Appendix 7A. Ecosystem and Socioeconomic Profile of the arrowtooth flounder stock in the Gulf of Alaska

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Executive Summary

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

National initiatives and North Pacific Fishery Management Council (NPFMC) Plan Teams and Scientific and Statistical Committee (SSC) recommendations suggest a high priority for conducting an ESP for the GOA arrowtooth flounder stock. In addition, annual guidelines for the Alaska Fisheries Science Center (AFSC) support research that improves our understanding of environmental forcing of ecosystem processes with a focus on variables that can provide direct input into or improve stock assessment and management. The GOA arrowtooth flounder ESP follows the standardized framework for evaluating ecosystem and socioeconomic considerations for GOA arrowtooth flounder, 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 arrowtooth flounder stock and present results of applying the ESP process through an indicator synthesis and subsequent indicator assessment. Analysis of the ecosystem and socioeconomic processes for GOA arrowtooth flounder by life history stage along with information from the literature identified a suite of indicators for testing and continued monitoring within the ESP. The GOA arrowtooth flounder stock was evaluated at the intermediate and advanced indicator analysis stages using both an external and integrated Dynamic Structural Equation Model (DSEM). Highlights of the indicator assessment are summarized below as considerations that can be used for evaluating concerns in the main stock assessment or other management decisions.

Acceptable Biological Catch (ABC) Considerations:

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

Predictive Indicators:

- Note: these will be completed once the final data is compiled for the full ESP in November

Contextual Indicators:

- Note: these will be completed once the final data is compiled for the full ESP in November

Fishery-Informed Indicators:

- Note: these will be completed once the final data is compiled for the full ESP in November.

Total Allowable Catch (TAC) Considerations:

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

- All ABC considerations above can be used to inform TAC considerations within the purview of the NPFMC TAC setting process.
- Note: these will be completed once the final data is compiled for the full ESP in November

Responses to SSC and Plan Team Comments on ESPs in General

"*The SSC strongly recommends that additional coordination among AFSC, NMFSAKRO, Council staff, Plan Team representatives, and SSC representatives be readily undertaken to ensure that the best scientific information available is being applied in support of National Standards 1, 2, 4, 6 and 8. This coordination should address the multiple Council decision-informing sources of social, economic and community information and include different scales of resolution (communitylevel, ecosystem-level, FMP-level, aggregated-species, single-species).*

The SSC reiterates convening a working group or workshop that can develop species-level and ecosystem-level indicators appropriate for the ESPs and ESRs to complement ACEPO and the Economic SAFEs…" (SSC, December 2023)

"*The Council recommends NOAA and Council staff review available data and recommend species-level socio-economic indicators appropriate for the Ecosystem and Socioeconomic Profiles (ESPs) to complement FMP-level data in ACEPO and the Economic SAFE report. The indicators could potentially reflect employment, scale and distribution of participation, markets and product form, major cost components, and other factors associated with each species warranting an ESP, if reliable and timely data are available at this level. These indicators would be reviewed by the SSC.*" (Council, December 2023)

We grouped these two recommendations together because our response applies to both recommendations. In summer of 2024, Council staff conducted several meetings with staff from the Alaska Regional Office and staff from the AFSC Economic and Social Sciences Research Program to discuss current products that include social, economic, and community information and ideas to address the concerns raised by the SSC and Council. The group determined that the timing of the ESPs with the specification process and current issues in the sablefish fishery provided an opportunity to produce a first product aimed at addressing the request from the SSC and the Council using the sablefish ESP as a case study. That suite of new socioeconomic indicators was provided to the Plan Teams and the SSC in the November and December 2024 meetings for review. The group that met over the summer also created a document describing the social and economic products created to inform the groundfish TAC-setting process. This document describes the ESP process, provides a list of socioeconomic information currently included in the ESPs, and includes a current list of recommended ESPs since their introduction in 2016. The SSC and Council plan to have a follow-up discussion of this document and the sablefish ESP to provide feedback on the role of socioeconomic indicators in ESPs and other products for the Council. This discussion was scheduled for June 2025, but has been delayed due to staff capacity until December 2025 or later. Once the discussion occurs, we will follow the guidance of the SSC and Council regarding which socioeconomic indicators to include in ESPs for informing TAC setting.

"*The CPT [Crab Plan Team] discussed a new approach to categorize ESP indicators into predictive and contextual indicators. ... The SSC provisionally supports this approach, but would like the opportunity to review an example ESP where this approach is applied before fully endorsing it.*" (SSC, June 2025)

Several crab ESPs are putting forward trial versions of the new approach and are being reviewed at the September Crab Plan Team. We intend to review the feedback from these initial examples from the CPT and the SSC and intend to follow the recommended approach with the finalized GOA arrowtooth flounder ESP at the November Groundfish Plan Team.

Responses to SSC and Plan Team Comments Specific to this ESP

"*The Teams recommend producing SPECs for the other focal species from the GOA IERP project next (Pacific cod, walleye pollock, Arrowtooth flounder, and POP). If time allows, it would be useful to produce a SPEC for a low-data species (perhaps "other rockfish," as it is a habitat-focused assemblage), and to include crab through interaction with the Crab Plan Team.*" (Groundfish Plan Team, 2016)

We have initiated an Ecosystem and Socioeconomic Profile or ESP for this stock in 2025. This is the updated terminology for what used to be known as the SPECs or Stock Profile and Ecosystem Considerations prior to the ESP formalization in 2017. This document is the first draft of that ESP and is designed to start the review process for which indicators to include and what indicator analysis to pursue for this ESP. We provide a suite of potential indicators and introduce a new indicator analysis method. In November we will incorporate any feedback received from the Plan Team and SSC on this document.

"*There appears to be a shift to lower recruitment in recent years, beginning in 2006 (i.e., the 2005 year class). The Team recommends investigating whether these lower recruitments are related to environmental conditions in the GOA.*"
"*The Team noted that the decrease in biomass began before the recent heatwaves in the north Pacific and is similar to drops observed in other flatfish during this time and may be potentially linked to extended poor recruitment during cold pattern in 2006-2007.*" (GOA Plan Team, November 2019)

We investigate these lower recruitment trends through the Ecosystem and Socioeconomic Profile (ESP) framework and provide a draft ESP at the September Plan Team for review of progress. An external Dynamic Structural Equation Model (DSEM) has been developed for this stock and is included in this draft ESP report. We plan to explore a few more external DSEMs for this stock following review of this document and then incorporate the best model into an integrated DSEM within the Rceattle platform that has been recommended for assessment of this stock. We plan to present the external model evaluation and the integrated model run as a research ecosystem model in the final ESP to be submitted for review at the November Plan Team. We also plan to have a discussion regarding the use of this research ecosystem model for informing management decisions. One avenue may be to use the ecosystem research model in the projections for off-cycle years to incorporate new ecosystem information in the advice.

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 it with 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. This 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., 2023). 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; Lynch et al., 2018) and recommended by the NPFMC Groundfish and Crab Plan Teams and the SSC.

This ESP for GOA arrowtooth flounder (*Atheresthes stomias*) follows the template for ESPs (Shotwell et al., 2023) and replaces the previous ecosystem considerations section in the main GOA arrowtooth flounder stock assessment and fishery evaluation (SAFE) report. Information from the original ecosystem considerations section may be found in Shotwell et al., 2021.

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

An ESP was recommended for GOA arrowtooth flounder by the Groundfish Plan Team in 2016 (NPFMC, 2016). The national initiative scores and AFSC research priorities also support conducting an ESP for the GOA arrowtooth flounder stock. The high biomass and important ecosystem role of arrowtooth flounder as a predator in the GOA ecosystem created a medium score for stock assessment prioritization (Methot, 2015). The vulnerability scores were moderate based on the productivity susceptibility analysis (Ormseth and Spencer, 2011). The new data classification scores for GOA arrowtooth flounder suggest a data-rich stock with high quality data for catch, size/age composition, and abundance, and moderate quality data for life history category and ecosystem linkages (Lynch et al., 2018). These initiative scores and data classification levels suggest a moderate to high priority for conducting an ESP for GOA arrowtooth flounder. Additionally, AFSC research priorities support studies that improve our understanding of environmental forcing of ecosystem processes with focus on variables that provide direct input into stock assessment and management (AFSC, 2021).

Data

Initial data collections were derived from Ecosystem Status Report (ESR) contributions and through personal communication with the contact authors of the contribution (e.g., Ressler et al., 2019). Essential fish habitat (EFH) model output and maps were provided by personal communication with the editors of the EFH update (2024 EFH Update Omnibus). Data were also collected from the literature and a variety of process studies, surveys, laboratory analyses, accounting systems, and regional reports (Table 7A.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), Resource Assessment and Conservation Engineering (RACE) Division, Resource Ecology and Fisheries Management (REFM) Division, Auke Bay Laboratory (ABL) Division) and other agencies (e.g., Alaska Department of Fish & Game). Data for juveniles through adults were consistently available from the AFSC bottom trawl surveys, and the North Pacific Observer Program administered by the Fisheries Monitoring and Analysis (FMA) division. Environmental data were derived from multiple remote sensing databases and from personnel at several universities (e.g., University of Washington).

The majority of GOA arrowtooth flounder economic value data were compiled and provided by the Alaska Fisheries Information Network (AKFIN). GOA arrowtooth flounder ex-vessel pricing data were derived from the NMFS Alaska Region Blend and Catch Accounting System, the NMFS Alaska Region At-sea Production Reports, and the ADFG Commercial Operators Annual Reports (COAR). GOA arrowtooth flounder first wholesale data were from NMFS Alaska Region At-sea and Shoreside Production Reports and ADFG 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), NOAA Fisheries, Fisheries Statistics Division, Foreign Trade Division of the U.S. Census Bureau (http://www.st.nmfs.noaa.gov/commercial-fisheries/foreign-trade/index), and the U.S. Department of Agriculture (http://www.ers.usda.gov/data-products/agricultural-exchange-rate-data-set.aspx). Information regarding the community involvement and percent value was derived from reports of the Community Development Quota (CDQ) Program.

Indicator Synthesis

In this synthesis section, we provide information on relevant ecosystem and/or socioeconomic processes through a thorough life history evaluation of the GOA arrowtooth flounder stock. We summarize important processes that may be helpful for identifying productivity bottlenecks and dominant pressures on the stock productivity with a conceptual model detailing ecosystem processes by life history stage (Figure 7A.1, Table 7A.2). We also evaluate processes directly involved in the prosecution of the fishery, economic drivers of fishery performance and fleet behavior, and community information to capture the scope of socioeconomic processes relevant to the GOA arrowtooth flounder stock (Table 7A.3).

Ecosystem Processes

We derived this ecosystem synthesis from a manuscript that had been specifically designed to input directly into an ESP when one was created for GOA arrowtooth flounder. The majority of the following text in this section is from Shotwell et al., 2022.

One of the most abundant groundfish species in the GOA, arrowtooth flounder (or arrowtooth) is currently managed as a single stock in the GOA and occurs in depths from 20 to 800 m, with highest catch-per-unit-effort between 100 and 300 m (Spies et al., 2019). There is some evidence that arrowtooth migrate to deeper water as they grow (Zador et al., 2011) and that larger fish may move to deeper water in winter and shallower water in summer (Spies et al., 2019). Size range breaks for the habitat distribution models were developed from the literature and stock assessment reports and were determined for larval (< 40 mm), early juvenile (< 160 mm), late juvenile (< 350 mm), and adult stages (≥ 350 mm) arrowtooth. Highly suitable larval habitat was characterized by bottom depth (200-900 m, 44%) and low current fluctuations (i.e., variability in surface ocean current direction, Laman et al., 2017) (18%) (Figure 7A.2, recreated from Shotwell et al., 2022). During the 2011 and 2013 GOAIERP field years, arrowtooth larvae were comparable in abundance in the eastern and western GOA but larval size distributions suggest that spawning may have occurred earlier and/or larval growth rates may have been slightly higher in the eastern survey area relative to the west (Siddon et al., 2019). Seasonal progression in distribution of larvae indicates transport onto the shelf from deep water with apparent enhanced shoreward transport in the major canyons intersecting the slope (e.g., Amatuli Trough and Outer Shelikof Strait) where "hot-spots" in larval abundance are observed (Doyle et al., 2018; Goldstein et al., 2020). On-shelf transport of larvae seems critical, and variability in such transport may have a significant influence on larval survival to the early juvenile settlement stage (Goldstein et al., 2020). Early and late juvenile habitat were very similar and indicative of habitat generalists with more restricted depths than the larval stage (30-200 m at 40% and 75-235 m at 55%, respectively), but including fine- and large-scale low-lying areas (e.g., flats, embayments, channels, and gullies, 19% and 16%, respectively), low bottom temperature (14% and 12%, respectively), and low tidal current (12% and 15%, respectively) (Figure 7A.2, recreated from Shotwell et al., 2022). Settled early juveniles (age-0) are more ubiquitous across depths in the GOA than previously understood and are encountered throughout coastal and shelf waters, and older juveniles also occur in deep water along the slope (Doyle et al., 2018). Additionally, arrowtooth juveniles were largely absent from the nearshore sampling during the GOAIERP indicating that inshore areas and bays are not used extensively as nursery habitat for this species (Doyle et al., 2018). Adult habitat included more depth range (100-470 m, 54%) than juvenile habitat but still indicative of habitat generalists utilizing benthic habitat extensively throughout the GOA from east to west, with low bottom temperature (20%), low-lying areas (9%), and low tidal current (7%). Recent trends in recruitment and biomass may indicate that arrowtooth has reached some maximum threshold in terms of habitat utilization in the GOA, and that density-dependent effects at the juvenile stage may dominate population trends going forward (Spies et al., 2019; Doyle et al., 2018).

Historical ichthyoplankton data indicate peak release of arrowtooth eggs in deep water over the slope in January to early February (Shotwell et al., 2022, Figure 3a) followed by a more extended peak in recently hatched larvae January to mid-March and continued presence of larvae in the plankton through summer months (Doyle and Mier, 2016). Arrowtooth exhibit an early life strategy termed a "holding pattern" because of slow larval growth in cold, food poor environments during winter to early spring while remaining almost exclusively over deep water (Doyle and Mier, 2016). The extended pelagic larval phase is characterized by very slow growth of larvae through April with an increased growth rate from May-June in association with warming water and spring peak in plankton production (Shotwell et al., 2022, Figure 3b). This slow growth during winter is considered advantageous in terms of extending utilization of lipid reserves prior to first-feeding. However, this strategy can cause an extreme mismatch with prey availability for first-feeding arrowtooth larvae during winter due to both a spatial and temporal separation from spring zooplankton production on shelf. Two hypotheses suggest potential mitigation of this mismatch by 1) "holding pattern" physiology which confers endurance during early ontogeny because of extended lipid reserves at very low physiological rates and 2) spatial/temporal synchrony with winter production of eggs/nauplii of the Necoalanus copepods that may be an important food source for first-feeding larvae (Doyle and Mier, 2016; Doyle et al., 2018; Doyle et al., 2019). These proposed mismatch mitigating factors may provide population resilience under "normal" conditions in the GOA, but arrowtooth early ontogeny may be particularly vulnerable to anomalous conditions such as significant warming events that could potentially speed up larval growth rates and/or disrupt timing of production of larval zooplankton prey. There was a positive (but weak) correlation between larval length and water temperature across the late spring GOA time series which may be indicative of enhanced growth during "warm" years (Doyle and Mier, 2016).

Similar to sablefish, early life stages of arrowtooth (Figure 7A.3, pre-settlement to settlement phases, recreated from Shotwell et al., 2022), have a fairly stable lipid and protein content. These fish are putting energy toward growth and not toward lipid energy storage. Average energy density of age-0 pelagic arrowtooth showed no change with size, although there were some interannual differences, which were attributed to changes in temperature and diet composition. Large copepods were most important in the diets of these fish, with small copepods and decapods less abundant but persistent (Debenham et al., 2019). Newly settled demersal arrowtooth from ancillary sampling showed a distinct shift from a copepod-dominated diet to one dominated by shrimp, euphausiids, and capelin even though pelagic feeding was still occurring. Energy density of the "settled" fish continued to remain stable as size increased, and held true until fish reached ~320 mm, a size fairly close to the size associated with 50% maturity. This implies resilience during age-0 to a range of biophysical conditions such as temperature and food availability (Debenham et al., 2019). Percent lipid content increased rapidly as arrowtooth matured to the adult stage and then appeared to level off at around 600 mm (Figure 7A.3, recreated from Shotwell et al., 2022), suggesting changes in diet following sexual maturity as may be expected in a generalist apex predator such as arrowtooth (Yang et al., 2006).

On-shelf transport may be an important process for larvae and early juveniles that were spawned in deep water along the continental slope to reach nurseries on the continental shelf for settlement. An IBM for arrowtooth provided new insight into potential larval drift patterns during the extended planktonic phase from winter spawning to summer settlement. High dispersion distances and complex drift trajectories included on-shelf and off-shelf transport and entrainment in features such as eddies and meanders (especially in the eastern GOA where the shelf is narrow) (Stockhausen et al., 2019). Evaluation of settlement success for larvae originating in deep water to the southwest of Kodiak Island suggests a high probability for these larvae to be "lost" to the GOA system (Stockhausen et al., 2019), and the role of eddies in retaining those larvae near nursery habitats in the GOA to enhance settlement magnitude and juvenile recruitment (Goldstein et al. 2020). The extended IBM for pollock (Parada et al., 2016) suggests that larvae that are advected outside of the GOA ecosystem may also have a "second chance" at settlement if they are transported through the Aleutian Island passes to suitable habitat in the southeast Bering Sea shelf (Doyle et al., 2018). This same opportunity could be possible for GOA arrowtooth flounder if they were swept into the Bering Sea shelf and a recent sablefish IBM suggests tracking particles exiting the GOA system or expanding the extent of the regional ocean model underlying the IBM would be allow for this exploration (Gibson et al., 2023).

Socioeconomic Processes

An economic performance report or EPR was previously prepared for this stock and other GOA flatfish stocks in 2021 (Ben Fissel, *pers. commun.*). The majority of the text in this section is from that document and will be updated for the final document with new information in November.

Arrowtooth flounder is the most significant flatfish species in the GOA in terms of market value and volume. The commercial fishery has been historically limited by the poor flesh quality caused by a proteolytic enzyme, but technological advances have allowed a directed fishery to emerge. Arrowtooth flounder is harvested by a combination of catcher vessels and catcher processors in the GOA. In 2020 it accounted for 81% of the retained GOA flatfish catch and 65% of the ex-vessel value (Table 7A.3a). Flatfish are targeted using trawl gear and are caught both as a target species and in fisheries targeting other groundfish. Catcher processors and catcher vessels participate in the fishery, though catcher processors primarily catch arrowtooth. Significant quantities of arrowtooth are also caught in the BSAI, however, the GOA has accounted for more than of 60% of the total Alaska catch of arrowtooth catch in recent years and 67% in 2020. Catcher vessels typically account for approximately 50-80% of the retained catch, though this can vary significantly year over year depending on how heavily catcher processors prosecute arrowtooth fishing.

GOA flatfish catches can be constrained by halibut interactions and halibut avoidance can influence seasonal fishing patterns. In 2014, Amendment 95 (regulations to reduce GOA halibut PSC limits) implemented changes to the accounting of halibut PSC sideboard limits for Amendment 80 vessels that allowed the fleet to increase their groundfish catch, mostly arrowtooth flounder. Also, Amendment 95 revised halibut PSC limit apportionments used by trawl catcher vessels from May 15 through June 30 that extended the deep-water species fishery allowing for an increase in arrowtooth flounder catch for this fleet. The GOA flatfish undergo relatively low fishing pressure and harvests are routinely 10-30% of the TAC in recent years. Arrowtooth abundances have remained stable since 2012, although abundance appears to have little influence on retained catch. Flatfish are typically only 5-10% of the Central Gulf's ex-vessel value because they are a comparatively lower priced species.

First-wholesale value of GOA flatfish in 2020 was $14.5 million, which was down slightly from 2019 and below the 2011-2015 average of $24.5 million (Table 7A.3b). Commensurate with the decrease in catch, production volume fell 7% to 14.1 thousand t. Most flatfish species are primarily processed as headed-and-gutted (H&G) with the exception of rex sole which is primarily sold as whole fish. Because of the minimal processing, changes in production largely reflect changes in catch levels. Before 2010 a significant share of shallow-water flatfish were processed as fillets, however this share has declined over time. The average first-wholesale price decreased 14% to $0.47 per pound in 2020 and was below the 2011-2015 average of $0.59 per pound. The decrease was largely due to a decrease in the rex sole, shallow-water, and flathead sole prices, which fell to $0.63, $0.47, and $0.40 per pound in 2020, respectively. Relative to other flatfish, rex sole tends to be the higher priced species. H&G and whole fish prices for other flatfish typically range from $0.60-$0.75 per pound.

The majority of flatfish produced in the U.S. are exported, primarily to Asia. The U.S. accounted for approximately 27% of global flatfish production in 2019 and Gulf of Alaska flatfish represent approximately 10% of the U.S. flatfish production (Table 7A.3c). U.S. trade data encodes the primary GOA flatfish (arrowtooth, rex sole and flathead sole) species with other flatfish exported from the U.S. in a non-specific general flatfish category which limits how informative it is for GOA flatfish specifically. The Alaska flatfish fishery became MSC certified in 2010 and received the Responsible Fishery Management (RFM) certification in 2014. Certification provides access to some markets and may enhance value. For flatfish in general, the majority are exported to China and some share of this product is re-processed into fillets and re-exported. Some arrowtooth exported to China is eaten as a less expensive flounder-type fish and has served as a substitute for more expensive fish. Previous reports indicated growing demand in China through 2016. Export quantities of NSPF flatfish increased in 2020 and average export prices fell 15% to $0.71 per pound and were below the 2011-2015 average (Table 7A.3c). Because of China's significance as a re-processor of flatfish products, the tariffs between the U.S. and China, which begun in 2018, have put downward pressure on flatfish prices which has inhibited value growth in flatfish markets. Flatfish were among the species to receive relief under the USDA Seafood Tariff Relief Program in 2019-2020. Industry lacks immediate alternative reprocessing options to China on a large scale. Export quantities of flatfish increased in 2020 from 2019 and the share of exports to China was within a typical range (Table 3). The COVID-19 pandemic created supply chain logistical difficulties, particularly in China, which put downward pressure on prices. In addition, foodservice closures in major markets also likely impacted prices negatively for flatfish finished goods.

Indicator Assessment

In this assessment section, we provide a time-series suite of indicators that represents the critical processes identified by the previous indicator synthesis section. These indicators must be useful for stock assessment in that they are regularly updated, reliable, and consistent. The indicator suite is then evaluated through a series of stages depending on the stock's data availability and stock assessment model complexity (Shotwell et al., 2023).

Indicator Suite

Arrowtooth flounder in the GOA exhibit a "high endurance" early life history strategy, characterized by winter spawning in deep water, where predation risk is relatively low. The cold temperatures and intrinsically low metabolic rates of the larvae allow for extended use of yolk reserves, reducing the risk of starvation in a food-poor environment. This slow growth is thought to be advantageous, extending the utilization of lipid reserves prior to first-feeding. However, this can also lead to a mismatch with prey availability, as first-feeding larvae are spatially and temporally separated from the spring zooplankton production on the shelf. The larval duration is protracted, leading to widespread dispersal of larvae across the Gulf of Alaska and into the Bering Sea. This prolonged pelagic phase, however, makes them dependent on oceanographic transport from offshore spawning locations to suitable inshore nursery habitats. Settlement success relies on transport routes that facilitate the delivery of larvae to the continental shelf. Mesoscale eddies and retention near suitable settlement habitats have been shown to enhance settlement and recruitment magnitude. Juvenile and adult arrowtooth flounder are habitat and prey generalists, showing some ontogenetic shifts in their diet and distribution. This ecological flexibility contributes to their high resilience to environmental change.

We created the following list of indicators based on the life history synthesis and economic performance for GOA arrowtooth flounder. The indicator suite is organized into categories: three for ecosystem indicators (larval to young-of-the-year or YOY, juvenile, and adult) and three for socioeconomic indicators (fishery informed, economic, and community). The indicator name and short description are provided in each heading. For ecosystem indicators, we include the proposed sign of the overall relationship between the indicator and a stock assessment parameter of interest (e.g., recruitment, natural mortality, growth), where relevant, and specify the lag applied if the indicator was tested in the ecosystem intermediate stage indicator analysis (see section below for more details). Each indicator heading is followed by bullet points that provide information on the contact and citation (where possible) for the indicator data, the status and trends for the current year, factors influencing those trends, and implications for fishery management. Time series of these indicators are provided in Figure 7A.4a (ecosystem indicators) and Figure 7A.4b (socioeconomic indicators).

The following nomenclature was used to describe these indicators within the list:

- "Average": Used if the value in the time series is near the long-term mean (dotted green line in Figure 7A.4).
- "Above average" or "Below average": Used if the value is above or below the mean but was within 1 standard deviation of the mean (in between solid green lines in Figure 7A.4).
- "Neutral": Used in Table 7A.4 for any value within 1 standard deviation of the mean.
- "High" or "Low": Used in Table 7A.4 if the value was more than 1 standard deviation above or below the mean (above or below the solid green lines in Figure 7A.4).

In some cases we include value-added products to more fully explore some of the indicators in the suite and allow for a more in depth interpretation of the indicator. At this time, we do not have any value-added indicators for GOA arrowtooth flounder but may include in the future.

Ecosystem Indicators:

<u>1. Larval to YOY Indicators (Figure 7A.4a.a-f)</u>

a. Spring Sea Surface Temperature: Early spring, February - April, daily sea surface temperatures (SST) based on the core EFH area of larval arrowtooth distribution in the Gulf of Alaska from the NOAA Coral Reef Watch Program which provides the Global 5km Satellite Coral Bleaching Heat Stress Monitoring Product Suite Version 3.1, derived from CoralTemp v1.0. product (NOAA Coral Reef Watch, 2018). Data available from 1985 to present. This seasonal and spatial distribution coincides with the peak larval timing for GOA arrowtooth in surface waters. Proposed sign of the relationship is negative. Contact: Matt Callahan

- Lag assigned for ecosystem indicator analysis: 1 year to age-1 recruitment
- Status and trends: The early spring SST in core EFH area in 2024 is slightly above the long-term average, an increase from slightly below the long-term average in 2023.
- Factors influencing trends: Many weather, climate and oceanographic factors influence sea surface temperatures (Holbrook et al., 2019). Generally, cool conditions are related to winter balances between heat loss, coastal runoff, and stratification, while warm conditions are associated with El Nino events and marine heatwaves (Janout et al., 2010).
- Implications: Warmer surface temperatures imply potentially less lipid-rich zooplankton species which may impact feeding conditions for larval arrowtooth flounder.

b. Spring Eddy Kinetic Energy: Spring eddy kinetic energy (EKE) calculated as seasonal mean (averaged Feb-Apr) anomalies from sea surface height at 0.125 degree resolution in the central Gulf of Alaska within an area from 160W to 146W and between the depth contours of 200-1000 m using the Smith and Sandwell 2-arc-minute bathymetry data. EKE is a measure of mesoscale energy in the ocean system (Ladd, 2020). A suite of satellite altimeters provides sea surface height. The Ssalto/Duacs altimeter products were produced and distributed by the Copernicus Marine and Environment Monitoring Service (CMEMS) (http://www.marine.copernicus.eu). Data available from 1993 to present. Proposed sign of the relationship is positive. Contact: Wei Cheng
   - Lag assigned for ecosystem indicator analysis: 1 year to age-1 recruitment
   - Status and trends: The spring EKE in central GOA in 2025 is at the long-term average, a decrease from an all time-series high in 2024.
   - Factors influencing trends: In the eastern Gulf of Alaska, interannual changes in surface winds (related to the Pacific Decadal Oscillation, El Niño, and the strength of the Aleutian Low) modulate the development of eddies (Combes and Di Lorenzo, 2007; Di Lorenzo et al., 2013). Regional scale gap-wind events may also play a role in eddy formation in the eastern Gulf of Alaska (Ladd and Cheng, 2016). In the western Gulf of Alaska, variability is related both to the propagation of eddies from their formation regions in the east and to intrinsic variability.
   - Implications: A lower energy period implies reduced retention in suitable habitat for young-of-the-year arrowtooth flounder and reduced cross-shelf transport to suitable nearshore nursery environments.

c. Spring Larval Arrowtooth: Spring arrowtooth larvae catch-per-unit-of-effort (CPUE) were summarized as natural log mean abundance for the core sampling area in the EcoFOCI spring surveys. The primary sampling gear used is a 60-cm bongo sampler fitted with 505-m mesh nets. Oblique tows are carried out mostly from 100 m depth to the surface or from 10 m off bottom in shallower water (Matarese et al., 2003). Historical sampling has been most intense in the vicinity of Shelikof Strait and Sea Valley during mid-May through early June. From this area and time, a subset of data has been developed into a time series of ichthyoplankton abundance. On-board counts give rapid estimates of relative abundance (Rapid Larval Assessment), which are presented in the year of collection, and subject to revision following detailed laboratory processing of samples. In 2023, time-series calculations were updated to use a model-based approach (sdmTMB; Anderson et al. 2022) instead of the previous area-weighted mean, in part to better account for variable survey coverage in recent years due to ship-time constraints. In 2023, the EcoFOCI survey was truncated due to vessel staffing, resulting in only partial coverage of the core survey area. Hence, 2023 estimates have greater uncertainty (Rogers and Axler 2023). Data available from 1981 to present. Proposed sign of the relationship is positive. Contact: Lauren Rogers
   - Lag assigned for ecosystem indicator analysis: 1 year to age-1 recruitment

- Status and trends: Arrowtooth larval abundance was very low in 2025, similar to observations in 2010, and a large reduction from above average in 2023.
- Factors influencing trends: Years of high abundance for the late winter to early spring shelf spawners were associated with cooler winters and enhanced alongshore winds during spring.
- Implications: Ichthyoplankton surveys can provide early-warning indicators for ecosystem conditions and recruitment patterns in marine fishes. The low abundance of arrowtooth larvae suggests poor to average foraging conditions and low reserves for overwintering potentially suggesting a poor 2023 year class.

d. Spring Larval Prey: Spring small copepods (<2 mm) were summarized as log-10 transformed mean catch per m3 for the core sampling area in Shelikof Strait and Sea Valley of the EcoFOCI spring surveys. The current survey year (if available) is often represented by a rapid zooplankton assessment to provide a preliminary estimate of zooplankton abundance and community structure (Kimmel et al., 2023). Ongoing work will determine the robustness of the rapid zooplankton assessment through comparison with quantitative data with high taxonomic resolution. Small copepods are prey for larval and early juvenile pollock. In 2023 timeseries were revised to standardize by gear type. Data available from 1994 to present. Proposed sign of the relationship is negative. Contact: Lauren Rogers and David Kimmel
    - Lag assigned for ecosystem indicator analysis: 1 year to age-1 recruitment
    - Status and trends: Small copepods have had elevated abundances during recent sampling, particularly during the marine heatwave of 2014-2016 and in 2019, and abundances in 2023 are lower than those observed recently.
    - Factors influencing trends: Small copepod abundances were reduced in spring and this makes sense with respect to life history characteristics of small copepods, e.g. multiple generations per year, faster turnover times, and metabolic rates that scale with temperature. Thus, cooler temperatures reduced the rate at which small copepod population increased. Recent warm years had high abundances of small copepods in spring and numbers in 2023 were lower than those peaks.
    - Implications: Zooplankton are an important prey base for larval and juvenile fishes in spring and summer. While small copepod numbers were reduced relative to recent spring values, numbers remained high indicating that there is likely a significant number of nauplii and smaller copepods available as prey for larval fishes.

e. Summer YOY Prey: Summer large copepods (> 2mm) were summarized as log-10 transformed mean catch per m3 for the core sampling area in Shelikof Strait and Sea Valley of the EcoFOCI late-summer surveys (August - September). 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., 2023). Ongoing work will determine the robustness of the rapid zooplankton assessment through comparison with quantitative data with high taxonomic resolution. Large copepods are important prey for young-of-the-year (YOY) pollock and other groundfishes in summer. In 2023 timeseries were revised to standardize by gear type. Data available from 2000 to present. Proposed sign of the relationship is positive. Contact: Lauren Rogers and David Kimmel
    - Lag assigned for ecosystem indicator analysis: 1 year to age-1 recruitment
    - Status and trends: Late summer, large copepod abundance declined from the early 2000s until the marine heatwave of 2014-2016. In 2023, large copepod numbers were similar to recent years and slightly higher than the marine heat wave years.
    - Factors influencing trends: Large copepod abundances are influenced by timing of the annual cohort of the dominant large species: C. marshallae, N. cristatus, and Neocalanus spp. The dominant large species in summer is C. marshallae as both other large species

have likely entered diapause. Long-term variability in mesozooplankton in this region is thought to be driven by Pacific Decadal Oscillation (PDO) and El Nino-Southern Oscillation (ENSO) cycles.

- Implications: Zooplankton are an important prey base for juvenile fishes in summer. Both large copepod numbers and euphausiid abundances were average during the late summer relative to long-term trends. Both are principal diet items for juvenile fish and these numbers appear to indicate adequate forage.

f. Summer/Fall YOY Prey: 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 (Ressler et al., 2019). Data available for variable years historically and biennially from 2013 to 2019. Proposed sign of the relationship is positive. Contact: Patrick Ressler

- Lag assigned for ecosystem indicator analysis: 1 year to age-1 recruitment
- Status and trends: Euphausiid abundance has dropped from a high in 2011 to a low in 2017 and only moderate recovery in 2019.
- Factors influencing trends: Factors controlling annual changes in euphausiid abundance are not well understood; possible candidates include bottom-up forcing by temperature and food supply, and top-down control through predation (Hunt et al., 2016).
- Implications: Zooplankton are an important prey base for juvenile fishes in summer. Euphausiid abundances have been steadily dropping in the acoustic survey since 2011 suggesting this prey resource has been declining over time. As a principal diet item for juvenile fish, these numbers appear to indicate poor foraging conditions. This indicator has not been updated since 2019 and may be discontinued in the future.

<u>2. Juvenile Indicators (Figure 7A.4a.g-i)</u>

g. Female Predation Mortality Age1: Estimate of arrowtooth flounder female age 1 predation mortality from the Climate-Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics (CEATTLE) that has recently been developed for understanding trends in total mortality for walleye pollock, Pacific cod, Pacific halibut, and arrowtooth flounder from the GOA (Adams et al., 2022). The model is fit to data from five fisheries and seven surveys between 1977 and the last full stock assessment model for the stocks in the model. Model estimates of predation mortality are empirically derived by bioenergetics-based consumption information and diet data from the GOA to inform predator-prey suitability (Holsman and Aydin, 2015; Holsman et al., 2019). Proposed sign of the relationship is negative. Contact: Grant Adams

- Not included in ecosystem indicator analysis
- Status and trends: the multi-species model estimates that natural mortality due to all sources for age-1 arrowtooth flounder peaked in 2001, then declined to a low in 2020, increased slightly in recent years, but remains low. Average age-1 mortality estimated by CEATTLE was 0.39 yr^{-1} for females.
- Factors influencing trends: Temporal patterns in total natural mortality reflect annually varying changes in predation mortality by pollock, Pacific cod, and arrowtooth flounder that primarily impact age-1 fish (but also impact older age classes). Predation mortality at age-1 for all species in the model is primarily driven by arrowtooth flounder and arrowtooth flounder biomass has been low since 2017 but has increased slightly in the following years (Shotwell et al., 2023b).

- Implications: There is evidence of time-varying predation mortality on age-1 female arrowtooth flounder due to the species modeled in CEATTLE that has been above the time-invariant single species stock assessment value in all years.

h. Male Predation Mortality Age1: Estimate of arrowtooth flounder male age 1 predation mortality from the Climate-Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics (CEATTLE) that has recently been developed for understanding trends in total mortality for walleye pollock, Pacific cod, Pacific halibut, and arrowtooth flounder from the GOA (Adams et al., 2022). The model is fit to data from five fisheries and seven surveys between 1977 and the last full stock assessment model for the stocks in the model. Model estimates of predation mortality are empirically derived by bioenergetics-based consumption information and diet data from the GOA to inform predator-prey suitability (Holsman and Aydin, 2015; Holsman et al., 2019). Proposed sign of the relationship is negative. Contact: Grant Adams
    - Not included in ecosystem indicator analysis
    - Status and trends: the multi-species model estimates that natural mortality due to all sources for age-1 arrowtooth flounder peaked in 2001, then declined to a low in 2020, increased slightly in recent years, but remains low. Average age-1 M estimated by CEATTLE was 0.48 yr^{-1} for males.
    - Factors influencing trends: Temporal patterns in total natural mortality reflect annually varying changes in predation mortality by pollock, Pacific cod, and arrowtooth flounder that primarily impact age-1 fish (but also impact older age classes). Predation mortality at age-1 for all species in the model is primarily driven by arrowtooth flounder and arrowtooth flounder biomass has been low since 2017 but has increased slightly in the following years (Shotwell et al., 2023b).
    - Implications: There is evidence of time-varying predation mortality on age-1 male arrowtooth flounder due to the species modeled in CEATTLE that has been above the time-invariant single species stock assessment value in all years.

i. Small Arrowtooth ADF&G: Arrowtooth lengths extrapolated to the population for small arrowtooth flounder (>=100 mm and <200 mm, likely age-1) in the Central and Western Gulf of Alaska and Eastern Aleutian Islands, from the Alaska Department of Fish and Game annual large-mesh bottom trawl surveys, 1992 to present (Spalinger and Silva, 2023). Data available from 1992 to present. Proposed sign of the relationship is positive. Contact: Kally Spalinger and Joletta Silva
    - Lag assigned for ecosystem indicator analysis: 0 years to age-1 recruitment
    - Status and trends: Small arrowtooth have been steadily declining since 2014 and below average for 7 of the last 10 years.
    - Factors influencing trends: Amount of arrowtooth caught in the survey is likely influenced by interannual variability in the spatial distribution of the stock and influx from recent large year classes.
    - Implications: The early to late juvenile stage of arrowtooth are not well sampled by other survey methods. The index of small arrowtooth from the ADF&G large-mesh bottom trawl survey lengths may be useful as an early signal of overwinter success for the early to late juvenile stages of arrowtooth flounder.

<u>3. Adult Indicators (Figure 7A.4a.j-q)</u>

j. CPUE Arrowtooth ADF&G: Arrowtooth CPUE (kg per km towed) in the Central and Western Gulf of Alaska and Eastern Aleutian Islands, from the Alaska Department of Fish and Game annual large-mesh bottom trawl surveys (Spalinger and Silva, 2023). Data available from 1992 to present. Proposed sign of the relationship is positive. Contact: Kally Spalinger and Joletta Silva
    - Not included in ecosystem indicator analysis

- Status and trends: CPUE was high several years in the mid-2000s and decreased steadily from 2005 to a low in 2013. CPUE has been slowly increasing since 2014 but has remained below the long-term average. In 2023 the index was at the mean.
- Factors influencing trends: Amount of arrowtooth caught in the survey is likely influenced by interannual variability in the spatial distribution of the stock and influx from recent large year classes. This survey likely contains a mix of different aged arrowtooth from age-1 through adult, and so the CPUE index is an index of cohort strength across several years and can be considered an index of nearshore arrowtooth abundance prior to returning to adult habitat.
- Implications: The CPUE of all ages sampled in the ADF&G large-mesh bottom trawl survey may be useful as an indicator of nearshore residency and useful for identifying continued survival of arrowtooth before transitioning to the shelf adult environment.

k. Arrowtooth Biomass Consumed: Estimate of arrowtooth flounder biomass consumed (mt) from the Climate-Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics (CEATTLE) that has recently been developed for understanding trends in total mortality for walleye pollock, Pacific cod, Pacific halibut, and arrowtooth flounder from the GOA (Adams et al., 2022). The model is fit to data from five fisheries and seven surveys between 1977 and the last full stock assessment model for the stocks in the model. Model estimates of predation mortality are empirically derived by bioenergetics-based consumption information and diet data from the GOA to inform predator-prey suitability (Holsman and Aydin, 2015; Holsman et al., 2019). Proposed sign of the relationship is negative. Contact: Grant Adams
    - Lag assigned for ecosystem indicator analysis: 0 years to age-1 recruitment
    - Status and trends: Estimates of biomass consumed of arrowtooth flounder as prey across all ages remains below the long-term mean. On average 5,294 mt of age-1 arrowtooth flounder was consumed annually by species included in CEATTLE and 25,560 mt on average across all ages of arrowtooth flounder.
    - Factors influencing trends: Population trends of predators and biomass of young arrowtooth flounder included in the CEATTLE model (arrowtooth flounder, pollock, Pacific cod, Pacific halibut) impact total biomass consumed of arrowtooth as prey.
    - Implications: As predator populations decline in the GOA so does the predation pressure on GOA arrowtooth flounder.

l. Summer Bottom Temperature: 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 to present. Proposed sign of the relationship is negative. Contact: Margaret Siple
    - Lag assigned for ecosystem indicator analysis: 0 year to age-1 recruitment
    - Status and trends: Lower bottom temperatures from 2021 through 2023 following the high and above average temperatures during the marine heatwave.
    - Factors influencing trends: Subsurface waters below mixed layers can absorb and store heat. These changes do not occur at the same timescales as changes in surface water temperatures, often showing delayed responses by a year or more. These temperature changes are also very small compared to surface waters. The warmer subsurface waters become, the less cooling capacity they have to absorb heat from surface waters (Siwicke, 2022).
    - Implications: Higher temperatures increase metabolism of predators that will ultimately increase consumption of arrowtooth (Holsman and Aydin, 2015).

m. Arrowtooth Area Occupied: 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 gamma distribution for residual variation in positive catch rates. We specified a model with 500 knot while using the fine_scale=TRUE feature to conduct bilinear interpolation from the location of knots to the location of extrapolation-grid cells. For the extrapolation-grid, we used the Gulf of Alaska grid that covers the spatial domain from which the bottom trawl survey randomizes sampling stations. Knots were distributed proportional to the spatial distribution of extrapolation-grid cells within this spatial domain. We calculated effective area occupied as the area required to contain the population at its average density (Thorson et al. 2016). We used epsilon bias-correction to correct for retransformation bias (Thorson and Kristensen, 2016). Data are available triennial since 1993 and biennial since 2000 to present. No directional relationship with the stock. Contact: Zack Oyafuso and Margaret Siple

- Not included in ecosystem indicator analysis
- Status and trends: The estimated effective area occupied for arrowtooth flounder moderately increased from 2023 and has remained above average since 2015.
- Factors influencing trends: The large expansion of effective area occupied is concurrent with an increase in the design-based estimate of total GOA arrowtooth flounder biomass.
- Implications: The increase in the effective area occupied in 2025 implies a wider spatial distribution covered by arrowtooth flounder in the GOA relative to the mean of the time series. Changes in the distributional characteristics of marine populations may impact the spatial distributions of fishing activities and trophic interactions.

n. Arrowtooth Center of Biomass East: 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 gamma distribution for residual variation in positive catch rates. We specified a model with 500 knot while using the fine_scale=TRUE feature to conduct bilinear interpolation from the location of knots to the location of extrapolation-grid cells. For the extrapolation-grid, we used the Gulf of Alaska grid that covers the spatial domain from which the bottom trawl survey randomizes sampling stations. Knots were distributed proportional to the spatial distribution of extrapolation-grid cells within this spatial domain. We calculated center of gravity as the biomass-weighted average of the location of extrapolation-grid cells (Thorson et al. 2016) available as northings and eastings. We used epsilon bias-correction to correct for retransformation bias (Thorson and Kristensen, 2016). Data are available triennial since 1993 and biennial since 2000 to present. No directional relationship with the stock. Contact: Zack Oyafuso and Margaret Siple

    - Not included in ecosystem indicator analysis
    - Status and trends: The center of gravity in the eastward direction shifted slightly west compared to 2023 and is now at the long-term mean.
    - Factors influencing trends: The westward shift in the center of gravity is current with an expansion of effective area occupied
    - Implications: Changes in the distributional characteristics of marine populations may impact the spatial distributions of fishing activities and trophic interactions.

o. Arrowtooth Center of Biomass North: 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 gamma distribution for residual variation in positive catch rates. We specified a model with 500 knot while using the fine_scale=TRUE feature to conduct bilinear interpolation from the location of knots to the location of extrapolation-grid cells. For the extrapolation-grid, we used the Gulf of Alaska grid that covers the spatial domain from which the bottom trawl survey randomizes sampling stations. Knots were distributed proportional to the spatial distribution of extrapolation-grid cells within this spatial domain. We calculated center of gravity as the biomass-weighted average of the location of extrapolation-grid cells (Thorson et al. 2016) available as northings and eastings. We used epsilon bias-correction to correct for retransformation bias (Thorson and Kristensen, 2016). Data are available triennial since 1993 and biennial since 2000 to present. No directional relationship with the stock. Contact: Zack Oyafuso and Margaret Siple

- Not included in ecosystem indicator analysis
- Status and trends: The center of gravity in the northward direction shifted slightly south compared to 2023 and is now at the long-term mean.
- Factors influencing trends: The southward shift in the center of gravity is current with an expansion of effective area occupied
- Implications: Changes in the distributional characteristics of marine populations may impact the spatial distributions of fishing activities and trophic interactions.

p. Adult Arrowtooth Condition: Summer stratum-biomass weighted morphometric condition of arrowtooth flounder. Morphometric condition was estimated using residuals of a length-weight regression fit to individual length-weight measurements collected during AFSC/RACE Gulf of Alaska bottom trawl surveys from 1993 to present. Proposed sign of the relationship is positive. Contact: Sean Rohan

- Lag assigned for ecosystem indicator analysis: 2 years to age-1 recruitment
- Status and trends: The condition of arrowtooth flounder in the GOA in 2023 was average, which continues the trend of neutral condition observed since 2019. Adult condition was highly variable from 2011 to 2017.
- Factors influencing trends: Many factors contribute to variation in morphometric condition so it is unclear which specific factors contributed to neutral condition of arrowtooth flounder in the GOA in 2023. Factors that may contribute to variation in morphometric condition include environmental conditions that affect prey quality and temperature dependent metabolic rates, survey timing, stomach fullness of individual fish, fish migration patterns, and the distribution of samples within survey strata. Additional information about the groundfish morphometric condition indicator and factors that can influence estimates of morphometric condition are described in the GOA Groundfish Morphometric Condition contribution in the 2023 Gulf of Alaska Ecosystem Status Report (O'Leary and Rohan, 2023).
- Implications: In the Gulf of Alaska, elevated temperatures during the 2014-2016 marine heatwave were associated with lower growth rates of arrowtooth flounder and lower morphometric condition in 2015 and 2017, likely because of a decrease in prey resources and increase in metabolic demand. Average condition suggests that arrowtooth flounder were able to find sufficient prey resources.

q. Arrowtooth Ration: Estimate of annual predation demand (ration) for Arrowtooth flounder from the Climate-Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics (CEATTLE) that has recently been developed for understanding trends in total mortality for walleye pollock, Pacific cod, Pacific halibut, and arrowtooth flounder from the GOA (Adams et al., 2022). The model is fit to data from five fisheries and seven surveys between 1977 and the last full stock assessment model for the stocks in the model. Model estimates of predation mortality are empirically derived by bioenergetics-based consumption information and diet data from the GOA to inform predator-prey suitability (Holsman and Aydin, 2015; Holsman et al., 2019). Proposed sign of the relationship is negative. Contact: Grant Adams

- Not included in ecosystem indicator analysis

- Status and trends: Annual ration declined steadily since 2012 to a low in 2021 and has increased slightly in 2022 - 2023 but is still below the long-term average
- Factors influencing trends: Decreasing population trends since mid-2000's result in decreasing demand for prey.
- Implications: Rates of cannibalism would decrease as the GOA arrowtooth flounder population decreases.

Socioeconomic Indicators:

Note: These indicators will be updated in the November document.

1. Fishery Informed Indicators (Figure 7A.4b.a-e)

a. Catch Catcher Vessels: Total arrowtooth flounder catch (mt) associated with catcher vessels (CV) in the Gulf of Alaska (GOA). Contact: Abby Jahn
   - Status and trends:
   - Factors influencing trends:
   - Implications:

b. Catch Catcher Processors: Total arrowtooth flounder catch (mt) associated with catcher processors (CP) in the Gulf of Alaska (GOA). Contact: Abby Jahn
   - Status and trends:
   - Factors influencing trends:
   - Implications:

c. Non-Target Catch Rockfish Fishery: Incidental catch estimates (mt) of arrowtooth flounder in the GOA rockfish fisheries excluding the arrowtooth fishery. Contact: Abby Jahn
   - Status and trends:
   - Factors influencing trends: Non-target catch in rockfish fisheries is influenced by the magnitude, spatial distribution, gear and other aspects of groundfish harvesting effort, as well as the size distribution, abundance, vertical spatial, and temporal distribution of the arrowtooth flounder stock.
   - Implications: Rapid changes of non-target catch may imply shifting distribution of the arrowtooth population into non-preferred habitat, which could increase competition and predation on arrowtooth flounder, particularly during a large recruitment event. Additionally, this catch could be viewed as an early indicator of large year classes or confirmatory of previously estimated year classes.

d. ABC Utilization: Percentage of the annual GOA arrowtooth flounder acceptable biological catch (ABC) that was harvested in the fishery. Contact: Kalei Shotwell
   - Status and trends:
   - Factors influencing trends:
   - Implications:

e. TAC Utilization: Percentage of the annual GOA arrowtooth flounder total allowable catch (TAC) that was harvested in the fishery. Contact: Kalei Shotwell
   - Status and trends:
   - Factors influencing trends:
   - Implications:

2. Economic Indicators (Figure 7A.4b.f-h)

f. Ex-vessel Value: Annual estimated real ex-vessel value measured in millions of dollars and inflation adjusted to 2024 USD. Contact: Russel Dame
   - Status and trends:
   - Factors influencing trends:
   - Implications:

g. Ex-vessel Price: Average real ex-vessel price per pound of GOA arrowtooth flounder measured in millions of dollars and inflation adjusted to 2024 USD. Contact: Russel Dame
   - Status and trends:
   - Factors influencing trends:
   - Implications:

h. Ex-vessel Revenue Per Effort: Annual estimated real revenue per unit effort measured in weeks fished and inflation adjusted to 2024 USD. Contact: Russel Dame
   - Status and trends:
   - Factors influencing trends:
   - Implications:

3. Community Indicators (Figure 7A.4b.i-i)

An analysis of commercial processing and harvesting data may be conducted to examine sustained participation for those communities substantially engaged in a commercial fishery. The Annual Community Engagement and Participation Overview (ACEPO) report evaluates engagement at the community level and focuses on providing an overview of harvesting and processing sectors of identified highly engaged communities for groundfish and crab fisheries in Alaska (Wise et al., 2022). An example of community indicators has been included in the Alaska sablefish ESP report (Shotwell and Dame, 2024) and we plan to include a similar set of indicators in the next report card for GOA arrowtooth flounder following review and recommendations for the Alaska sablefish ESP report and discussion at the NPFMC regarding the role of socioeconomic indicators in ESPs.

Indicator Monitoring Analysis

Ecosystem and socioeconomic indicators are monitored through distinct workflows, depending on the management decisions they are intended to inform (Figure C.3). Ecosystem indicators generally inform the acceptable biological catch (ABC) and can either be incorporated directly into the model through predictive or causal inference or indirectly through contextual avenues such as risk tables (Dorn and Zador, 2020). Socioeconomic indicators related to the performance or behavior of the fishery can also impact the ABC both directly by informing time-varying fishery selectivity and indirectly through context in the risk table. Other socioeconomic indicators such as those related to the economics of the fishery or the communities that are supported by the fishery impact decisions further downstream of the stock assessment process and generally are used in decisions related to total allowable catch (TAC). Additionally, all indicators selected for monitoring in the ESP may inform TAC deliberations.

We evaluated the ecosystem indicators through a series of stages using statistical tests that increase in complexity depending on the data availability of the stock (Shotwell et al., 2023). The beginning stage is a relatively simple evaluation by traffic light scoring. This evaluates the indicator value from each year relative to the mean of the whole time series and includes the proposed sign of the overall relationship between the indicator and the stock health. The intermediate stage uses importance methods related to a stock assessment parameter of interest (e.g., recruitment, growth, catchability). These regression techniques provide predictive performance for the parameter of interest and are run separate from the stock assessment model. They provide the direction, magnitude, uncertainty of the effect, and an estimate of inclusion probability. The advanced stage is used for providing visibility on current research ecosystem models and may be used for testing a research ecosystem linked stock assessment model where output can be compared with the current operational stock assessment model to understand information on retrospective patterns, prediction performance, and comparisons to model outputs.

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

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

Ecosystem Indicator Analysis

The GOA arrowtooth flounder stock is data rich with an associated age-structured assessment model; therefore, estimates of recruitment were available for this stock and could be evaluated at either the intermediate or advanced levels. At this time we have completed an intermediate stage method and results from this analysis are used to categorize ecosystem indicators as a) predictive indicators that demonstrate a robust quantitative relationship with the population process of interest, b) contextual indicators that provide anticipatory information to inform a management concern or highlight a potential red flag related directly to the status or health of the stock, but lack predictive skill, or c) monitoring indicators that do not demonstrate quantitative links to population processes, nor provide information that is immediately relevant to the stock and/or fishery managers. The intent of this indicator categorization is to succinctly communicate potential red flags for the stock based on current-year indicator trends and stock-indicator relationships, while providing a mechanism to down-weight indicators that do not quantitatively inform population processes. Monitoring indicators are reported in this document and will continue to be evaluated annually, but we limit our interpretation and synthesis to predictive and contextual indicators in an effort to communicate only the most relevant ecosystem considerations for setting biological reference points for the current year.

A Dynamic Structural Equation Model or DSEM is a multivariate time series statistical modeling framework that can estimate simultaneous and lagged effects and handle missing values (Thorson *et al.*, 2024). This modeling framework allows us to assess whether ecosystem variables interact to affect an outcome, such as recruitment (Champagnat et al. *accepted*, Thorson et al. 2024). DSEM can be run in the external form on the recruitment estimates outside the stock assessment model (Thorson et al., 2024) or it can be integrated within the model structure (Champagnat et al., *accepted*). Rceattle is the newly proposed and accepted stock assessment platform for this stock (Adams et al., 2020, Adams and Shotwell, 2024) and an integrated DSEM branch has recently been added to the platform. A substantial amount of new survey and fishery data along with updated growth curves, size/age transition matrices, and an age error matrix have been added to this model since the last full assessment in 2021 (Shotwell et al., 2025). These are being reviewed by the Groundfish Plan Team in September 2025. We, therefore, decided to use the external DSEM to evaluate several model options using the recruitment estimates from the last full assessment in 2021, and plan to integrate the best model into the Rceattle platform once the data updates are approved by the Groundfish Plan Team. At this time we have explored several models using the external DSEM r package and provide preliminary results of this exploration. We plan to explore a few more model iterations, determine the best model, and integrate that model into the DSEM branch of Rceattle. We will present results of both the external runs and integrated run in the final ESP document in November.

To develop a conceptual model to explain how ecosystem variables (indicators collated in this ESP) may explain variation in recruitment, we consulted both subject matter experts and the literature. An initial full model was then developed (Figure 7A.5), which was subsequently paired down to a simplified version to be estimable (see Thorson et al. 2024, Thorson et al. *preprint*, Champagnat et al. *accepted* for more detail). Briefly, our paired down model (hereafter, causal model) only included linkages to observed variables that were justifiable based on the literature and expert opinion to ensure the model would converge (Figure 7A.6). The time series of the data used in the causal model with estimates of uncertainty are provided in Figure 7A.7.

We then fit the causal model using the *dsem* package in R (v4.4.2), and following Champagnat et al. (*accepted*), we fit two other models for comparison: one modeling recruitment as independent and identically distributed (iid) and one modeling recruitment as a first order autoregressive (AR1) process. We compared relative support for these three models using Akaike's information criteria (AIC). We found that the causal model explained the most variation in recruitment from 1977-2021 compared to modeling recruitment as iid or as AR1 (Table 7A.5). A list and description of the linkages in the causal model, the hypothesized direction of the relationship based on subject matter experts and the literature review, and the associated lags are provided in Table 7A.6a. The effect estimates and p-value for these linkages are provided in Table 7A.6b along with the associated data title from the ESP suite, any change in relationship between the hypothesized and estimated sign and some suggestions for future improvement on the data proxies representing the causal model linkages. Figure 7A.8 provides the linkages and estimates with lags in an easier to visualize format following the conceptual model (Figure 7A.1). Four covariates were highly significant in the causal model: spring sea surface temperature, summer/fall YOY prey (euphausiids), larval abundance, and predation on arrowtooth estimated through consumption. The sign from euphausiids and the predation covariates was different than we originally anticipated and we provide some ideas on potential ways to improve the covariate in Table 7A.6b. These improvements and running the causal model with new estimates of recruitment from the 2025 operational model may change the estimated effects; therefore, we do not expand on reasons for the difference in sign at this time. However, should this persist following the updates to the model and data, we should consider if the linkage is actually representing a different mechanism than originally proposed (e.g., density dependence instead of predation). The improvement in AIC from the iid or AR1 models suggests that including ecosystem covariates identified in this ESP in a model to explain recruitment improves our understanding of how recruitment may vary over time. This external DSEM model shows promise for integrating this information into the assessment model to explain variation in GOA arrowtooth flounder recruitment.

Once we complete the exploratory external DSEM and integrate the best model into the Rceattle platform, we plan to summarize recent indicator trends and provide management considerations in a five year status table of the indicators organized into predictive, contextual, or monitoring categories (Table 7A.4). At this time the table is organized by the original categories of larval/YOY, juvenile, and adult. Indicator status is evaluated based on being greater than ("high"), less than ("low"), or within ("neutral") one standard deviation of the long term mean. Potential concerns for the health or status of the stock are identified using predictive relationships (predictive ecosystem indicators) or proposed mechanistic relationships (contextual ecosystem indicators) with the stock, and are communicated as a sign and associated color relative to the indicator value and directional indicator-stock relationship. The sign of the relationship for predictive indicators will be based on the DSEM results, while the sign for contextual or monitoring indicators will be based on the conceptual model and hypothesized relationship with the stock (Table 7A.2, Figure 7A.1). The color of the status cell (also referred to as the "traffic light") is related to the sign of the indicator and the status. If a high value of an indicator generates good conditions for the stock and is also greater than one standard deviation above the mean, then that table cell is colored blue. If a high value generates poor conditions for the stock and is greater than one standard deviation above the mean, then that table cell is colored red. All values less than or equal to one standard deviation from the long-term mean are average and there is no assigned color. Also, if the sign of the relationship between an ecosystem indicator and the stock is unclear, no relationship is assigned.

At this time we only have current data from a handful of indicators. These will be updated for the final ESP in November and reorganized into the predictive, contextual, and monitoring categories. Given the original categories of the indicators, results from the traffic light table (Table 7A.4a) indicate that larval/YOY indicators were neutral and low relative to the long-term mean, while all adult indicators with 2025 updates remained neutral within one standard deviation of their long-term mean. When data are updated for 2025, the Executive Summary at the beginning of this document will provide a summary of predictive and contextual indicator trends, and an interpretation of results from the intermediate and advance stage indicator analysis that can be used to inform ABC and TAC decisions.

Socioeconomic Monitoring

In November, we plan to present five fishery informed indicators and three economic indicators that depict a historical time-series of key socioeconomic information for the GOA arrowtooth flounder fishery. Each indicator will use historical data through 2025 for fishery informed indicators and 2024 for economic indicators. A one-year lag is presented to account for post-season adjustments of vessel revenues (and submission deadlines of COAR Buying reports, our primary economic data source) and to capture the end-of-year retained catch information. Select socioeconomic indicators may have an associated value-added indicator that provides additional detail and context at a more granular level than state- or fishery-wide. Similar to the overall socioeconomic indicators, each value-added indicator uses a historical time-series to analyze information at a region, gear, or size specific level. Select associated indicators, where stated, use in-season data through October 2025 to provide the most current information available. At this time only the catch indicators could be updated through 2025. Catcher vessel catch was low while catcher processor vessel catch and non-target catch in the rockfish fishery was neutral compared to the long-term mean. We plan to evaluate trends in these indicators and where relevant will use to inform the risk table for GAO arrowtooth flounder.

Conclusion

The GOA arrowtooth flounder ESP follows the standardized framework for evaluating the various ecosystem and socioeconomic considerations for this stock (Shotwell et al., 2023). The indicator synthesis provides a comprehensive literature review with accompanying ecological synthesis and mechanism tables to support indicator selection. Seventeen ecosystem and eight socioeconomic indicators were identified to monitor for GOA arrowtooth flounder stock. There were sufficient data and a complex stock assessment model available for this stock and, therefore, the ecosystem indicators were evaluated using intermediate stage methods and will be evaluated using advanced methods for the final document. The intermediate method explored to date was an external DSEM on recruitment. In the first model exploration this method identified four significant indicators in the best model (AIC = 733) for explaining variability in GOA arrowtooth flounder recruitment.

In the November assessment, we will provide several overarching takeaways from the indicator synthesis and assessment results. This information can be used for evaluating concerns in the main stock assessment or other management decisions and we will organize the results by acceptable biological catch (ABC) and total allowable catch (TAC) considerations. Indicators that can inform ABC include predictive, contextual, or fishery-informed indicators. Indicators that can inform TAC include all ABC indicators as well as economic and community indicators. Predictive indicator results have potential to be used within the stock assessment model in an ecosystem linked assessment. Additionally, the best DSEM can be integrated directly into the Rceattle platform and reduction in recruitment uncertainty can be determined. Predictive, contextual, and fishery-informed indicators can be used for risk tables. Given that the GOA arrowtooth flounder assessment is on a four-year cycle, we also suggest that the integrated DSEM run could be used as a projection model for off-cycle assessment updates. In this way, relevant ecosystem information can be incorporated into the advice to provide a better understanding of potential recruitment trends projected into the future. This can be particularly important when the operational stock assessment model may not be updated for a longer period of time.

Data Gaps and Future Research Priorities

While current indicator assessments offer a valuable set of proxy indicators, there are notable areas for improvement. The list below summarizes the data gaps and future research priorities for this ESP by ecosystem and socioeconomic category.

Ecosystem Priorities

- Abundance of YOY arrowtooth in the late fall EcoFOCI survey and associated prey
- Condition of juvenile arrowtooth groundfish from bottom trawl surveys
- Development of high-resolution remote sensing (e.g., regional surface temperature, transport estimates, primary production estimates) or climate model indicators (e.g., bottom temperature, nutrient-phytoplankton-zooplankton variables) to assist with the current multi-year data gap for many indicators.
- Development of large-scale indicators from multiple data to understand prey trends at the spatial scale relevant to management (e.g., regional to area-wide estimates of zooplankton biomass, offshore to nearshore monitoring of arrowtooth larvae) and align the spatial and temporal extent of available zooplankton or other productivity indicators to the specific needs of the GOA arrowtooth flounder stock in the future.
- Increased sampling of predator diets in fall and winter to understand predation on YOY arrowtooth flounder during their first autumn and winter, when predation mortality is thought to be significant.

Socioeconomic Priorities

- Reorganization of indicators by scale, structure, and dependence per December 2022 SSC request that may result in a transition of indicators currently reported and a potential shift in focus
- Re-evaluation of fishery performance indicators to potentially include:
    - CPUE measures (e.g., proportion of the catch by gear, level of effort by gear)
    - Fleet characteristics (e.g., number of active vessels, number of processors)
    - Spatial distribution measures (e.g., center of gravity, area occupied)
- Re-evaluation of economic indicators to potentially include:
    - Percentage of total allowable catch (TAC) harvested by active vessels
    - Measures by product type (e.g., proportion landed, price per pound)
    - Revenue per unit effort by area, gear, and product type

- Evaluation of additional sources of socioeconomic information to determine what indicators could be provided in the ESP that are not redundant with indicators already provided in the Economic SAFE and the ACEPO report.
- Consideration of the timing of indicators that are delayed by 1 to several years depending on the data source from the annual stock assessment cycle and when updates can be available.
- Consideration on how to include local knowledge, traditional knowledge, and subsistence information to understand recent fluctuations in stock health, shifts in stock distributions, or changes in size or condition of species in the fishery per SSC recommendation.

As indicators are improved or updated, they may replace those in the current set of ecosystem or socioeconomic indicators to allow for refinement of the indicator analyses and potential evaluation of performance and risk. Incorporating additional importance methods in the intermediate stage indicator analysis may also be useful for evaluating the full suite of indicators and may allow for identifying robust indicators for potential use in the operational stock assessment model. The annual request for information (RFI) for the groundfish and crab ESPs will include these data gaps and research priorities that could be developed for the next ESP assessment (please contact the editors of this ESP for more details).

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Tables

Table 7A.1: List of data sources used in the ESP evaluation for GOA arrowtooth flounder.

Title	Description	Years	Extent
Coral Reef Watch	NOAA Coral Reef Watch Program distributes daily global 5km satellite sea surface temperature data (https://coralreefwatch.noaa.gov/index.php)	1985-present	Gulf of Alaska
CMEMS	Copernicus Marine and Environment Monitoring Service distributes Ssalto/Duacs altimeter products (http://www.marine.copernicus.eu)	1993-present	Gulf of Alaska
EcoFOCI Spring Survey	Shelf larval survey in spring using oblique 60 cm bongo tows, fixed-station grid, catch per unit effort in numbers per 10 m^2	1981-present	Shelikof Strait and Sea Valley
ADF&G Large Mesh Survey	Bottom trawl survey of crab and groundfish on fixed-grid station design using eastern otter trawl	1992-present	Western GOA to Aleutian Islands
AFSC Bottom Trawl Survey	Bottom trawl survey of crab and groundfish in June through August, Gulf of Alaska using Poly Nor'Eastern trawl on stratified random sample grid, catch per unit of effort in metric tons	1991-present	Gulf of Alaska
REEM Diet Database	Food habits data and associated analyses collected by the Resource Ecology and Ecosystem Modeling (REEM) Program, AFSC on multiple platforms	1990-present	Gulf of Alaska
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
NMFS Alaska Regional Office	Catch, economics, and social values for fishing industry, data processed and provided by Alaska Fisheries Information Network	1992-present	Alaska
Reports & Online	ADFG Commercial Operators Annual Reports, AKRO At-sea Production Reports, Shoreside Production Reports, FAO Fisheries & Aquaculture Department of Statistics	2011-present	Alaska, U.S., Global

Table 7A.2: Ecological information by life history stage for GOA arrowtooth flounder. Subscripts are references, please see Note below table.

Stage	Habitat & Distribution	Phenology	Age, Length, Growth	Energetics	Diet	Predators & Competitors
Spawning	Deep, shelf edge, mesopelagic, troughs, canyons, slope (≥300 m, most ≥400 m)(5,13)	Jan-Apr, peak mid-January, 17 wks(13,20,21)	1^{st} mature: 6 yr 50%: 10-11 yr, 47♀/42♂ cm(22)	Oviparous, high fecundity (0.25-2.22·10^6 eggs)(13), 4.2-5.4°C(5)	Fish > 40 cm: pollock, herring, capelin, shrimp, euphausiids (18,22)	P: Pacific cod, halibut, Steller sea lions, sharks, fisheries(22), C: shelf groundfish(22)
Egg	Shelf edge, slope (most ≥400 m)(5), mesopelagic, troughs, canyons(13)	Incubation 15-20 days(5), peak egg - peak larval 4 wks(20)	Egg size: 1.58-1.98 mm, larger egg size(20, RACE)	Incubation temp is 4.3-5.4 °C	Extended lipid reserves(21), yolk is homogenous	
Larvae	Shelf edge, slope (early stage ≥400m, late stage 50(16)-200 m), mesopelagic, troughs, canyons (5,13)	Jan-Aug(6,16,21), peak mid-Feb, extended, 26 wks(20)	3.9-26 mm SL, ascend as yolk-sac larvae(5,13), slow growth Jan-Apr		Possibly lipid-rich, deep water, oceanic copepod eggs and nauplii(21)	P: Pacific ocean perch (infrequent), other fishes(18), C: share larval period with Pacific halibut(13)
YOY	Shelf, nearshore, coastal areas (6,13)		26-40 mm FL(6,13	No relation size and energy density	Large/small copepods	P: Adult arrowtooth flounder, pollock, cod(17)
Juvenile	Shelf, nearshore (6-200+ m), near bays, straits, coastal areas, mixed mud, sand, not gravel, near rocky(1,2,3,4,8,12,14)	Settlement timing September(6)	ages 0-2 yrs (40-211 mm)(4,6,7), 0-1yr roughly 20 cm(22)	5-9.5°C and 32-33 ppt (temp preference < with age)(1,2,3)	mysids, cumaceans, euphausiids, other crustaceans(1,19)	P: Adult arrowtooth flounder, pollock, cod, halibut, sablefish (17,22)
Pre-recruit	Nearshore, shelf (100-200+ m)(14), near bays, straits, coastal areas, mixed mud and sand, near rocky(1,2,12)		age-2+ (200-390 mm)(9), females mature as young as age-3 (>400 mm)(10) deeper depth with age	Energy density > with length prior to maturity	euphausiids, pollock, capelin, shrimp, (9,17,19,22)	P: Adult arrowtooth flounder, cod, sablefish, halibut (17,22)
Adult	Abundant, 20-800m, most 100-300m, mesopelagic, troughs, canyons, shelf/slope(22)	First recruit to survey and fishery age 3, length 40 cm(22)	Max: 23yr, 79♀/40-63♂cm Average: 10 yrs, L_inf: 81.9♀/49.7♂ cm, K: 0.102♀, 0.236♂ (22)		Fish 15-30cm: shrimp, capelin, euphausiids, misc fish, herring(18,22)	P: Pacific cod, halibut, Steller sea lions, sharks, fisheries(22), C: shelf groundfish(22)

Note: Subscripts in table correspond to the following citations in sequential order 1. Norcross et al. (1993), 2. Norcross et al. (1994), 3. Norcross et al. (1999), 4. Abookire et al. (2001), 5. Blood et al. (2007), 6. Bouwens et al. (1999a), 7. Bouwens et al. (1999b), 8. Blackburn and Jackson (1982), 9. Knoth and Foy (2008), 10. Stark (2008), 11. Kendall and Ferraro (1988), 12. Haight et al. (2006), 13. Doyle et al. (2009), 14. Carlson et al. (1982), 15. Boeing and Duffy-Anderson (2008), 16. Bailey and Picquelle (2002), 17. Yang and Nelson (2000), 18. Yang (1993), 19. Smith et al. (1978), 20. Doyle and Mier (2012), 21. Doyle and Mier (2016), 22. Spies and Turnock (2013), 23. Bailey et al. (2008).

Table 7A.3a: GOA flatfish ex-vessel market data. Total and retained catch (thousand metric tons), number of vessel, catcher vessel share of retained catch, value (million US$), price (US$ per pound), arrowtooth flounder share of GOA flatfish retained catch, and GOA share of arrowtooth retained catch; 2011-2015 average and 2016-2020.

	2011-2015 Average	2016	2017	2018	2019	2020
Total catch K mt	35.74	28.1	33.3	25.8	31.9	28.8
Retained catch K mt	28.8	23.6	29.3	22.6	28.2	24.4
Catcher Processors #	5.4	5	4	4	4	5
Catcher Vessels #	28	27	19	34	30	22
Catcher Vessel Share of Retained	56%	75%	50%	78%	76%	78%
Ex-vessel value M US$	$8.6	$6.3	$7.9	$6.4	$6.2	$5.0
Ex-vessel price US$/lb	$0.135	$0.114	$0.119	$0.132	$0.098	$0.084
Arrowtooth Share of Retained[1]	73%	75%	85%	72%	80%	81%
Rex Sole Share of Retained	10%	7%	4%	5%	4%	4%
Shallow Flatfish Share of Retained	14%	15%	7%	11%	9%	17%
GOA share of AK Arrowtooth catch	57%	66%	82%	73%	72%	67%

Source: NMFS Alaska Region Blend and Catch-accounting System estimates; and ADF&G Commercial Operators Annual Reports (COAR). Data compiled and provided by the Alaska Fisheries Information Network (AKFIN).

Table 7A.3b: GOA flatfish first-wholesale market data. Production (thousand metric tons), value (million US$), price (US$ per pound), arrowtooth flounder, rex sole and flathead sole share of GOA flatfish value and price (US$ per pound), and head-and-gut share of value; 2011-2015 average and 2016-2020.

	2011-2015 Average	2016	2017	2018	2019	2020
First-wholesale production K mt	15.7	12.6	17.8	12.8	15.2	14.1
First-wholesale value M US$	$24.5	$21.0	$37.1	$18.3	$18.1	$14.5
First-wholesale price/lb US$	$0.71	$0.76	$0.95	$0.65	$0.54	$0.47
Arrowtooth share of value	52%	63%	85%	59%	65%	65%
Arrowtooth price/lb US$	$0.59	$0.73	$0.99	$0.57	$0.48	$0.46
Rex sole share of value	24%	16%	8%	19%	18%	10%
Rex sole price/lb US$	$1.04	$1.02	$0.99	$0.98	$0.98	$0.63
Shallow flatfish share of value	15%	13%	4%	13%	10%	18%
Shallow flatfish price/lb US$	$0.82	$0.77	$0.63	$0.73	$0.60	$0.47
H&G share of value	61%	70%	75%	61%	69%	63%

Source: 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).

Table 7A.3c: Flatfish U.S. trade and global market data. Global production (thousand metric tons), U.S. share of global production, GOA share of U.S. production, U.S. NSPF2 export volume (thousand metric tons), U.S. export value (million US$), U.S. export price (US$ per pound), China's share of U.S. exports of generic (NSPF) frozen flatfish and the Chinese Yuan/U.S. Dollar exchange rate; 2011-2015 average and 2016-2020.

	2011-2015 Average	2016	2017	2018	2019	2020
Global production of flounder, halibut, and sole K mt	1,013.9	989.3	975.5	973.7	946.4	-
US share global production	31.8%	27.1%	26.7%	25.5%	26.9%	-
GOA FMP flatfish share of U.S.[1]	9.0%	8.8%	11.2%	9.1%	11.1%	-
Export quantity of NSPF Frozen Flatfish K mt	14.6	18.3	22.9	14.1	17.1	22.2
Export value of NSPF Frozen Flatfish M US$	$24.7	$31.7	$44.0	$26.5	$31.6	$34.8
Export price/.b of NSPF Frozen Flatfish US$	$0.77	$0.78	$0.87	$0.85	$0.84	$0.71
Share of U.S. exports of NSPF Frozen Flatfish to China[2]	64.1%	61.9%	77.1%	81.1%	80.3%	78.5%
Exchange rate, Yuan/Dollar	6.42	6.61	6.75	6.64	6.90	6.75

Source: FAO Fisheries & Aquaculture Dept. Statistics http://www.fao.org/fishery/statistics/en. U.S. Department of Agriculture http://www.ers.usda.gov/data-products/agricultural-exchange-rate-data-set.aspx.

1 - The GOA FMP share of U.S. production is calculated as the GOA retained catch divided by the FAO's U.S. production of flounder, halibut and sole.

2 - NSPF (not specifically provided for) Flatfish is a non-specific flatfish category for U.S. exports.

Table 7A.4a: Ecosystem indicator status analysis for GOA arrowtooth flounder, including indicator title and the indicator status of the last five years. The indicator status is designated with text, (greater than = "high", less than = "low", or within 1 standard deviation = "neutral" of the long-term mean). Fill color of the cell is based on the proposed sign of the overall relationship between the indicator and the stock (blue or italicized text = good conditions for the stock, red or bold text = poor conditions, white = average conditions). A gray fill and text = "NA" will appear if there were no data for that year.

Indicator Category	Indicator Title	2021 Status	2022 Status	2023 Status	2024 Status	2025 Status
Larval_YOY	Spring Sea Surface Temperature	neutral	neutral	neutral	neutral	NA
	Spring Eddy Kinetic Energy	*high*	neutral	neutral	*high*	neutral
	Spring Larval Arrowtooth	neutral	NA	neutral	NA	**low**
	Spring Larval Prey	neutral	NA	neutral	NA	NA
	Summer YOY Prey	NA	NA	neutral	NA	NA
	Summer/Fall YOY Prey	NA	NA	NA	NA	NA
Juvenile	Female Predation Mortality Age1	*low*	neutral	*low*	NA	NA
	Male Predation Mortality Age1	*low*	neutral	*low*	NA	NA
	Small Arrowtooth ADF&G	neutral	neutral	neutral	NA	NA
Adult	CPUE Arrowtooth ADF&G	neutral	neutral	neutral	NA	NA
	Arrowtooth Biomass Consumed	*low*	neutral	neutral	NA	NA
	Summer Bottom Temperature	neutral	NA	neutral	NA	NA
	Arrowtooth Area Occupied	**high**	NA	neutral	NA	neutral
	Arrowtooth Center of Biomass East	**low**	NA	neutral	NA	neutral
	Arrowtooth Center of Biomass North	**low**	NA	neutral	NA	neutral
	Adult Arrowtooth Condition	neutral	NA	neutral	NA	NA
	Arrowtooth Ration	*low*	neutral	neutral	NA	NA

Table 7A.4b: Socioeconomic indicator status table for GOA arrowtooth flounder, including indicator title and the indicator status of the last five years. The indicator status is designated with text, (greater than = “high”, less than = “low”, or within 1 standard deviation = “neutral” of the long-term mean). A gray fill and text = “NA” will appear if there were no data for that year.

Indicator category	**Indicator**	**2021 Status**	**2022 Status**	**2023 Status**	**2024 Status**	**2025 Status**
Fishery Informed	Catch Catcher Vessels	low	low	low	neutral	low
	Catch Catcher Processors	neutral	neutral	neutral	neutral	neutral
	Non-Target Catch Rockfish Fishery	high	high	neutral	neutral	neutral
	ABC Utilization	neutral	neutral	neutral	NA	NA
	TAC Utilization	low	low	low	NA	NA

Table 7A.5: The simplified causal model had the most support for explaining variation in recruitment compared to modeling recruitment as independent and identically distributed (iid) or modeling recruitment as a first order autoregressive process (ar1, see text).

Model	AIC
causal	733.0
iid	781.2
ar1	737.5

Table 7A.6a: Description of linkages included in the simplified causal directed acyclic graph (DAG) to explain recruitment of arrowtooth flounder in the GOA sourced from expert opinion and the literature (cited where applicable). Hypothesized causal relationship and lag of effect.

Link	Description	Relationship / Lag
Temperature to predation	Higher temperatures increase metabolism that will increase consumption (Holsman and Aydin, 2015).	Positive / 0
Euphausiids to age-1 recruitment	Euphausiids are a common prey of age-1 arrowtooth (Paul et al., 1999, Doyle et al., 2018).	Positive / 1
Temperature to small calanoid copepods	Marine heatwave influences the size (warm = more small copepods) and abundance of the copepod community (low large copepods in spring; Kimmel et al., 2023).	Positive / 0
Small calanoid copepods to larval abundance	Trophic modeling studies suggest biomass of arrowtooth flounder may be strongly influenced by changes in bottom-up production in plankton; fish < 200 mm eat zooplankton (Aydin et al., 2007; Doyle et al., 2018).	Negative / 0
Eddy kinetic energy (eke) to larval abundance	More eddy kinetic energy (EKE) in western GOA determines years of high recruitment (Goldstein et al., 2020)	Positive / 0
Adult condition to larval abundance	More energy reserves (Rohan et al., 2023) can be allocated to spawning and eggs/larvae would have more lipid reserves providing resilience from increased temperatures	Positive / 1
Larval abundance to age-1 recruitment	Recruitment and biomass may be related to density dependent effects at juvenile stage (Shotwell et al., 2022).	Positive / 1
Nearshore age-1 to age-1 recruitment	The abundance of age-1 fish in ADFG nearshore survey (Spalinger et al., 2023) relates to the abundance of age-1 recruits	Positive / 0
Predation to recruitment	Pacific cod and pacific halibut represent the highest proportion of predation on > 30 mm individual arrowtooth flounder; Cannibalism on the individuals 30-299 mm (Doyle et al., 2018, Adams et al., 2022).	Negative / 0

Table 7A.6b: Results of linkages included in the simplified causal directed acyclic graph (DAG) with associated data from the ESP, estimate of effect with associated p-value, difference (if any) between hypothesized relationship and estimated relationship, and suggestions for indicator improvements.

Link	Data from ESP (Indicator Title)	Estimate (P-value)	Relationship Change	Improvement Suggestions
Temperature to predation	Summer Bottom Temperature	0.15 (0.07)	None	Match bottom temperature to period of predation on age-1 arrowtooth with MOM6
Euphausiids to age-1 recruitment	Summer/Fall YOY Prey	-0.42 (<0.001)	Positive to Negative	Longer time series during YOY pelagic existence, e.g., EcoFOCI fall euphausiids time series
Temperature to small calanoid copepods	Spring Sea Surface Temperature	0.49 (<0.001)	None	More refined spatial match to pelagic arrowtooth larvae
Small calanoid copepods to larval abundance	Spring Larval Prey	-0.07 (0.7)	None	Determine actual prey size for arrowtooth larvae in late spring from diet samples, could switch to large copepod time series
Eddy kinetic energy (eke) to larval abundance	Spring Eddy Kinetic Energy	-0.14 (0.52)	Positive to Negative	Determine if entrainment leads to higher prey or being swept out of system, refine seasonal match
Adult condition to larval abundance	Adult Arrowtooth Condition	0.16 (0.53)	None	Refine to just mature adults rather than all arrowtooth
Larval abundance to age-1 recruitment	Spring Larval Arrowtooth	0.23 (0.04)	None	Determine if a YOY summer/fall index also exists for additional data linkages
Nearshore age-1 to age-1 recruitment	Small Arrowtooth ADF&G	-0.09 (0.34)	Positive to Negative	Refine size range based on new size age matrix in model, remove Aleutian samples
Predation to recruitment	Arrowtooth Biomass Consumed	0.41 (<0.001)	Negative to Positive	Switch to more prominent predator of arrowtooth age-1 (e.g., Pacific cod adult biomass)

Figures

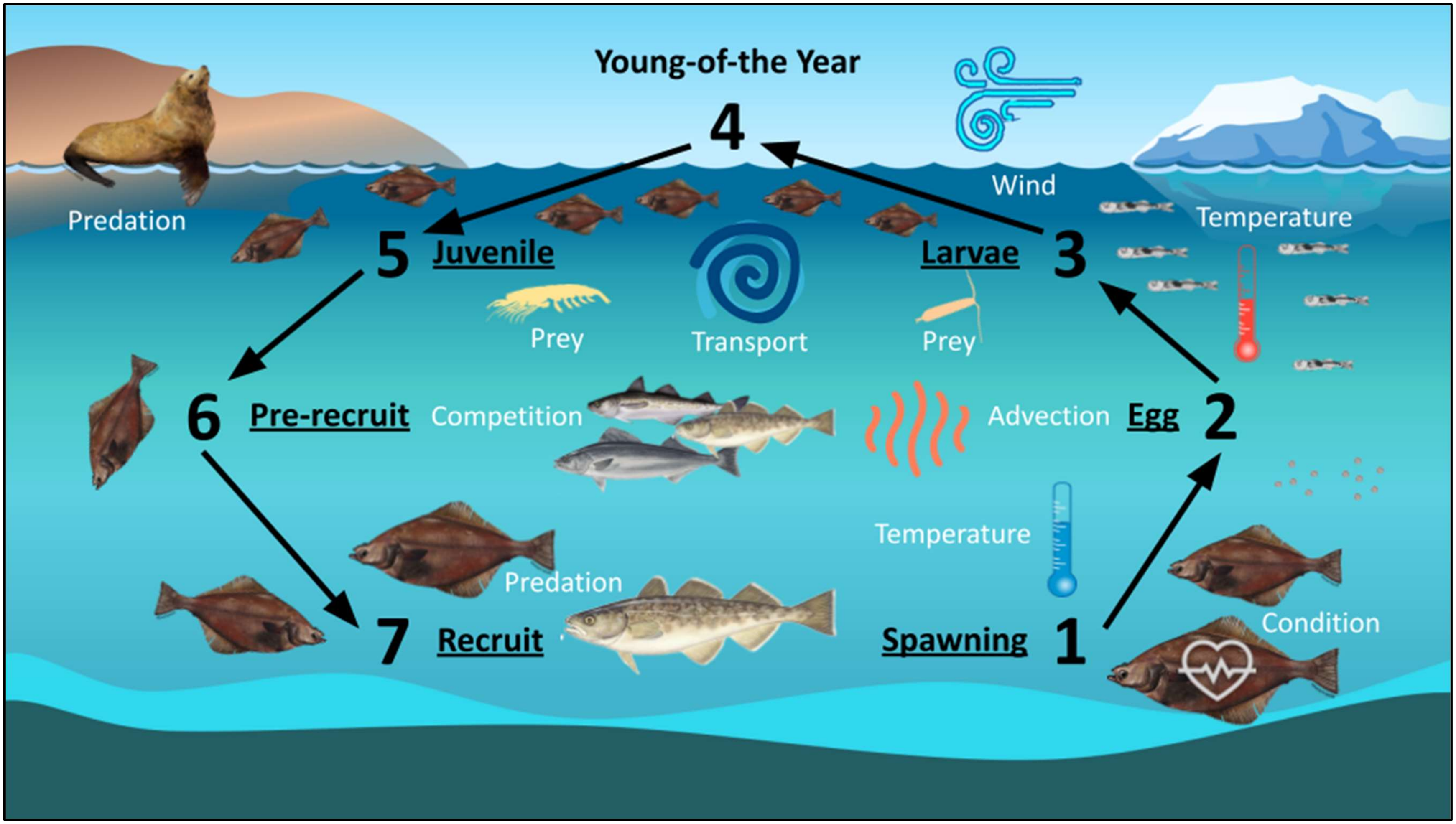

Figure 7A.1: Life history conceptual model for GOA arrowtooth flounder summarizing seven stages from Table 7A.2 with key ecosystem processes affecting survival by life history stage.

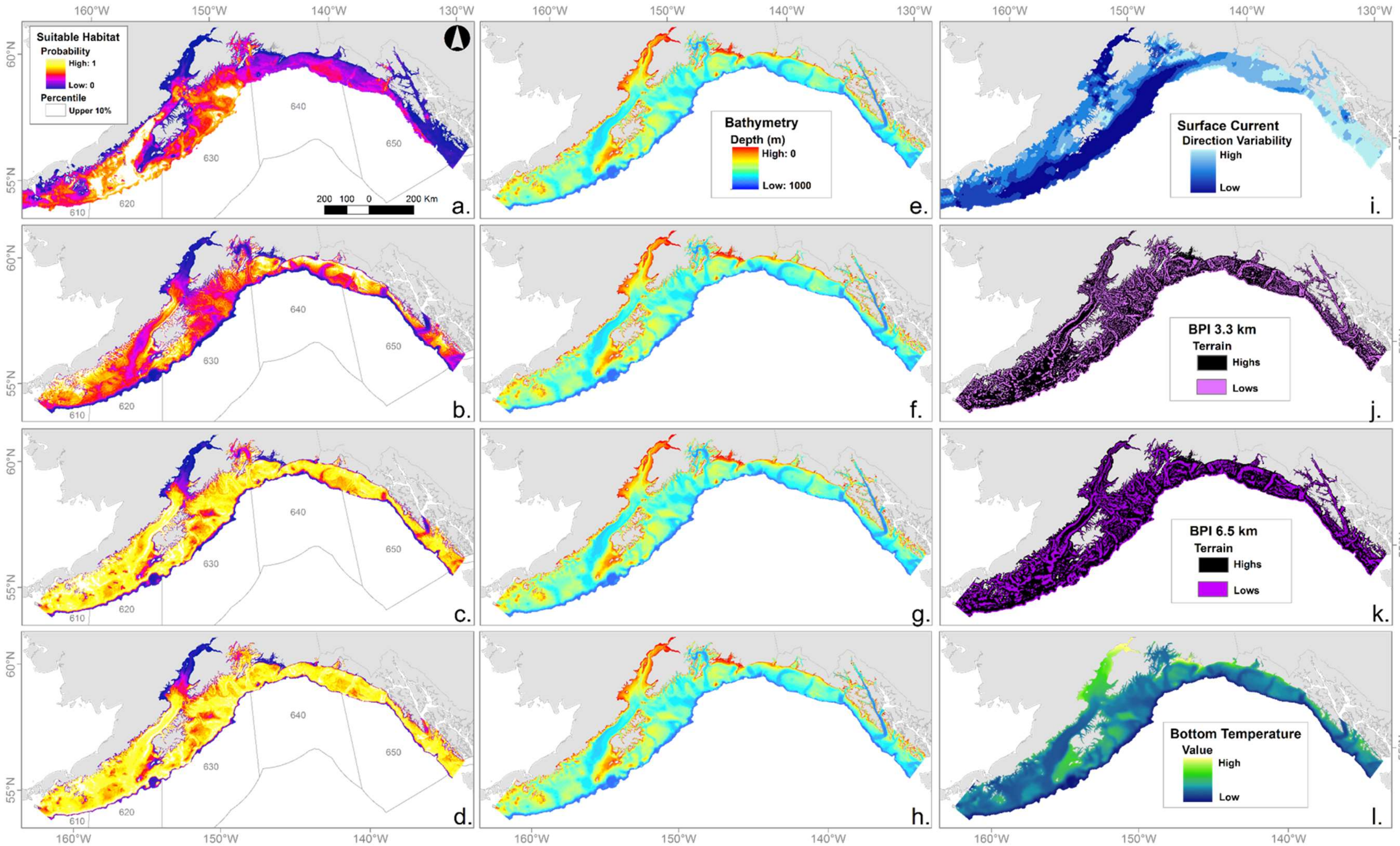

Figure 7A.2: GOA arrowtooth flounder probability of suitable habitat by life stage (a = larval, b = early juvenile, c = late juvenile, and d = adult) with corresponding predictor habitat variables representing the highest (e,f,g,h = depth) and second highest contribution (i = surface current direction variability, j,k = bathymetric position index, and l = bottom temperature). Upper 10 percentile of suitable habitat is shown in white within the probability of suitable habitat range (yellow to purple). Reproduced from Shotwell et al., 2022.

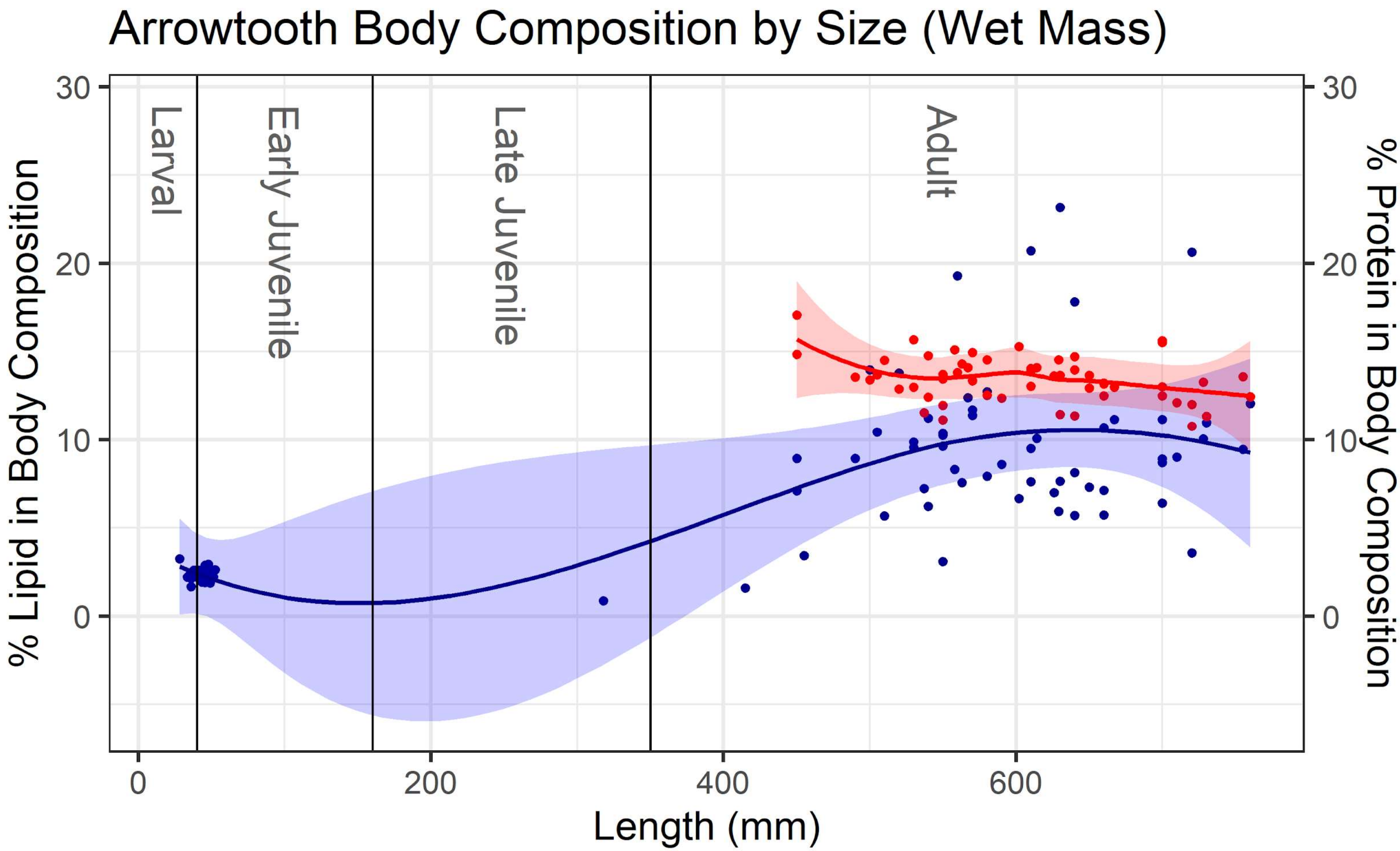

Figure 7A.3: GOA arrowtooth flounder percent body composition by length (mm), blue dots are % lipid by size, red dots are % protein by size and lines represent smoother (loess) for trend visualization. Vertical lines depict the size at different life stage transitions. Reproduced from Shotwell et al., 2022.

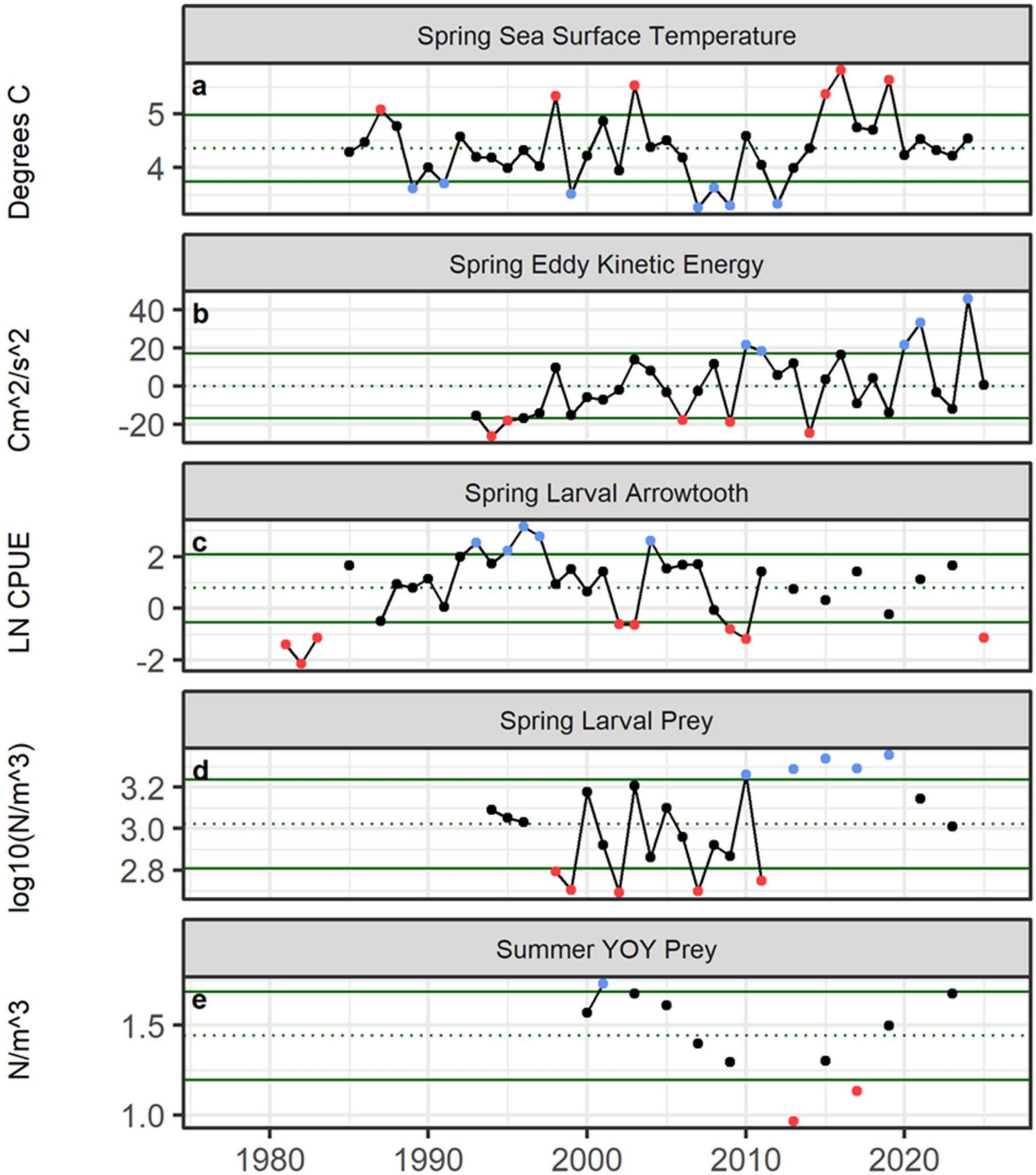

Figure 7A.4a: Selected ecosystem indicators for GOA arrowtooth flounder with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. Dots in the time series are colored if above or below 1 standard deviation of the time series mean and the color represents the proposed relationship for stock (blue for good conditions, red for poor conditions), black circle for neutral.

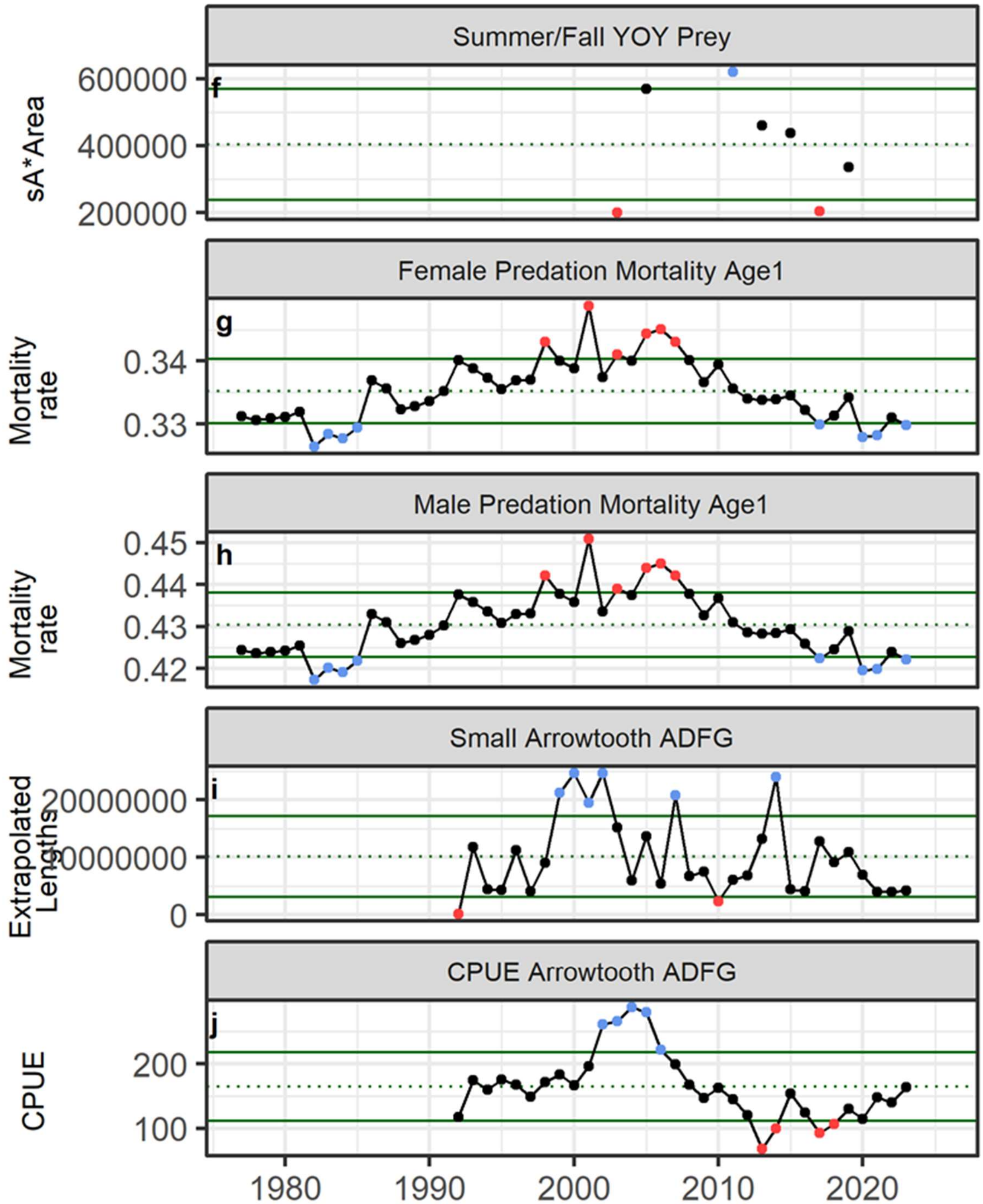

Figure 7A.4a (cont.): Selected ecosystem indicators for GOA arrowtooth flounder with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. Dots in the time series are colored if above or below 1 standard deviation of the time series mean and the color represents the proposed relationship for stock (blue for good conditions, red for poor conditions), black circle for neutral.

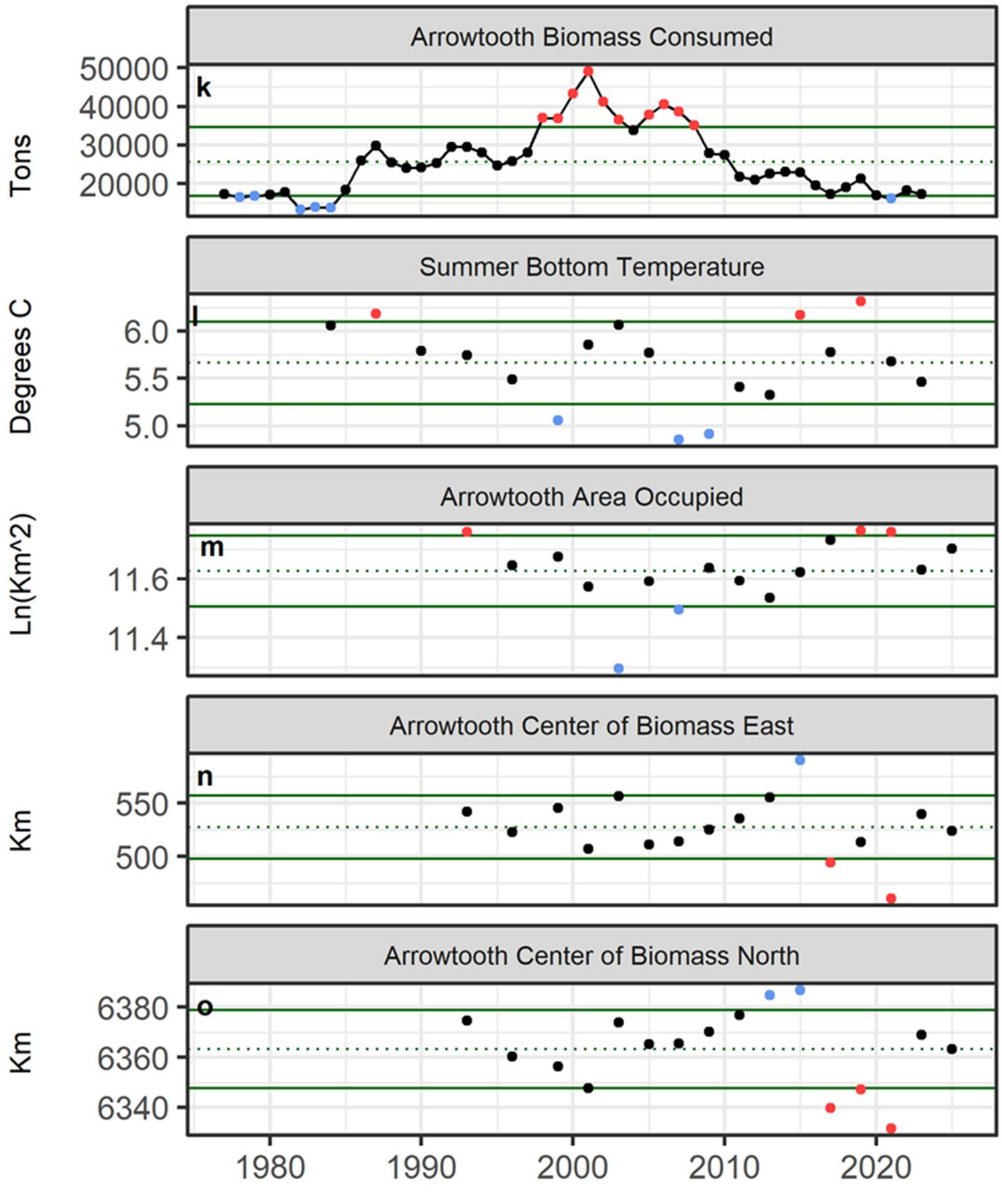

Figure 7A.4a (cont.): Selected ecosystem indicators for GOA arrowtooth flounder with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. Dots in the time series are colored if above or below 1 standard deviation of the time series mean and the color represents the proposed relationship for stock (blue for good conditions, red for poor conditions), black circle for neutral.

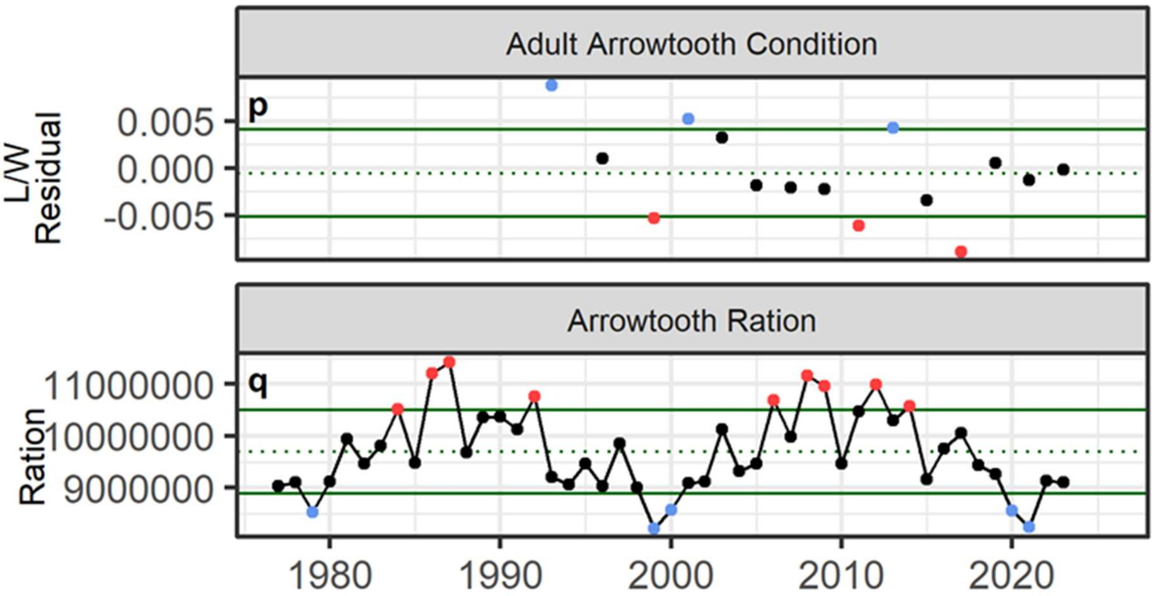

Figure 7A.4a (cont.): Selected ecosystem indicators for GOA arrowtooth flounder with time series ranging from 1977 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series. Dots in the time series are colored if above or below 1 standard deviation of the time series mean and the color represents the proposed relationship for stock (blue for good conditions, red for poor conditions), black circle for neutral.

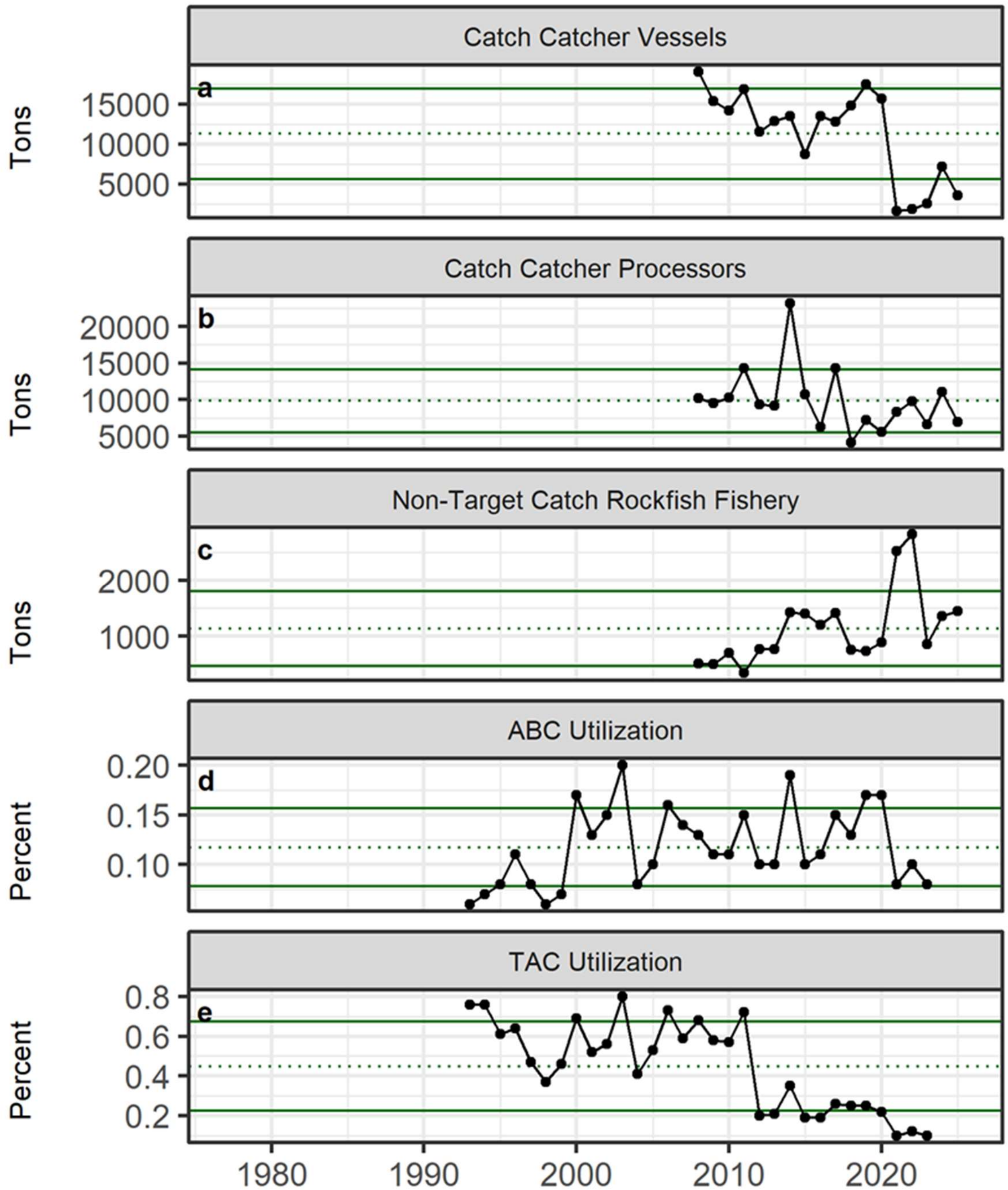

Figure 7A.4b: Selected socioeconomic indicators for GOA arrowtooth flounder with time series ranging from 1990 – present. Upper and lower solid green horizontal lines represent 1 standard deviation of the time series mean. Dotted green horizontal line is the mean of the time series.

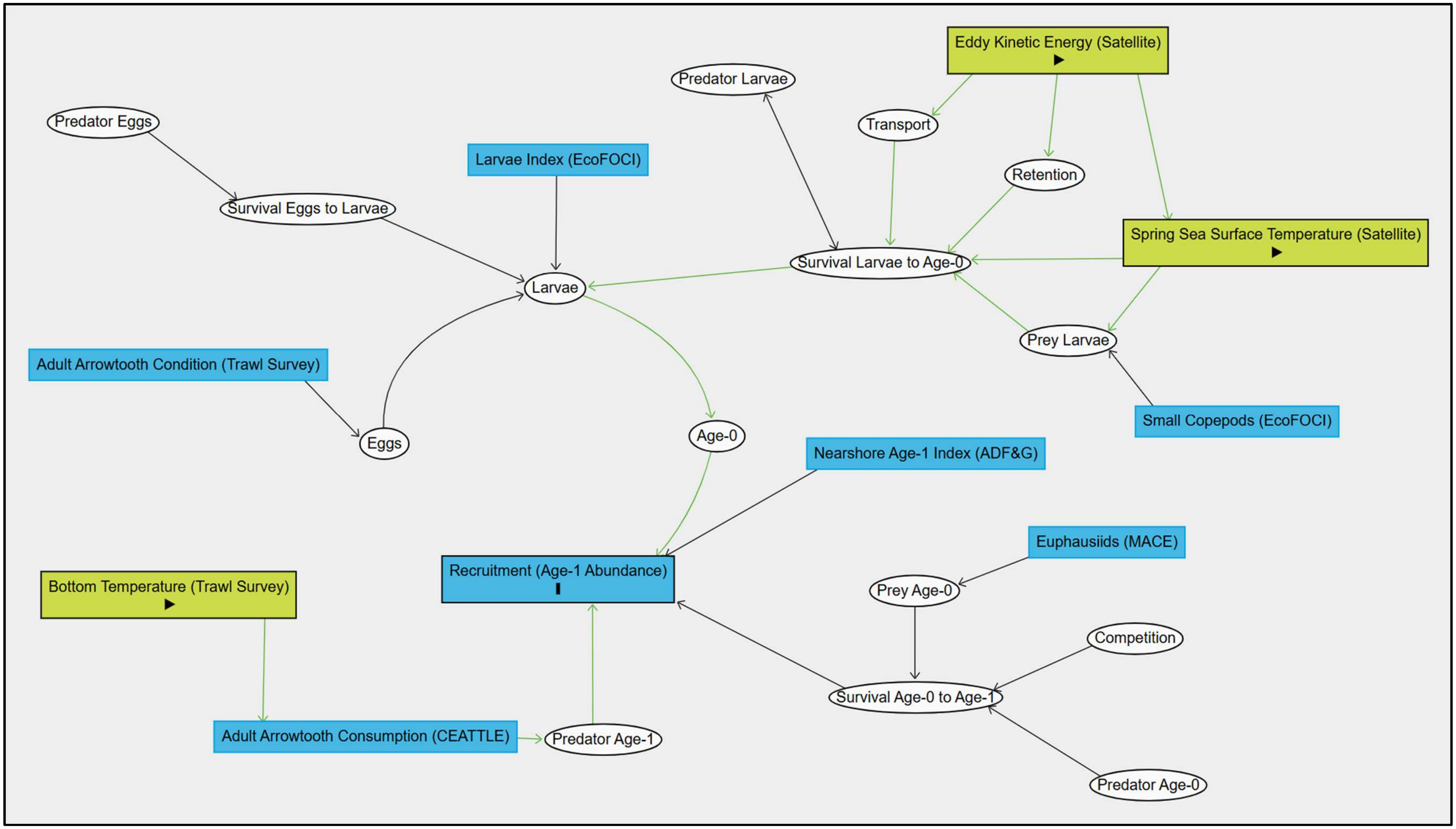

Figure 7A.5: The full causal model (as a directed acyclic graph or DAG made in daggity.net) illustrating causal linkages that may explain arrowtooth age-1 recruitment. White ovals are unobserved or latent variables, blue boxes are observed covariates, green boxes with a play symbol are observed exposure variables, and the blue box with an I symbol is the response variable. Green arrows are causal paths from the exposure to the response variable. There are no biasing paths (red arrows) identified in this DAG.

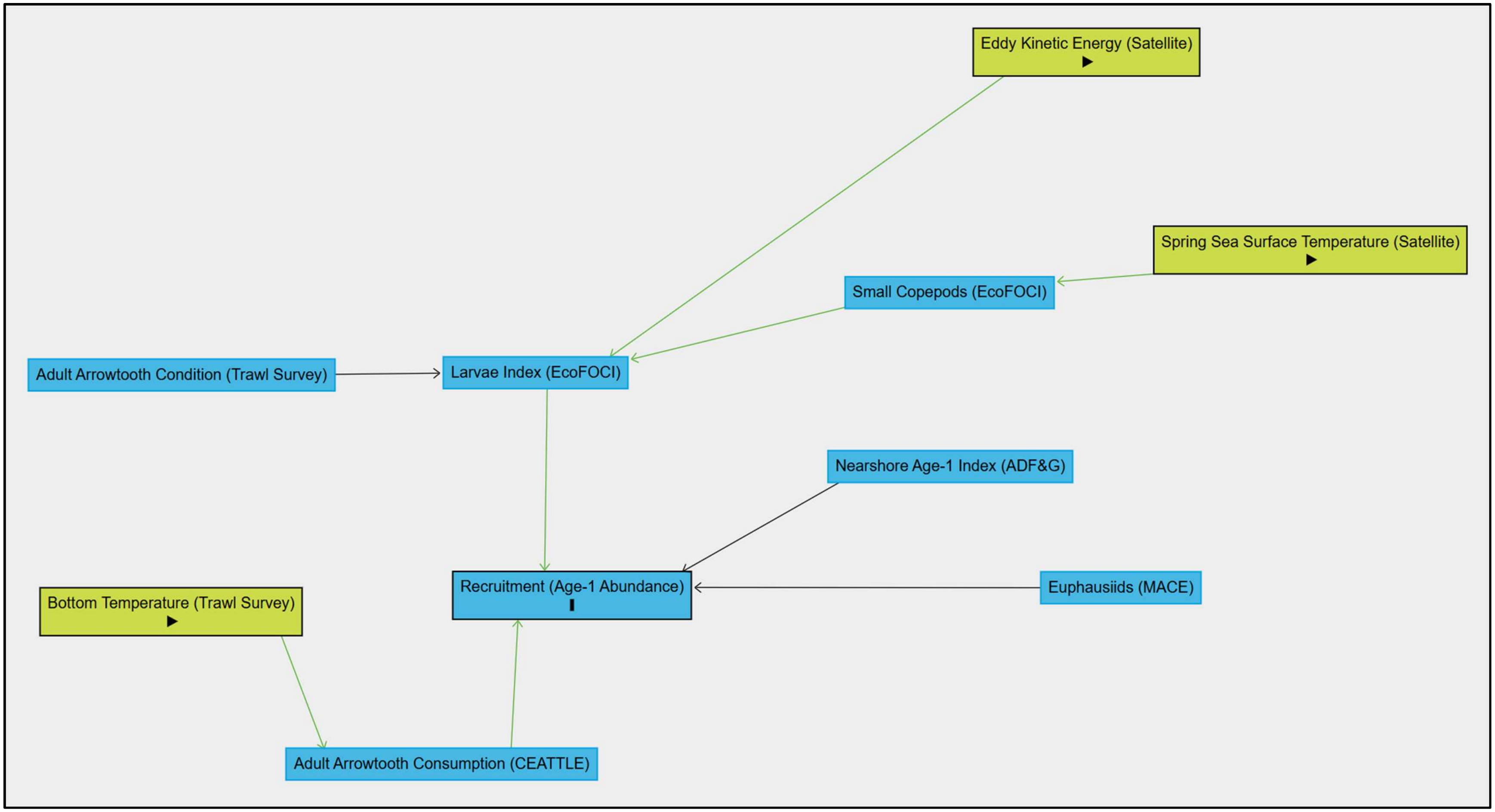

Figure 7A.6: The simplified causal model fitted using a dynamic structural equation model (DSEM) r package that was paired down from the initial, full model to be estimable. Note there is a one-year lag on the relationship between adult condition and larval abundance, larval abundance and age-1 recruits, and euphausiid abundance and age-1 recruits. Blue boxes are observed covariates, green boxes with a play symbol are observed exposure variables, and the blue box with an I symbol is the response variable. Green arrows are causal paths from the exposure to the response variable. There are no biasing paths (red arrows) identified in this DAG.

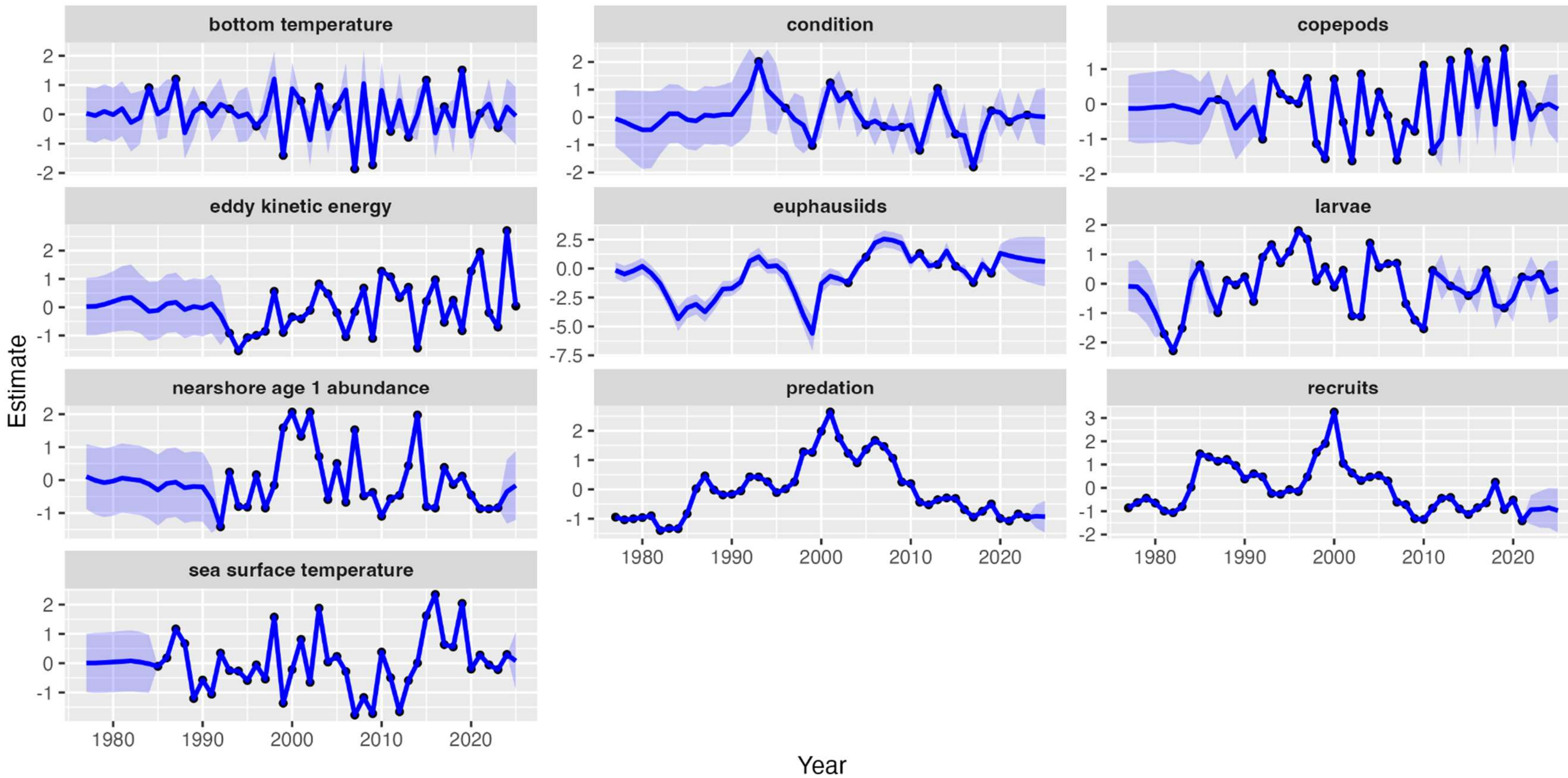

Figure 7A.7: Time series of recruitment (outcome) and covariates estimated using a dynamic structural equation model (DSEM) for the causal model.

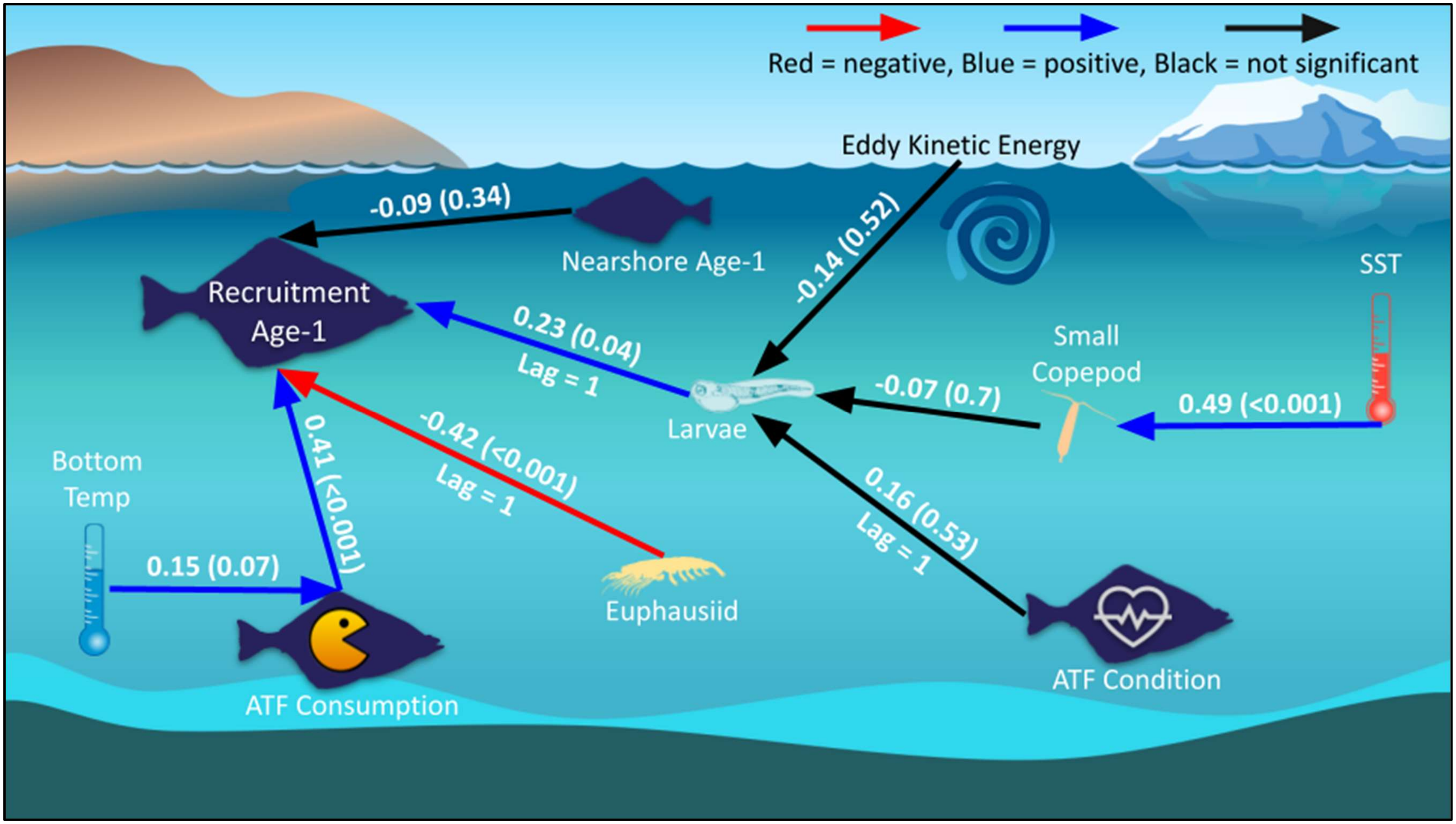

Figure 7A.8 Simplified causal model of GOA arrowtooth flounder with estimated effects. Lag = 0 years unless otherwise stated on the arrow. Numbers are the estimated effect of the covariate on age-1 recruitment and the associated p-value in parentheses. Blue arrows represent a positive relationship, red arrows represent a negative one, and black arrows were non-significant relationships. SST = sea surface temperature, ATF = arrowtooth flounder.