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., 2023a). 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 Gulf of Alaska (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 using an external dynamic structural equation model (DSEM) following Bigman et al., *in review*. 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:

- Sea surface temperature in the GOA increased to a high in 2025 from near average temperatures in 2020-2024 suggesting prey for arrowtooth larvae may be dominated by small copepods and impact feeding conditions and lower overwinter survival for arrowtooth larvae.
- Summer/fall prey for young-of-the-year (YOY) arrowtooth measured by euphausiid abundance has not been updated since 2019 and is unlikely to continue in the future.
- Bottom temperatures increased in 2025 to above average following previous two surveys of below average temperatures suggesting increased metabolism of predators and higher consumption of age-1 arrowtooth.
- Estimates of biomass consumed of arrowtooth flounder as prey across all ages have slightly increased since the low in 2021 but remain below the long-term mean in 2025.

Contextual Indicators:

- Eddy kinetic energy (EKE) decreased to average in the eastern GOA and decreased to well below average in the western GOA in 2025 suggesting average conditions for retention away from suitable nursery habitat in the east but decreased retention in suitable nursery habitat in the west resulting in lower overwinter survival
- The low abundance of arrowtooth larvae suggests poor to average foraging conditions and low reserves for overwintering potentially suggesting a poor 2025 year class.
- Recent warm years had high abundances of small copepods in spring and numbers in 2021 and 2023 (the two most recent survey data available) decreased to average consistent with the average sea surface temperatures.

- There is evidence of time-varying predation mortality on age-1 female and male arrowtooth flounder due to the species modeled in the CEATTLE multispecies model that has been above the time-invariant single species stock assessment value (0.2 and 0.35, respectively) in all years.
- The index of small arrowtooth from the nearshore survey continues to be below average in 2025 suggesting poor overwinter success for recent year classes.
- Average juvenile and adult condition suggest that arrowtooth flounder were able to find sufficient prey resources.
- The catch-per-unit-of-effort of arrowtooth flounder in the nearshore survey has decreased to below average in 2025 and suggests decreased abundance in the nearshore habitat
- Expansion of area occupied and a shift to the southwest in the center of gravity suggest the arrowtooth flounder population could be shifting out of the survey area and this could impact survey selectivity

Fishery-Informed Indicators:

- Catch from catcher vessels increased from 2025 but catch from catcher processors continued to decline and is near the time series low.
- Incidental catch of arrowtooth flounder in the rockfish fishery remains similar to the last two years and slightly above the time series long term mean.
- ABC and TAC utilization decreased from 2024 to 2025 by approximately 40% reflecting declines in catch trends and were near the lowest in the time series.

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.
- Status and trends of relevant economic or community indicators will be included in future ESP reports

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.

"The Teams recommended developing a multi-variate indicator that synthesizes the contextual ecosystem time series to measure how anomalous the current year is relative to historical conditions. The Teams also suggested that this synthesis could be expanded with a cluster analysis similar to the temperature cluster

analysis approach presented in the Ecosystem Status Report by Kelly Kearney. Members also expressed interest in the potential for DSEM integration to provide a structured pathway for ecosystem variables to directly inform assessment models and projections." (JPT, September 2026)

In past ESPs, we have included a simple traffic light score time series as a way to summarize all the indicators in an ESP. We broke this down by organizational category (larvae/YOY, juvenile, adult) and overall. The score was a useful way to determine the health of the stock without letting any one indicator dominate. The Crab Plan Team then initiated the categorizing by predictive and contextual indicators as a way to further weight indicators that were evaluated with a statistical analysis with respect to some parameter of interest for the stock (mostly recruitment). The first example of this was using the Bayesian Adaptive Sampling (BAS) method, but that was very restrictive to long, gap-free time series. With the onset of dynamic structural equation modeling (DSEM) we can now use that for our analysis and dramatically increase the indicators that can be evaluated for predictive versus contextual. Once that occurs the suite of contextual indicators could be summarized as a whole using that original score metric. That simple score analysis could certainly be expanded to a cluster analysis and we plan to develop that for the contextual indicators of future ESPs. Regarding DSEM as a structural pathway, we have initiated two projects to accomplish this within the AFSC, a discussion group and training curriculum (see details in responses below).

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)

The ecosystem and socioeconomic profile or ESP 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. We initiated collecting indicators for this stock through a mini ESP process in 2024 and presented those to the GOA Groundfish Plan Team in September 2024. A first full draft of this ESP was presented to the September GOA Groundfish Plan Team in 2025 and was designed to start the review process for which indicators to include and what indicator analysis to pursue for this ESP. We provided a suite of potential indicators and introduced a new indicator analysis method through the *dsem* R package platform. The Plan Team endorsed the indicator suite and DSEM application but was unsure whether they could provide a reasonable level of review for the ESP-DSEM process as a whole. They provided an additional recommendation to address this (see below in the GOA GPT, September 2025 comment)

"*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 investigated these lower recruitment trends through the ecosystem and socioeconomic profile (ESP) framework and provided a draft ESP at the September Plan Team for review of progress. An external DSEM has been developed for this stock and was included in the draft ESP in 2025. Since that time we have explored a few more external DSEMs for this stock and included them as a case study in a paper led by J. Bigman which is currently in review at Fish and Fisheries. We include an updated version of that model in this document with new covariate data and plan to integrate it within the Rceattle platform that has been recommended for assessment of this stock. We present the finalized external model evaluation as a research ecosystem model in this full ESP to be submitted for review at the September Plan Team in 2026. The results of this model were used in the assessment to inform the risk table regarding shifts in recruitment under the population dynamics considerations section. We hope to have a discussion regarding further use of this research ecosystem model for informing management decisions. One avenue may be to use the ecosystem research model in the harvest projections for off-cycle years to incorporate new ecosystem information along with new catch in the advice for this stock.

"The Team recommended the AFSC expert group develop proposed guidance for how to evaluate DSEM fits in the context of interpreting ESPs and also provide some guidance on a framework of how this effort can best be used in a management context." (GOA GPT, September 2025)

"The SSC recommends considering variable selection or multiple candidate causal models along with a selection framework and supports the ESP team's approach to categorizing indicators as predictive/contextual/monitoring, which aligns with the CPT's approach. The SSC also looks forward to seeing more details in December on the socioeconomic indicators. Finally, the SSC endorses the GOA GPT's recommendation that the AFSC expert group on causal models develop guidance on evaluating DSEM fits within the context of interpreting ESPs as well as guidance on a framework for how these causal models can best be used in a management context." (SSC, October 2025)

Following the introduction of the GOA arrowtooth flounder ESP and the associated modeling effort, the GOA Groundfish Plan Team (GPT) provided the above recommendation in a general sense regarding how DSEM applications should be included in the ESP workflow for interpreting the included indicators. The SSC agreed and endorsed the new categorizing framework. In response to the request for an expert group, scientists at the AFSC started a discussion group in winter/spring 2026 to generate a set of guideline diagnostics for evaluating DSEMs and initiated a training workshop series with the NEFSC to make DSEM an integral part of the ESP process at both science centers. The first 3-day training workshop was held in Juneau, Alaska in April 2026 and included participants from AFSC, NEFSC, UAF, and other agencies. Training included instruction on causal modeling, how to run the r package *dsem*, and various breakout sessions for hands-on training using a fake peanut butter and jelly flounder (somewhat modeled after arrowtooth flounder) as a test case. A second workshop is planned in September 2026 at the NEFSC to train staff in the population dynamics and ecosystem branches on how to incorporate DSEM into their ESP workflow.

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., 2023a). 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., 2023a) 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 an indicator synthesis 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 indicator synthesis 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. comm.*). The data supporting the report has been updated to 2024 (Anna Ableman, *pers. comm.*) and used to update the text from the original report.

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 2024 it accounted for 90% of the retained GOA flatfish catch and 88% of the ex-vessel value (Table 7A.3a,b). 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 50% of the total Alaska catch of arrowtooth catch in recent years and 65% in 2024 (Table 7A.3a). 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 2024 was $20.4 million, which is a large increase from 2023 and above the 2015-2019 average of $22.6 million (Table 7A.3b). Commensurate with the increase in catch, production volume increased to 11.2 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. The average first-wholesale price has remained stable over the last three years and was $0.83 per pound in 2024 and was above the 2015-2019 average of $0.73 per pound. The stability seems largely due to arrowtooth flounder prices and was $0.86 per pound in 2024. Relative to other flatfish, arrowtooth flounder tends to be the higher priced species, which is a switch from rex sole prior to 2021. 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 2023 and Gulf of Alaska flatfish represent approximately 10% of the U.S. flatfish production but has decreased to 5.3% in 2023 (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 Marine Stewardship Council (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 Not Specifically Provided For (NSPF) flatfish increased in 2024 and average export prices have remained stable for the past three years at $0.8 per pound and was similar to the 2015-2019 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 began 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 2024 from 2023 and the share of exports to China was within a typical range overall (Table 7A.3c). 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.

Proposed Indicators

We provided a proposed list of indicators through the first draft full ESP (Shotwell et al., 2025a) and two presentations to the GOA Groundfish Plan Team in September 2024 and 2025. Please refer to the NPFMC's eagenda of the September Plan Team under the item "ESP & Socioecon indicators update" (https://meetings.npfmc.org/Meeting/Details/3056) for the 2024 presentation and the item "Arrowtooth flounder & ESP" (https://meetings.npfmc.org/Meeting/Details/3099) for the 2025 presentation.

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., 2023a).

Indicator Selection

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 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:

1. Larval to YOY Indicators (Figure 7A.4a.a-f)

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. Contact: Matt Callahan
   - Link and lag assigned for ecosystem indicator analysis: positive link to small copepods with 0 year lag
   - Status and trends: The early spring SST in the core EFH area in 2025 is well above the long-term average, similar to the heatwave year of 2015 and an increase from 2024.
   - 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 larger lipid-rich zooplankton species and more small copepods which may impact feeding conditions for larval arrowtooth flounder. Due to their extended larval duration, warmer surface waters could also impact or burn through arrowtooth larvae lipid reserves.

b. Spring Eddy Kinetic Energy EGOA: Eddy kinetic energy (EKE) calculated as seasonal mean from spawning through final settlement (averaged January to October) anomalies from sea surface height at 0.125 degree resolution in the eastern Gulf of Alaska within an area from 146°W to 135°W and from 1000 m to 200 km offshore using the Smith and Sandwell 2-arc-minute bathymetry data. EKE is a measure of mesoscale energy in the ocean system (Ladd, 2020). 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. Contact: Wei Cheng
   - Link and lag assigned for ecosystem indicator analysis: negative link to arrowtooth larvae with 0 year lag
   - Status and trends: The EKE in eastern GOA in 2025 is at the long-term average, a decrease from above average 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).
   - Implications: More eddy kinetic energy (EKE) in the eastern GOA increases retention farther away from suitably nursery habitat resulting in lower overwinter survival (Goldstein et al., 2020).

c. Spring Eddy Kinetic Energy WGOA: Eddy kinetic energy (EKE) calculated as seasonal mean from spawning through final settlement (averaged January to October) anomalies from sea surface height at 0.125 degree resolution in the western Gulf of Alaska within an area from 160°W to 146°W and from 1000 m to 200 km offshore using the Smith and Sandwell 2-arc-minute bathymetry data. EKE is a measure of mesoscale energy in the ocean system (Ladd, 2020). 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. Contact: Wei Cheng

- Link and lag assigned for ecosystem indicator analysis: positive link to arrowtooth larvae with 0 year lag
- Status and trends: The EKE in western GOA in 2025 is well below the long-term average, a decrease from second highest value in 2024.
- Factors influencing trends: 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: More eddy kinetic energy (EKE) in western GOA increases retention near more suitable nursery habitat resulting in higher overwinter survival (Goldstein et al., 2020).

d. 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. Contact: Lauren Rogers

- Link and lag assigned for ecosystem indicator analysis: positive link to arrowtooth age-1 recruitment with 1 year lag
- 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 2025 year class.

e. 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

- Link and lag assigned for ecosystem indicator analysis: negative link to arrowtooth larvae with 0 year lag

- 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 the 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.

f. 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. Contact: Lauren Rogers and David Kimmel
   - Link and lag assigned for ecosystem indicator analysis: positive link to arrowtooth larvae with 0 year lag but not used in indicator analysis due to mismatch in timing as arrowtooth feeding primarily on euphausiids at this time.
   - 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.

g. 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. Contact: Patrick Ressler
   - Link and lag assigned for ecosystem indicator analysis: positive link to arrowtooth age-1 recruitment with 1 year lag
   - 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>

h. 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). Contact: Grant Adams
   - Not included in ecosystem indicator analysis for recruitment. This indicator is included to provide information on natural mortality for female arrowtooth.
   - Status and trends: The multi-species model estimates that natural mortality due to all sources for age-1 arrowtooth flounder peaked in 1983, then declined through the next two decades, remained steady until an increase from 2016-2019, then decreased again and has remained low to present. Average age-1 mortality estimated by CEATTLE was 0.38 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 (0.2) in all years.

i. 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). Contact: Grant Adams
   - Not included in ecosystem indicator analysis for recruitment. This indicator is included to provide information on natural mortality for male arrowtooth.
   - Status and trends: The multi-species model estimates that natural mortality due to all sources for age-1 arrowtooth flounder peaked in 1983, then declined through the next two decades, remained steady until a increase from 2016-2019, then decreased again and has

remained low to present. Average age-1 mortality estimated by CEATTLE was 0.47 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 (0.35) in all years.

j. 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. Contact: Kally Spalinger and Joletta Silva
   - Link and lag assigned for ecosystem indicator analysis: positive link to arrowtooth age-1 recruitment with 0 year lag
   - Status and trends: Small arrowtooth have been steadily declining since 2014 and below average for 8 of the last 11 years. They continue to be below average in 2025.
   - 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.

k. Juvenile Arrowtooth Condition: Summer stratum-biomass weighted morphometric condition of juvenile (less than 460 mm) 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 1990 to present. Contact: Sean Rohan
   - Not included in ecosystem indicator analysis for recruitment. This indicator is included to provide information on growth for arrowtooth prior to maturity.
   - Status and trends: Juvenile GOA arrowtooth flounder condition has been neutral but lower than average for the past four GOA surveys conducted from 2019 to 2025.
   - 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 2025. 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 2025 Gulf of Alaska Ecosystem Status Report (Prohaska and Rohan, 2026).
   - 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.

3. Adult Indicators (Figure 7A.4a.j-q)

l. 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, 2025). Data available from 1992 to present. Contact: Kally Spalinger and Joletta Silva
   - Not included in ecosystem indicator analysis for recruitment. This indicator is included to provide information on nearshore abundance for arrowtooth flounder as a potential alternative survey index of abundance.
   - 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 and has since declined in 2024 and again in 2025 to below average.
   - 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.

m. 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). Contact: Grant Adams
   - Link and lag assigned for ecosystem indicator analysis: negative link to arrowtooth age-1 recruitment with 0 year lag
   - Status and trends: Estimates of biomass consumed of arrowtooth flounder as prey across all ages have slightly increased since the low in 2021 but remain below the long-term mean.
   - 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.

n. 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 1993 to present (Rohan and Barnett, 2026). Data are available triennial since 1993 and biennial since 2000. Contact: Sean Rohan
   - Link and lag assigned for ecosystem indicator analysis: positive link to predation (via biomass consumed) with 0 year lag

- Status and trends: Lower bottom temperatures from 2021 through 2023 following the high and above average temperatures during the marine heatwave. Increase in 2025 to above average.
- 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).

o. 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. Contact: Zack Oyafuso and Margaret Siple
   - Not included in ecosystem indicator analysis for recruitment. This indicator is included to provide information on distribution of arrowtooth flounder.
   - Status and trends: The estimated effective area occupied for arrowtooth flounder in 2025 moderately increased from 2023 and has remained above average since 2015.
   - Factors influencing trends: The large expansion of effective area occupied is concurrent with a shift to the southwest of the population and 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.

p. 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 for recruitment. This indicator is included to provide information on distribution of arrowtooth flounder.
- 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.

q. 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 for recruitment. This indicator is included to provide information on distribution of arrowtooth flounder.
   - 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.

r. Adult Arrowtooth Condition: Summer stratum-biomass weighted morphometric condition of adult (greater than or equal to 460 mm) 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
   - Link and lag assigned for ecosystem indicator analysis: positive link to arrowtooth larvae with 1 year lag
   - Status and trends: Adult GOA arrowtooth flounder condition has been neutral for the last four GOA surveys and at the long-term average for the past three surveys conducted from 2019 to 2025.
   - 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 2025. 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 2025 Gulf of Alaska Ecosystem Status Report (Prohaska and Rohan, 2026).

- 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 to allocate to spawning.

s. 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). Contact: Grant Adams
    - Not included in ecosystem indicator analysis for recruitment. This indicator is included to provide information on bioenergetics and natural mortality of arrowtooth flounder.
    - 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:

<u>1. Fishery Informed Indicators (Figure 7A.4b.a-e)</u>

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: Catch from catcher vessels increased in 2026 but remain below average since 2021
    - Factors influencing trends: TBD
    - Implications: TBD

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: Catch continued to decline and is near the time series low.
    - Factors influencing trends: TBD
    - Implications: TBD

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: incidental catch of arrowtooth flounder in the rockfish fishery remains similar to the last two years and slightly above the time series long term mean.
    - 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: ABC utilization decreased from 2024 to 2025 by approximately 38% reflecting declines in catch trends and were near the lowest in the time series.
   - Factors influencing trends: TBD
   - Implications: TBD

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: TAC utilization decreased from 2024 to 2025 by approximately 42% reflecting declines in catch trends and were near the lowest in the time series.
   - Factors influencing trends: TBD
   - Implications: TBD

<u>2. Economic Indicators (Figure 7A.4b.f-h) TBD (Examples for Future)</u>

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

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

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

<u>3. Community Indicators (Figure 7A.4b.i-i) TBD (Information for Future)</u>

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 Analysis

Ecosystem and socioeconomic indicators are monitored through distinct workflows, depending on the management decisions they are intended to inform (Figure 7A.5). 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 have recently adopted a new system to evaluate the suite of ESP indicators through structural frameworks rather than continuing with the regression based methods of previous ESPs. This is in response to requests by the SSC to further investigate causal inference, recent success of using these methods with other species (e.g., GOA pollock in Champagnat et al., 2026), and the increasing need to develop mechanistic understanding before applying statistical diagnosis. We present a stepwise workflow that navigates from qualitative mapping to integrated modeling, allowing for evaluation progress to be based on the data availability of the stock (Shotwell et al., 2023a). As an integral part of this workflow we use dynamic structural equation modeling (DSEM) which is a multivariate state-space time-series statistical modeling framework that can estimate simultaneous and lagged causal effects while natively handling missing observations (Thorson et al., 2024). Because environmental data are notoriously sparse, DSEM models the true ecosystem dynamics as latent states and can interpolate over years with missing data. This modeling framework allows us to assess whether complex networks of ecosystem variables interact to causally affect an outcome, such as recruitment (Champagnat et al., 2026; Thorson et al., 2024). To test these hypotheses, DSEM can be applied using three structures: 'detached', 'external', or 'internal'. The detached DSEM is exclusively related to the ecosystem or socioeconomic indicators excluding the stock assessment parameter of interest (e.g., Siddon et al., 2024). The 'external' DSEM evaluates causal links outside the stock assessment by assuming model estimates are data (e.g., Thorson et al., 2024; Bigman et al. *in review*), while the 'internal' DSEM integrates directly within the stock assessment model (e.g., Champagnat et al., 2026). When integrated into a stock assessment (e.g., via Rceattle), the assessment and DSEM models are estimated jointly, allowing the biological parameters and the environmental drivers to inform one another while better accounting for covariation among latent states (Champagnat et al., 2026).

This paradigm shift from traditional regression-based methods to the structural workflow fundamentally transforms ecosystem monitoring from descriptive correlation to mechanistic explanation (Arif and MacNeil, 2022). Standard traffic light systems show whether an indicator is above or below average, but they fail to explain how that anomaly propagates through the food web. Replacing this with qualitative Directed Acyclic Graph (DAG) construction forces researchers to outline their exact biological assumptions before touching the data ("science before statistics"; McElreath, (2020)). Multiple regression is mathematically unable to represent multi-step pathways. Standard multiple regression treats candidate drivers as an undifferentiated "causal salad," where indiscriminate covariate adjustment partials out shared variance and frequently introduce severe confounding, overcontrol bias (inadvertently blocking indirect pathways through intermediate trophic mediators), and collider bias (generating spurious associations by conditioning on common descendants) (Arif and MacNeil, 2022). This graphical foundation allows analysts to specify the entire hypothesized network of simultaneous and lagged pathways, evaluating direct and indirect effects globally rather than relying on isolated regression equations (Champagnat et al., 2026). When estimated dynamically through state-space frameworks like DSEM, the workflow can accommodate common time-series challenges, such as missing survey years and temporal autocorrelation, by modeling latent states and joint covariance structures (Champagnat et al., 2026). Ultimately, this approach reduces the risk of relying on spurious or unstable historical correlations under changing climate regimes, providing a more structurally consistent framework to support risk tables and climate-informed assessments (Arif and MacNeil, 2022; Champagnat et al., 2026).

Step-by-Step Workflow

We use the following guideline workflow to evaluate the mechanistic underpinning of the ecosystem and socioeconomic indicators in the ESP with regard to stock population dynamics and community health.

1.) The Mechanism Table (Theory & Evidence): This is the foundation of analysis based on first principles, literature synthesis, expert knowledge, and group/team consensus. Before drawing any arrows or conducting any statistical modeling, synthesize background biological, environmental, and socioeconomic knowledge into an explicit hypothesis-based structured table. Identify candidate indicators from the Indicator Selection section (e.g., life-history conceptual diagrams and indicator suites) that are most relevant to population processes (recruitment, growth, natural mortality) or socioeconomics. For each hypothesized relationship, detail the driver and response variable, the hypothesized mechanism and references, the expected sign of the response (+/-), the temporal lag(s) involved, and the team's confidence in each causal hypothesis. The table building process grounds the eventual statistical analysis in actual biology.

2.) The DAG Construction (Causal Mapping): Translate the mechanism table into a visual network such as a directed acyclic graph (DAG). This step establishes the strict causal architecture. Represent analytical units and time steps as nodes and direct causal dependencies as directed arrows (edges), while explicitly accommodating lags. Use a graphical tool (e.g., dagitty at https://www.dagitty.net/dags.html) to define the environmental exposures and population outcomes and confirm that all biasing pathways are identified and blocked. This can include confounding bias through unblocked common causes, overcontrol bias through intermediate mediators on a direct path, and collider bias through inadvertently conditioning on a mutually caused variable. Essentially, debug the logic of the mechanism table before touching any time-series data.

3.) Base Network Validation via Detached DSEM (The Reality Check): Test the pathways in the DAG using actual data. First ensure that all input data are standardized (centered and scaled or logged as necessary, as a best practice), set baseline independent and identically distributed (IID) and/or first-order autoregressive (AR1) latent structure for all nodes (provides a baseline for missing data imputation and allows for later model comparisons), verify that simultaneous and lagged paths yield an invertible Hessian matrix of the fixed effects and that observation error (if specified) is not set too low (can prevent convergence). Next, fit a detached DSEM exclusively on the ecosystem or socioeconomic drivers excluding the stock parameter of interest (e.g., recruitment). Then quantify the path coefficients and test if the data actually supports the arrows you drew in the DAG. Accomplish this by 1) confirming the model returns an invertible (non-singular) Hessian matrix and that absolute marginal log-likelihood gradients are < 0.001, 2) verifying reasonable parameter standard errors (not on bounds or non-zero), 3) checking the estimated path coefficients for signs that differ from the expected sign (proposed in the mechanism table) and investigate assumptions if they flip, 4) addressing collinearity and change the DAG if necessary, and 5) check that the process error does not collapse to zero (a sign of overfitting). If this baseline ecosystem network proves unstable or lacks statistical power, adjust your causal assumptions before complicating things with a response variable.

4.) Predict Response Variable via External/Internal DSEM (The Final Link): Once the underlying ecosystem structure is validated, connect the validated subnetwork to the focal stock assessment parameter of interest (e.g., recruitment). This step completes the chain of events from physics to fish. It simultaneously accounts for observation error, process error, and complex lagged feedback loops across biological, physical, or socioeconomic time-series while naturally imputing missing data. Decide whether to run as an external or internal DSEM. For the external DSEM, fit the structural DAG to the validated indicators alongside extracted time-varying parameter estimates from an existing operational stock assessment model (i.e., modeled recruitment is the response). This will create a standalone ecological model used to forecast recruitment trends for the ESP. For the internal DSEM, embed the validated structural equations from Step 3 directly within the stock assessment model platform (e.g., the DSEM branch of Rceattle or SCEAM in TMB) to evaluate the joint likelihood across assessment data (catches, size/age compositions) and ecosystem indicators. Check for strict convergence gradients (< 0.001) and a positive-definite Hessian matrix as with the previous step. Verify that recruitment process error does not collapse to zero, which flags artificial overfitting.

5.) Scientific Validation and Decision Support (The Refinement): Evaluate the model's statistical robustness and compare competing hypotheses. Select the most parsimonious, causally defensible model configuration to provide qualitative or quantitative decision support for harvest specifications. The outputs of these dynamic structural models allow for direct comparisons with operational stock assessments and provide the Council with robust insights into retrospective patterns, unexplained variance reduction, predictive performance under climate scenarios, and community trade-offs. This step involves:
   a.) Model Selection: Fit alternative configurations of the DSEM (e.g., removing weak linkages or adding unmapped theoretical paths) and compare them using metrics like the Akaike Information Criterion (AIC) to find the most parsimonious model (also see Bigman et al. *in review* for discussion of model selection). When comparing competing DAGs (e.g., simple vs. moderate vs. complex trophic structures), ensure the time-series data includes all variables as latent structures (either IID or AR1), retaining unlinked variables as background nodes.
   b.) Residual Diagnostics: Analyze the differences between the model's predictions and actual observations (often using R packages like DHARMa for family = fixed settings or standard residuals and q-q plots if using family = standard normal) to verify that the model correctly captured variance without leaving hidden, unmodeled patterns.
   c.) Unexplained Variance Reduction: Confirm that the causal model meaningfully reduces unexplained process variance in the focal stock parameter (e.g., $\text{sigma}^2_{\text{unexplained}}$) compared to baseline IID and AR1 models.
   d.) Out-of-Sample Forecasting Skill: Perform a 5- to 10-year retrospective peel (Leave-Future-Out cross-validation) and confirm that the one-year-ahead forecast Root Mean Squared Error (RMSE) outperforms the status-quo assessment (as in Champagnat et al. 2026).
   e.) Simulation Self-Test: Use the `simulate()` function in the dsem package on the fitted model object to generate synthetic time series and refit the model to verify that causal path coefficients (*betas*) are recovered without systematic bias.

The sequential steps of the structural workflow can serve as progressive diagnostic gates for evaluating and monitoring the indicator suite, where the extent of progression is naturally determined by the data availability and assessment tier of the stock. For data-limited stocks (e.g., catch-only or survey-limited stocks lacking age structure), ESP teams can complete Steps 1 through 3 by building the mechanism table, constructing hypothesized DAGs, and using graphical checks to eliminate confounding and collider bias, providing an immediate qualitative foundation to inform risk tables. Data-moderate stocks (e.g., stocks with empirical environmental and trophic survey time series but lacking annual population dynamic estimates) can advance through Step 4 (Detached DSEM). At this intermediate step, ESP teams run state-space models directly on the subnetwork of ecosystem or socioeconomic indicators to validate intermediate mediators, interpolate gaps in time-series, and screen for robust contextual indicators before relating to a population response variable. Finally, data-rich stocks with age- or length-structured assessment models (providing annual estimates of recruitment, biomass, or natural mortality) can execute the full workflow through Steps 5 and 6. These stocks can evaluate candidate indicators against stock parameters of interest using either external or internal DSEM. As operational assessment platforms (e.g., Rceattle, WHAM, SPoRC) incorporate native DSEM modules (e.g., Champagnat et al., 2026), this integrated pathway will become more accessible across multiple fisheries, establishing consistent, standardized diagnostic criteria throughout the stock assessment review process.

Ecosystem Indicator Analysis

The GOA arrowtooth flounder stock is data rich with an age-structured assessment model; therefore, estimates of recruitment are available for this stock and can be evaluated Step 6 of our workflow. For this assessment, we have completed an external DSEM analysis reproduced from Bigman et al., (*in review*).

The results from this analysis are used to categorize ecosystem indicators into the three distinct categories based on their validated pathways: 1) predictive indicators that demonstrate a robust, direct, or indirect quantitative causal relationship with the population process of interest (e.g., recruitment) and showing significant path coefficients, b) contextual indicators that provide critical anticipatory or background information to 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 validated causal links to population processes (e.g., yielding negligible path coefficients or those in the opposite sign as hypothesized in the mechanism table), 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 structurally validated stock-indicator relationships, while providing an avenue 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, causally grounded ecosystem considerations for setting biological reference points for the current year.

Analysis Methods

Rceattle is the newly proposed and accepted stock assessment platform for the GOA arrowtooth flounder stock (Adams et al., 2020; Adams and Shotwell, 2024), and an integrated DSEM branch has recently been added to the platform and is proposed for operational use for GOA pollock in 2026. 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., 2025b). These are concurrently being reviewed by the Groundfish Plan Team in September 2026. Consequently, we decided to utilize the external DSEM option to evaluate several alternative DAGs using the recruitment estimates from the last approved assessment (Shotwell et al., 2025b). This external phase serves as a critical structural diagnostic step to check DAG-data consistency and inspect the DAG structure and resulting effect size signs, magnitude, and significance, ensure model convergence and optimization, provide residual diagnostics, compare model configurations via AIC and variance reduction, and identify the most parsimonious DAG.

Once these data updates are approved by the Groundfish Plan Team for the operational assessment, we plan to integrate the best-fit causal model directly into the Rceattle platform. At this time we have explored several model configurations using the external DSEM and provide the results of this structural exploration (Bigman et al., *in review*). We use the results to categorize our suite of indicators into predictive or contextual categories. In the future, we plan to explore a few more model configurations, determine the best model, and integrate that model into the DSEM branch of Rceattle.

Steps 1: Mechanism Table

We explore influences on age-1 recruitment in this analysis because there has been a shift to lower recruitment since 2006 with only slightly above average recruitment events in 2017 and 2018 (Shotwell et al., 2025b). Additionally, the GOA Plan Team requested the authors of the stock assessment investigate whether lower recruitment is related to environmental conditions in the GOA. The Plan Team also noted that this decrease in recruitment occurred before the recent heatwaves in the GOA but are concurrent with low recruitment observed in other flatfish stocks in the GOA and may be linked to extended poor recruitment from a cold pattern in 2006-2007 (Shotwell et al., 2021). Due to staffing capacity, the full ESP was not initiated until 2025. At that time, we organized an ESP team which consisted of the ESP facilitator and stock assessment lead, several subject matter experts, an ecosystem status report representative, and an economic scientist representative. The ESP team then initiated the life history synthesis with a focus on understanding influences on recruitment.

Following the synthesis, the ESP team created a mechanism table from the literature and expert opinion which included hypothesized links, the literature sources supporting each link, the hypothesized direction and lag for each link, and the confidence in each link (Table 7A.5). Confidence was based on the ESP team discussions and workshop reviews, relevance to stock-specific information versus that from other regions, directly observed versus modeled relationships, and amount of literature supporting each link. We identified ten mechanistic linkages that were hypothesized to directly or indirectly inform arrowtooth flounder age-1 recruitment.

Steps 2: DAG Construction

Information in the mechanism table paired with the life history synthesis was then used to develop a full life history DAG (i.e. one that includes all life stages) to explain how ecosystem variables may be related to variation in age-1 recruitment (Figure 7A.6). This initial full DAG was created to include all potential linkages and latent variables that may explain age-1 recruitment. We created the initial full DAG using the online *dagitty* platform (https://dagitty.net/) and ensured there were no open biasing paths (Figure 7A.6, green lines are indirect paths, black lines direct paths). This full DAG was subsequently paired down to a simplified version to be estimable (see Thorson et al. 2024, Champagnat et al. 2026, and Bigman et al., *In Review* for more details on this process). Briefly, our simplified DAG only included linkages from the mechanism table for which proxy indicators were available as time series in the ESP suite (i.e., linkages included if variables in the model had available data). This DAG was also confirmed to have no open biasing paths by *dagitty* (Figure 7A.7, green lines indirect paths, black lines direct path) implying that there was no confounding, overcontrol or collider bias in the DAG. The time series of the data used in the simplified DAG with estimates of uncertainty are provided in Figure 7A.8.

Step 3-5: DSEM and Scientific Validation

To evaluate our casual network within a unified dynamic state-space framework, we fit our simplified structural DAG (“structural model”) (Figure 7A.7) to the 1977–2024 recruitment time series using the *dsem* package in R (v4.4.2; Thorson et al., 2024; Champagnat et al., 2026). Following Bigman et al., (*in review*), we compared the structural model against three baseline and alternative configurations: (1) recruitment modeled as independent and identically distributed (IID), (2) recruitment modeled as a first-order autoregressive process (AR1), and (3) a "regression” model where the DAG was restricted to only direct hypothesized correlates (Spring Larval Prey, Small Arrowtooth ADF&G at lag-1, Arrowtooth Biomass Consumed, and Summer/Fall YOY Prey). All candidate models converged, as confirmed by positive-definite Hessian matrices and maximum absolute marginal log-likelihood gradients < 0.001. Model goodness-of-fit was validated using randomized leave-one-out (LOO) quantile residuals plotted via the `DHARMa` package (Figures 7A.9a-d). Residual diagnostic plots showed little evidence of model misspecification (i.e., no significant deviations, dispersion issues, or outlier patterns) for the structural, IID, and AR1 models (Figures 7A.9a,b,d). The regression model showed a slight departure of the lower (0.25) residual quantile from its expected value (Figure 7A.9c), suggesting some remaining structure in the lower portion of the predictive distribution. This could reflect model misspecification such as nonlinear effects, omitted pathways, or an inadequately specified lag structure. Relative model support was evaluated using Akaike’s Information Criterion (AIC; Burnham and Anderson, 2002; Thorson et al., 2024) alongside the reduction in unexplained recruitment process variance ($\text{sigma}^2_{\text{unexplained}}$). The structural model demonstrated the highest overall support by AIC compared to the other three models and the structural model and regression model demonstrated a similar reduction in unexplained recruitment variation (Table 7A.6). We recommend the structural model over the IID, AR1 or regression model because by explicitly mapping the multiple biophysical pathways across temporal lags, it explains the highest proportion of recruitment process variance, eliminates systematic residual patterns, and provides a parsimonious, ecosystem-linked framework for fishery decision support.

The hypothesized causal linkages, their literature and expert-derived mechanisms, and their associated lags are detailed in Table 7A.5, while the parameter estimates, standard errors, and *p*-values are reported in Table 7A.7 and graphically summarized in Figure 7A.10a,b (aligned with our conceptual model, Figure 7A.1). Four variables exhibited statistically significant causal paths to recruitment: Spring Sea Surface Temperature, Spring Arrowtooth Larvae, Summer/Fall YOY Prey (euphausiids), and Arrowtooth Biomass Consumed which is an estimate of predation on arrowtooth from the Rceattle multispecies model. By estimating total causal effects (integrating both direct and indirect pathways across simultaneous and lagged time steps) we quantified the net influence of each ecosystem driver on recruitment (Table 7A.8). Interestingly, the estimated signs for Summer/Fall YOY Prey and Arrowtooth Biomass Consumed diverged from our initial *a priori* hypotheses. This divergence highlights critical feedback loops and potential nonlinearities in early life-history stages, and we outline specific recommendations in Table 7A.7 for refining these indicator proxies prior to integrating the structural model into the Rceattle assessment platform.

We plan to include some of these recommendations and the new estimates of recruitment from the approved 2026 operational model in the next iteration of this ESP-DSEM model. We also plan to run a detached DSEM to check the internal machinery of the simplified DAG. These additional improvements and network validation combined with running an internal version of DSEM within Rceattle may change the estimated effects; therefore, we do not expand on reasons for the difference in sign at this time. However, should these unexpected signs 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), or if we need to find alternative data sources as the time-series of some of the indicators were extremely patchy and sparse. The performance of the external structural model suggests that including ecosystem variables identified in this ESP in the operational stock assessment model will help to explain variation in GOA arrowtooth flounder recruitment.

<u>Decision Support</u>

We use the results of the external DSEM structural model 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.4a). The four indicators with significant relationships from the external DSEM analysis (Spring Sea Surface Temperature, Spring Arrowtooth Larvae, Summer/Fall YOY Prey (euphausiids), and Arrowtooth Biomass Consumed) are included in the predictive category. Two indicators were included in the monitoring category (Summer YOY Prey and Arrowtooth Ration) due to mismatch in timing and not immediately relevant for management advice. The remaining indicators were included in the contextual category.

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. At this time, the sign of the relationship for all indicators is based on the conceptual model and hypothesized relationship with the stock (Table 7A.2, Figure 7A.1). We recognize that two indicator signs were different in the structural model compared to the hypothesized signs in the original conceptual model and mechanism tables (Table 7A.7). However, given that the improvement suggestions were to replace both indicators, we opt to keep the sign as originally hypothesized and highlight the current status and trends with a note of caution. 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.

Results from the traffic light table (Table 7A.4a) indicate that predictive indicators had two poor conditions (red) in 2025 (Spring SST and Spring Arrowtooth Larvae) with the remaining predictive and contextual indicators at neutral status, within one standard deviation of their long-term mean. We provide summary statements regarding these predictive and contextual trends at the beginning of this document. This information is used directly in the risk table write up for the population dynamics and ecosystem considerations sections that can be used to inform ABC and TAC decisions (Shotwell et al., 2026). Another use of this information could be through updating the projected recruitment estimates for the off-cycle harvest projection as this stock is on a four year cycle. This could serve as an avenue for including the uncertainty in the environment as well as the updated catch information without updating the operational assessment model while still informing recommended quotas.

Socioeconomic Monitoring

Due to staff capacity issues we were only able to provide updates to the five fishery informed indicators to depict a historical time-series of key socioeconomic information for the GOA arrowtooth flounder fishery. In future ESPs we plan to include a core set of socioeconomic indicators following discussions from the Groundfish Plan Teams and SSC (see sablefish ESP, Shotwell and Dame, 2024). Generally, historical data through the current year are available for fishery informed indicators and a one-year lag is presented for economic indicators 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 of the current year to provide the most current information available. Catcher vessel catch increased from last year but continues to have low status below 1 standard deviation of the long-term mean. Catcher processor vessel catch and non-target catch in the rockfish fishery decreased from last year but remain in neutral status being within one standard deviation of the long-term mean. ABC utilization decreased from above average to below average but still neutral status while TAC utilization remains low and has been for the last five years. We plan to evaluate trends in these indicators in the future when staff capacity increases and where relevant the results will be used to inform the risk table for GOA arrowtooth flounder.

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
- 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:
  - o CPUE measures (e.g., proportion of the catch by gear, level of effort by gear)
  - o Fleet characteristics (e.g., number of active vessels, number of processors)
  - o Spatial distribution measures (e.g., center of gravity, area occupied)
- Re-evaluation of economic indicators to potentially include:
  - o Percentage of total allowable catch (TAC) harvested by active vessels
  - o Measures by product type (e.g., proportion landed, price per pound)
  - o 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 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).

Conclusion

The GOA arrowtooth flounder ESP follows the standardized framework for evaluating the various ecosystem and socioeconomic considerations for this stock (Shotwell et al., 2023a). The indicator synthesis provides a comprehensive literature review with accompanying ecological synthesis and mechanism tables to support indicator selection. Nineteen ecosystem and five 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 through the entire ESP-DSEM workflow (Steps 1-5). Ecosystem indicators were categorized according to the results of the recommended external DSEM structural model exploration on recruitment. This model identified four variables that exhibited statistically significant causal paths to recruitment, Spring Sea Surface Temperature, Spring Arrowtooth Larvae, Summer/Fall YOY Prey (euphausiids), and Arrowtooth Biomass Consumed (estimate of predation on arrowtooth from the multispecies model). These four indicators were categorized as predictive and the remaining indicators were categorized as contextual, except two (Summer YOY Prey and Arrowtooth Ration) that were categorized as monitoring. We provide summary statements of status and trends in the Executive Summary of this document.

This information can be used for evaluating concerns in the main stock assessment or other management decisions and we 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 external 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.

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Literature Cited

Abookire, A.A., Piatt, J.F., Norcross, B.L., 2001. Juvenile groundfish habitat in Kachemak Bay, Alaska, during late summer. Alaska Fish. Res. Bull. 8 (1), 45–56. Life history table reference arrowtooth #4.

Adams, G., K., Holsman, S., Barbeaux, M., Dorn, P., Hulson, J., Ianelli, C., Monnahan, K., Shotwell, I., Spies, I., Stewart, and A., Punt. 2022. Multispecies model estimates of time-varying natural mortality of groundfish in the Gulf of Alaska. In Ferriss, B., and Zador, S., 2022. Ecosystem Status Report 2022: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 1007 West Third, Suite 400, Anchorage, Alaska 99501.

Adams, G., Shotwell, S.K., 2024. Bridging the Gulf of Alaska arrowtooth flounder assessment to CEATTLE to improve parameter estimation, account for cannibalism, and increase climate readiness. North Pacific Fishery Management Council, Anchorage, AK. Available from https://meetings.npfmc.org/Meeting/Details/3056.

AFSC (Alaska Fisheries Science Center). 2021. Strategic Science Plan FY2023 - FY2027. Available online at https://www.fisheries.noaa.gov/s3/2022-02/AFSC-SSP_31JAN22_508.pdf.

Anderson, S.C., Ward, E.J., English, P.A., and Barnett, L.A.K. 2022. sdmTMB: an R package for fast, flexible, and user-friendly generalized linear mixed effects models with spatial and spatiotemporal random fields. bioRxiv. https://doi.org/10.1101/2022.03.24.485545.

Arif, S., and M. A. MacNeil. 2023. Applying the structural causal model framework for observational causal inference in ecology. Ecological Monographs 93(1): e1554. https://doi.org/10.1002/ecm.1554

Aydin, K.Y., Gaichas, S.K., Ortiz, I., Kinzey, D.H., Friday, N., 2007. A comparison of the Bering Sea, Gulf of Alaska, and Aleutian Islands large marine ecosystems through food web modeling. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-178.

Bailey, K.M., Picquelle, S.J., 2002. Larval distribution of offshore spawning flatfish in the Gulf of Alaska: potential transport pathways and enhanced onshore transport during ENSO events. Mar. Ecol. Prog. Ser. 236, 205–217. Life history table reference arrowtooth #16.

Bailey, K.M., Abookire, A.A., Duffy-Anderson, J.T., 2008. Ocean transport paths for the early life history stages of offshore-spawning flatfishes: a case study in the Gulf of Alaska. Fish Fish. 9, 44–66. Life history table reference arrowtooth #23.

Blackburn, J.E., Jackson, P.B., 1982. Seasonal Composition and Abundance of Juvenile and Adult Marine Finfish and Crab Species in the Nearshore Zone of Kodiak Island's Eastside during April 1978 through March 1979; (In) Outer Continental Shelf Environmental Assessment Program, Final Reports of Principal Investigators, vol. 54, pp. 377–570. RU 0552. Life history table reference arrowtooth #8.

Blood, D.M., Matarese, A.C., Busby, M.S., 2007. Spawning, Egg Development, and Early Life History Dynamics of Arrowtooth Flounder (Atheresthes stomias) in the Gulf of Alaska, vol. 7. NOAA Professional Paper NMFS, 29 p. Life history table reference arrowtooth #5.

Boeing, W.J., Duffy-Anderson, J.T., 2008. Ichthyoplankton dynamics and biodiversity in the Gulf of Alaska: responses to environmental change. Ecol. Indicat. 8 (3), 292–302. Life history table reference arrowtooth #15.

Bouwens, K.A., Paul, A.J., Smith, R.L., 1999a. Growth of juvenile arrowtooth flounders from Kachemak Bay, Alaska. Alaska Fish. Res. Bull. 6 (1), 35–40. Life history table reference arrowtooth #7.

Bouwens, K.A., Smith, A., Paul, A.J., Rugen, W., 1999b. Length at and timing of hatching and settlement for arrowtooth flounders in the Gulf of Alaska. Alaska Fish. Res. Bull. 6 (1), 41–48. Life history table reference arrowtooth #6.

Carlson, H.R., Haight, R.E., Krieger, K.J., 1982. Species Composition and Relative Abundance of Demersal Marine Life in Waters of Southeastern Alaska, 1969-81. U.S. Department of Commerce, Juneau, AK. Life history table reference arrowtooth #14.

Champagnat, J., C. C. Monnahan, J. Y. Sullivan, J. T. Thorson, S. K. Shotwell, L. Rogers, and A. E. Punt. 2026. Causal models as a scientific framework for next-generation ecosystem and climate-linked stock assessments. Fish and Fisheries. https://doi.org/10.1111/faf.70092.

Clyde, M. A., J. Ghosh, and M. L. Littman. 2011. Bayesian Adaptive Sampling for Variable Selection and Model Averaging. Journal of Computational and Graphical Statistics 20:80-101.

Combes, V., and E. Di Lorenzo. 2007. Intrinsic and forced interannual variability of the Gulf of Alaska mesoscale circulation. Progress in Oceanography 75:266–286.

Debenham, C., Moss, J., Heintz, R., 2019. Ecology of age-0 arrowtooth flounder (Atheresthes stomias) inhabiting the Gulf of Alaska. Deep-Sea Res. II. 165, 140–149.

Di Lorenzo, E., D. Mountain, H. Batchelder, N. Bond, and E. Hofmann. 2013. Advances in marine ecosystem dynamics from US GLOBEC: The horizontal-advection bottom-up forcing paradigm. Oceanography 26:22–33.

Dorn, M., and S. Zador. 2020. A risk table to address concerns external to stock assessments when developing fisheries harvest recommendations. Ecosystem Health and Sustainability 6:1813634.

Doyle, M.J., Picquelle, S.J., Mier, K.L., Spillane, M.C., Bond, N.A., 2009. Larval fish abundance and physical forcing in the Gulf of Alaska, 1981-2003. Prog. Oceanogr. 80 (3–4), 163–187. Life history table reference arrowtooth #13.

Doyle, M.J., Mier, K.L., 2012. A new conceptual model framework for evaluating the early ontogeny phase of recruitment processes among marine fish species. Can. J. Fish. Aquat. Sci. 69, 2112–2129. Life history table reference arrowtooth #20.

Doyle, M.J., Mier, K.L., 2016. Early life history pelagic exposure profiles of selected commercially important fish species in the Gulf of Alaska. Deep-Sea Res. Pt. II: Top. Studies Oceanogr 132, 162–193. Life history table reference arrowtooth #21.

Doyle, M.J., Debenham, C., Barbeaux, S.J., Buckley, T.W., Pirtle, J.L., Spies, I.B., Stockhausen, W.T., Shotwell, S.K., Wilson, M.T., Cooper, D.W., 2018. A full life history synthesis of Arrowtooth Flounder ecology in the Gulf of Alaska: exposure and sensitivity to potential ecosystem change. J. Sea Res. 142, 28–51. https://doi.org/ 10.1016/j.seares.2018.08.001.

Doyle, M.J., S.L. Strom, K.O. Coyle, A.J. Hermann, C. Ladd, A.C. Matarese, S.K. Shotwell, and R.R. Hopcroft. Early life history phenology among Gulf of Alaska fish species: Strategies, synchronies, and sensitivities. 2019. Deep Sea Research Part II: Topical Studies in Oceanography 165 (2019): 4173.

Gibson, G.A., W.T. Stockhausen, K. Shotwell, A.L. Deary, J.L. Pirtle, K.O. Coyle, A.J. Hermann. 2023. Can seamounts in the Gulf of Alaska be a spawning ground for sablefish settling in coastal nursery grounds? Fisheries Research. 261: 106625. DOI: https://doi.org/10.1016/j.fishres.2023.106625

Goldstein, E.D., Pirtle, J.L., Duffy-Anderson, J.T., Stockhausen, W.T., Zimmermann, M., Wilson, M.T., Mordy, C.W., 2020. Eddy retention and seafloor terrain facilitate cross- shelf transport and delivery of fish larvae to suitable nursery habitats. Limnol. Oceanogr. 65, 2800–2818. https://doi.org/10.1002/lno.11553.

Grace, J. B., and K. M. Irvine. 2020. Scientist's guide to developing explanatory statistical models using causal analysis principles. Ecology 101(4): e02962. https://doi.org/10.1002/ecy.2962.

Haight, R.E., Reid, G.M., Weemes, N., 2006. Distribution and habitats of marine fish and invertebrates in Katlian Bay, southeastern Alaska, 1967 and 1968. AFSC Processed Rep. 2006-04, 60 p Alaska Fish. Sci. Cent., Natl. Mar. Fish. Serv., NOAA. Auke Bay Laboratory, 11305 Glacier Highway, Juneau, AK 99801. Life history table reference arrowtooth #12.

Holbrook, N. J., H. A. Scannell, A. Sen Gupta, J. A. Benthuysen, M. Feng, E. C. J. Oliver, L. Alexander, M. Burrows, M. Donat, A. Hobday, P. Moore, S. Perkins-Kirkpatrick, D. Smale, S. Straub, and T. Wernberg. 2019. A global assessment of marine heatwaves and their drivers. Nature Communications 10:1–13.

Holsman, K. K., & Aydin, K. 2015. Comparative methods for evaluating climate change impacts on the foraging ecology of Alaskan groundfish. Marine Ecology Progress Series, 521, 217-235.

Holsman, K. K., K. Aydin, J. Sullivan, T. Hurst, and G. H. Kruse. 2019. Climate effects and bottomup controls on growth and size-at-age of Pacific halibut (Hippoglossus stenolepis) in Alaska (USA). Fisheries Oceanography 28:345–358.

Hunt, G. L., P. H. Ressler, G. A. Gibson, A. De Robertis, K. Aydin, M. F. Sigler, I. Ortiz, E. J. Lessard, B. C. Williams, and A. Pinchuk. 2016. Euphausiids in the eastern Bering Sea: A synthesis of recent studies of euphausiid production, consumption and population control. Deep Sea Research Part II: Topical Studies in Oceanography 134:204–222.

Janout, M. A., T. J. Weingartner, T. C. Royer, and S. L. Danielson. 2010. On the nature of winter cooling and the recent temperature shift on the northern Gulf of Alaska shelf. Journal of Geophysical Research: Oceans 115:C05023

Kendall, A.W., Ferraro, P., 1988. Ichthyoplankton of the Gulf of Alaska near Kodiak Island, March to June 1985. NWAFC Processed Rep. 88-03, 88 p Northwest and Alaska Fish. Cent, 7600 Sand Point Way NE, Seattle, WA 98115-0070. Life history table reference arrowtooth #11.

Kimmel, D., Axler, K., Cormack, B., Crouser, D., Fennie, W., Keister, J., Lamb, J., Pinger, C., Rogers, L., Suryan, R. 2023. Current and Historical Trends for Zooplankton in the Western Gulf of Alaska. In Ferriss, B., and Zador, S., 2023. Ecosystem Status Report 2023: Gulf of Alaska, North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306, Anchorage, AK 99501.

Knoth, B.A., Foy, R.J., 2008. Temporal variability in the food habits of arrowtooth f lounder (Atheresthes stomias) in the Western Gulf of Alaska. U. S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-184, 30 p. Life history table reference arrowtooth #9.

Ladd, C., Cheng, W., Salo, S., 2016. Gap winds and their effects on regional oceanography Part II: Kodiak Island, Alaska. Deep-Sea Res. Pt. II: Top. Studies Oceanogr. 132, 54–67.

Ladd, C., 2020. Eddies in the Gulf of Alaska. In: Ferriss, B., Zador, S. (Eds.), Ecosystem Considerations 2020: Status of the Gulf of Alaska Marine Ecosystem. Stock Assessment and Fishery Evaluation Report. North Pacific Fishery Management Council, 2020, 605 W 4th Ave, Suite 306, Anchorage, AK 99501. 220 pp.

Lynch, P. D., R. D. Methot, and J. S. Link (eds.). 2018. Implementing a Next Generation Stock Assessment Enterprise. An Update to the NOAA Fisheries Stock Assessment Improvement Plan. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-F/SPO-183, 127 p

Matarese, A.C., Blood, D.M., Picquelle, S.J., and Benson, J.L. 2003. Atlas of abundance and distribution patterns of ichthyoplankton from the northeast Pacific Ocean and Bering Sea ecosystems based on research conducted by the Alaska Fisheries Science Center (1972-1996). U.S. Dep. Commer., NOAA Prof. Paper NMFS 1, 281 pp.

McElreath, R. (2020). Statistical rethinking: A Bayesian course with examples in R and Stan, CRC press.

Methot, R. D. Jr. (ed.). 2015. Prioritizing fish stock assessments. NOAA Tech. Memo. NMFS-F/SPO152, 31 p

NOAA Coral Reef Watch. 2018, updated daily. NOAA Coral Reef Watch Version 3.1 Daily Global 5km Satellite Coral Bleaching Degree Heating Week Product, Jun. 3, 2013-Jun. 2, 2014. College Park, Maryland, USA: NOAA Coral Reef Watch. Data set accessed 2020-09-01 at ftp://ftp.star.nesdis.noaa.gov/pub/sod/mecb/crw/data/5km/v3.1/nc/v1.0/daily/dhw/.

Norcross, B.L., Holladay, B.A., Frandsen, M., 1993. Recruitment of Juvenile Flatfish in Alaska, Phase 1. Final Contract Report. Institute of Marine Science, University of Alaska Fairbanks, Fairbanks, AK (unpublished report). Life history table reference arrowtooth #1.

Norcross, B.L., Holladay, B.A., Mueter, F.J., Frandsen, M., 1994. Recruitment of Juvenile Flatfish in Alaska, Phase 2. Final Contract Report. Institute of Marine Science, University of Alaska Fairbanks, Fairbanks, AK (unpublished report). Life history table reference arrowtooth #2.

Norcross, B.L., Blanchard, A., Holladay, B.A., 1999. Comparison of models for defining nearshore flatfish nursery areas in Alaskan waters. Fish. Oceanogr. 8 (1), 50–67. Life history table reference arrowtooth #3.

O'Leary, C., Laman, N., Rohan, S. 2023. Gulf of Alaska groundfish condition. In Ferriss, B., and Zador, S., 2021. Ecosystem Status Report 2023: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306, Anchorage, AK 99501.

Ormseth, O.A. and P.D., Spencer. 2011. An assessment of vulnerability in Alaska groundfish. Fish. Res.112:127–133.

Paul, A.J., Paul, J.M., Smith, R.L., Bouwens, K.A., 1999. Food consumption and growth of juvenile arrowtooth flounders. Alaska Fishery Research Bulletin. 6(2): 104-107.

Parada, C., Hinckley, S., Horne, J., Mazur, M., Hermann, A., Curchister, E., 2016. Modeling connectivity of walleye pollock in the Gulf of Alaska: are there any linkages to the Bering Sea and aleutian Islands? Deep-Sea Res. Pt. II: Top. Studies Oceanogr. 132, 227–239.

Ressler, P.H. 2019. Gulf of Alaska Euphausiids. In: S. Zador and E. Yasumiishi (Ed.), Ecosystem Considerations for 2019, Stock Assessment and Fishery Evaluation Report. Technical report, North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306, Anchorage, AK 99501.

Rogers, L.A., and Axler, K. 2023. Larval Fish Abundance in the Gulf of Alaska 1981-2023. In Ferriss, B., and Zador, S., 2023. Ecosystem Status Report 2021: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 1007 West Third, Suite 400, Anchorage, Alaska 99501.

Rohan, S. K. and Barnett, L.A.K. 2026. coldpool: AFSC/RACE Groundfish Assessment Program oceanographic data products. R package version 3.6-1. doi: 10.5281/zenodo.16915338.

Shotwell, S., Pirtle, J., Watson, J., Deary, A., Doyle, M., Barbeaux, S., Dorn, M. W., Gibson, G. A., Goldstein, E. D., Hanselman, D. H., Hermann, A. J., Hulson, P. J. F., Laurel, B. J., Moss, J. H., Ormseth, O. A., Robinson, D., Rogers, L. A., Rooper, C. N., Spies, I., Strasburger, W.W., Suryan, R.M., Vollenweider, J. J. 2022. Synthesizing integrated ecosystem research to create informed stock- specific indicators for next generation stock assessments. Deep Sea Research Part II: Topical Studies in Oceanography, 198, 105070.

Shotwell, S.K., K., Blackhart, C. Cunningham, E. Fedewa, D., Hanselman, K., Aydin, M., Doyle, B., Fissel, P., Lynch, O., Ormseth, P., Spencer, S., Zador. 2023a. Introducing the Ecosystem and Socioeconomic Profile, a proving ground for next generation stock assessments. Coastal Management. 51:5-6, 319-352, DOI: 10.1080/08920753.2023.2291858.

Shotwell, K., D.H Hanselman, W. Palsson, and B.C. Williams. 2023b. Assessment of the arrowtooth flounder stock in the Gulf of Alaska. North Pacific Fishery Management Council, Anchorage, AK. Available from https://www.npfmc.org/library/safe-reports/.

Shotwell, S.K., and Dame, R. 2024. Appendix 3D. Ecosystem and Socioeconomic Profile of the Sablefish stock in Alaska - Report Card. *In*: Goethel, D.R., and Cheng, M.L.H. 2024. Assessment of the Sablefish stock in Alaska. North Pacific Fishery Management Council, Anchorage, AK. Available from https://www.npfmc.org/library/safereports/.

Shotwell, S.K., and R. Dame. 2025a. Appendix 7A. Ecosystem and Socioeconomic Profile of the arrowtooth flounder stock in the Gulf of Alaska. In: Shotwell, S.K., G.D. Adams, D.H. Hanselman, J. Sullivan. 2025. Assessment of the arrowtooth flounder stock in the Gulf of Alaska. North Pacific Fishery Management Council, Anchorage, AK. Available online from https://meetings.npfmc.org/CommentReview/DownloadFile?p=bf063c69-6938-4205-ab2a-5bc027aa4cd0.pdf&fileName=GOA%20ATF%20ESP.pdf.

Shotwell, S.K., Adams, G. and Hanselman, D. 2025b. Assessment of the arrowtooth flounder stock in the Gulf of Alaska - Data Review. North Pacific Fishery Management Council, Anchorage, AK. Available from https://meetings.npfmc.org/Meeting/Details/3099.

Siddon, E.C., De Forest, L.G., Blood, D.M., Doyle, M.J., Matarese, A.C., 2019. Early life history ecology for five commercially and ecologically important fish species in the eastern and western Gulf of Alaska. Deep-Sea Res. Pt. II: Top. Studies Oceanogr. https://doi.org/10.1016/j.dsr2.2016.06.022.

Siddon, E. 2024. Ecosystem Status Report 2024: Eastern Bering Sea, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 1007 West 3rd Ave., Suite 400, Anchorage, Alaska 99501.

Sigler, M. F., M. P. Eagleton, T. E. Helser, J. V. Olson, J. L. Pirtle, C. N. Rooper, S. C. Simpson, and R. P. Stone. 2017. Alaska Essential Fish Habitat Research Plan: A Research Plan for the National Marine Fisheries Service's Alaska Fisheries Science Center and Alaska Regional Office. AFSC Processed Rep. 2015-05, 22 p. Alaska Fish. Sci. Cent., NOAA, Natl. Mar. Fish. Serv., 7600 Sand Point Way NE, Seattle WA 98115.

Siwicke, K. 2022. Summary of temperature and depth recorder data from the Alaska Fisheries Science Center's longline survey (2005–2021). U.S. Dep. Commer., NOAA Tech. Memo. NMFSAFSC-437, 74 p.

Smith, R.L., Paulson, A.C., Rose, J.R., 1978. Food and feeding relationships in the benthic and demersal fishes of the Gulf of Alaska and Bering Sea. In: Environmental Assessment of the Alaskan Continental Shelf, Final Reports, Biological Studies 1:33- 107 RU 0284. Life history table reference arrowtooth #19.

Spalinger, K., and J. Silva. 2023. Large-mesh bottom trawl survey of crab and groundfish: Kodiak, Chignik, South Peninsula, and Eastern Aleutian Management Districts, 2022. Alaska Department of Fish and Game, Fishery Managment Report No. 23-7, Anchorage.

Spies, I., Turnock, B.J., 2013. Assessment of the arrowtooth flounder stock in the Gulf of Alaska. In: Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Gulf of

Alaska. North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306 Anchorage, AK 99501. Life history table reference arrowtooth #22.

Spies, I., Aydin, K., Ianelli, J.N., Palsson, W., 2019. Assessment of the arrowtooth f lounder stock in the Gulf of Alaska. In: Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Gulf of Alaska. North Pacific Fishery Mngt. Council, 605 W 4th Ave, Suite 306 Anchorage, AK 99501.

Stark, J.W., 2008. Age- and length-at-maturity of female arrowtooth flounder (Atheresthes stomias) in the Gulf of Alaska. Fish. Bull., U.S. 106, 328–333. Life history table reference arrowtooth #10.

Stockhausen, W.T., Coyle, K.O., Hermann, A.J., Blood, D., Doyle, M.J., Gibson, G.A., Hinckley, S., Ladd, C., Parada, C., 2019a. Running the gauntlet: connectivity between spawning and nursery areas for arrowtooth flounder (Atheresthes stomias) in the Gulf of Alaska, as inferred from a biophysical individual-based model. Deep-Sea Res. Pt. II: Top. Studies Oceanogr. 165, 127–139.

Thorson, J.T., and K. Kristensen. 2016. Implementing a generic method for bias correction in statistical models using random effects, with spatial and population dynamics examples. Fish. Res. 175:6674. https://doi.org/10.1016/j.fishres.2015.11.016

Thorson, J.T., M.L. Pinsky, and E.J. Ward. 2016. Model-based inference for estimating shifts in species distribution, area occupied and centre of gravity. Methods in Ecology and Evolution 7:990–1002. doi:10.1111/2041-210X.12567.

Thorson, J.T. and L.A.K. Barnett. 2017. Comparing estimates of abundance trends and distribution shifts using single- and multispecies models of fishes and biogenic habitat. ICES Journal of Marine Science 74:1311–1321. doi:10.1093/icesjms/fsw193.

Thorson, J.T. 2018. Three problems with the conventional delta-model for biomass sampling data, and a computationally efficient alternative. Canadian Journal of Fisheries and Aquatic Sciences 75:1369–1382. doi:10.1139/cjfas-2017-0266.

Thorson, J.T. 2019. Guidance for decisions using the Vector Autoregressive Spatio-Temporal (VAST) package in stock, ecosystem, habitat and climate assessments. Fisheries Research 210:143–161. doi:10.1016/j.fishres.2018.10.013.

Thorson, J.T., Andrews, A.G., Essington, T.E., and Large, S.I., 2024. Dynamic structural equation models synthesize ecosystem dynamics constrained by ecological mechanisms. Methods in Ecology and Evolution. 15(4). 744-755. https://doi.org/10.1111/2041-210X.14289.

Wise, S., S. Kasperski, A. Abelman, J. Lee, M. Parks, and J. Reynolds. 2022. Annual Community Engagement and Participation Overview. Report from the Economic and Social Sciences Program of the Alaska Fisheries Science Center. 98 pp.

Yang, M.-S., 1993. Food habits of the commercially important groundfishes in the Gulf of Alaska in 1990. U.S. Dep. Commer. NOAA Tech. Memo. NMFS-AFSC-22, 150 p. Life history table reference arrowtooth #18.

Yang, M.-S., Nelson, M.W., 2000. Food habits of the commercially important groundfishes in the Gulf of Alaska in 1990, 1993, and 1996. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-112, 174 p. Life history table reference arrowtooth #17.

Yang, M.-S., Dodd, K., Hibpshman, R., Whitehouse, A., 2006. Food Habits of Groundfishes in the Gulf of Alaska in 1999 and 2001, 199 p. U.S. Dep. Commer., NOAA Tech. Memo., NMFS-AFSC-164, 199 p.

Zador, S., Aydin, K., Cope, J., 2011. Fine-scale analysis of arrowtooth flounder Atherestes stomias catch rates reveals spatial trends in abundance. Mar. Ecol. Prog. Ser. 438, 229–239.

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)	1st 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. Years covered include the 2015-2019 average and annual from 2020-2024.

	2015-2019 Average	2020	2021	2022	2023	2024
Total catch K mt	29.38	28.9	13	14.4	11.2	22.8
Retained Catch K mt	25.05	24.36	8.53	10.66	8.37	18.72
Catcher Processors #	4.4	5	4	6	3	5
Catcher Vessels #	25.6	22	4	4	10	9
Catcher Vessel Share of Retained	65.77%	78.24%	12.43%	10.79%	20.79%	40.06%
Ex-vessel value M $	$6.77	$4.97	$1.57	$2.96	$1.61	$3.82
Ex-vessel price lb $	$0.12	$0.08	$0.08	$0.12	$0.07	$0.09
Arrowtooth Share of Retained	78.56%	81.08%	90.67%	93.5%	96.94%	89.5%
Rex Sole Share of Retained	5.54%	4.19%	2.74%	3.38%	4.56%	2.67%
Shallow Flatfish Share of Retained	10.78%	16.88%	1.78%	2.35%	10.16%	6.93%
GOA share of AK Arrowtooth catch	71.52%	66.76%	49.14%	59.84%	56.46%	64.77%

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. Years covered include the 2015-2019 average and annual from 2020-2024.

	2015-2019 Average	**2020**	**2021**	**2022**	**2023**	**2024**
First-wholesale production K mt	14.08	14.13	5.39	6.1	5.37	11.22
First-wholesale value M US$	$22.59	$15.52	$7.2	$10.8	$9.74	$20.42
First-wholesale price/lb US$	$0.73	$0.5	$0.61	$0.8	$0.82	$0.83
Arrowtooth share of value	68.68%	59.43%	72.69%	87.58%	87.11%	87.77%
Arrowtooth price/lb US$	$0.7	$0.45	$0.55	$0.83	$0.85	$0.86
Rex sole share of value	14.38%	12.26%	3.31%	5.96%	4.62%	3.7%
Rex sole price/lb US$	$0.96	$0.83	$0.51	$0.65	$0.72	$0.78
Shallow flatfish share of value	10.2%	20.57%	19.29%	4.19%	6.89%	5.58%
Shallow flatfish price/lb US$	$0.75	$0.58	$0.91	$0.58	$0.64	$0.6
H&G share of value	68.71%	62.21%	96.69%	93.66%	87.26%	82.98%

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. Years covered include the 2015-2019 average and annual from 2020-2024.

	2015-2019 Average	2020	2021	2022	2023	2024
Global production of flounder, halibut, and sole K mt	970.42	921.8	863.32	858.08	791.21	-
US share global production	27%	28%	23%	29%	27%	-
GOA FMP flatfish share of U.S.[1]	11.31%	11.3%	6.54%	5.75%	5.27%	-
Export quantity of NSPF Frozen Flatfish K mt	16.9	22.22	25.86	23.37	16.54	22.98
Export value of NSPF Frozen Flatfish M US$	$31.29	$34.78	$37.5	$41.19	$30.95	$42.35
Export price/lb of NSPF Frozen Flatfish US$	$0.84	$0.71	$0.66	$0.8	$0.85	$0.84
Share of U.S. exports of NSPF Frozen Flatfish to China[2]	75.19%	78.46%	70.14%	52.33%	73.87%	78.08%
Exchange rate, Yuan/Dollar	6.63	6.9	6.45	6.74	7.08	7.2

[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.

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.

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
Predictive	Spring Sea Surface Temperature	neutral	neutral	neutral	neutral	*high*
	Spring Arrowtooth Larvae	neutral	NA	neutral	NA	**low**
	Summer/Fall YOY Prey	NA	NA	NA	NA	NA
	Arrowtooth Biomass Consumed	neutral	neutral	neutral	neutral	neutral
Contextual	Spring Eddy Kinetic Energy East GOA	neutral	neutral	neutral	neutral	neutral
	Spring Eddy Kinetic Energy West GOA	*high*	neutral	neutral	*high*	neutral
	Spring Larval Prey	neutral	NA	neutral	NA	NA
	Female Predation Mortality Age1	*low*	neutral	neutral	neutral	neutral
	Male Predation Mortality Age1	*low*	neutral	neutral	neutral	neutral
	Small Arrowtooth ADF&G	neutral	neutral	neutral	**low**	neutral
	Juvenile Arrowtooth Condition	neutral	NA	neutral	NA	neutral
	Arrowtooth CPUE ADF&G	neutral	neutral	neutral	neutral	neutral
	Summer Bottom Temperature	neutral	NA	neutral	NA	neutral
	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	neutral
Monitoring	Summer YOY Prey	NA	NA	neutral	NA	NA
	Arrowtooth Ration	**low**	neutral	neutral	neutral	neutral

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	low	neutral	low	high	neutral
	TAC Utilization	low	low	low	low	low

Table 7A.5: Description of mechanistic 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	Hypothesized Direction / Lag	Confidence
Temperature to predation	Higher temperatures increase metabolism and then consumption (Holsman and Aydin, 2015).	Positive / 0	High
Euphausiids to age-1 recruitment	Euphausiids are a common prey of age-1 arrowtooth (Paul et al., 1999, Doyle et al., 2018).	Positive / 1	Medium
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	High
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	Medium
Eddy kinetic energy (eke) in eastern GOA to larval abundance	More eddy kinetic energy (EKE) in the eastern GOA increases retention farther away from suitably nursery habitat resulting in lower overwinter survival (Goldstein et al., 2020).	Negative / 0	Medium
Eddy kinetic energy (eke) in western GOA to larval abundance	More eddy kinetic energy (EKE) in western GOA increases retention near more suitable nursery habitat resulting in higher overwinter survival (Goldstein et al., 2020).	Positive / 0	Medium
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	Medium
Larval abundance to age-1 recruitment	Larval CPUE reflects reproductive output and early life stage mortality and can be an early indicator of recruitment (Rogers et al., 2023)	Positive / 1	Medium/ Low
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	Medium/ High
Predation to recruitment	Pacific cod and halibut represent the highest proportion of predation on > 30 mm arrowtooth flounder; cannibalism on the individuals 30-299 mm (Doyle et al., 2018, Adams et al., 2022).	Negative / 0	Medium/ Low

Table 7A.6. Model selection results for arrowtooth flounder recruitment. The structural model (represented by the simplified DAG) had better predictive accuracy as measured by AIC compared to modeling recruitment a first order autoregressive process (ar1), as independent and identically distributed (IID) or modeling recruitment, or as a function of the direct links in the DAG (regression). σR, unexplained is the value of the standard deviation of the response variable (recruits), indicating variability in the response that is unexplained by the model, and the reduction in this unexplained variation from the IID model.

Model	AIC	ΔAIC	$\sigma_{R,\ unexplained}$	% reduction in unexplained variation
structural	852.5	0	0.420	82%
regression	855.3	2.7	0.416	83%
AR1	858.7	6.2	0.716	49%
IID	888.4	35.9	1.000	0%

Table 7A.7: 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	0.17 (0.04)	None	Match bottom temperature to period of predation on age-1 arrowtooth with MOM6
Euphausiids to age-1 recruitment	Summer/Fall YOY Prey	-0.57 (<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	0.48 (<0.001)	None	More refined spatial match to pelagic arrowtooth larvae
Small calanoid copepods to larval abundance	Spring Larval Prey	-0.14 (0.38)	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) in western GOA to larval abundance	WGOA Spring Eddy Kinetic Energy	0.13 (0.46)	None	Determine if entrainment leads to higher prey or being swept out of system, refine to connectivity metrics from individual based models or cross-shelf currents
Eddy kinetic energy (eke) in eastern GOA to larval abundance	EGOA Spring Eddy Kinetic Energy	-0.13 (0.46)	None	Refine to variable representing along-shelf currents or strength of Alaska stream or Alaska coastal current
Adult condition to larval abundance	Adult Arrowtooth Condition	0.27 (0.09)	None	Possibly refine to condition of larger female adult spawners that are fully selected by gear
Larval abundance to age-1 recruitment	Spring Larval Arrowtooth	0.16 (0.29)	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	0.00 (0.98)	None	Refine size range based on new size age matrix in model, remove Aleutian samples
Predation to recruitment	Arrowtooth Biomass Consumed	0.29 (0.02)	Negative to Positive	Switch to more prominent predator of arrowtooth age-1 (e.g., Pacific cod adult biomass)

Table 7A.8. Value of the (maximum) total effect on recruitment in the structural model. Abbreviations: SST = sea surface temperature, copepods = small copepod abundance, larvae = larval abundance, age1 = recruits (abundance of age 1 fish), eke_east = eastern Gulf of Alaska eddy kinetic energy, eke_west = western Gulf of Alaska eddy kinetic energy, cond - adult condition, nearshore age1 = nearshore age 1 fish abundance, bt = bottom temperature, pred = predation mortality, euph = euphausiids.

Pathway	Peak total effect	Peak lag
sst → copepods → larvae → age1	-0.01	1
copepods → larvae → age1	-0.02	1
eke_east → larvae → age1	-0.02	1
eke_west → larvae → age1	0.02	1
cond → larvae → age1	0.04	2
larvae → age1	0.16	1
nearshore_age1 → age1	0.00	0
bt → pred → age1	0.05	0
pred → age1	0.29	0
euph → age1	-0.57	1

Figures

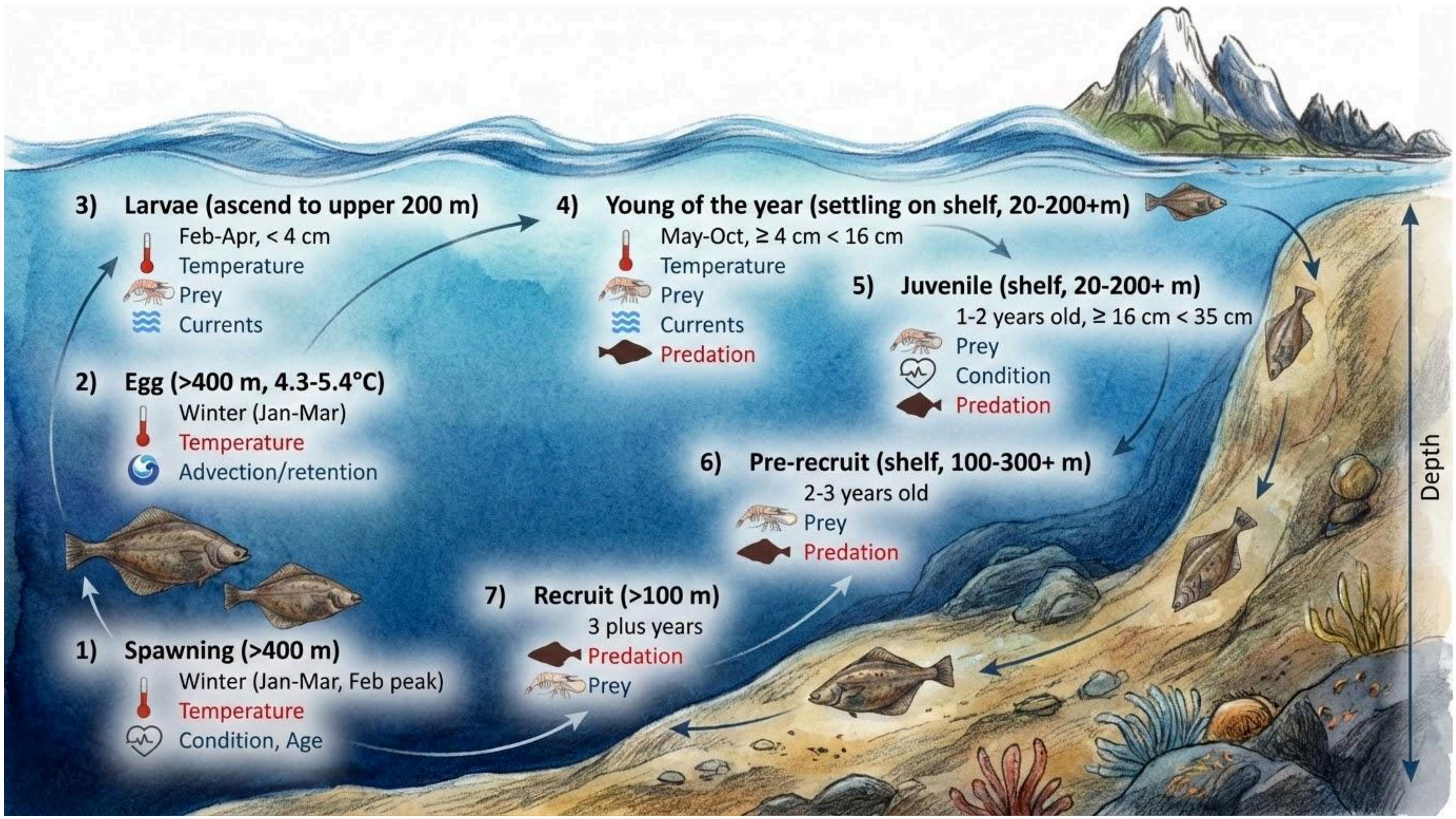


Figure 7A.1: Life history conceptual model for GOA arrowtooth flounder summarizing seven stages from Table 7A.2 with key ecosystem processes affecting survival by life history stage.

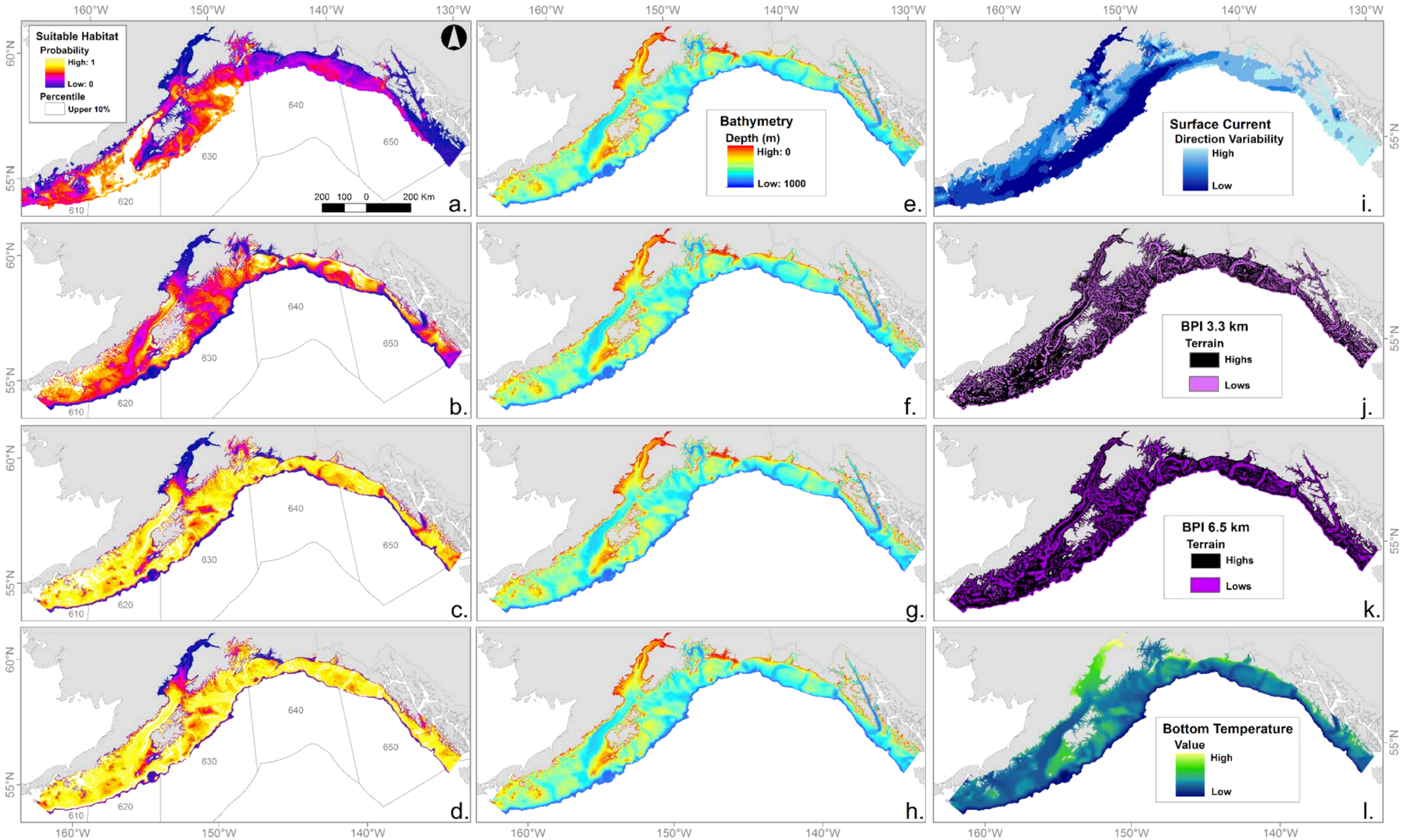


Figure 7A.2: GOA arrowtooth flounder probability of suitable habitat by life stage (a = larval, b = early juvenile, c = late juvenile, and d = adult) with corresponding predictor habitat variables representing the highest (e,f,g,h = depth) and second highest contribution (i = surface current direction 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.

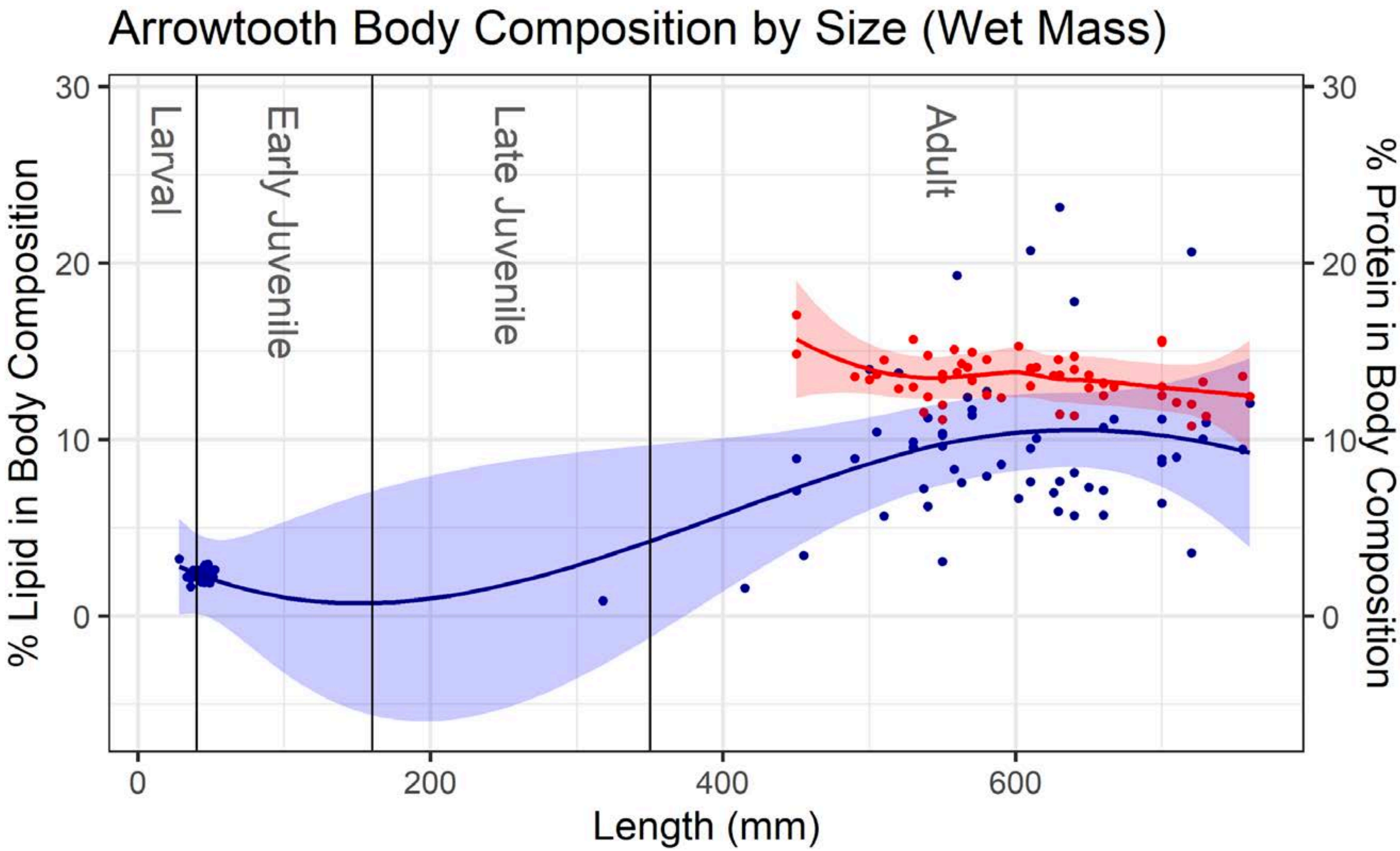


Figure 7A.3: GOA arrowtooth flounder percent body composition by length (mm), blue dots are % lipid by size, red dots are % protein by size and lines represent smoother (loess) for trend visualization. Vertical lines depict the size at different life stage transitions. Reproduced from Shotwell et al.,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

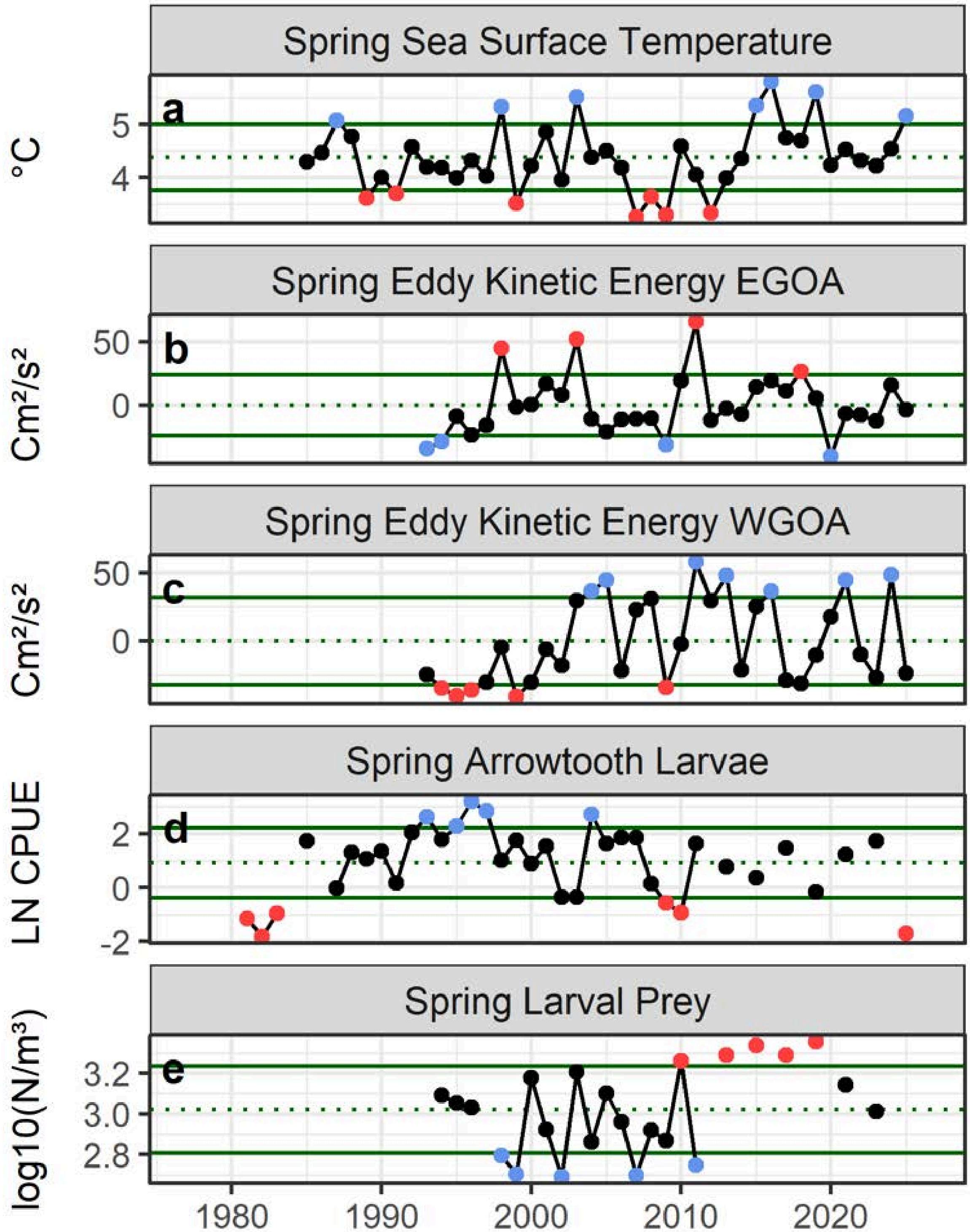


Figure 7A.4a: Selected ecosystem indicators for GOA arrowtooth flounder with time series ranging from 1977 – present. Upper and lower solid green horizontal lines = 1 standard deviation of the time series mean. Dotted green horizontal line = mean of the time series. Dots in the time series are colored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

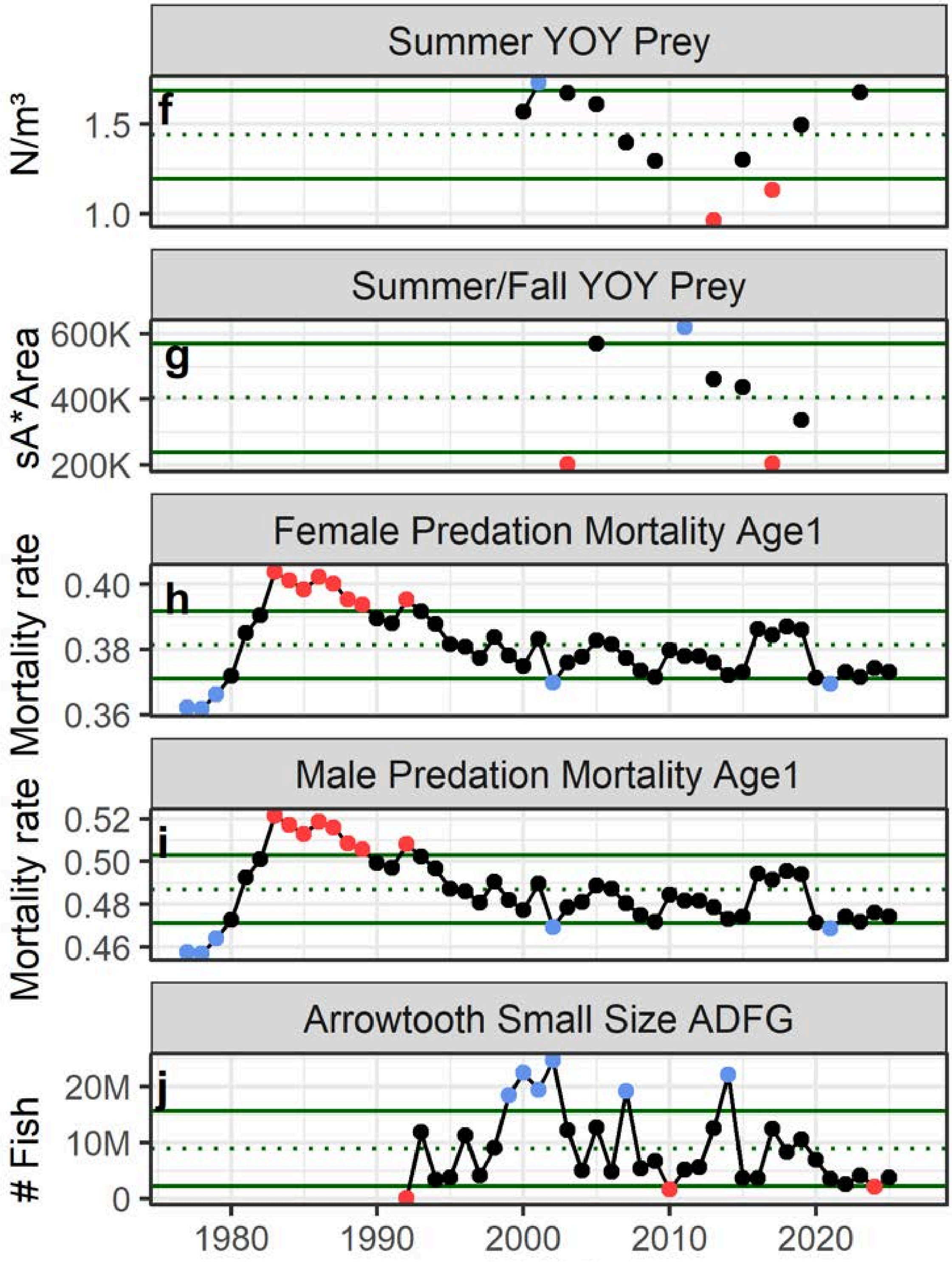


Figure 7A.4a (cont.): Selected ecosystem indicators for GOA arrowtooth flounder with time series ranging from 1977 – present. Upper and lower solid green horizontal lines = 1 standard deviation of the time series mean. Dotted green horizontal line = mean of the time series. Dots in the time series are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

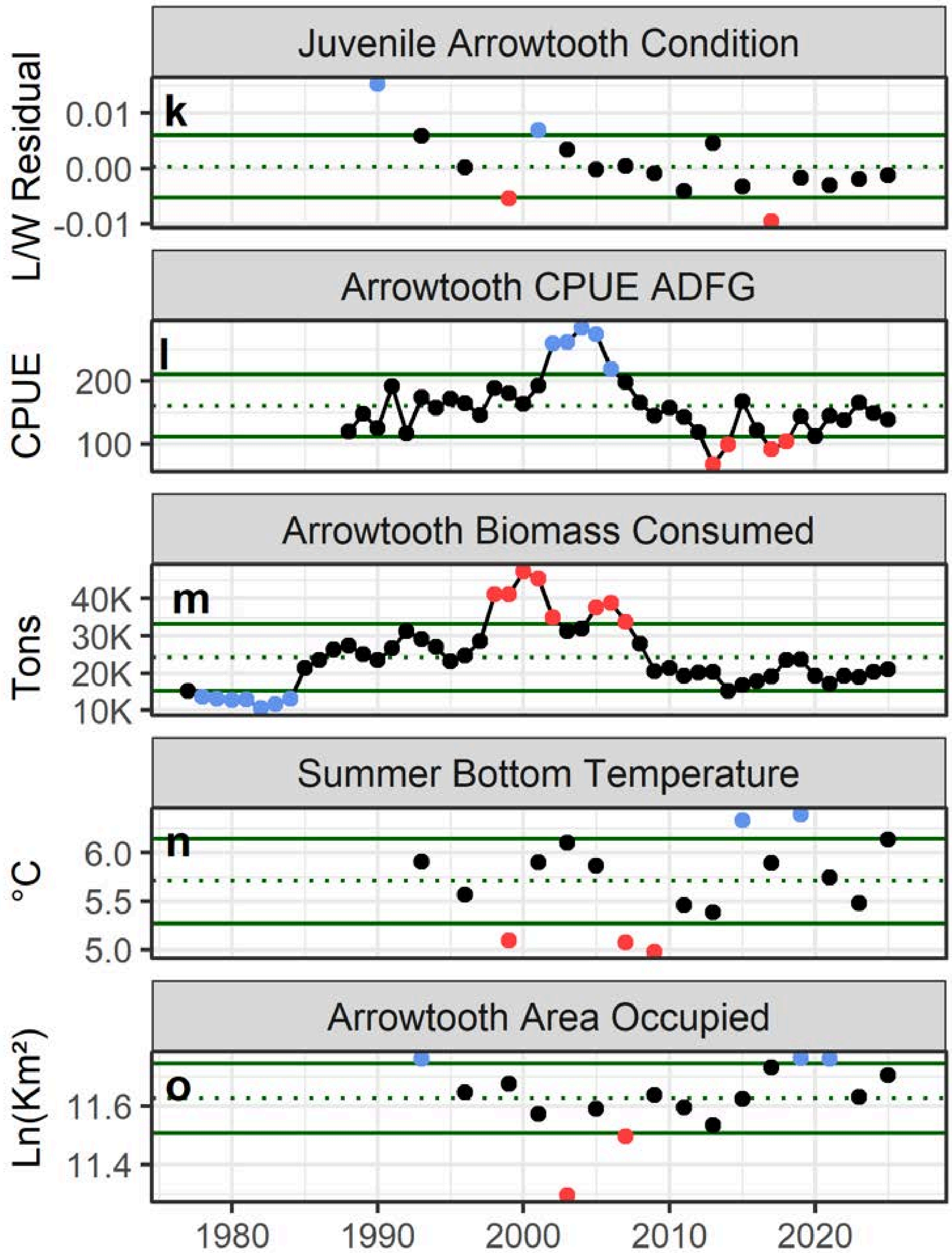


Figure 7A.4a (cont.): Selected ecosystem indicators for GOA arrowtooth flounder with time series ranging from 1977 – present. Upper and lower solid green horizontal lines = 1 standard deviation of the time series mean. Dotted green horizontal line = mean of the time series. Dots in the time series are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

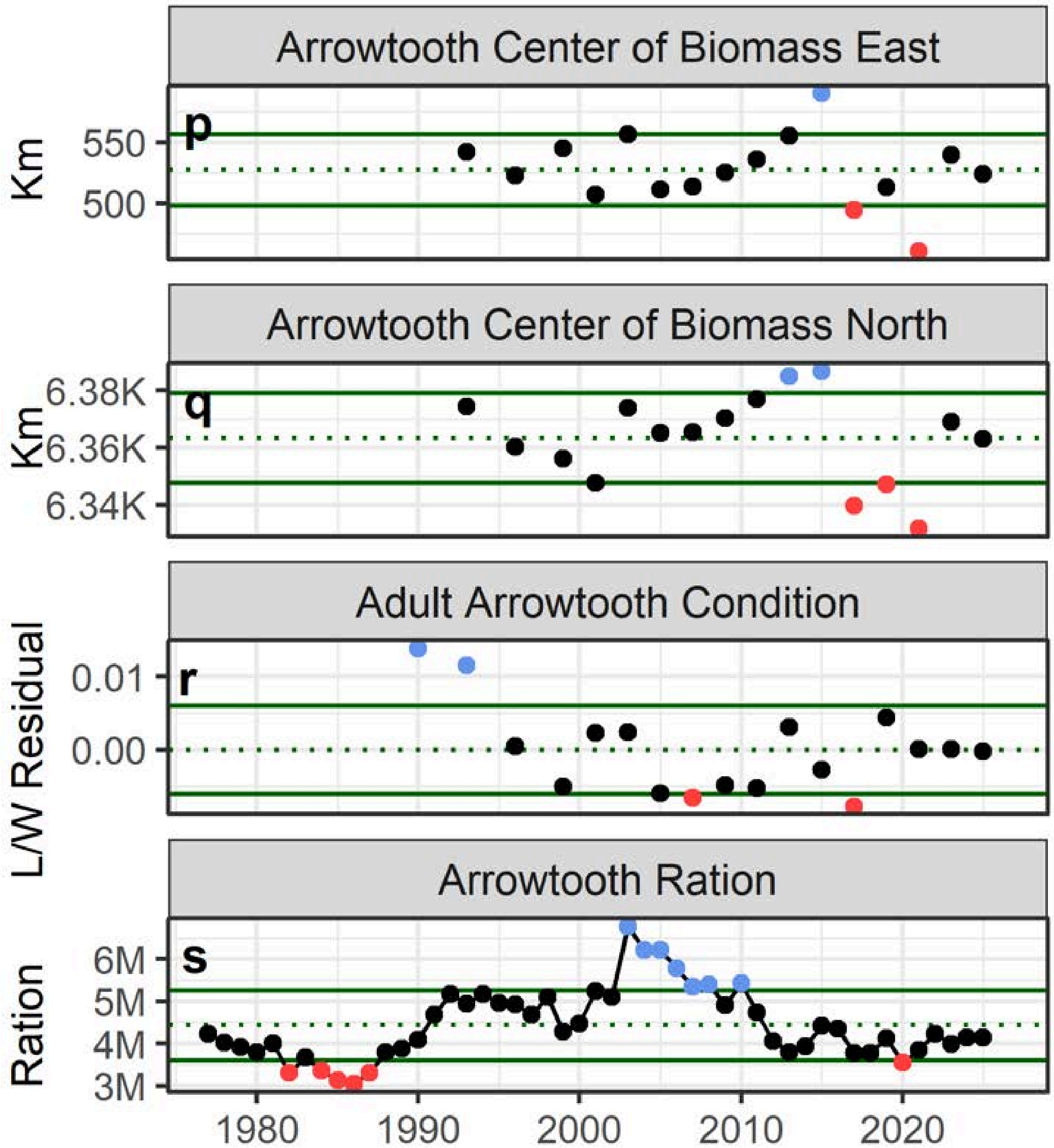


Figure 7A.4a (cont.): Selected ecosystem indicators for GOA arrowtooth flounder with time series ranging from 1977 – present. Upper and lower solid green horizontal lines = 1 standard deviation of the time series mean. Dotted green horizontal line = mean of the time series. Dots in the time series are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

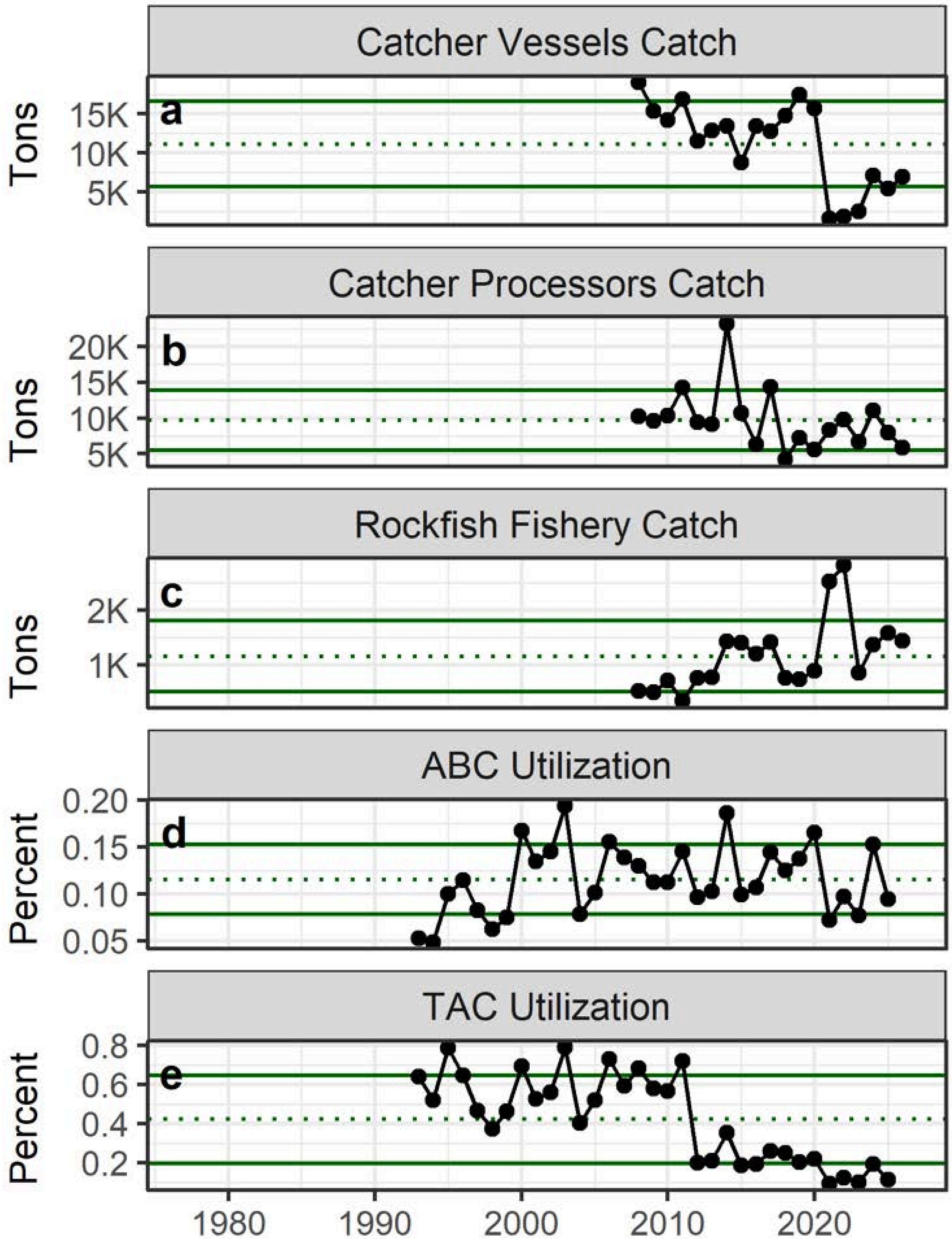


Figure 7A.4b: Selected socioeconomic indicators for GOA arrowtooth flounder with time series ranging from 1990 – present. Upper and lower solid green horizontal lines = 1 standard deviation of the time series mean. Dotted green horizontal line = the mean of the time series.

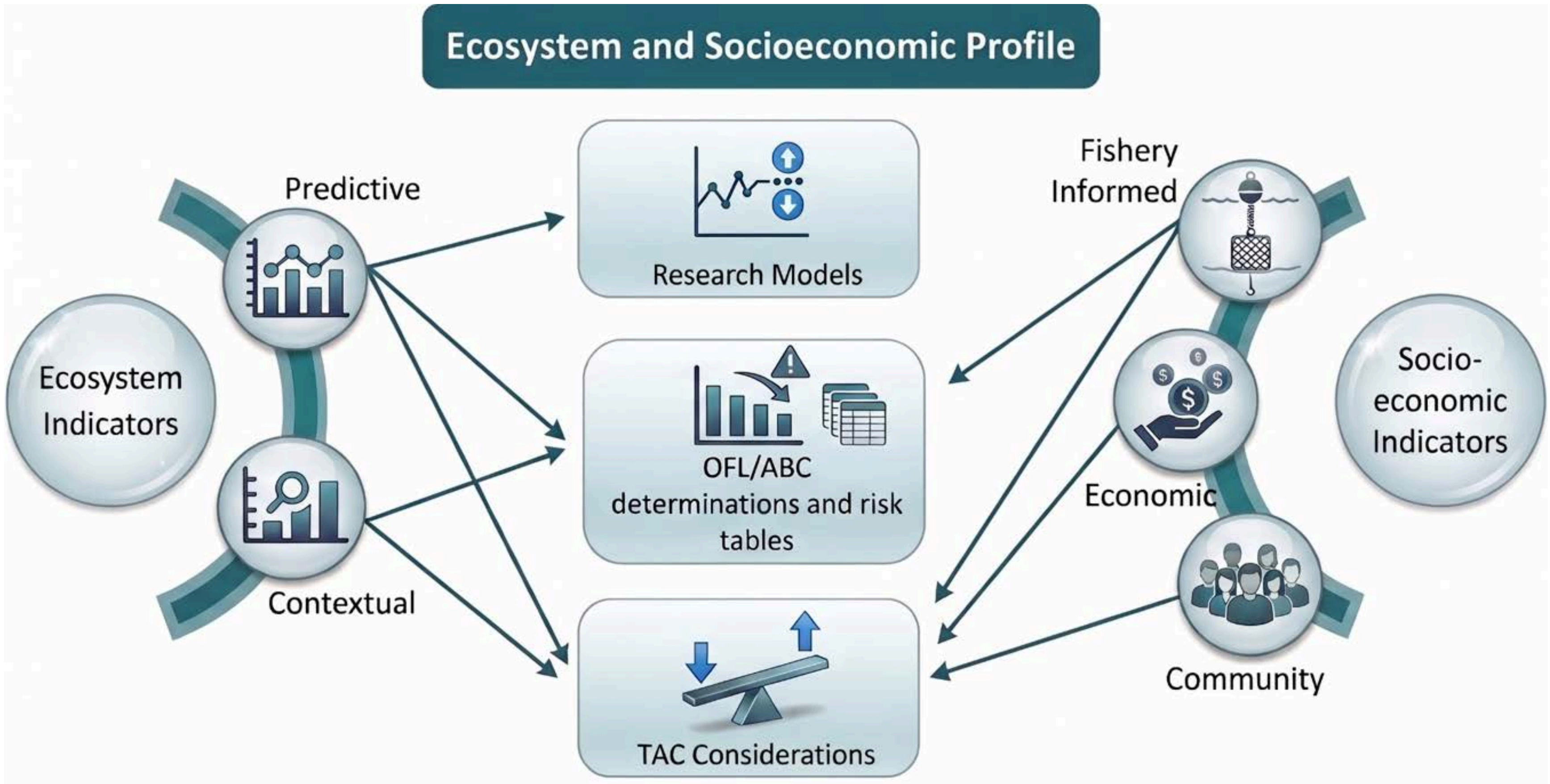


Figure 7A.5: Schematic of decision pathways for ecosystem and socioeconomic indicators

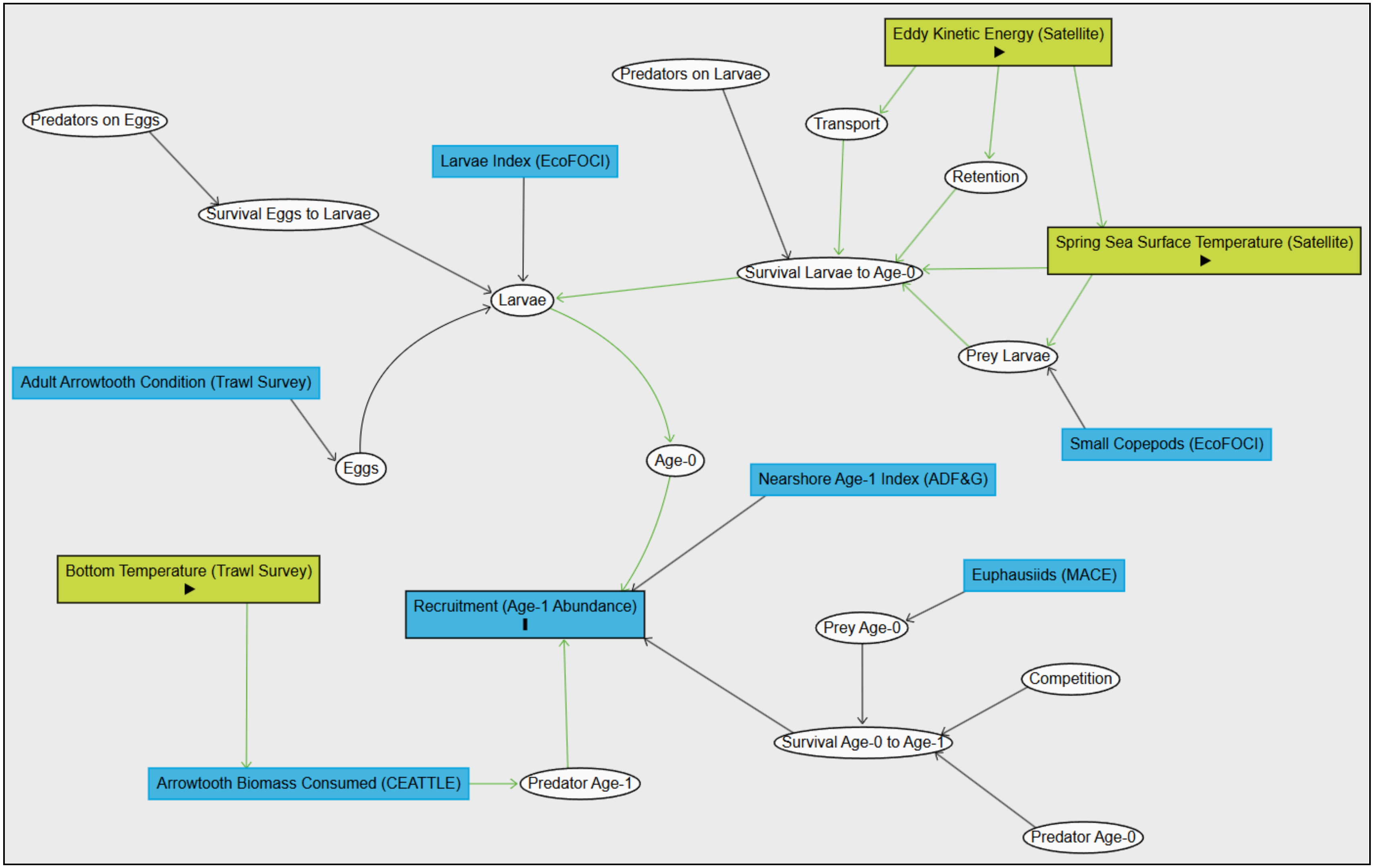


Figure 7A.6: The full causal model (as a directed acyclic graph or DAG made in https://dagitty.net/) illustrating causal linkages that may explain arrowtooth age-1 recruitment. White ovals are unobserved or latent variables, blue boxes are observed covariates, green boxes with a play symbol are observed 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.

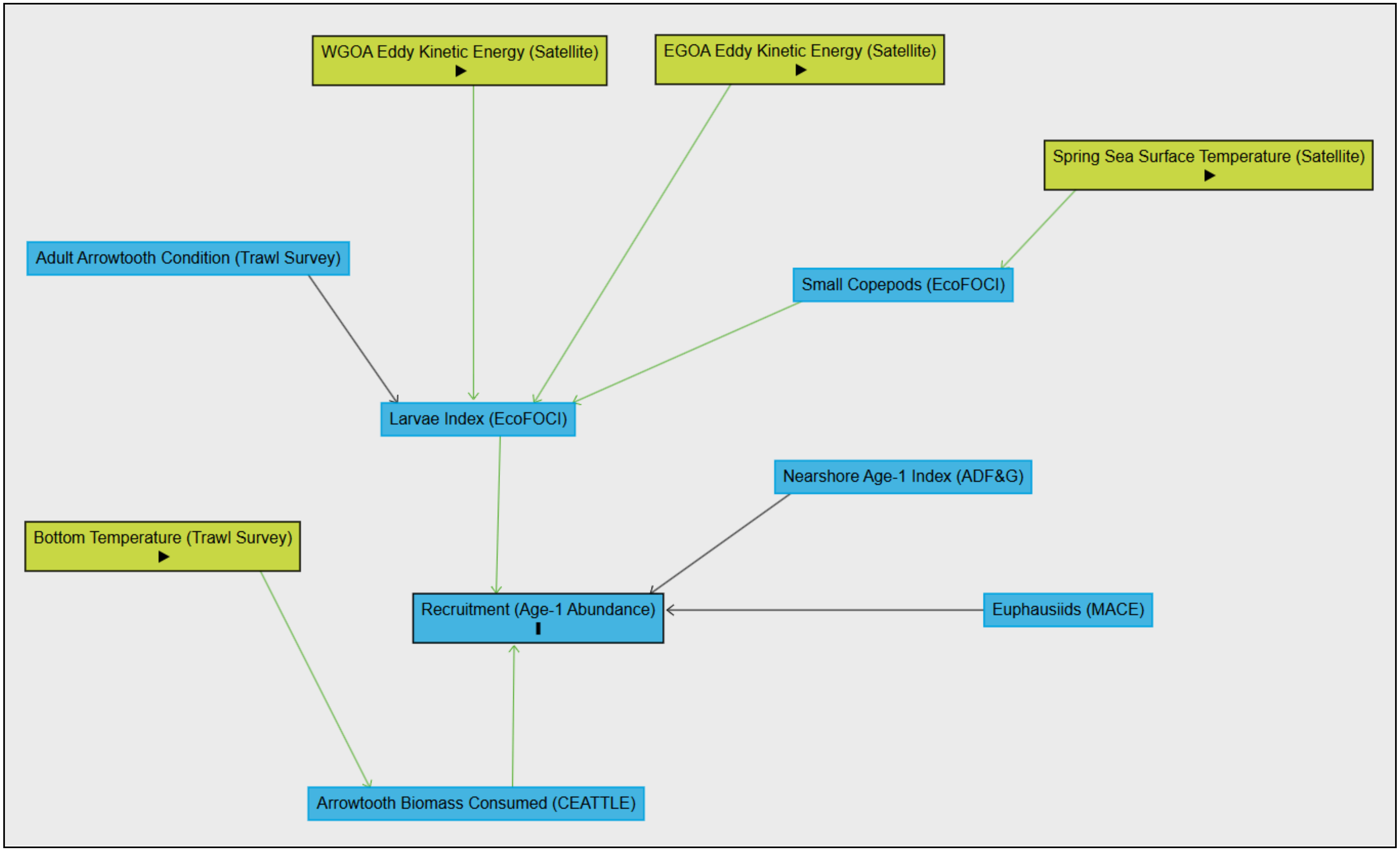


Figure 7A.7: The simplified causal model fitted using a dynamic structural equation model (DSEM) r package that was paired down from the initial, full model to be estimable. Note there is a one-year lag on the relationship between adult condition and larval abundance, larval abundance and age-1 recruits, 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.

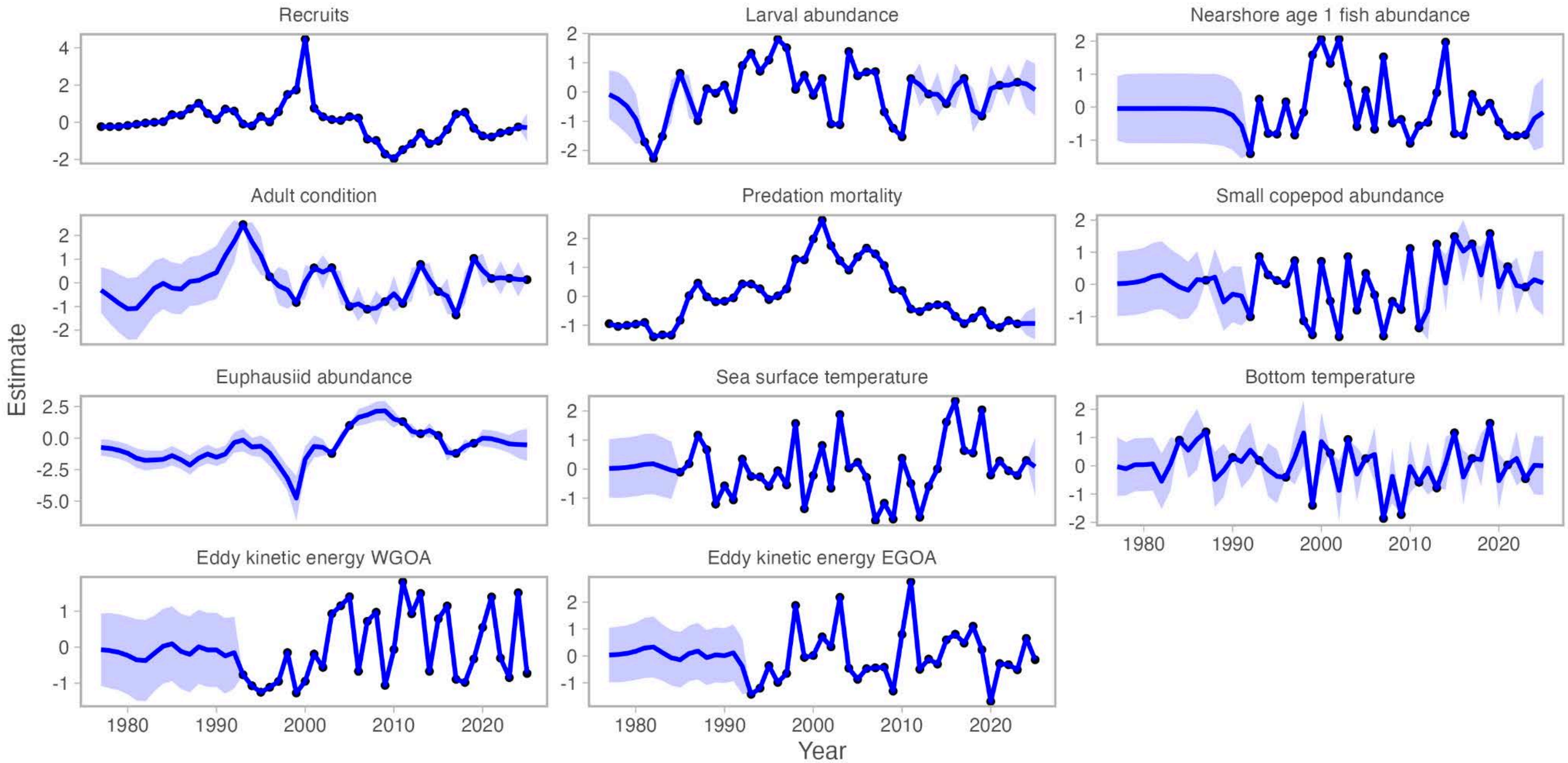


Figure 7A.8: Time series of scaled recruitment (outcome) and covariates estimated using a dynamic structural equation model (DSEM) for the causal model (see Figure 7A.7). Reproduced from Bigman et al., *in review*.

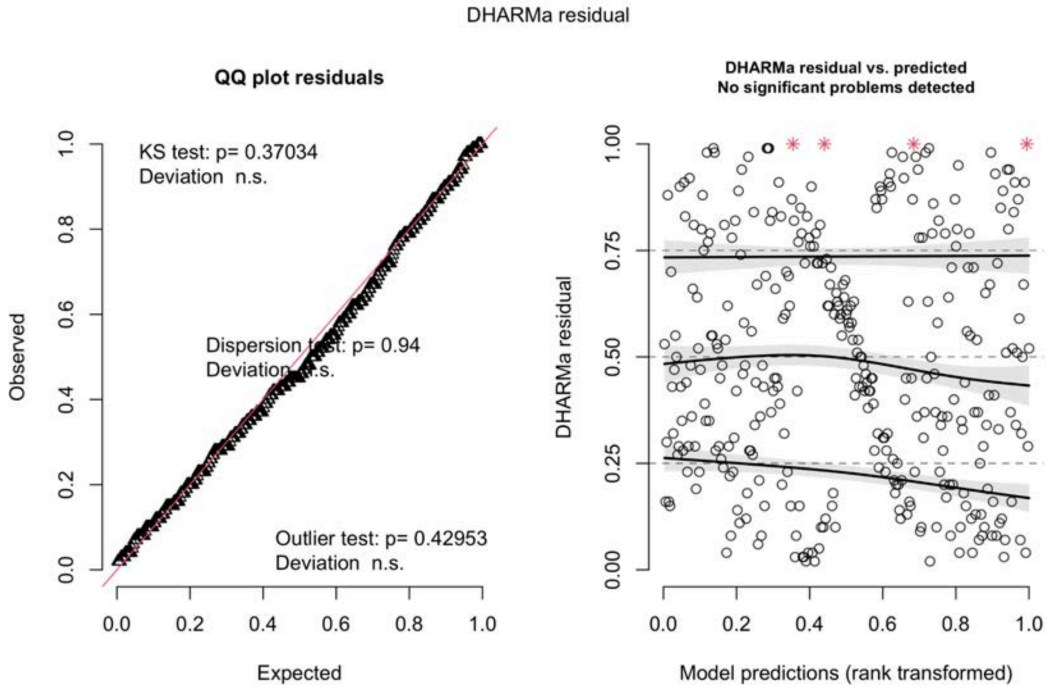


Figure 7A.9a. Leave-one-out residuals plotted using the DHARMa package for the arrowtooth flounder DSEM where recruitment is modeled as independent and identically distributed (IID). QQ plot (left) and residuals plotted against predictions (right). Red stars on the left plot indicate simulation outliers (data points outside range of simulated values); note probability of an outlier depends on the number of simulations (i.e., if outliers present, could be due to the number of simulations). Reproduced from Bigman et al., *in review*.

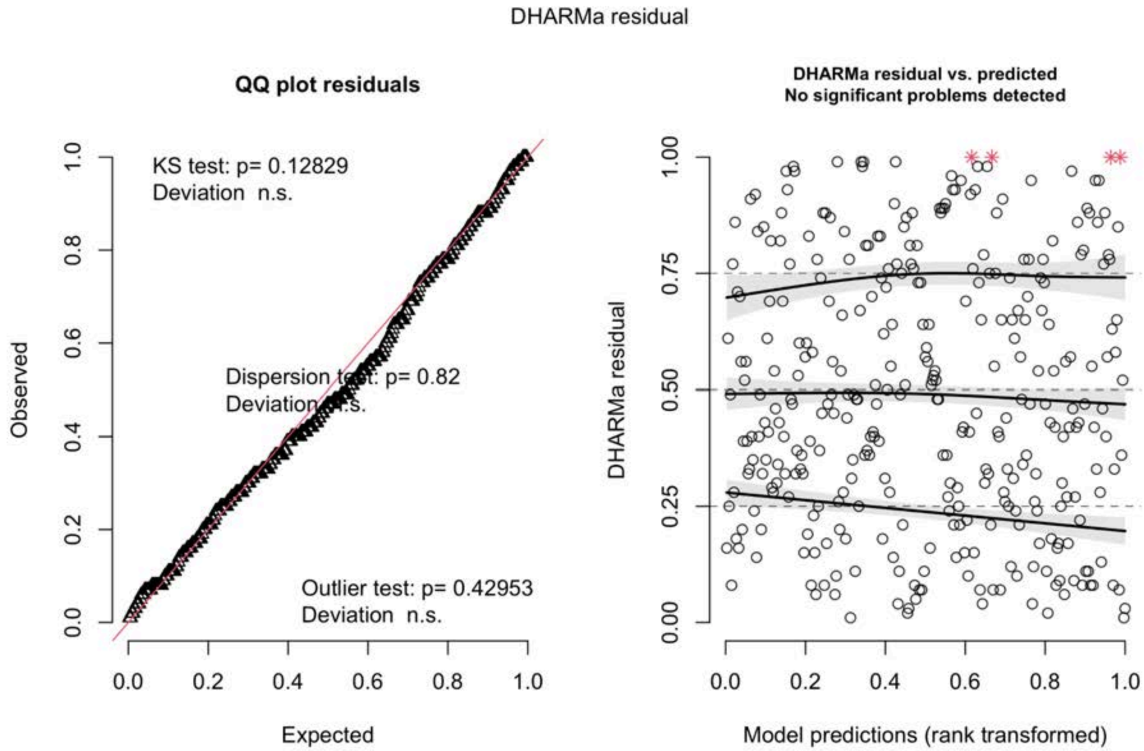


Figure 7A.9b. Leave-one-out residuals plotted using the DHARMa package for the arrowtooth flounder DSEM where recruitment is modeled as an autoregressive process (AR1). QQ plot (left) and residuals plotted against predictions (right). Red stars on the left plot indicate simulation outliers (data points outside range of simulated values); note probability of an outlier depends on the number of simulations (i.e., if outliers present, could be due to the number of simulations). Reproduced from Bigman et al., *in review*.

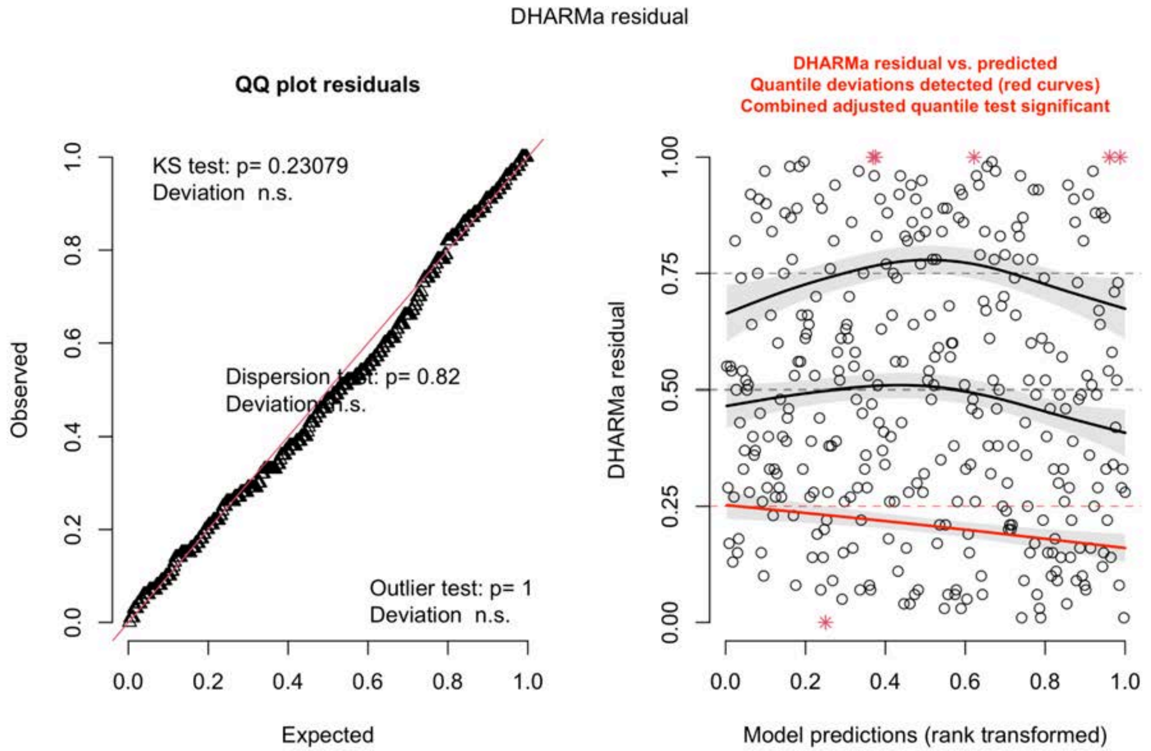


Figure 7A.9c. Leave-one-out residuals plotted using the DHARMa package for the regression model of the arrowtooth flounder case study where only direct links from the full causal DAG are included (see text). QQ plot (left) and residuals plotted against predictions (right). Red stars on the left plot indicate simulation outliers (data points outside range of simulated values); note probability of an outlier depends on the number of simulations (i.e., if outliers present, could be due to the number of simulations). Note while the model generally fits well, the lower quantile regression (0.25 quantile) deviates from the expected quantile, suggesting some structure in the response that is not being captured by the model. This suggests that there are missing covariates or links between covariates, nonlinear effects, or incorrect lag structures. Reproduced from Bigman et al., *in review*.

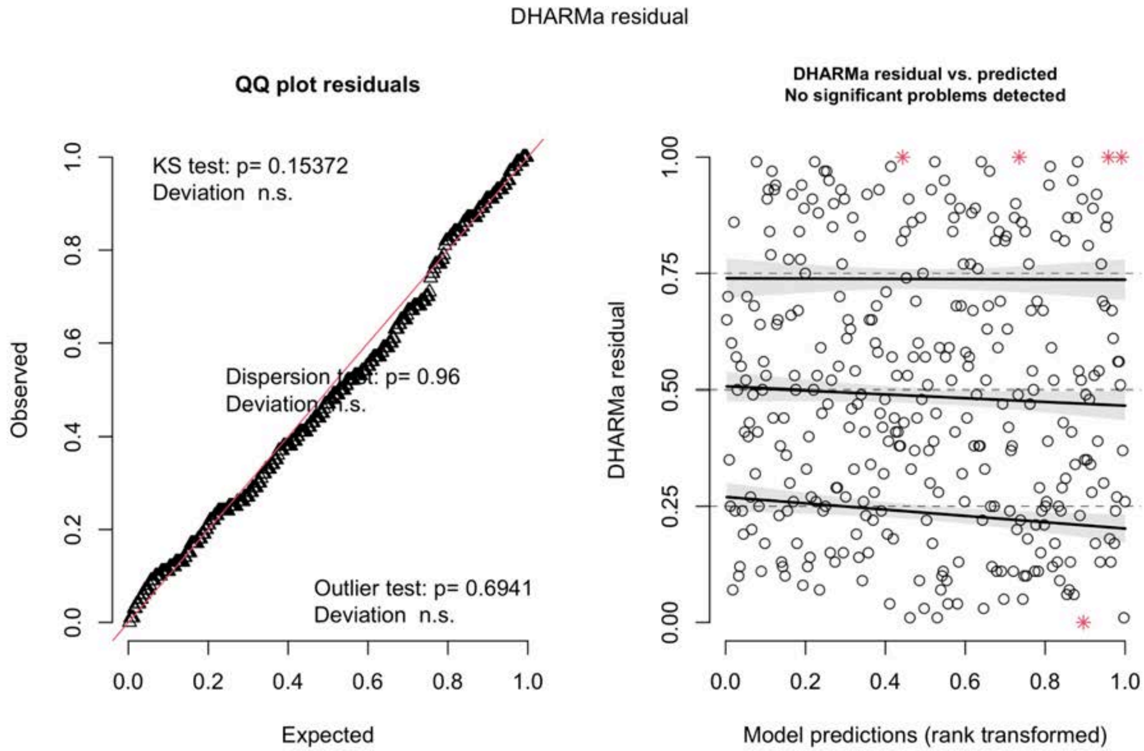


Figure 7A.9d. Leave-one-out residuals plotted using the DHARMa package for the causal model of the arrowtooth flounder case study (see text). QQ plot (left) and residuals plotted against predictions (right). Red stars on the left plot indicate simulation outliers (data points outside range of simulated values); note probability of an outlier depends on the number of simulations (i.e., if outliers present, could be due to the number of simulations). Reproduced from Bigman et al., *in review*.

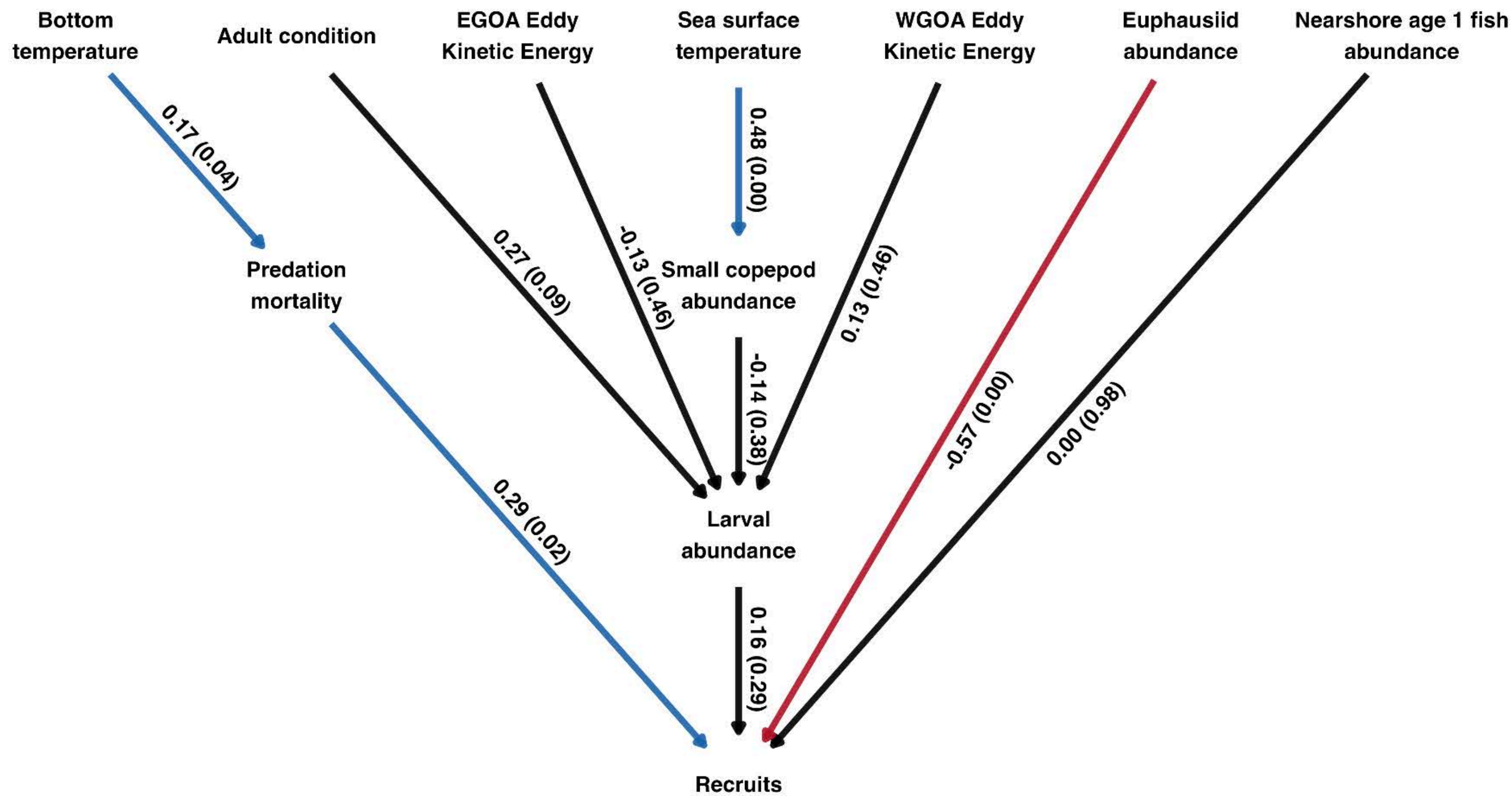


Figure 7A.10a. The causal model to explain arrowtooth flounder recruitment with estimated effects and p-values (in parentheses). The direction of the arrow indicates the hypothesized causal relationship and the color indicates the sign (red = negative, blue = positive, black is not significant). Lags and more detail about the variables can be found in Table 1. Reproduced from Bigman et al., *in review*.

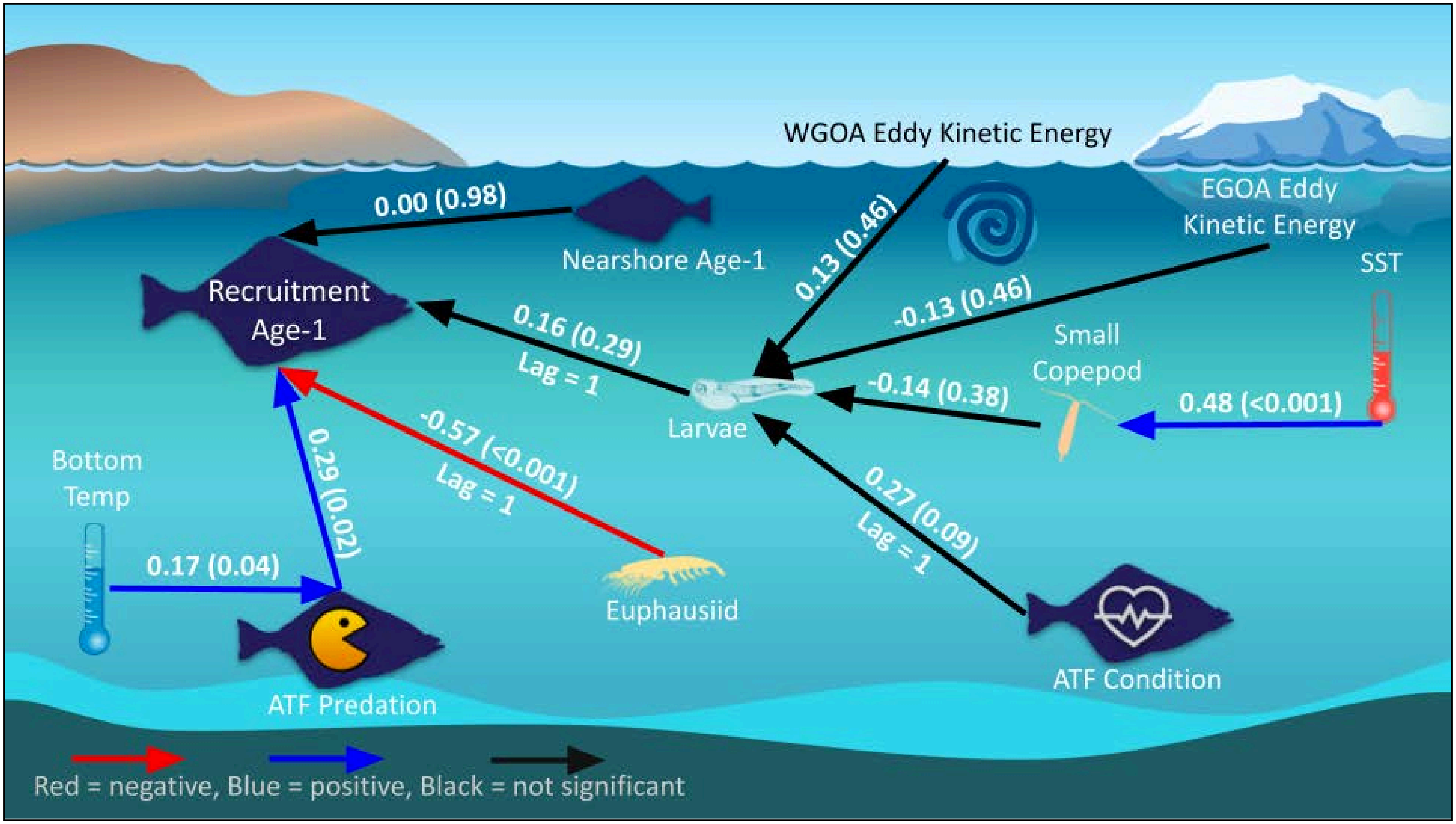
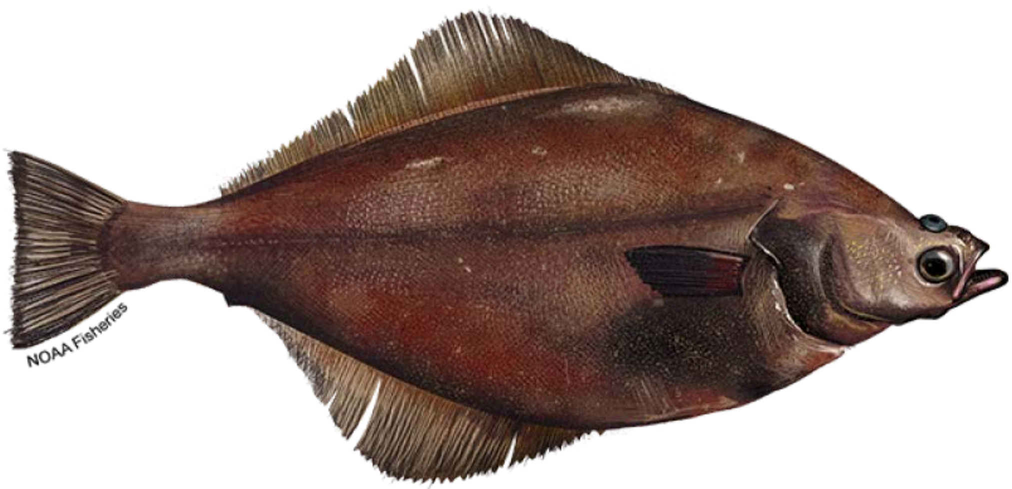


Figure 7A.10b Simplified causal model of GOA arrowtooth flounder with estimated effects. Lag = 0 years unless otherwise stated on the arrow. Numbers are the estimated effect of the covariate on age-1 recruitment and the associated p-value in parentheses. Blue arrows represent a positive relationship, red arrows represent a negative one, and black arrows were non-significant relationships. SST = sea surface temperature, ATF = arrowtooth flounder.

7. Assessment of the arrowtooth flounder stock in the Gulf of Alaska

S. Kalei Shotwell, Grant Adams, Dana Hanselman

September 2026



With Contributions from:

Matt Callahan, Ned Laman, Beth Matta, Margaret Siple, Jane Sullivan

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Executive Summary

The scheduled frequency for some stock assessments was changed in response to a review of the National Stock Assessment Prioritization effort (Methot 2015; Hollowed et al. 2016). In previous years, Gulf of Alaska (GOA) flatfish stocks were assessed on a biennial stock assessment schedule to coincide with the availability of new survey data. Following a prioritization review, it was recommended that GOA arrowtooth flounder (*Atheresthes stomias*) change to a quadrennial stock assessment schedule with a full stock assessment produced every four years and a harvest projection produced in the second year following the operational full assessment. For this year, we present an operational full assessment consisting of new survey and fishery data as well as recommend harvest levels for the next two years.

We use a statistical age-structured model as the primary assessment tool for the GOA arrowtooth flounder stock which qualifies it as a Tier 3a stock. This assessment consists of a population dynamics model, which uses survey and fishery data to generate a historical time series of population estimates, and a projection model, which uses results from the population dynamics model to predict future population estimates and recommended harvest levels. The data sets used in this assessment include total catch biomass, fishery size compositions, bottom trawl survey biomass estimates, and bottom trawl survey age compositions. This assessment is also paired with an ecosystem and socioeconomic profile (ESP) to evaluate additional information on recruitment and natural mortality that is not currently used in the operational model (Appendix 7A).

The following substantive changes have been made in the GOA arrowtooth flounder assessment relative to the last operational full stock assessment and fishery evaluation (SAFE) report (Shotwell et al., 2021). This report follows from the approved data update report provided to the Groundfish Plan Team in September 2025 (https://meetings.npfmc.org/Meeting/Details/3099) and includes the original bridging exercise, completed in 2024 (Appendix 7B).

Summary of Changes in Assessment Inputs:

Changes in the input data:

- Updated estimates of catch through August 22, 2026.
- Updated all fishery length compositions and included new compositions 2021-2025
- Updated all AFSC trawl survey biomass point-estimates and standard errors and included new estimates from 2025
- Updated all AFSC trawl survey age compositions and included new compositions from 2025
- Removed AFSC trawl survey estimates and associated age compositions from non-standardized AFSC surveys and during years with low confidence in arrowtooth identification (pre-1993)
- Removed all fishery length compositions prior to the Observer Program (pre-1991) and years with fewer than 300 samples
- Changed fishery length composition bins to match observed length distribution
- Updated the length-at-age transition matrices with new bin structure and data through 2023
- Updated the weight-at-age vectors with data through 2023
- Updated the ageing error matrix with all available age precision information (through 2021)

Changes in the assessment methodology (see Appendix for bridging of these models)*:*

- Model software changed from Automatic Differentiation Model Builder (ADMB) to Template Model Builder (TMB) within the Rceattle platform.
- Model 25.0: single-species TMB based Rceattle model with data improvements that fixes sex-specific M (females = 0.2 and males = 0.35) and treats annual recruitment as random effects.
- Model 25.1: Model 25.0 but estimates sex-specific M instead of fixing M.

- Research models are presented in the ecosystem and socioeconomic profile (ESP, Appendix 7A) and are used as references in the population dynamics and ecosystem section of the risk table. Models included are the following:
  - A cannibalism-enhanced single species model which is the multi-species TMB based Rceattle that estimates sex-, age-, and time-varying M due to cannibalism from arrowtooth (M2), sex-specific residual mortality (M1), and treats annual recruitment as random effects for creating indicators of age-1 predation mortality, arrowtooth biomass consumed, and arrowtooth ration. These indicators are used for understanding shifts in natural mortality.
  - Following Bigman et al., *in review*, a mechanism table regarding arrowtooth recruitment developed by the ESP team are evaluated within a unified dynamic state-space framework that fits a simplified structural directed acyclic graph (DAG) to the 1977-2024 recruitment time series from Shotwell et al., 2025 using the *dsem* package in R (v4.4.2) categorize predictive indicators that explain variability in recruitment estimates.

Summary of Results

ABC recommendation

The projected total biomass for 2027 is 1,437,490 t. The recommended ABC for 2027 is 134,083 t which equals the maximum allowable ABC under Tier 3a. This ABC is a 12% increase from the 2026 ABC of 119,985 t and a 12% increase from the projected 2027 ABC of 119,985 t from the last year's assessment (https://files.npfmc.org/SAFE/2025/GOAatf.pdf). The 2027 GOA-wide OFL for arrowtooth flounder is 157,261 t.

Reference values for arrowtooth flounder are summarized in the following table with the recommended 2027 OFL and ABC in **bold**:

Quantity	As estimated or *specified in **2024*** for: 2025	2026	As estimated or *recommended this* year for: 2027*	2028*
M (natural mortality – female, male)	0.2, 0.35	0.2, 0.35	0.2, 0.35	0.2, 0.35
Tier	3a	3a	3a	3a
Projected total (age 1+) biomass (t)	1,316,560	1,341,280	1,437,490	1,447,782
Projected female spawning biomass (t)				
Estimate	699,407	696,032	874,501	879,111
$B_{100\%}$	1,018,700	1,018,700	1,073,870	1,073,870
$B_{40\%}$	407,478	407,478	429,548	429,548
$B_{35\%}$	356,544	356,544	375,855	375,855
F_{OFL}	0.225	0.225	0.1179	0.1179
$maxF_{ABC}$	0.185	0.185	0.0994	0.0994
F_{ABC}	0.185	0.185	0.0994	0.0994
OFL (t)	142,832	143,347	**157,261**	157,060
*max*ABC (t)	119,547	119,985	134,083	133,901
ABC (t)	119,547	119,985	**134,083**	133,901
Status	As determined *in 2024* for: 2023	2024	As determined *this* year for: 2025	2026
Overfishing	No	n/a	No	n/a
Overfished	n/a	No	n/a	No
Approaching overfished	n/a	No	n/a	No

*Projections are based on an estimated catch of 16,835 t for 2026 and estimates of 12,409 t and 12,409 t used in place of maximum permissible ABC for 2027 and 2028.

The stock is not being subject to overfishing, is not currently overfished, nor is it approaching a condition of being overfished.

The tests for evaluating these three statements on status determination require examining the official total catch from the most recent complete year and the current model projections of spawning biomass relative to $B_{35\%}$ for 2027 and 2028. The official total catch for 2025 is 13,380 t, which is less than the 2025 OFL of 142,832 t; therefore, the stock is not being subjected to overfishing. The estimates of spawning biomass for 2027 and 2028 from the current year (2026) projection model are 874,501 and 879,111 t, respectively. Both estimates are well above the estimate of $B_{35\%}$ at 375,855 t and, therefore, the stock is not currently overfished nor approaching an overfished condition. The F from the author's recommended model that would make last year's catch equal to last year's OFL is F=0.138.

Summary of Specified Catch Estimation

In this GOA arrowtooth flounder assessment, the estimated current year catch, we use an expansion factor to the catch in August by the 5-year average of catch taken between August 22 and December 31 in the last five complete catch years (e.g. 2021-2025) for this year. The 2026 catch through August 22nd was 12,622 t. The total catch in 2026 was estimated to be 16,835 t based on the proportion caught through this date for the past 5 years (75%). The estimates of total catch in 2027 and 2028 were based on the percentage of catch to ABC (yield ratio) in the most recent five complete years. The current yield ratio is 10% and results in an estimated catch of 12,409 t for both 2027 and 2028.

5 Year Projections

The following table shows the projections for the next 5 years based on the author's catch projection recommendation (constant fraction of F based on the yield ratio) for 2027 and 2028 and harvest projection Scenario 3 (average F from the past 5 years) for 2029-2031.

Year	Catch	OFL	ABC	SSB	Mean Relative SSB
2027	12,409	157,261	134,083	874,501	0.814
2028	12,409	157,060	133,901	879,111	0.819
2029	13,294	156,925	13,294*	881,522	0.821
2030	13,303	157,087	13,303*	883,701	0.823
2031	13,359	157,788	13,359*	887,134	0.826

*Note: For Scenario 3 projections (2029–2031), the `spmR` projection model sets the ABC output to equal the expected catch derived from the average recent fishing mortality, rather than calculating the maximum permissible ABC for those respective years.

Spatial Apportionment: Biologically-informed Recommended Distributions (BRDs)

The following table shows the recommended ABC apportionment for 2027 and 2028. Please refer to the *Area Allocation of Harvests* section for information regarding the apportionment rationale for GOA arrowtooth flounder.

Area Apportionment		Western 19.1%	Central 59.9%	WestYakutat 7.23%	EastYakutat 13.80%	Total 100%
2027	ABC (t)	25,572	80,318	9,692	18,501	134,083
2027	OFL (t)					157,261
2028	ABC (t)	25,537	80,209	9,679	18,476	133,901
2028	OFL (t)					157,060

Summaries for Plan Team

Species	Year	Biomass[1]	OFL	ABC	TAC	Catch[2]
Arrowtooth Flounder	2025	1,316,560	142,832	119,547	100,454	13,380
	2026	1,341,280	143,347	119,985	100,769	12,622
	2027	1,437,490	157,261	134,083	n/a	n/a
	2028	1,447,782	157,060	133,901	n/a	n/a

Stock	Area	2026				2027		2028	
		OFL	ABC	TAC	Catch[2]	OFL	ABC	OFL	ABC
Arrowtooth Flounder	W		33,716	14,500	66		25,572		25,537
	C		68,511	68,511	12,517		80,318		80,209
	WY		6,719	6,719	25		9,692		9,679
	EY		11,039	11,039	14		18,501		18,476
	Total	143,347	119,985	100,769	12,622	157,261	134,083	157,060	133,901

[1]Total biomass (ages 1+) from the age-structured model

[2]Current as of August 22, 2026. Source: NMFS Alaska Regional Office Catch Accounting System via the AKFIN database (http://www.akfin.org).

Responses to SSC and Plan Team Comments

General Stock Assessment Comments

"The Team recommended as a best practice that appendices be linked in the front of the document (as with the sablefish assessment) to allow for an easier review of the appendices." (Joint Plan Team, November 2023)

There are three appendices for the GOA arrowtooth flounder assessment, the bridging document submitted in September 2025, the new full ecosystem and socioeconomic profile (ESP), and the supplemental catch information. These are all included at the end of the report so there is no additional link to track. The appendix can be quickly accessed through the document navigation window.

Combined recommendations on the risk table:
"The SSC continues to support a three-category risk table with categories normal, increased, and extreme, and requests that the category descriptions be revised to cover the range covered by the original table."
"The SSC reiterates that only fishery performance indicators that provide some inference regarding biological status of the stock should be used."
"The SSC recommends that the risk tables consider potential future risks when these can be anticipated."
"When risk scores are reported, the SSC requests that a brief justification for each score be provided, even when that score indicates no elevated risk."
(SSC, December 2023)

We use the newly updated risk table with three categories and updated descriptions for developing the risk table for this assessment. The new table is included in the SAFE introduction for reference and we do not repeat it here. The "fishery performance" category has been renamed to "fishery-informed stock considerations" and we only use the indicators that were listed by the SSC, namely "CPUE, fishery spatial and temporal patterns, and catches of thin or unhealthy fish (i.e., poor condition)" (SSC Minutes, December 2023, pg. 3). We also consulted with the Alaska regional office on any trends that we identified through this risk table evaluation.

Regarding a potential future risk to this assessment. We did not identify additional risk this year in the risk table categories because we received all the available survey and fishery information that we would normally have received at this time in the year. Our risk scores for this year were all level 1 and we provide justification for these scores in the "Reduction from maximum ABC" section below.

"The Team appreciates the greater use of Input Sample Size (ISS) for age and length composition data from surveys. The Team also recommended that authors continue to work with other research partners to develop methods and software to develop an ISS for fishery age and length composition samples. (GOA Plan Team, September 2025)

An R package is in development (pers. comm. Hulson) for calculating fishery input sample sizes for age and length composition data. The 2026 GOA arrowtooth flounder model utilizes the number of hauls as the yearly input sample sizes for survey and fishery age- and length-composition data currently and will explore use of input sample size for all sources of composition data when the fishery ISS package is ready for use.

"Multiple GOA assessments may use, or could potentially use, water temperature covariates, and the Team recommended that authors continue to collaborate across assessments to develop a temperature

product using spatial delta correction that calibrates numerical models (e.g., HYCOM) and in situ *measurements."* (GOA Plan Team, September 2025)

The GOA arrowtooth ESP includes both a sea surface temperature and a bottom temperature indicator in the indicator suite and the ESP-DSEM workflow evaluates the utility of these two indicators to explain variation in recruitment. Both variables had statistically significant relationships with recruitment and were categorized as predictive in the ESP. This information is used along with other water temperature data from the GOA ecosystem status report within the risk table of this assessment. The ESP results linkage table (Appendix 7A.7) provides some improvement suggestions for the two temperature variables to consider using high resolution hydrographic models (e.g., MOM6) to better represent the spatial and temporal period of pelagic occupancy for larval arrowtooth and the location of the arrowtooth spawning population with respect to predation on age-1 arrowtooth. We will consider these in future iterations of the GOA arrowtooth ESP.

Comments Specific to this Assessment

"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 full ESP as an appendix to this report. An external Dynamic Structural Equation Model (DSEM) was developed for this stock and preliminary results were presented to the GOA Groundfish Plan Team (GPT) in September 2025. This external DSEM has been finalized for publication and is currently in review (Bigman et al., *In Review*). We have extended this external DSEM and integrated it within the Rceattle platform through a development branch that includes DSEM for explaining recruitment variability. The results of this model are used to categorize the indicators within the ESP into predictive and contextual. These are all used to inform the risk table categories of population dynamics and ecosystem considerations. Results are summarized in the Executive Summary table and detailed in the Risk Table and ABC Recommendations section.

"The Team also noted the potential of using AFSC longline survey data for Arrowtooth flounder as they are caught in significant numbers on that survey."
"The SSC requests the authors investigate including IPHC survey data in this assessment, and whether fishery catch-at-age information is available for inclusion in the model." (SSC, December 2019)

We provide a review of the available data from the Alaska Fisheries Science Center (AFSC) longline survey, the International Pacific Halibut Commission (IPHC) survey, and fishery ages in this assessment. We also provide information from a nearshore bottom trawl survey from the Alaska Department of Fish and Game (ADF&G) that is currently used in the ESP to create an indicator of small (<20 cm) fish and is included in the research DSEM model. The survey information is included in the list of additional surveys in the "Other Data" section, while the fishery ages information is included in the "Fishery Data" section.

"*The Team recommended that the TMB version of the single species model be used in 2025 and brought forward to the September meeting.*" (GOA Plan Team, September 2024)
"*The SSC supports the GOA GPT recommendation that the bridging exercise was sufficient to go forward with the TMB single-species model using CEATTLE in 2025.*" (SSC, October 2024)

"*The SSC agrees with the GOA GPT and the author's recommendation to bring forward Model 25.0 and Model 25.1 for November.*" (SSC, October 2025)

The GOA GPT and the SSC both recommend the transition of the GOA arrowtooth flounder model in ADMB to TMB via the Rceattle framework. They also determined that the bridging exercise we provided in September and October of 2024 was sufficient and we did not need to bring forward the ADMB model prior to the full assessment in 2025. In September 2025, we provided a review of the data improvements for 2025 and included the 2024 bridging document as an appendix. The GOA GPT and the SSC recommended we bring forward the updated data models and the alternative in November 2025. This was delayed due to the government shutdown and the final models are presented in September 2026.

Introduction

Arrowtooth flounder (*Atheresthes stomias*) are relatively large flatfish that range from central California to the eastern Bering Sea (EBS), and as far west as the Kuril Islands (Orlov 2004). Arrowtooth flounder occur in waters from about 20m to 800m, although catch per unit effort (CPUE) from survey data is highest between 100m and 300m. Spawning occurs in deep water (>400 meters) in the Gulf of Alaska (GOA) and along the shelf break in the eastern Bering Sea (Doyle et al. 2018). Migration patterns are not well known for arrowtooth flounder; however, there is some indication that arrowtooth flounder move into deeper water as they grow, similar to other flatfish (Zimmerman and Goddard 1996). Fisheries data off Washington suggest that larger fish may migrate to deeper water in winter and shallower water in summer (Rickey 1995). Arrowtooth flounder spawn in deep waters (>400m) along the continental shelf break in winter (Blood et al. 2007). They are batch spawners, spawning from fall to winter off Washington State at depths greater than 366m (Rickey 1995).

The age composition of the species shows fewer males relative to females as fish increase in age, which suggests higher natural mortality (M) for males (Wilderbuer and Turnock 2009). To account for this process, natural mortality has typically been fixed at 0.2 for females and 0.35 for males in the model. Different options for natural mortality were considered in the 2017 assessment, which evaluated natural mortality as a function of the size of the fish (Charnov 1982, Gislason et al. 2010, Lorenzen 1996). The distribution of ages appears to vary by region and sex. Males were not observed older than age 20 prior to 2005 in the GOA; however, males age 21 have been observed in every survey since that time. The sex ratio of arrowtooth flounder also varies by region. In the GOA, the long-term average observed ratio from fishery observer length frequency collections is 69% female, 31% male. Survey length compositions from the Bering Sea indicate that the proportion female is 70% on the Bering Sea shelf, 72% on the Bering Sea slope, and 62% in the Aleutian Islands. Information concerning the genetic stock structure of arrowtooth flounder is not currently available, although efforts are underway to initiate research. For a complete description, summary table, and conceptual diagram of the GOA arrowtooth flounder life history, please refer to the GOA arrowtooth flounder ecosystem and socioeconomic profile (ESP) for this stock (Shotwell et al., 2026, also included as Appendix 7A in this report).

Fishery and Management History

Management of the arrowtooth flounder stock in the GOA has changed over time. Prior to 1990, flatfish catch in the GOA was reported as an aggregate of all flatfish species. The bottom trawl fishery in the GOA primarily targets rock, rex and Dover sole. The North Pacific Fisheries Management Council divided the flatfish assemblage into four categories for management in 1990; “shallow flatfish” and “deep flatfish”, flathead sole, and arrowtooth flounder. Arrowtooth flounder was separated from the group and managed under a separate ABC because of its present high abundance and low commercial value. In the GOA, arrowtooth flounder were first managed under a separate assessment in 2001. They are currently managed as a single stock but the ABC is specified separately for the western GOA (NMFS area 610), central GOA (620, 630), west Yakutat, and east Yakutat/southeast Alaska.

The area of highest abundance of arrowtooth flounder in the GOA is in the central and western gulf. The directed fishery takes place throughout the GOA, but is primarily in the central GOA (NMFS area 630). Arrowtooth flounder are typically caught with bottom trawl nets. Outside of the directed fishery, they are primarily caught as bycatch in the Other Flatfish fisheries. Viable products were developed for arrowtooth flounder around 2008, which prevented the muscle from degrading rapidly when heated (Greene and Babbitt 1990, Wasson et al. 1992, Porter et al. 1993). Until that time it was not targeted as a commercial fishery. Several methods exist to neutralize the enzymes that cause the flesh to degrade, including chilling to near zero or immediate processing and freezing (Reppond et al. 1993). The arrowtooth flounder currently caught, processed, and sold each year from the GOA are typically exported to China for reprocessing, with some product going to South Korea and Japan. Reprocessed arrowtooth from China may also be sold to Japan as fillets and engawa (frills), the US and Europe as fillets, among other countries. They are eaten as less expensive fillets, used raw in sashimi, or used to manufacture surimi.

Joint venture fisheries started in the late 1970s and the U.S. domestic Observer Program was phased in starting in 1987 and was completely domestic by 1990. Reliable cruise and vessel records started in 1991. Arrowtooth flounder catch was available from observer at-sea sampling applied to the Alaska Regional Office blend estimates for 1991 to the present. The estimate of annual arrowtooth flounder catch between 1960 and 1990 was extrapolated from total flatfish catch by multiplying the proportion of arrowtooth in observer sampled flatfish catches (nearly 50%) by the reported flatfish catch (1960-1977 from Murai et al. 1981 and 1978-1993 from Wilderbuer and Brown (1993) (Table 7.1).

Bycatch

The primary fisheries that caught arrowtooth flounder as bycatch from 1991 to present are the pollock, rockfish, and Pacific cod fisheries (Table 7.2). For the arrowtooth fishery from 2022-2026 (Table 7.3), the largest bycatch groups are on average Pacific cod (874 t/year), Pacific ocean perch (825 t/year), pollock (719 t/year), Flathead sole (460 t/year), Rex sole (369 t/year), and shallow water flatfish (350 t/year). Non-FMP species catch in the arrowtooth fishery is generally dominated on average by miscellaneous fish, sculpin, squid, sea stars, and grenadiers in that order (Table 7.4). Grenadiers used to be a larger component of the non-FMP species catch in the arrowtooth fishery which may imply that the fishery is distributed in shallower water on average than previously.

Discards

Gulf-wide discard rates (percent of the total catch discarded within management categories) of arrowtooth flounder were available for the years 1991 to present (Table 7.5). Discards of arrowtooth flounder have ranged from approximately 5.2% to 98% with an average of 46.6%. Discards have been decreasing steadily since the peak in 1994 to fairly low discard rates in recent years with a small uptick in 2021-2023, but are now near the lowest in the time series (Table 7.5).

Data

New data used in this assessment include estimates of total catch, trawl survey biomass estimates and standard errors from the AFSC GOA bottom trawl survey, and sex-specific trawl survey age and fishery length-frequencies from observer sampling. Length composition data were available from each survey; however, length data are only used in the model for each year when age composition data are not available. Age compositions for GOA arrowtooth flounder were available or will be available for all survey years; therefore survey length compositions are not used in the model. They are only included in this document for illustration purposes. The model simulates the dynamics of the population and compares the expected values of the population characteristics to data observed from AFSC surveys and fishery sampling programs.

The following data sources were available for use in the model. Bolded years indicate new data inputs for this year's assessment.

Source	Data	Years
AFSC GOA bottom trawl survey	Survey biomass and standard error	1993,1996,1999,2001,2003,2005,2007,2009 2011,2013,2015,2017,2019,2021,**2023**,**2025**
	Age Composition	1993,1996,1999,2001,2003,2005,2007,2009 2011,2013,2015,2017,2019, **2021**,**2023 2025**
U.S. fisheries	Catch Biomass	1977-2021, **2022-2026**
	Length composition	1991-2020, **2021-2025**

*Note catch is current up to 8/22/2026

Fishery Data

Catch

The catches for arrowtooth flounder remain well below the TAC (Table 7.1). Estimates have ranged from 15,000 – 36,000 t since the year 2000, averaging 24,000 t, and the ratio of catch to TAC averaged 36% overall and 13% in the past five years. Catches were below 10,000 t, on average, prior to 1990, and increased to an average of approximately 16,000 t in the 1990's and 24,000 t in the 2000's. Catch as of August 22, 2026 was 12,622 t. Total allowable catch for 2025 and 2026 was 100,454 t and 100,769 t.

Fishery Age and Length Compositions

Otoliths have been collected sporadically in the fishery since 1982 but sample sizes are generally low following the initiation of the Observer Program in 1990 (Table 7.6). It may be possible to age some of these otoliths during years when the samples were higher (>100) through the AFSC Age and Growth prioritization system; however, the ageing request would need to be evaluated within the scope of the AFSC Age and Growth available staff time and resources (J. Short and B. Matta, *pers. comm.*). Also, the years when otoliths were higher are fairly sporadic, and ageing of these otoliths may not be worth the extra effort given the amount of otoliths aged by the AFSC Age and Growth program each year. At the time of this assessment, the staffing capacity was limited and no fishery otoliths could be aged for GOA arrowtooth flounder. Future ageing of available otoliths for this stock will be determined based on the AFSC and the Age and Growth Program priorities.

The number of fisheries otoliths and length observations taken by fisheries observers by year, 1991 to present, are provided in Table 7.6. Sample sizes (number of individual fish) for the fishery length data by sex were under 300 for males in 1992, 1994, 1996, and 1998; therefore, we do not use this information in the model. The distribution of male and female length observations over all available years since the Observer Program began are shown in Figure 7.1. There are no clear directional long-term trends in the length data but there is variation over time. Also data between 1991 and early 2000s appears to contain more larger females with a greater spread than any following year in the time series. Observers did not consistently begin identifying arrowtooth flounder and Kamchatka flounder to species until 2008, and the catch accounting system did not speciate Kamchatka flounder until 2011 (Bryan et al., 2020). Generally there are very few Kamchatka flounder caught in the GOA bottom trawl surveys, but there may be some in the fishery and we plan to investigate this further to determine if this may be a reason to not use this early fishery length data prior to consistent identification in 2008. We will include results of this investigation in the next full assessment and may further limit the fishery length composition used in the model. Median length composition in the fishery is 46 cm overall, with 49 cm for females and 42 cm for males, respectively.

Survey Data

AFSC Bottom Trawl Survey Biomass Estimates

Bottom trawl surveys were conducted on a triennial basis in the Gulf of Alaska starting in 1984 through 1999 and became biennial starting in 2001. The triennial AFSC surveys used a nor'easter trawl. A different survey design was used in the eastern GOA in 1984 and much of the survey effort in the western and central GOA in 1984 and 1987 was conducted by Japanese vessels that used a different net design than the U.S. vessels. Additionally, the trawl used in the 1984 and 1987 surveys had no bobbin or roller gear, which would cause the gear to be more in contact with the bottom than current trawl gear, and may have restricted the locations of trawl sites to more trawlable areas. The triennial surveys covered all areas of the GOA out to a depth of 500 m (in some surveys to 700 m or 1,000 m), but the 2001 biennial survey did not sample the eastern GOA. We use an average estimate of the previous three surveys (1993, 1996, 1999) to estimate the eastern GOA biomass for 2001 as in past assessments. Analyses of species identification confidence for the bottom trawl survey data (Stevenson and Hoff, 2009; Orr et al., 2014) indicated that a moderate level of confidence was attained for arrowtooth flounder starting in 1980 for the Gulf of Alaska and Aleutian Islands survey and in 1992 for the eastern Bering Sea shelf survey. Additionally, recently survey strata adjustments have occurred in a data cleaning effort of the bottom trawl survey data and consistency in species identification confidence estimates have resulted in data only available since 1992 for arrowtooth flounder. There is also now a new species code for unidentified arrowtooth/Kamchatka flounder which has been applied to data prior to 1992. We, therefore, use information starting from 1993 for the GOA bottom trawl surveys.

The survey catchability coefficient (q) in the assessment model was assumed to be 1.0. AFSC has conducted studies to estimate the escapement under the survey net and herding of fish into the net. The percent of arrowtooth flounder caught that were in the path of the net varies by size from about 80% at 27 cm (about age 3) to about 96% at greater than 45cm (equal to or greater than age 7 for females and age 10 for males) (Somerton et al. 2007). Somerton et al. (2007) estimated the effect of herding combined with escapement under the net to be an effective multiplier of about 1.3 on survey catch for arrowtooth flounder. The combination of escapement under the net and herding into the net indicates that abundance would be about 23% less than the estimated survey abundance. At this time we assume q to be 1.0 but may explore estimating q in the future given this herding experiment.

Survey biomass estimates increased to 3 million tons in 2003, and have since declined to approximately 1 million metric tons from 2017 to present (Table 7.7). Survey biomass has generally been declining since 2003, and the 2017 estimate was the lowest estimate on record. The 2019 to the present estimates were each slightly higher than the previous survey (Figure 7.2). The most current 2025 survey increased by 22% from the previous survey and is now just below the long-term average. Survey estimates of biomass by area (Table 7.8) are generally highest in the central GOA (Chirikof and Kodiak regions). The eastern (southeastern and Yakutat) and western GOA (Shumagin) have similar biomass estimates of arrowtooth flounder (Figure 7.3). The Kodiak area has experienced the greatest declines in arrowtooth flounder biomass since 2003, but has recovered slightly since 2017.

Spatial distribution maps of catch per unit effort (CPUE) data for the most recent three surveys are available from the AFSC GOA bottom trawl survey (Figure 7.4). CPUE by haul indicates that the highest abundance has generally occurred in the central GOA, to the southwest and to the northeast of Kodiak Island, although some larger hauls appear in southeast Alaska in the most recent survey (Figure 7.4, top graph). The highest CPUE typically appears in the Chirikof region of the central GOA, NMFS area 620.

AFSC Bottom Trawl Survey Age and Length Compositions

Otoliths from the 1993 to 2025 AFSC trawl surveys have been aged and are used in the model (Table 7.9, Figure 7.5). Differences in ageing methodology exist but are not expected to bias results (D. Anderl, *pers. comm.*). Ages for both females and males are more spread out prior to the 2015 survey. Median age composition for females and males is age 11 and 10, respectively. Length composition data are not used when age data are available or anticipated to be available in the following assessment year. Length frequency data were collected opportunistically for arrowtooth flounder on three GOA surveys conducted in 1985, 1986, and 1989. These surveys were not part of the standard AFSC GOA bottom surveys but the length frequency data have been included in previous assessments. As these opportunistically collected length compositions are not part of the standard survey protocol, we no longer use this information in the model. Length frequency data from all AFSC surveys indicates no long term trends, and that females are larger than males (Table 7.10, Figure 7.6a,b). Larger fish for both sexes often appear in the eastern GOA. Median length composition is 40 cm overall, with 46 cm for females and 35 cm for males, respectively.

Other Data

Alaska Department of Fish and Game Large Mesh Bottom Trawl Survey

ADF&G's large-mesh bottom trawl survey of crab and groundfish has been conducted annually from 1988 to present using the research vessel Resolution, with a 400-mesh eastern otter trawl designed to sweep a 12.2 m path (Spalinger and Silva, 2023). The survey uses a fixed-grid station design, with all areas sampled each year, and is conducted in the Kodiak, Chignik, South Peninsula, and Eastern Aleutian Tanner crab districts of Westward Registration Area J, which includes Pacific Ocean waters south of the latitude of Cape Douglas (58°51.10' N lat), west of 149° E long., and east of 172°W long., and Bering Sea waters south of 54°36.00' N lat and east of 172° W long.

We have included the ADF&G survey as an indicator within the ESP for arrowtooth founder (Appendix 7A) to monitor the catch-per-unit-of-effort (CPUE) of this additional bottom trawl survey source and also keep track of small arrowtooth in the nearshore habitat (>=100 mm and <200 mm, likely age-1). CPUE generally increased from the onset of the survey until mid 2000s and then dropped until the time series low in 2013 and has steadily increased to the present which is close to the long-term average (Figure 7.7). Information on extrapolated lengths are also available and are used to create the small arrowtooth indicator. We include the annual length composition data here as an additional source for understanding trends in size for arrowtooth flounder (Figure 7.8). Some cohorts appear to be clearly tracked in this survey particularly from 2001 and 2013. Median length composition is 37 cm, similar to the bottom trawl survey; however, no sex-structure data are available for this survey.

AFSC Longline Survey

The AFSC longline survey has been conducted annually since 1988, and relative population numbers (RPNs) and relative population weights (RPWs) have been computed for each year and are available since 1992 for Arrowtooth and Kamchatka flounder combined (Figure 7.9). The AFSC longline survey was conducted annually over the continental slope region of the BSAI and the GOA. The GOA stations were sampled annually until 2023 and biennial thereafter on odd years, while the Bering Sea was sampled on odd years and the Aleutian Islands in even years until 2023 and biennially on even years thereafter. This survey provides data on the relative abundance of Arrowtooth flounder in the form of RPNs and RPWs for fish on the continental slope as indices of stock abundance. Relative population abundance indices are computed annually using survey catch per unit of effort (CPUE) rates that are multiplied by the area size of the stratum within each geographic area. These relative population indices are available by numbers (RPN) and weights (RPW) for a given species (Rodgveller et al. 2011). The survey is primarily directed at sablefish, but also catches considerable numbers of arrowtooth flounder. Also, historically, arrowtooth flounder and Kamchatka flounder were not separated by species and were just recently separated out in

2019. Therefore, we provide RPNs for arrowtooth and Kamchatka flounder combined to see changes throughout the entire time series (Figure 7.9). Results for this survey concerning flatfish, should also be viewed with some caution, as the RPNs and RPWs do not take into account possible effects of competition for hooks with other species caught on the longline, especially sablefish.

RPNs in the GOA show a somewhat decadal cyclic pattern since the mid-1990s to about 2010 and then have declined to present low values, with a steep decline at the onset of the 2014 marine heatwave, similar to the bottom trawl survey estimates. Values range from a high in 1999 to a low in 2025. This same pattern is evident in the BSAI time series for Arrowtooth and Kamchatka flounder except the pattern is more variable and the decline is less steep. Some of the fluctuations may be related to changes in the abundance of sablefish regarding competition for hooks among species. The 2025 longline survey RPN value for Arrowtooth and Kamchatka flounder combined is down 33% from 2023 (Figure 7.9), and is the lowest of the time series.

Length data are also collected for Arrowtooth flounder during longline surveys and compositions are available since 1992 (Figure 7.10). A clear shift in size has occurred throughout the time series with increasing abundance of larger fish sampled until the mid-2000s, after which a shift to small fish occurs until about 2017. In recent years there are fewer fish in the survey which may have to do with the declines in the population and less of the stock in the slope environment where the survey primarily samples or due to hook competition with sablefish. Median length composition is 59 cm; however no sex-structure data are available for this survey.

International Pacific Halibut Commission Survey

The International Pacific Halibut Commission (IPHC) conducts a longline survey each year to assess Pacific halibut. This survey differs from the AFSC longline survey in gear configuration and sampling design, but also catches arrowtooth flounder. More information on this survey can be found in Soderlund et al. (2009). A major difference between the AFSC and the IPHC surveys is that the IPHC survey samples the shelf consistently from 1-500 meters, whereas the AFSC longline survey samples the slope and select gullies from 150 to 1000 meters. Because the majority of effort occurs on the shelf in shallower depths, the IPHC survey samples more suitable arrowtooth flounder habitat than the AFSC longline survey and is similar to the AFSC bottom trawl survey; however, lengths of arrowtooth flounder are not taken on the IPHC survey.

RPNs have been computed for each year of the IPHC survey and are presented from 1998 to 2021 for arrowtooth flounder (Figure 7.11). RPNs in the GOA have ranged from a low RPN in 2017 to a high in 2000 and also generally follow the trajectory of the AFSC bottom trawl survey since 2005 when the population started to decline. RPNs are generally higher in the CGOA as with the AFSC bottom trawl survey. RPNs increased in 2021 in all areas except the WGOA when compared to 2020. The 2021 GOA estimate is 44% above the 2019 estimate (2020 was not completely sampled) and is now 48% below the long-term average for the time series. Changes to the sampling protocol and coverage of the IPHC longline survey have recently occurred. As such, we do not recommend using this survey in the model as these changes will limit the survey utility moving forward.

Comparison of Length Data

We provide a comparison of length compositions across the multiple data sources that exist for GOA arrowtooth flounder (Figure 7.12). The median lengths suggest that the different surveys and fishery overlap with different aspects of the GOA arrowtooth flounder population. The AFSC longline survey has overall the larger individuals and the survey spatial extent covers more of the shelf/slope habitat, while the bottom trawl surveys have similar sized individuals and cover more of the shelf and nearshore habitat. The cohorts are more visible in the ADF&G survey than the bottom trawl survey. The fishery appears to be fairly steady over time but often has a large range in sizes which could reflect fishing behavior or observer sampling rather than the true distribution of the stock. Age data from the survey were available for all years and so the model does not use the length compositions at this time. However, the ADF&G and the AFSC longline survey length compositions could be a valuable source of information within the model in the future and we plan to investigate their utility in future assessments.

Analytical Approach

We use a previously developed climate-enhanced multi-species statistical catch-at-age modeling framework called CEATTLE (Climate-Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics, Holsman et al., 2016) that has been expanded for groundfish in the GOA using TMB (Rceattle, Adams et al., 2022, Kristensen et al., 2016) as the basis for this assessment model and alternative model explorations for GOA arrowtooth flounder. Developed in part from the underpinnings of multi-species statistical catch-at-age analysis (MSCAA, Jurado-Molina et al., 2005) and multi-species virtual population analysis (MSVPA; (Jurado-Molina et al., 2005; Magnusson, 1995), Rceattle can link single-species age-structured models (Table 7.11) through predation mortality conditioned on the temperature-dependent bioenergetic demand and diet-based prey-selectivity patterns of predators (Curti et al., 2013; Holsman et al., 2016; Kinzey and Punt, 2009). Predation mortality assumes a Holling Type II functional response and parameters are either pre-specified or estimated by fitting to survey and fishery data (Table 7.12). Rceattle can be run in single-species mode by "turning-off" time-varying predation mortality or in multi-species mode by "turning-on" time-varying predation mortality. Rceattle has been expanded to flexibly fit any number of species and model parameterizations. Please see the GitHub repository on Rceattle (https://github.com/grantdadams/Rceattle) for more details.

Transition from AD Model Builder

We provided a bridging assessment in November 2024 during an off-cycle year to transition from the bespoke model that used Automatic Differentiation Model Builder (ADMB) software (Fournier et al. 2012) to the current model that uses Rceattle (Appendix 7B). This model bridging exercise was accepted by the GOA Groundfish Plan Team and SSC in December 2024 and both advisory bodies recommended use of the Rceattle platform for the full assessment in 2025. In September 2025, we provided a review of extensive data improvements for 2025 that are detailed further in this assessment under the "Parameters Estimated Outside the Assessment Model" section. The GOA Groundfish Plan Team and the SSC accepted those data improvements and recommended the authors bring forward the base model with those data improvements included in November 2025. The full assessment was delayed one year due to the government shutdown. We start this assessment following the October 2025 accepted model.

Parameters Estimated Outside the Assessment Model

Rceattle uses the same inputs as the ADMB single-species assessment model (ADMB model, Shotwell et al., 2021) used to provide management advice in addition to diet and bioenergetics data (Adams et al., 2022) (Table 7.13). Catchability for the AFSC bottom trawl survey is assumed to be 1, and age-at-maturity, weight-at-age, age-length conversion matrix, and ageing error matrix are all estimated outside the model (see details below). All data and assumed uncertainties are consistent with the ADMB model. Diet and bioenergetics data were derived from the AFSC stomach sampling program from 1990 to 2015 (Adams et al., 2022, Holsman et al. 2023, Holsman & Aydin 2015). Time-series of bottom temperature derived from the Climate Forecast System Reanalysis for the Pacific cod assessment (Hulson et al., 2023) was used to parametrize consumption and diet composition.

Natural Mortality

Natural mortality (*M*) rates for Gulf of Alaska arrowtooth flounder were estimated using the methods of Wilderbuer and Turnock (2009). A higher natural mortality for males than females was used to fit the age and size composition data, which are about 70% females. A value of *M*=0.35 for males was chosen so that the survey selectivities for males and females both reached a maximum close to 1.0. A likelihood profile on male natural mortality resulted in a mean and mode of 0.354 with 95% confidence intervals of 0.32 to 0.38 (Turnock et al. 2002, Figure 10.14). Model runs examining the effect of different natural mortality values for male Arrowtooth flounder can be found in the Appendix of the 2000 SAFE (Turnock et al., 2000). Differential natural mortality by sex can be a factor that needs consideration in management of targeted fish stocks, however, since GOA arrowtooth flounder is currently exploited at low levels, this effect was not a concern for this stock (Wilderbuer and Turnock 2009).

A catch-curve analysis was conducted to provide sex-specific estimates of total mortality (*Z*) from AFSC bottom trawl survey specimen data from 1993 - 2023 (Figure 7.13). Numbers-at-age were tallied separately for males and females. To reduce the influence of selectivity and variable year-class strength at younger ages, the analysis was restricted to ages 6 and older. At older ages, bins with very low sample sizes (<5 fish) were excluded to avoid undue leverage. This analysis of specimen data suggests a total mortality of 0.22 for females and 0.28 for males which is in line with the previous estimates of natural mortality (Wilderbuer and Turnock, 2009) given the low exploitation rate of arrowtooth flounder. This also suggests that the natural mortalities estimated for arrowtooth flounder in the previous bridging model explorations (Appendix 7B) might be too high to be biologically plausible. Several caveats exist from a pooled catch-curve analysis, particularly that recruitment and selectivity are stable, but it can be a useful check on assumed values.

The research multispecies model presented in the ESP (Appendix 7A) suggests that the natural mortality is much higher for younger ages of arrowtooth over all years. Average *M* at age 1 from the multispecies model was equal to 0.335 for females (range 0.326 to 0.349) and 0.43 for males (range 0.417 to 0.451). Average *M* at age 2 was equal to 0.356 for females (range 0.343 to 0.374) and 0.458 for males (range 0.439 to 0.485). In a recent paper on the GOA multispecies model, Adams et al., (2022) estimated that on average approximately 27,000 to 37,000 t of arrowtooth were consumed annually by predators in the models explored and that of those species considered (Pacific halibut, arrowtooth, Pacific cod, walleye pollock), arrowtooth was the primary consumer. This amount of cannibalism can exceed the removals by the fishery in many years and could be explored further to understand the impact on natural mortality.

Growth

Growth was estimated from length and age data from AFSC GOA bottom trawl surveys from 1993 to 2023 and incorporated in the assessment using a length-age conversion matrix.

Length-at-Age

There are two length-age conversion matrices (one for females and one for males) that are generated from AFSC GOA bottom trawl survey population extrapolated age-length data from 1993 to 2023.

Length bins were defined in 2 cm increments spanning from 20 cm to 75 cm, with the uppermost bin treated as a plus group (≥75 cm). This is a change from the non-sequential length bin structure initiated at the start of this assessment in 2000 (Turnock et al., 2002). We determined that this new length bin structure adequately captures the distribution of length samples present in the fishery compositions, which are the only length compositions used in this model at this time. The previous length bin structure was initiated when fewer ages were available for this model and it relied more on the survey length compositions. Age bins were defined for ages 1–20, with an additional plus group for ages 21 and older. These are the same age bins that have been used since first initiated in 2015 (Spies et al., 2015).

For each sex, mean length-at-age and standard deviations were estimated from survey specimen data. The distribution of length at each age was assumed to follow a normal distribution with these estimated means and standard deviations. Conditional probabilities for each age–length cell were computed by integrating the normal distribution between successive bin boundaries. Specifically, the probability of observing length bin l given age *a* was calculated as:

$$P(L \in bin\, l \mid a) = \Phi(L_{l+1};\, \mu_a, \sigma_a) - \Phi(L_l;\, \mu_a, \sigma_a)$$

where Φ is the cumulative normal distribution function, L_l is the lower boundary of length bin l, L_{l+1} is the boundary of the next bin, μ_a is the mean length-at-age *a*, and σ_a is the standard deviation at age *a*. The first bin was defined from -∞ to the second bin boundary, and the final bin was defined from the last boundary to +∞ to form a proper probability distribution. Matrices were calculated separately for females and males to account for sex-specific growth differences (Figure 7.14a,b).

Weight at Age

Weight at age used in the model is based on a von Bertalanffy relationship determined from the stratified age collection on GOA bottom trawl surveys from 1993-2023. First, weight–length relationships were estimated separately for males and females by fitting the log–linear model

$$ln(W) = \alpha + \beta\, ln(L),$$

where W is whole body weight (kg) and L is fork length (cm). These regressions provided sex-specific scaling exponents (β) that capture allometric growth in weight relative to length (Figure 7.15).

Second, a von Bertalanffy growth function was fit to observed length-at-age for each sex from the survey specimen data used in the previous section,

$$L(a) = L_{\infty}\left(1 - e^{(-k(a - t0))}\right)$$

where *a* is age (years), *L*∞ is the asymptotic length, *k* is the growth coefficient, and *t0* is the theoretical age at zero length.

Predicted mean weight-at-age was then computed by combining the two models,

Ŵ(a) = exp(α) [L(a)]^β,

$$W_a = e^{\alpha} L_a^{\beta}$$

using the sex-specific von Bertalanffy parameters (*L*∞, *k*, *t0*) and the corresponding weight–length exponent (*β*). This two-step approach stabilizes estimation by constraining the weight-at-age function to the empirically observed weight–length relationship.

Final weight-at-age vectors were tabulated for ages 1–20, with an additional 21+ plus group. The plus group value was calculated as the weighted mean of predicted weights for all observed ages ≥21, using sample frequencies as weights. These vectors were used as model input in the assessment (Figure 7.16).

Ageing Error

An ageing error transition matrix was first implemented for GOA arrowtooth flounder in 2017 and used the estimated percent agreement among two age readers for age samples from 1991-2015. Ageing for arrowtooth flounder began in the early 1990s in the Bering Sea and the GOA ageing started several years later. The initial legacy matrix for GOA arrowtooth flounder includes data from the Bering Sea, possibly due to limited data for the GOA at the time this matrix was included in the model. This initial legacy matrix was computed using a model that incorporates a linear increase in the standard deviation of ageing error and assumed ageing error was normally distributed (Dorn et al., 2003, Methot, 2000). Percent agreement was predicted by the sum probability that both readers were correct, that both readers were off by one year in the same direction, and the probability that both age readers were off by two years in the same direction (Methot, 2000).

For 2025, we updated our ageing error matrices with new reader testing data up to 2021 and only using data from the GOA. Sample sizes of the raw paired age readings from the GOA bottom trawl survey are provided in Figure 7.17. There are four possible age fields for all ageing collections: read_age, test_age, update_age, and final_age. Read_age is the estimate made by the main reader for a given collection, and test_age is the estimate made by a second independent reader to assess precision and relative bias between readers. Final_age is the final resolved age that is passed along to end users and is usually the same as the read_age. The read_age can differ from the final_age for a number of reasons such as if the reader and tester resolved discrepancies to the tester age or a new third age, or if the reader re-examined the otolith and determined that their initial age was wrong (as sometimes happens during outlier evaluation). The update_age captures how discrepancies were resolved and whether outliers were re-examined (Beth Matta, *pers. comm.*).

We used the test_age and the final_age data and evaluated three approaches for constructing the ageing error matrix (AEM) used to account for misclassification of otolith ages: (1) an empirical matrix derived directly from paired test–final readings on recent collections, (2) a modeled matrix following the framework of Candy et al. (2012), and (3) the legacy matrix previously used in the assessment (Figure 7.18a,b). The empirical matrix is simple and transparent, directly reflecting observed discrepancies between independent test ages and final resolved ages. It shows relatively high agreement on the diagonal for younger ages, with error increasing at older ages. However, the empirical matrix can be noisy in sparsely sampled age classes, particularly in the plus group. The Candy-style modeled matrix smooths the empirical error patterns by fitting statistical models to the absolute and signed error distributions. This approach enforces logical constraints (e.g., no negative ages, capping at 21+) and provides more stable estimates at older ages, where paired samples are limited. It also allows for asymmetric error, consistent with a tendency toward under-ageing at advanced ages. Future efforts may use the AFSC “read_codes” in the Candy model which it was designed to use.

The old matrix exhibited lower diagonal probabilities at ages 2–10 compared to the new empirical and Candy matrices, implying a higher assumed rate of misclassification at young ages (Figure 7.19). In contrast, both the new empirical and Candy-modeled matrices indicated stronger reader agreement at younger ages, with diagonal probabilities generally above those of the old matrix. At intermediate and older ages, all matrices showed declining agreement probabilities with greater spread into adjacent bins, but the patterns differed. The new empirical matrix showed more variability and some asymmetry, consistent with observed under-ageing at older ages. Overall, the new empirical matrix best reflects current reader performance, showing improved agreement at young ages relative to the old matrix. The empirical matrix best represents the current observed ageing performance, while the Candy-style matrix provides a robust, smoothed alternative less affected by small sample sizes. For this assessment we recommend using the new empirical matrix as the base case, with the Candy-style matrix as a future sensitivity run to evaluate robustness. Both improve upon the old matrix by incorporating updated reader performance and contemporary data.

Maturity

Maturity-at-age was based on a maturity-at-length study by Zimmerman (1997) through 2013. Length at 50% maturity was estimated at 47 cm with a logistic slope of -0.3429 from Arrowtooth flounder sampled in hauls from in the September 1993 bottom trawl survey (Zimmerman 1997). Elsewhere in their range, length at 50% maturity was 36.8 cm for females and 28.0 cm for males from survey data in 1992 off Washington, with logistic slopes of -0.54 and -0.893 respectively (Rickey 1995). Arrowtooth flounder had length at 50% maturity of 44 cm for females and 29 cm for males off the coast of Oregon (Rickey 1995). Spawning fish were found in depths from 108m to 360m in March to August in the Gulf of Alaska (Hirshberger and Smith 1983) from analysis of trawl surveys from 1975 to 1981. Most observations of spawning fish have been in the northeastern Gulf, off Prince William Sound, off Cape St. Elias, and Icy Bay.

A study was conducted in 2008 that examined maturity-at-age that estimates age at maturity rather than length at maturity (Stark 2008). In this study, a sample of 301 fish was taken in February 2002 and a separate collection (226 fish) was taken in July 2003, both from the central GOA. Parameter estimates based on the February sample were used in the current study because Arrowtooth flounder spawn during winter months. The estimate of logistic 50% maturity was 7 years, the logistic slope (B) was 1.3817 and the intercept (A) was -9.6183. Fish matured at a slightly younger age in the 2008 study compared to the 1997 study. This maturity ogive (Stark 2008) has been used in the model since 2015. Age at 50% maturity is age 7 in females, and is 20% in age 6 fish.

Parameters Estimated Inside the Assessment Model

For arrowtooth flounder in the GOA, the single-species Rceattle spans 1977 to present and is parameterized similarly to the ADMB model (Adams et al., 2022; Shotwell et al., 2021). Parameters estimated inside the model include the number-at-age in the first year of the assessment, the number of recruits in subsequent years, the fishing mortality rates for each year, and survey/fishery selectivity. Similar to the ADMB model, separate fishery selectivities were estimated non-parametrically for each age, up to age-19, and the shape of the selectivity curve was constrained to be a smooth function. Survey selectivities were modeled using a two-parameter ascending logistic function. The selectivities by age were estimated separately for females and males. A differential age-invariant natural mortality is assumed or estimated for each sex and resulted in a predicted fraction female of about 0.70, which is close to the fraction female in the fishery and survey length and age data. Multinomial distribution weights were adjusted using the Francis method (Spies et al. 2017) and were left at the values in the 2021 assessment (Shotwell et al., 2021). Rceattle calculates McAllister and Ianelli (1997) weights allowing for easy sample size tuning and can directly estimate weights using the dirichlet-multinomial distribution. This can be explored in future assessments but was not attempted here due to the already large number of changes made to this assessment. The arrowtooth model assumed multinomial likelihoods for composition data and log-normal likelihoods for index and catch data (Table 7.14).

Despite similarities with the ADMB model, the Rceattle model also has the following differences:

- Rceattle assumes a single sex-combined input sample size, avoiding the mis-specification and allowing the sex ratio to be correctly estimated. Additionally, Rceattle uses the predicted and observed age composition for observed ages in the multinomial likelihood (accounting for ageing error; see 4th point below).
- The non-parametric fishery selectivity penalties in Rceattle are sex-invariant (Table 7.14), while in the ADMB model, these penalties are different for males and females.
- The log-normal likelihoods used by the Rceattle model include a log-normal bias correction and exclude an added constant of 0.0001 that was included in the ADMB model. Rceattle also utilizes the complete probability distribution rather than the simplified form used in the ADMB model.

- To account for ageing error, Rceattle multiplies the expected true age composition by the ageing error matrix to derive the expected observed age-composition.

Parameters estimated inside the model are described in Table 7.15.

Description of Alternative Models

The following are the alternative models to be evaluated in this assessment. These alternative models were approved by the Groundfish Plan Team and the Scientific and Statistical Committee (SSC) for use in the 2025 full assessment (September GOA Plan Team Minutes 2024, October SSC Minutes 2024).

- Model 25.0_old: single-species TMB based Rceattle model with data improvements that fixes sex-specific *M* (females = 0.2 and males = 0.35) and treats annual recruitment as random effects but uses data from last year that was presented in September 2025. This is effectively the base model with old data.
- Model 25.0: single-species TMB based Rceattle model with data improvements that fixes sex-specific *M* (females = 0.2 and males = 0.35) and treats annual recruitment as random effects and uses data up through the present. This is the base model with new data.
- Model 25.1: Model 25.0 but estimates sex-specific *M* instead of fixing *M*. This is the only alternative model to evaluate.

Since these models were presented to the September Plan Team in 2025, we completed the formal model review process and proceeded with the full assessment similar to what we would have done in November 2025 if the federal government was not shutdown. Even though this assessment is being presented in September, this is considered the final assessment; therefore, we did not make any additional changes to what was presented last year except to include new data since September 2025.

We also have two research models that we reference for additional information while deliberating over which of these two candidate models to recommend. These are not sensitivity models used to address model evaluation choices (e.g., model specification, data weighting). Rather these are models that are consistently updated at the schedule of this stock assessment to provide context on ecosystem or environmental influences on the stock and may be used to support model choices, decisions in the risk table, or future research plans. For these reasons the research models are reported in the ecosystem and socioeconomic profile (ESP, Appendix 7A). The first research model is a multi-species TMB based Rceattle model that estimates total mortality for pollock, Pacific cod, Pacific halibut, and arrowtooth flounder, fit to data from five fisheries and seven survey between 1977 and last full assessment for the stocks in the model (Adams et al., 2022). 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). The second research model is an external dynamic structural equation model (DSEM) used to predict recruitment estimates from the operational stock assessment model following the methods in Bigman et al., *in review*. Both research models provide statistical evidence for emphasizing a suite of indicators reported in the ESP. These are categorized as predictive indicators and used to support data or modeling choices as well as decisions resulting from the risk table assessment. Additional details on both research models are included in the ESP (Appendix 7A).

Age Structured Model Results

Model Evaluation

An overview of the likelihood components and parameter estimates for the three models are provided in Table 7.16. We also provide comparisons plots of the time series, residual diagnostics, jitter analysis, self-tests, and likelihood profiles for Models 25.0 and 25.1 and do not include Model 25.0_old as it was very similar to Model 25.0 (Figures 7.20-7.26). Convergence was confirmed for all models with an invertible Hessian and a maximum gradient component of 6.91×10^{-5}, 5.62×10^{-5}, and 1.70×10^{-5} for Model 25.0 old, Model 25.0, and Model 25.1, respectively.

The overall trends in total biomass, spawning stock biomass (SSB), and recruitment are qualitatively similar between the models, but the absolute population scale and magnitude differ substantially (Figure 7.20a-c). Regarding the parameter estimates, natural mortality (*M*) differs between Model 25.0 and 25.1 by 65% for females and 16% for males. Mean recruitment scale increases more than 3-fold in 25.1 to balance these higher natural mortality rates. This in turn causes higher population turnover rate in Model 25.1 and scales the total biomass up by 38% in the projected 2027 biomass. Conversely the 2027 projected spawning biomass decreases by 19% in Model 25.1 because fewer fish now survive to the older spawning ages. Estimates of unfished SSB in Model 25.1 also decrease because of this compressed age structure in the population. The recruitment variability (σ_r) is very consistent between the two models as the random effects estimation remains stable across the different population scales.

Both models fit the catch time series almost perfectly (Figure 7.20e and the NLL is very similar Table 7.16); however, Model 25.1 has a marginally better fit to the bottom trawl survey index because the larger population scale is able to track the survey trends with more flexibility (Figure 7.20f, NLL lower in Table 7.16). The estimated selectivity curves show some structural confounding between *M* and selectivity (Figure 7.20g). In Model 25.0, the fishery and survey selectivities are similar between males and females with the fisheries selectivity estimating a dome-shape for both sexes (peak at age 9 for females and age 8 for males). This dome-shape suggests that the larger, older fish are present in the population but the fishery is just not capturing them. This may be due to the spatial extent of the fishery. In Model 25.1, the female fishery selectivity curve is shifted to become asymptotic due to the higher estimated natural mortality (*M*=0.33). Basically these females die instead of assuming the gear did not see the older fish. This relieves some of the tension in the disagreement between the data sources and Model 25.1 has a much lower NLL for the fishery length compositions (Table 7.16).

We provide specific details of residuals, jitter analysis, self-tests, and likelihood profiles in sections below. Generally, residual diagnostics indicate remaining lack of fit in both models (Figure 7.21a-e). Model 25.1 exhibits stronger blocking in the female bottom-trawl age-composition residuals, while both models show persistent striped or blocked patterns in the fishery length-composition residuals. These patterns suggest that the remaining misfit is likely structural rather than simply a consequence of inappropriate data weighting and may reflect the assumed selectivity form, spatial or temporal changes in fishery sampling or selectivity, or limitations in the fishery length-composition data. Composition Standard Deviation of Normalized Residuals (SDNR) values below 1 indicate that residual variability is somewhat lower than expected under the current input weights rather than evidence of extra-multinomial overdispersion (Figure 7.21d-e). Jitter analysis confirmed that Model 25.0 possesses highly stable global convergence with all perturbed runs successfully returning to a single global minimum, whereas Model 25.1 exhibits structural instability characterized by separate biomass trajectories of different scales and multiple local likelihood minima (Figure 7.22a-b). Simulation self-tests demonstrated that Model 25.0 achieved highly precise and unbiased parameter recovery, while Model 25.1 shows wider confidence intervals and mild estimation bias due to strong parameter trade-offs between estimated selectivity and natural mortality (Figure 7.23a-b). Likelihood profiling revealed a severe data conflict in Model 25.0 where fishery length and survey age datasets pull natural mortality in opposite directions, a tension that is statistically resolved in Model 25.1 as the datasets reach a clear consensus near the estimated maximum likelihood values (Figures 7.24 and 7.25).

All diagnostics taken together, Model 25.0 provides the more stable, biologically plausible population trajectories. Estimating sex-specific natural mortality in Model 25.1 results in substantial changes in both survey and fishery selectivity, along with markedly higher estimated natural mortality, mean recruitment (Figure 7.20c), and total biomass, and lower spawning biomass relative to Model 25.0. The magnitude of these changes indicates strong confounding among natural mortality, selectivity, recruitment, and population scale and suggests that the data do not independently identify these processes well under the current model structure. The estimates of *M* are also highly contradictory of the catch curve analysis and unrealistically high for adult flatfish. Additionally, if adult M were actually near the estimated values, we would not observe as many old fish as we currently do in our standard survey age samples. We, therefore, select Model 25.0 with fixed sex-specific natural mortality as the author preferred model because it provides more stable population trajectories and avoids the extreme shifts in recruitment, selectivity, and population scale produced when natural mortality is freely estimated. However, the strong response of Model 25.1 to increase the estimate of *M* indicates unresolved structural uncertainty associated with natural mortality and selectivity and that some segment of the population experiences higher mortality than the fixed estimates. There is evidence from the multispecies model that young arrowtooth (ages 1-2) experience high rates of cannibalism and estimates of age-1 natural mortality suggest natural morality rates averaging 0.335 to 0.458 (Appendix A). Future work should therefore focus on the following main areas: 1) evaluating alternative survey and fishery selectivity structures, 2) re-evaluating the fishery length composition data and composition weights, 3) incorporating additional data sources that sample different portions of the population (such as the ADF&G bottom-trawl and longline surveys), 4) potentially estimating catchability to evaluate improvement in fit, and 5) estimating age-varying natural mortality in Rceattle by fixing or constraining *M* to empirical values from the catch-curve analysis for adults (0.22 for females and 0.28 for males) and estimating predation mortality for younger age classes (such as ages 1-5). Alternative composition likelihoods, including the Dirichlet-multinomial, should also be evaluated as part of this work.

Time Series Results

Plots of total biomass, spawning biomass, recruitment, fishing mortality rate, fishery catch, bottom trawl index, and selectivity are included to show the comparison across models (Figure 7.20a-g). The shape of the time series for all models was similar but the magnitude differed substantially between the models that fixed *M* versus estimating *M*. Total biomass from the author preferred Model 25.0 has a strong expansion that peaks in 2005 followed by a long term drop since late 2000s that reaches a historic low in 2018. Female spawning stock biomass follows a similar trajectory with a lag peaking in 2008, dropping to a historic low in 2021 and rebuilding since that time. Model estimates of total and female spawning biomass with uncertainty for the author preferred model are presented in Table 7.17.

Age 1 recruitment features two very large events in 1999 and 2000 that are the most productive period of this stock and resulted in the female spawning biomass peak of 2008. A prolonged weak recruitment period followed these large events reaching a low point in 2010 that corresponds to the decline of the spawning stock that occurred in the 2010s. A moderate recovery has occurred with the potential 2016-2018 year classes. (Figure 7.20c and Table 7.18). Recent estimates of recruitment are likely not reliable, as the presence of older fish in the time series is needed to lend certainty to recruitment estimates. However, the size of the 2016-2018 year classes appears to be supported by the most recent age composition data with the 2017 year class being the strongest followed by 2018 (Figures 7.21b,c) and supporting the slow increase of the female spawning stock biomass.

Evaluation of Models and Associated Uncertainty

Following the recent methodological recommendations of Trijoulet et al. (2023), Stewart and Monnahan (2025), and Kapur et al. (2024), goodness-of-fit to composition data was evaluated using One-Step-Ahead (OSA) residuals alongside aggregate fits and Pearson residuals via the afscOSA package within Rceattle. Pearson residuals for multinomial composition data are inherently correlated across age/length bins and violate standard normality assumptions, often leading to false diagnoses of model misspecification. We present the Pearson and OSA residuals for both Model 25.0 and 25.1 (Table 7.19, Figure 7.21a-e).

In Model 25.0, Pearson residuals display massive residual bubbles (z-scores exceeding ±160 in early fishery lengths and ±11 in survey ages). In contrast, OSA residuals de-correlate the data and reveal that residuals are well-behaved with magnitudes bounded within normal statistical bounds (-3 to +3). This effectively eliminates the false misspecification flags of the Pearson residuals. The Standard Deviation of Normalized Residuals (SDNR) for composition data ranges from 0.75 to 0.87 (below the null expectation of 1.0), indicating that the data are being slightly overweighted within the likelihood (overdispersion) under input sample sizes. This implies that input sample weights could be tuned or parameterized via Dirichlet-Multinomial likelihoods to help internally adjust composition weighting and achieve variance balance. Model 25.0 and Model 25.1 accurately reproduce the observed ~70% female dominance in the survey and fishery catches. In Model 25.0, fishery selectivity is estimated to be dome-shaped for both sexes, peaking at age 9 for females and age 8 for males. In Model 25.1, higher estimated female natural mortality ($M = 0.33$) shifts female fishery selectivity to become more asymptotic, resolving the trade-off between mortality and gear selectivity. The survey biomass index does show a high SDNR for both models and wider residual bounds. This is driven by the large 2003 biomass estimate and likely represents common sampling issues in bottom trawl surveys (e.g., sampling a few large tows, shifts in catchability).

Sensitivity to Model Specification

We did not run any formal sensitivity analyses to the model specification but did try a run using the integrated Dirichlet-Multinomial data weighting and it did not substantially change the poor fits to some of the length composition data. This further supports the investigation into the selectivity curve.

Convergence Status and Criteria

For Model 25.0, convergence was confirmed for all models as mentioned above with an invertible Hessian. Newton steps using the inverse Hessian confirmed that the model stabilized at a true quadratic minimum. A 100-run jitter analysis (perturbing parameter starting values by ±10%) demonstrated exceptional convergence stability for Model 25.0 (Figure 7.22a) where all jittered runs returned to the global minimum and all NLL values within approximately 10^{-8} or less of the best solution (Figure 7.22). There were zero instances of alternate local minima or parameters hitting estimation bounds. While the majority of the runs clustered around the global minimum for Model 25.1 (Figure 7.22b), there was a distinct, separate bar on the far right of the histogram representing jitter runs that settled into completely different sub-optimal local minima that was several likelihood units higher than the global minimum. This corresponded to a distinct lower biomass trajectory at a completely different population scale and suggests a flat likelihood surface with multiple local minima.

Self-tests evaluate parameter estimability by simulating data from the model's maximum likelihood estimates and evaluating whether the model can accurately recover those "true" parameters. Model 25.0 achieved highly precise and unbiased parameter recovery (Figure 7.23a). Because natural mortality is fixed, the model has fewer degrees of freedom, allowing for extremely robust estimation of annual recruitment deviates and selectivity parameters. Model 25.1 showed wider confidence bounds and minor bias in parameter recovery during self-tests (Figure 7.23b). This highlights the strong parameter confounding between natural mortality and selectivity. The self-test confirms that minor random perturbations in composition data can cause Model 25.1 to slide along the selectivity-mortality trade-off surface, making these parameters difficult to independently identify with absolute certainty.

Likelihood Profiles on Key Parameters

Likelihood profiling was conducted for recruitment variability (σ_r) and natural mortality (M) to verify that the parameters are mathematically estimable and to identify if different data sources are in conflict. For both Model 25.0 and 25.1, profiling σ_r across 0.2 to 1.4 (Figure 7.24a-b) demonstrated a well-defined, smooth parabolic minimum at $\sigma_r \approx 0.28$–0.30 when evaluated under penalized maximum likelihood, and an estimate of $\sigma_r = 0.477$ when recruitment deviates are treated as random effects. This confirms that recruitment variance is fully estimable within Rceattle, resolving a known limitation in the legacy ADMB model where σ_r had to be fixed at 0.707.

The profile on *M* for Model 25.0 revealed a direct data conflict. The bottom trawl survey age composition and survey biomass index lean to higher natural mortality rates while the fishery length compositions strongly favor a low natural mortality rate (Figure 7.25a). In contrast, the estimate of *M* for Model 25.1is at the point where the data sources are in closest statistical agreement ($M_{female} = 0.33$ and $M_{male} = 0.41$) and so the individual component profiles are flatter and more consistent with one another than in Model 25.0 (Figure 7.25b).

Retrospective Analysis (within model)

Retrospective analysis is the examination of the consistency among successive estimates of the same parameters obtained as new data are added to a model. Retrospective analysis has been applied most commonly to age-structured assessments and can arise for many reasons, ranging from bias in the data (e.g., catch misreporting, non-random sampling) to different types of model misspecification (e.g., incorrect values of natural mortality, temporal trends in values set to be invariant). For this assessment, a within-model retrospective analysis was conducted for the last 10 years of the time-series by dropping all data one year at a time. This was conducted on all models but we only show results for the author preferred Model 25.0 for total biomass, spawning stock biomass, and recruitment.

One common measure of the retrospective bias is Mohn's revised ρ ("rho") which indicates the size and direction of the bias (Hanselman et al. 2013). The revised Mohn's ρ statistics were small overall at 0.036, 0.050, and -0.008 for total biomass, spawning biomass, and recruitment, respectively and indicating that the estimates increase or decrease relative to the terminal year estimates only slightly as data are removed from the assessment (Figure 7.26a-c). Retrospective patterns across all models are mild and well within established guidelines (where $|\rho| < 0.20$ indicates acceptable retrospective performance for long-lived species, Hurtado-Ferro et al., 2015).

Although there are no guidelines regarding how large ρ (absolute value) should be before an assessment is declared to exhibit an important retrospective bias, the ρ's for the two models are very small compared with many other Alaska groundfish species. Examining retrospective trends can show potential biases in the model, but may not identify their source. Other times a retrospective trend is merely a matter of the model having too much inertia in the age-structure and other historic data to respond to the most recent data. This retrospective pattern is considered mild, though the cause may be the "one-way" nature of the survey biomass trend during the 10-year retrospective window. It is difficult to isolate the cause of this pattern but several possibilities exist. For example, hypotheses could include environmental changes in catchability, time-varying natural mortality, or changes in selectivity of the fishery or survey.

Historical Retrospectives (between models)

We did not perform a historical retrospective analysis for this assessment as we have already provided this information in the bridging exercise when we changed the platform from ADMB to Rceattle. Please see Appendix 7B for more details. The current assessment model is qualitatively similar to all models used for management advice from 2019 onwards. Some changes have occurred in the historical estimates due to removal of non-standard surveys and composition data based on low sample size.

Projections and Harvest Recommendations

Specified Catch Estimation

In response to Plan Team recommendations, we established a consistent methodology for estimating current-year and future year catches in order to provide more accurate two-year projections of ABC and OFL to management. In the past, two standard approaches in flatfish models have been employed; assume the full TAC will be taken, or use a certain date prior to publication of assessments as a final estimate of catch for that year. Both methods have disadvantages. If the author assumes the full TAC is taken every year, but it rarely is, the ABC will consistently be underestimated. Conversely, if the author assumes that the catch taken by the around a month before the assessment report is the final catch, and substantial catch is taken thereafter, ABC will consistently be overestimated.

Therefore, in this GOA arrowtooth flounder assessment, for current year catch, we use an expansion factor to the catch in August by the 5-year average of catch taken between August 22 and December 31 in the last five complete catch years (e.g. 2021-2025) for the current year. The 2026 catch through August, 2022 was 12,622 t. The total catch in 2026 was estimated to be 16,835 t based on the proportion caught through this date for the past 5 years (75%). The estimates of total catch in 2027 and 2028 were based on the percentage of catch to ABC or yield ratio in the most recent five complete years. The current yield ratio is 0.10 and results in an estimated catch of 12,409 t for both 2027 and 2028.

Amendment 56 Reference Points

Amendment 56 to the GOA and BSAI Groundfish Fishery Management Plans (FMPs) define ABC and OFL for the groundfish fisheries, where the fishing mortality rate is denoted *F,* stock biomass (or spawning stock biomass, as appropriate) is *B*, and the *F* and *B* levels corresponding to MSY (or proxies).

We use the projection from the standard projection model used for AFSC assessments (using R package spmR, https://github.com/afsc-assessments/spmR) to calculate the Amendment 56 reference points. These values were also bridged to the output from the projection within Rceattle and differed by less than 0.2% in all cases. We plan to explore further use of the Rceattle projection model for future assessments. In the author recommended model, the projected total biomass estimate for 2027 from the stock assessment projection model is 1,437,490 t and the projected female spawning biomass estimate is at 874,501 t. The reference fishing mortality rate for arrowtooth flounder is determined by the amount of reliable population information available. Equilibrium female spawning biomass is calculated by applying the female spawning biomass per recruit resulting from a constant $F_{40\%}$ harvest to an estimate of average equilibrium recruitment. Year classes spawned in 1977-2025 are used to calculate the average equilibrium recruitment. This results in an estimate of $B_{40\%}$ = 429,548 t for 2027. Projected 2027 female spawning biomass is compared to $B_{40\%}$ to determine the Tier level. The stock assessment model estimates the 2027 level of female spawning biomass at 874,501 t. Since reliable estimates of *B*, $B_{40\%}$, $F_{40\%}$, and $F_{35\%}$ exist and $B>B_{40\%}$, arrowtooth flounder reference fishing mortality is defined in Tier 3a. For 2027 the recommended $F_{ABC} = F_{40\%} = 0.0994$ and $F_{OFL}= F_{35\%} = 0.1179$ (fully-selected *F* values).

Specification of OFL and Maximum Permissible ABC

Acceptable biological catch is estimated for 2027 by applying the $F_{40\%}$ fishing mortality rate and age-specific fishery selectivities to the projected 2027 estimate of age-specific total biomass. This results in a 2027 *ABC* of 134,083 t. There were no retrospective patterns or risk table concerns to suggest that altering the *ABC* from this value is warranted. The overfishing level is estimated for 2027 by applying the $F_{35\%}$ fishing mortality rate and age-specific fishery selectivities to the projected 2027 estimate of age-specific total biomass. This results in a 2027 *OFL* of 157,261 t.

Standard Harvest Scenarios, Projection Methodology, and Projection Results

A standard set of projections is required for each stock managed under Tiers 1, 2, or 3 of Amendment 56. This set of projections encompasses seven harvest scenarios designed to satisfy the requirements of Amendment 56, the National Environmental Protection Act, and the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA).

For each scenario, the projections begin with the vector of current year (2026) numbers-at-age estimated in the assessment. This vector is then projected forward to the beginning of the following year (current year +1) using the schedules of natural mortality and selectivity described in the assessment and the best available estimate of total (year-end) catch for the current year. In each subsequent year, the fishing mortality rate is prescribed on the basis of the spawning biomass in that year and the respective harvest scenario. In each year, recruitment is drawn from an inverse Gaussian distribution whose parameters consist of maximum likelihood estimates determined from recruitments estimated in the assessment. Spawning biomass is computed in each year based on the time of peak spawning and the maturity and weight schedules described in the assessment. Total catch is assumed to equal the catch associated with the respective harvest scenario in all years. This projection scheme is run 1,000 times for each scenario to obtain distributions of possible future stock sizes, fishing mortality rates, and catches. We use the spmR package (https://github.com/afsc-assessments/spmR) to calculate these standard seven scenarios.

Five of the seven standard scenarios are designed to provide a range of harvest alternatives that are likely to bracket the final TACs for the next 2 fishing years and are as follows ("max F_{ABC}" refers to the maximum permissible value of F_{ABC} under Amendments 56, assessment yr = year the assessment is conducted for the following year's fishery).

> *Scenario 1*: In all future years, F is set equal to *max* F_{ABC}. (Rationale: Historically, TAC has been constrained by ABC, so this scenario provides a likely upper limit on future TACs.)
>
> *Scenario 2*: In the event that catch is likely to be less than the recommended ABC in either of the first two projection years, *Scenario 2* must be conducted, using the best estimates of catch in those two years (otherwise, *Scenario 2* can be omitted if the author's recommended ABCs for the next two years are equal to the maximum permissible ABCs). In all future years after the first two projection years, F is set equal to a constant fraction ("author's F") of max F_{ABC}, where this fraction is equal to the ratio of the F_{ABC} value for *assessment yr+1* recommended in the assessment, to the maxF_{ABC} for *assessment yr+1*, and catches for *assessment yr+1 and yr+2* are estimated at their most likely values given the assessment *yr+1 and yr+2* recommended ABCs under this scenario. (Rationale: When F_{ABC} is set at a value below max F_{ABC}, it is often set at the value recommended in the stock assessment; also, catch tends not to equal ABC exactly.)
>
> *Scenario 3*: In all future years, F is set equal to the *assessment yr-5* to *assessment yr-1* average F. (Rationale: For some stocks, TAC (and catch) can be well below ABC, and recent average F may provide a better indicator of future catches than those from F_{TAC} or F_{ABC}.)
>
> *Scenario 4 (optional)*: In all future years, the upper bound on F_{ABC} is set at a selected fraction of F_{ABC}. (Rationale: This scenario provides a likely lower bound on F_{ABC} that still allows future harvest rates to be adjusted downward when stocks fall below reference levels.). This scenario is optional and is up to the author's discretion. If *Scenario 4* is presented, state the selected fraction of F_{ABC} used in the projection.
>
> *Scenario 5*: In all future years, F is set equal to zero. (Rationale: In extreme cases, TAC may be set at a level close to zero.)

Two other scenarios are needed to satisfy the MSFCMA's requirement to determine whether a stock is currently in an overfished condition or is approaching an overfished condition. These two scenarios are as follow (for Tier 3 stocks, the MSY level is defined as $B_{35\%}$):

Scenario 6: In all future years, F is set equal to F_{OFL}. (Rationale: This scenario determines whether a stock is overfished. If the stock is 1) above its MSY level in *assessment yr+1* or 2) above 1/2 of its MSY level in *assessment yr+1* and expected to be above its MSY level in *assessment yr+10* under this scenario, then the stock is not overfished.)

Scenario 7: In *assessment yr+1 and yr+2*, F is set equal to max F_{ABC}, and in all subsequent years, F is set equal to F_{OFL}. (Rationale: This scenario determines whether a stock is approaching an overfished condition. If the stock is 1) above its MSY level in *assessment yr+2* or 2) above 1/2 of its MSY level in *assessment yr+1* and expected to be above its MSY level in *assessment yr+12* under this scenario, then the stock is not approaching an overfished condition.).

Simulation results for the seven projection scenarios indicate that arrowtooth flounder are not currently overfished and the stock is not considered to be approaching an overfished condition (Table 7.20). The stock projection at the average exploitation rate for the past 5 years (Figure 7.20b) indicates that the stock will remain above $B_{40\%}$ if fished at this rate for the next 12 years. A phase-plane diagram showing the time-series of female spawning biomass estimates relative to the harvest control rule (Figure 7.27) shows that the female spawning biomass is above $B_{40\%}$ and that the stock is lightly exploited relative to reference points, and that this trend is expected to continue through at least 2028. The ABC and TAC values that have been used to manage the combined stock since 1990 are presented in Table 7.1.

Risk Table and ABC Recommendation

The following is a synthesis and interpretation of the most recent ecosystem and socioeconomic information available for GOA arrowtooth flounder from the ecosystem and socioeconomic profile (ESP, Shotwell et al., 2026, Appendix A) and the Gulf of Alaska Ecosystem Status Report (Ferriss, 2026). This information supports the risk table scores and is organized below by the proposed risk table categories. We include information related to recruitment from 2024 - 2026 (e.g., larvae, young-of-the-year or YOY, and early juvenile) in the population dynamics considerations section and information on current conditions impacting late stage juveniles or adults in the ecosystem considerations section. Where applicable, we also include information on fishery performance indicators that are provided in the ESP.

We identified four predictive ecosystem indicators that quantitatively predict GOA arrowtooth flounder recruitment using an external dynamic structural equation model (DSEM) following Bigman et al., *in review* for indicator selection and importance (see Appendix A for more details). These indicators are emphasized in BOLD below.

Category Summary:

Assessment-related considerations	*Population dynamics considerations*	*Environmental/ ecosystem considerations*	*Fishery-informed stock considerations*
Level 1: Normal	**Level 1:** Normal	**Level 1:** Normal	**Level 1:** Normal

The author preferred assessment model has some unresolved structural uncertainty but it produces stable population trajectories. Of the 2024-2026 age-0 year classes represented in the model, 2025 was potentially a low survival year for age-0 arrowtooth flounder (due to environmental and prey conditions). The adult population experienced approximately average environmental conditions with moderate prey resources in 2026 (limited reporting). El Niño conditions in 2027 are not expected to impact adult survival at the population level, but distribution shifts may occur. There are no concerns regarding fishery-informed considerations.

Assessment Considerations:

The GOA Arrowtooth flounder assessment is based on a time series of all standard NMFS groundfish surveys dating back to 1993. Ages from NMFS surveys are available for all of those years. The model evaluation between fixed and estimated M suggests there is unresolved structural uncertainty associated with *M* and selectivity and that future work should include evaluating different selectivity curves and estimating *M* for younger ages. Indeed, indicators from the ESP (Appendix A) on M for age-1 suggest that natural mortality varies through time and is substantially higher for these ages, potentially due to the high rates of cannibalism for this stock. That said, the author preferred Model 25.0 exhibits good convergence, reasonable OSA residuals, excellent convergence stability from the jitter runs, and achieved high precision and unbiased parameter recovery in the self-tests. The retrospective pattern for the author preferred model is well within acceptable retrospective performance with a Mohn's ρ for female spawning biomass calculated at 0.050, indicating that there is little effect due to retrospective bias. We, therefore, rate assessment considerations at a Level 1, normal.

Population Dynamics Considerations:

In 2024, age-0 arrowtooth flounder experienced environmental conditions conducive to higher survival in the western GOA due to stronger eddies (enhancing cross-shelf and along-shelf transport to nursery habitat in the western GOA, Cheng 2025, Appendix A) and average to warmer **sea surface temperatures** (Callahan 2025; Appendix A) and slightly increased **biomass consumed** (Adams 2025; Appendix A).

In 2025, age-0 **arrowtooth flounder larvae** in Shelikof Strait were observed in near-record low spring (Rogers et al. 2026, in Ferriss 2026 & Appendix A). Stronger eddies in the eastern GOA (Sitka; Cheng 2026; in Ferriss 2026 & Appendix A) is linked to transport away from preferred nursery habitat. Presettlement juvenile ATF may have experienced temperatures in the upper end of their 5°C - 9.5°C range (Moss et al., 2016) in the pelagic shelf waters in 2025, but post-settlement juvenile ATF probably did not experience bottom temperatures beyond that range. Reduced spring copepod availability (Hopcroft et al. 2026 and Kimmel et al. 2026; in Ferriss 2026 & Appendix A) may also have contributed to this lower survival. Numerous lower trophic level indicators suggested lower productivity in the GOA winter and spring of 2025 (Ferriss 2026)

In 2026, age-0 arrowtooth flounder experienced average environmental conditions in the GOA (PEEC 2026), although not all environmental data have been synthesized to-date. Prey for larval ATF included elevated spring 2026 euphausiid biomass but below average biomass of copepods in the northern GOA (Seward Line) (Hopcroft 2026; in PEEC 2026).

Ecosystem Considerations:

Distribution:
Area occupied of the GOA bottom trawl survey model-based estimates for arrowtooth flounder expanded in 2025 and the center of gravity moved to the southwest (Oyafuso 2025; Appendix A), towards/along the Alaskan peninsula and potentially to deeper waters (as observed in Yang et al. 2019). 2025 GOA ocean temperatures were largely above average throughout the year, potentially indicating a similar distribution in 2027 if the GOA warms in response to El Niño.

Environmental Processes

Adult arrowtooth flounder likely experienced approximately average temperatures in the GOA at depth in the winter/spring of 2026 (Levine et al., 2026, Callahan et al., 2026, and Danielson et al., 2026; in PEEC 2026). The arrowtooth flounder captured by the bottom trawl survey experienced warmer waters at depth in 2025 (average 6.2°C), but this does not exceed any known thermal limits (Ferriss et al., 2026; in Ferriss 2026). Winter eddy were of moderate strength across the GOA in 2026 (Cheng, 2026; in PEEC 2026).

The upcoming El Niño conditions in 2027 may bring warm surface waters that potentially reach deeper waters along the shelf, and have the potential to disrupt zooplankton and forage fish populations. These changes in environmental and prey resources are not considered a threat to the adult arrowtooth flounder population, which can move to deeper depths for thermal refuge and feed on a wide range of prey (Lemagie et al. 2026; in PEEC 2026). El Niño impacts may be observed in changes to the adult distribution.

Prey:

The summer body condition of adult arrowtooth flounder sampled by the bottom trawl survey continued to be average in 2025, similar to 2021 and 2023, indicating adequate quality and quantity of prey resources (Rohan 2025; Appendix A), although geographical differences were observed. Arrowtooth flounder had negative fish condition in all NMFS areas observed except Chirikof (620) and Kodiak (630) (Prohaska and Rohan, 2026; in Ferriss 2026). Juvenile body condition increased slightly to near average in 2025 from below average in 2021 and 2023 (Rohan 2025; Appendix A), suggesting improving prey resources for juveniles.

Adult prey resources are considered mixed but adequate in aggregate across prey groups. Relative to the past few years, SE Alaska Sitka and Craig herring populations remained elevated, capelin populations are moderate, prickleback and sandfish populations remain reduced, and eulachon populations show mixed trends (Whelan et al. 2026, Siple et al., 2026, Hebert et al., 2026, Pochardt et al. 2026; in Ferriss 2026 and Smith et al., 2026, Whelan et al., 2026, Morella 2026; in PEEC 2026). Groundfish populations (as prey for arrowtooth flounder) have mixed trends but in aggregate the groundfish biomass remains relatively stable (Whitehouse et al. 2026; in Ferriss 2026).

Competitors and Predators:

Competition is considered low but potentially increasing due to the status of other apex predators, including Pacific cod, Pacific halibut, and sablefish in the GOA. These three stocks remain below their long-term population mean, although cod and halibut increased in the survey biomass from 2023 - 2025 (Whitehouse and Gaichas, 2026; in Ferriss 2026).

Primary predators in the GOA remain relatively low. Pacific halibut and Pacific cod populations have increased from 2023 - 2025 but remain below their long-term mean. Steller sea lion population trends remain relatively stable in the western and eastern GOA as last measured in 2024, although western populations remain below their population mean (Sweeney and Gelatt 2026; in Ferriss 2026). Skates remain relatively stable through most of their population range in the GOA, with the possible exception of western GOA (Cronin-Fine et al., 2026). Little is known about population trends of sharks.

Fishery-informed Stock Considerations:

The stock is underutilized with average percent ABC utilization at 12%. There is no concern regarding the ability of the fishery to catch arrowtooth flounder. At the current time, fishery indicators from the ESP are not showing a contrasting pattern from the stock biomass trend, unusual spatial pattern of fishing, changes in the percent of TAC taken, or changes in the duration of fishery openings.

Spatial Apportionment: Biologically-informed Recommended Distributions (BRDs)

Arrowtooth Flounder is managed as a single stock in the GOA. However, the ABC is apportioned by management area based on the fraction of the survey biomass in each area. The western region (WGOA) is NMFS reporting area 610 (Shumagin), central region (CGOA) is 620 and 630 (Chirikof and Kodiak), and west Yakutat and east Yakutat / southeast Alaska (SE) result from the combined NMFS areas 640 and 650 redistributed such that the west Yakutat area is between 147°W and 140°W and the east Yakutat/SE is the portion east of 140°W. The fraction of the biomass in the four areas was determined by applying a time series of survey biomass estimates and their coefficients of variation, CV's, to a random effects model. The CGOA has shown a decline in biomass since 2003 with some recovery since 2019, while the other regions have remained relatively constant, with some decline after 2015 in the eastern area and after 2021 in the western area but some recovery in the most recent surveys (Figure 7.3).

The following table shows recommended area apportionments based on the proportion of survey biomass projected for each area using the survey averaging random effects model developed by the survey averaging working group. This year's area apportionment uses the 2025 AFSC GOA bottom trawl survey estimates. We provided the recommended area apportionment for the last full assessment and last assessment's area apportionment for comparison (Shotwell et al., 2024).

	Western	Central	West Yakutat	East Yakutat/SE	Total
2021 Area Apportionment	28.1%	57.1%	5.6%	9.2%	100%
2026 ABC (t)	33,716	68,511	6,719	11,039	119,985
2027 ABC (t)	33,716	68,511	6,719	11,039	119,985
2026 Area Apportionment	19.1%	59.9%	7.23%	13.80%	100%
2027 ABC (t)	25,572	80,318	9,692	18,501	134,083
2028 ABC (t)	25,537	80,20	9,679	18,476	133,901

Status Determination

In addition to the seven standard harvest scenarios, Amendments 48/48 to the BSAI and GOA Groundfish Fishery Management Plans require projections of the likely OFL two years into the future. While Scenario 6 gives the best estimate of OFL for 2027, it does not provide the best estimate of OFL for 2028, because the mean 2027 catch under Scenario 6 is predicated on the 2027 catch being equal to the 2027 OFL, whereas the actual 2027 catch will likely be less than the 2027 OFL. The executive summary contains the appropriate one- and two-year ahead projections for both ABC and OFL.

Under the MSFCMA, the Secretary of Commerce is required to report on the status of each U.S. fishery with respect to overfishing. This report involves the answers to three questions: 1) Is the stock being subjected to overfishing? 2) Is the stock currently overfished? 3) Is the stock approaching an overfished condition?

Is the stock being subjected to overfishing? The official catch estimate for the most recent complete year (2025) is 13,380 t. This is less than the 2025 OFL of 142,832 t. Therefore, the stock is not being subjected to overfishing.

Harvest Scenarios #6 and #7 are intended to permit determination of the status of a stock with respect to its minimum stock size threshold (MSST). Any stock that is below its MSST is defined to be overfished.

Any stock that is expected to fall below its MSST in the next two years is defined to be approaching an overfished condition. Harvest Scenarios #6 and #7 are used in these determinations as follows:

Is the stock currently overfished? This depends on the stock's estimated spawning biomass in 2025:

a) If spawning biomass for 2026 is estimated to be below ½ $B_{35\%}$, the stock is below its MSST.
b) If spawning biomass for 2026 is estimated to be above $B_{35\%}$ the stock is above its MSST.
c) If spawning biomass for 2026 is estimated to be above ½ $B_{35\%}$ but below $B_{35\%}$, the stock's status relative to MSST is determined by referring to harvest Scenario #6 (Table 7.20). If the mean spawning biomass for 2036 is below $B_{35\%}$, the stock is below its MSST. Otherwise, the stock is above its MSST.

Is the stock approaching an overfished condition? This is determined by referring to harvest Scenario #7:

a) If the mean spawning biomass for 2028 is below ½ $B_{35\%}$, the stock is approaching an overfished condition.
b) If the mean spawning biomass for 2028 is above $B_{35\%}$, the stock is not approaching an overfished condition.
c) If the mean spawning biomass for 2028 is above ½ $B_{35\%}$ but below $B_{35\%}$, the determination depends on the mean spawning biomass for 2039. If the mean spawning biomass for 2039 is below $B_{35\%}$, the stock is approaching an overfished condition. Otherwise, the stock is not approaching an overfished condition.

Based on the above criteria and Table 7.20, the stock is not currently overfished, and is not approaching an overfished condition. The tests for evaluating these two statements on status determination require examining the current model projections of spawning biomass relative to $B_{35\%}$ for 2026 and 2028. The estimates of spawning biomass for 2026 and 2028 from the current year (2026) projection model are 867,675 t and 879,111 t, respectively. Both estimates are well above the estimate of $B_{35\%}$ at 375,182 t and, therefore, the stock is not currently overfished nor approaching an overfished condition.

FLimit

The F from the author's recommended model that would have produced a catch for last year equal to last year's OFL was F=0.1074. We calculated this value within the Rceattle platform.

Ecosystem Considerations

Please see Appendix 7A for the full ecosystem and socioeconomic profile or ESP. The ESP provides a unique opportunity to explore unaccounted-for uncertainty through an ecosystem and socioeconomic approach to fisheries management. The new data in this updated model includes some promising signs for above-average 2017-2019 year class which is concurrent with a cooler year in the GOA following the 2014-2016 marine heatwaves and suggests improved conditions for arrowtooth young-of-the-year during 2017-2019. Recruitment trends are explored further within the ESP.

Data Gaps and Research Priorities

Analysis of the herding and escapement studies for arrowtooth flounder would result in improved estimates of selectivities and catchability. Otoliths have been aged through the 2025 survey, but continued ageing will allow monitoring of growth trends. A correlation between bottom temperatures and catchability has been observed in arrowtooth flounder and other flatfish; whether a similar relationship exists for GOA arrowtooth flounder would provide helpful information for the estimation of catchability. In addition, an examination of catchability may benefit the model. In the future, we may plan to explore the utility of model-based survey time series (e.g., VAST model) as a way to integrate the additional surveys that may be useful to include for the GOA arrowtooth flounder model (e.g., AFSC longline survey or ADF&G bottom trawl survey). Investigation into the proper weighting for sample sizes is ongoing and we plan to use "best practices" guidance on this topic when it becomes available. We may also explore using the Dirichlet-multinomial in the future to better estimate effective sample size for the composition data. We plan to keep the multispecies and ESP-DSEM model updated along with the operational model so we can inform the risk table and potentially incorporate this information into recruitment of the harvest projection during off-cycle assessments.

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Literature Cited

Adams, G. D., Holsman, K. K., Barbeaux, S. J., Dorn, M. W., Ianelli, J. N., Spies, I., Stewart, I. J., & Punt, A. E. (2022). An ensemble approach to understand predation mortality for groundfish in the Gulf of Alaska. *Fisheries Research*, *251*(October 2021), 106303. https://doi.org/10.1016/j.fishres.2022.106303

Bigman, J., Thorson, J.T., Large, S.I., Shotwell, S.K., Monnahan, C.C., Gonzalez, S., Wise, S. *In Review*. Dynamic structural equation models for ecosystem-based fisheries management: case studies and a practical guide. Fish and Fisheries.

Blood, D. M., A. C. Matarese, and M. S. Busby. 2007. Spawning, egg development, and early life history dynamics of Arrowtooth Flounder (Atheresthes stomias) in the Gulf of Alaska. U.S. Dep. Commer., NOAA Prof. Pap. NMFS 7, 28 p.

Bryan, M. Dorn, M., Stockhausen, W., Barbeaux, S., Ianelli, J,. Lowe, S., McGilliard, C., Monnahan, C., Spencer, P., Spies, I. and Thompson, T. 2020. Evaluating the impact of not having recent survey data in Alaska Fisheries Science Center groundfish and crab stock assessment models.

Candy, S.G., Nowara, G.B., Welsford, D., McKinlay, J.P., 2012. Estimating an ageing error matrix for Patagonian toothfish (Dissostichus eleginoides) otoliths using between-reader integer errors, readability scores, and continuation ratio models. Fish. Res. 115, 14–23. https://doi.org/10.1016/j.fishres.2011.11.005.

Charnov, E. L. The Theory of Sex Allocation (Princeton Univ. Press, Princeton, 1982.

Cronin-Fine. L, 2026. Assessment of the Skates Stock Complex in the Gulf of Alaska. North Pacific Fishery Management Council, Anchorage, AK. Available from https://www.npfmc.org/library/safereports/

Curti, K. L., Collie, J. S., Legault, C. M., & Link, J. S. (2013). Evaluating the performance of a multispecies statistical catch-at-age model. *Canadian Journal of …*, *484*(January), 470–484. https://doi.org/10.1139/cjfas-2012-0229

Dorn, M.W., 1992. Detecting environmental covariates of Pacific whiting Merluccius productus growth using a growth-increment regression model. Fishery Bulletin 90: 260-275.

Dorn, M., Aydin, K., Barbeaux, S., Guttormsen, M., Spalinger, K., and Palsson, W. 2003. Assessment of the walleye pollock stock in the Gulf of Alaska. In Stock Assessment and Fishery Evaluation Report for Groundfish Resources of the Gulf of Alaska. Prepared by the Gulf of Alaska Groundfish Plan Team, North Pacific Fishery Management Council, P.O. Box 103136, Anchorage, AK 99510. North Pacific Fisheries Management Council, Anchorage, AK.

Doyle, M.J., Debenham, C., Barbeaux, S.J., Buckley, T.W., Pirtle, J.L., Spies, I.B., Stockhausen, W.T., Shotwell, S.K., Wilson, M.T., Cooper, D.W., 2018. A full life history synthesis of Arrowtooth Flounder ecology in the Gulf of Alaska: exposure and sensitivity to potential ecosystem change. J. Sea Res. 142, 28–51. https://doi.org/10.1016/j.seares.2018.08.001.

Ferriss, B.E. 2026. Ecosystem Status Report 2026: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 1007 West Third, Suite 400, Anchorage, Alaska 99501.

Fournier, D.A., Skaug, H.J., Ancheta, J., Ianelli, J., Magnusson, A., Maunder, M.N., Nielsen, A., and Sibert, J. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optim. Methods Softw. 27:233-249.

Gislason, H., Daan, N., Rice, J.C. and Pope, J.G., 2010. Size, growth, temperature and the natural mortality of marine fish. Fish and Fisheries, 11(2), pp.149-158.

Greene, D.H., and J.K. Babbitt. 1990. Control of muscle softening and protease-parasite interactions in Arrowtooth Flounder, Atheresthes stomias. J. Food Sci. 55(2): 579-580.

Hanselman, D.H., B. Clark, and M. Sigler. 2013. Report of the groundfish plan team retrospective investigations group, part II: the compilation. Presented at September 2013 Plan Team, 12 pp. http://www.afsc.noaa.gov/REFM/stocks/Plan_Team/2013/Sept/Retrospectives_2013_final3.pdf.

Hirshberger, W.A., and G.B. Smith. 1983. Spawning of twelve groundfish species in the Alaska and Pacific coast regions, 1975-81. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC:44, 50p.

Hollowed, A. B., et al. (2016). Alaska Fisheries Science Center (AFSC) stock assessment prioritization results. Unpublished report. North Pacific Fishery Management Council. Anchorage, AK.

Holsman, K. K., & Aydin, K. (2015). Comparative methods for evaluating climate change impacts on the foraging ecology of Alaskan groundfish. Marine Ecology Progress Series, 521, 217-235.

Holsman, K. K., Ianelli, J., Aydin, K., Punt, A. E., & Moffitt, E. A. (2016). A comparison of fisheries biological reference points estimated from temperature-specific multi-species and single-species climate-enhanced stock assessment models. *Deep Sea Research Part II: Topical Studies in Oceanography*, *134*, 360–378. https://doi.org/10.1016/j.dsr2.2015.08.001

Holsman, K. K., K. Aydin, J. Sullivan, T. Hurst, and G. H. Kruse. 2019. Climate effects and bottomup controls on growth and size-at-age of Pacific halibut (Hippoglossus stenolepis) in Alaska (USA). Fisheries Oceanography 28:345–358.

Holsman, K. K., Barnes, C., Aydin, K., Laurel, B., Hurst T., & Heintz T. (2023). Patterns in Foraging and Energetics of Walleye Pollock, Pacific Cod, Arrowtooth Flounder, and Pacific Halibut. In: Elizabeth Sidden (Ed.), *Ecosystem Status Report 2023: Eastern Bering Sea, Stock Assessment and Fishery Evaluation Report*, North Pacific Fishery Management Council, 1007 West 3rd Ave., Suite 400, Anchorage, Alaska 99501.

Hulson, P.-J. F., Barbeaux, S. J., Ferriss, B., Echave, K., Nielsen, J., Shotwell, S. K., Laurel, B., Spies, I., Litzow, M., Mcdermott, S., Rand, K., Levy, C., Wang, M., & Rogers, L. (2023). *Assessment of the Pacific cod stock in the Gulf of Alaska Pacific cod*.

Hurtado-Ferro, F., Szuwalski, C. S., Valero, J. L., Anderson, S. C., Cunningham, C. J., Johnson, K. F., Licandeo, R., McGilliard, C. R., Monnahan, C. C., Muradian, M. L., Ono, K., Vert-Pre, K. A., Whitten, A. R., & Punt, A. E. 2015. Looking in the rearview mirror: bias and retrospective patterns in integrated, age-structured stock assessment models. ICES Journal of Marine Science, 72(1), 99–110.

Jurado-Molina, J., Livingston, P. A., & Ianelli, J. N. (2005). Incorporating predation interactions in a statistical catch-at-age model for a predator-prey system in the eastern Bering Sea. *Canadian Journal of Fisheries and Aquatic Sciences*, *62*(8), 1865–1873. https://doi.org/10.1139/f05-110

Kapur, M. S., Haltuch, M. A., Connors, B., Berger, A., Holt, K., Marshall, K., & Punt, A. E. (2024). Range-wide contrast in management outcomes for transboundary Northeast Pacific sablefish. Canadian Journal of Fisheries and Aquatic Sciences, 81(7), 810-827. https://doi.org/10.1139/cjfas-2024-0008

Kinzey, D., & Punt, A. E. (2009). Multispecies and Single-Spieces Models of Fish Population Dynamics: Comparing Parameter Estimates. *Natural Resource Modelling*, *22*(1), 67–104.

Kristensen, K., Nielsen, A., Berg, C. W., Skaug, H., & Bell, B. M. (2016). TMB : Automatic Differentiation and Laplace Approximation. *Journal of Statistical Software*, *70*(5), 1–21. https://doi.org/10.18637/jss.v070.i05

Lorenzen, K., 1996. The relationship between body weight and natural mortality in juvenile and adult fish: a comparison of natural ecosystems and aquaculture. Journal of fish biology, 49(4), pp.627642.

Magnusson, K. (1995). An overview of the multispecies VPA—theory and applications. *Reviews in Fish Biology and Fisheries*, *212*, 195–212. https://doi.org/10.1007/BF00179756

McAllister, M. K., & Ianelli, J. N. (1997). Bayesian stock assessment using catch-age data and the sampling-importance resampling algorithm. Canadian Journal of Fisheries and Aquatic Sciences, 54(2), 284-300.

Methot, R.D. 2000. Technical description of the stock synthesis assessment program. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-43, 46 p.

Methot Jr., R. D. (editor). (2015). Prioritizing fish stock assessments. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-F/SPO-152, 31 p.

Moss, J. H., et al. "Surviving the Gauntlet: A comparative study of the pelagic, demersal, and spatial linkages that determine groundfish recruitment and diversity in the Gulf of Alaska ecosystem."

NPRB GOA Project G81 Upper Trophic Level Final Report). Anchorage, AK: North Pacific Research Board. NWAFC Processed Rep (2016): 88-21.

Murai, S., H. A. Gangmark, and R. R. French. 1981. All-nation removals of groundfish, Herring, and shrimp from the eastern Bering Sea and northeast Pacific Ocean, 1964-80. NWAFC report. 40p.

Orlov, A.M., 2004. Migrations of various fish species between Asian and American waters in the North Pacific Ocean. Aqua, Journal of Ichthyology and Aquatic Biology, 8(3), pp.109-124.

Orr, J. W., D. T. Drumm, E. A. Laman, D. E. Stevenson, and G. R. Hoff. 2014. Species identification confidence in the Gulf of Alaska and Aleutian Islands surveys (1980-2011). AFSC Processed Rep. 2014-01, 258 p. Alaska Fish. Sci. Cent., NOAA, Natl. Mar. Fish. Serv., 7600 Sand Point Way NE, Seattle WA 98115.

PEEC 2026. Preview of Ecosystem and Economic Conditions Workshop. May 25-28, 2026. NOAA Alaska Fisheries Science Center, Seattle, WA, USA. (https://docs.google.com/document/d/1XUsvHh2frm7YD3Cemfa5omS0IEzBeU89y3IInK4Tx7A/edit?tab=t.0#heading=h.95r7ro4r01pj)

Porter, R.W., B.J. Kouri, and G. Kudo. 1993. Inhibition of protease activity in muscle extracts and surimi from Pacific Whiting, Merluccius productus, and Arrowtooth Flounder, Atheresthes stomias. Mar. Fish. Rev. 55(3):10-15.

Reppond, K.D., D.H. Wasson, and J.K. Babbitt. 1993. Properties of gels produced from blends of Arrowtooth Flounder and Alaska pollock surimi. J. Aquat. Food Prod. Technol., vol. 2(1):83-98.

Rickey, M.H. 1995. Maturity, spawning, and seasonal movement of Arrowtooth Flounder, Atheresthes sto- mias, off Washington. Fish. Bull., U.S. 93(1):127-138.

Rodgveller, C. J., Sigler, M. F., Hanselman, D. H., & Ito, D. H. (2011). Sampling efficiency of longlines for Shortraker and Rougheye Rockfish. Marine and Coastal Fisheries, 3(1), 1-14. https://doi.org/10.1080/19425120.2011.558447

Shotwell, S. K., Spies, I., Ianelli, J. N., Aydin, K., Hanselman, D. H., Palsson, W., Siwicke, K., Sullivan, J., & Yasumiishi, E. (2021). *Assessment of the Arrowtooth flounder stock in the Gulf of Alaska*. https://apps-afsc.fisheries.noaa.gov/refm/docs/2019/GOAatf.pdf

Shotwell, S.K., Adams, G.D., Hanselman, D.H., von Szalay, P., and Williams, B.C. 2024. Assessment of the arrowtooth flounder stock in the Gulf of Alaska. In: Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska. North Pacific Fishery Management Council, Anchorage, AK. Available from https://www.npfmc.org/library/safereports/.

Shotwell, S.K., J. Bigman, and R. Dame. 2026. Appendix 7A. Ecosystem and Socioeconomic Profile of the arrowtooth flounder stock in the Gulf of Alaska. In: Shotwell, S.K., G.D. Adams, D.H. Hanselman. 2026. Assessment of the arrowtooth flounder stock in the Gulf of Alaska. North Pacific Fishery Management Council, Anchorage, AK. Available from https://www.npfmc.org/library/safe-reports/.

Soderlund, E., E. Anderson, C. L. Dykstra, T. Geernaert, and A. M. Ranta. 2009. 2008 standardized stock assessment survey. Int. Pac. Comm. Report of Assessment and Research Activities 2008 469-496.

Somerton, D.A., P.T. Munro, K.L. Weinberg, 2007. Whole-gear efficiency of a benthic survey trawl for flatfish. Fish. Bull. 105:278–291.

Spalinger, K., and J. Silva. 2023. Large-mesh bottom trawl survey of crab and groundfish: Kodiak, Chignik, South Peninsula, and Eastern Aleutian Management Districts, 2022. Alaska Department of Fish and Game, Fishery Managment Report No. 23-7, Anchorage.

Spies, I., K. Aydin, J.N. Ianelli, and W. Palsson. 2015. Assessment of the arrowtooth flounder stock in the Gulf of Alaska. In Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska. North Pacific Fishery Mngt. Council, 605 W 4th Ave, Suite 306 Anchorage, AK 99501.

Stark, J. 2008. Age- and length-at-maturity of female Arrowtooth Flounder (Atheresthes stomias) in the Gulf of Alaska. Fish. Bull 106: 328-333.

Stewart, I. J., & Monnahan, C. C. (2025). Diagnosing common sources of lack of fit to composition data in fisheries stock assessment models using one-step-ahead (OSA) residuals. Canadian Journal of Fisheries and Aquatic Sciences. https://doi.org/10.1139/cjfas-2025-0158

Stevenson, D. E., and G. R. Hoff. 2009. Species identification confidence in the eastern Bering Sea shelf survey (1982-2008). AFSC Processed Rep. 2009-04, 46 p. Alaska Fish. Sci. Cent., NOAA, Natl. Mar. Fish. Serv., 7600 Sand Point Way NE, Seattle WA 98115.

Trijoulet, V., Albertsen, C. M., Kristensen, K., Legault, C. M., Miller, T. J., & Nielsen, A. (2023). Model validation for compositional data in stock assessment models: Calculating residuals with correct properties. Fisheries Research, 257, 106487. https://doi.org/10.1016/j.fishres.2022.106487

Turnock, B.J., T.K. Wilderbuer and E.S. Brown. 2000. Arrowtooth Flounder. In Stock Assessment and Fishery Evaluation Report for the 2001 Gulf of Alaska Groundfish Fishery. 30 p. Gulf of Alaska Groundfish Plan Team, North Pacific Fishery Management Council, P. O. Box 103136, Anchorage, Ak 99510.

Turnock, B.J., T.K. Wilderbuer and E.S. Brown. 2002. Arrowtooth Flounder. In Stock Assessment and Fishery Evaluation Report for the 2002 Gulf of Alaska Groundfish Fishery. Gulf of Alaska Groundfish Plan Team, North Pacific Fishery Management Council, P. O. Box 103136, Anchorage, Ak 99510.

Wasson, D.H., K.D. Reppond, J.K. Babbitt, and J.S. French. 1992. Effects of additives on proteolytic and functional properties of Arrowtooth Flounder surimi. J. Aquat. Food Prod. Technol., vol. 1(3/4):147-165.

Wilderbuer, T. K., and E. S. Brown. 1993. Flatfish. In T. K. Wilderbuer (editor), Condition of groundfish resources of the Gulf of Alaska as assessed in 1993. U.S. Dep. Commer., NOAA Tech. Memo, NMFS F/NWC-165.

Wilderbuer, T.K. and B.J. Turnock. 2009. Differential Sex-Specific Natural Mortality of Arrowtooth Floun- der in Alaska: Implications for Exploitation and Management. North American Journal of Fisheries Man- agement Vol. 29 (2).

Zimmerman, M., and P. Goddard. 1996. Biology and distribution of Arrowtooth Flounder, Atheresthes stomias, and Kamchatka flounders (A. evermanni) in Alaskan waters. Fish. Bull., U.S.

Zimmerman, M. 1997. Maturity and fecundity of Arrowtooth Flounder, Atheresthes stomias, from the Gulf of Alaska. Fish. Bull. 95:598-611.

Auxiliary Files

The repository for the Rceattle code, model files, and output graphics is available at:
https://github.com/grantdadams/GOA-ATF-ESP

Tables

Table 7.1: Catch, OFL, ABC, and TAC for arrowtooth flounder in the Gulf of Alaska from 1977 to the present. Values are in metric tons. Arrowtooth flounder ABC was separated from the flatfish ABC after 1990. Source: AKFIN database (https://akfinbi.psmfc.org/analytics/). Catch value for 2026 is accurate as of August 22, 2026.

Year	Catch	OFL	ABC	TAC
1977	9,449			
1978	8,409			
1979	7,579			
1980	7,848			
1981	7,433			
1982	4,639			
1983	6,331			
1984	3,457			
1985	1,539			
1986	1,221			
1987	4,963			
1988	5,138			
1989				
1990	7,706		194600	32000
1991	17,301		340100	20000
1992	21,916		303880	25000
1993	19,078	427000	321290	30000
1994	22,918	451690	236240	30000
1995	18,279	275930	198130	35000
1996	22,477	231416	198130	35000
1997	16,363	231416	197840	35000
1998	12,958	280800	208340	35000
1999	16,142	295970	217110	35000
2000	24,211	308880	145360	35000
2001	19,926	173910	148150	38000
2002	21,213	173550	146260	38000
2003	30,254	171060	155140	38000
2004	15,758	181390	194930	38000
2005	19,989	228130	216900	38000
2006	27,739	253900	177844	38000
2007	25,508	207678	184008	43000
2008	29,270	214828	226470	43000
2009	24,912	266914	221512	43000
2010	24,496	261022	215882	43000
2011	31,139	254271	213150	43000
2012	20,886	250100	212882	103300
2013	21,967	247196	210451	103300
2014	36,662	229248	195358	103300
2015	19,418	226390	192921	103300
2016	20,057	219430	186188	103300
2017	27,144	219327	186093	103300
2018	18,964	180697	150945	76300
2019	24,714	174598	145841	99295
2020	21,243	153017	128060	96969
2021	9,989	151723	126970	97372
2022	11,627	143100	119779	96501
2023	9,194	142749	119485	94286
2024	18,183	142485	119249	94141
2025	13,380	142832	119547	100454
2026	12,622	143347	119985	100769

Table 7.2: Catch (t) of Arrowtooth flounder as bycatch in other fisheries from 1991 - present. Other fisheries and Atka Mackerel category not included due to confidentiality (# vessels or # processors is fewer than or equal to 2). Source: NMFS AKRO Blend/Catch Accounting System via AKFIN 10/30/2021.

Year	Flatfish	Halibut	Pacific Cod	Pollock	Rockfish	Sablefish
1991	3,202		283	1,375	2,941	197
1992	11,295		3,005	1,314	3,657	1,235
1993	12,919		1,970	862	1,044	1,702
1994	16,656		3,191	1,135	898	979
1995	12,344		2,795	380	1,671	1,076
1996	17,842		1,341	587	2,062	612
1997	10,976		3,034	508	1,233	506
1998	8,267		2,113	306	1,709	561
1999	7,849		4,000	1,084	2,378	699
2000	17,856		2,165	928	2,417	840
2001	10,641		4,777	2,481	1,532	494
2002	18,076		590	659	1,422	464
2003	25,616	50	1,214	659	1,350	254
2004	10,475	47	1,715	1,162	2,020	242
2005	15,597	61	765	2,312	961	274
2006	22,491	36	1,029	2,747	1,085	351
2007	21,201	80	1,433	1,631	688	474
2008	23,647	29	3,007	1,569	517	500
2009	22,658	59	757	759	497	179
2010	20,729	36	373	2,495	707	156
2011	27,843	21	598	2,019	341	314
2012	17,521	11	854	1,341	763	396
2013	17,161	195	1,508	1,784	766	544
2014	30,750	127	1,364	2,598	1,426	397
2015	14,626	111	1,180	1,758	1,397	345
2016	15,828	61	1,420	1,290	1,197	260
2017	23,516	78	537	1,335	1,416	253
2018	14,922	68	110	2,668	761	424
2019	21,428	71	243	2,019	733	221
2020	17,426	48	51	2,417	890	412
2021	5,953	72	150	811	2,523	481
2022	7,416	132	97	770	2,823	390
2023	7,168	106	82	788	860	189
2024	15,484	146	293	590	1,362	307
2025	10,972	99	215	409	1,575	111
2026	12,489	36	268	28	1,428	79
Average	15,857	74	1,348	1,322	1,418	470

Table 7.3: Incidental catch of FMP groundfish species caught in Arrowtooth flounder target fishery in the Gulf of Alaska for the most recent five years. Conf. = Confidential data since # vessels or # processors is fewer than or equal to 2. Source: NMFS AKRO Blend/Catch Accounting System via AKFIN 8/22/2026.

Group Name	2022	2023	2024	2025	2026	Average
Arrowtooth Flounder	6,918	7,024	15,243	10,556	10,418	10,032
Pacific Cod	415	514	988	1,186	1,264	874
Pacific Ocean Perch	689	883	927	1,163	464	825
Pollock	150	198	1,054	1,174	1,020	719
Flathead Sole	234	238	665	633	531	460
GOA Rex Sole	240	253	417	462	470	369
GOA Shallow Water Flatfish	50	159	390	543	610	350
Sablefish	394	276	294	198	210	274
GOA Dusky Rockfish	44	332	93	221	12	141
GOA Skate, Big	30	60	134	128	139	98
Northern Rockfish	81	42	81	125	4	67
Atka Mackerel	12	Conf.	Conf.	58	115	61
GOA Deep Water Flatfish	55	45	53	38	38	46
GOA Skate, Longnose	10	8	43	76	64	40
Shark	19	68	62	29	9	38
BSAI Skate, GOA Skate, Other	20	6	26	5	9	13
Rougheye Rockfish	3	7	24	8	19	12
Other Rockfish	12	12	13	10	3	10
GOA Demersal Shelf Rockfish				12	2	7
Shortraker Rockfish	7	3	5	Conf.	Conf.	5
GOA Thornyhead Rockfish	6	Conf.	3	Conf.	1	4
Octopus		2	2	0	0	1
Halibut			Conf.			

Table 7.4: Non-FMP species bycatch estimates in tons for Gulf of Alaska Arrowtooth flounder fishery for the most recent five years. Conf. = Confidential data since # vessels or # processors is fewer than or equal to 2. Source: NMFS AKRO Blend/Catch Accounting System via AKFIN 8/22/2026.

Group Name	2022	2023	2024	2025	2026
Benthic urochordata	Conf.	Conf.	Conf.		Conf.
Bivalves	0.01	0.03	0.65	Conf.	0.04
Brittle star unidentified	Conf.	Conf.	Conf.	0.18	Conf.
Corals Bryozoans - Corals Bryozoans Unidentified		Conf.	0.26	Conf.	0.04
Eelpouts	Conf.	Conf.	0.10	0.16	Conf.
Giant Grenadier	Conf.	Conf.	0.67	0.18	8.14
Greenlings	Conf.	Conf.		0.32	0.05
Grenadier - Rattail Grenadier Unidentified	Conf.		Conf.		
Hermit crab unidentified	0.05	0.05	0.03	0.09	Conf.
Invertebrate unidentified	0.28			Conf.	0.07
Misc crabs	0.29	0.01	1.09	0.09	0.10
Misc crustaceans	0.03	Conf.	0.23	0.02	0.02
Misc fish	46.77	25.60	54.87	95.67	150.64
Misc inverts (worms etc)	Conf.	Conf.	Conf.	Conf.	0.02
Pacific Sand lance	Conf.	Conf.		Conf.	
Pandalid shrimp	0.56	0.11	0.63	0.32	0.21
Polychaete unidentified		Conf.			Conf.
Sculpin	24.80	10.57	20.73	6.62	30.49
Scypho jellies	0.30	Conf.	6.33	1.82	0.85
Sea anemone unidentified	0.42	Conf.	0.35	Conf.	0.14
Sea pens whips	Conf.	Conf.	0.02	0.03	Conf.
Sea star	2.24	3.42	8.14	16.21	4.30
Smelt (Family Osmeridae)	0.47	Conf.	0.36	Conf.	0.21
Snails	0.27	0.03	0.14	0.17	0.11
Sponge unidentified	0.05	Conf.	0.02	0.46	0.07
Squid	15.64	9.77	6.88	5.31	0.78
State-managed Rockfish	1.41	Conf.		1.33	
Stichaeidae	Conf.	Conf.	0.26	0.07	0.06
urchins dollars cucumbers	0.41	0.22	0.79	1.81	0.19

Table 7.5: Percent of the Arrowtooth Flounder in the GOA discarded and retained by commercial fishing operations 1991 to present. Source: Source: NMFS AKRO Blend/Catch Accounting System via AKFIN 8/22/2026.

Year	Percent discarded	Percent retained
1991	87.5	12.5
1992	97.7	2.3
1993	91.9	8.1
1994	98.0	2.0
1995	87.6	12.4
1996	75.8	24.2
1997	81.8	18.2
1998	84.1	15.9
1999	73.6	26.4
2000	57.4	42.6
2001	66.8	33.2
2002	50.3	49.7
2003	56.8	43.2
2004	57.7	42.3
2005	39.9	60.1
2006	42.2	57.8
2007	40.8	59.2
2008	29.9	70.1
2009	48.5	51.5
2010	40.8	59.2
2011	21.8	78.2
2012	24.0	76.0
2013	26.2	73.8
2014	10.3	89.7
2015	11.9	88.1
2016	9.6	90.4
2017	7.9	92.1
2018	8.7	91.3
2019	5.7	94.3
2020	6.5	93.5
2021	18.5	81.5
2022	11.5	88.5
2023	11.0	89.0
2024	6.6	93.4
2025	6.6	93.4
2026	2.6	97.4

Table 7.6: The number of fisheries length observations taken by fisheries observers, and the number of hauls from which those samples were taken, by year, 1990 to present. Source: NMFS AKRO Blend/Catch Accounting System via AKFIN 8/22/2026.

Year	Number of Age Observations	Number of Length Observations	Weights applied to fishery length comps	
			Females	Males
1990		333	7	7
1991	100	2770	95	89
1992		196	2	2
1993		648	12	12
1994		59		
1995	160	1242	10	10
1996		647	15	15
1997	50	1317	14	14
1998		1390	6	4
1999	2	2124	129	122
2000	9	5115	200	200
2001	2	5134	200	200
2002	29	6732	200	200
2003		12629	200	200
2004	1	3947	200	200
2005		5631	200	200
2006		6606	200	200
2007	4	7960	200	200
2008	33	7409	200	200
2009		6647	200	200
2010	23	5946	200	200
2011	8	8428	200	200
2012	44	7204	200	200
2013		6235	200	200
2014	52	11918	200	200
2015		8737	200	200
2016		8368	200	200
2017	2	12220	200	200
2018	80	5710	200	200
2019	110	6888	200	200
2020	111	5418	200	200
2021	96	5332	200	200
2022	108	6376	200	200
2023	84	4538	200	200
2024	124	7924	200	200
2025	107	6066	200	200

Table 7.7: Biomass estimates, standard errors, coefficient of variation (CV), number of hauls, and maximum depth (m) from bottom trawl surveys, 1993-2025. *The 2001 survey biomass for the eastern GOA was estimated by using the average of the 1993 to 1999 biomass estimates in eastern GOA.

Survey	Biomass (t)	Standard error	CV	Number of hauls
NMFS triennial 1993	1,547,834	100,045	0.06	770
NMFS triennial 1996	1,629,517	114,241	0.07	800
NMFS triennial 1999	1,238,474	98,789	0.08	755
NMFS 2001	1,621,892*	151,663	0.11	487
NMFS 2003	2,800,835	370,587	0.13	801
NMFS 2005	1,887,549	125,170	0.07	831
NMFS 2007	1,921,870	149,766	0.08	812
NMFS 2009	1,763,413	158,664	0.09	817
NMFS 2011	1,732,498	179,093	0.10	665
NMFS 2013	1,280,077	128,998	0.10	547
NMFS 2015	1,656,370	133,789	0.08	767
NMFS 2017	1,033,811	74,650	0.07	535
NMFS 2019	1,074,099	67,256	0.06	537
NMFS 2021	1,123,404	82,933	0.07	526
NMFS 2023	1,184,806	123,992	0.10	523
NMFS 2025	1,442,691	147,241	0.10	431

Table 7.8: Survey biomass estimates (t) for 1984 to current survey by area; Western (NMFS area 610), Central (620 and 630), and Eastern (640, 650). The 2001 survey biomass for the eastern GOA was estimated by using the average of the 1993 to 1999 biomass estimates in the eastern GOA.

Year	Western GOA	Central GOA	Eastern GOA	Total
1993	211,404	1,115,814	220,616	1,547,834
1996	197,539	1,174,336	257,642	1,629,517
1999	142,207	843,371	252,896	1,238,474
2001	185,432	1,175,305	251,980	1,360,738
2003	339,701	2,192,234	268,900	2,800,835
2005	214,322	1,436,163	237,063	1,887,549
2007	262,475	1,432,441	226,954	1,921,870
2009	283,430	1,199,757	280,226	1,763,413
2011	223,864	1,171,382	337,253	1,732,498
2013	202,380	761,687	316,010	1,280,077
2015	236,861	911,243	508,266	1,656,370
2017	308,674	517,689	207,449	1,033,811
2019	275,841	583,681	214,577	1,074,099
2021	358,912	618,751	145,740	1,123,404
2023	116,742	782,218	285,845	1,184,806
2025	222,369	845,497	374,825	1,442,691

Table 7.9: The number of bottom trawl survey age and length observations taken on the survey with hauls and weights applied to the age compositions. Length compositions are not used in the model.

				Weights applied to survey age comps	
Year	Number of Age Observations	Number of Length Observations	Number of Hauls	Females	Males
1993	1031	24,569	839	200	200
1996	664	23,409	868	200	200
1999	876	23,493	870	200	200
2001	1393	14,060	528	200	200
2003	1044	25,995	877	200	200
2005	1093	25,890	912	200	200
2007	1126	22,997	894	200	200
2009	1160	23,793	883	200	200
2011	900	18,642	704	200	200
2013	825	12,716	592	200	200
2015	829	21,065	836	200	200
2017	898	14,572	576	200	200
2019	886	15,869	575	200	200
2021	935	14,995	562	200	200
2023	921	13,602	555	200	200
2025	751	24,569	839	200	200

Table 7.10: The number of male and female arrowtooth flounder lengths recorded on AFSC bottom trawl survey, 1993 to present. Please note these data are not fit in the author recommended model.

Year	Females	Males	Unknown	Total
1993	16,592	7,941	36	24,569
1996	15,448	7,936	25	23,409
1999	15,350	8,076	67	23,493
2001	9,434	4,624	2	14,060
2003	16,873	9,047	75	25,995
2005	17,147	8,680	63	25,890
2007	15,058	7,883	56	22,997
2009	15,468	8,287	38	23,793
2011	12,019	6,518	105	18,642
2013	8,169	4,531	16	12,716
2015	13,178	7,834	53	21,065
2017	9,136	5,393	43	14,572
2019	9,749	6,084	36	15,869
2021	9,376	5,611	8	14,995
2023	8,619	4,966	17	13,602
2025	16,592	7,941	36	24,569

Table 7.11: General population dynamics equations in Rceattle for species i, sex s, age a, and length l in year y, and for survey or fishery f_i. See Table 7.15 for parameter definitions.

Definition	Equation
Initial abundance	$N_{isa1} = \{\underline{R}_{F_i} e^{\left(-\sum_{j=1}^{a-1} M1_{isj} + \tau_{ia}\right)} \rho_{i1}\ if\ a < A_i$ $N_{isA_i1} = \frac{\underline{R}_{F_i} e^{\left(-\sum_{j=1}^{a-1} M1_{isj} + \tau_{ia}\right)} \rho_{i1}}{\left(1 - e^{\left(-M1_{isA_i}\right)}\right)}\ if\ a = A_i$
Recruitment	$N_{is1y} = R_{isy} = \underline{R}_i e^{\tau_{iy}} \rho_{i1}$
Numbers at age	$N_{isa+1y+1} = N_{isay} e^{-Z_{isay}}$ $N_{isA_iy+1} = N_{isA_i-1y} e^{-Z_{isA_i-1y}} + N_{isA_iy} e^{-Z_{isA_iy}}$
Survey biomass (kg)	$\hat{CPUE}: B_{f_iy} = \sum_s \sum_a N_{isay} e^{-Month_{f_i} * Z_{isay}} W_{f_isay} sel_{f_isay} q_{f_iy}$
Catch-at-age	$C_{f_isay} = \frac{F_{f_isay}}{Z_{isay}} \left(1 - e^{-Z_{isay}}\right) N_{isay}$
Total catch (kg)	$\hat{C}^{*}_{f_iy} = \sum_s \sum_j \frac{F_{f_isay}}{Z_{isay}} \left(1 - e^{-Z_{isay}}\right) N_{isay} W_{f_isay}$
Age-1+ biomass (kg)	$B_{iy} = \sum_s \sum_{a>0} N_{isay} W_{B_iay}$
Spawning biomass at age (kg)	$SB_{iay} = N_{i1ay} e^{-Month_{ssb_i}/12 * Z_{i1ay}} W_{ssb_i1ay} \delta_{ia}$
Total mortality at age (single-species)	$Z_{isay} = M1_{isa} + \sum_{f_i} F_{f_isay}$
Total mortality at age (multi-species)	$Z_{isay} = M1_{isa} + M2_{isay} + \sum_{f_i} F_{f_isay}$
Fishing mortality at age and fleet	$F_{f_isay} = \underline{F}_{f_i} e^{\epsilon_{f_iy}} sel_{f_isay}$
Projected fishing mortality	$F_{f_isay} = F_{Target_i} sel_{f_isay} \psi_{f_i}$
Predicted age composition	$\hat{O}_{f_is\hat{a}y} = \frac{\sum_a C_{f_isay} AE_{i\hat{a}a}}{\sum_s \sum_{\hat{a}} \sum_a C_{f_isay} AE_{i\hat{a}a}}\quad if\ f_i$ = fishery $\hat{O}_{f_is\hat{a}y} = \frac{\sum_a N_{isay} e^{-Month_{f_i} * Z_{isjy}} sel_{f_isay} AE_{i\hat{a}a}}{\sum_s \sum_{\hat{a}} \sum_a N_{isay} e^{-Month_{f_i} * Z_{isjy}} sel_{f_isay} AE_{i\hat{a}a}}\quad if\ f_i$ = survey
Predicted length composition	$\hat{O}_{f_isly} = \frac{\sum_{\hat{a}} \sum_a C_{f_isay} AE_{i\hat{a}a} ATM_{isal}}{\sum_s \sum_l \sum_{\hat{a}} \sum_a C_{f_isay} AE_{i\hat{a}a} ATM_{isal}}\quad if\ f_i$ = fishery $\hat{O}_{f_isly} = \frac{\sum_{\hat{a}} \sum_a N_{isay} e^{-Month_{f_i} * Z_{isay}} sel_{f_isay} AE_{i\hat{a}a} ATM_{isal}}{\sum_s \sum_l \sum_{\hat{a}} \sum_a N_{isay} e^{-Month_{f_i} * Z_{isjy}} sel_{f_isay} AE_{i\hat{a}a} ATM_{isal}}\quad if\ f_i$ = survey

Table 7.12: Predation mortality equations for predator species p, sex b, age j, and prey species i, sex s and age a. For parameter definitions see Table 7.15.

Definition	**Equation**
Predation mortality	$M2_{isay} = \sum_{pbj}\left(\frac{\underline{N}_{pbjy}\delta_{pbjy}\hat{S}_{pbjisa}}{\left(\sum_{isa}\left(\hat{S}_{pbjisa}\underline{B}_{isay}\right)+B_{p}^{other}\left(1-\sum_{isa}\left(\hat{S}_{pbjisa}\right)\right)\right)}\right)$
Predator-prey suitability	$S\hat{}_{pbjisa} = \frac{1}{n_y}\sum_{y}\left(\frac{\frac{\underline{U}_{psaisa}}{w_{isay}\underline{N}_{isay}^{H_i}}}{\sum_{isa}\left(\frac{\underline{U}_{pbjisa}}{w_{isay}}\right)+\frac{1-\sum_{isa}\underline{U}_{pbjisa}}{B_p^{other}}}\right)$
Individual specific ration ($kg\ kg^{-1}\ yr^{-1}$)	$\delta_{pbjy} = \varphi_{pbjy}\alpha_p^{\delta}W_{pbjy}^{\left(1+\beta_p^{\delta}\right)}f\left(T_y\right)_p$
Temperature scaling algorithms	$f\left(T_y\right)_p = V^{X}e^{(X(1-V))}$
…	$V = \left(T_p^{cm} - T_y\right)/\left(T_p^{cm} - T_p^{co}\right)$
…	$X = \left(Z^2\left(1 + (1 + 40/Y)^{0.5}\right)^2\right)/400$
…	$Z = ln\left(Q_p^c\right)\left(T_p^{cm} - T_p^{co}\right)$
…	$Y = ln\left(Q_p^c\right)\left(T_p^{cm} - T_p^{co} + 2\right)$

Table 7.13: Time-series and sources of data used in Rceattle

Source	**Data type**	**Data collection cycle**
NMFS bottom trawl survey	Absolute biomass	Triennial and Biennial (1984 to present)
	Age composition	1984 to present
	Diet composition	1990-2015
Holsman and Aydin (2015)	Bioenergetic demand	1990-2015
Fishery	Total catch	Annual (1977 to present up to a specified date)
	Length composition	1977 to present

Table 7.14: Components of the likelihood function for species i, sex s, age a, or length l during year y for survey s or fishery f. For parameter definitions see Table 7.15.

Description	Equation
Data components	
Survey biomass	$ln\left(B_{f_i y}\right) \sim N\left(ln\left(\hat{B}_{f_i y}\right) - \frac{\sigma^2_{f_i y}}{2}, \sigma^2_{f_i y}\right)$
Total catch	$ln\left(C^*_{f_i y}\right) \sim N\left(ln\left(C\hat{}^*_{f_i y}\right) - \frac{\sigma^2_{f_i y}}{2}, \sigma^2_{f_i y}\right)$
Age composition	$-\sum_i n_{f_i y} \sum_s \sum_{\hat{a}} \sum_y \left(\hat{O}_{f_i s \hat{a} y} + 0.00001\right) * ln\left(O_{f_i s \hat{a} y} + 0.00001\right)$
Length composition	$-\sum_i n_{f_i y} \sum_s \sum_l \sum_y \left(\hat{O}_{f_i s l y} + 0.00001\right) * ln\left(O_{f_i s l y} + 0.00001\right)$
Penalties	
Non-parametric selectivity	$\sum_i \sum_s \sum_a^{A_i - 1} \chi_{f_i} \left[ln\left(\frac{e^{\psi_{f_i s a}}}{e^{\psi_{f_i s a+1}}}\right) - ln\left(\frac{e^{\psi_{f_i s a+1}}}{e^{\psi_{f_i s a+2}}}\right)\right]^2$ $\chi_{f_i} = 0 \quad if\; e^{\psi_{f_i s a}} \le e^{\psi_{f_i s a+1}}$
Recruitment deviate	$\tau_{iy} \sim N\left(-\frac{\sigma^2_{R_i}}{2}, \sigma^2_{R_i}\right)$
Fishing mortality deviate	$\epsilon_{f_i y} \sim \epsilon_{f_i y} * \epsilon_{f_i y}$

Table 7.15. Parameter definitions for Rceattle.

Category	**Parameter**	**Definition**
Index	i	Species
	s	Sex
	a	Age
	$\hat{a}$	Observed age
	A	Plus group
	l	Length
	y	Year
	Y	Last year of estimation (not projection)
	p	Predator species
	b	Predator sex
	j	Predator age
	k	Predator length
	f_i	Fleet/survey
Population model	R_{isy}	Recruitment
	$\underline{R}_i$	Mean recruitment
	τ_{iy}	Annual recruitment deviate
	δ_{ia}	Maturity-at-age
	ρ_{ia}	Sex-ratio
	$M1_{isa}$	Residual mortality yr^{-1}
	$M2_{isay}$	Predation-mortality yr^{-1}
	$F_{f_i say}$	Fleet-specific fishing mortality yr^{-1}
	F_{isay}	Total fishing mortality yr^{-1}
	Z_{isay}	Total mortality yr^{-1}
	$\underline{F}_{f_i}$	Mean fishing mortality yr^{-1}
	$\epsilon_{f_i y}$	Annual fishing mortality deviate
	ψ_{f_i}	Fishing mortality apportionment per fleet
	N_{isay}	Numbers-at-age
	$\underline{N}_{isay}$	Average numbers-at-age
	SB_{ijy}	Spawning-stock-biomass (kg)
	B_{isay}	Biomass (kg)
	$\underline{B}_{isay}$	Average biomass (kg)
Predation model	$\hat{S}_{pbjisa}$	Predator-prey suitability
	H_i	Holling functional response parameter
	B_p^{other}	Biomass of “other prey” (kg)

	T_y	Observed bottom temperature (°C)
	T_p^{co}	Thermal optima for consumption (°C)
	T_p^{cm}	Thermal limit of consumption (°C)
	Q_p^c	Rate at which consumption increased over relatively low water temperatures
	$\alpha_p^\delta, \beta_p^\delta$	Weight specific intercept and slope of maximum consumption
	φ_{pbj}	Scalar for maximum to observed consumption
	$\underline{U}_{pbj,isa}$	Average proportion of prey-at-age in the stomach of a predator-at-age
Observation model		
	$\hat{CPUE}: B_{f_i y}$	Survey/fishery relative biomass (kg)
	$sel_{f_i say}$	Selectivity
	$q_{f_i y}$	Catchability
	W	Weight (kg)
	$C_{f_i say}$	Catch-at-age
	$C\hat{}^{*}_{f_i y}$	Total catch (kg)
	$\hat{O}_{f_i s\hat{a}y} / \hat{O}_{f_i sly}$	Predicted age/length composition
	$AE_{i\hat{a}a}$	Ageing error matrix
	ATM_{isal}	Age-transition matrix (growth trajectory)
	$\hat{S}_{pbjisa}$	Predator-prey suitability

Table 7.16. Model comparison table.

	Model 25.0 (fix M and old data)	**Model 25.0 (fix M and new data)**	**Model 25.1 (Model 25.0 new but est M)**
Platform	Rceattle (TMB)	Rceattle (TMB)	Rceattle (TMB)
Likelihoods			
Catch	-99.665	-103.817	-103.828
Fishery length composition	87.570	89.378	65.628
Survey biomass	4.280	4.289	-2.464
Survey age composition	34.316	37.059	35.407
Recruit deviations	-5.520	-7.452	-8.311
Selectivity penalties	18.439	19.203	13.716
Total Joint NLL	39.4188	38.6514	0.1475
Marginal NLL	71.6126	73.34795	37.1384
Number of parameters	92	94	96
Estimates			
q-trawl	1	1	1
Mean Recruitment (thousand)	735,190	743,237	2,503,196
Recruitment Variability (σ_r)	0.290	0.281	0.276
Natural Mortality (M) female	0.20 (fixed)	0.20 (fixed)	0.330
Natural Mortality (M) male	0.35 (fixed)	0.35 (fixed)	0.407
2027 total biomass (t)		1,437,490	1,980,340
2027 spawning biomass (t)		874,501	709,459
$B_{100\%}$ (t)		1,073,870	829,454
$B_{40\%}$ (t)		429,548	331,781

Table 7.17: Estimated total (age 1+) total biomass (t), and female spawning biomass (SSB) (t) for Model 25.0. Lower 95% and upper 95% uncertainty intervals are provided.

Year	Biomass (t)	95% LCI (Biomass)	95% UCI (Biomass)	SSB (t)	95% LCI (SSB)	95% UCI (SSB)
1977	1,692,662	1,540,862	1,859,417	1,073,375	976,997	1,179,261
1978	1,680,938	1,529,145	1,847,799	1,065,476	969,128	1,171,401
1979	1,669,683	1,516,484	1,838,359	1,058,757	962,444	1,164,708
1980	1,658,943	1,502,396	1,831,803	1,053,161	956,903	1,159,103
1981	1,648,129	1,486,758	1,827,015	1,047,685	951,566	1,153,512
1982	1,638,648	1,471,999	1,824,163	1,042,417	946,450	1,148,115
1983	1,633,413	1,462,057	1,824,852	1,038,463	941,007	1,146,012
1984	1,627,823	1,453,139	1,823,506	1,031,953	929,413	1,145,806
1985	1,627,694	1,451,643	1,825,096	1,027,698	918,698	1,149,631
1986	1,632,365	1,457,201	1,828,585	1,025,705	911,110	1,154,714
1987	1,640,760	1,468,908	1,832,718	1,025,106	906,517	1,159,208
1988	1,649,649	1,483,714	1,834,142	1,022,684	901,924	1,159,613
1989	1,661,843	1,503,879	1,836,401	1,021,564	900,448	1,158,970
1990	1,677,447	1,528,368	1,841,067	1,024,476	904,795	1,159,988
1991	1,687,671	1,547,406	1,840,650	1,026,010	909,595	1,157,325
1992	1,688,368	1,556,078	1,831,906	1,022,963	911,426	1,148,148
1993	1,683,597	1,557,762	1,819,597	1,019,715	914,434	1,137,117
1994	1,679,378	1,558,094	1,810,103	1,021,755	923,308	1,130,699
1995	1,669,024	1,550,671	1,796,410	1,020,285	928,176	1,121,534
1996	1,662,288	1,545,611	1,787,773	1,020,583	933,650	1,115,611
1997	1,651,540	1,535,545	1,776,296	1,017,262	933,996	1,107,951
1998	1,652,004	1,536,079	1,776,678	1,018,976	937,623	1,107,388
1999	1,663,868	1,547,624	1,788,843	1,020,150	939,722	1,107,461
2000	1,688,100	1,571,932	1,812,853	1,015,203	935,343	1,101,880
2001	1,715,262	1,598,919	1,840,070	1,003,875	924,287	1,090,316
2002	1,748,319	1,630,938	1,874,147	999,303	919,577	1,085,942
2003	1,773,128	1,654,535	1,900,222	1,000,145	920,060	1,087,201
2004	1,778,310	1,659,239	1,905,926	1,004,905	924,265	1,092,581
2005	1,789,573	1,670,903	1,916,671	1,034,884	953,420	1,123,310
2006	1,787,981	1,670,501	1,913,723	1,071,621	988,517	1,161,712
2007	1,769,348	1,653,878	1,892,881	1,095,267	1,009,582	1,188,225
2008	1,743,722	1,631,120	1,864,097	1,101,277	1,015,617	1,194,161
2009	1,703,458	1,594,776	1,819,546	1,090,113	1,006,673	1,180,470
2010	1,657,223	1,553,323	1,768,074	1,076,393	995,576	1,163,770
2011	1,603,599	1,504,787	1,708,899	1,060,737	982,317	1,145,418
2012	1,539,815	1,445,808	1,639,935	1,036,230	960,129	1,118,362
2013	1,489,566	1,399,516	1,585,409	1,013,306	940,097	1,092,217
2014	1,442,978	1,355,749	1,535,820	981,021	911,605	1,055,723
2015	1,387,061	1,301,373	1,478,391	929,372	864,006	999,684

2016	1,357,597	1,272,104	1,448,836	889,749	827,765	956,374
2017	1,338,415	1,252,215	1,430,549	852,797	793,143	916,937
2018	1,326,028	1,238,549	1,419,685	817,917	759,653	880,649
2019	1,335,305	1,245,227	1,431,900	798,653	740,986	860,808
2020	1,346,311	1,251,491	1,448,315	780,881	722,975	843,424
2021	1,361,869	1,259,907	1,472,084	770,390	711,383	834,292
2022	1,386,595	1,275,861	1,506,940	778,417	717,875	844,066
2023	1,404,788	1,284,367	1,536,499	797,174	734,418	865,293
2024	1,421,443	1,290,817	1,565,289	826,712	759,948	899,342
2025	1,425,564	1,284,574	1,582,029	849,005	776,162	928,683
2026	1,433,446	1,282,075	1,602,690	867,675	787,930	955,491

Table 7.18: Estimated age 1 recruitment (x 1,000), from Model 25.0. Lower 95% and upper 95% uncertainty intervals (CIs) are provided.

Year	Recruitment (thousands)	95% LCI (thousands)	95% UCI (thousands)
1977	706,214	407,799	1,223,000
1978	705,712	407,987	1,220,699
1979	704,981	408,479	1,216,704
1980	712,132	413,418	1,226,681
1981	720,416	419,301	1,237,772
1982	729,632	426,388	1,248,539
1983	733,904	431,015	1,249,645
1984	738,186	436,113	1,249,488
1985	789,276	471,028	1,322,547
1986	784,776	471,873	1,305,168
1987	831,476	505,182	1,368,521
1988	873,263	535,906	1,422,987
1989	799,527	495,401	1,290,355
1990	758,447	472,464	1,217,538
1991	840,818	531,108	1,331,132
1992	823,209	521,307	1,299,951
1993	725,604	458,679	1,147,865
1994	713,501	453,151	1,123,429
1995	783,794	505,707	1,214,802
1996	743,551	476,367	1,160,592
1997	825,569	531,369	1,282,656
1998	954,564	618,599	1,472,992
1999	992,349	637,429	1,544,889
2000	1,370,102	903,097	2,078,603
2001	849,555	547,516	1,318,214
2002	781,083	510,054	1,196,130
2003	759,348	498,948	1,155,651
2004	750,632	493,982	1,140,626
2005	778,543	517,608	1,171,019
2006	766,261	516,048	1,137,792
2007	606,450	401,338	916,388
2008	594,460	401,578	879,987
2009	490,880	323,971	743,779
2010	455,962	298,195	697,201
2011	524,629	354,813	775,721
2012	569,431	387,853	836,018
2013	651,708	452,746	938,105
2014	578,721	392,452	853,400
2015	602,287	405,927	893,634

2016	695,965	468,692	1,033,443
2017	825,640	552,626	1,233,530
2018	888,582	588,003	1,342,814
2019	801,538	520,857	1,233,472
2020	708,221	452,009	1,109,663
2021	662,351	414,542	1,058,295
2022	639,997	391,212	1,046,994
2023	670,378	402,650	1,116,124
2024	693,764	406,834	1,183,059
2025	690,679	397,967	1,198,684
2026	714,460	408,276	1,250,267

Table 7.19: Comparative One-Step-Ahead (OSA) goodness-of-fit diagnostics for Model 25.0 and Model 25.1 across major data components.

Data Group	Obs (N)	Model 25.0 SDNR [95% Conf. Interval]	Model 25.1 SDNR [95% Conf. Interval]	Model 25.0 OSA Range	Model 25.1 OSA Range
Survey Age Compositions (Fleet 1)	656	0.833 [0.946, 1.054]	0.873 [0.946, 1.054]	[-1.73, 1.62]	[-1.65, 2.10]
Survey Biomass Index (Fleet 1)	16	2.098 [0.646, 1.354]	1.911 [0.646, 1.354]	[-3.56, 3.64]	[-3.29, 3.28]
Fishery Total Catch (Fleet 3)	50	0.325 [0.802, 1.197]	0.277 [0.802, 1.197]	[-0.61, 0.69]	[-0.59, 0.49]
Fishery Length Compositions (Fleet 3)	1767	0.858 [0.967, 1.033]	0.755 [0.967, 1.033]	[-2.11, 1.26]	[-1.52, 1.45]
All Residuals Combined	2489	0.860 [0.972, 1.028]	0.802 [0.972, 1.028]	[-2.07, 1.36]	[-1.60, 1.69]

Table 7.20: Projected spawning biomass, fishing mortality, and yield for Arrowtooth flounder under seven harvest scenarios (columns) designed to satisfy the requirements of Amendment 56, NEPA, and MSFCMA. Spawning biomass and yield are in t. $B_{40\%}$ = 429,548 t, $B_{35\%}$ = 375,855 t, $F_{40\%}$ = 0.0994 and $F_{35\%}$ = 0.1179 in 2027.

Year	Maximum Permissible F	Author's F*	Half Maximum F	5-Year Average F	No Fishing	Overfished	Approaching Overfished
			Spawning Biomass (t)				
2026	867,675	867,675	867,675	867,675	867,675	867,675	867,675
2027	874,501	874,501	874,501	874,501	874,501	874,501	874,501
2028	879,111	879,111	879,111	879,111	879,111	879,111	879,111
2029	881,522	881,522	881,522	881,522	881,522	762,136	781,146
2030	784,413	784,413	863,369	883,701	894,718	667,380	699,818
2031	704,174	704,174	847,872	887,134	908,794	593,206	619,655
2032	640,107	640,107	835,648	892,115	923,805	536,884	557,942
2033	590,992	590,992	827,468	899,319	940,293	495,712	512,167
2034	554,102	554,102	822,766	908,242	957,712	466,146	478,831
2035	526,319	526,319	820,363	917,854	975,043	444,839	454,405
2036	505,302	505,302	819,335	927,351	991,498	431,441	438,107
2037	490,217	490,217	819,440	936,629	1,007,000	423,765	428,291
2038	479,732	479,732	820,066	945,208	1,021,111	419,445	422,448
2039	471,234	471,234	819,408	951,357	1,032,111	415,826	417,771
2040	464,263	464,263	817,486	955,132	1,040,062	412,761	413,981
			Fishing Mortality (fully-selected F)				
2026	0.0118	0.0118	0.0118	0.0118	-	0.0118	0.0118
2027	0.0087	0.0087	0.0087	0.0087	-	0.0087	0.0087
2028	0.0087	0.0087	0.0087	0.0087	-	0.1179	0.0994
2029	0.0994	0.0994	0.0269	0.0093	-	0.1179	0.0994
2030	0.0994	0.0994	0.0269	0.0093	-	0.1179	0.1179
2031	0.0994	0.0994	0.0269	0.0093	-	0.1179	0.1179
2032	0.0994	0.0994	0.0269	0.0093	-	0.1179	0.1179
2033	0.0994	0.0994	0.0269	0.0093	-	0.1179	0.1179
2034	0.0994	0.0994	0.0269	0.0093	-	0.1177	0.1179
2035	0.0994	0.0994	0.0269	0.0093	-	0.1128	0.1141
2036	0.0981	0.0981	0.0269	0.0093	-	0.1088	0.1098
2037	0.0961	0.0961	0.0269	0.0093	-	0.1064	0.1072
2038	0.0945	0.0945	0.0269	0.0093	-	0.1051	0.1055
2039	0.0933	0.0933	0.0269	0.0093	-	0.1040	0.1043
2040	0.0926	0.0926	0.0269	0.0093	-	0.1034	0.1036
			Yield (t)				
2026	16,835	16,835	16,835	16,835	-	16,835	16,835
2027	12,409	12,409	12,409	12,409	-	12,409	12,409
2028	12,409	12,409	12,409	12,409	-	157,060	133,901
2029	133,774	133,774	37,867	13,294	-	137,049	119,520

2030	119,847	119,847	37,077	13,303	-	121,986	127,266
2031	109,214	109,214	36,519	13,359	-	111,156	115,242
2032	101,457	101,457	36,190	13,461	-	103,706	106,789
2033	96,002	96,002	36,058	13,601	-	98,759	101,043
2034	92,192	92,192	36,052	13,756	-	95,319	97,143
2035	89,504	89,504	36,113	13,912	-	90,252	92,230
2036	86,868	86,868	36,202	14,056	-	86,876	88,240
2037	84,362	84,362	36,283	14,180	-	85,124	85,996
2038	82,404	82,404	36,311	14,271	-	84,062	84,598
2039	80,811	80,811	36,263	14,321	-	83,069	83,397
2040	79,636	79,636	36,162	14,339	-	82,332	82,517

*Projections are based on estimated catches of 12,409 t and 12,409 t used in place of maximum permissible ABC for 2027 and 2028 in response to a Plan Team request to obtain more accurate two-year projections.

Figures

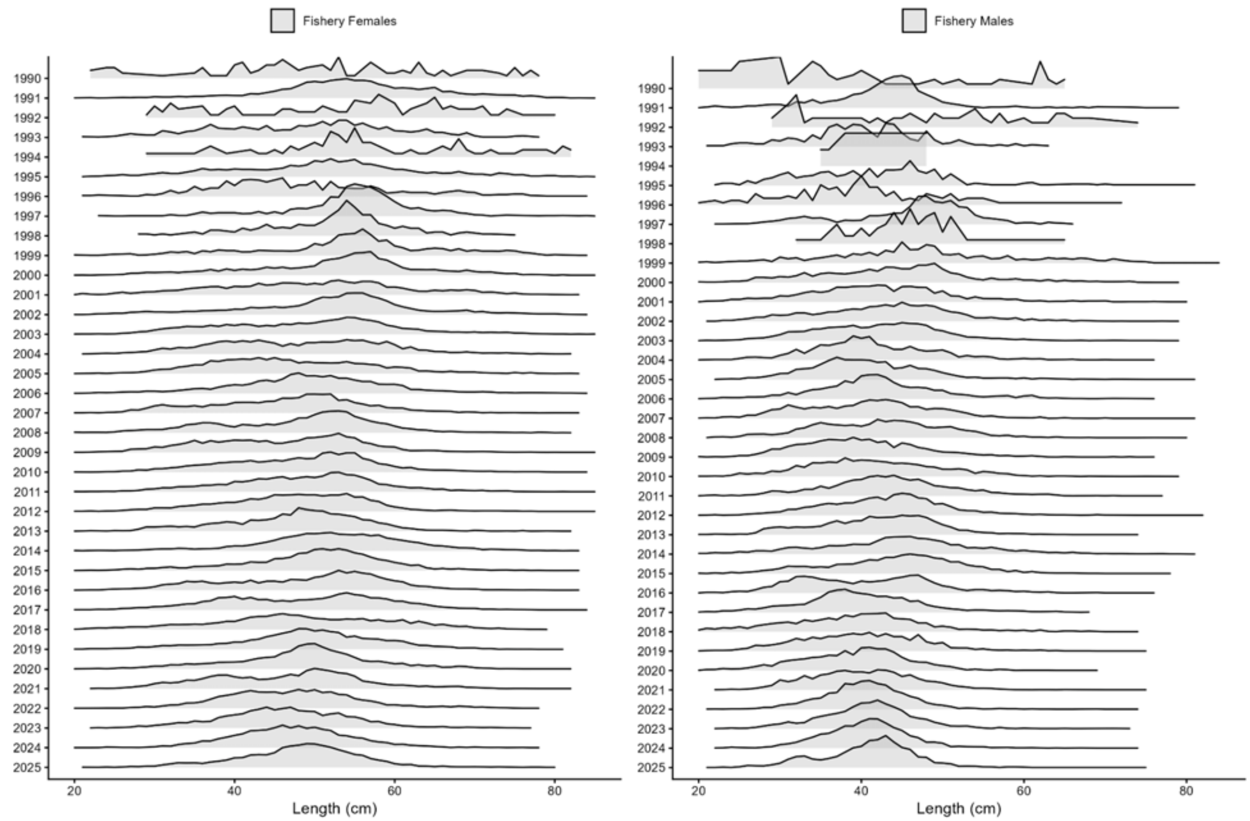


Figure 7.1. Length distribution from fisheries observers from 1990 to present.

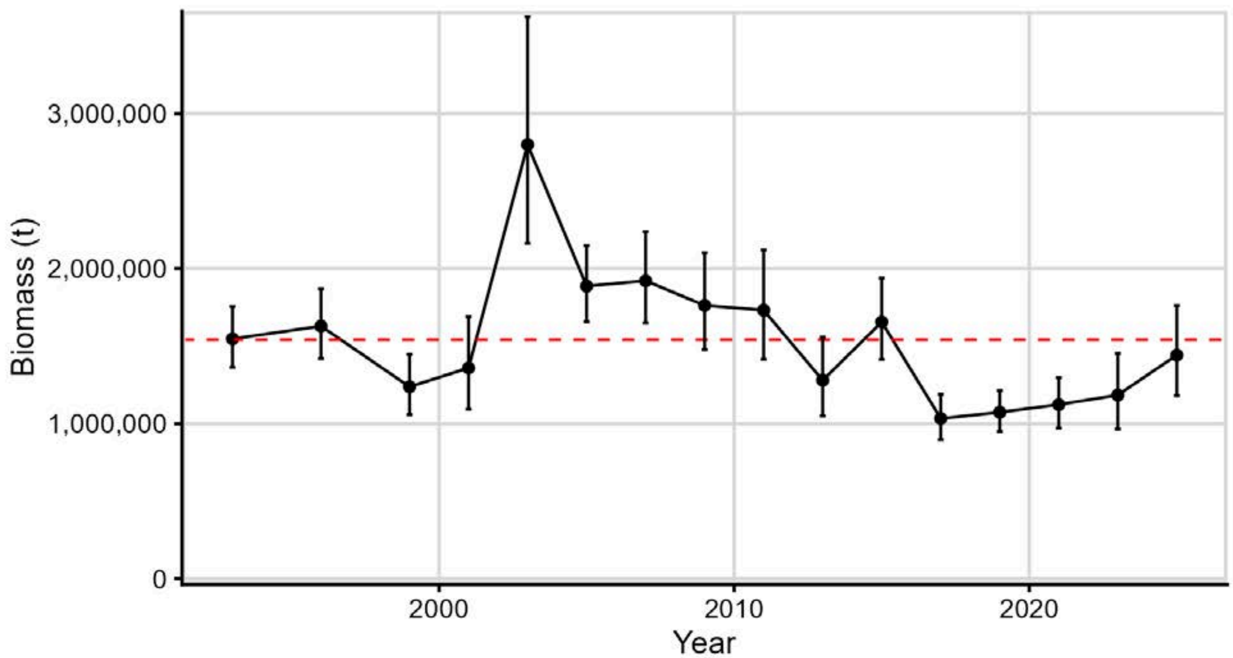


Figure 7.2. Biomass estimates of arrowtooth flounder from the Alaska Fisheries Science Center (AFSC) bottom trawl survey 1993 to the most recent survey.

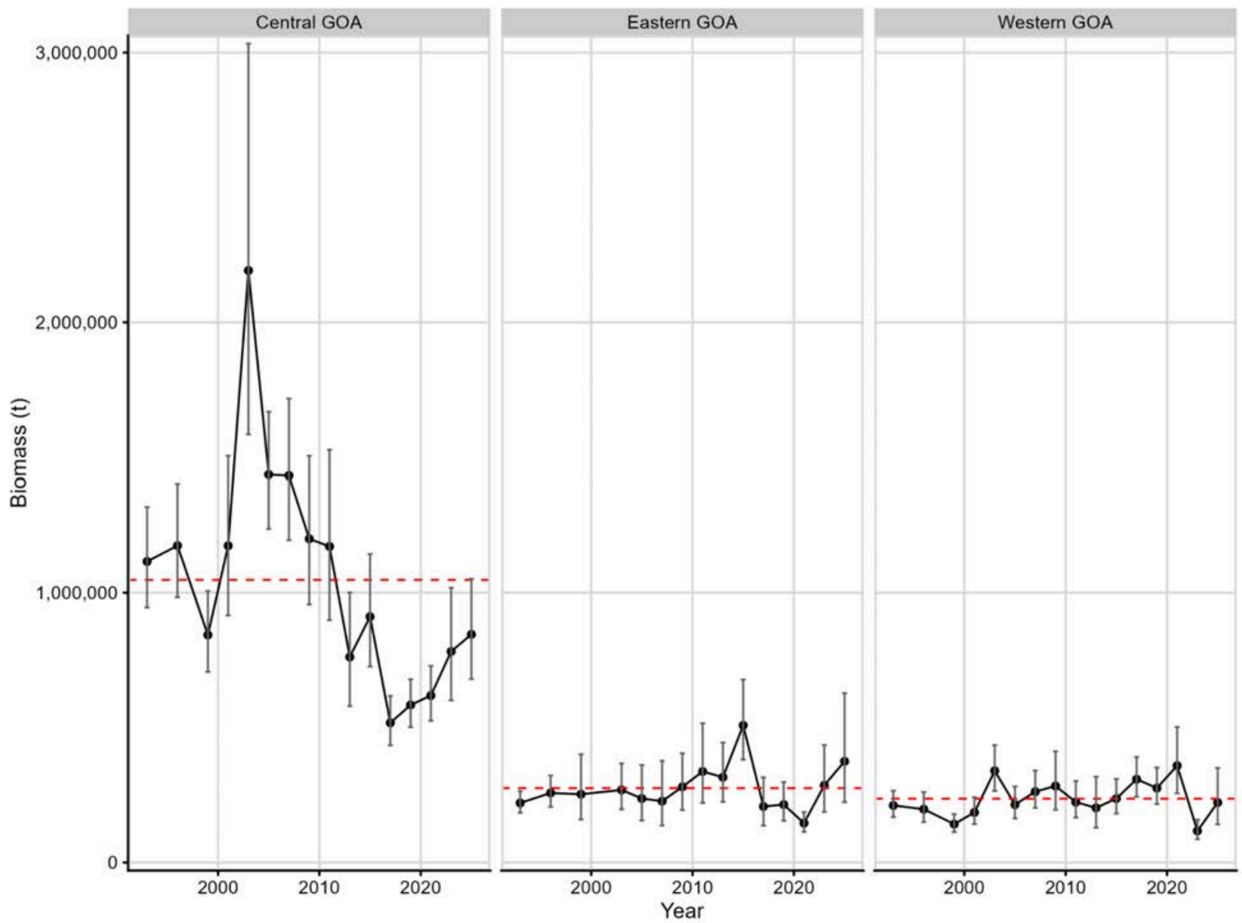


Figure 7.3. Area specific biomass estimates of arrowtooth flounder from the Alaska Fisheries Science Center (AFSC) bottom trawl survey 1993 to the most recent survey.

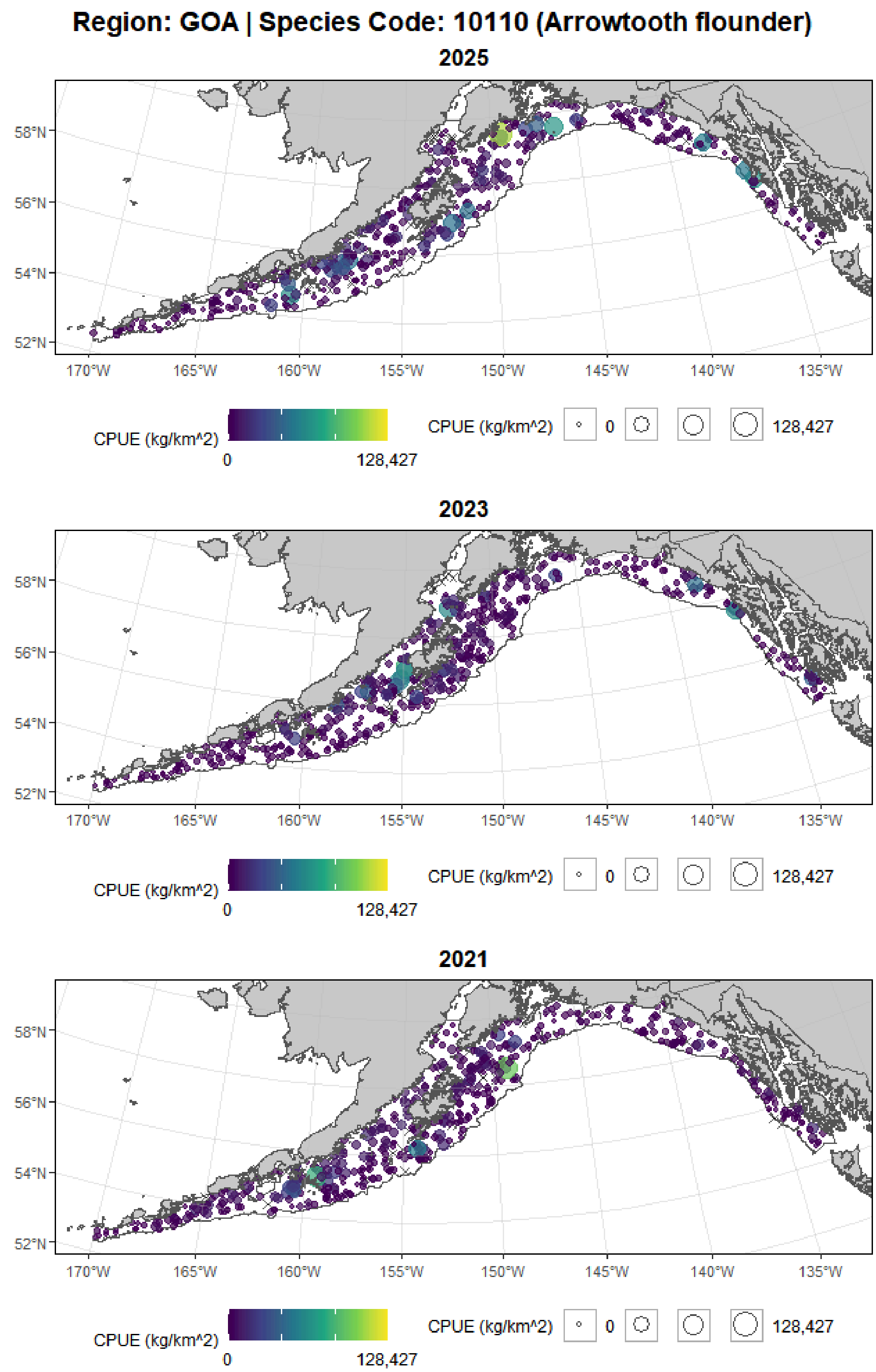


Figure 7.4 Arrowtooth flounder survey cpue by tow from the Alaska Fisheries Science Center (AFSC) bottom trawl survey for three most recent surveys.

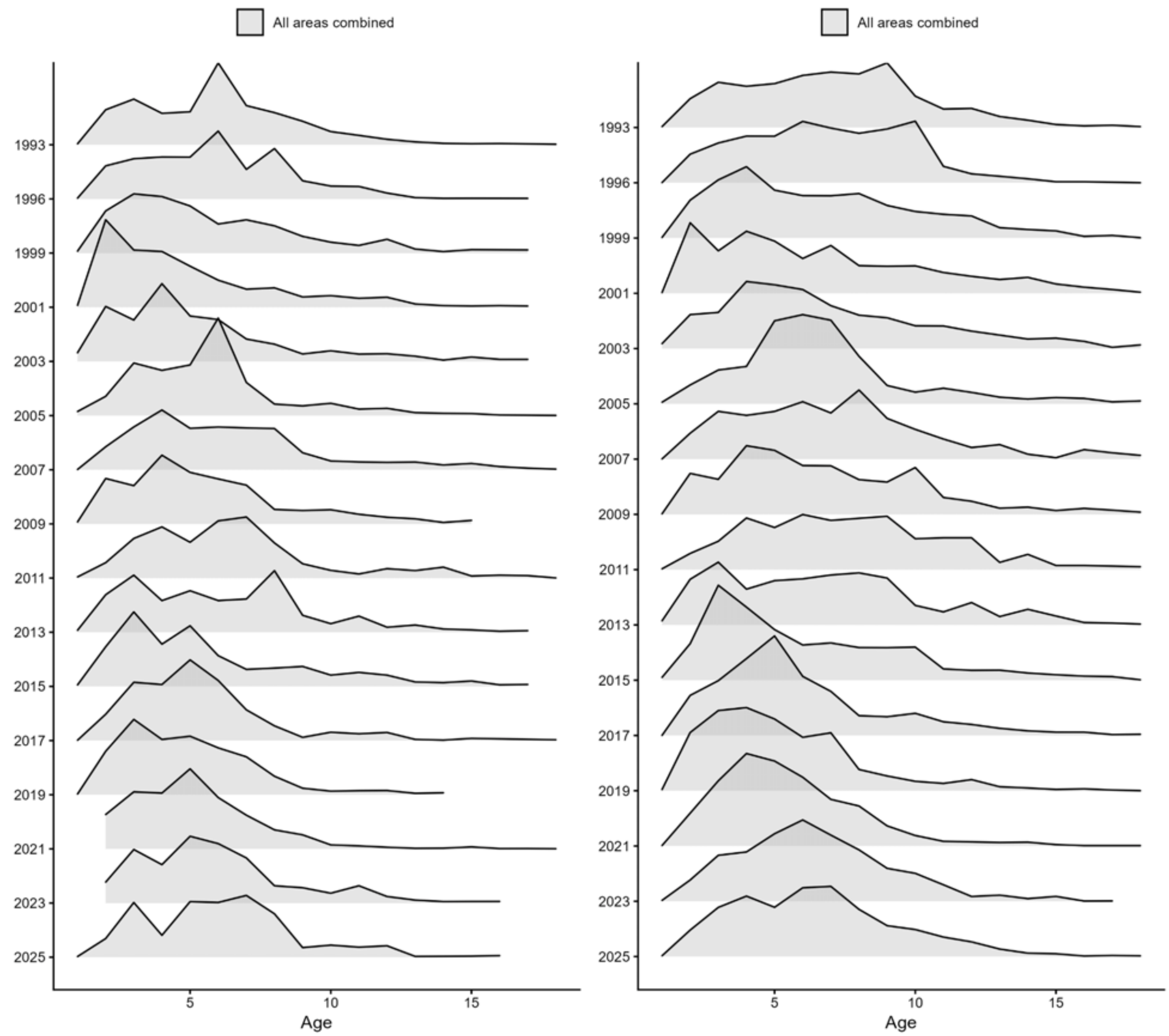


Figure 7.5. Age composition data for female (on the right) and male (on the left) arrowtooth flounder from the Alaska Fisheries Science Center (AFSC) bottom trawl surveys 1993 to the present.

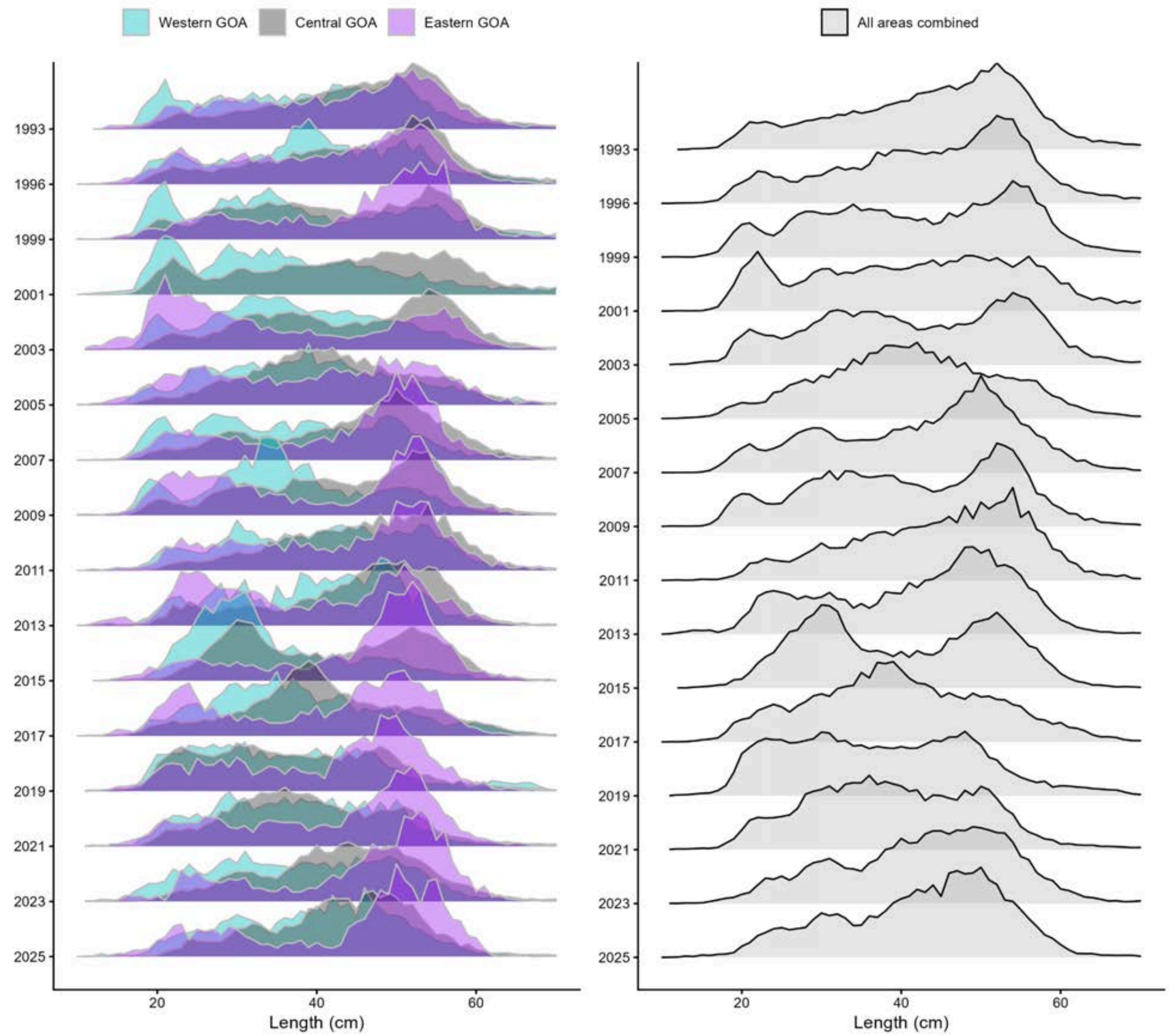


Figure 7.6a. Length composition data for female arrowtooth flounder from the Alaska Fisheries Science Center (AFSC) bottom trawl surveys 1993 to the present.

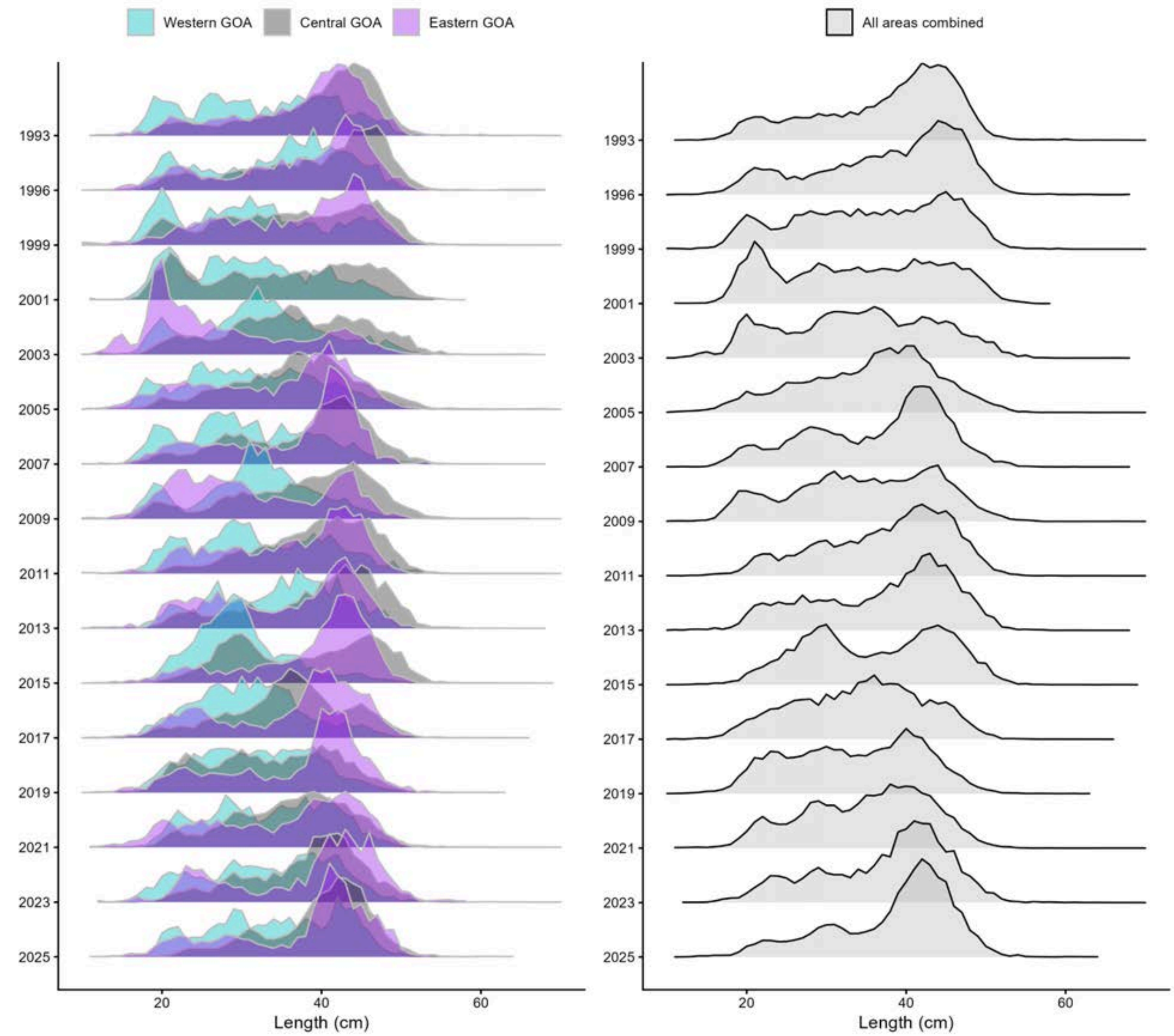


Figure 7.6b. Length composition data for male arrowtooth flounder from the Alaska Fisheries Science Center (AFSC) bottom trawl surveys 1993 to the present.

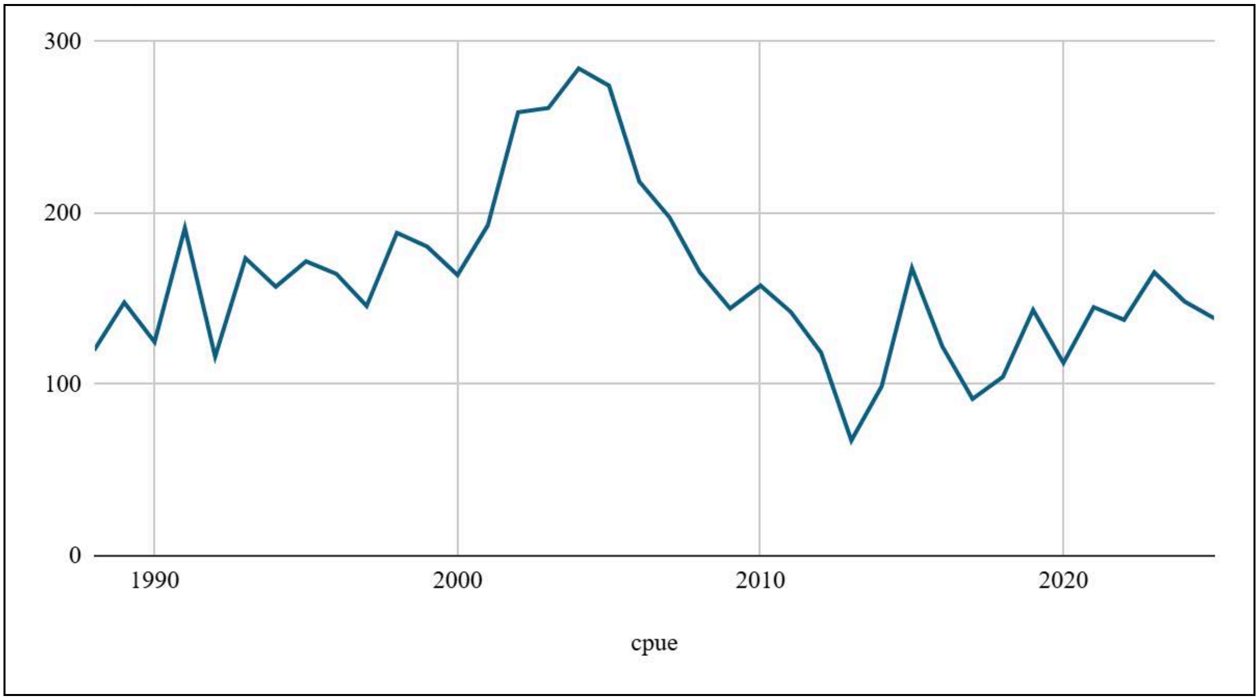


Figure 7.7. Catch per unit of effort for arrowtooth flounder from the Alaska Department of Fish and Game (ADF&G) large-mesh bottom trawl survey 1988 to present.

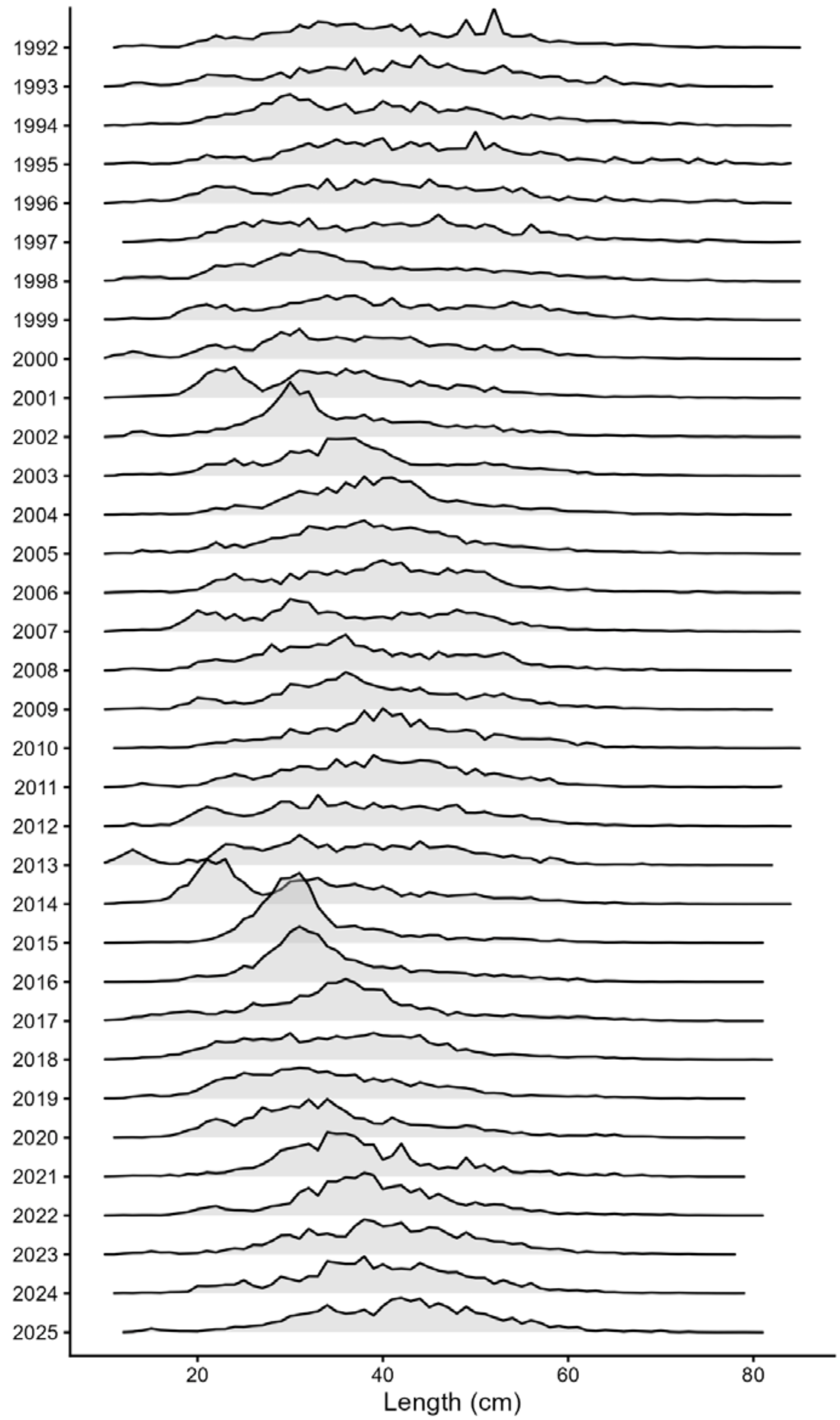


Figure 7.8. Length composition data for arrowtooth flounder from the Alaska Department of Fish and Game (ADF&G) large-mesh bottom trawl surveys 1993 to the present.

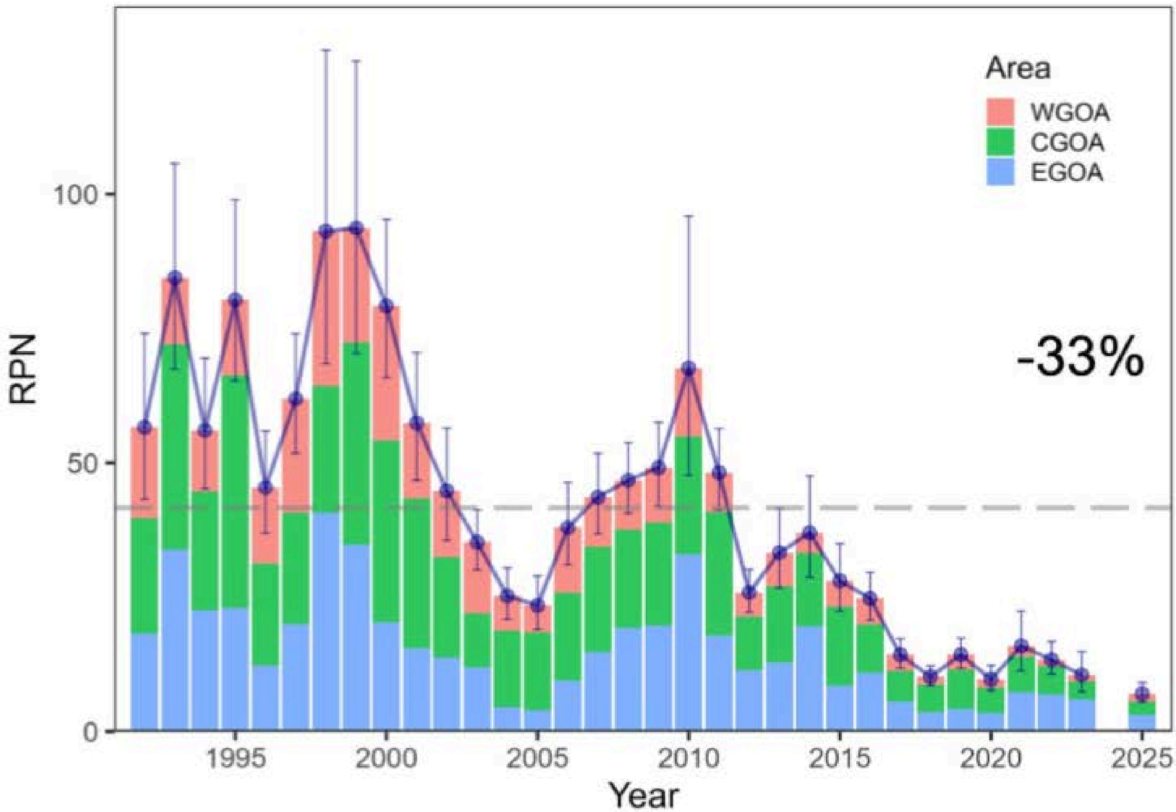


Figure 7.9. Relative population numbers for arrowtooth flounder and Kamchatka flounder combined from the Alaska Fisheries Science Center (AFSC) longline survey 1992 to the most current survey. The percentage in bold represents the change to the most recent survey estimate from the previous survey estimate.

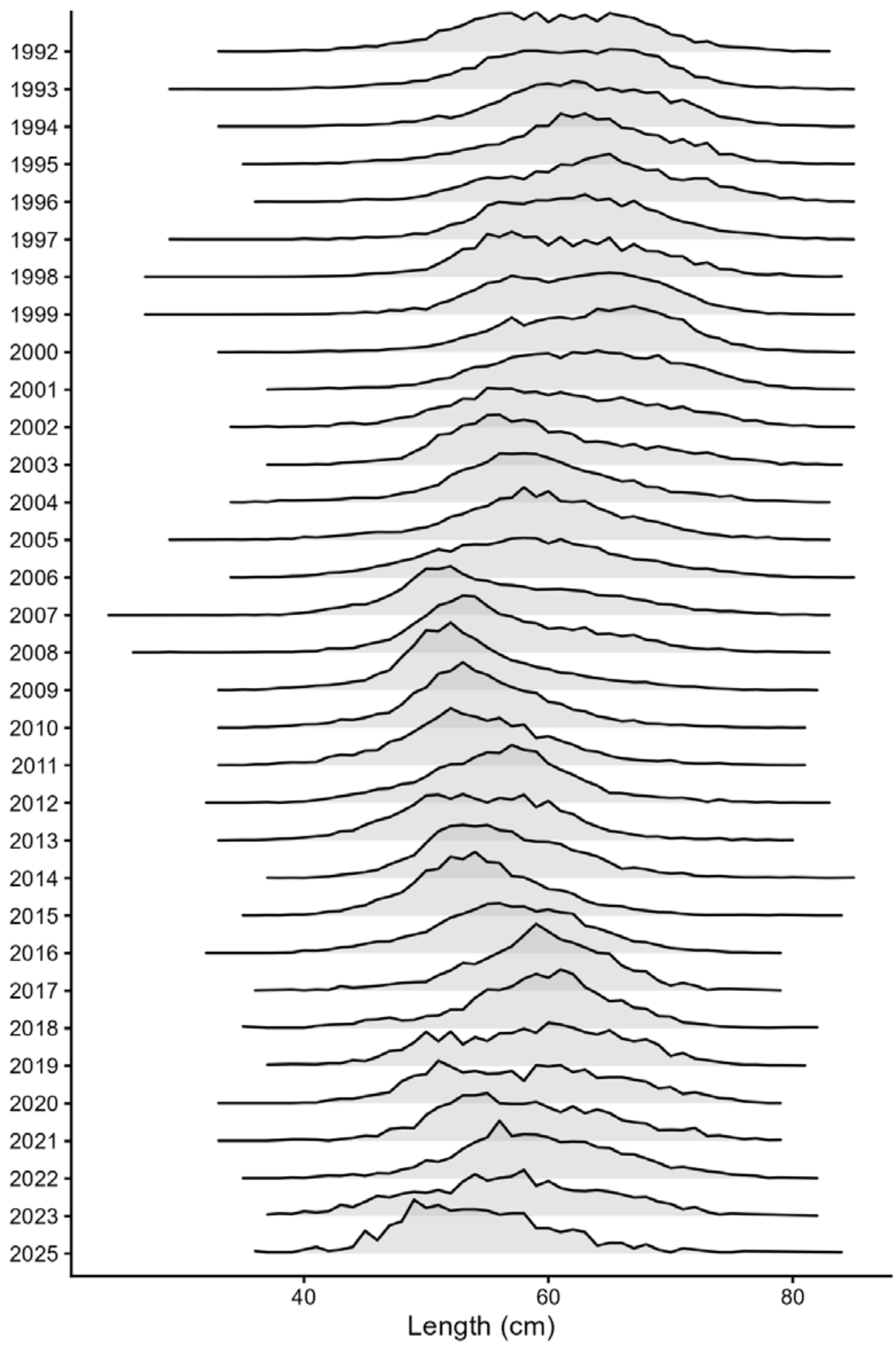


Figure 7.10. Length composition data for arrowtooth flounder from the Alaska Fisheries Science Center (AFSC) longline surveys 1992 to the present.

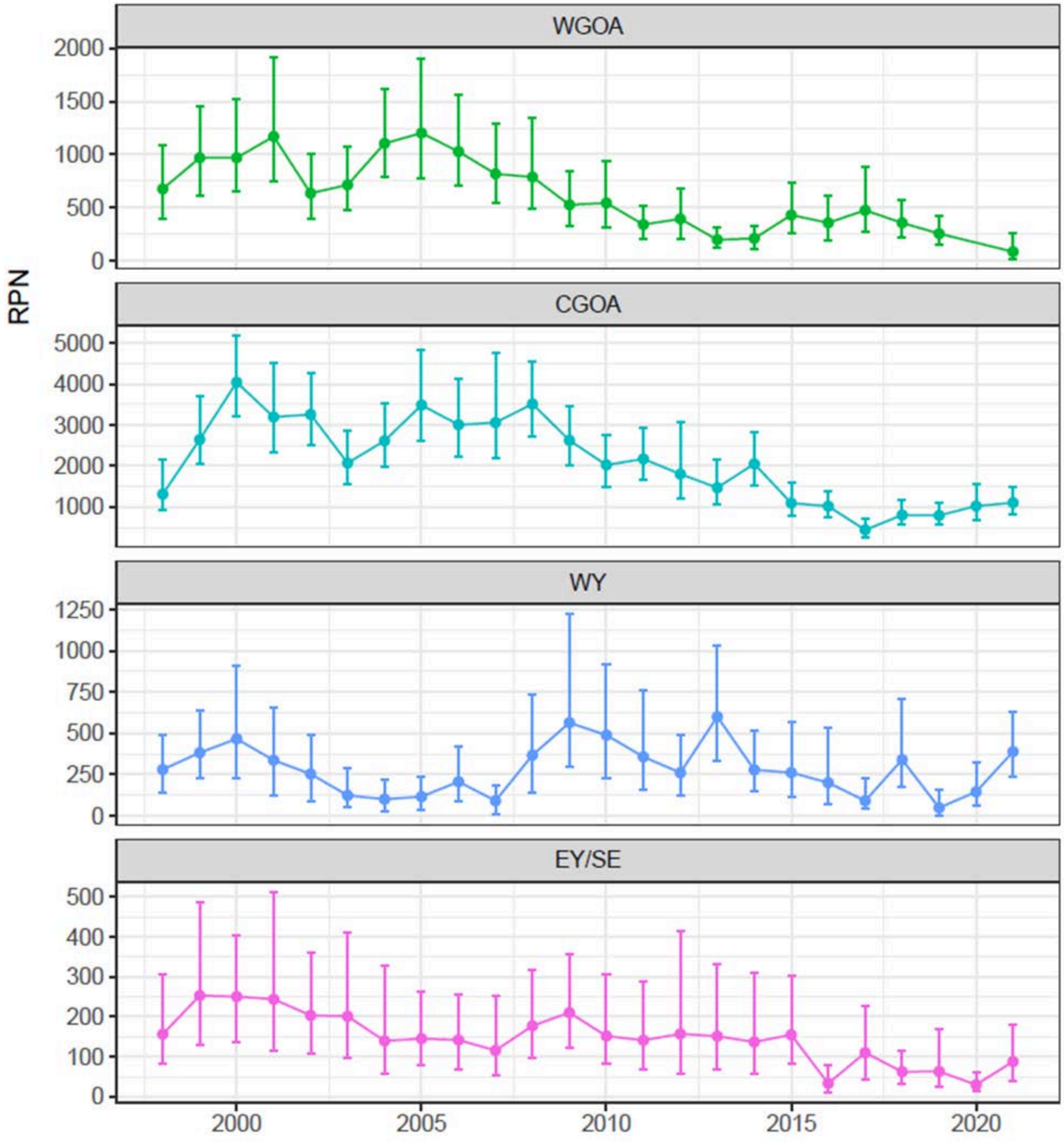


Figure 7.11. Relative population numbers (RPN) for arrowtooth flounder from the International Pacific Halibut Commission (IPHC) survey 1998 to 2021 (Note: this will be updated in November). WGOA = western Gulf of Alaska, CGOA = central Gulf of Alaska, WY = west yakutat, EY/SE = east yakutat/southeast Alaska.

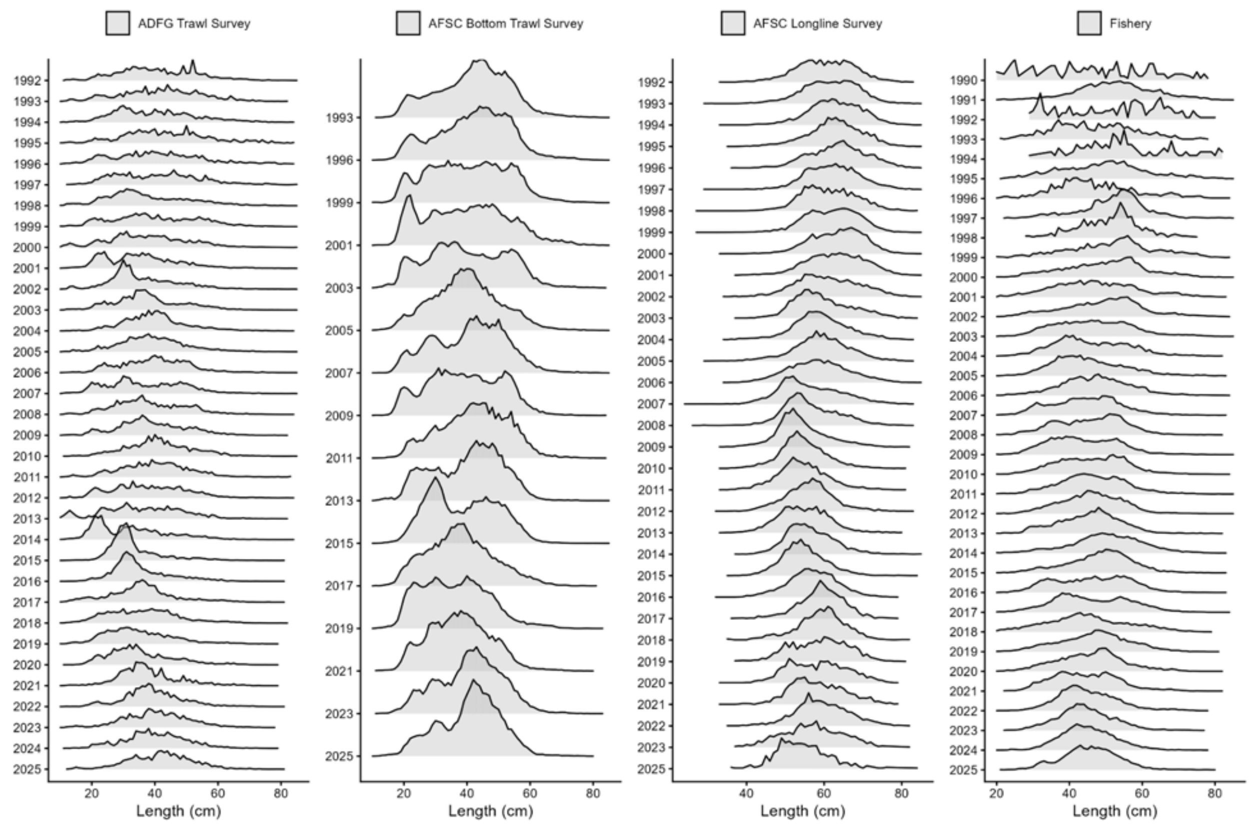


Figure 7.12. Comparison of length compositions across multiple data sources for GOA arrowtooth flounder.

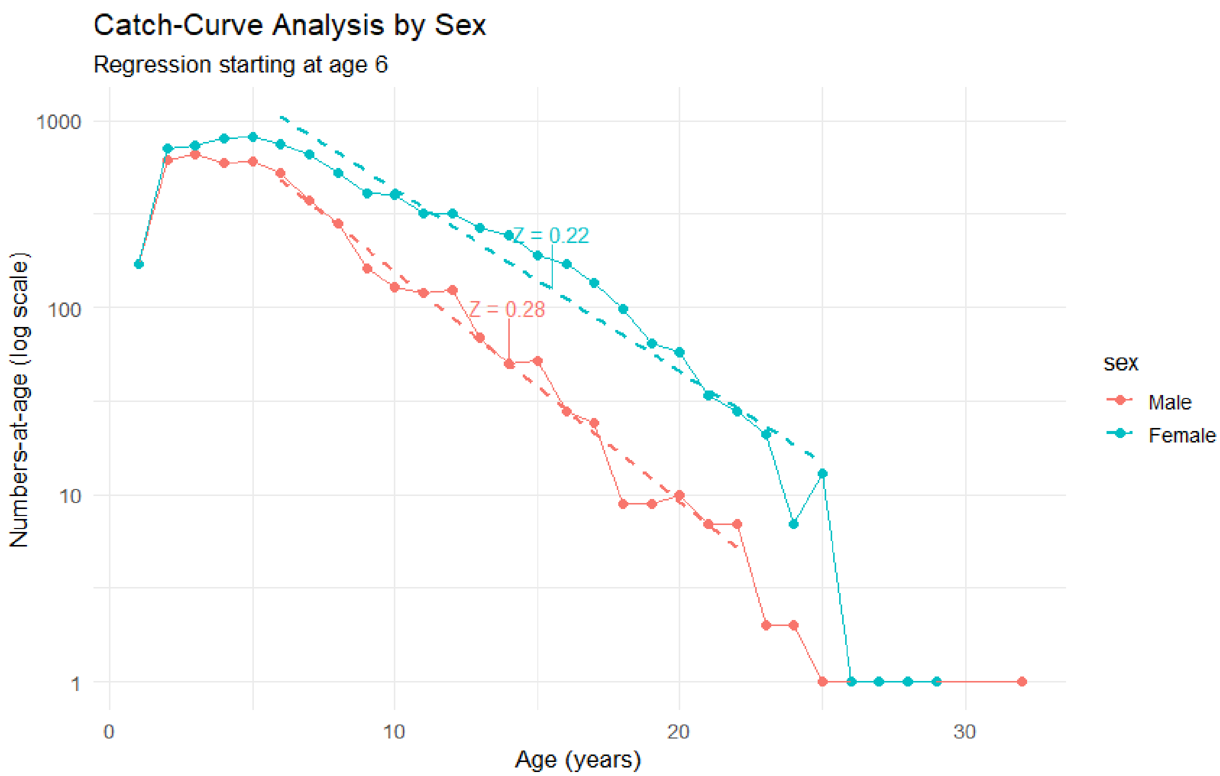


Figure 7.13. Catch curves for male and female arrowtooth flounder with associated estimates of total mortality.

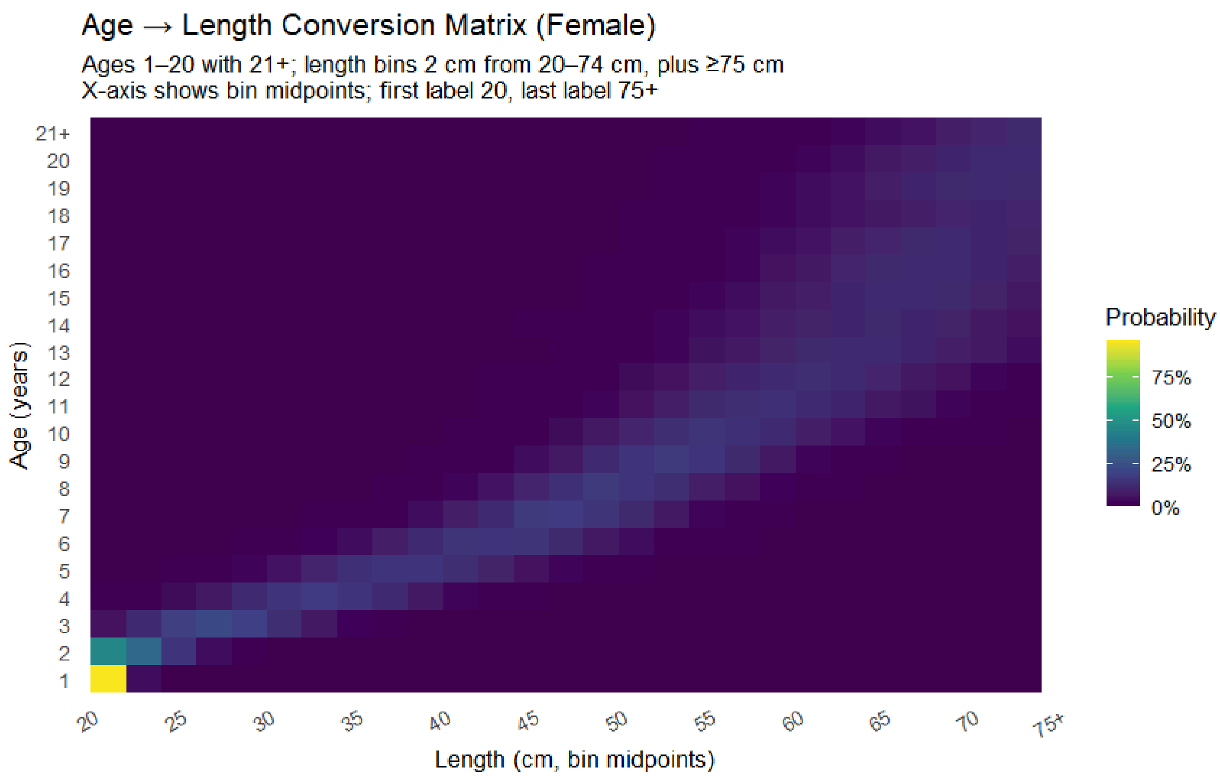


Figure 7.14a. Length conversion matrix for female arrowtooth flounder.

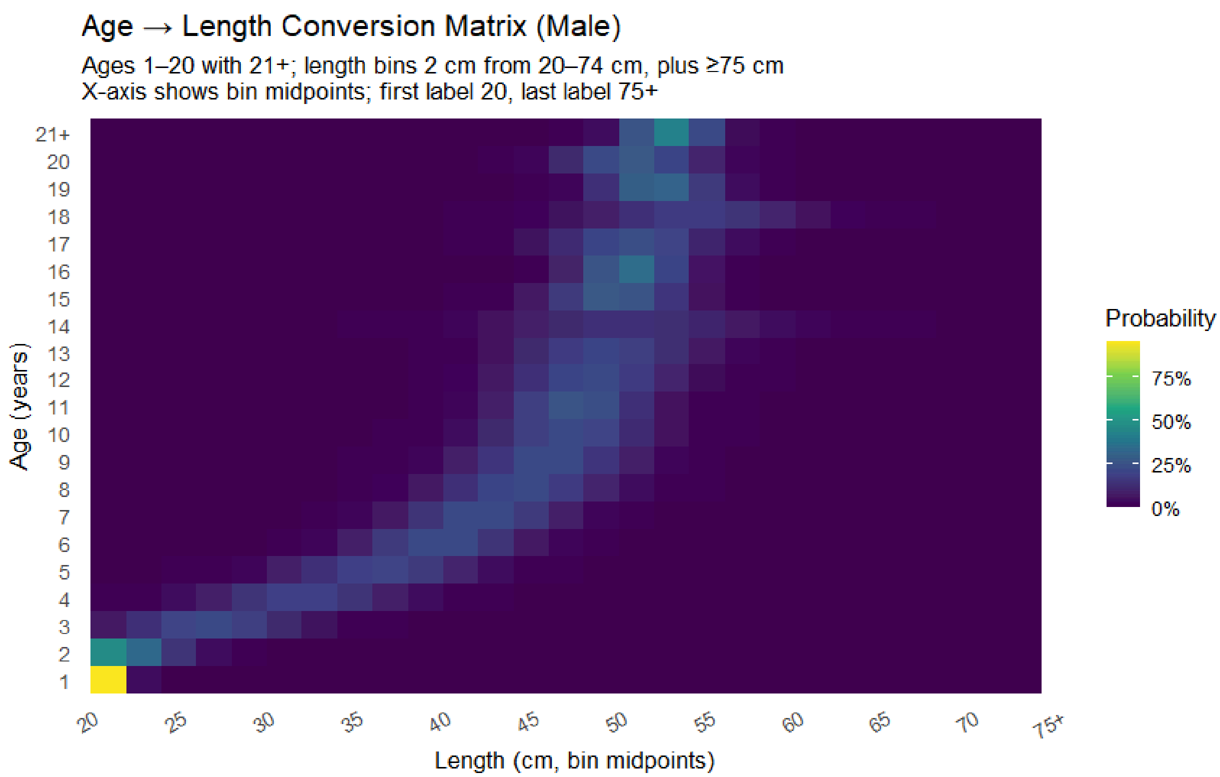


Figure 7.14b. Length conversion matrix for male arrowtooth flounder.

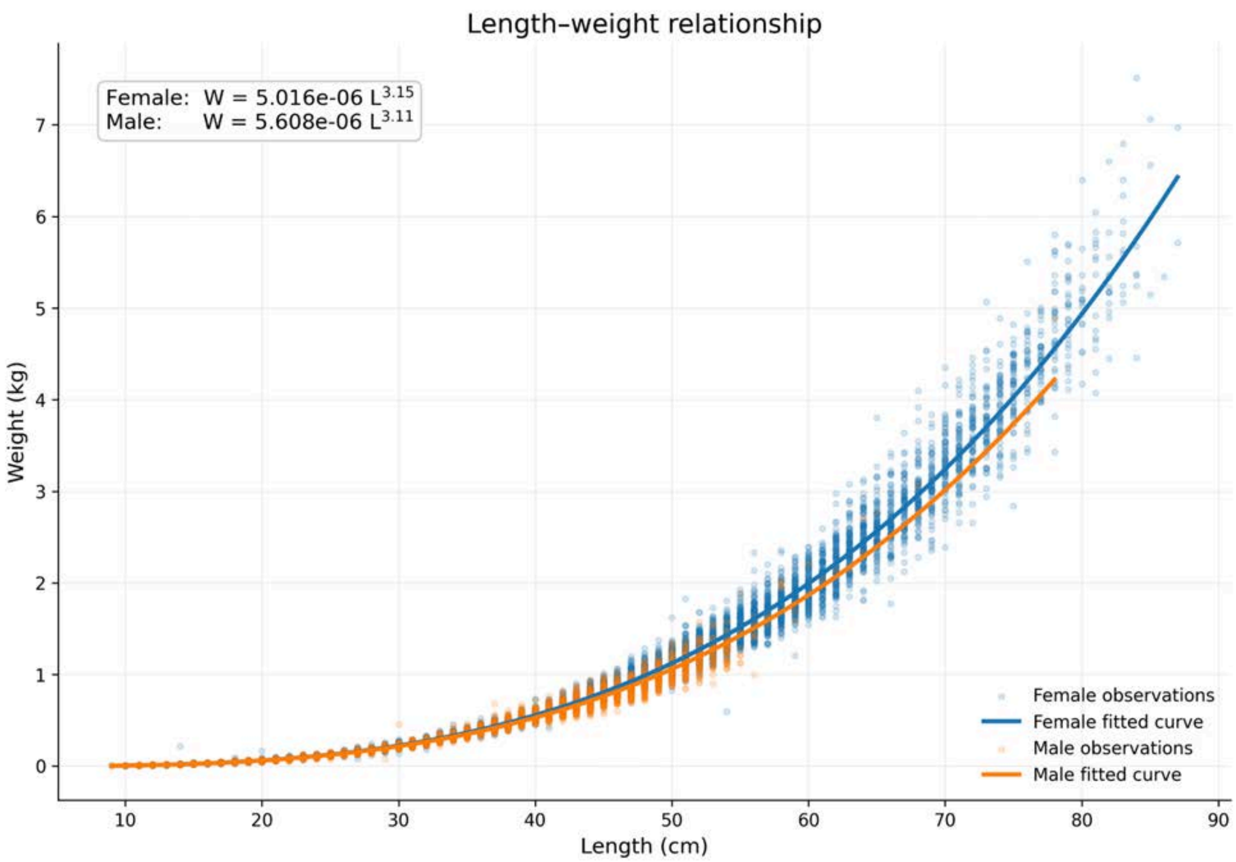


Figure 7.15. Allometric length-weight relationship for female and male arrowtooth flounder from AFSC bottom trawl survey 1993 to 2023.

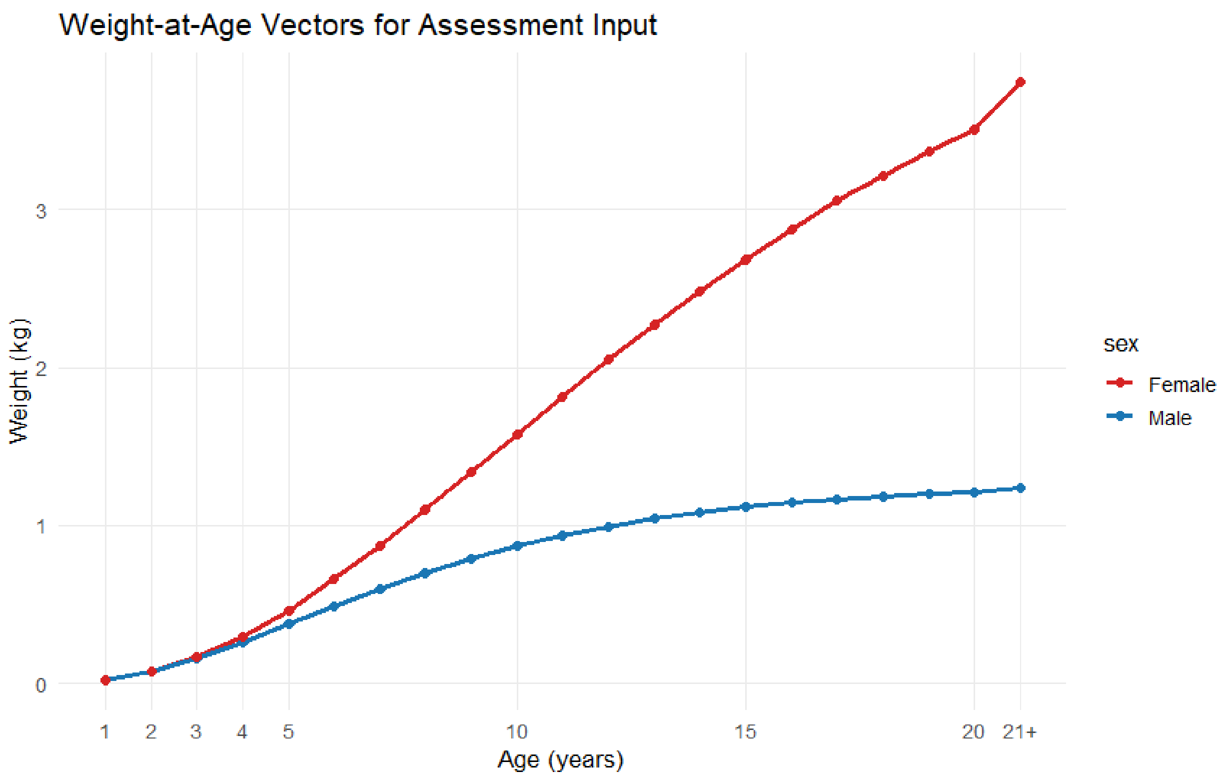


Figure 7.16. Weight at age vectors for female and male arrowtooth flounder.

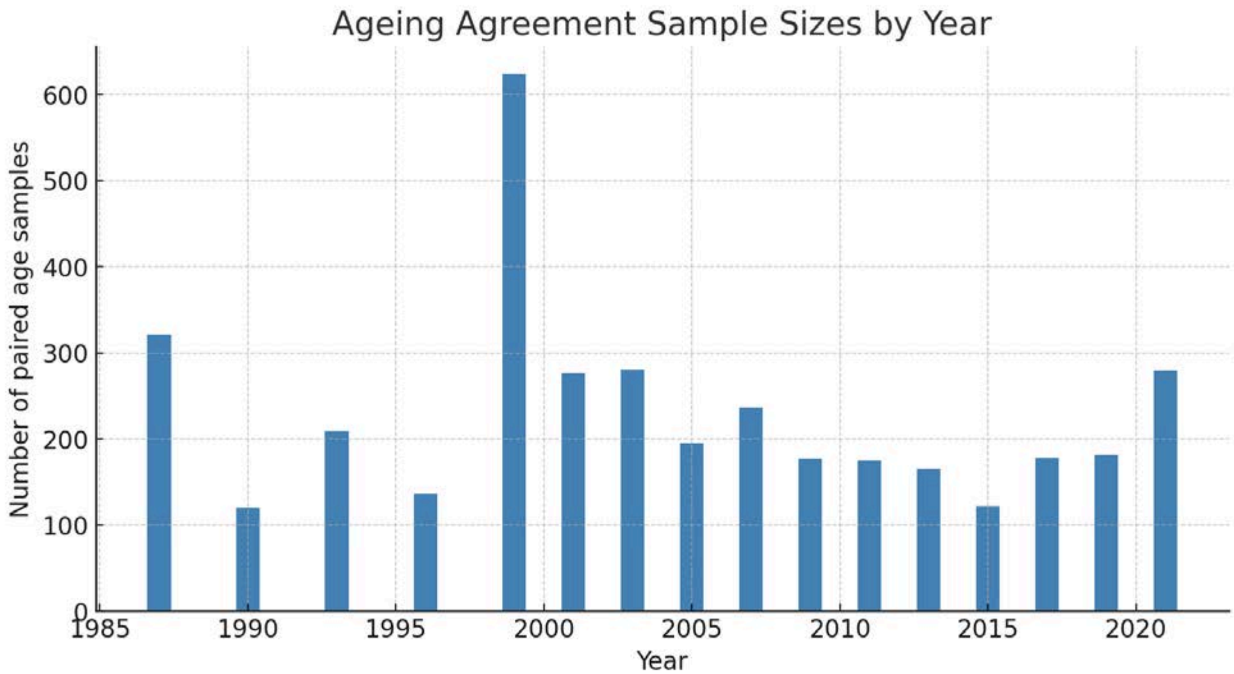


Figure 7.17. Sample sizes of raw paired age reading for arrowtooth flounder from Gulf of Alaska AFSC bottom trawl surveys through 2021.

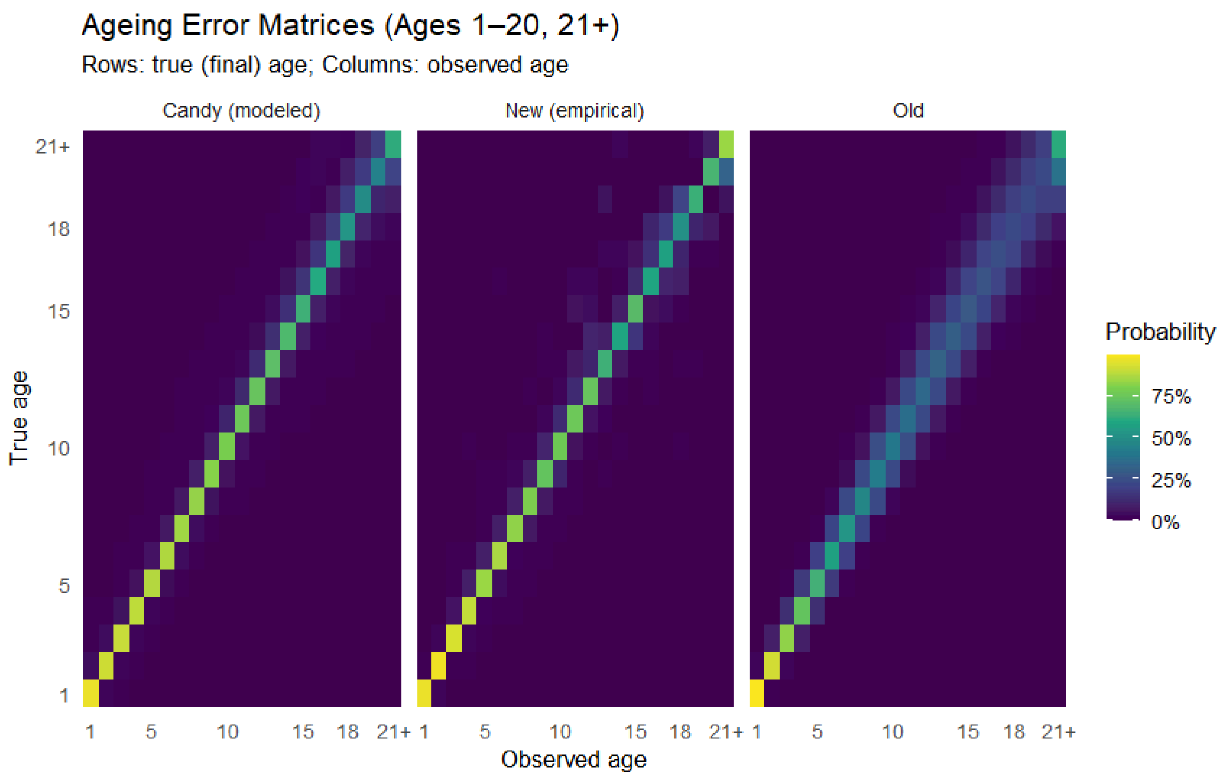


Figure 7.18a. Comparison of three ageing error matrices from the previous stock assessment, empirically-derived, and Candy et al., 2012 framework.

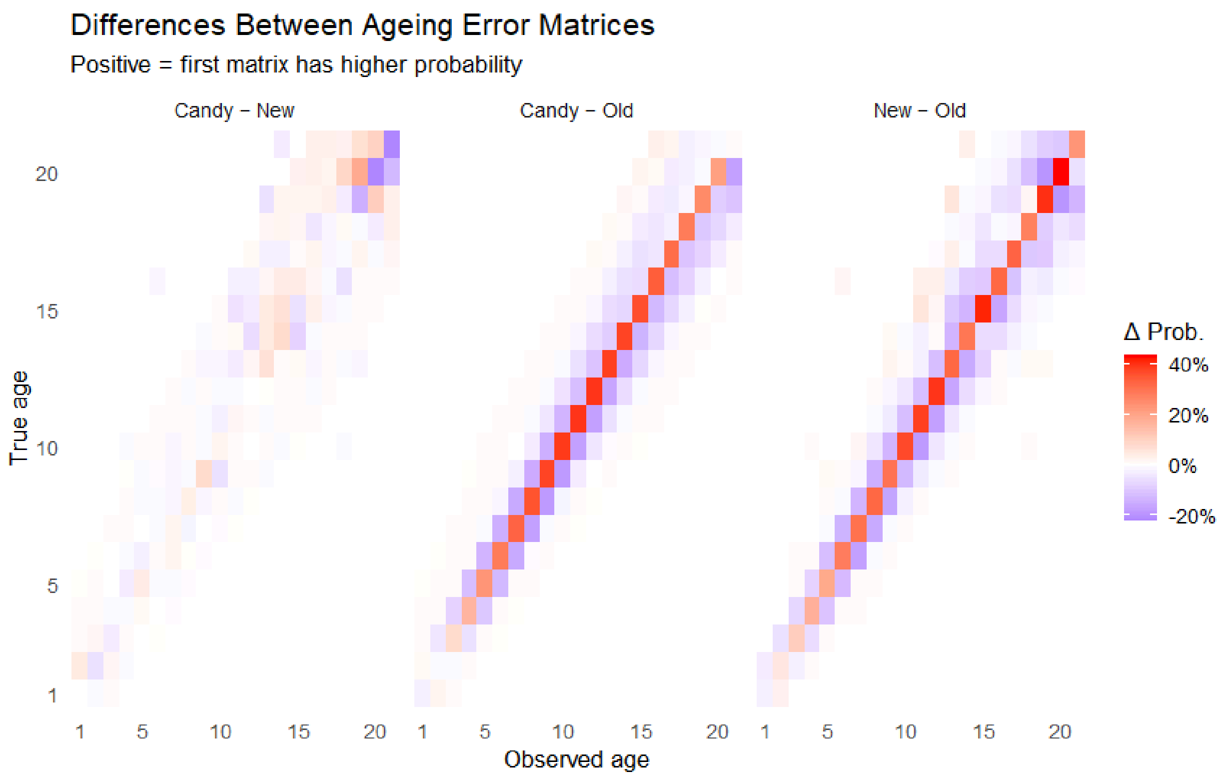


Figure 7.18b. Differences between three ageing error matrices for arrowtooth flounder from the previous stock assessment, empirically-derived, and Candy et al., 2012 framework.

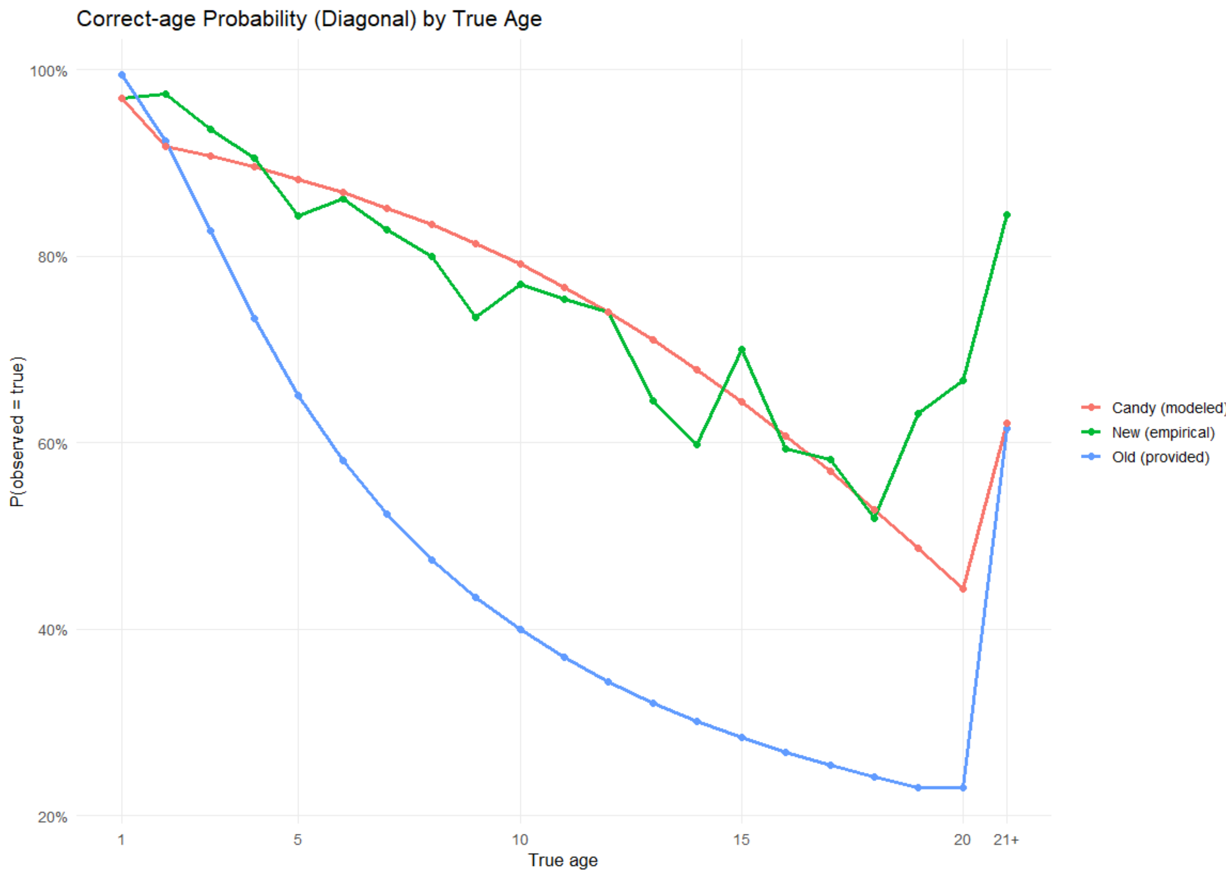


Figure 7.19. Diagonal probabilities for three ageing error matrices of arrowtooth flounder from the previous stock assessment, empirically-derived, and Candy et al., 2012 framework.

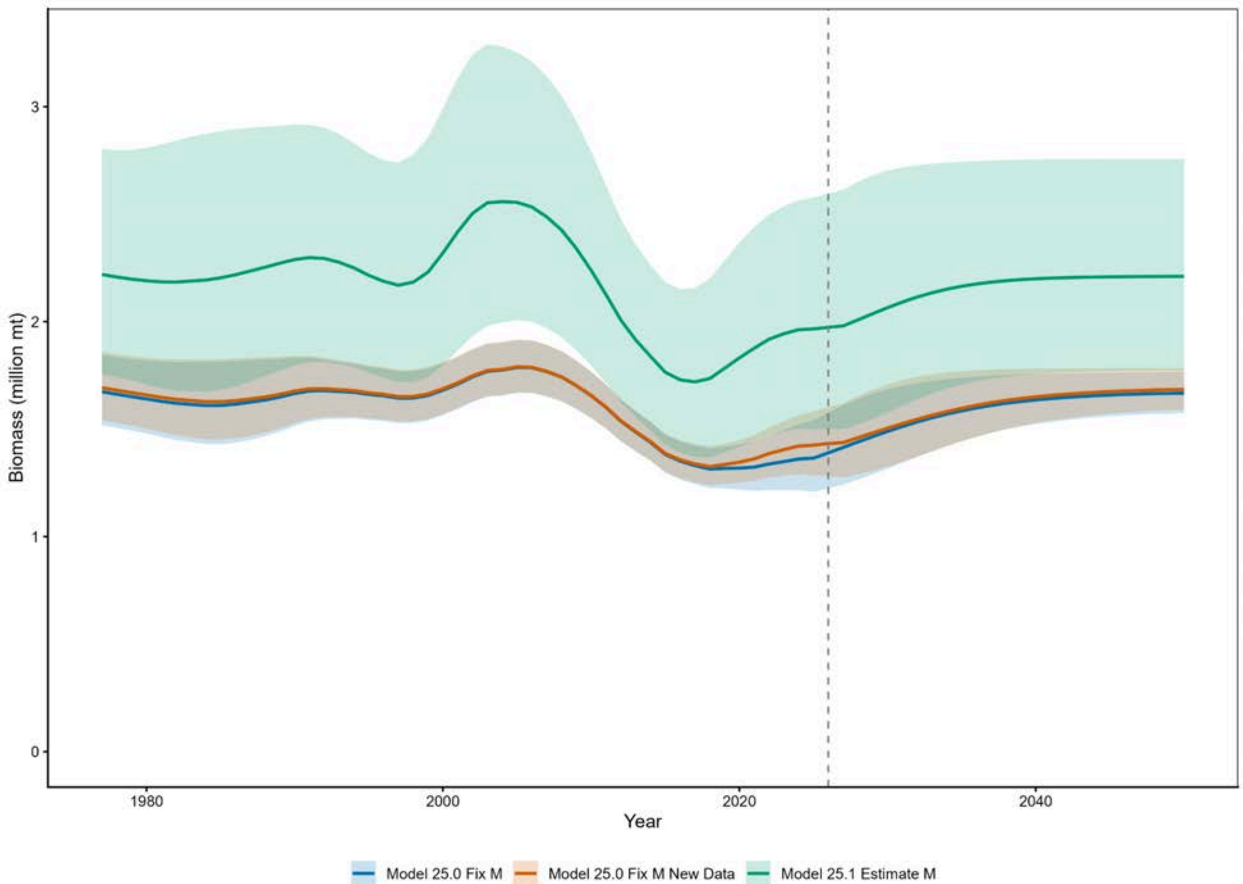


Figure 7.20a: Comparison of total biomass (age 1+) from the three models for arrowtooth flounder.

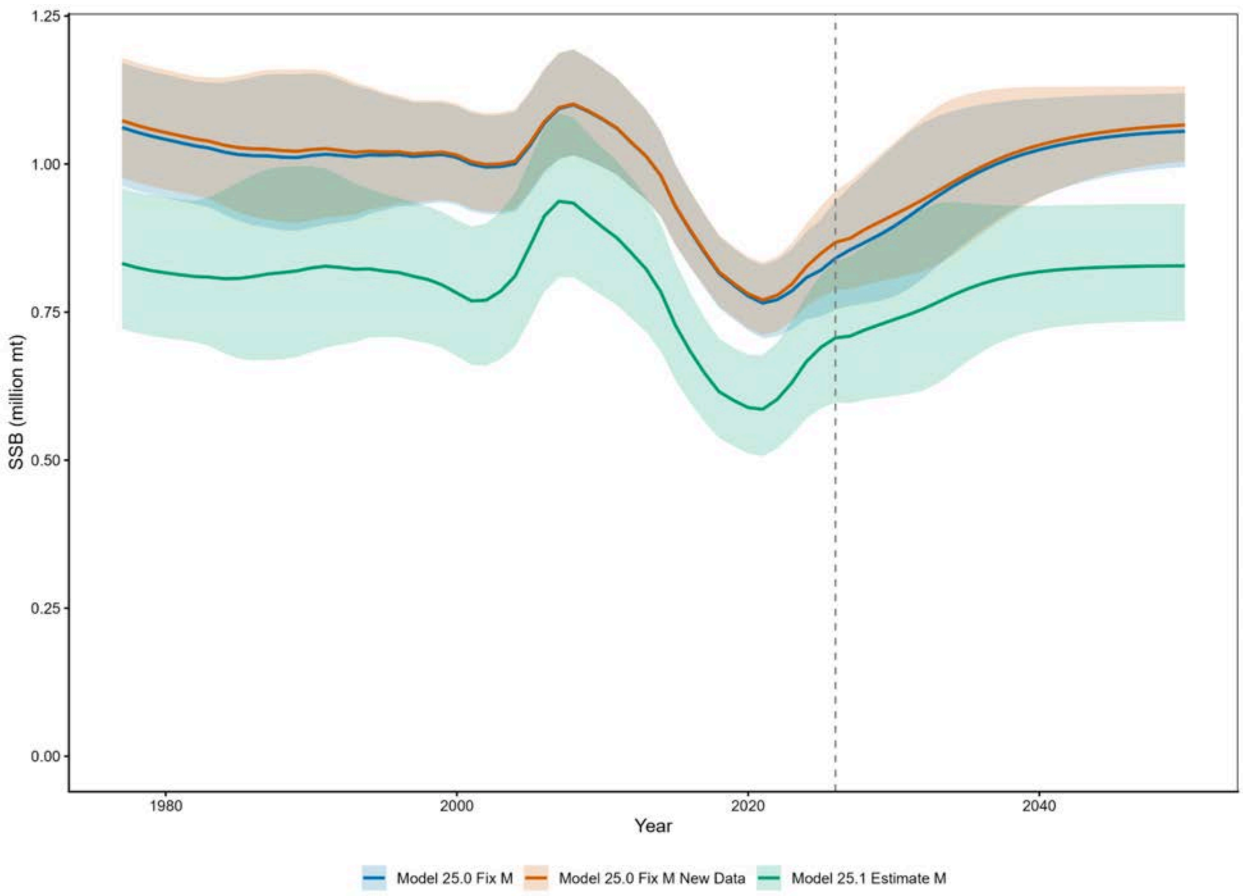


Figure 7.20b: Comparison of spawning stock biomass (SSB) from the three models for arrowtooth flounder.

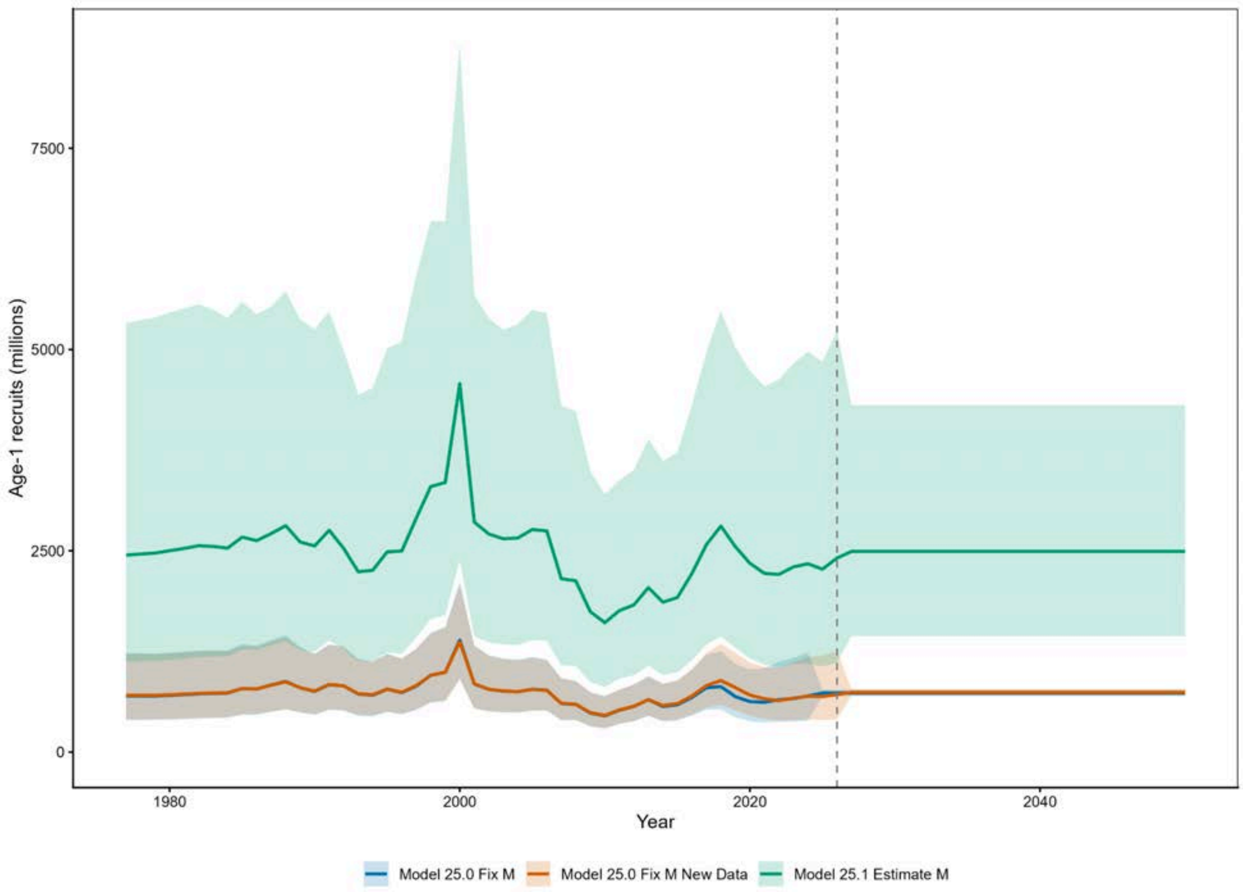


Figure 7.20c: Comparison of recruitment (age-1) from the three models for arrowtooth flounder.

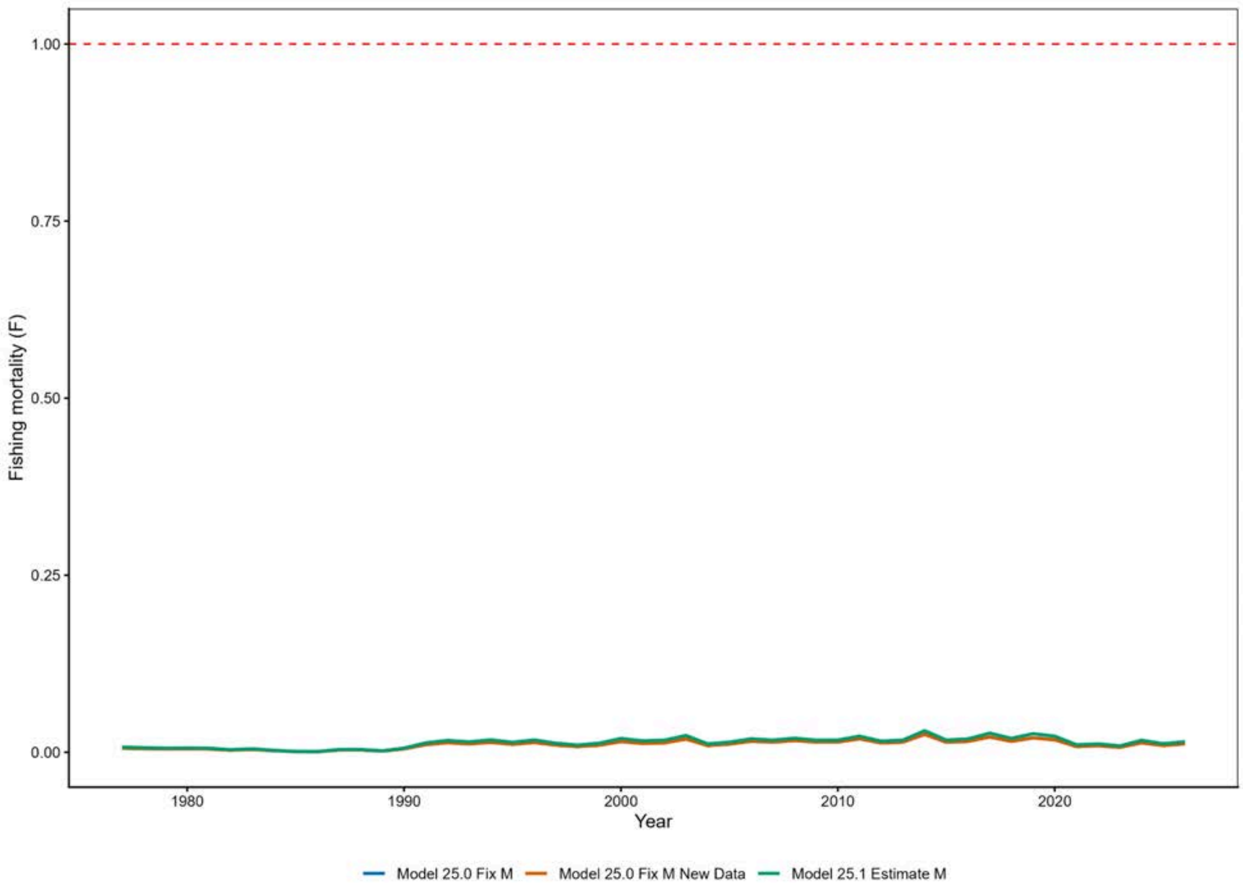


Figure 7.20d: Comparison of fishing mortality rate (F) from the three models for arrowtooth flounder.

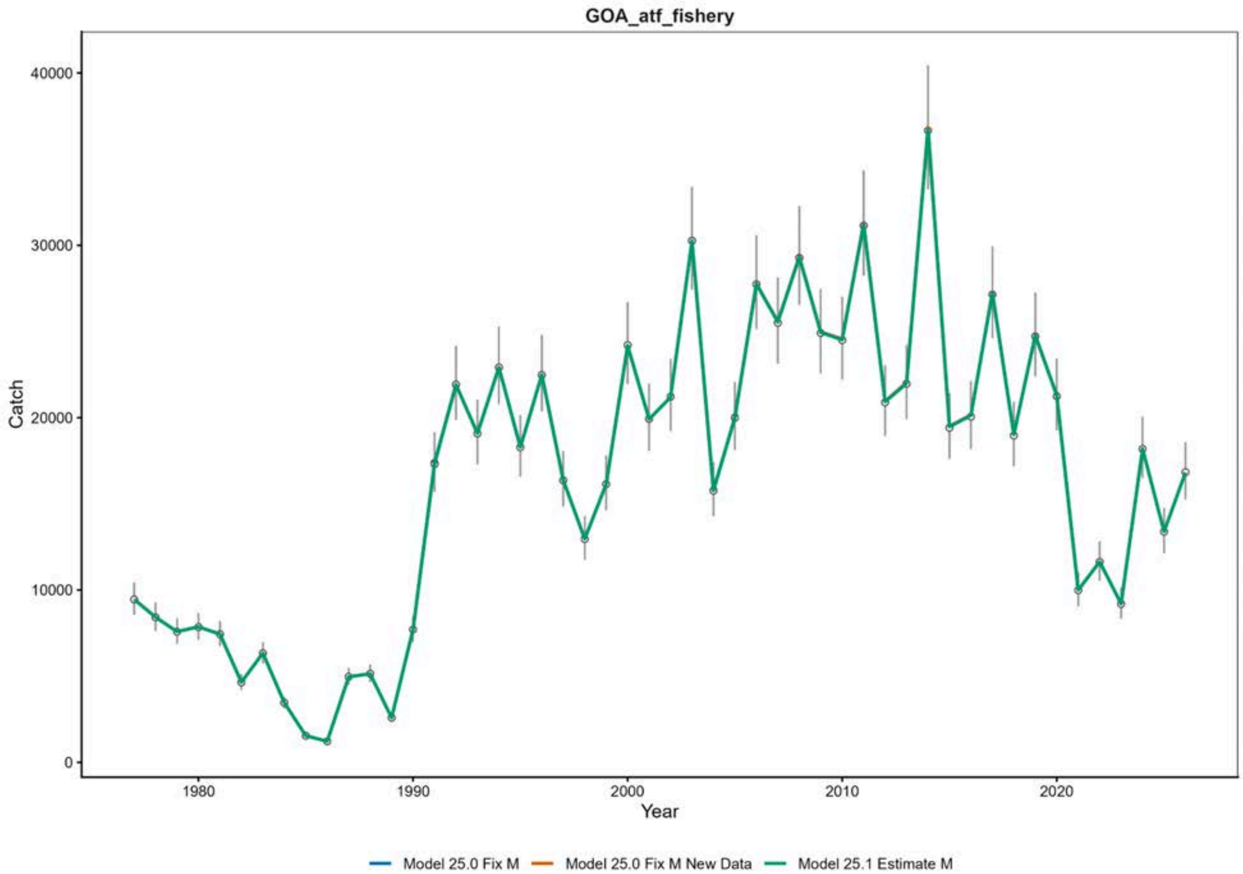


Figure 7.20e: Comparison of fit to the catch data from the three models for arrowtooth flounder.

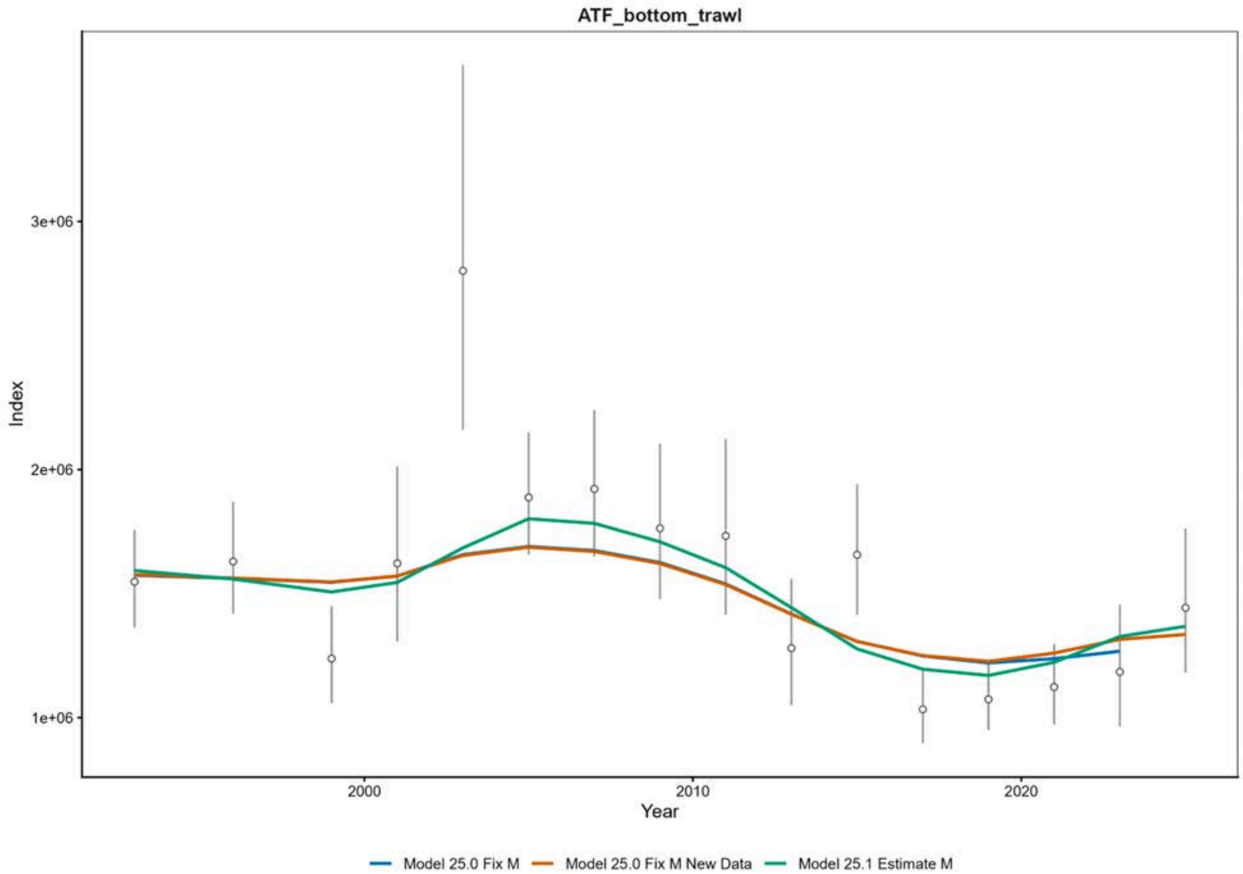


Figure 7.20f: Comparison of fit to the bottom trawl survey index from the three models for arrowtooth flounder.

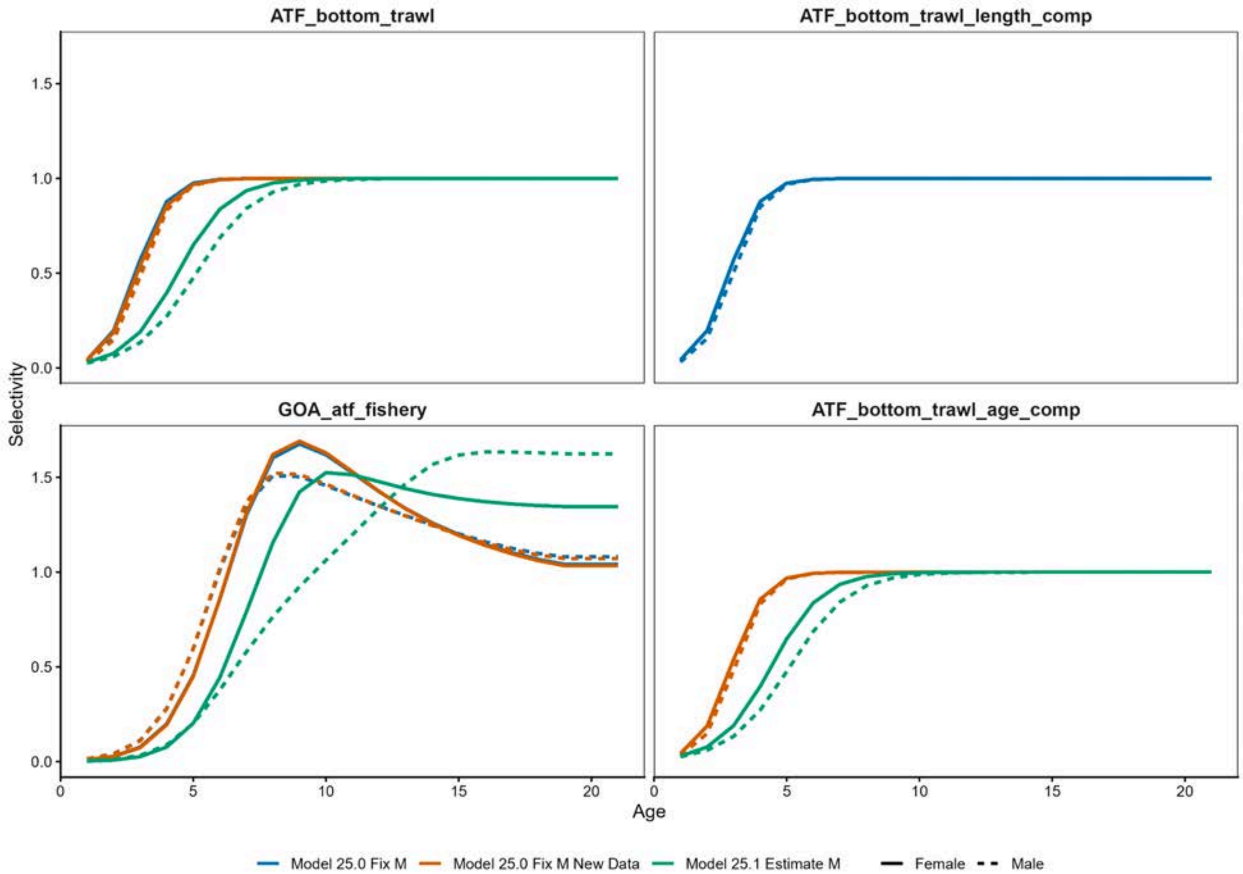


Figure 7.20g: Comparison of selectivity from the three models for arrowtooth flounder.

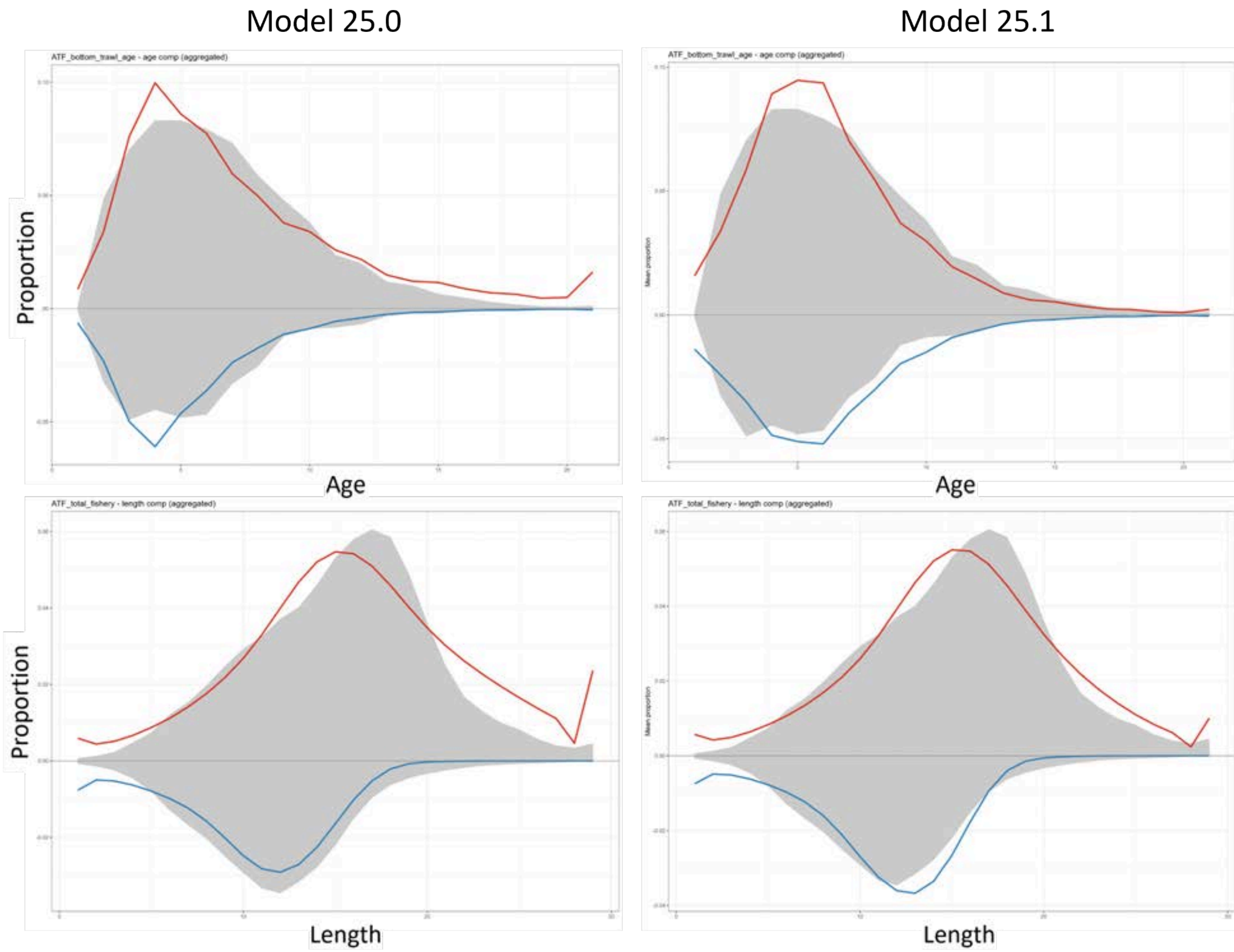
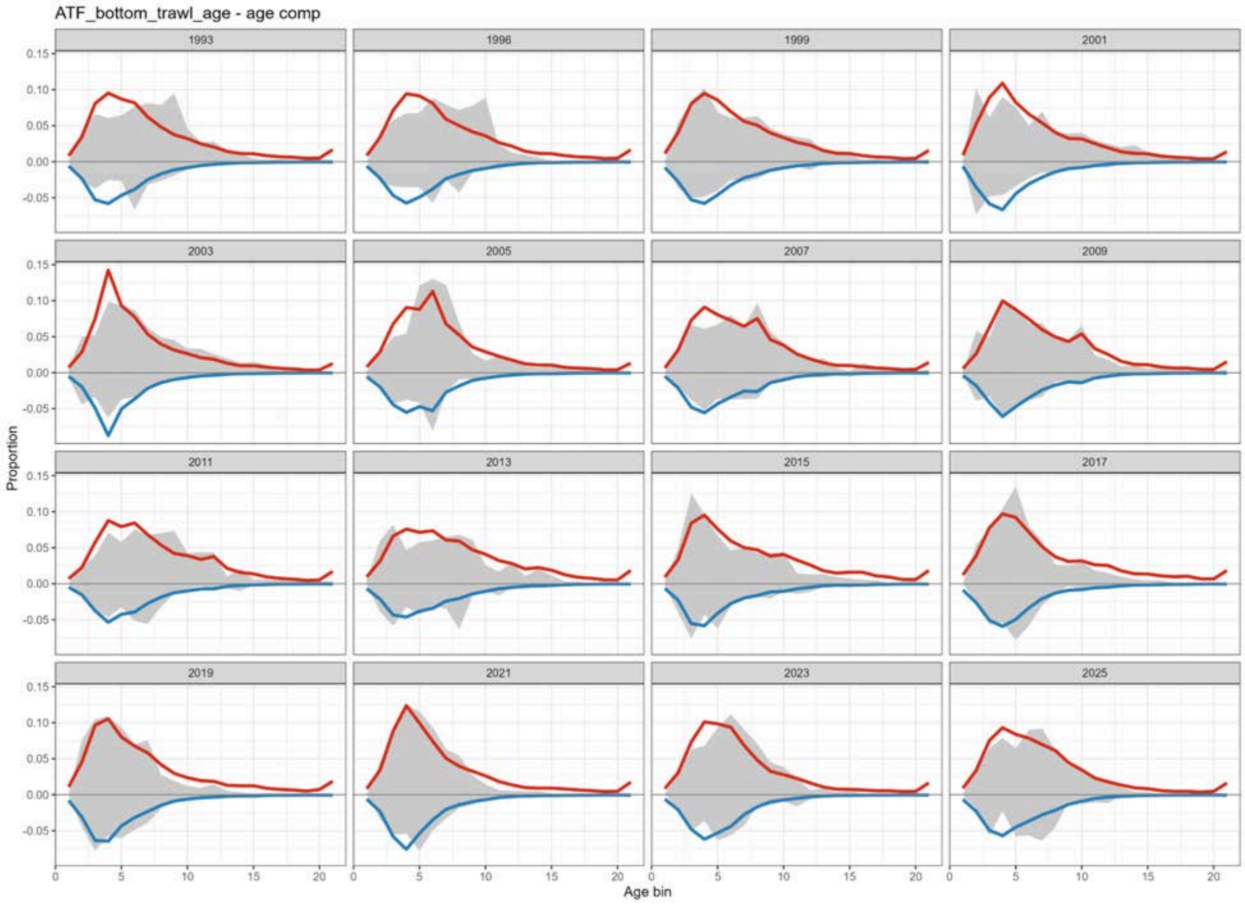


Figure 7.21a: Fits to aggregated age and length composition for the bottom trawl survey (top) and fishery (bottom) observed and expected (lines) size/age-composition data for Model 25.0 (left) and Model 25.1 (right). Females are red and males are blue.


ATF_bottom_trawl_age - age comp
1993
1996
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
2023
2025
Proportion
Age bin

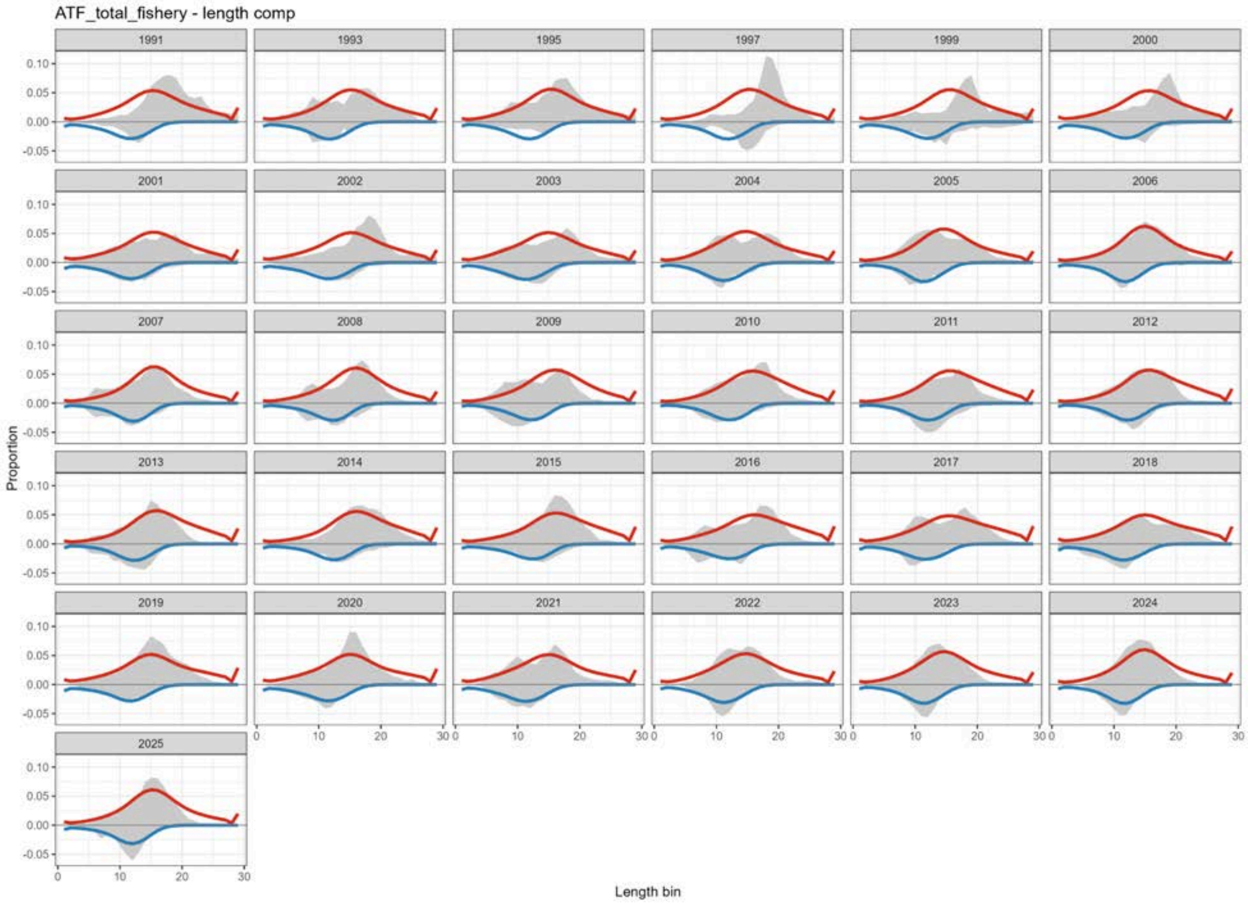
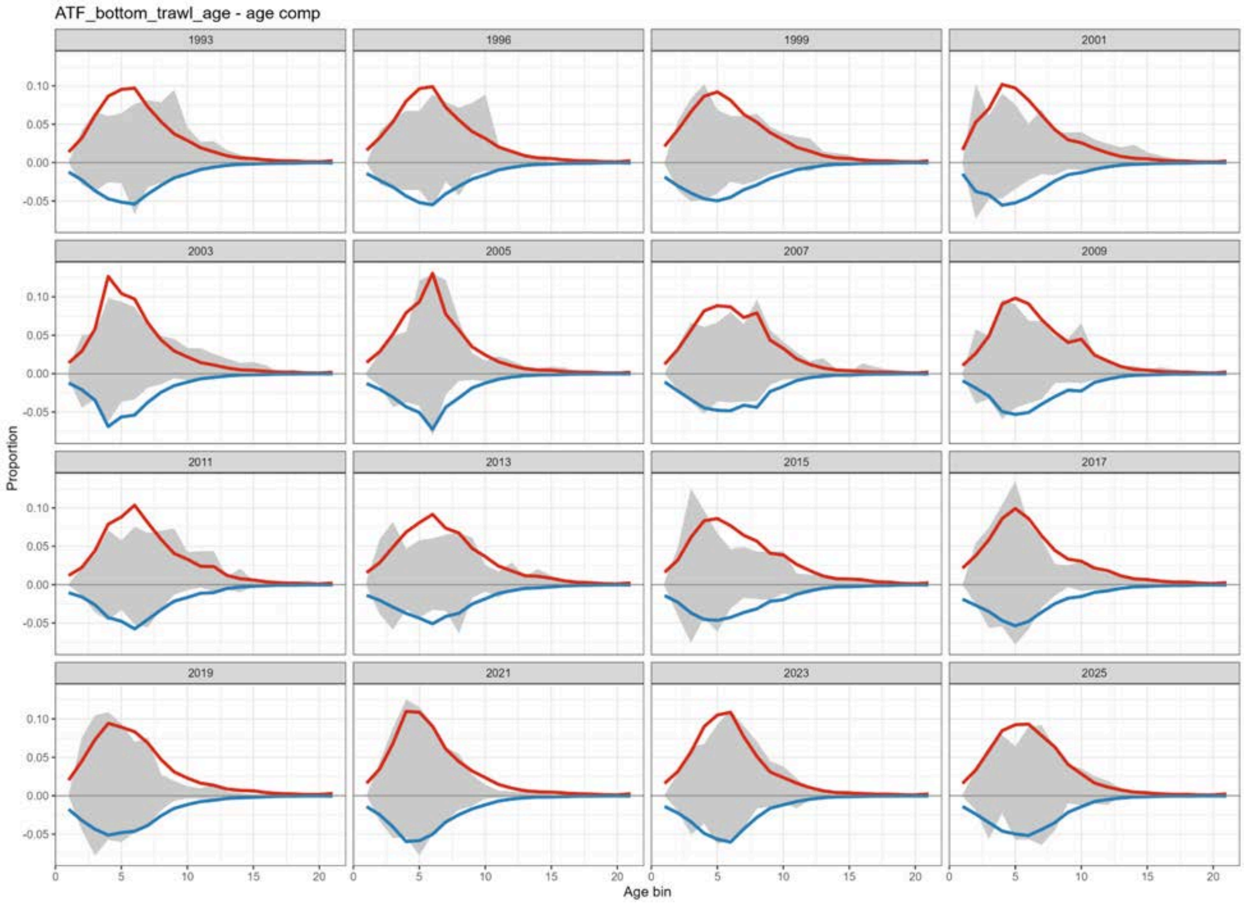


Figure 7.21b: Fits to annual age and length compositions for the bottom trawl survey (top) and fishery (bottom) observed and expected (lines) size/age-composition data for Model 25.0. Females are red and males are blue.



ATF_bottom_trawl_age - age comp
1993
1996
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
2023
2025
Proportion
Age bin

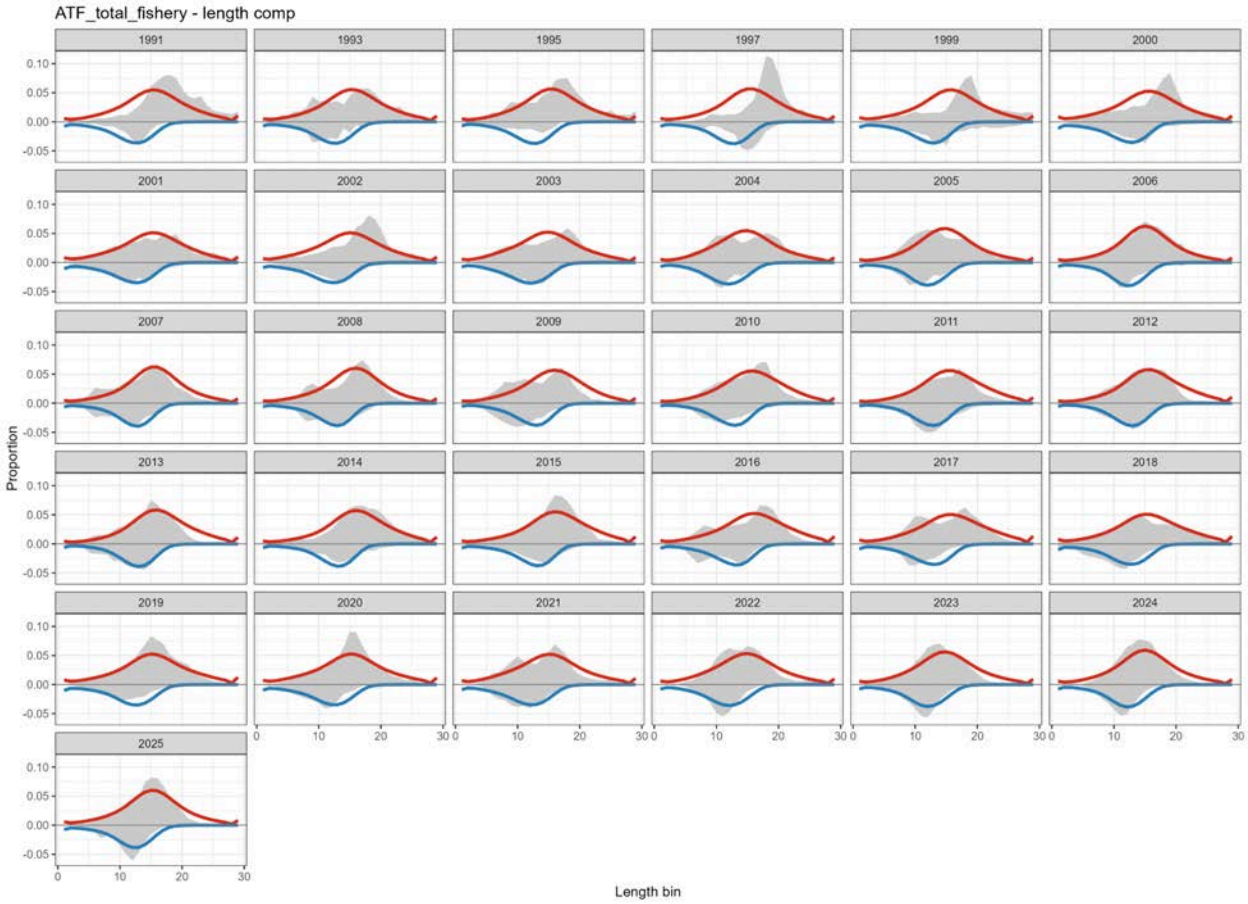


Figure 7.21c: Fits to annual age and length compositions for the bottom trawl survey (top) and fishery (bottom) observed and expected (lines) size/age-composition data for Model 25.1. Females are red and males are blue.

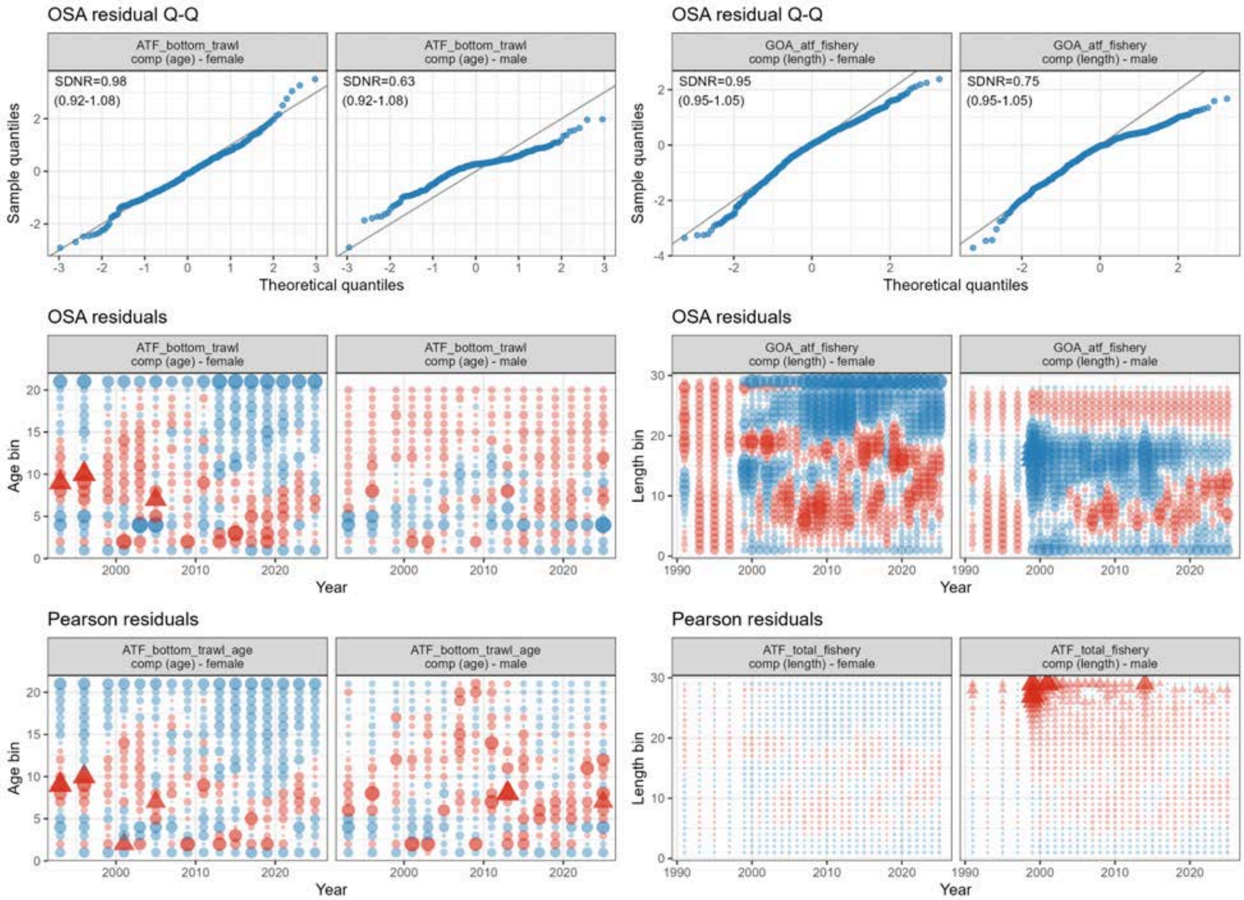


Figure 7.21d: Results from one-step-ahead residual analysis for Model 25.0.

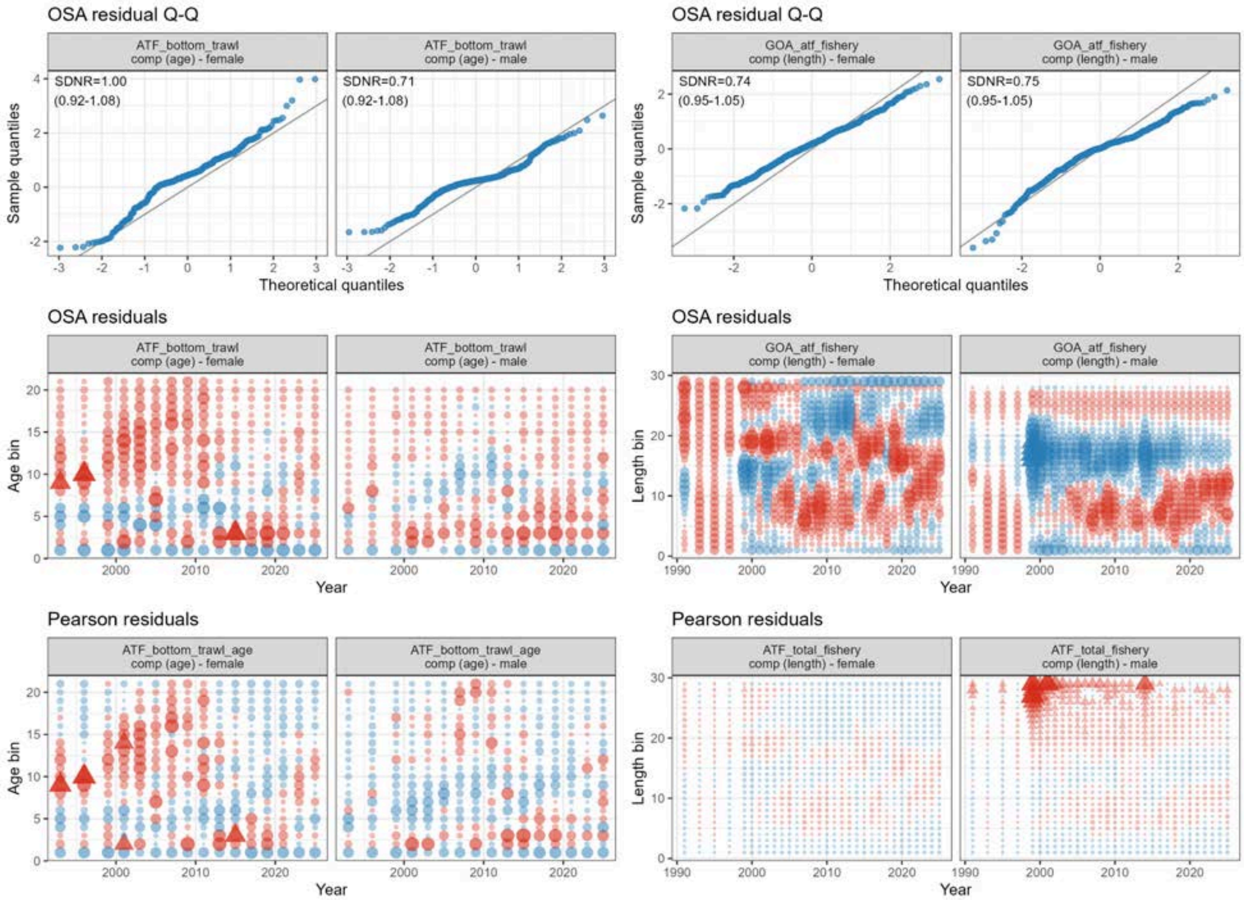


Figure 7.21e: Results from one-step-ahead residual analysis for Model 25.1.

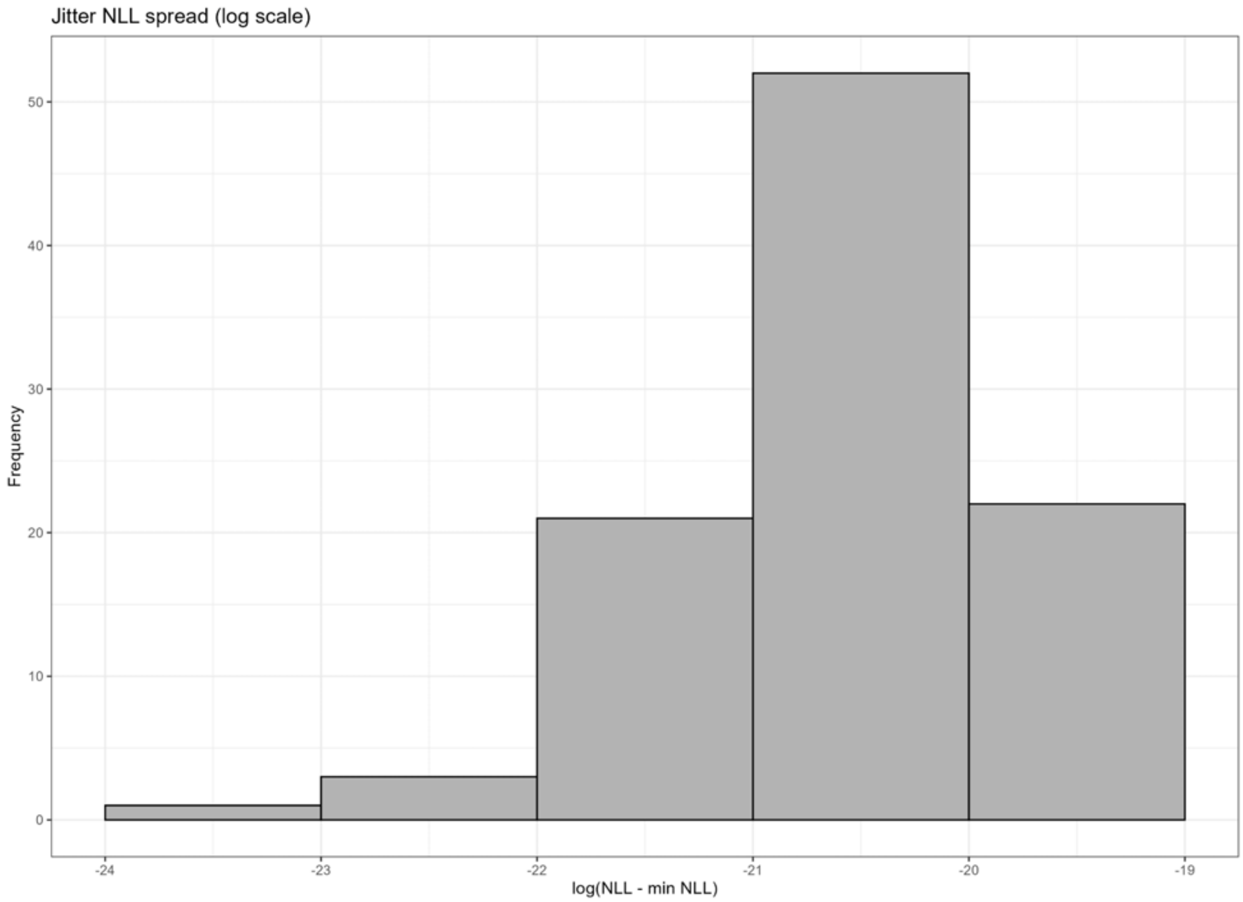


Figure 7.22a: Results from the jitter analysis for Model 25.0.

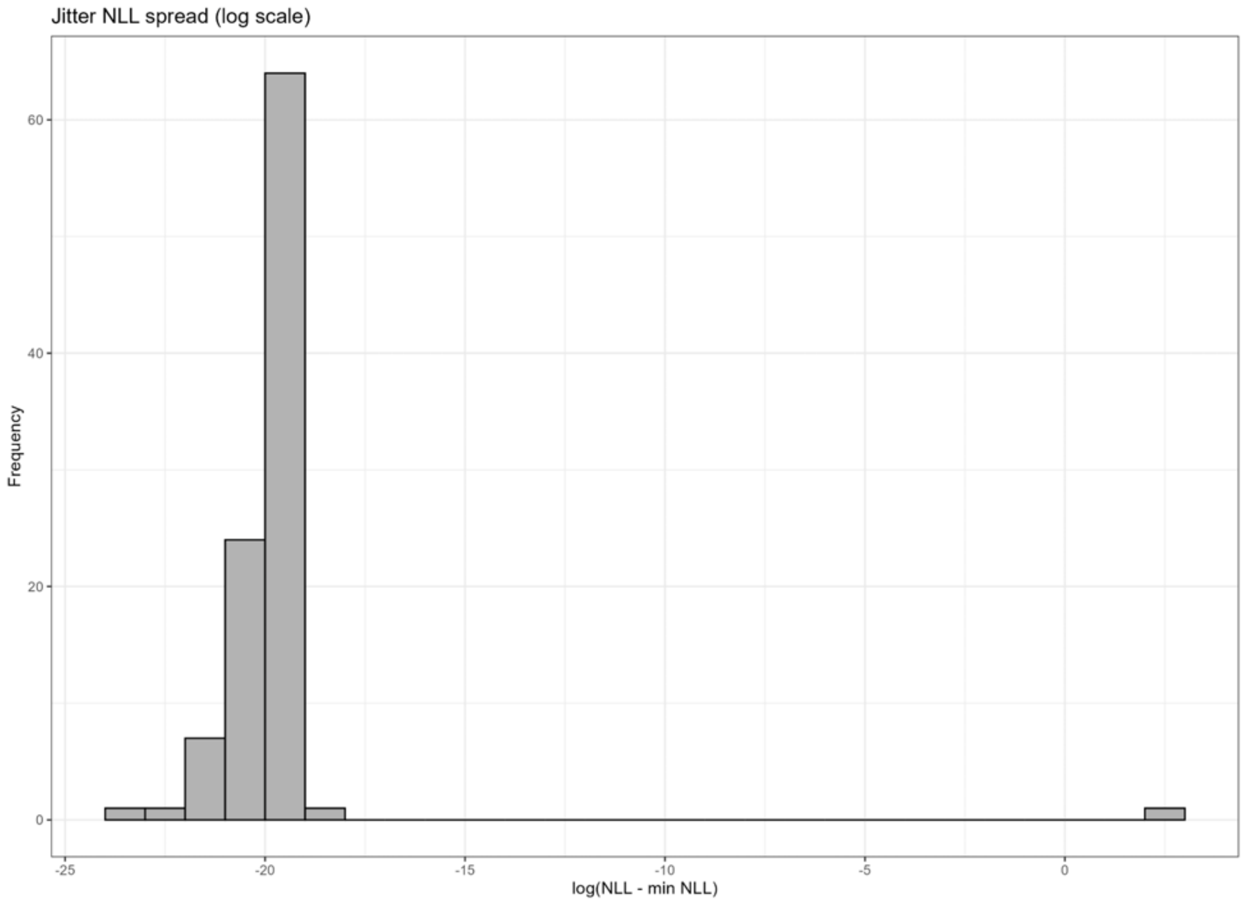


Figure 7.22b: Results from the jitter analysis for Model 25.1.

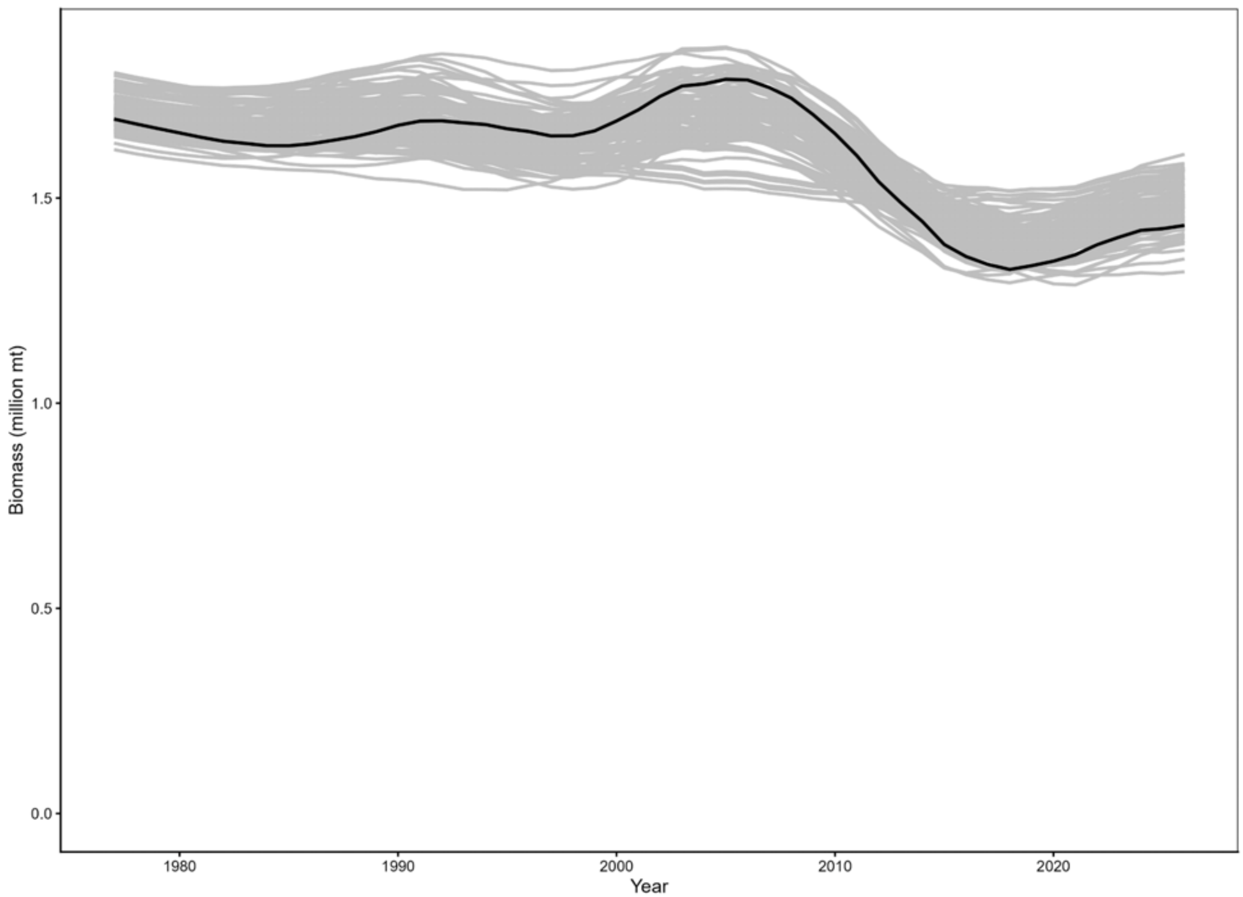


Figure 7.23a: Results from the self-test simulations for Model 25.0.

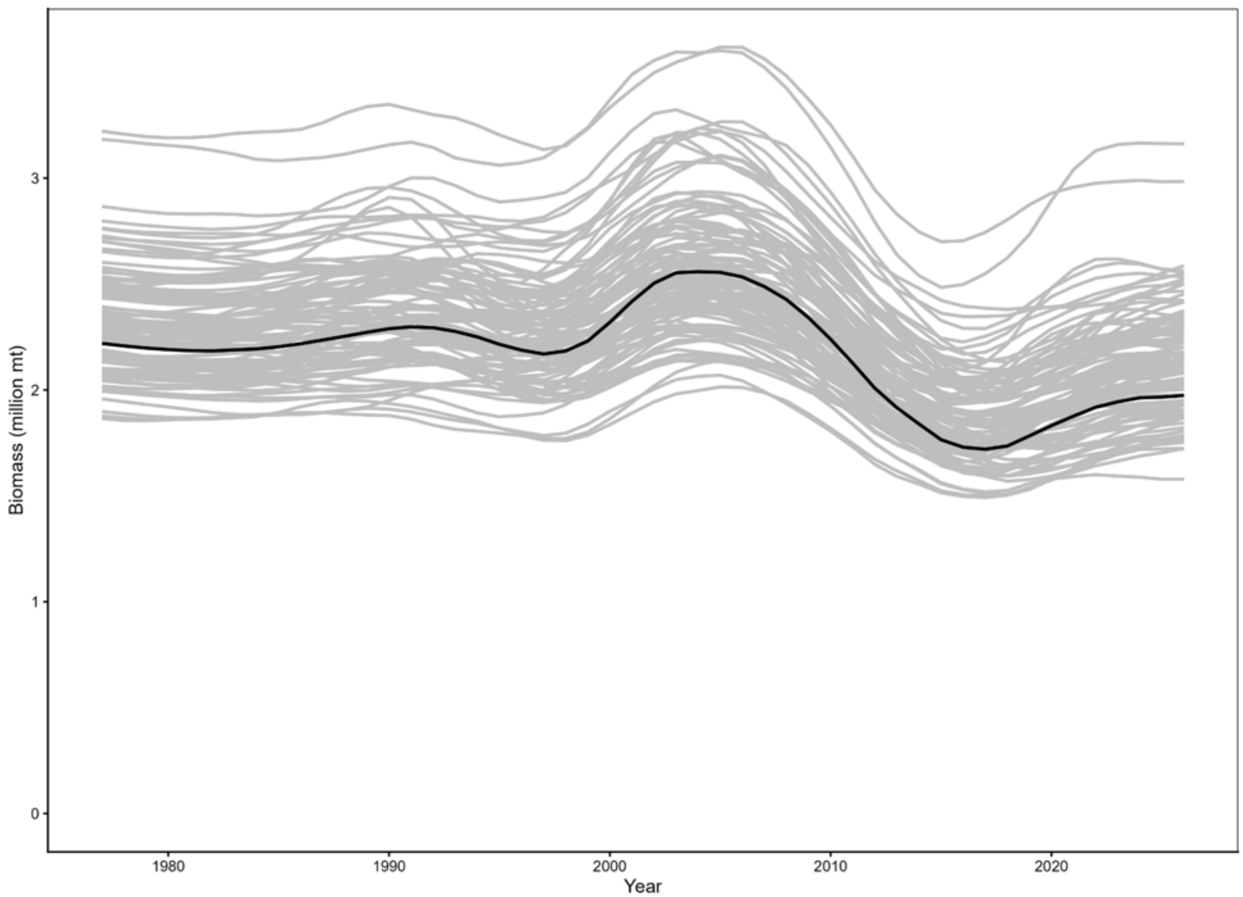


Figure 7.23b: Results from the self-test simulations for Model 25.1.

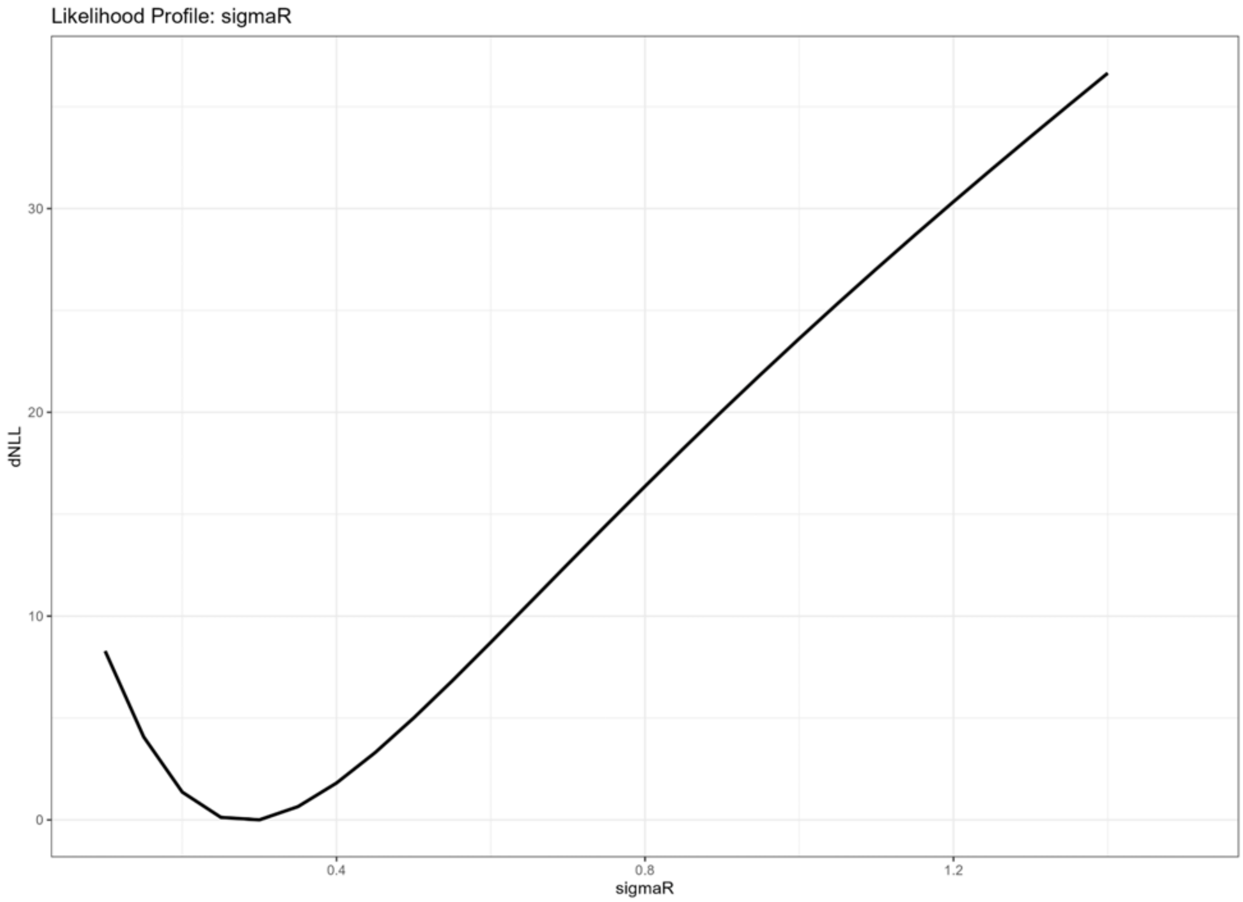


Figure 7.24a: Likelihood profile of sigma R for Model 25.0.

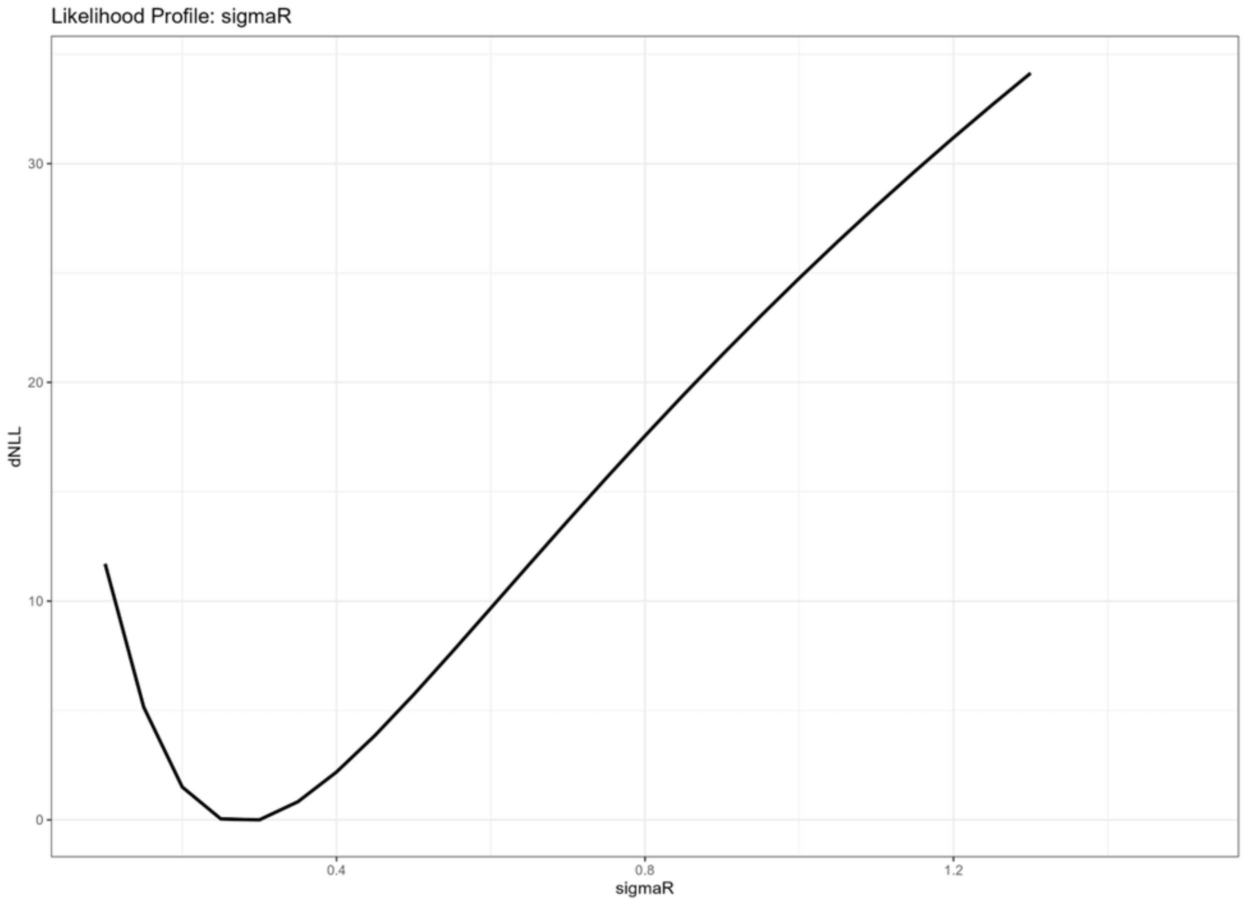


Figure 7.24b: Likelihood profile of sigma R for Model 25.1.

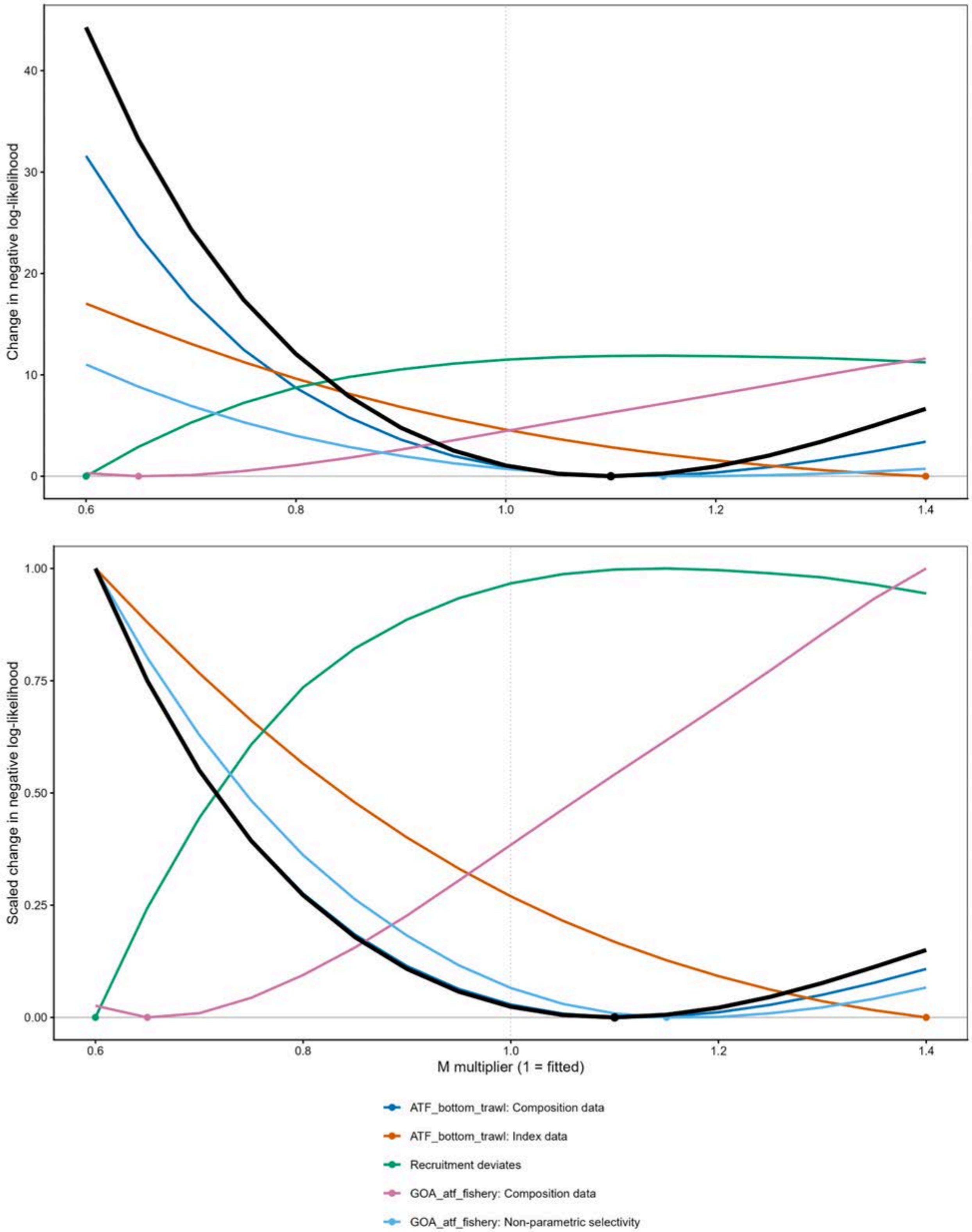


Figure 7.25a: Component likelihood profile (upper) and scaled component likelihood profile (lower) of natural mortality (*M*) by sex for Model 25.0.

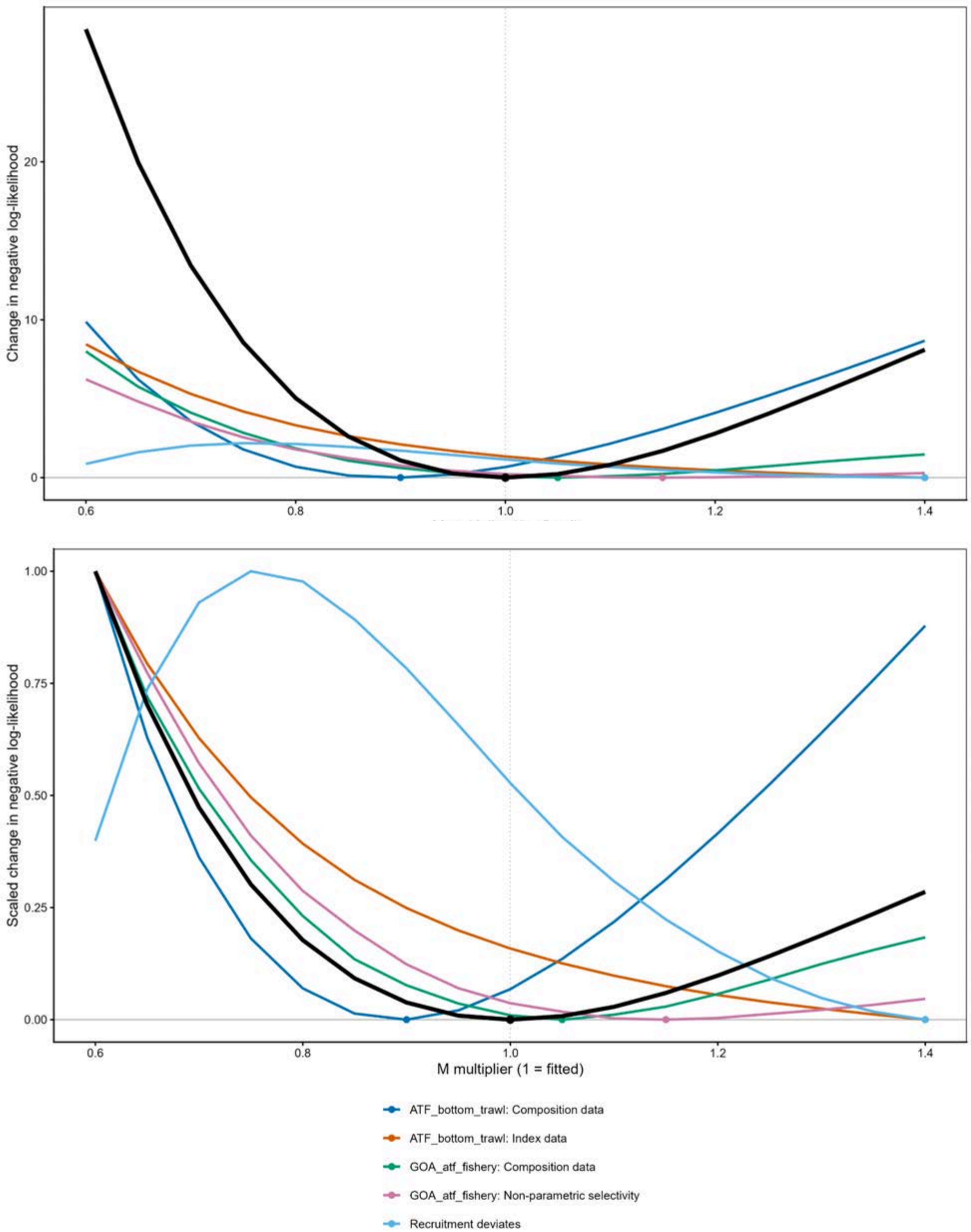


Figure 7.25b: Component likelihood profile (upper) and scaled component likelihood profile (lower) of natural mortality (*M*) by sex for Model 25.1.

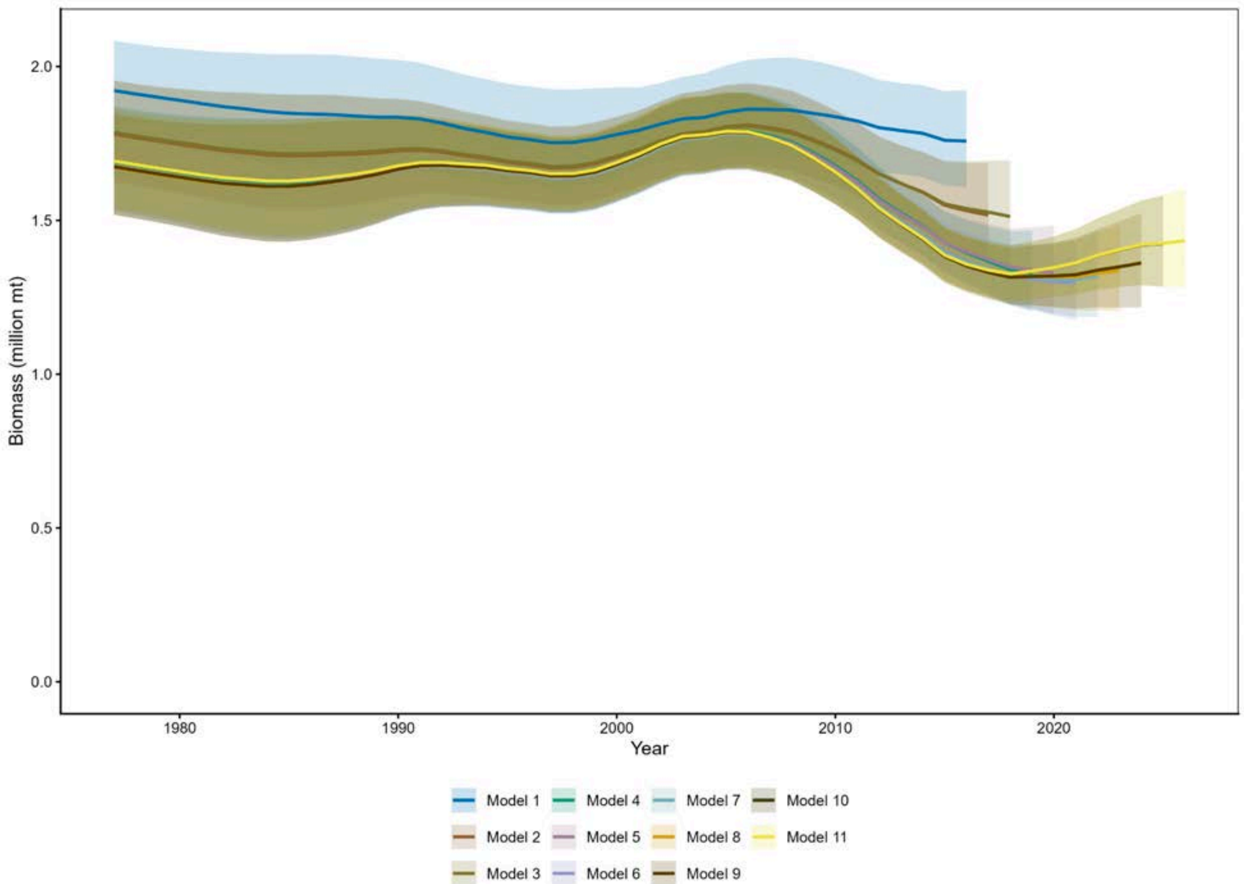


Figure 7.26a: Results from the retrospective analysis for total biomass for Model 25.0. Mohn's rho is 0.036.

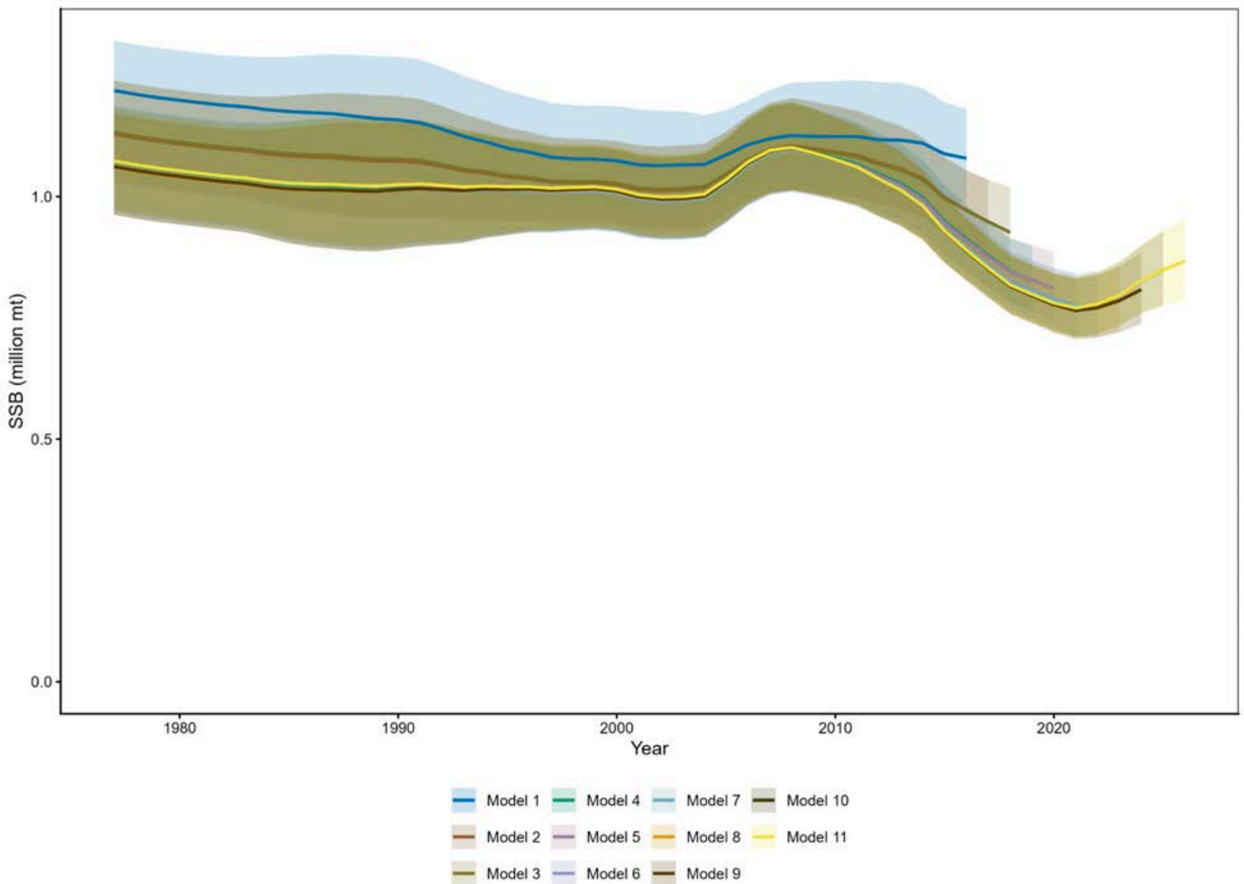


Figure 7.26b: Results from the retrospective analysis for spawning stock biomass (SSB) for Model 25.0. Mohn's rho is 0.050.

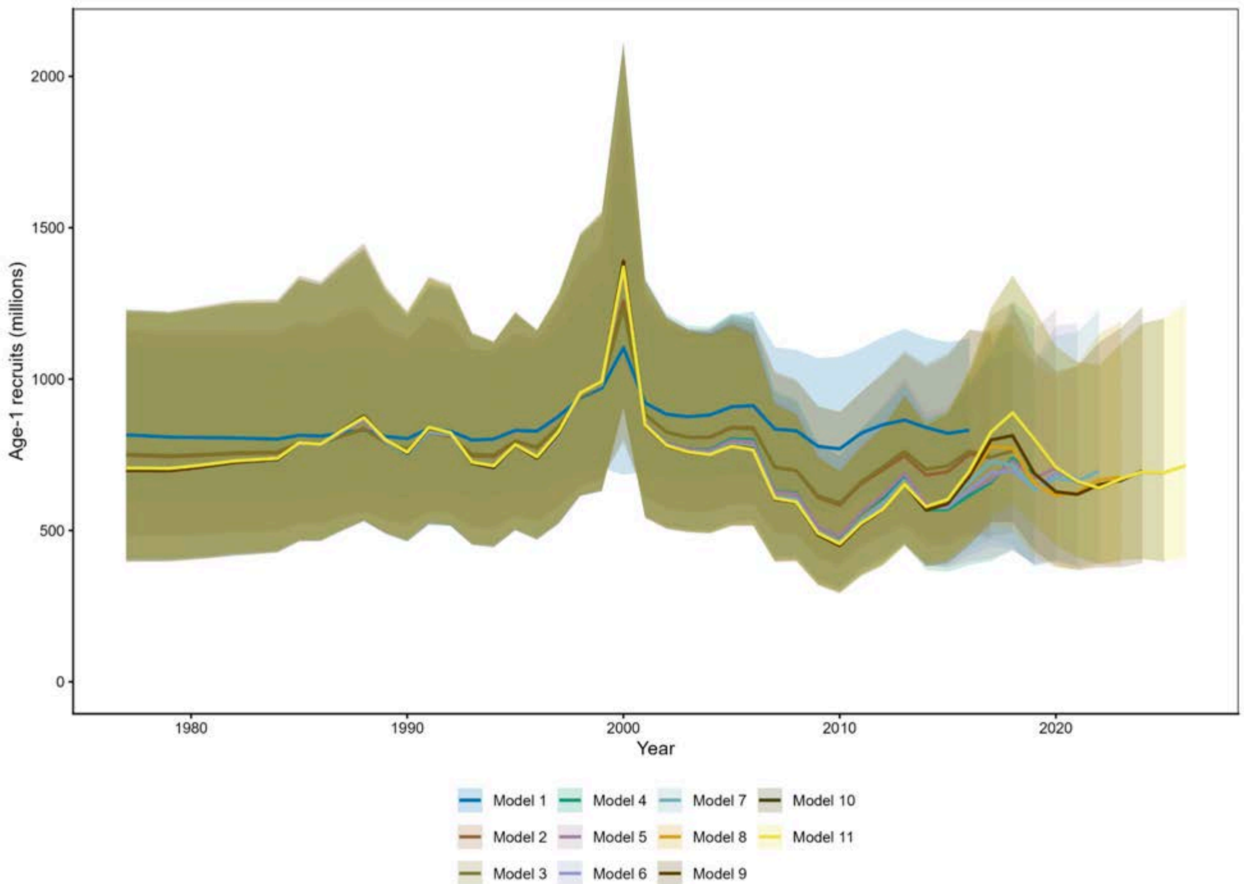


Figure 7.26c: Results from the retrospective analysis for recruitment (age-1) for Model 25.0. Mohn's rho is -0.008.

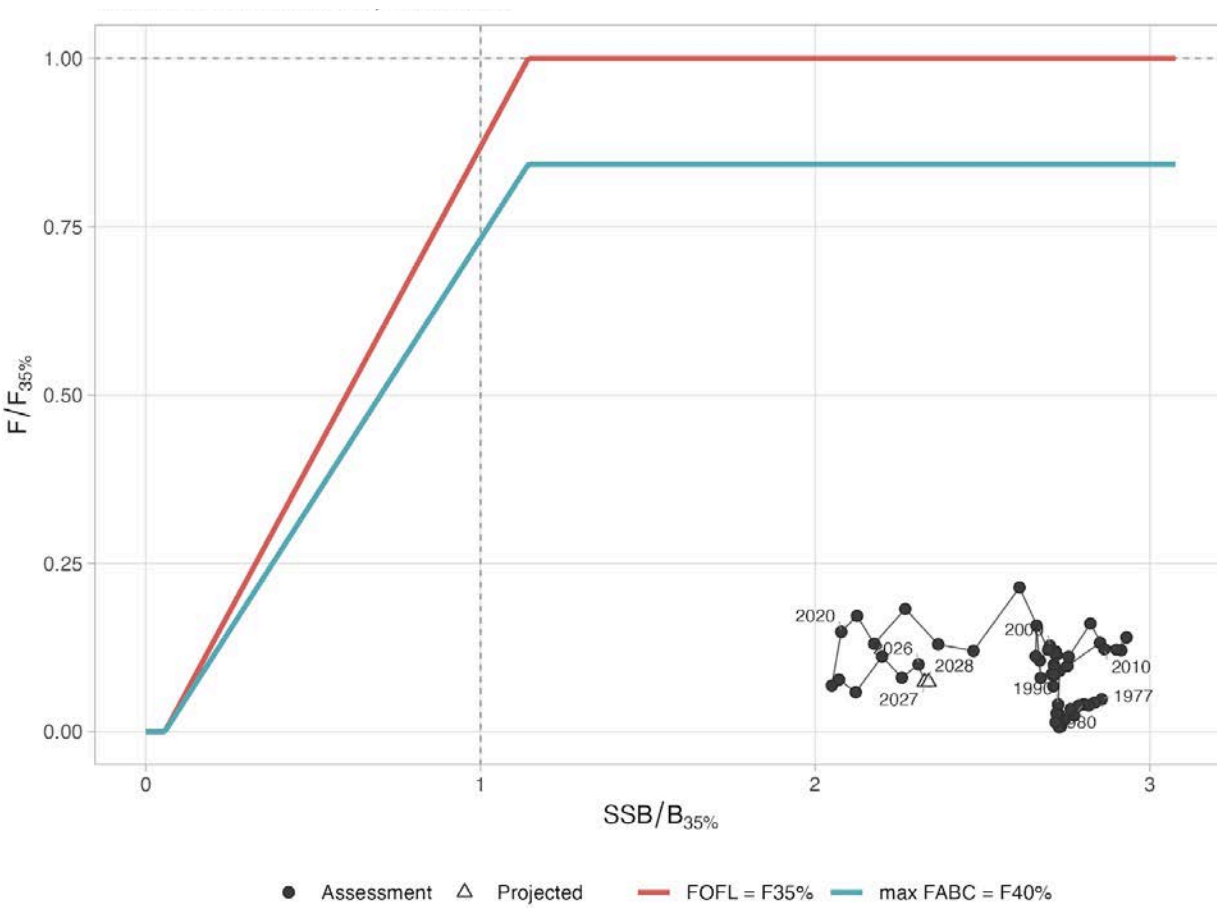


Figure 7.27: Fishing mortality rate and female spawning biomass from 1977 to present compared to the F35% and F40% control rules for the author preferred model (Model 25.0). Vertical lines are B35% and B40%.

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

S. Kalei Shotwell, Jenny Bigman, and Russel Dame (Editors)

September 2026

With Contributions from:

ESP Team: Grant D. Adams, Jennifer Bigman, Russel Dame, Bridget Ferriss, Esther Goldstein

ESP Data: Matt Callahan, Wei Cheng, David Kimmel, Abby Jahn, Jean Lee, Zack Oyafuso, Lauren Rogers, Sean Rohan, Margaret Siple, Joletta Silva, Kally Spalinger

This report may be cited as: Shotwell, S.K., J. Bigman, and R. Dame. 2026. Appendix 7A. Ecosystem and Socioeconomic Profile of the arrowtooth flounder stock in the Gulf of Alaska. *In*: Shotwell, S.K., G.D. Adams, D.H. Hanselman. 2026. Assessment of the arrowtooth flounder stock in the Gulf of Alaska. North Pacific Fishery Management Council, Anchorage, AK. Available from https://www.npfmc.org/library/safe-reports/.

This appendix is reviewed separately from the main operational assessment document. Please refer to the NPFMC eagenda at https://meetings.npfmc.org/Meeting/Details/5140 to access the full ecosystem and socioeconomic profile (ESP) document.

Appendix 7B: Bridging the Gulf of Alaska arrowtooth flounder assessment to CEATTLE to improve parameter estimation, account for cannibalism, and increase climate readiness

Grant Adams and Kalei Shotwell

September 2024

Executive Summary

Recommendations from the Groundfish Plan Team and the Scientific and Statistical Committee (SSC) for the Gulf of Alaska (GOA) arrowtooth flounder (ATF) stock assessment and fishery evaluation (SAFE) over the past several years included investigation of the following elements:

- Recent lower recruitment trends and relationship to environmental conditions in the GOA, including the development of an ESP
- Lack of fit in female survey age and fishery length compositions, including interactions between female natural mortality and selectivity
- Incorporation of predation mortality estimates from the GOA CEATTLE model
- Update growth and age-length conversion matrices

In response to these recommendations and to improve our ability to investigate these concerns, we plan to improve the current GOA ATF assessment model in two main ways. First, we want to bridge from the current Automatic Differentiation Model Builder (ADMB) software to Template Model Builder (TMB) and second we want to include the impact of predation mortality by exploring the multi-species age-structured stock assessment model. We plan to do this by using the CEATTLE (Climate-Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics) model that has been expanded for groundfish in the GOA (Holsman et al., 2016, Adams et al., 2022) using TMB (Kristensen et al., 2016).

Background

The current GOA ATF stock assessment model is based on an age-structured model using ADMB software (Fournier et al. 2012). The framework uses automatic differentiation and allows estimation of highly-parameterized and non-linear models. The approach consists of an assessment model, which uses survey and fishery data to generate a historical time series of population estimates, and a projection model which uses results from the assessment model to predict future population estimates and recommended harvest levels. The assessment model is fit to survey abundance data, survey age data, and fishery length composition data with a harvest control rule to model the status and productivity of these stocks and set quotas.

The current operational model using ADMB has been used for the GOA and the Bering Sea and Aleutian Islands (BSAI) ATF stock assessments since 2015 and stems from the "generalized" ADMB model developed for Alaska flatfish (J. Ianelli, pers. comm.). The model incorporates ages 1-20 with 21 and greater in a plus group, estimates age-based selectivity up to age 19 with full selectivity after age 19, and uses 26 length bins starting at 10 cm to a 75 cm plus group and defined at 2 and 3 cm intervals (see last full assessment for more details, Shotwell et al., 2021). A Markov chain Monte Carlo (MCMC) is performed in ADMB to capture variability in recruitment, female spawning biomass, and total (age 1+) biomass. No spawner-recruit curve is used in the model. Instead, we calculated average recruitment with an estimated lognormal deviation for each year of the model with the exception of the final year. In the final modeled year, recruitment is set to median recruitment. Recruitment deviations are freely estimated but with a modest penalty on extreme deviations from the mean value (σ_r value). Age at recruitment is set to one in the model. Recruitment is informed by subsequent age and length composition and there is little information to inform recruitment in the final few years because selectivity is low for younger ATF. Ages 2-21 are subject to a sex-specific vector of instantaneous rates of natural mortality. Natural mortality is subscripted for sex, as males appear to have higher natural mortality than females in this species (Wilderbuer and Turnock 2009, 0.2 for females, 0.35 for males). Fishery selectivity is estimated as a smooth, age- and sex-specific non-parametric function through age 19. Survey selectivity is modeled using a two parameter ascending logistic function for males and females (four parameters total). Please refer to the most recent full SAFE report (Shotwell et al., 2021) for more details on the current assessment model (hereafter referred to as the ADMB model).

Justification

Since 2019, recommendations from the Groundfish Plan Team and the SSC for the GOA ATF SAFE have included investigation of the following elements:

- Recent lower recruitment trends and relationship to environmental conditions in the GOA, including the development of an ESP
- Lack of fit in female survey age and fishery length compositions, including interactions between female natural mortality and selectivity
- Incorporation of predation mortality estimates from the GOA CEATTLE model
- Update growth and age-length conversion matrices

The goals of this document are to describe how we intend to start addressing these recommendations by 1) updating the current ADMB model to TMB to improve parameter estimation and 2) accounting for both the impacts of cannibalism and fishery removals in the population dynamics assessment model used for arrowtooth flounder.

TMB (Kristensen et al., 2016) is based on ADMB, but allows for improved estimation of hierarchical non-linear models. TMB, often considered a successor to ADMB, can estimate time-varying parameters (e.g. recruitment deviations) as random effects using marginal maximum likelihood rather than the penalized likelihood used in ADMB. This allows proper estimation of associated variance parameters, which can bias management quantities if misspecified. For example, the current ADMB assessment does not have an explicit recruitment variance parameter, rather the ADMB assessment penalizes annual recruitment deviates by squaring them in the log-likelihood (*i.e.* rec_dev^2). This parameterization implicitly assumes a variance of 0.707, which may not accurately reflect the amount of variability in recruitment. Moving to TMB will allow estimation of recruitment deviates as random effects and allow estimation of age- and sex-specific non-parametric selectivity penalties or other selectivity forms.

Arrowtooth flounder are generalist predators. Analyses from bottom trawl survey diet data show a non-trivial amount of cannibalism particularly on the small to medium (30-299 mm) sizes (Doyle et al., 2018). An ontogenetic shift occurs in ATF diet with smaller fish (<200 mm) consuming primarily euphausiids and capelin to larger fish consuming mostly walleye pollock and increasing amounts of flatfish as they age. Predation on ATF varies with their habitat utilization from pelagic zooplanktivorous predators (e.g., walleye pollock, northern rockfish, Pacific ocean perch) while ATF are small (<30 mm) to increasing amounts of benthic predation (particularly from Pacific cod, Pacific halibut, and larger ATF) as ATF age. The larger ATF (>400 mm) are consumed by the largest predators (e.g., sleeper sharks) (Doyle et al., 2018). Adams et al. (2022) estimated that on average approximately 27,000 to 37,000 t of ATF were consumed annually by predators in the models explored and that of those species considered (Pacific halibut, ATF, Pacific cod, walleye pollock), ATF was the primary consumer. The fishery has caught between 1,200 to 37,000 mt of ATF between 1977 and 2023. Catch was on average around 17,000 mt since 1991 and has been decreasing from the maximum in 2014 at 37,000 mt to about 10,000 mt since 2021 (see Table 7.3 in Shotwell et al, 2021). In some years cannibalism can largely exceed the removals by the fishery and potentially impact harvest recommendations, highlighting the need to account for the impacts of cannibalism on the population dynamics of ATF (Adams et al., 2022).

A preliminary ecosystem and socioeconomic profile or ESP has recently been created for GOA ATF that includes several mechanistically derived physical and biological indicators to evaluate the impacts of the ecosystem on ATF (Doyle et al., 2018; Shotwell et al., 2022; Ferriss, 2023). Indicators in this report include estimated ATF annual ration, ATF biomass eaten due to cannibalism, and sex-specific natural mortality (*M*) for ages 1 and 2 from the most recent GOA CEATTLE model (Adams et al., 2023) over the years 1977 to 2023. ATF ration averages 9.7 million t and ranges from 8.2-11.4 million t, clearly showing the impact this predator has in the GOA ecosystem. Biomass eaten due to cannibalism ranges from 13,000 t to 49,000 t and averages 26,000 t, supporting the Adams et al., 2022 results. Cannibalism exceeds catch in all years up until 2011 where it becomes comparable to catch. Since 2021, cannibalism has again exceeded catch due to the recent lower harvest levels. Sex-specific *M* for ages 1 and 2 are much higher than the ADMB model fixed estimates of 0.2 for females and 0.35 for males (Shotwell et al., 2021). Average *M* at age 1 was equal to 0.335 for females (range 0.326 to 0.349) and 0.43 for males (range 0.417 to 0.451). Average *M* at age 2 was equal to 0.356 for females (range 0.343 to 0.374) and 0.458 for males (range 0.439 to 0.485). The variable *M* by sex and age from the multi-species models from Adams et al., 2023 supports exploring the estimation of sex- and age-specific *M* for ATF.

In the GOA, climate can impact the population dynamics of groundfish related to stock assessment through recruitment, bioenergetics/growth, and mortality (Anderson and Piatt, 1999; Clark and Hare, 2022). Additionally, this can have impacts on cannibalism in arrowtooth flounder via temperature-dependent foraging rates, changing species distributions, and shifts in abundance of conspecific predators (Barnes et al., 2018; Holsman and Aydin, 2015). These shifts in predator-prey interactions undermine the assumptions of time-invariant natural mortality (and the equilibrium assumptions of reference points), highlighting the need to evaluate the impact of climate-driven dynamics on management recommendations for ATF. Currently the ADMB model for arrowtooth is not configured for exploration and estimation of climate-linkages. Development of models that can allow incorporation and testing of multiple climate-linkages would be valuable for evaluating future management performance and explaining historical population variability.

Methods

We use a previously developed climate-enhanced multi-species statistical catch-at-age modeling framework called CEATTLE (Climate-Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics, Holsman et al., 2016) that has been expanded for groundfish in the GOA using TMB (Adams et al., 2022, Kristensen et al., 2016) as the basis for the new assessment model explorations for ATF. Developed in part from the underpinnings of multi-species statistical catch-at-age analysis (MSCAA, Jurado-Molina et al., 2005) and multi-species virtual population analysis (MSVPA; (Jurado-Molina et al., 2005; Magnusson, 1995), CEATTLE links single-species age-structured models (Table 7A.1) through predation mortality conditioned on the temperature-dependent bioenergetic demand and diet-based prey-selectivity patterns of predators (Curti et al., 2013; Holsman et al., 2016; Kinzey and Punt, 2009). Predation mortality assumes a Holling Type II functional response and parameters are either pre-specified or estimated by fitting to survey and fishery data (Table 7A.2). CEATTLE can be run in single-species mode by "turning-off" time-varying predation mortality or in multi-species mode by "turning-on" time-varying predation mortality.

Data

CEATTLE uses the same inputs as the ADMB single-species assessment model (ADMB model, Shotwell et al., 2021) used to provide management advice in addition to diet and bioenergetics data (Adams et al., 2022) (Table 7A.5). Catchability for the AFSC bottom trawl survey is assumed to be 1, and age-at-maturity, weight-at-age, age-length conversion matrix, and ageing error matrix are all estimated outside the model. All data and assumed uncertainties are consistent with the ADMB model. Diet and bioenergetics data were derived from the AFSC stomach sampling program from 1990 to 2015 (Adams et al., 2022, Holsman et al. 2023, Holsman & Aydin 2015). Time-series of bottom temperature derived from the Climate Forecast System Reanalysis for the Pacific cod assessment (Hulson et al., 2023) was used to parametrize consumption and diet composition.

Model Structure

For arrowtooth flounder in the GOA, the single-species CEATTLE spans 1977 to 2023 and is parameterized similarly to the ADMB model (Adams et al., 2022; Shotwell et al., 2021). The effects of changing climate are accounted for by conducting projections with temperature that determine consumption rates over time. Parameters estimated inside the model include the number-at-age in the first year of the assessment, the number of recruits in subsequent years, the fishing mortality rates for each year, and survey/fishery selectivity. Similar to the ADMB model, separate fishery selectivities were estimated non-parametrically for each age, up to age-19, and the shape of the selectivity curve was constrained to be a smooth function. Survey selectivities were modeled using a two-parameter ascending logistic function. The selectivities by age were estimated separately for females and males. A differential age-invariant natural mortality is assumed or estimated for each sex. CEATTLE assumes multinomial likelihoods for composition data and log-normal likelihoods for index and catch data (Table 7A.3). Despite similarities, the assessment model and CEATTLE have the following differences:

1. In the case of age-composition data, the multinomial in the ADMB model is defined as:

$$NLL = -\sum_i\sum_y n_{f_i 1y}\sum_a\left(\hat{O}_{f_i 1ay} + 0.00001\right) * ln\left(O_{f_i 1ay} + 0.00001\right) - \sum_i\sum_y n_{f_i 2y}\sum_a\left(\hat{O}_{f_i 2ay} + 0.00001\right) * ln\left(O_{f_i 2ay} + 0.00001\right)$$

   where $\hat{O}_{f_i 1ay}$ is the predicted age composition from fleet f_i for species *i* for sex (1 = females; 2 = males) for true age a and year *y*, $O_{f_i 1ay}$ is the observed true age composition, and $n_{f_i 1y}$ is the sex-specific sample size. The ADMB model, therefore, assumes the input sample sizes are sex-specific, but the observed and true age compositions are calculated relative to both sexes as in Table 7A.1, resulting in a mis-specified multinomial distribution. CEATTLE, instead assumes a single sex-combined input sample size ($n_{f_i y}$) avoiding the mis-specification and allowing the sex ratio to be correctly estimated. Additionally, CEATTLE uses the predicted and observed age composition for observed ages in the multinomial likelihood (accounting for ageing error; see point 4 below).
2. The non-parametric fishery selectivity penalties (χ_{f_i}) in CEATTLE are sex-invariant (Table 7A.3), while in the ADMB model, these penalties are different for males and females.
3. The log-normal likelihoods used by the CEATTLE model include a log-normal bias correction and exclude an added constant of 0.0001 that was included in the ADMB model. CEATTLE also

utilizes the complete probability distribution rather than the simplified form used in the ADMB model.

4. To account for ageing error, the ADMB model multiplies the observed age composition data by the ageing error matrix $\hat{O}_{f_i 1 a y} = \hat{O}_{f_i 1 \hat{a} y} AE_{i a \hat{a}}$. However, CEATTLE multiplies the expected true age composition by the ageing error matrix to derive the expected observed age-composition $O_{f_i 1 \hat{a} y} = O_{f_i 1 a y} AE_{i a \hat{a}}$.
5. Multinomial distribution weights for the ADMB model are not updated with new data (weights in the 2017 assessment are the same in 2021). However, CEATTLE calculates McAllister and Ianelli (1997) weights allowing for easy sample size tuning. CEATTLE can also be easily updated so that composition weights are directly estimated using the dirichlet-multinomial distribution.

Models

We present four bridging models to demonstrate the major transitions from the ADMB platform to the multi-species CEATTLE model:

1. ADMB model: current operational single-species ADMB based assessment from the 2021 SAFE (Shotwell et al., 2021) and updated catch to 2023 (Shotwell et al., 2023).
2. TMB single-spp (species) fixed natural mortality (*M*) model: the single-species TMB based CEATTLE model that fixes sex-specific *M* (females = 0.2 and males = 0.35) and treats annual recruitment as random effects.
3. TMB single-spp (species) estimated *M* model: the single-species TMB based CEATTLE model that estimates sex-specific *M* and treats annual recruitment as random effects.
4. TMB multi-spp (species) model: the "multi-species" CEATTLE based cannibalism model that estimates sex-, age-, and time-varying *M* due to cannibalism from ATF (M2), sex-specific residual mortality (*M1*), and treats annual recruitment as random effects.

The sex-specific residual mortality (*M1*) in the "multi-species" CEATTLE model represents mortality due to predation from other species, disease, senescence, etc. We also created a series of sub-models to demonstrate bridging between the ADMB model and the TMB model in CEATTLE (between models 1 and 2 listed above). Please see the appendix for details on this section of the model bridging exercise. Due to differences in likelihood specifications between the ADMB model and CEATTLE, likelihood components are not directly comparable, however, see the appendix for a more extensive bridging.

Results

Both the ADMB and single-species CEATTLE model that fixed sex-specific *M* (models 1 & 2) showed similar if not exactly similar trends in recruitment, spawning stock biomass, and biomass (Figure 7A.1). The single-species model that estimated *M* and the multi-species CEATTLE model that included cannibalism (models 3 & 4) led to higher estimates of recruitment and biomass, owing to higher estimates of total natural mortality for younger age-classes (Figure 7A.2). The single-species model that estimated *M* estimated it to be 0.296 for females and 0.383 for males, which is higher than the 0.2 and 0.35 assumed by the current assessment. The multi-species model that estimated sex-, age-, and time-varying mortality, mortality due to cannibalism (*M2*) only impacted ages 1-6 for females and ages 1-7 for males. For females, total mortality estimated on average as age-1 = 0.335, age-2 = 0.356, age-3 = 0.351, age-4 = 0.321, age-5 = 0.31, and age-6 = 0.307 between 1977 and 2023. For males, total mortality estimated on average as age-1 = 0.43, age-2 = 0.458, age-3 = 0.455, age-4 = 0.408, age-5 = 0.395, age-6 = 0.39, and age-7 = 0.389 between 1977 and 2023 (Figure 7A.2). However, both the single-species model that estimated *M* and the multi-species model led to lower estimates of spawning stock biomass than the

ADMB model due to higher estimates of mortality for older fish. In the multi-species model residual mortality (*e.g.* total natural mortality for age-8+ fish) was estimated as $M1$ = 0.307 for females and $M1$ = 0.388 for males. This was also higher than the natural mortality of 0.2 and 0.35 assumed by the assessment for females and males, respectively. The multi-species model also estimated that cannibalism peaked in 2001 to 49,122 t, but has decreased in recent years as biomass has decreased (Figure 7A.3).

The single-species CEATTLE model that estimated M led to the lowest log-likelihood among the CEATTLE models evaluated (Table 7A.6). However, the multi-species CEATTLE model led to a lower log-likelihood than the single-species model that fixed M (Table 7A.6), owing to an improved fit to the survey biomass, survey age-composition, and fishery length-composition data (Figures 7A.4-6). Both the single-species model that estimated M and the cannibalism model had similar log-likelihoods for the data components, but differed in likelihood penalties. Both the ADMB and single-species CEATTLE model that fixed M (models 1 & 2) had similar pearson and OSA residual patterns (Figure 7A.4 & 7A.5). OSA residuals from the survey age composition data were smaller for the single-species model that estimated M and the cannibalism model (Figure 7A.5). Females from the survey age-data early in the time series had a positive trend for the 1979 cohort across all models (Figure 7A.4). All models fit the 22nd length bin from males poorly from the fishery length composition data (Figure 7A.6). Due to the large residuals from the fishery length-composition data, OSA residuals did not converge. Both the ADMB and single-species CEATTLE model that fixed M (models 1 & 2) had similar estimates of survey and fishery selectivity (Figure 7A.7). Selectivity in the single-species model that estimated M and the multi-species model (Models 3 & 4) was more asymptotic for the fishery than in the single-species models that fixed M (Models 1 & 2; Figure 7A.7). All models had similar fits to the survey index data (Figure 7A.8). There were no severe retrospective patterns in the single- or multi-species models across 10 annual peels (Figure 7A.9). The single-species model that estimated M and the multi-species model were consistent in their estimates of M and $M1$, respectively, across peels (Figure 7A.10). The single-species model that estimated M had slightly lower Mohn's rho (0.08) than the single-species model that fixed M and the multi-species model (both at 0.09). However, across both single- and multi-species CEATTLE models, treating annual recruitment deviates as random effects led to lower retrospective bias than when treating them as penalized deviates assuming sigmaR = 0.707. Profiling sigmaR when treating recruitment deviates as random effects or as penalized deviates indicated an inability to estimate sigmaR in ADMB (Figure 7A.11) because the highest density was at sigmaR = 0.

Discussion and Recommendation

Estimating the single-species arrowtooth flounder stock assessment in TMB using CEATTLE has multiple benefits when compared to the current ADMB model. CEATTLE was developed with three goals in mind: 1) flexibly and easily recreate single-species AFSC groundfish assessments in TMB, 2) allow easy model development and reparameterization (*i.e.* multiple observation models can easily be estimated and compared), and 3) allow estimation of time- and age-varying predation mortality for trophically linked species. Currently, the ADMB assessment has a few elements that are mis-specified that are not present in CEATTLE (differences 1, 4, and 5 above). These can be easily corrected in ADMB, however, CEATTLE also allows for correct estimation of recruitment by treating recruitment deviates as random effects. Likelihood profiles of sigmaR show that estimating variance in recruitment is not possible in ADMB. Additionally, comparison of CEATTLE models estimated using penalized maximum likelihood and marginal maximum likelihood show that estimation of sigmaR has impacts on derived quantities used for management. Treating recruitment deviates as random effects also leads to lower retrospective bias than estimating the models using penalized maximum likelihood. Bridging also suggests that estimation using CEATTLE is able to find a better fit to the data than the current ADMB model (see Appendix). Using CEATTLE, improvements to the model could be explored including using the marginal maximum likelihood approach to estimate the non-parametric selectivity penalties or explore other time-varying selectivity functions that may better fit the composition data. We therefore recommend using TMB as the assessment platform via CEATTLE moving forward for GOA ATF.

Accounting for cannibalism in the population dynamics of arrowtooth flounder using CEATTLE demonstrated a better fit to the observed data than the single-species CEATTLE and ADMB models that fixed *M*. Natural mortality was estimated to be higher than the values assumed by the assessment when estimated in both single- and multi-species frameworks. As a result fishery selectivity was estimated to be more asymptotic than when *M* was fixed. Additionally, cannibalism in most years has been more than removals by the fishery. However, given the difficulty in defining Tier 3 reference points for multi-species models, using the multi-species CEATTLE model for the assessment may not make sense. Rather, the multi-species model could be used to inform estimates of mortality in the single-species assessment and supplement the assessment by informing on the impacts of both fishery removals and cannibalism on the stock (*i.e.* project the multi-species model with the recommended ABC). For future iterations, it would be useful to update the time-series of diet data in the model, and explore including other time-varying elements (e.g., weight-at-age data, age-length conversion matrices, diet data). All of which can be easily implemented in CEATTLE and are currently used for other models. Therefore, our recommendations for future assessments include:

- Move the stock assessment model to Template Model Builder (TMB) to correctly treat recruitment deviates as random effects and explicitly estimate the associated variance parameter.
- Estimate sex-specific, but age- and time-invariant natural mortality (*M*).
- Update the weight-at-age and length-at-age transition matrices with recent data and explore the potential for time-varying growth in the assessment model.
- Update the ageing error matrix with recent age data.
- Utilize the multi-species model to inform age- and (possibly) time-varying *M*.
- Explore model sensitivity to different assumptions of catchability (*i.e.* catchability is estimated).

Code and data

https://github.com/grantdadams/GOA-ATF-ESP/tree/master

References

Adams, G. D., Holsman, K. K., Barbeaux, S. J., Dorn, M. W., Ianelli, J. N., Spies, I., Stewart, I. J., & Punt, A. E. (2022). An ensemble approach to understand predation mortality for groundfish in the Gulf of Alaska. *Fisheries Research*, *251*(October 2021), 106303. https://doi.org/10.1016/j.fishres.2022.106303

Adams, G., Holsman, K., Hulson, P., Monnahan, C., Shotwell, K., Stewart, I., and Punt, A. (2023) Multispecies model estimates of time-varying natural mortality of groundfish in the Gulf of Alaska. In: Ferriss, B.E. 2023. Ecosystem Status Report 2023: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 1007 West Third, Suite 400, Anchorage, Alaska 99501.

Anderson, P. J., & Piatt, J. F. (1999). Community reorganization in the Gulf of Alaska following ocean climate regime shift. Marine Ecology Progress Series, 189, 117-123.

Barnes, C. L., Beaudreau, A. H., Hunsicker, M. E., & Ciannelli, L. (2018). Assessing the potential for competition between Pacific Halibut (*Hippoglossus stenolepis*) and Arrowtooth Flounder (*Atheresthes stomias*) in the Gulf of Alaska. PloS one, 13(12), e0209402.

Clark, W. G., & Hare, S. R. (2002). Effects of climate and stock size on recruitment and growth of Pacific halibut. North American Journal of Fisheries Management, 22(3), 852-862.

Curti, K. L., Collie, J. S., Legault, C. M., & Link, J. S. (2013). Evaluating the performance of a multispecies statistical catch-at-age model. *Canadian Journal of …*, *484*(January), 470–484. https://doi.org/10.1139/cjfas-2012-0229

Doyle, M.J., Debenham, C., Barbeaux, S.J., Buckley, T.W., Pirtle, J.L., Spies, I.B., Stockhausen, W.T., Shotwell, S.K., Wilson, M.T., Cooper, D.W., 2018. A full life history synthesis of Arrowtooth Flounder ecology in the Gulf of Alaska: exposure and sensitivity to potential ecosystem change. J. Sea Res. 142, 28–51. https://doi.org/10.1016/j.seares.2018.08.001.

Ferriss, B.E. (2023) Ecosystem Status Report 2023: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 1007 West Third, Suite 400, Anchorage, Alaska 99501.

Fournier, D.A., Skaug, H.J., Ancheta, J., Ianelli, J., Magnusson, A., Maunder, M.N., Nielsen, A., and Sibert, J. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optim. Methods Softw. 27:233-249.

Holsman, K. K., & Aydin, K. (2015). Comparative methods for evaluating climate change impacts on the foraging ecology of Alaskan groundfish. Marine Ecology Progress Series, 521, 217-235.

Holsman, K. K., Ianelli, J., Aydin, K., Punt, A. E., & Moffitt, E. A. (2016). A comparison of fisheries biological reference points estimated from temperature-specific multi-species and single-species climate-enhanced stock assessment models. *Deep Sea Research Part II: Topical Studies in Oceanography*, *134*, 360–378. https://doi.org/10.1016/j.dsr2.2015.08.001

Holsman, K. K., Barnes, C., Aydin, K., Laurel, B., Hurst T., & Heintz T. (2023). Patterns in Foraging and Energetics of Walleye Pollock, Pacific Cod, Arrowtooth Flounder, and Pacific Halibut. In: Elizabeth Sidden (Ed.), *Ecosystem Status Report 2023: Eastern Bering Sea, Stock Assessment and Fishery Evaluation Report*, North Pacific Fishery Management Council, 1007 West 3rd Ave., Suite 400, Anchorage, Alaska 99501.

Hulson, P.-J. F., Barbeaux, S. J., Ferriss, B., Echave, K., Nielsen, J., Shotwell, S. K., Laurel, B., Spies, I., Litzow, M., Mcdermott, S., Rand, K., Levy, C., Wang, M., & Rogers, L. (2023). *Assessment of the Pacific cod stock in the Gulf of Alaska Pacific cod*.

Jurado-Molina, J., Livingston, P. A., & Ianelli, J. N. (2005). Incorporating predation interactions in a statistical catch-at-age model for a predator-prey system in the eastern Bering Sea. *Canadian Journal of Fisheries and Aquatic Sciences*, *62*(8), 1865–1873. https://doi.org/10.1139/f05-110

Kinzey, D., & Punt, A. E. (2009). Multispecies and Single-Spieces Models of Fish Population Dynamics: Comparing Parameter Estimates. *Natural Resource Modelling*, *22*(1), 67–104.

Kristensen, K., Nielsen, A., Berg, C. W., Skaug, H., & Bell, B. M. (2016). TMB : Automatic Differentiation and Laplace Approximation. *Journal of Statistical Software*, *70*(5), 1–21. https://doi.org/10.18637/jss.v070.i05

Magnusson, K. (1995). An overview of the multispecies VPA—theory and applications. *Reviews in Fish Biology and Fisheries*, *212*, 195–212. https://doi.org/10.1007/BF00179756

McAllister, M. K., & Ianelli, J. N. (1997). Bayesian stock assessment using catch-age data and the sampling-importance resampling algorithm. Canadian Journal of Fisheries and Aquatic Sciences, 54(2), 284-300.

NPFMC. (2017). *Fishery Management Plan for Groundfish of the Bering Sea and Aleutian Islands Management Area*.

NPFMC. (2019). *Fishery Management Plan for Groundfish of the Gulf of Alaska*. *August*.

Shotwell, S. K., Spies, I., Ianelli, J. N., Aydin, K., Hanselman, D. H., Palsson, W., Siwicke, K., Sullivan, J., & Yasumiishi, E. (2021). *Assessment of the Arrowtooth flounder stock in the Gulf of Alaska*. https://apps-afsc.fisheries.noaa.gov/refm/docs/2019/GOAatf.pdf

Shotwell, S.K., J.L. Pirtle, J. Watson, A. Deary, M. Doyle, S.J. Barbeaux, M. Dorn, G.A. Gibson, E. Goldstein, D.H. Hanselman, A.J. Hermann, P.J.F. Hulson, B. Laurel, J.H. Moss, O. Ormseth, D. Robinson, L.A. Rogers, C.N. Rooper, I. Spies, W. Strasburger, R.M. Suryan, J.J. Vollenweider (2022) Synthesizing integrated ecosystem research to create informed stock-specific indicators for next generation stock assessments. Deep-Sea Res. Pt. II: Top. Studies. Oceanogr. 198. DOI: https://doi.org/10.1016/j.dsr2.2022.105070

Shotwell, S., Hanselman, D., Siwicke, K., Spies, I. and Sullivan, J. (2023) Assessment of the arrowtooth flounder stock in the Gulf of Alaska. In: Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska. North Pacific Fishery Management Council, Anchorage, AK.

Wilderbuer, T.K. and B.J. Turnock. 2009. Differential Sex-Specific Natural Mortality of Arrowtooth Floun- der in Alaska: Implications for Exploitation and Management. North American Journal of Fisheries Man- agement Vol. 29 (2).

Tables

Table 7A.1. General population dynamics equations in CEATTLE for species i, sex s, age a, and length l in year y, and for survey or fishery f_i. See Table 4 for parameter definitions.

Definition	Equation
Initial abundance	$N_{isa1} = \{ \underline{R}_{F_i} e^{\left(-\sum_{j=1}^{a-1} M1_{isj} + \tau_{ia}\right)} \rho_{i1} \; if\ a < A_i$ $N_{isA_i1} = \frac{\underline{R}_{F_i} e^{\left(-\sum_{j=1}^{a-1} M1_{isj} + \tau_{ia}\right)} \rho_{i1}}{\left(1 - e^{\left(-M1_{isA_i}\right)}\right)} \; if\ a = A_i$
Recruitment	$N_{is1y} = R_{isy} = \underline{R}_i e^{\tau_{iy}} \rho_{i1}$
Numbers at age	$N_{isa+1y+1} = N_{isay} e^{-Z_{isay}}$ $N_{isA_iy+1} = N_{isA_i-1y} e^{-Z_{isA_i-1y}} + N_{isA_iy} e^{-Z_{isA_iy}}$
Survey biomass (kg)	$\widehat{CPUE}: B_{f_iy} = \sum_s \sum_a N_{isay} e^{-Month_{f_i} * Z_{isay}} W_{f_isay} sel_{f_isay} q_{f_iy}$
Catch-at-age	$C_{f_isay} = \frac{F_{f_isay}}{Z_{isay}} \left(1 - e^{-Z_{isay}}\right) N_{isay}$
Total catch (kg)	$\hat{C}^*_{f_iy} = \sum_s \sum_j \frac{F_{f_isay}}{Z_{isay}} \left(1 - e^{-Z_{isay}}\right) N_{isay} W_{f_isay}$
Age-1+ biomass (kg)	$B_{iy} = \sum_s \sum_{a>0} N_{isay} W_{B_iay}$
Spawning biomass at age (kg)	$SB_{iay} = N_{i1ay} e^{-Month_{ssb_i}/12 * Z_{i1ay}} W_{ssb_i1ay} \delta_{ia}$
Total mortality at age (single-species)	$Z_{isay} = M1_{isa} + \sum_{f_i} F_{f_isay}$
Total mortality at age (multi-species)	$Z_{isay} = M1_{isa} + M2_{isay} + \sum_{f_i} F_{f_isay}$
Fishing mortality at age and fleet	$F_{f_isay} = \underline{F}_{f_i} e^{\epsilon_{f_iy}} sel_{f_isay}$
Projected fishing mortality	$F_{f_isay} = F_{Target_i} sel_{f_isay} \psi_{f_i}$
Predicted age composition	$\hat{O}_{f_is\hat{a}y} = \frac{\sum_a C_{f_isay} AE_{i\hat{a}a}}{\sum_s \sum_{\hat{a}} \sum_a C_{f_isay} AE_{i\hat{a}a}} \quad if\ f_i$ = fishery $\hat{O}_{f_is\hat{a}y} = \frac{\sum_a N_{isay} e^{-Month_{f_i} * Z_{isjy}} sel_{f_isay} AE_{i\hat{a}a}}{\sum_s \sum_{\hat{a}} \sum_a N_{isay} e^{-Month_{f_i} * Z_{isjy}} sel_{f_isay} AE_{i\hat{a}a}} \quad if\ f_i$ = survey
Predicted length composition	$\hat{O}_{f_isly} = \frac{\sum_{\hat{a}} \sum_a C_{f_isay} AE_{i\hat{a}a} ATM_{isal}}{\sum_s \sum_l \sum_{\hat{a}} \sum_a C_{f_isay} AE_{i\hat{a}a} ATM_{isal}} \quad if\ f_i$ = fishery

	$\hat{O}_{f_i sly} = \frac{\sum_{\hat{a}}\sum_{a} N_{isay} e^{-Month_{f_i} * Z_{isay}} sel_{f_i say} AE_{ia\hat{a}} ATM_{isal}}{\sum_{s}\sum_{l}\sum_{\hat{a}}\sum_{a} N_{isay} e^{-Month_{f_i} * Z_{isjy}} sel_{f_i say} AE_{ia\hat{a}} ATM_{isal}} \; if \; f_i = \text{survey}$

Table 7A.2. Predation mortality equations for predator species p, sex b, age j, and prey species i, sex s and age a. For parameter definitions see Table 4.

Definition	**Equation**
Predation mortality	$M2_{isay} = \sum_{pbj}\left(\frac{\underline{N}_{pbjy}\delta_{pbjy}\hat{S}_{pbjisa}}{\left(\sum_{isa}\left(\hat{S}_{pbjisa}\underline{B}_{isay}\right)+B_{p}^{other}\left(1-\sum_{isa}\left(\hat{S}_{pbjisa}\right)\right)\right)}\right)$
Predator-prey suitability	$S\hat{}_{pbjisa} = \frac{1}{n_y}\sum_{y}\left(\frac{\frac{\underline{U}_{psaisa}}{w_{isay}\underline{N}_{isay}^{H_i}}}{\sum_{isa}\left(\frac{\underline{U}_{pbjisa}}{w_{isay}}\right)+\frac{1-\sum_{isa}\underline{U}_{pbjisa}}{B_{p}^{other}}}\right)$
Individual specific ration ($kg\ kg^{-1}\ yr^{-1}$)	$\delta_{pbjy} = \varphi_{pbjy}\alpha_{p}^{\delta}W_{pbjy}^{\left(1+\beta_{p}^{\delta}\right)}f\left(T_y\right)_p$
Temperature scaling algorithms	$f\left(T_y\right)_p = V^{X}e^{(X(1-V))}$
…	$V = \left(T_{p}^{cm} - T_y\right)/\left(T_{p}^{cm} - T_{p}^{co}\right)$
…	$X = \left(Z^{2}\left(1 + (1 + 40/Y)^{0.5}\right)^{2}\right)/400$
…	$Z = ln\left(Q_{p}^{c}\right)\left(T_{p}^{cm} - T_{p}^{co}\right)$
…	$Y = ln\left(Q_{p}^{c}\right)\left(T_{p}^{cm} - T_{p}^{co} + 2\right)$

Table 7A.3. Components of the likelihood function for species i, sex s, age a, or length l during year y for survey s or fishery f. For parameter definitions see Table 4.

Description	**Equation**
Data components	
Survey biomass	$ln\left(B_{f_i y}\right) \sim N\left(ln\left(\hat{B}_{f_i y}\right) - \frac{\sigma^2_{f_i y}}{2}, \sigma^2_{f_i y}\right)$
Total catch	$ln\left(C^*_{f_i y}\right) \sim N\left(ln\left(C\hat{}^*_{f_i y}\right) - \frac{\sigma^2_{f_i y}}{2}, \sigma^2_{f_i y}\right)$
Age composition	$-\sum_i n_{f_i y} \sum_s \sum_{\hat{a}} \sum_y \left(\hat{O}_{f_i s\hat{a}y} + 0.00001\right) * ln\left(O_{f_i s\hat{a}y} + 0.00001\right)$
Length composition	$-\sum_i n_{f_i y} \sum_s \sum_l \sum_y \left(\hat{O}_{f_i sly} + 0.00001\right) * ln\left(O_{f_i sly} + 0.00001\right)$
Penalties	
Non-parametric selectivity	$\sum_i \sum_s \sum_a^{A_i - 1} \chi_{f_i} \left[ln\left(\frac{e^{\psi_{f_i sa}}}{e^{\psi_{f_i sa+1}}}\right) - ln\left(\frac{e^{\psi_{f_i sa+1}}}{e^{\psi_{f_i sa+2}}}\right)\right]^2$ $\chi_{f_i} = 0 \quad if\, e^{\psi_{f_i sa}} \leq e^{\psi_{f_i sa+1}}$
Recruitment deviate	$\tau_{iy} \sim N\left(-\frac{\sigma^2_{R_i}}{2}, \sigma^2_{R_i}\right)$
Fishing mortality deviate	$\epsilon_{f_i y} \sim \epsilon_{f_i y} * \epsilon_{f_i y}$

Table 7A.4. Parameter definition for CEATTLE.

Category	Parameter	Definition
Index	i	Species
	s	Sex
	a	Age
	$\hat{a}$	Observed age
	A	Plus group
	l	Length
	y	Year
	Y	Last year of estimation (not projection)
	p	Predator species
	b	Predator sex
	j	Predator age
	k	Predator length
	f_i	Fleet/survey
Population model	R_{isy}	Recruitment
	$\underline{R}_i$	Mean recruitment
	τ_{iy}	Annual recruitment deviate
	δ_{ia}	Maturity-at-age
	ρ_{ia}	Sex-ratio
	$M1_{isa}$	Residual mortality yr^{-1}
	$M2_{isay}$	Predation-mortality yr^{-1}
	$F_{f_i say}$	Fleet-specific fishing mortality yr^{-1}
	F_{isay}	Total fishing mortality yr^{-1}
	Z_{isay}	Total mortality yr^{-1}
	$\underline{F}_{f_i}$	Mean fishing mortality yr^{-1}
	$\epsilon_{f_i y}$	Annual fishing mortality deviate
	ψ_{f_i}	Fishing mortality apportionment per fleet
	N_{isay}	Numbers-at-age
	$\underline{N}_{isay}$	Average numbers-at-age
	SB_{ijy}	Spawning-stock-biomass (kg)
	B_{isay}	Biomass (kg)
	$\underline{B}_{isay}$	Average biomass (kg)
Predation model	$\hat{S}_{pbjisa}$	Predator-prey suitability
	H_i	Holling functional response parameter
	B_p^{other}	Biomass of "other prey" (kg)
	T_y	Observed bottom temperature (°C)
	T_p^{co}	Thermal optima for consumption (°C)
	T_p^{cm}	Thermal limit of consumption (°C)

	Q^{c}_{p}	Rate at which consumption increased over relatively low water temperatures
	α^{δ}_{p}, β^{δ}_{p}	Weight specific intercept and slope of maximum consumption
	φ_{pbj}	Scalar for maximum to observed consumption
	$\underline{U}_{pbj,isa}$	Average proportion of prey-at-age in the stomach of a predator-at-age
Observation model		
	$CP\hat{U}E: B_{f_i y}$	Survey/fishery relative biomass (kg)
	$sel_{f_i say}$	Selectivity
	$q_{f_i y}$	Catchability
	W	Weight (kg)
	$C_{f_i say}$	Catch-at-age
	$C\hat{}^{*}_{f_i y}$	Total catch (kg)
	$\hat{O}_{f_i s\hat{a} y}/\hat{O}_{f_i sly}$	Predicted age/length composition
	$AE_{i\hat{a}a}$	Ageing error matrix
	ATM_{isal}	Age-transition matrix (growth trajectory)
	$\hat{S}_{pbjisa}$	Predator-prey suitability

Table 7A.5. Time-series and sources of data used in CEATTLE model

Source	**Data type**	**Data collection cycle**
NMFS bottom trawl survey	Absolute biomass	Triennial and Biennial (1984-2021)
	Age composition	1984-2019
	Diet composition	1990-2015
Holsman and Aydin (2015)	Bioenergetic demand	1990-2015
Fishery	Total catch	Annual (1977-2023)
	Length composition	1977-2020

Table 7A.6. Model comparison table. Note, likelihoods from the ADMB model are not comparable with CEATTLE.

	ADMB	**CEATTLE Single-spp (fix M)**	**CEATTLE Single-spp (est M)**	**CEATTLE multi-spp**
Platform	ADMB	TMB	TMB	TMB
Likelihoods				
Catch	4.31803e-08	-97.51	-97.38	-94.38
Fishery length composition	816.17	83.32	63.94	63.76
Survey biomass	27.86	1.16	-3.94	-4.44
Survey age composition	276.91	43.36	40.49	40.54
Recruit deviations	5.04	24.30	19.26	21.96
Selectivity penalties	7.30	9.91	6.48	6.95
F regularity	21.20	20.44	21.08	22.20
Joint NLL	**177.67**	**84.99**	**49.94**	**56.61**
Marginal NLL		96.47	66.18	68.92
Number of parameters	158	92	94	94
Estimates				
q-trawl	1	1.0	1.0	1.0
Mean Recruitment (thousand)	801,987	806,846	1,921,099	2,451,550
σ_r	0.707	0.477	0.445	0.462
2023 total biomass (t)	1,276,460	1,273,952	1,631,329	1,747,704
2023 spawning biomass (t)	696,871	718,708	550,638	548,410
$B_{100\%}$ (t)	1,018,700	1,684,452	2,045,104	2,141,534
$B_{40\%}$ (t)		673,781	818,042	856,614
$SSB_{100\%}$ (t)		984,431	752,438	738,569
$SSB_{40\%}$ (t)	407,478	393,772	300,975	295,428

Figures

Figure 7A.1. Time-series of estimated age-1 recruitment (millions; top panel), total biomass (million mt; middle panel), spawning stock biomass (million mt; bottom panel) as determined from the 2023 ADMB assessment, CEATTLE single-species fixed M and estimated M, and multi-species (cannibalism) models.

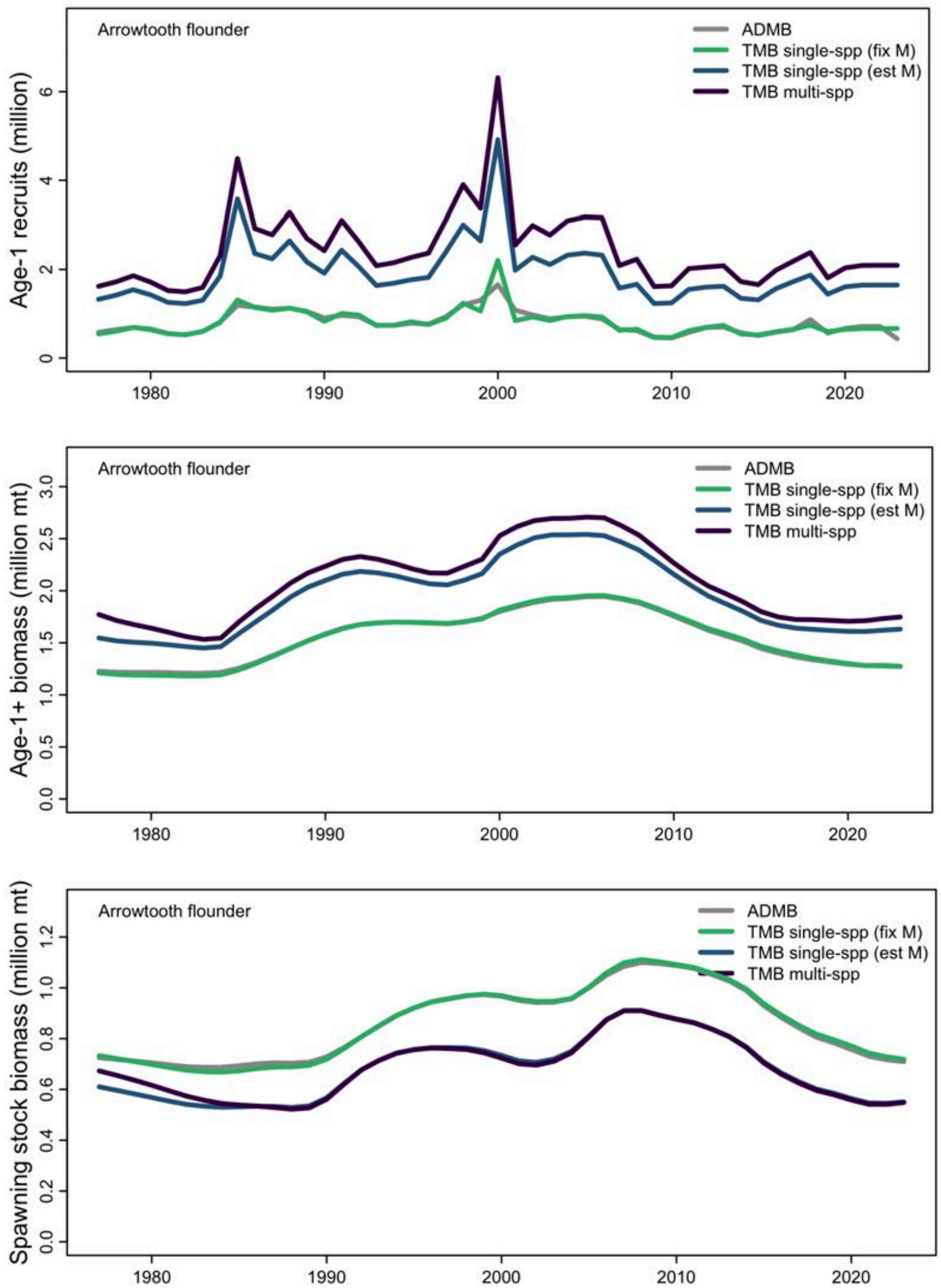


Figure 7A.2a. Time-series of total natural mortality at age-1 (top-left panel), age-2 (top-right panel), age-3 (bottom-left panel), and age-4 (bottom-right panel) from the single- and multi-species (cannibalism) CEATTLE models. For the single-species ADMB and CEATTLE single-species with fixed *M*, natural mortality is set at 0.2 for females and 0.35 for males.

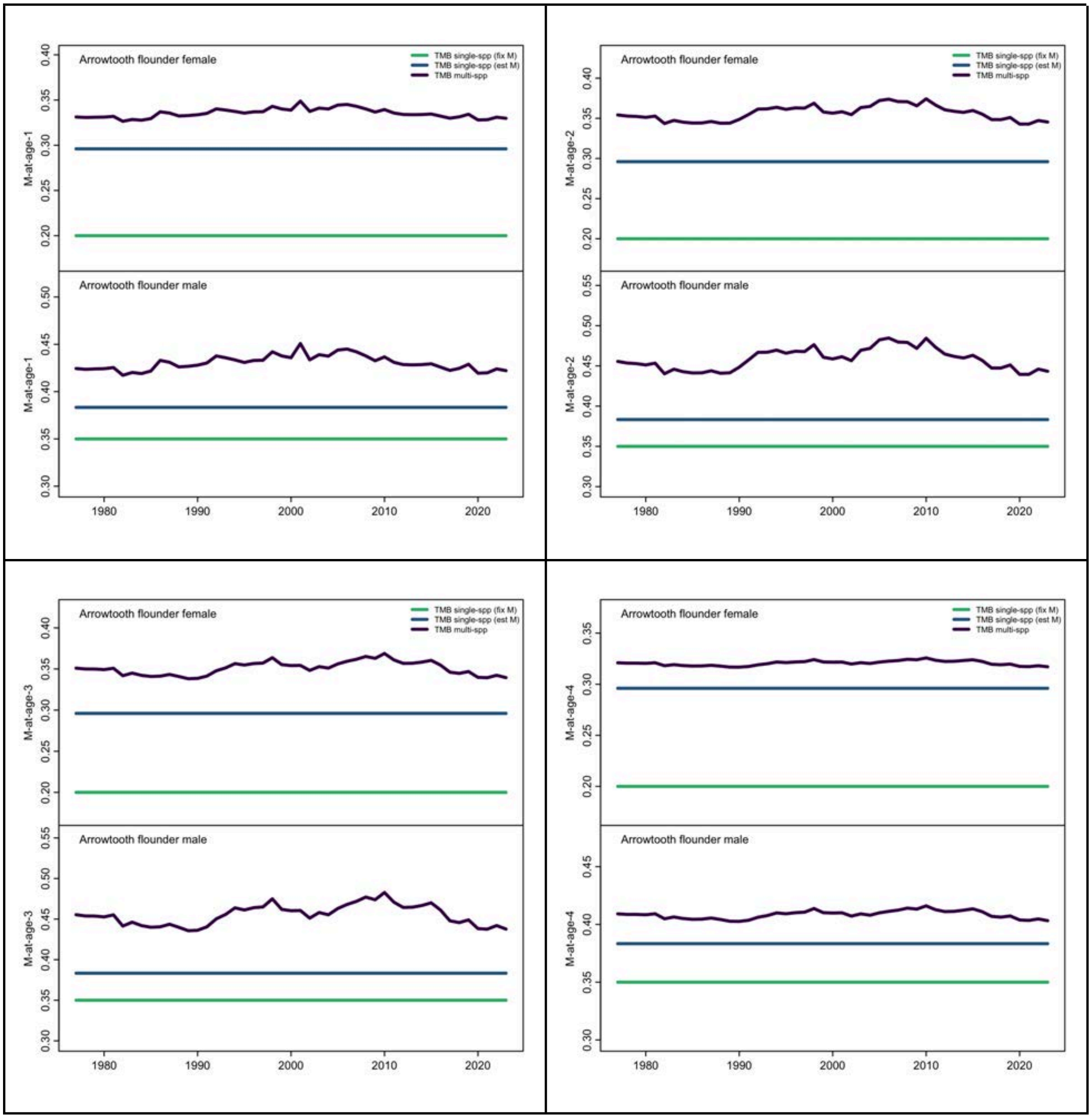


Figure 7A.2b. Time-series of total natural mortality at age-5 (top-left panel), age-6 (top-right panel), age-7 (bottom-left panel), and age-8 (bottom-right panel) from the single- and multi-species (cannibalism) CEATTLE models. For the single-species ADMB and CEATTLE single-species with fixed *M*, natural mortality is set at 0.2 for females and 0.35 for males.

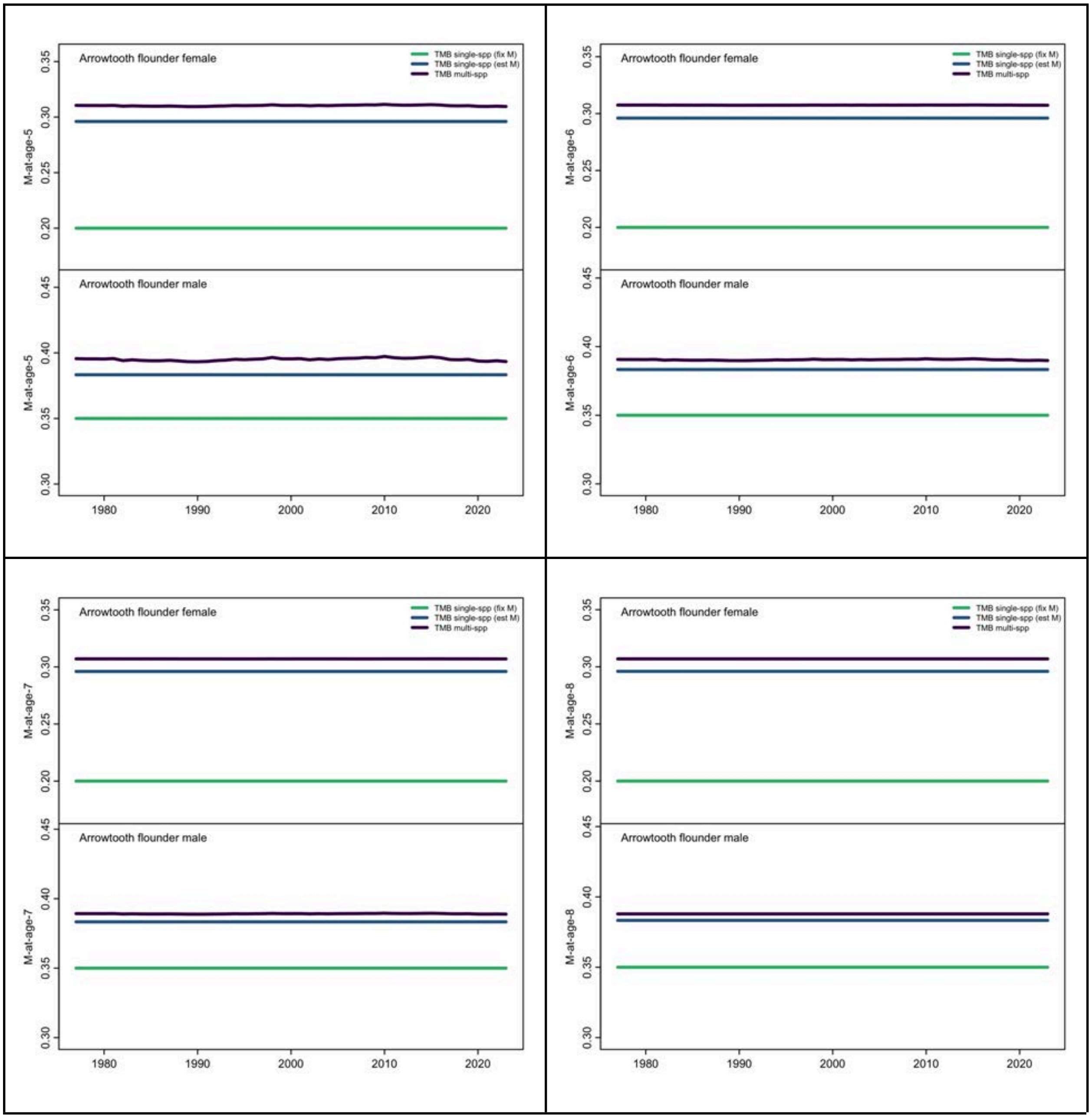
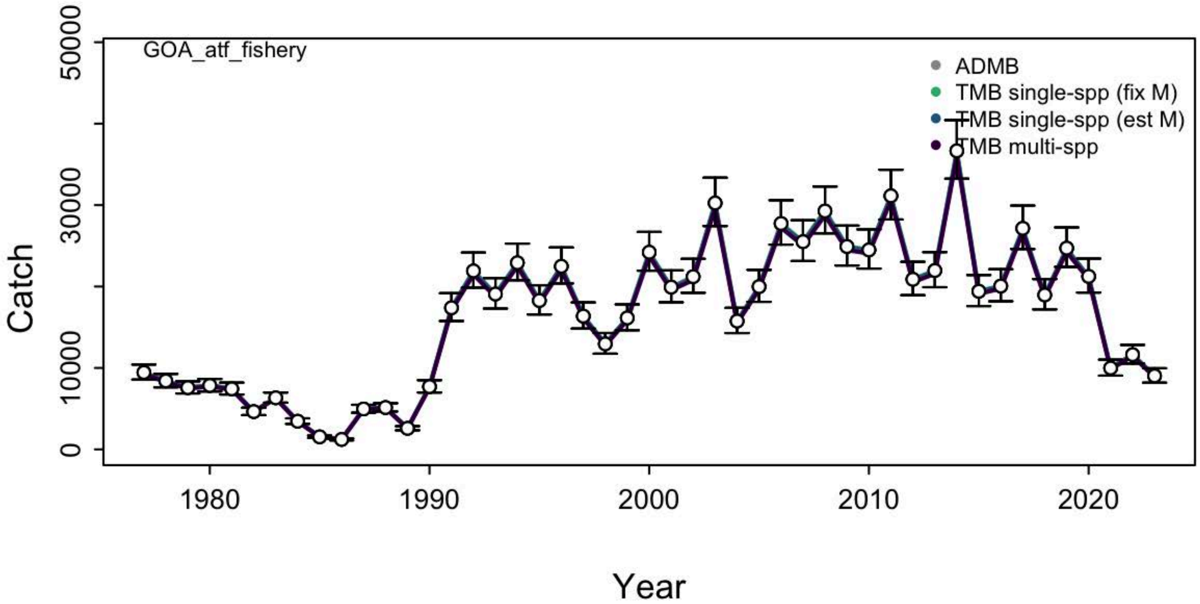


Figure 7A.3. Time-series of estimated and observed catch (mt) and biomass consumed (mt) as prey as determined from the 2023 ADMB assessment and CEATTLE single- and multi-species (cannibalism) models.



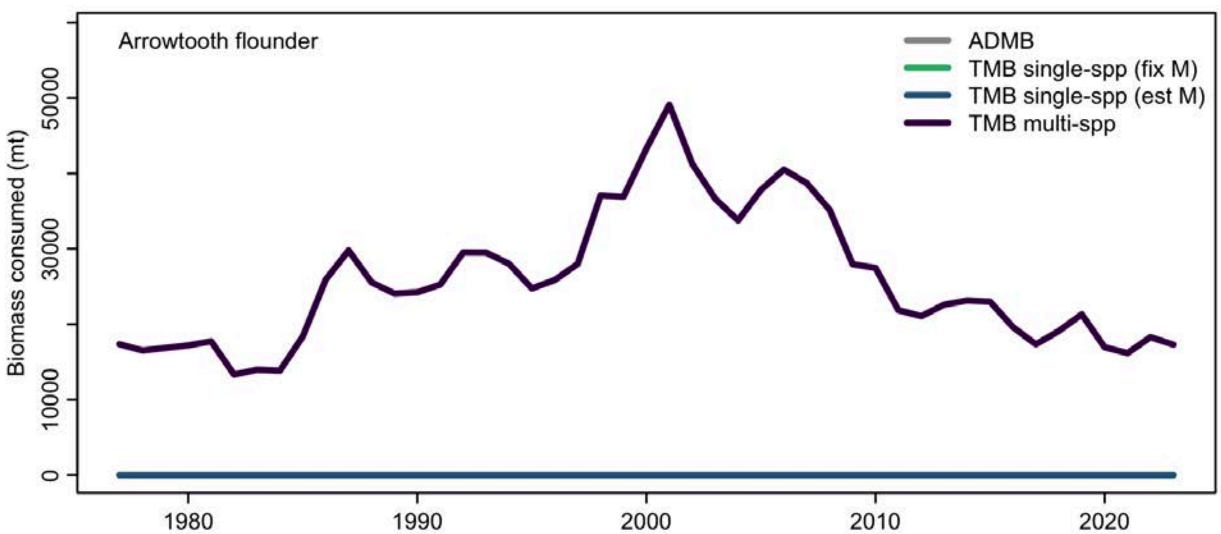
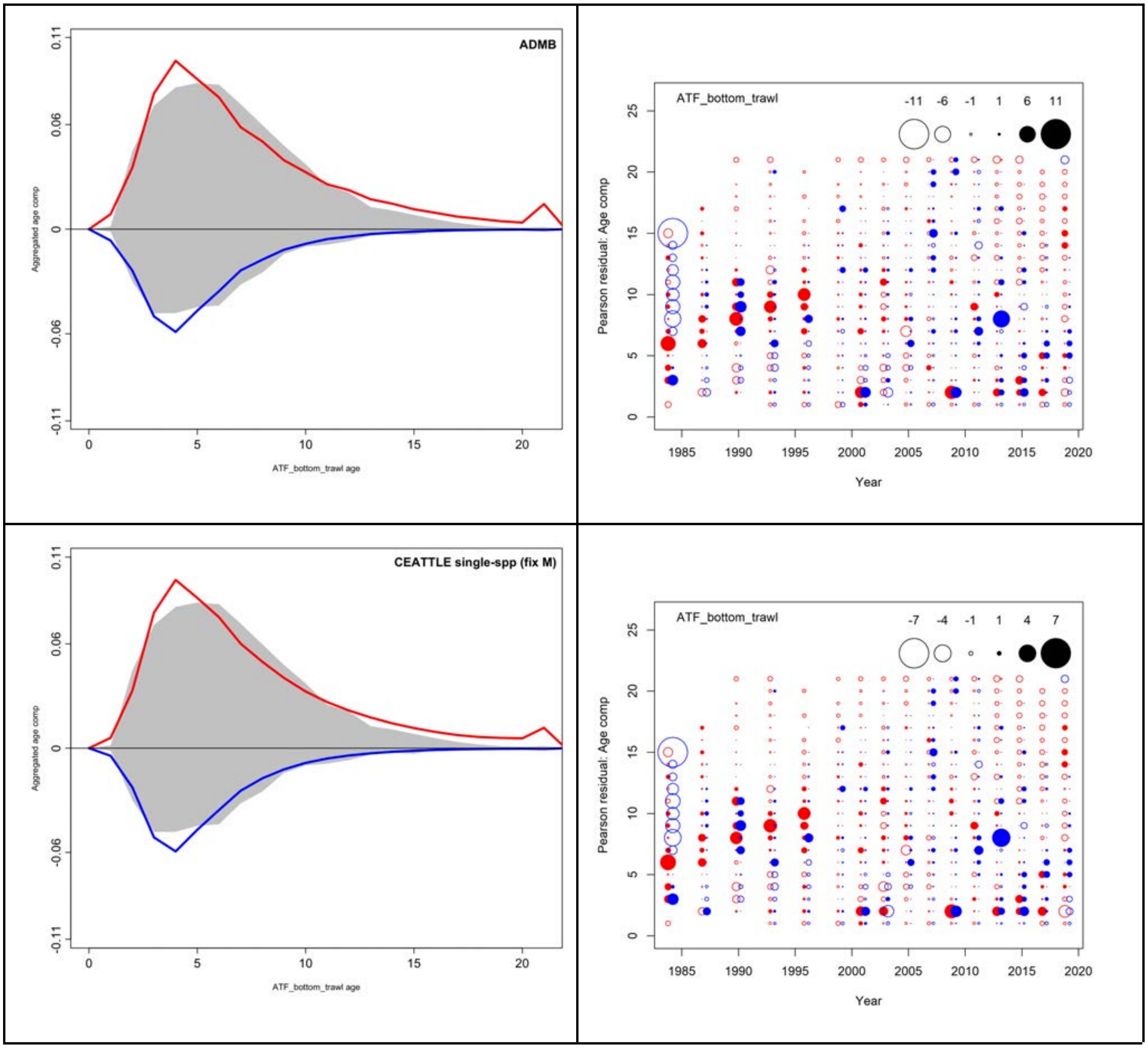


Figure 7A.4. Fits to aggregated and pearson residuals of observed and expected bottom trawl survey age-composition data between the ADMB model and CEATTLE single- and multi-species models. Females are red and males are blue. NOTE: difference in z-scale.



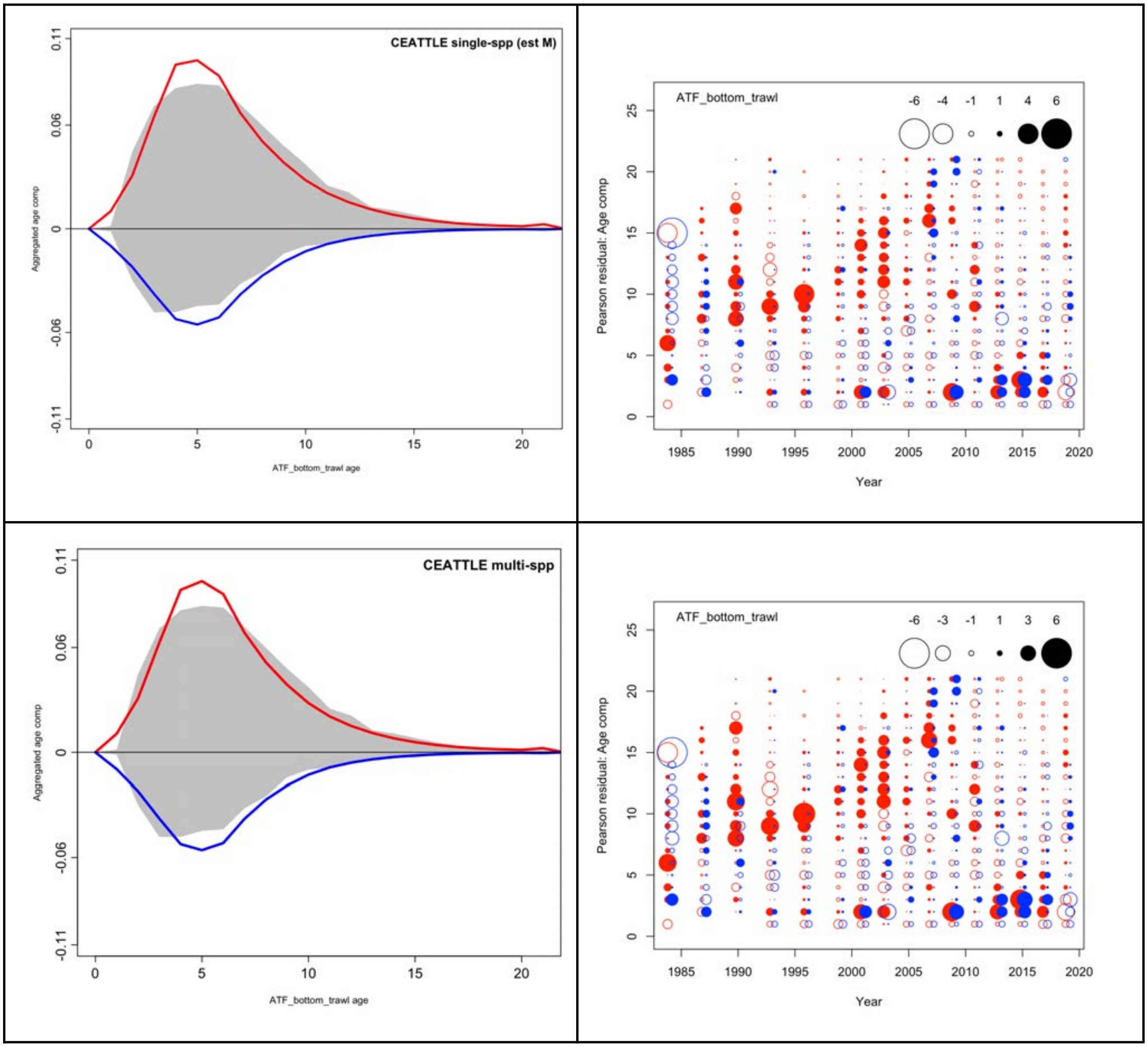

CEATTLE single-spp (est M)
Aggregated age comp
ATF_bottom_trawl age
ATF_bottom_trawl
Pearson residual: Age comp
Year
-6 -4 -1 1 4 6
CEATTLE multi-spp
Aggregated age comp
ATF_bottom_trawl age
ATF_bottom_trawl
Pearson residual: Age comp
Year
-6 -3 -1 1 3 6

Figure 7A.5. One step ahead (OSA) residuals of observed and expected bottom trawl survey age-composition data between the ADMB model and CEATTLE single- and multi-species models. NOTE: difference in z-scale.

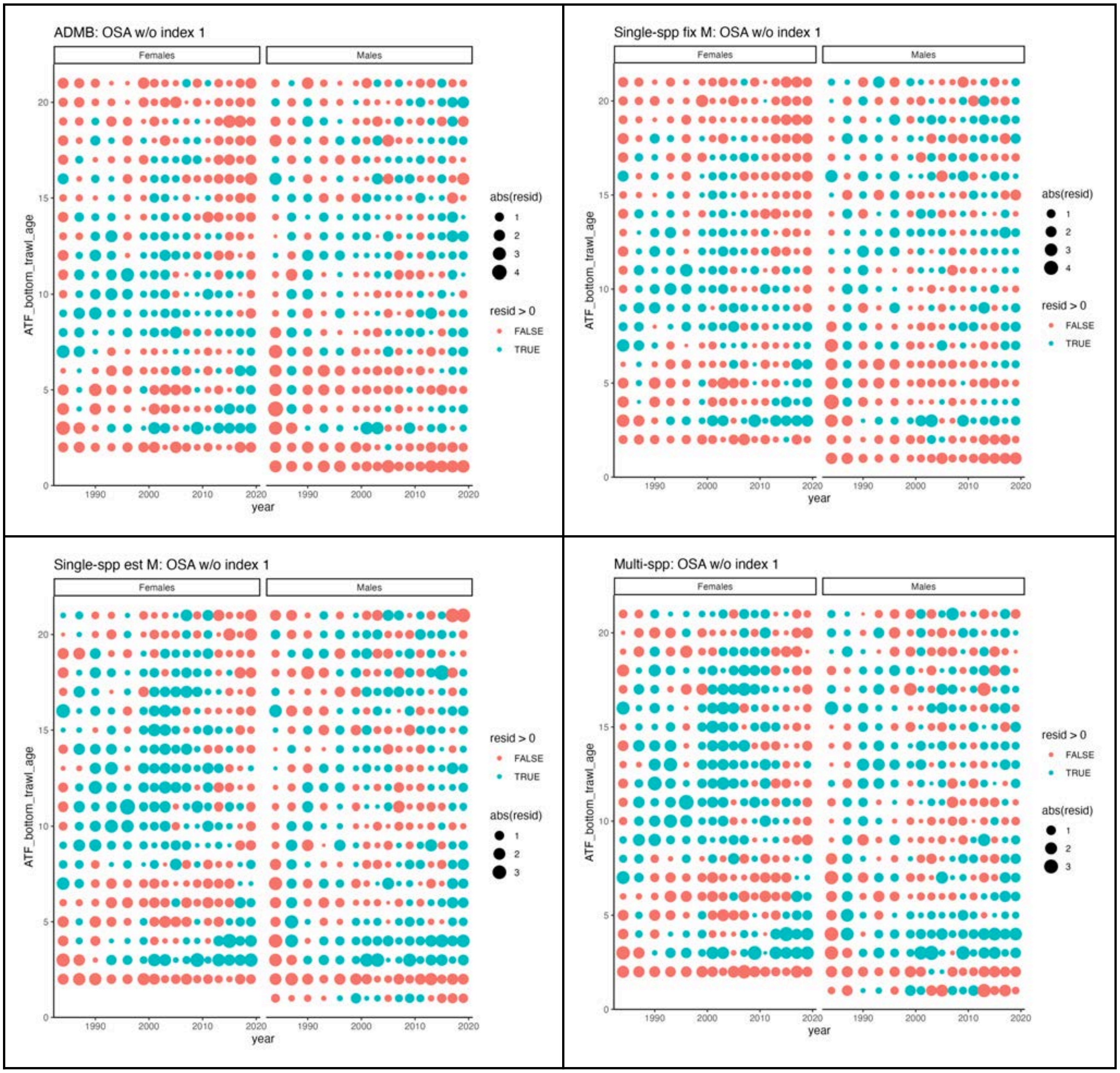
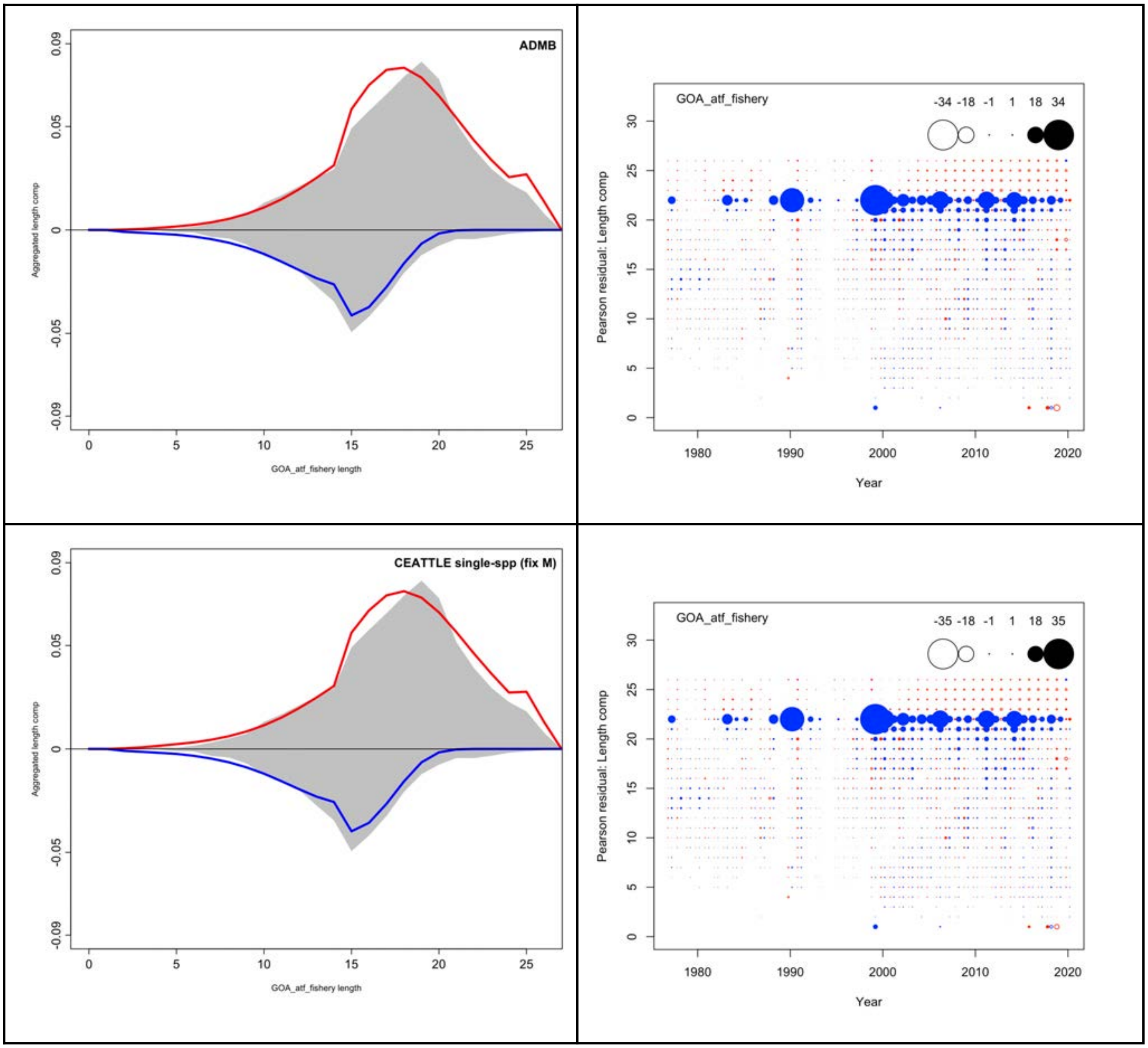


Figure 7A.6. Fits to aggregated and pearson residuals of observed and expected fishery length-composition data between the ADMB model and CEATTLE single- and multi-species models. Females are red and males are blue. NOTE: difference in z-scale.



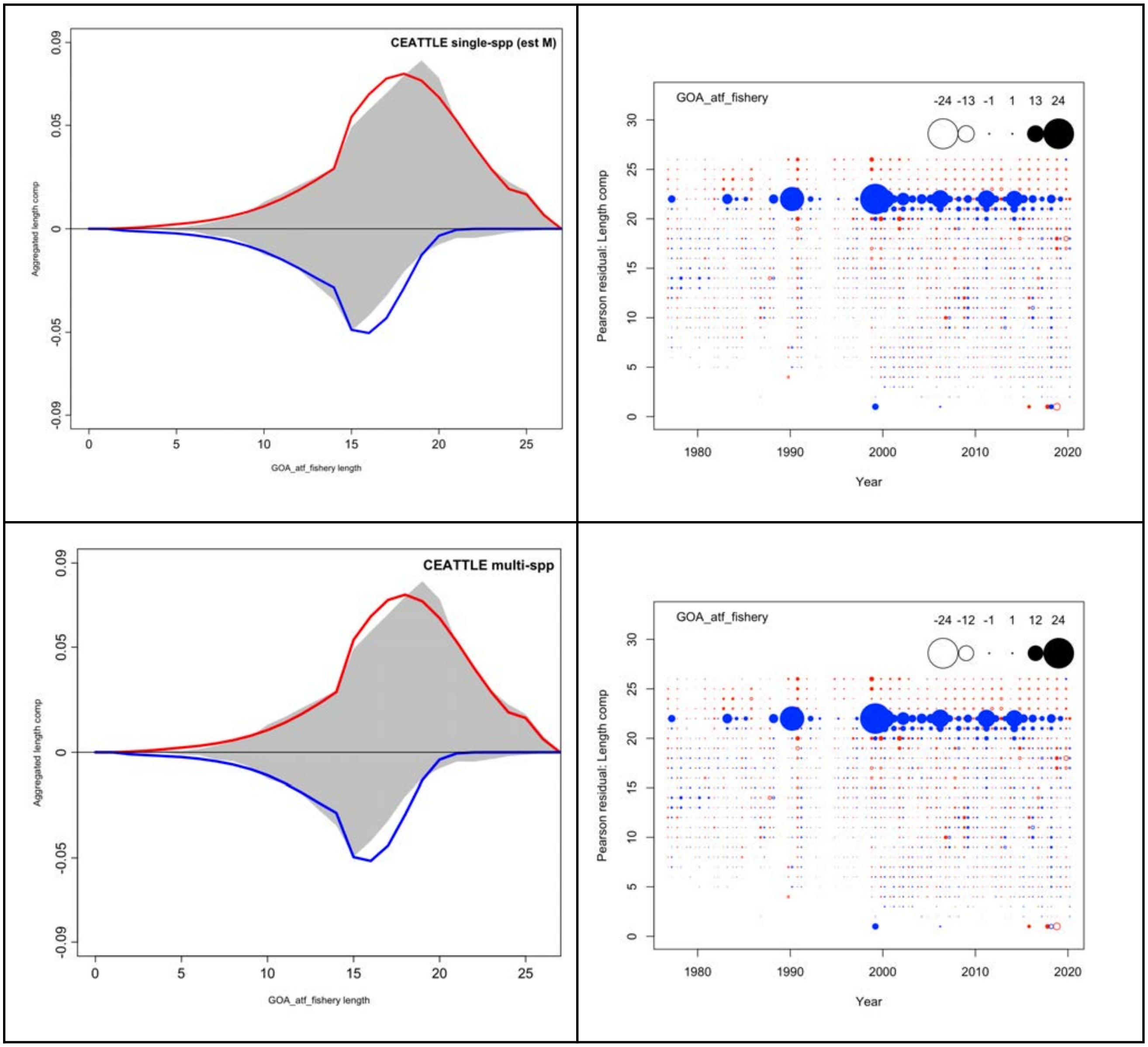
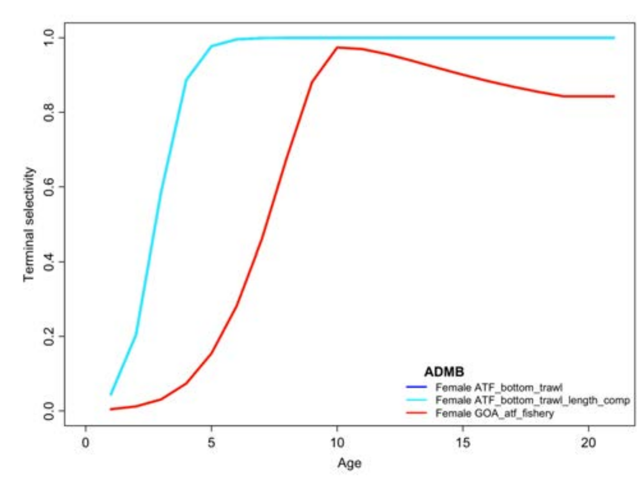
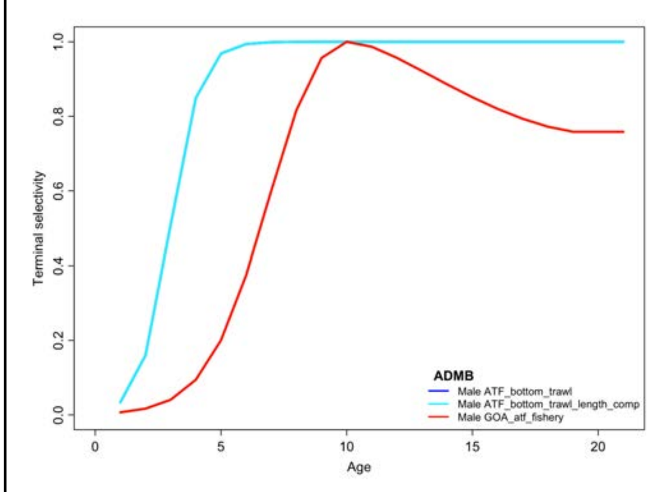
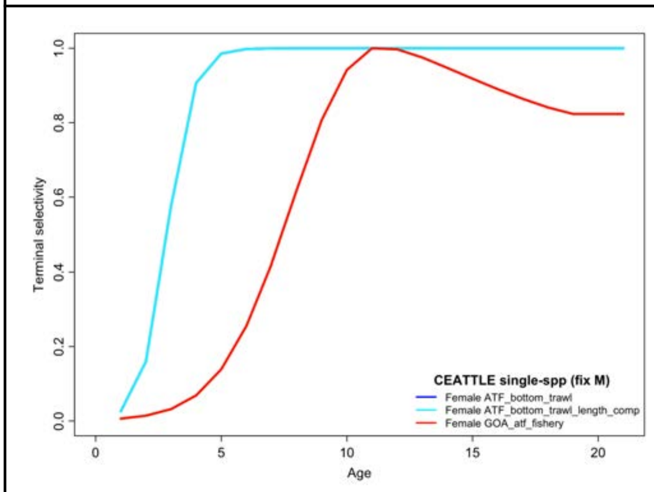
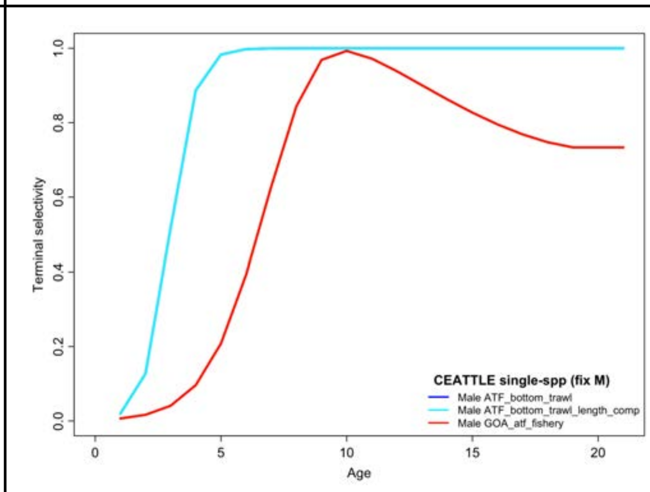
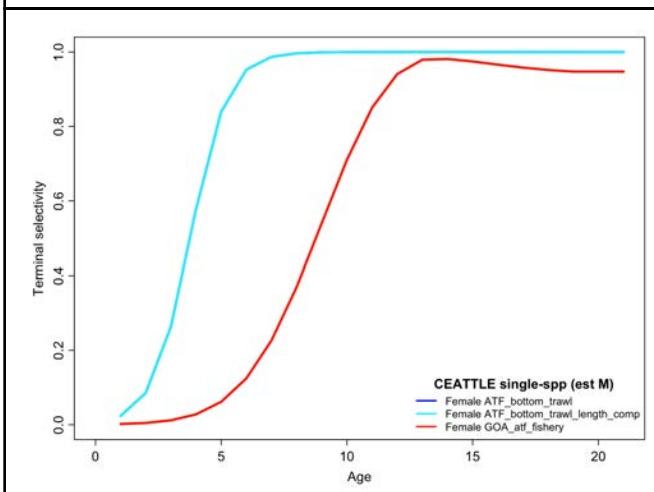
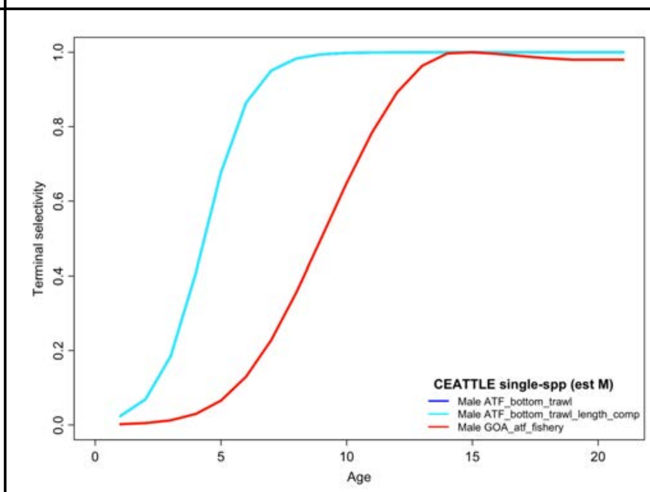

CEATTLE single-spp (est M)
Aggregated length comp
GOA_atf_fishery length
GOA_atf_fishery
-24 -13 -1 1 13 24
Pearson residual: Length comp
Year
CEATTLE multi-spp
Aggregated length comp
GOA_atf_fishery length
GOA_atf_fishery
-24 -12 -1 1 12 24
Pearson residual: Length comp
Year

Figure 7A.7. Estimated selectivity between the ADMB model and CEATTLE single- and multi-species models.

Females	**Males**
	
	
	

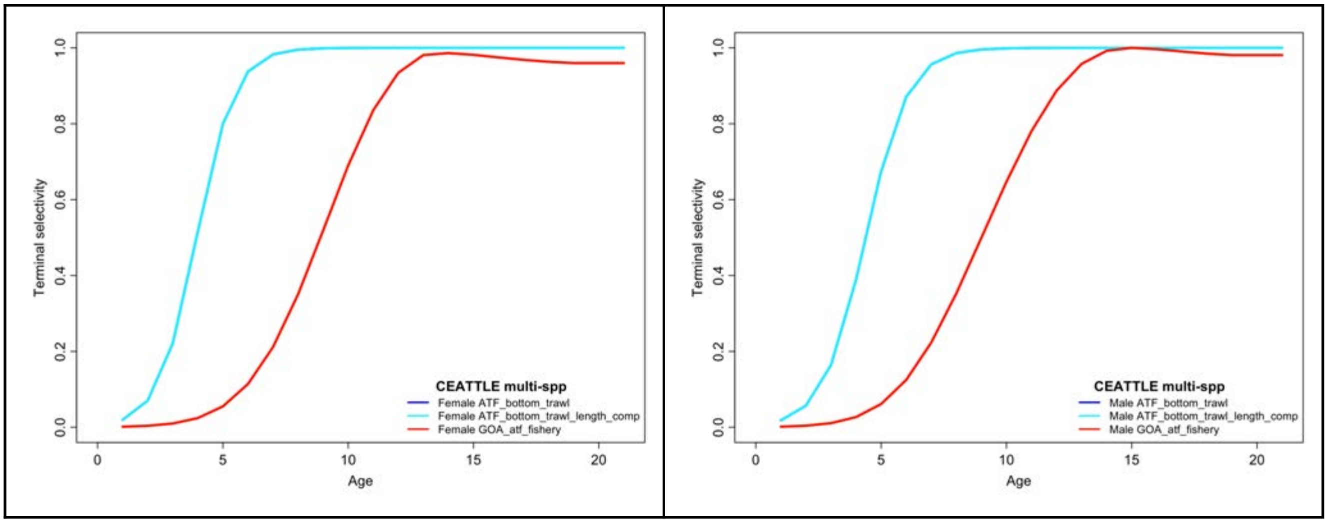

Terminal selectivity
Age
CEATTLE multi-spp
Female ATF_bottom_trawl
Female ATF_bottom_trawl_length_comp
Female GOA_atf_fishery
Male ATF_bottom_trawl
Male ATF_bottom_trawl_length_comp
Male GOA_atf_fishery

Figure 7A.8. Observed (circles) and expected (lines) AFSC trawl survey biomass across the ADMB model and CEATTLE single- and multi-species models.

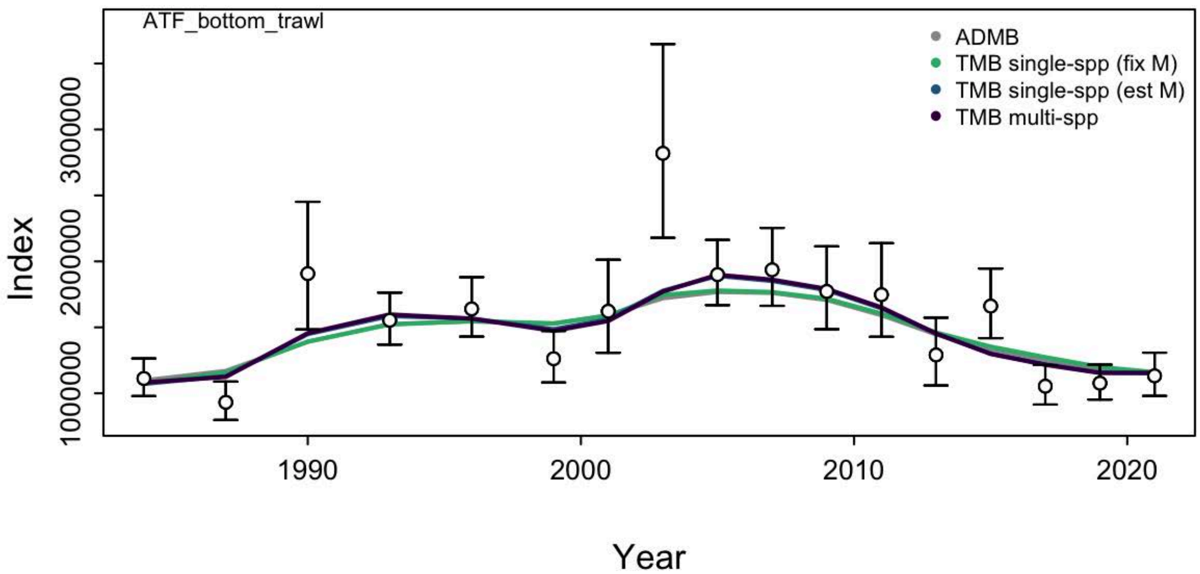


Figure 7A.9. Retrospective spawning age-1+ total biomass estimates across CEATTLE single- and multi-species models. Mohn's rho is indicated in the upper right hand corner. The left column are models where recruitment deviates are treated as penalized deviates (similar to ADMB) and the right column are models where recruitment deviates are treated as random effects.

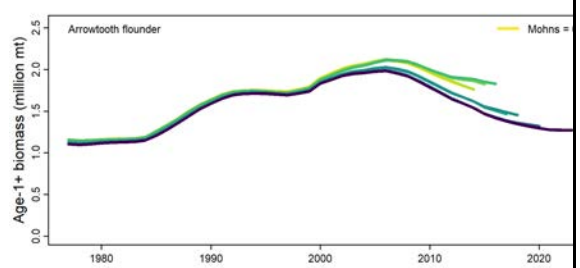
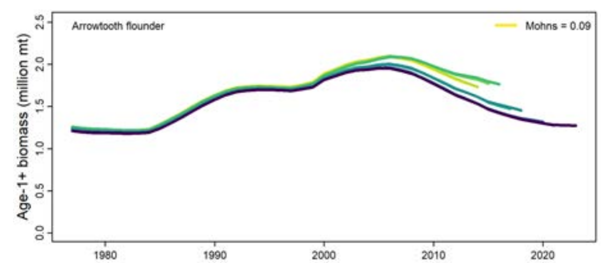
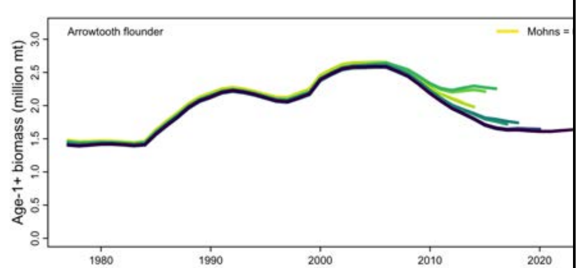
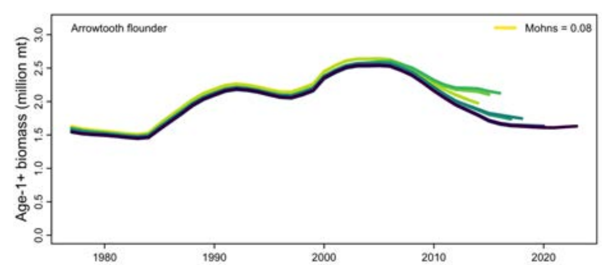
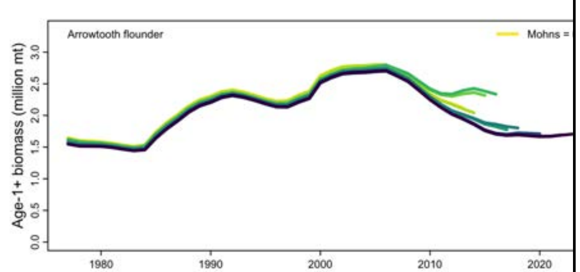
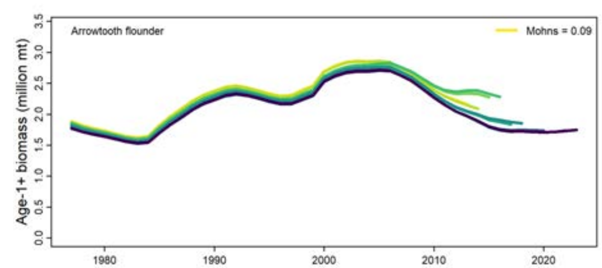
Model	Penalized likelihood	Marginalized likelihood
2. Single-spp fix M		
3. Single-spp est M		
4. Multi-spp		

Figure 7A.10. Retrospective estimates of total natural mortality (*M*) and residual natural mortality (*M1*) for CEATTLE single-species models that estimated *M* and multi-species models where recruitment deviates are treated as random effects.

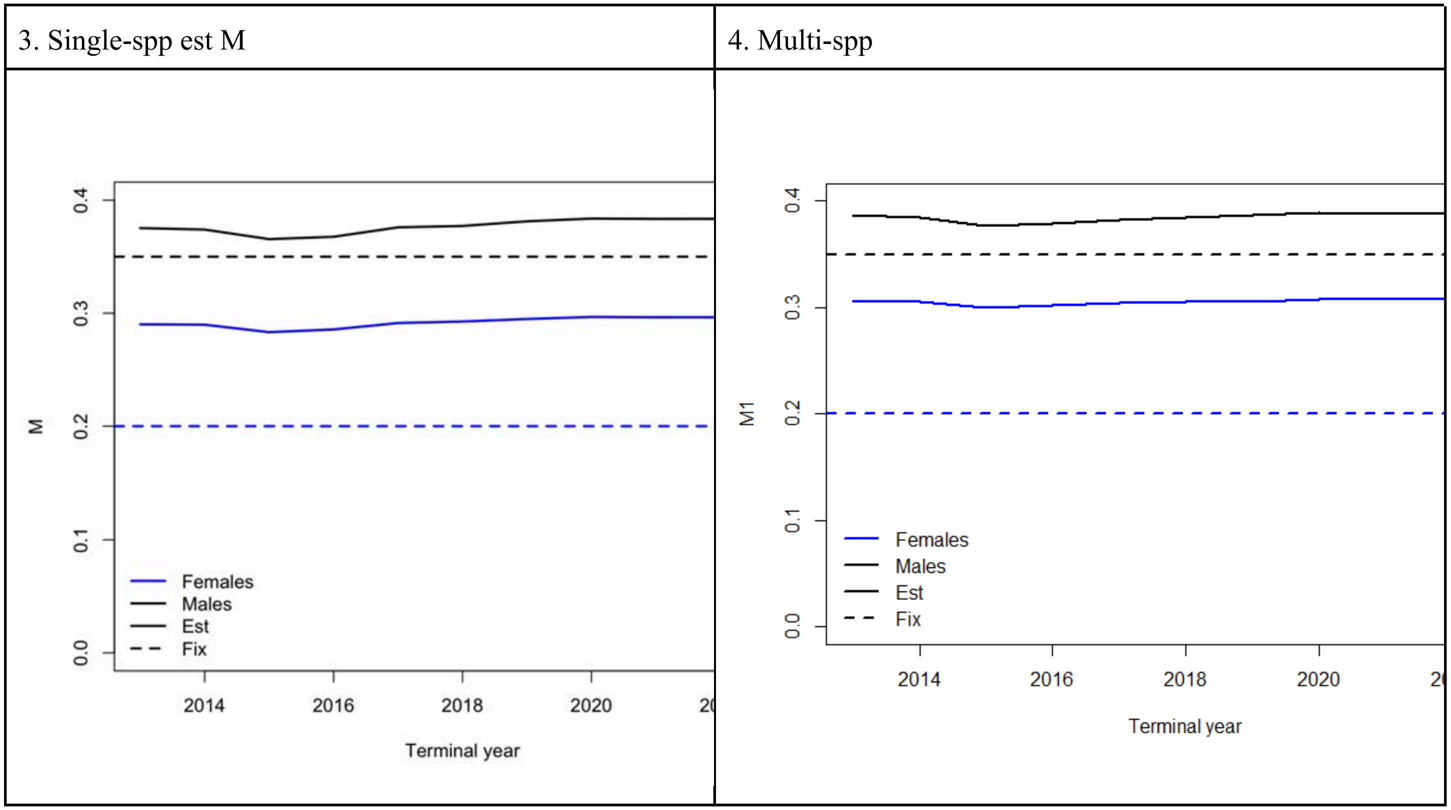
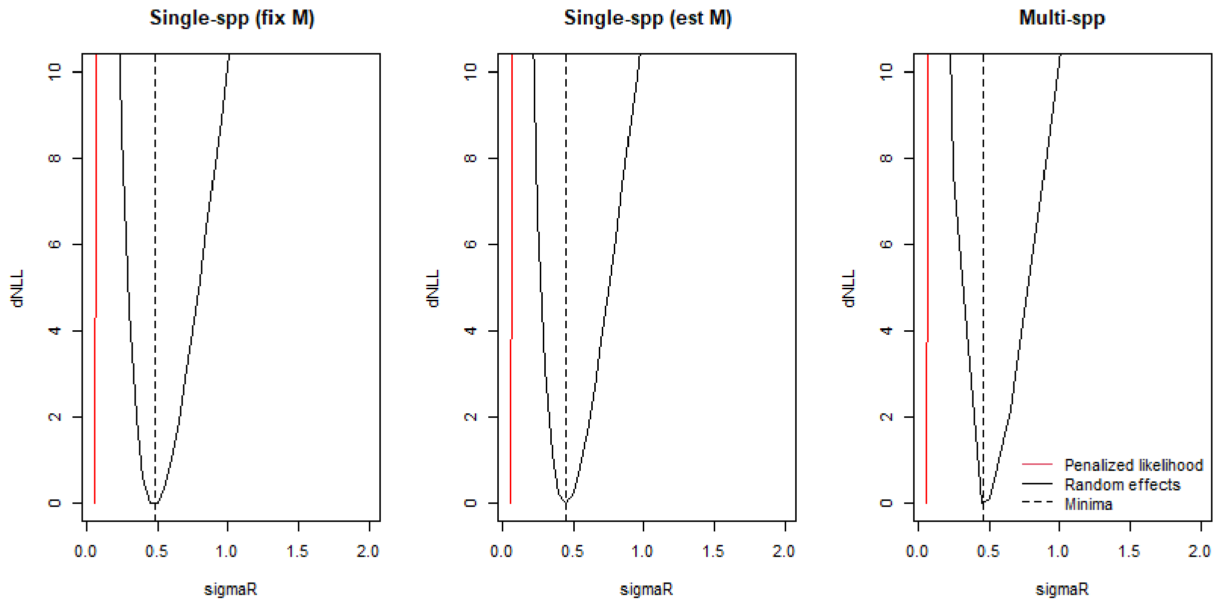


Figure 7A.11. Likelihood profiles for variance in recruitment (sigmaR) across CEATTLE single- and multi-species models where recruitment deviates are treated as penalized deviates (similar to ADMB) or as random effects.



Supplementary Material

Model bridging

A series of models were developed to bridge the ADMB model to CEATTLE and evaluate the impacts of the previous four differences on model outputs:

- *Base model*: a base 2023 ADMB model. This model uses the 2021 SAFE assessment parametrization and extends the model and catch series to 2023, rather than use a separate projection module.
- *Bridging model 1*: The 2023 ADMB model with the multinomial likelihood correctly specified by setting the fishery length sample size for males to the same value as females and where the non-parametric selectivity penalties are set the same for males and females (40 and 100). Note, setting the penalties to 10 and 200 (female specification) for both sexes did not result in a converged model.
- *Bridging model 2*: CEATTLE where the maximum likelihood parameter estimates from *bridging model 1* are used as fixed inputs. Structurally, this model is exactly the same as *bridging model 1* but likelihood components are fully specified and include the log-normal bias correction.
- *Bridging model 3*: CEATTLE where the model parameters are estimated using TMB.
- *Bridging model 4*: ADMB model where the maximum likelihood parameter estimates from *bridging model 3* (CEATTLE) are used as fixed inputs.
- *Bridging model 5*: Same as model 3, however, the ageing error matrix is correctly applied to the expected true age-composition.
- *Bridging model 6*: Same as model 4, however, the recruitment deviates are treated as random effects and the associated variance parameter is estimated.

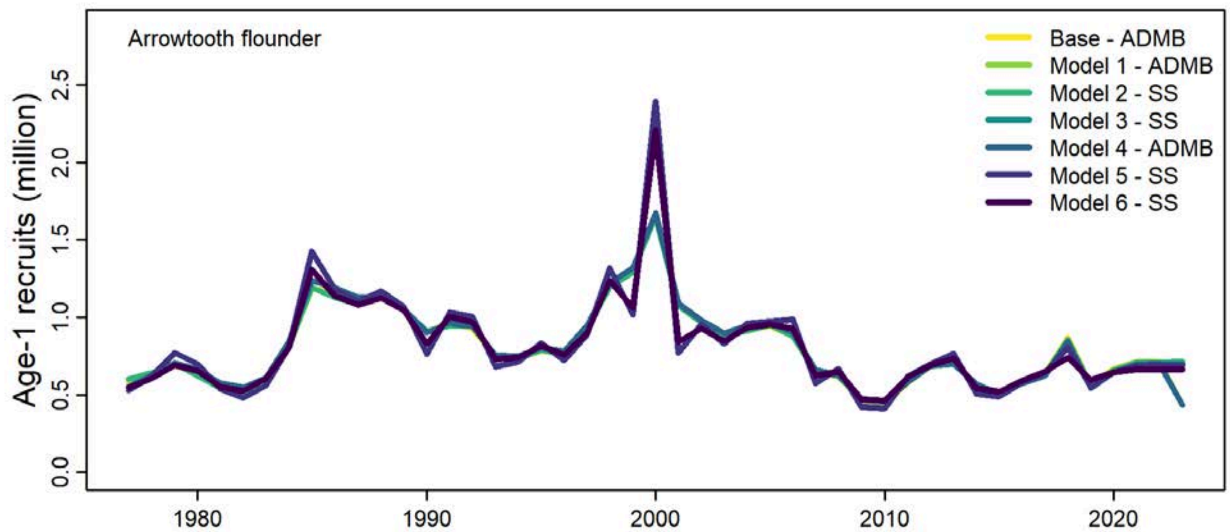
Results

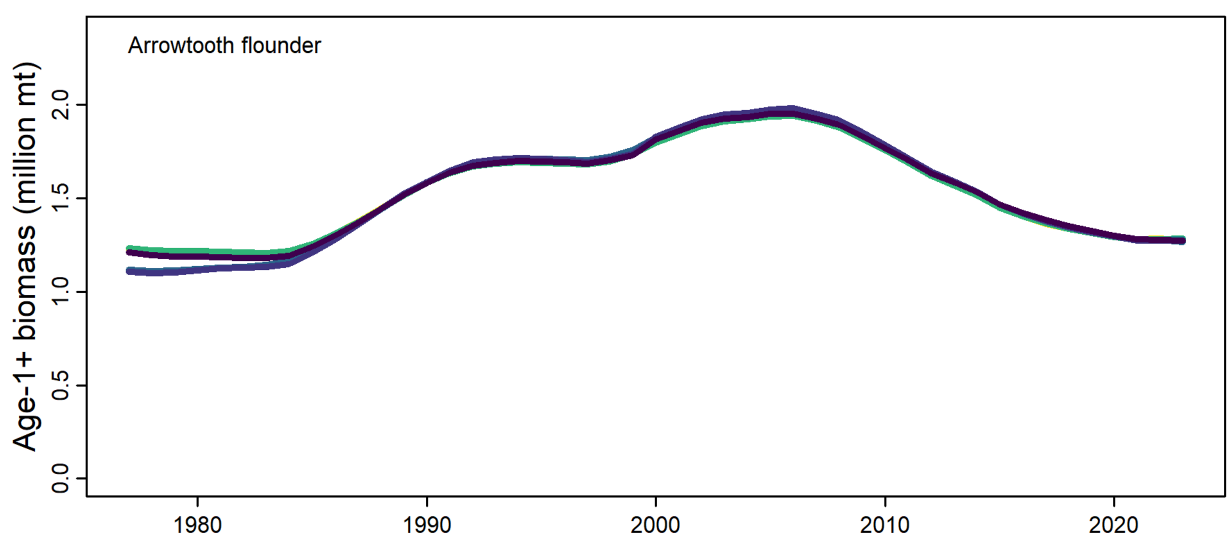
All single-species bridging models showed similar if not exactly similar trends in recruitment, spawning stock biomass, and biomass (Figure S1). Bridging model 1 and 2 had the same derived quantities, given that the parameters from the ADMB model were input into CEATTLE. This included total predicted catch, selectivity, and predicted survey biomass. Similarly, the likelihood component for non-parametric selectivity penalties were the same between bridging model 1 and 2 (Table S1). However, other likelihood components differed because CEATTLE uses the full probability distribution rather than simplified forms. Bridging model 2 and 3 had overlapping estimates of recruitment, spawning stock biomass, and biomass indicating that the minor changes in the log-likelihood formulations and optimization between ADMB and CEATTLE. Bridging model 3 resulted in a lower negative log-likelihood than when using the maximum likelihood parameter estimates from ADMB, suggesting that optimization is improved in TMB. Similarly, bridging model 4 (CEATTLE parameters input into ADMB) had lower negative log-likelihood components for survey index and fishery length data than bridging model 2, but due to high penalties on catch fits in ADMB, had a higher total negative log-likelihood. Correcting the specification of the ageing error matrix resulted in a higher log-likelihood, but estimates of total biomass and spawning biomass from bridging model 5 were extremely similar to bridging model 3. For bridging model 6, treating recruitment deviates as random effects resulted in a lower variance parameter (sigmaR = 0.48) than the value implicitly assumed by ADMB (sigmaR = 0.707). This resulted in slightly elevated estimates of biomass and spawning stock biomass in the first 10 years of the time series.

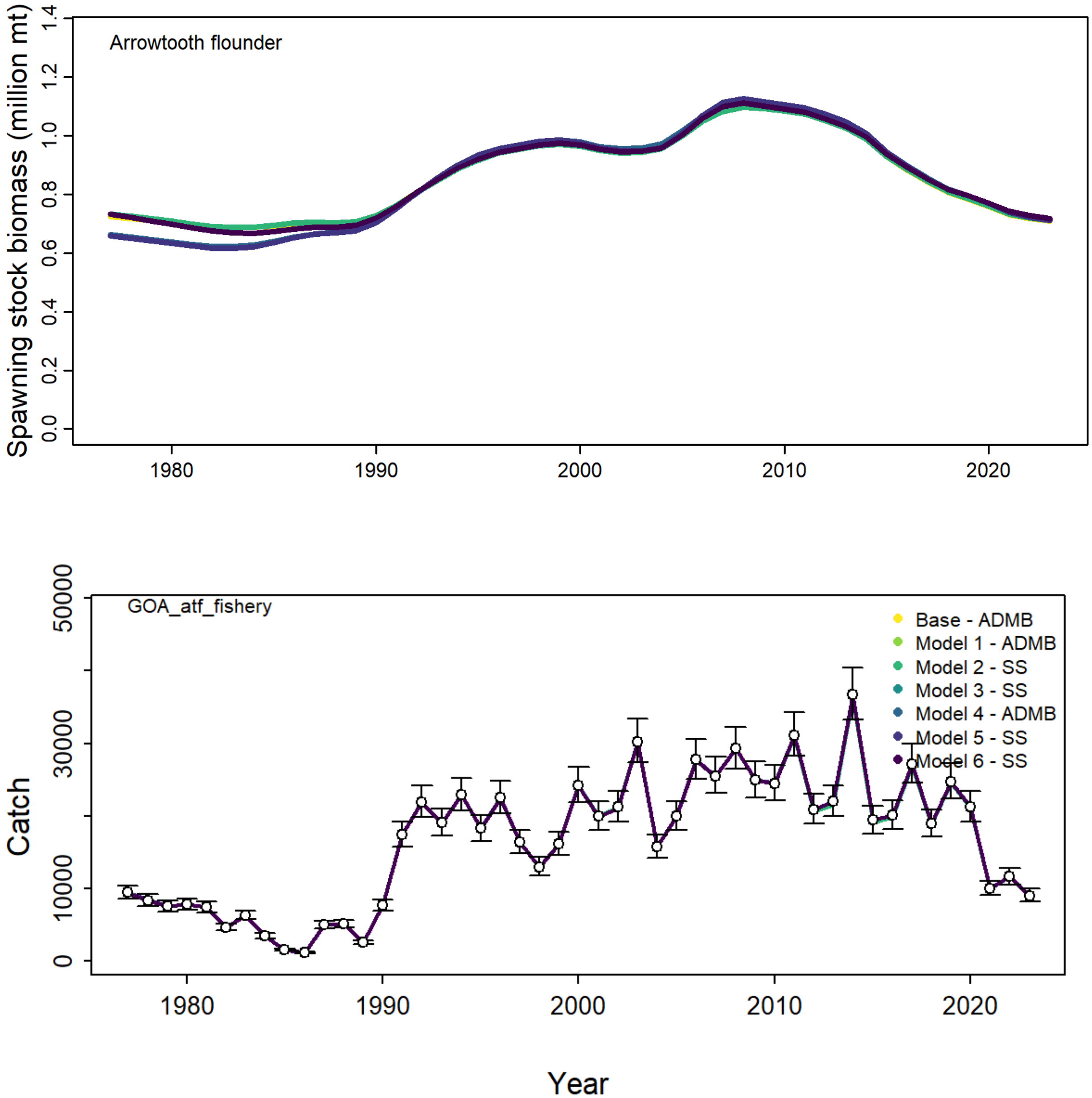
Table S1. Model comparison of the bridging models.

	Base	***1***	***2***	***3***	***4***	***5***	***6***
Platform	*ADMB*	*ADMB*	*TMB*	*TMB*	*ADMB*	*TMB*	*TMB*
Likelihoods							
Catch	4.32e-08	6.41e-07	-97.28	-97.52	0.00205	-97.52	-97.51
Fishery length compositio n	816.17	841.17	85.23	83.08	823.03	83.25	83.32
Survey biomass	27.86	28.16	1.84	0.82	27.19	-0.31	1.16
Survey age compositio n	276.91	275.98	32.67	32.93	278.16	42.80	43.36
Recruit deviations	5.04	5.03	47.57	44.41	6.06	45.51	24.30
Selectivity penalties	7.30	8.72	8.73	9.91	9.91	10.39	9.91
F regularity	21.20	21.31	21.31	19.35	19.35	19.19	20.44
Joint NLL	**177.67**	**181.95**	**100.08**	**92.97**	**195.81**	**103.31**	**84.99**
Marginal NLL							96.47
Number of parameters	158	158	158	158	158	158	92
Estimates							
q-trawl	1	1	1.0	1.0		1.0	1.0
Mean Recruitmen t (thousand)	801,987	800,286	806,206	815,324	800,286	814,450	806,846
σ_r	0.707	0.707	0.707	0.707	0.707	0.707	0.48
$F_{40\%}$							
2023 total biomass (t)	1,273,800	1,270,450	1,284,926	1,279,433	1,265,700	1,272,617	1,273,952
2023 spawning biomass (t)	709,254	710,935	710,935	713,886	713,886	712,504	718,708
$B_{100\%}$ (t)			1,684,224	1,702,520		1,700,424	1,684,452
$B_{40\%}$ (t)			673,690	681,008		680,170	673,781
$SSB_{100\%}$ (t)			984,753	995,141		993,804	984,431
$SSB_{40\%}$ (t)			393,901	398,056		397,522	393,772
ABC$_{F40\%}$ (t)							

Figure S1. Time-series of age-1 recruitment (millions; top panel), total biomass (million mt; upper middle panel), spawning stock biomass (million mt; lower middle panel), and catch (mt; bottom panel) as determined from the ADMB and bridging models.






Arrowtooth flounder
Spawning stock biomass (million mt)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1980
1990
2000
2010
2020
GOA_atf_fishery
Base - ADMB
Model 1 - ADMB
Model 2 - SS
Model 3 - SS
Model 4 - ADMB
Model 5 - SS
Model 6 - SS
Catch
0
10000
30000
50000
Year

Appendix 7C: Supplemental Catch

Table 7C1. Removals (kg) of Arrowtooth Flounder from the Gulf of Alaska (GOA) from sources other than those included in the Alaska Region's official estimate of catch, 1990-2025. Source NMFS Alaska Region: Sourced by the AKR.V_NONCOMMERCIAL_FISHERY_CATCH table, August 22, 2026. Abbreviations: IPHC (International Pacific Halibut Commission), ADFG (Alaska Department of Fish and Game), NMFS (National Marine Fisheries Service).

Year	ADF&G	IPHC	NMFS	Total
1990			28,436	28,436
1991	63		26,500	26,563
1992			24,583	24,583
1993	79		32,112	32,191
1994			22,765	22,765
1995			39,303	39,303
1996			25,564	25,564
1997			27,172	27,172
1998	4,738		33,620	38,357
1999	16,905		40,891	57,796
2000	8,262		35,558	43,819
2001	13,567		26,229	39,796
2002	5,019		16,461	21,480
2003	15,835		13,881	29,716
2004	5,758		13,153	18,911
2005	15,754		11,224	26,978
2006	5,748		16,634	22,382
2007	8,956		17,089	26,045
2008	843		16,162	17,005
2009	6,685		14,921	21,606
2010	106,283	11,047	16,281	133,611
2011	94,651	8,110	102,137	204,898
2012	82,785	8,422	7,461	98,668
2013	47,220	6,060	77,021	130,301
2014	65,577	9,197	16,878	91,652
2015	117,947	5,535	117,720	241,202
2016	76,752	4,310	7,016	88,078
2017	72,073	2,145	47,730	121,948
2018	69,744	4,057	3,576	77,377
2019	101,337	5,072	51,247	157,656
2020	76,268	2,645	4,026	82,939
2021	89,916	5,291	55,734	150,941
2022	85,379	2,488	5,669	93,535
2023	95,739	4,044	55,148	154,931
2024	106,008	1,762	15	107,785