud(18)		>250 mm FL(11), age 2+ yrs(10)		Euphausiids, copepods, pollock(16),	Arrowtooth flounder (~50% <20 cm) (19), sablefish, Pacific cod, Pollock (17), juvenile groundfish, macroalgae (12,18), macroinvertebrates (18)

Table 2b. Key processes affecting survival by life history stage for GOA pollock.

Stage		Processes Affecting Survival	Relationship to GOA Pollock
Adult	**Recruit**	1. Top-down predation increase on age 3+ 2. Bottom-up control on juvenile consumption	Increases in main predator of pollock would be negative but minor predators may indicate pollock biomass increase. Increases in primary prey biomass would be positive for pollock but may increase competition.
	Spawning	1. Distribution 2. Surface and bottom temperature[10]	Increased distribution spread of adult pollock may be negative as pollock would experience non-preferred habitat and potentially lower quality prey options. Increases in temperature may be negative causing early maturation, mismatch with spring bloom.
Offshore to Nearshore Pelagic	**Egg**	1. Water column density 2. Advection/retention 3. Predation	Increases in density, advection, and predation would be negative for egg stage resulting in sinking or dispersal from preferred habitat and adequate zooplankton prey.
	Yolk-sac Larvae	1. Temperature-mediated metabolic rate 2. Currents that facilitate nearshore transport (6,8,10) 3. Predation	Increases in temperature would increase metabolic rate and may result in rapid yolk-sac absorption that may lead to mismatch with prey. Current direction to preferred habitat would be positive for pollock while predation increases would be negative.
	Feeding Larvae	1. Temperature-mediated metabolic rate 2. Currents that facilitate nearshore transport (6,8,10) 3. Predation	Increases in temperature would increase metabolic rate and may result in poor condition if feeding conditions are not optimal. Current direction to preferred habitat would be positive for pollock while predation increases would be negative.
	Juvenile	1. Spring/summer/fall abundance of zooplankton prey (11) 2. Advection/retention (offshore) 3. Predation	Increases in preferred zooplankton prey would be positive for pollock condition and relative biomass of pollock may also be measured by minor predators of pollock. Advection offshore may be positive for pollock to arrive at preferred habitat. Predation would be negative for pollock.
	Pre-Recruit	1. Bottom-up control juvenile consumption 2. Top-down predation increase on age 3+	Increases in main predator of pollock would be negative but minor predators may indicate pollock biomass increase. Increases in primary prey biomass would be positive for pollock but may increase competition.

Table 3a. Pollock in the Gulf of Alaska ex-vessel market data. Total and retained catch (thousand metric tons), ex-vessel value (million US$), price (US$ per pound), the Central Gulf's share of value, and number of trawl vessels; 2011-2013 average, and 2014-2018.

	Avg 11-13	2014	2015	2016	2017	2018
Total Catch K mt	94.0	142.6	167.6	177.1	186.2	158.1
Retained Catch K mt	91.8	141.2	163.0	176.0	184.3	155.7
Ex-vessel Value M $	$ 34.4	$ 37.9	$ 43.6	$ 32.3	$ 35.2	$ 42.2
Ex-vessel Price/lb $	$ 0.169	$ 0.122	$ 0.119	$ 0.083	$ 0.087	$ 0.123
Central Gulf Share of Value	75%	88%	80%	63%	72%	76%
Vessels #	70.0	72.0	65.0	70.0	65.0	71.0

Table 3b. Pollock in the Gulf of Alaska first-wholesale market data. First-wholesale production (thousand metric tons), value (million US$), price (US$ per pound), and head and gut, fillet, surimi, and roe production volume (thousand metric tons), price (US$ per pound), and value share; 2011-2013 average, and 2014-2018.

		Avg 11-13	2014	2015	2016	2017	2018
All Products	**Volume K mt**	36.1	54.7	59.8	75.1	78.1	69.1
All Products	**Value M $**	$ 84.5	$ 105.8	$ 105.1	$ 106.4	$ 96.7	$ 104.9
All Products	**Price lb $**	$ 1.06	$ 0.88	$ 0.80	$ 0.64	$ 0.56	$ 0.69
Head & Gut	**Volume K mt**	18.4	29.7	30.3	27.8	37.4	39.8
Head & Gut	**Price lb $**	$ 0.68	$ 0.62	$ 0.61	$ 0.38	$ 0.36	$ 0.41
Head & Gut	**Value share**	33%	38%	39%	22%	31%	35%
Fillets	**Volume K mt**	5.8	8.2	9.1	14.3	15.7	13.1
Fillets	**Price lb $**	$ 1.59	$ 1.35	$ 1.30	$ 1.26	$ 1.01	$ 1.17
Fillets	**Value share**	24%	23%	25%	37%	36%	32%
Surimi	**Volume K mt**	8.5	12.3	14.7	13.4	10.6	9.8
Surimi	**Price lb $**	$ 1.19	$ 0.89	$ 0.85	$ 0.97	$ 0.76	$ 0.96
Surimi	**Value share**	27%	23%	26%	27%	18%	20%
Roe	**Volume K mt**	1.7	3.5	3.1	0.5	1.1	2.4
Roe	**Price lb $**	$ 3.07	$ 2.03	$ 1.22	$ 1.39	$ 1.80	$ 1.83
Roe	**Value share**	14%	15%	8%	2%	4%	9%

Table 3c. Pollock U.S. trade and global market data. Global production (thousand metric tons), U.S. share of global production, GOA share of global production; 2011-2013 average, and 2014-2019.

	Avg 11-13	2014	2015	2016	2017	2018
Global Pollock Catch K mt	3,243	3,245	3,373	3,476	3,488	-
U.S. Share of Global Catch	40%	44%	44%	44%	44%	-
GOA share of global	3%	4%	5%	5%	5%	-

Source: NMFS Alaska Region Blend and Catch-accounting System estimates; NMFS Alaska Region At-sea Production Reports; and ADF&G Commercial Operators Annual Reports (COAR). Data compiled and provided by the Alaska Fisheries Information Network (AKFIN). FAO Fisheries & Aquaculture Dept. Statistics http://www.fao.org/fishery/statistics/en. NMFS Alaska Region Blend and Catch-accounting System estimates.

Table 4a. First stage ecosystem indicator analysis for GOA pollock 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 GOA pollock of the current year conditions relative to 1 standard deviation of the long-term mean (yellow = average, blue = good, red = poor, no fill = no current year data).

Title	Description	Recent
Annual Heatwave	Regional daily mean sea surface temperatures from NOAA climate model processed following Hobday et al., 2016 to obtain marine heatwave cumulative intensity. Please contact S. Barbeaux for more details.	🟥 +
Summer Bottom Temperature	Average summer bottom temperature (ºC) over all hauls of the RACE GOA shelf bottom trawl survey. Available from AKFIN or online survey database.	●
Spring Copepods Larvae Shelikof	Mean abundance of small copepods (< 2 mm) in core Shelikof area measured in log scale numbers per meter cubed with associated rapid zooplankton assessment (Kimmel et al., 2019)	🟨 ●
Summer Copepods YOY Shelikof	Mean abundance of large copepods (> 2 mm) in core Shelikof area measured in log scale numbers per meter cubed with associated rapid zooplankton assessment (Kimmel et al., 2019)	-
Summer Euphausiid Abundance Kodiak	Acoustic backscatter per unit area classified as euphausiids and integrated over the water column and across Kodiak core survey area from MACE summer survey (Ressler et al., 2019)	-
Auklet Reproductive Success Chowiet	Proportion of parakeet auklet nest sites with fledged chicks from total nest sites with eggs laid from Chowiet Island (Higgins et al., 2018)	●
Spring Pollock CPUE Larvae Shelikof	Mean abundance of larval pollock taken in bongos from core sampling area in Shelikof Strait during EcoFOCI spring survey with rapid assessment (Rogers et al., 2019)	🟥 -
Summer Pollock CPUE YOY Shelikof	Mean abundance of YOY pollock taken in midwater trawl from core area in WGOA area during EcoFOCI summer survey with rapid assessment (Rogers et al., 2019)	+
Summer Pollock Condition YOY Shelikof	Body condition of YOY pollock taken in midwater trawl from core area in WGOA area during EcoFOCI summer survey with rapid assessment (Rogers et al., 2019)	●
Summer Pollock CPUE YOY Kodiak	Catch per unit effort of YOY pollock in beach seine from fixed sites in nearshore Kodiak survey (Laurel et al., 2019)	+

Pollock Relative Biomass YOY Aiktak	Relative biomass of pollock measured from screening burrows of tufted puffins diets at Aiktak Island (Youngren et al., 2019)	●
Summer Pollock Predation Age-1	Predation mortality estimates of age-1 pollock from multiple data sources and models (Barnes et al., *In Review*)	●
Summer Pollock Euphausiid Diet Juvenile	Proportion-by-weight of pollock taken from summer bottom trawl survey samples in GOA (K. Aydin, *pers. commun.*)	-
Fall Pollock Condition Adult Fishery	Length-weight regression of pollock sampled by observers in the fall pollock fishery (M. Dorn, *pers. commun.*)	●
Winter Pollock Condition Adult Acoustic	Length-weight regression of pollock sampled in Shelikof Strait during the late winter MACE acoustic survey (M. Dorn, *pers. commun.*)	-
Summer Pollock Center of Gravity East	Biomass-weighted average of the location of extrapolation-grid cells in northings or eastings from spatio-temporal model of pollock in the summer bottom trawl survey (Thorson and Barnett, 2017)	●
Summer Pollock Area Occupied	Area required to contain the population at its average biomass from spatio-temporal model of pollock in the summer bottom trawl survey (Thorson and Barnett, 2017)	+
Arrowtooth Biomass Assessment	Total biomass estimates from arrowtooth flounder stock assessment model output (Spies et al., 2017)	●
Steller Sea Lion Adult Counts	Non-pup estimates of Steller sea lions from the GOA portion of the western Distinct Population Segment (ESR GOA 2018)	●

Table 4b. First stage socioeconomic indicator analysis for GOA pollock 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 GOA pollock of the current year conditions relative to 1 standard deviation of the long-term mean (yellow = average, blue = good, red = poor, no fill = no current year data).

Title	Description	Recent
Winter-Spring Pollock CPUE Fishery	Catch of pollock in tons/hour from the winter-spring (first trimester) of the pollock fishery (M. Dorn, *pers. commun.*)	+
Summer-Fall Pollock CPUE Fishery	Catch of pollock in tons/hour from the summer-fall (third trimester) of the pollock fishery (M. Dorn, *pers. commun.*)	●
Annual Pollock Real Ex-vessel Price	Estimate of real ex-vessel value in price per pound inflation adjusted to 2018 USD (B. Fissel, *pers. commun.*)	●
Annual Pollock Roe per unit Catch	Roe per-unit-catch calculated as 1000*(roe production)/(retained catch) (B. Fissel, *pers. commun.*)	●
Annual Percent Revenue Pollock in Kodiak	Percentage of the total revenue Kodiak gets from the GOA pollock fishery (aka, local quotient) (S. Wise, *pers. commun.*)	+

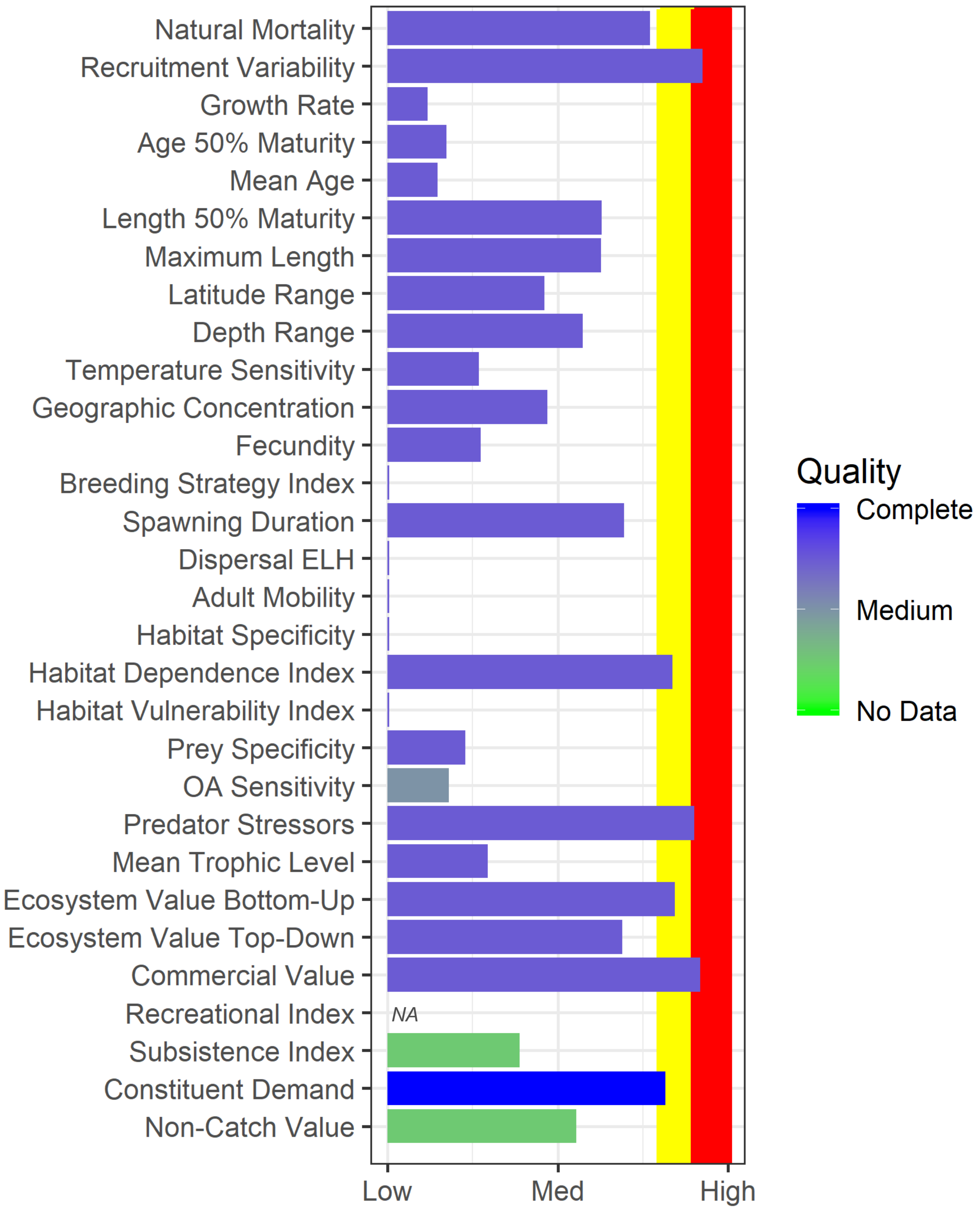

Figure 1. Baseline metrics for pollock graded as percentile rank over all groundfish in the FMP. Red bar indicates 90th percentile, yellow bar indicates 80th percentile. Higher rank values indicate a vulnerability and color of the horizontal bar describes data quality of the metric (see Shotwell et al., *In Review*, for more details on the metric definitions). Ecosystem indicators above and socioeconomic indicators below the horizontal black line.

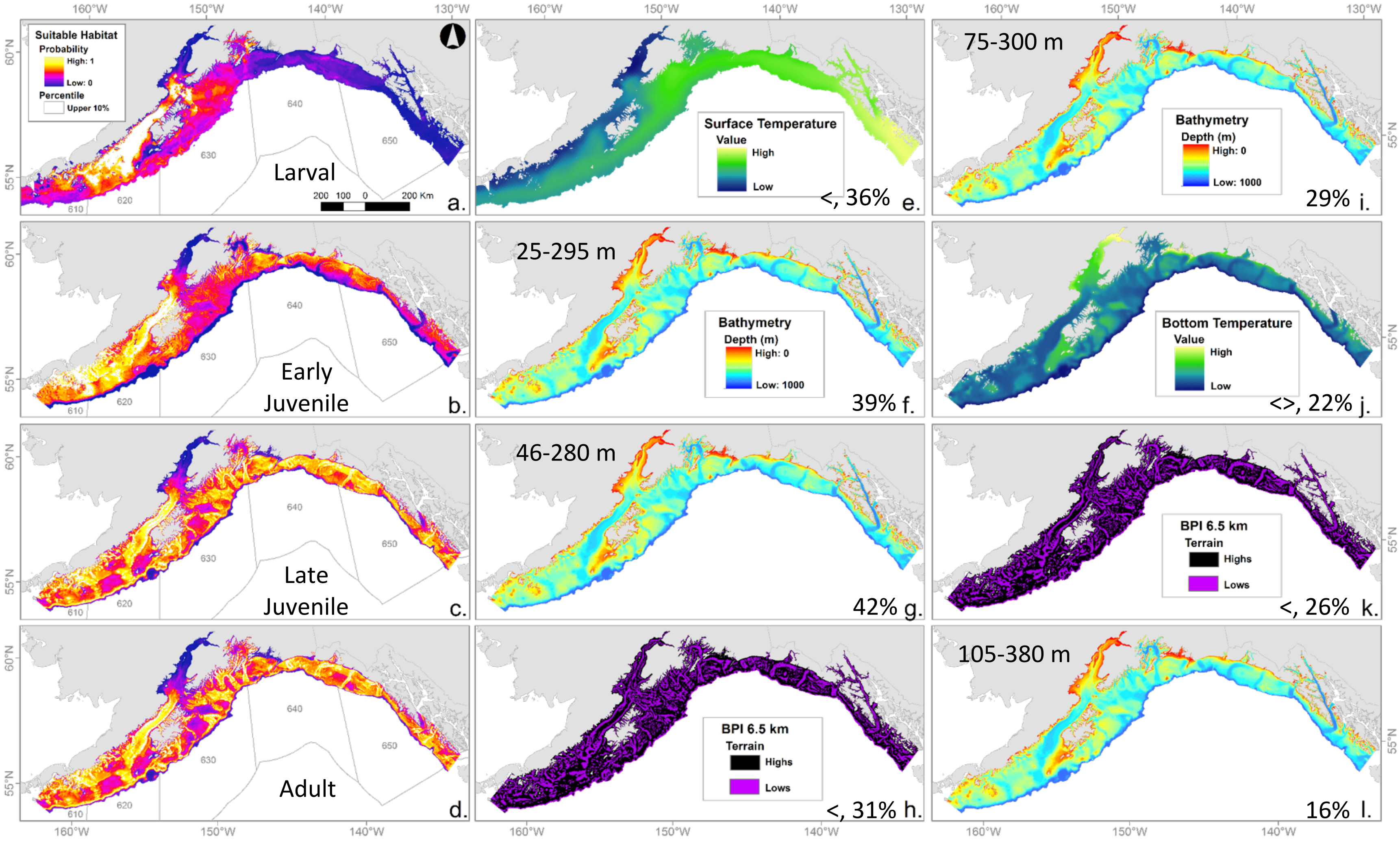

Figure 2. Pollock probability of suitable habitat by life stage (a = larval, b = early juvenile, c = late juvenile, and d = adult) with corresponding predictor habitat variables representing the highest (e = surface temperature, f = depth, g = depth, h = bathymetric position index) and second highest contribution (i = depth, j = bottom temperature, k = bathymetric position index, and l = depth). Upper 10 percentile of suitable habitat is shown in white within the probability of suitable habitat range (yellow to purple). Sign (<, >, <>) of the deviation from mean direction and the percent of contribution to predict suitability provided for each non-depth variable. Range provided for depth. See Shotwell et al., *In Review* for more details.

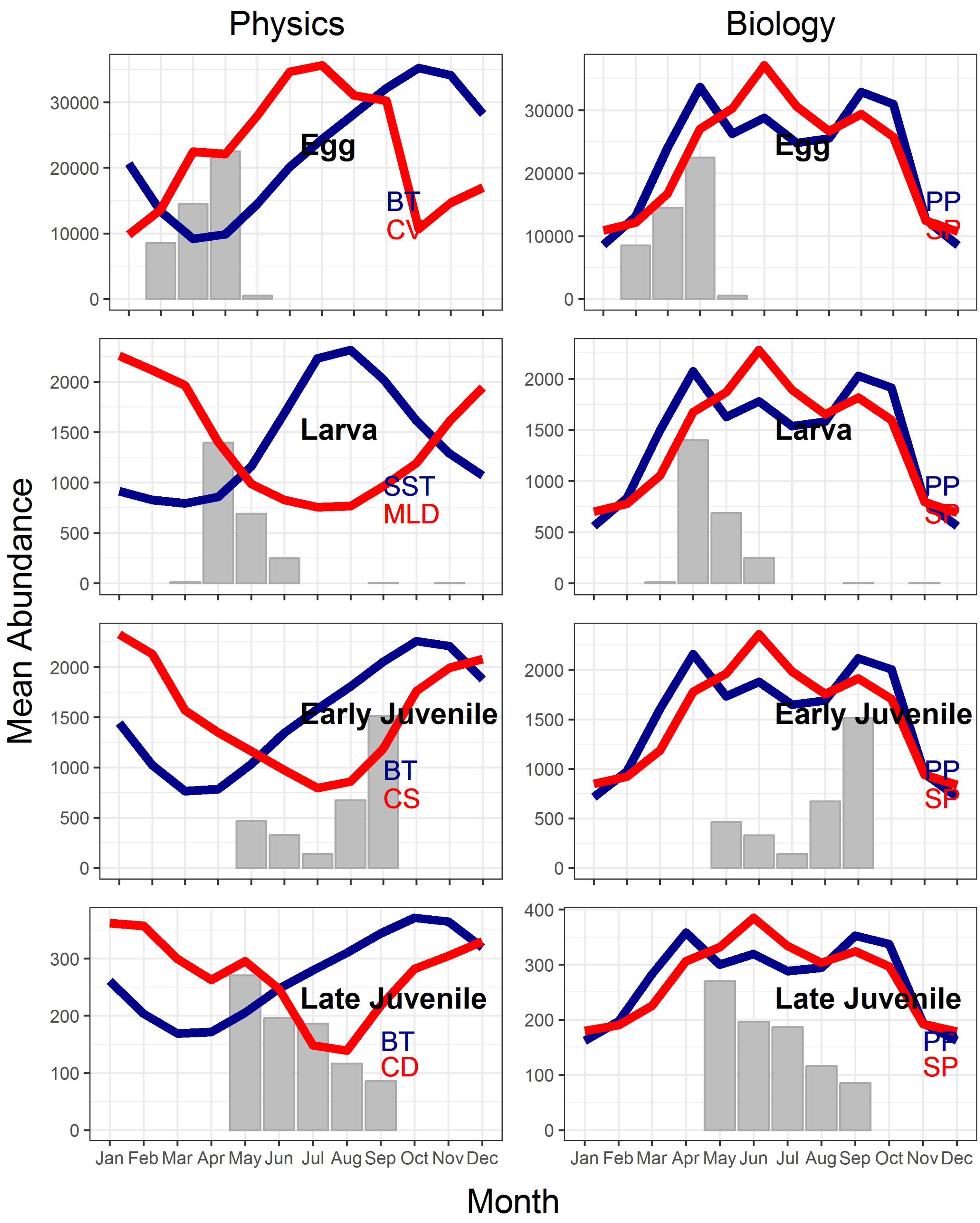

Figure 3. Pollock average abundance by month over all years available for the egg, larval (yolk-sac and feeding), nearshore juvenile, and offshore juvenile stages. Relevant climatologies from the hydrographic and plankton models provide physical and biological indices (SST = surface temperature, MLD = mixed layer depth, BT = bottom temperature, CD/CS/CV are current direction, speed and variability, PP/SP are primary and secondary productivity, see Laman et al., 2017, Gibson et al., *In Press*, for more details).

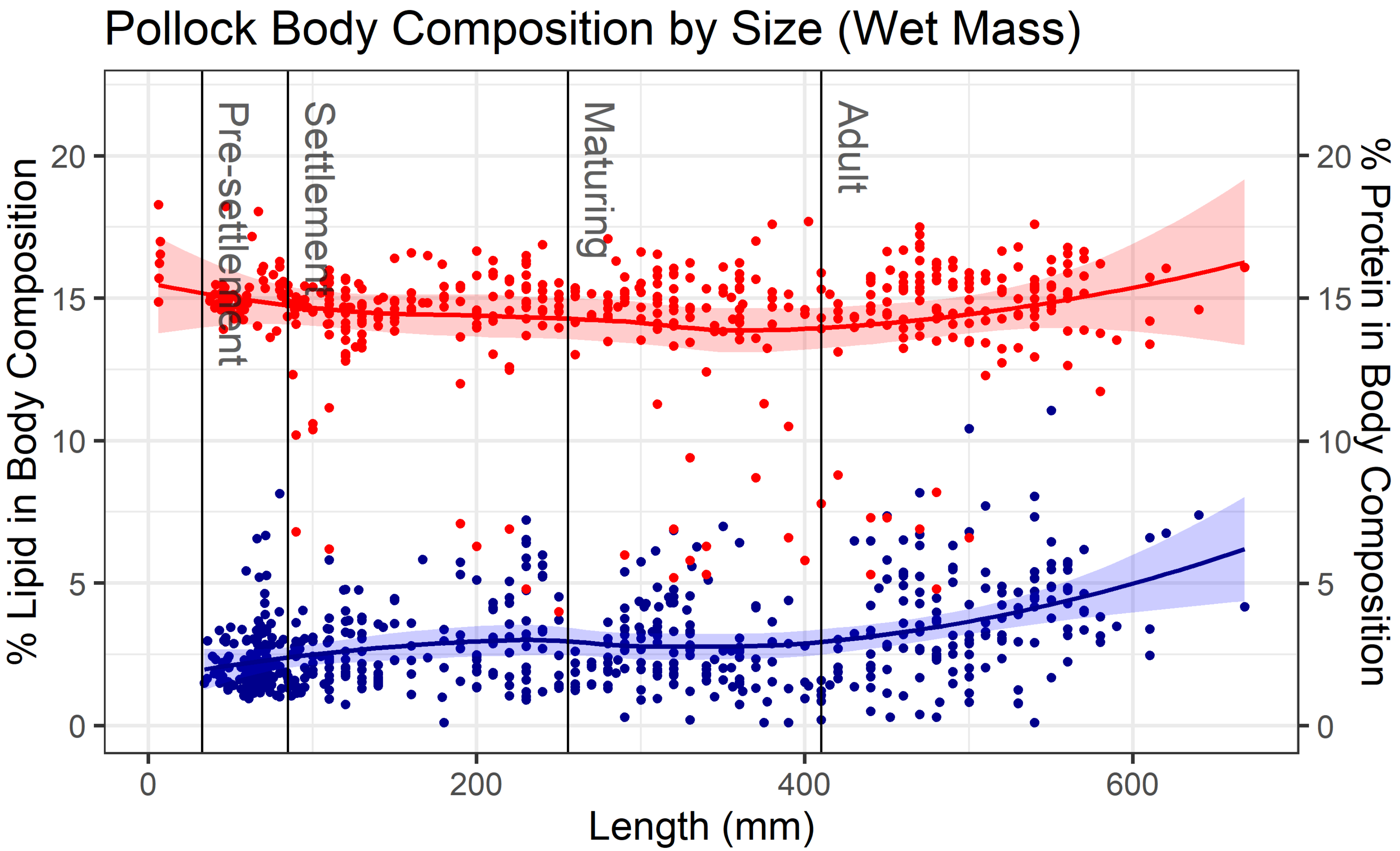

Figure 4. Percent body composition by length (mm), blue dots are % lipid by size, red dots are % protein by size and lines represent smoother (loess) for trend visualization. Horizontal lines depict the average size at different life stage transitions and the adult transition is based on size at 50% female maturity.

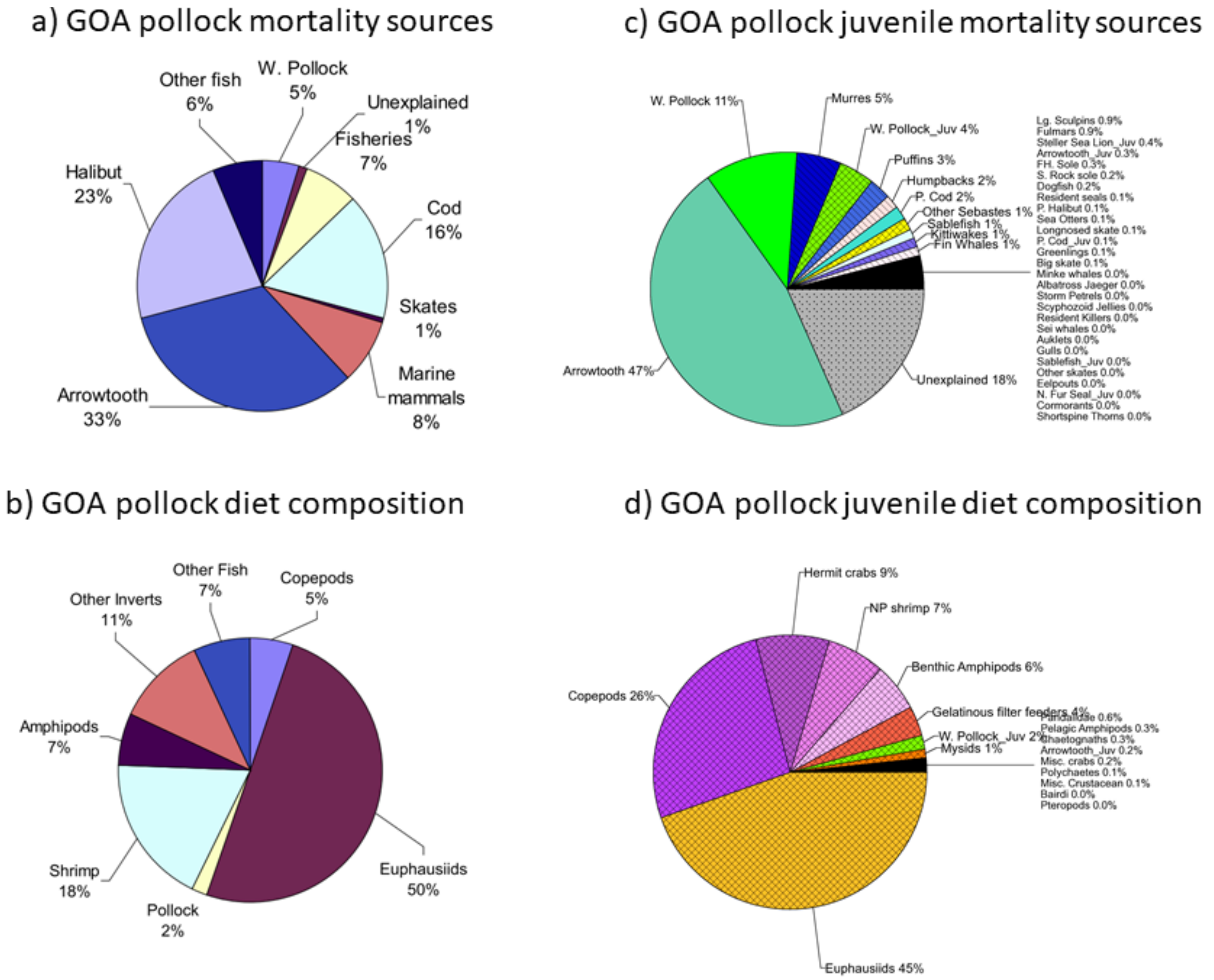

Figure 5. Sources of predation mortality for (a) adult (>20 cm) and (c) juvenile pollock (<20 cm) in the GOA, and diet composition for (b) adult and (d) juvenile pollock in the GOA. Reproduced from Gaichas et al., 2015 and Dorn et al., 2018. NOTE: The colors in each pie will be updated for the final document to all be consistent with respect to categories.

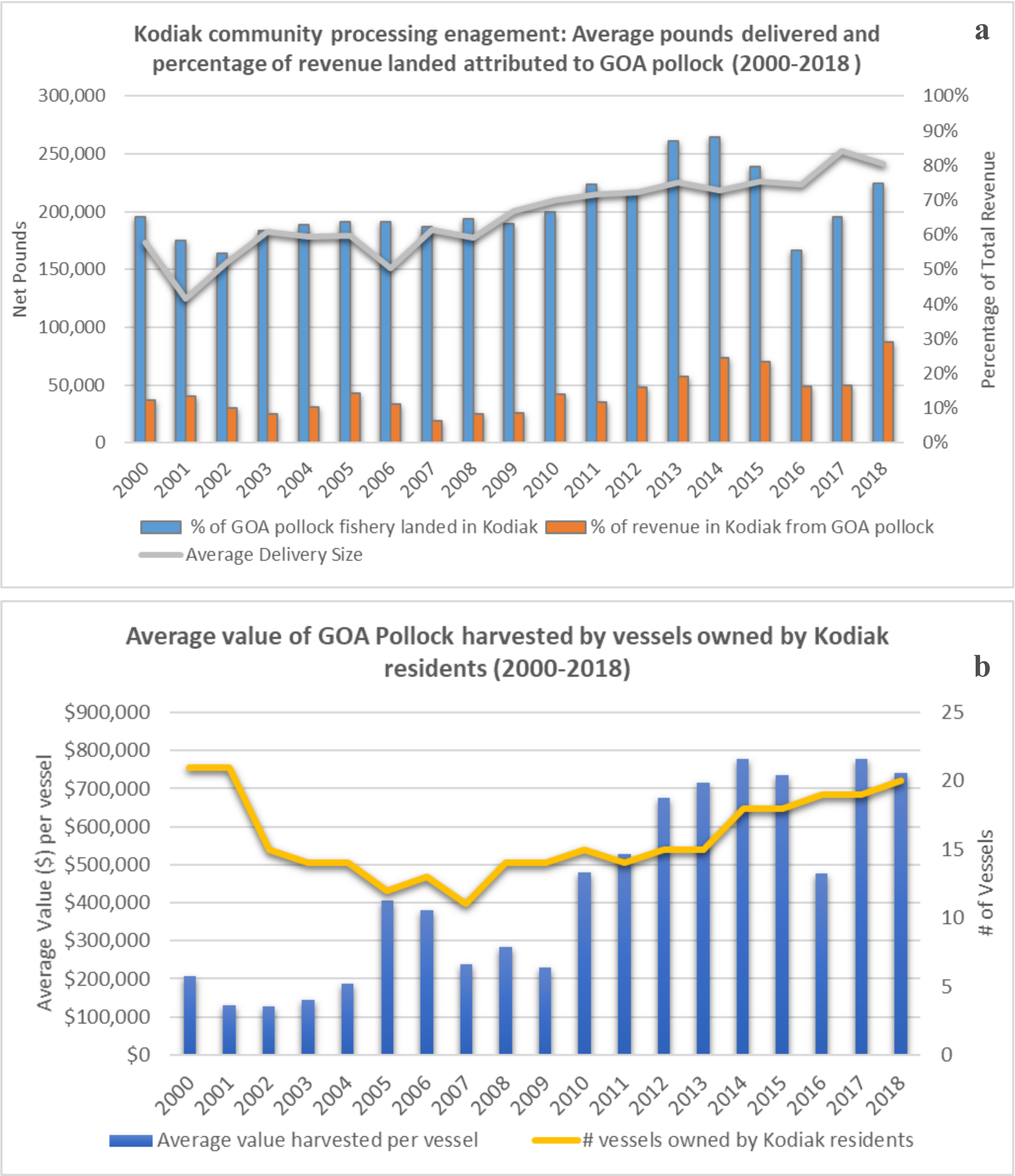

Figure 6. Community profile information for GOA pollock with (a) community engagement in processing GOA pollock for Kodiak expressed in average volume delivery, regional quotient, and local quotient percentage and (b) Kodiak harvest value per vessel and active vessels owned by residents.

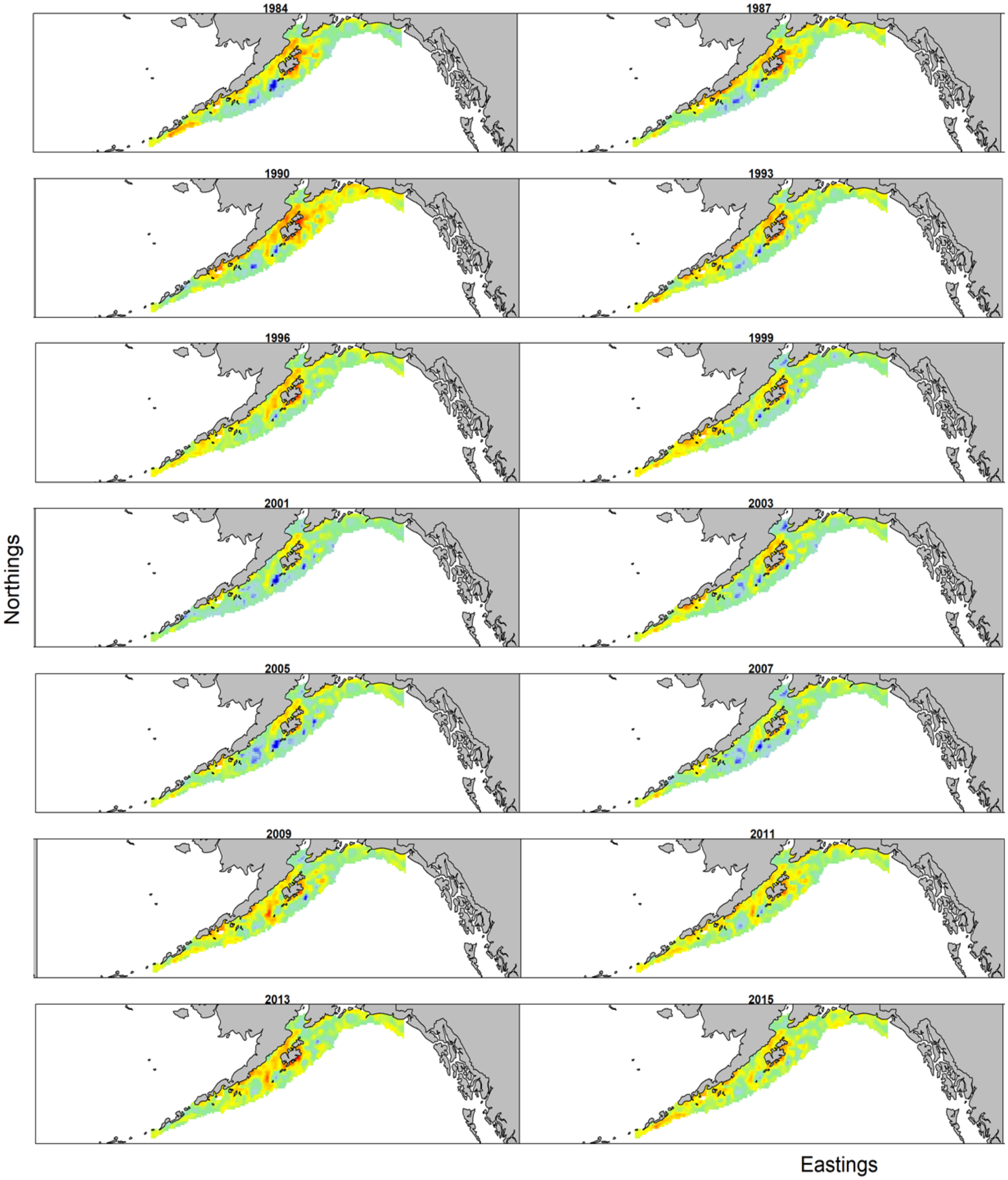

Figure 7: Spatio-temporal delta-generalized linear mixed model using standard settings for an "index standardization" model (Thorson 2019), implemented using the package VAST (Thorson and Barnett 2017) in the R statistical environment (R Core Team 2017). NOTE: this will be replaced with same graphic but for age 1 pollock in the final document.

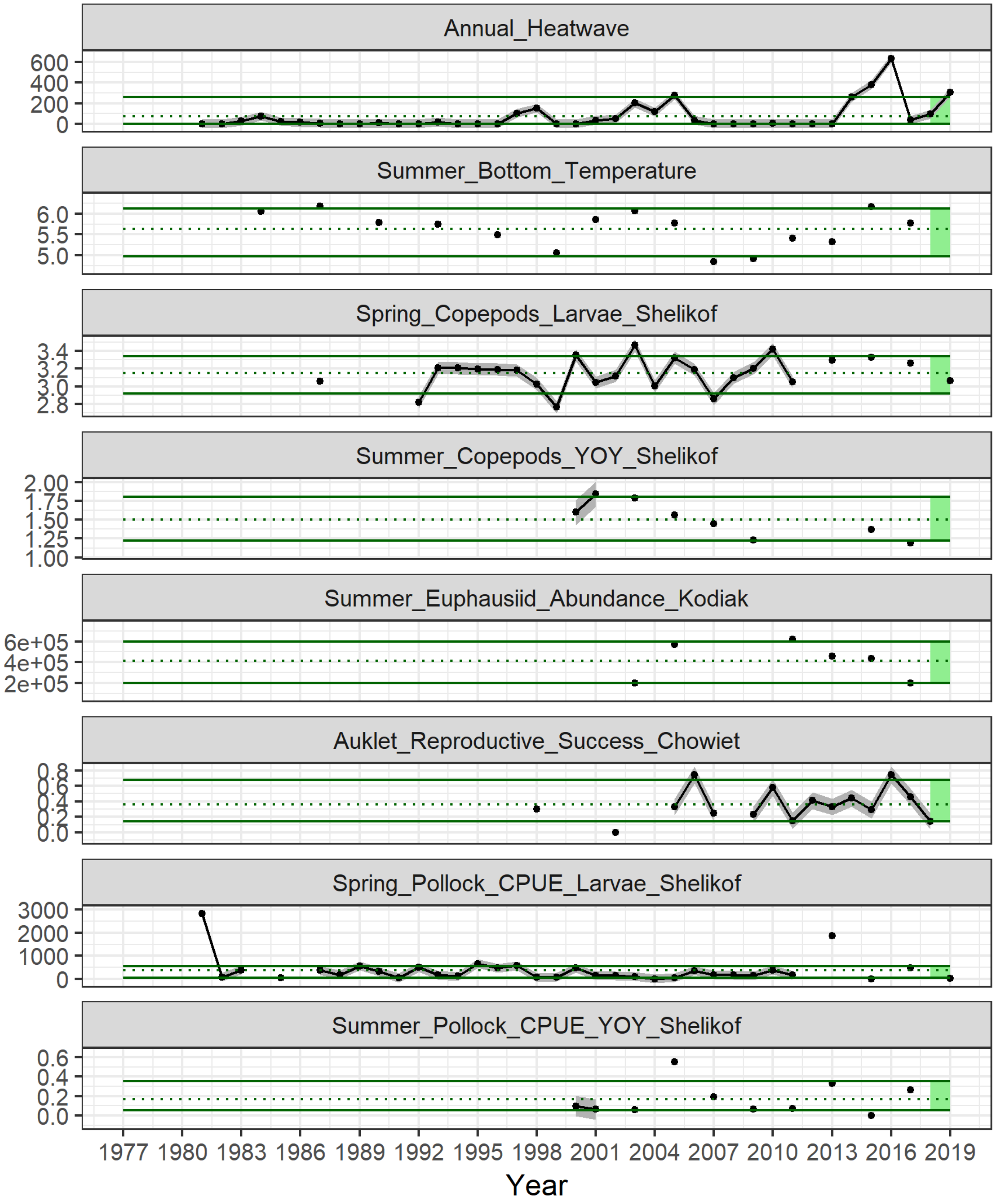

Figure 8. Selected indicators for GOA pollock with time series ranging from 1977 – present. Upper and lower solid green horizontal lines are 90th and 10th percentiles of time series. Dotted green horizontal line is mean of time series. Light green shaded area represents most recent year for traffic light analysis.

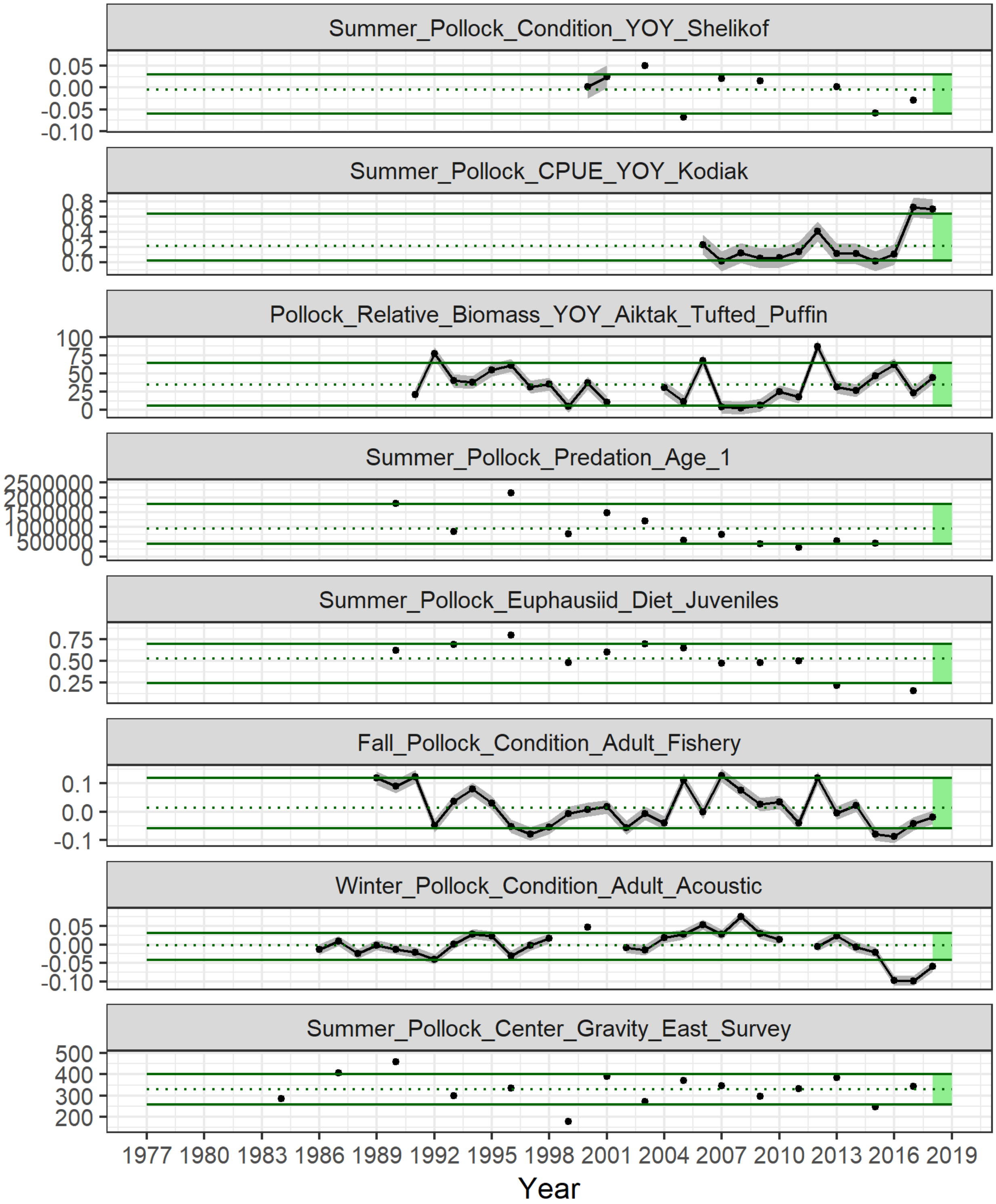

Figure 8 (cont.). Selected indicators for GOA pollock with time series ranging from 1977 – present. Upper and lower solid green horizontal lines are 90th and 10th percentiles of time series. Dotted green horizontal line is mean of time series. Light green shaded area represents most recent year for traffic light analysis.

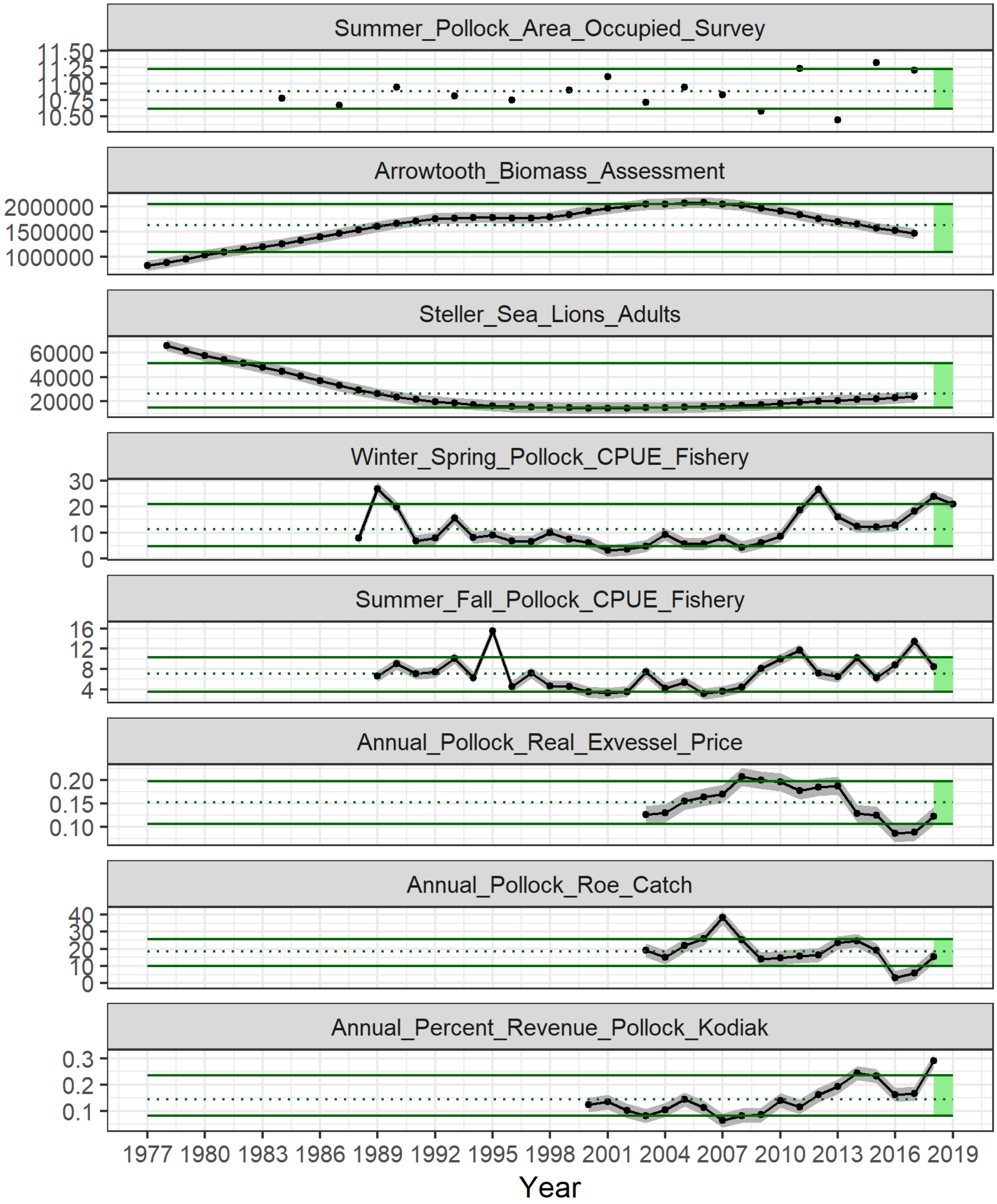

Figure 8 (cont). Selected indicators for GOA pollock with time series ranging from 1977 – present. Upper and lower solid green horizontal lines are 90th and 10th percentiles of time series. Dotted green horizontal line is mean of time series. Light green shaded area represents most recent year for traffic light analysis.

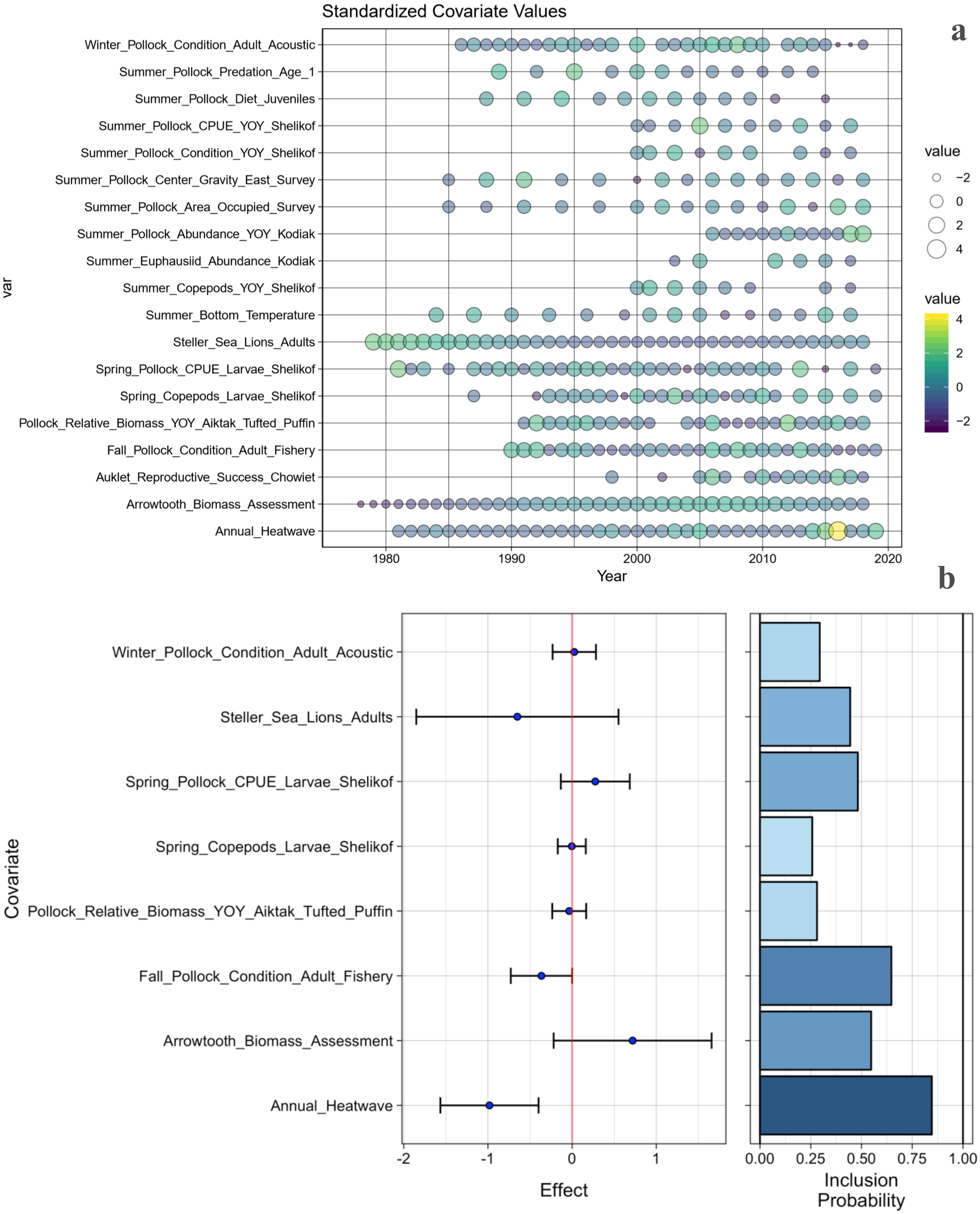

Figure 9: Bayesian adaptive sampling output showing (a) standardized covariates prior to subsetting and (b) the mean relationship and uncertainty (1 standard deviation) with log GOA pollock recruitment, in each estimated effect (left bottom graph), and marginal inclusion probabilities (right bottom graph) for each predictor variable of the subsetted covariate set.

NOTE: This will be completed for the final document in November.

Figure 10: Example one-page template for conducting a partial ESP of GOA pollock