ARROWTOOTH FLOUNDER (*ATHERESTHES STOMIAS*) STOCK ASSESSMENT FOR BRITISH COLUMBIA IN 2021

*Arrowtooth Flounder (*Atheresthes stomias*).*
Source: Kristina Anderson, DFO.

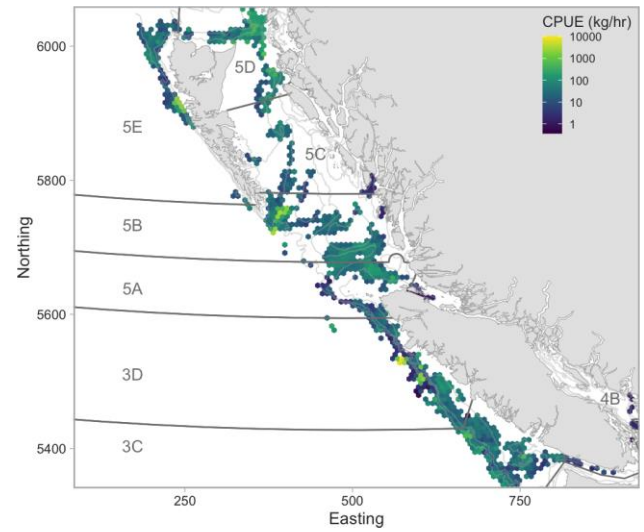

Figure 1. Spatial distribution of commercial catch per unit effort (CPUE) from 1996 to 2021 for Arrowtooth Flounder with Pacific Marine Fisheries Commission (PMFC) major areas outlined with solid lines. This assessment is for all offshore areas combined (3CD5ABCDE, excludes 4B). Cells are 7 km wide and are only shown in cases where there are at least 3 unique vessels in a given cell to meet privacy requirements.

Context:

*Arrowtooth Flounder (*Atheresthes stomias*, Turbot) is an important component of the bottom trawl fishery in British Columbia. The species is managed as a coastwide stock. Prior to the introduction of freezer trawlers in the mid-2000s, most of the historical catch of Arrowtooth Flounder was discarded at sea due to proteolysis, which occurs in the muscle tissue of this species a short time after it is caught, making the flesh unpalatable. In the past decade, markets have been established for fillets frozen at sea. Consequently, the freezer trawl fleet has taken an increasing proportion of the coastwide catch. Fisheries and Oceans Canada (DFO) Fisheries Management Branch requested that DFO Science Branch provide advice regarding the coastwide assessment of this stock relative to reference points that are consistent with DFO's Fishery Decision-Making Framework Incorporating the Precautionary Approach (DFO 2009), including the implications of various harvest strategies on stock status.*

*This Science Advisory Report is from the October 19-20 and December 5, 2022 regional peer review on the Arrowtooth Flounder (*Atheresthes stomias*) Stock Assessment for British Columbia in 2021. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.*

SUMMARY

- Arrowtooth Flounder (*Atheresthes stomias*) is a commercially important flatfish species in British Columbia (BC), which occurs along the BC coast. In the past decade, markets have been established for Arrowtooth Flounder fillets frozen at sea.
- All areas of Canada's Pacific coast, excluding waters between Vancouver Island and the BC mainland, were assessed using a two-fleet, two-sex, catch-at-age model implemented in a Bayesian framework to quantify uncertainty of estimated quantities. The model, which assumes a single coastwide stock, was fit to commercial and survey data from 1996 to 2021. Catch data prior to 1996 were not used due to unknown levels of releases at sea before the introduction of at-sea observers.
- Reference points based on maximum sustainable yield (MSY) were strongly impacted by the relationship between the estimates of maturity and commercial age selectivity, unrealistically suggesting that all vulnerable biomass could be taken without repercussions to the stock. Consequently, MSY reference points were not recommended for this stock. Advice presented to management is relative to reference points based on $0.2B_0$ (Limit Reference Point; LRP) and $0.4B_0$ (proposed Upper Stock Reference; USR), where B_0 is the unfished spawning biomass (males plus females) at the mean recruitment level. Probabilities using an alternative USR of $0.35B_0$ are also presented.
- The median spawning biomass (with 5th and 95th percentiles of the Bayesian results) at the beginning of 2022 (B_{2022}) was estimated to be 0.37 (0.26, 0.51) of B_0. The base model had an estimated probability close to zero of being below the LRP ($P(B_{2022} < 0.2B_0)$) and a probability of 0.66 of being below the proposed USR ($P(B_{2022} < 0.4B_0)$).
- Given the median relative spawning biomass for 2022 ($0.37B_0$), the stock is currently considered to be in the cautious zone relative to the LRP of $0.2B_0$ and proposed USR of $0.4B_0$.
- Advice to management is presented in the form of a decision table, which reports the probability of the biomass for 2023-2026 being below the reference points $0.2B_0$, $0.35B_0$, and $0.4B_0$, as well as the probability of the biomass declining. Projections of the stock across a range of constant annual catches of 0 to 15 kt in 1 kt increments from 2022-2026 are provided.
- The reference removal rate ($U_{0.4B0}$ = 0.105 of vulnerable population annually), which is equivalent to an annual removal of approximately 4.4 kt, was estimated by projecting the stock for 50 years and finding the constant catch where the stock reached $0.4B_0$ assuming continuing low recruitment as was estimated over the period from 2010 to 2019.
- The size of catches and discards prior to 1996, the lack of random-stratified surveys prior to 2005 that together cover the entire coast, the estimation of maturity and selectivity curves, the assumed magnitude of recruitment variability, and the estimation of B_0 are major sources of uncertainty in this assessment that make it challenging to estimate the size and productivity of the stock.
- Given that the stock is estimated to be below $0.4B_0$ (proposed USR) in the base model, and that survey indices are declining coincident with declining estimated spawning biomass and recruitment, it is recommended that the current assessment be updated in two years when one additional survey has been run in each area of the coast. In the longer term, it is suggested that conducting this assessment using a management procedure approach could provide management advice that more explicitly handles the uncertainties identified in this system.

INTRODUCTION

Arrowtooth Flounder (*Atheresthes stomias*, Family Pleuronectidae), also locally called Turbot, is a species of flatfish that occurs in the offshore waters of British Columbia (BC). Arrowtooth Flounder is primarily taken by the groundfish bottom trawl fishery, although it is also encountered in small amounts by hook and line fisheries, particularly those targeting Pacific Halibut (*Hippoglossus stenolepis*). Catches are highest on the edge of the continental shelf, as well as along the edges of the main gullies in Queen Charlotte Sound and the eastern portion of Dixon Entrance (Figure 1). Catches have typically been more than 70% female (based on data since 1996). Prior to the introduction of freezer trawlers in the mid-2000s, most of the historical catch of Arrowtooth Flounder was discarded at sea. This was largely due to proteolysis in the muscle tissue of this species, which occurs a short time after being caught, making the flesh unpalatable and unmarketable. In the past decade, markets have been established for fillets frozen at sea.

A single stock has been identified along the BC coast based on a lack of observable differences in mean weight, length, or growth between the North (Pacific Marine Fisheries Commission (PFMC) major areas 5ABCDE) (Figure 1) and South (3CD), and among three regional areas (5DE, 5ABC, 3CD). The available age data show that Arrowtooth Flounder reach a maximum age for sampled females and males at 27 and 23 years, respectively. Arrowtooth Flounder exhibit sexual dimorphism; after sexual maturity, females grow faster than males and reach a larger maximum size. The maximum lengths of sampled female and male Arrowtooth Flounder are 61.8 and 47.2 cm, respectively.

ASSESSMENT

This stock assessment evaluated the BC coastwide population, excluding waters between Vancouver Island and the BC mainland, harvested by two commercial bottom trawl fleets (Freezer trawlers; Shoreside) using a two-sex, catch-at-age model. This model was tuned to annual estimates (covering 1996-2021) of commercial catch from the two fleets, four fishery-independent trawl survey series (Queen Charlotte Sound, Hecate Strait, and West Coast Vancouver Island synoptic surveys, and the Hecate Strait Multi-species Assemblage survey), one fishery-based discard catch per unit effort (CPUE) series, and age composition data from the two commercial fleets and three of the four surveys. The model is based on the Integrated Statistical Catch Age Model (ISCAM) framework (Martell 2011). A two-sex, two-fleet model was chosen based on advice from the Arrowtooth Flounder Technical Working Group. Due to sexual dimorphism and a high proportion of females (79%) in the catch, the stock was modelled using two sexes. The previous Arrowtooth Flounder stock assessment was single sex and only modeled the female population (Grandin and Forrest 2017).

The commercial fishery was characterized by two fleets (Freezer trawlers and Shoreside) to capture differences in selectivity. Commercial catch was summarized by fishing year (Feb. 21-Feb. 20) and included both estimated discards and landings (Figure 2). Prior to 1996, entire tows were thought to have been discarded without reporting. This large amount of unreported discarding prior to 1996 made attempts to reconstruct catch prior to 1996 untenable due to the uncertainty involved. Therefore, all catch data prior to the introduction of 100% at-sea observer coverage in 1996 were omitted from this assessment.

Growth and maturity parameters were estimated outside the catch-at-age model and entered into the model as fixed parameters. Age composition data by year were included for the three synoptic surveys and the two commercial fisheries. Age proportion weighting was based on a stratified scheme that adjusted for unequal sampling effort across depth strata and tow biomass density (surveys) or quarterly period within a year and tow catch weight (commercial).

The base model for this assessment assumed a fixed natural mortality of 0.20 for females and 0.35 for males. The model estimated the steepness of the stock-recruit function, catchability for each survey and for the discard CPUE index, and age selectivity for each of the three synoptic surveys and for the two commercial fleets (Figure 3).

Model fitting was conducted with a Markov Chain Monte Carlo (MCMC) Metropolis Hastings sampling procedure. From a total chain length of 10 million, every 5,000th sample was retained to yield 2,000 MCMC samples (reduced to 1,000 after dropping the first 1,000 samples as burn-in) to generate a joint posterior distribution for the estimated parameters.

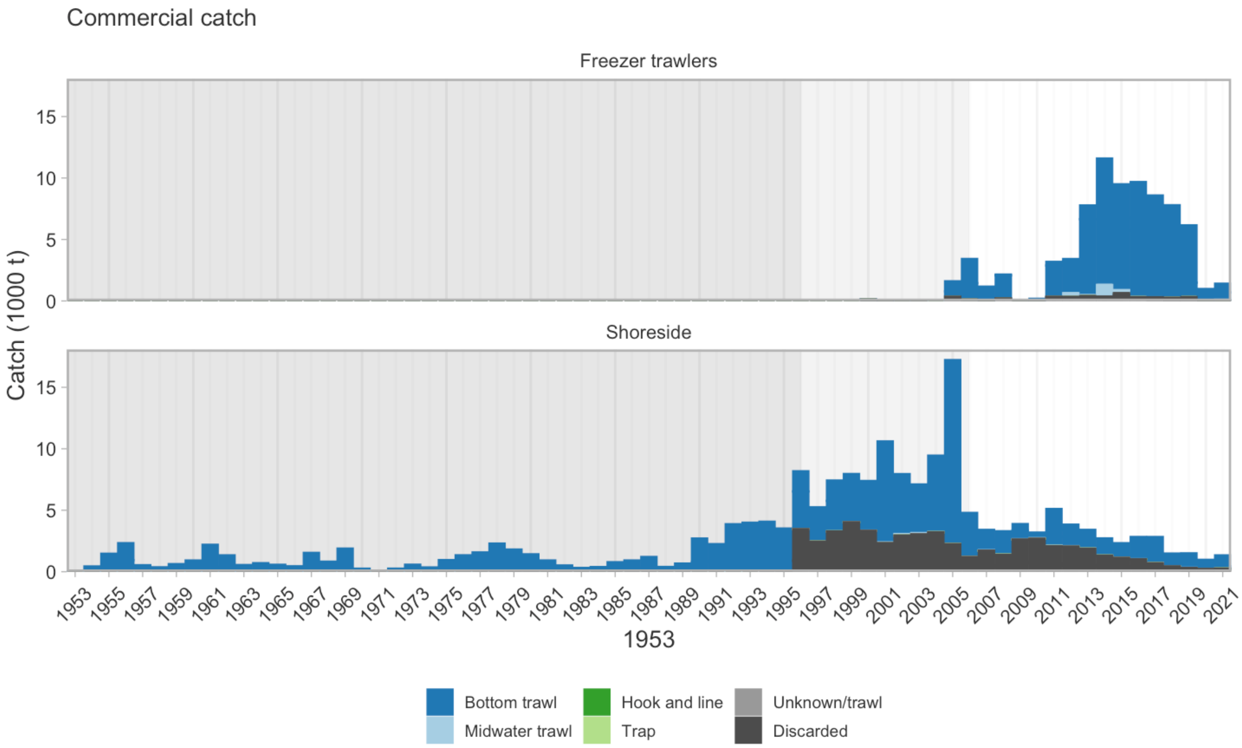

Figure 2. Commercial catch of Arrowtooth Flounder by fleet. Each year of catch starts on Feb. 21 and ends on Feb. 20. For example, 2005 represents all catches from Feb. 21, 2005 to Feb. 20, 2006.

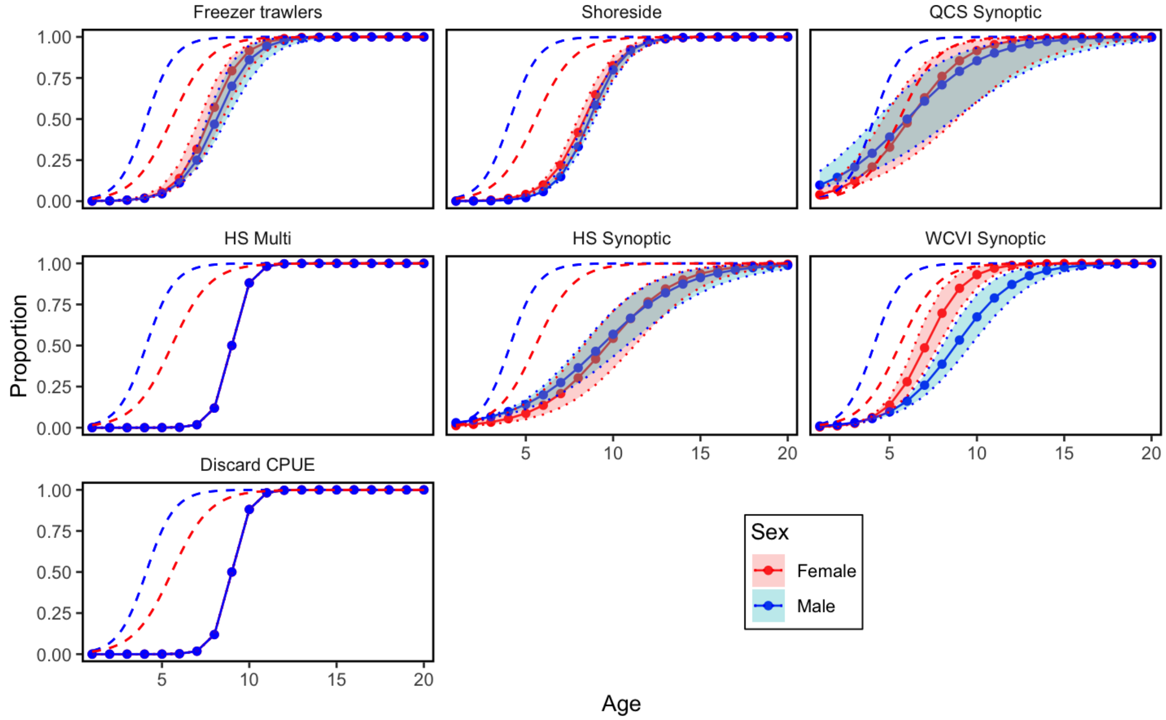

Figure 3. Estimated and fixed selectivities by sex for the base model. The dots show estimated median selectivity-at-age, and the shaded areas show the 95% credible intervals (CI). Single dotted lines with no CI (HS Multi, Discard CPUE) represent fixed selectivities. Dashed lines represent maturity-at-age based on logistic curves fit to the proportion of mature fish at age.

MSY-based reference points were not used in this assessment to provide advice as they are strongly impacted by the relationship between estimated maturity ogives and commercial age selectivity and commercial selectivity was estimated well to the right of maturity (Figure 3), which was deemed implausible. The estimated values of F_{MSY} (instantaneous fishing mortality at MSY) were large, resulting in values of U_{MSY} (annual exploitation rate producing MSY) close to the upper limit of 1. This result potentially means that all vulnerable biomass could be taken without repercussions to the stock because a large proportion of the mature biomass was evaluated to be not vulnerable to the fishery, based on the model estimated selectivity function. This conclusion was not believed to be credible and as a result, B_0-based reference points were adopted for this stock.

Advice to managers is presented here as a decision table that provides probabilities of being below reference points (LRP = $0.2B_0$; USR = $0.4B_0$), as well as an alternative USR value of $0.35B_0$ for a range of constant catch levels. The LRP = $0.2B_0$ and USR = $0.4B_0$ reference points were agreed to in the previous Arrowtooth Flounder assessment (DFO 2015). The LRP of $0.2B_0$ is a common proxy for recruitment overfishing (Myers et al. 1994; Sainsbury 2008). The equivalence of $0.2B_0$ to $0.4B_{MSY}$ suggests a Schaefer surplus production assumption. The North Pacific Fishery Management Council (NPFMC) in Alaska also uses an upper operational control point of $0.4B_0$ below which fishing mortality F would be ramped down (NPFMC 2020, Tier 3 3b, p. 19). The value $0.35B_0$ was suggested by some meeting participants as an alternative given that the estimated production curve is not symmetric and $0.4B_0$ is sometimes chosen as a proxy for B_{MSY} (e.g., Australia: Department of Agriculture and Water Resources 2018).

The estimated annual relative spawning biomass for the coastwide stock has declined since 2011 with a flattening trend from 2020-2022 (Figure 4). This flattening of the biomass trajectory coincided with the reduction in total allowable catch (TAC) in 2020, and consequently commercial catch (Figure 2), from a TAC of 14 kt to 5 kt. For the base model, the estimated median spawning biomass at the beginning of 2022 relative to equilibrium unfished biomass (B_{2022}/B_0) was 0.37 (0.26, 0.51; 2.5th and 97.5th percentiles of Bayesian results, respectively).

Median posterior estimates of age-1 recruits are shown in Figure 5. It was assumed that recruitment followed a Beverton-Holt stock-recruit function with estimated unfished recruitment R_0 and steepness h (with a prior mean of 0.85 and coefficient of variation of 0.1). The large variability around the estimates for 2020 and 2021 was due to the lack of information in the data for these years. The assessment results show declines in the estimated recruitment since 2009 (Figure 5).

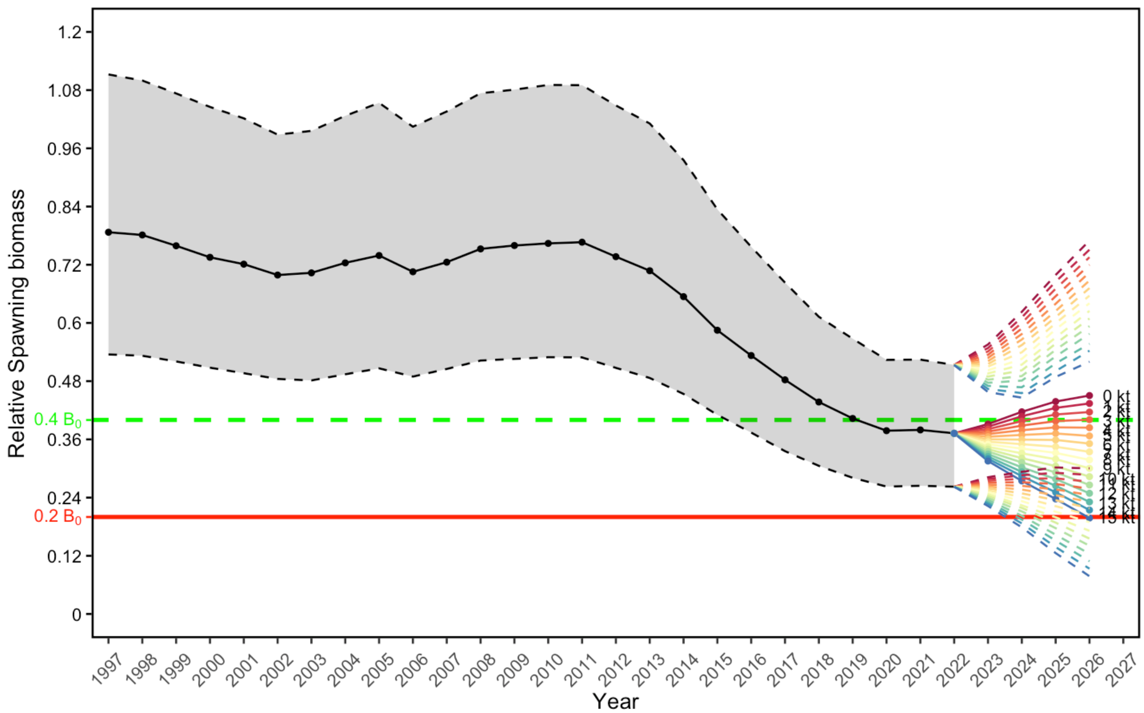

Figure 4. Estimated relative spawning biomass (B_t/B_0) for the base model. The shaded area represents the 95% credible interval (CI) and the solid line with points represents the median. Horizontal lines indicate the $0.2B_0$ (solid red) and proposed $0.4B_0$ (dashed green) reference points. The colored dots from 2023 to 2026 are the medians of the posteriors for the projected catch levels, with solid lines connecting them; the dashed lines from 2023 to 2026 represent the 95% CIs for those posteriors. The constant catch values are shown as text on the right of the end points of each projected trajectory. See the decision table (Table 1) for probabilities of being under reference points and of the stock declining for each catch level.

Projections and Reference Points

The stock was projected for four years (Figure 4, Figure 6) using randomly sampled recruitment deviations from the period 2010-2019 thereby assuming that recent below-average recruitment continues (Figure 5). The highly uncertain 2020 and 2021 recruitment estimates were omitted. The x-axis in Figure 6 shows the relative spawning biomass in a projected year given catch levels applied in the previous year (y-axis). The median 2026 biomass values show that catches of 3 kt or less result in a 2026 biomass at or above the $0.4B_0$ reference point (proposed USR). All other catch levels except for 15 kt result in biomass values that are between the $0.2B_0$ and $0.4B_0$ reference points. The 15 kt catch level results in a 2026 biomass below the $0.2B_0$ LRP. However, these results are based only on the medians for each catch level. Figure 6 also shows the uncertainty (95% CI and 50% CI) for each catch level. The lower right panel shows that for catches of 3 kt or less, the median 2026 relative spawning biomass will be at or above $0.4B_0$, and that catches of 5 kt or less will ensure that there is a greater than 0.95 probability (95%) that the 2026 biomass will be above $0.2B_0$. Specific values related to these results are found in the decision table (Table 1).

A decision table with the probabilities of each projected year being below $0.2B_0$ (LRP), $0.4B_0$ (proposed USR), and $0.35B_0$ (alternative USR) (Table 1) is presented. Also shown in the decision table are the probabilities of each projected years' relative biomass being less than the relative biomass of the previous year, given the catch levels applied. Using the example above of 5 kt, the decision table shows that in 2026, there is a 0.004 probability (0.4%) that the biomass will be less than $0.2B_0$.

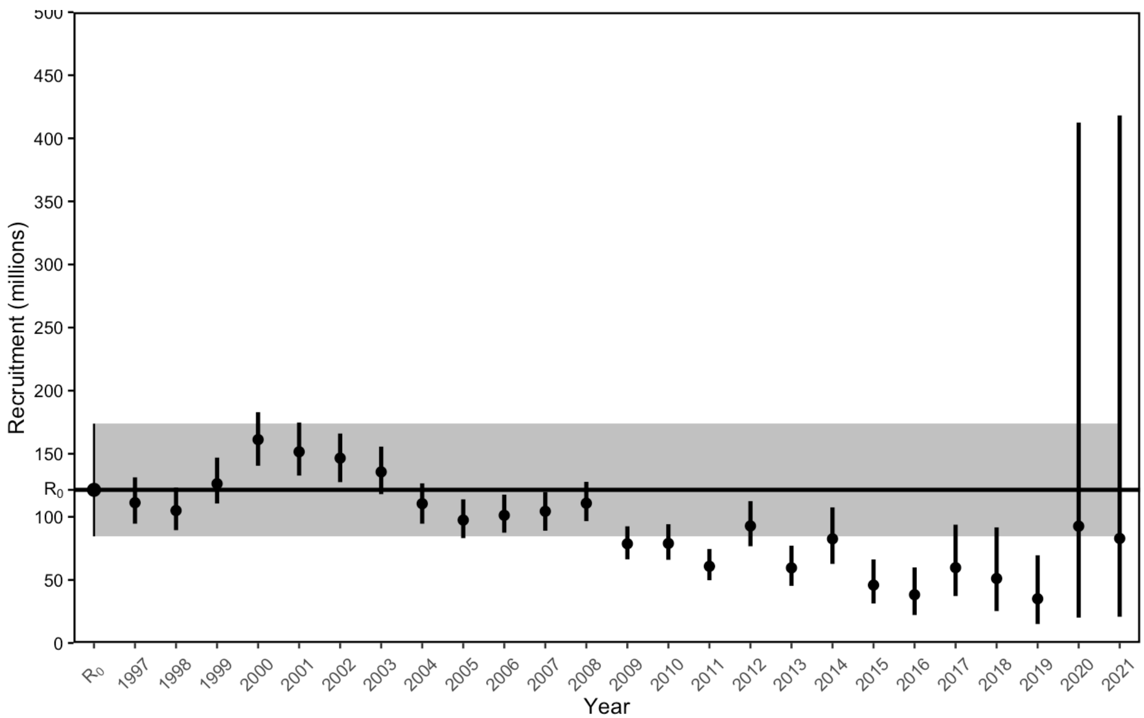

Figure 5. Recruitment of Arrowtooth Flounder from the base model. The black points are the medians of the posteriors, the vertical black lines are the 95% credible intervals (CIs) for the posteriors, the point at R_0 (unfished recruitment) is the median estimate for the initial recruitment parameter R_0, and the vertical line over that point and shaded ribbon across the time series is the 95% CI for R_0.

The reference removal rate was calculated by projecting the stock for 50 years to find the constant catch and fishing mortality F where the stock would reach $0.4B_0$, assuming that the lower-than-average recruitment over the period 2010-2019 continues (Table 2). Recruitment deviations in these projections were randomly sampled from the last 10 years of estimated deviations (2010-2019), not including the highly uncertain 2020 and 2021 estimates. The calculated value for the reference removal rate was 0.105 of the vulnerable population annually ($U_{0.4B0}$), which is equivalent to an annual removal of approximately 4.4 kt (Table 2). This means that if recruitment remained at levels seen in 2010-2019 (Figure 5), an annual total catch (landings and discards) of 4.4 kt would be expected to bring the biomass close to $0.4B_0$ in the long-term. This calculation also assumed that factors such as such natural mortality, growth rate, and maturity-at-age remained constant.

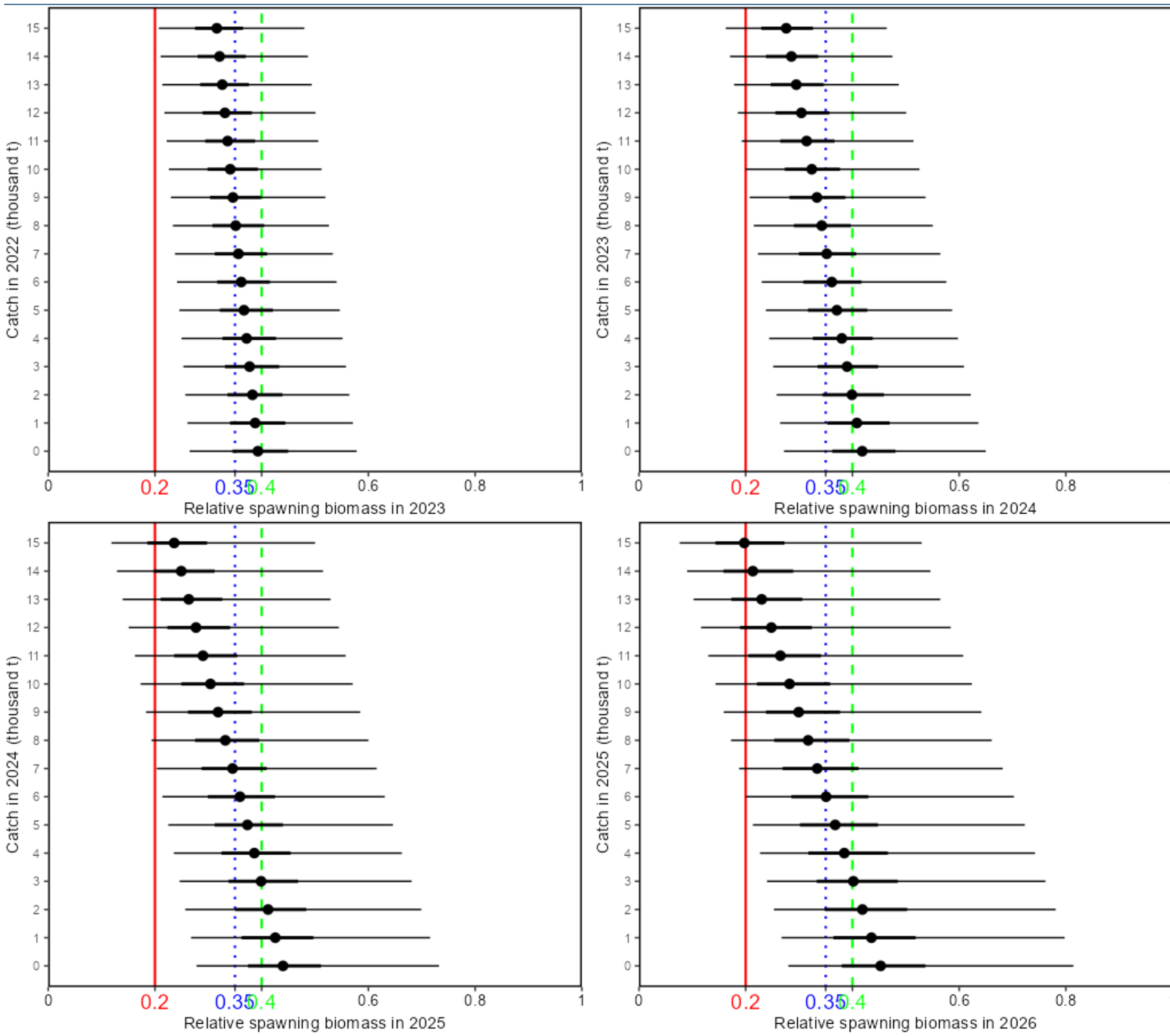

Figure 6. Projected 2023-2026 relative spawning biomass for catch occurring in 2022. Black points are medians of the posterior, thick lines are the 50% CI (25%-75%), and thin lines are the 95% CI (2.5%-97.5%). The solid red line is the LRP, 0.2B_0, the dotted blue line is the 0.35B_0 line, and the dashed green line is the proposed USR, 0.4B_0.

Table 1. Decision table for the base model showing probabilities that projected biomass is below selected reference points and benchmarks. For example, for a catch of 10 kt there is a 0.001 probability that the 2023 biomass will fall below the LRP of $0.2B_0$, a 0.787 probability that it will fall below the proposed USR of $0.4B_0$, and a 0.922 probability that the biomass in 2023 will be less than the biomass in 2022. For projections beyond 2023 (2024-2026), the catch is the same value for each projected year in each row of the table. For the example of a constant catch each year of 10 kt, the probability that the biomass will decline from one year to the next is 0.922 from 2022 to 2023, 0.782 from 2023 to 2024, 0.742 from 2024 to 2025, and 0.770 from 2025 to 2026.

Catch (kt)	$P(B_{2023}< 0.2B_0)$	$P(B_{2024}< 0.2B_0)$	$P(B_{2025}< 0.2B_0)$	$P(B_{2026}< 0.2B_0)$	$P(B_{2023}< 0.35B_0)$	$P(B_{2024}< 0.35B_0)$	$P(B_{2025}< 0.35B_0)$	$P(B_{2026}< 0.35B_0)$	$P(B_{2023}< 0.4B_0)$	$P(B_{2024}< 0.4B_0)$	$P(B_{2025}< 0.4B_0)$	$P(B_{2026}< 0.4B_0)$	$P(B_{2023}< B_{2022})$	$P(B_{2024}< B_{2023})$	$P(B_{2025}< B_{2024})$	$P(B_{2026}< B_{2025})$
0	0.000	0.000	0.000	0.000	0.262	0.171	0.118	0.107	0.543	0.410	0.352	0.315	0.044	0.093	0.161	0.233
1	0.000	0.000	0.000	0.000	0.286	0.210	0.168	0.161	0.576	0.461	0.401	0.377	0.162	0.165	0.233	0.304
2	0.000	0.000	0.000	0.001	0.307	0.260	0.227	0.236	0.602	0.512	0.447	0.434	0.262	0.251	0.307	0.373
3	0.000	0.000	0.001	0.001	0.331	0.307	0.298	0.295	0.633	0.556	0.512	0.495	0.418	0.227	0.370	0.434
4	0.000	0.001	0.001	0.001	0.362	0.349	0.355	0.367	0.657	0.606	0.573	0.574	0.570	0.429	0.427	0.508
5	0.000	0.001	0.001	0.004	0.387	0.400	0.411	0.430	0.675	0.642	0.629	0.633	0.669	0.516	0.495	0.567
6	0.001	0.001	0.001	0.010	0.436	0.440	0.466	0.496	0.701	0.689	0.685	0.687	0.748	0.587	0.565	0.624
7	0.001	0.001	0.006	0.023	0.472	0.498	0.525	0.571	0.719	0.724	0.735	0.739	0.815	0.656	0.613	0.669
8	0.001	0.001	0.013	0.050	0.500	0.552	0.597	0.644	0.741	0.790	0.777	0.780	0.856	0.710	0.671	0.707
9	0.001	0.004	0.026	0.092	0.525	0.598	0657	0.700	0.764	0.824	0.811	0.813	0.898	0.753	0.706	0.742
10	0.001	0.008	0.047	0.143	0.559	0.646	0.713	0.745	0.787	0.843	0.847	0.836	0.922	0.782	0.742	0.770
11	0.002	0.012	0.082	0.208	0.584	0.696	0.750	0.782	0.815	0.869	0.869	0.865	0.942	0.907	0.769	0.798
12	0.003	0.022	0.125	0.268	0.619	0.742	0.796	0.821	0.836	0.892	0.882	0.884	0.954	0.831	0.789	0.820
13	0.004	0.036	0.174	0.337	0.643	0.786	0.833	0.838	0.854	0.907	0.901	0.899	0.964	0.856	0.807	0.841
14	0.004	0.054	0.230	0.421	0.673	0.827	0.853	0.862	0.881	0.923	0.914	0.909	0.971	0.875	0.829	0.862
15	0.005	0.083	0.300	0.506	0.698	0.854	0.874	0.888	0.892	0.932	0.927	0.924	0.977	0.893	0.850	0.876

Table 2. Reference rates, calculated as the constant rate at which fishing needs to occur on an annual basis by each fleet long term (50 years) to bring the relative spawning biomass to within 50 t of $0.4B_0$ given recent average recruitment continues. In this case, the routine was able to come within 6.4 t of $0.4B_0$. The F values are the instantaneous fishing mortalities and the U values are the annual exploitation rates. The last column shows the long term annual catch by fleet and the total. This is the value which, if caught every year for the long term is expected to result in the biomass being close to $0.4B_0$.

Fleet	$F_{0.4B0}$	$U_{0.4B0}$	Catch (kt)
Freezer trawlers	0.066	0.064	1.566
Shoreside	0.042	0.041	2.840
Total	-	-	4.406

Ecosystem Considerations and Climate Change

Ecosystem considerations were examined including predators and prey, body condition, and water temperature. Arrowtooth Flounder are prey generalists (Fargo et al. 1981; Yang 1993; Doyle et al. 2018). Stomach content data were not collected on the surveys used in this assessment. However, from stomach samples collected in the early 1990s in the Gulf of Alaska, Arrowtooth Flounder consumed a diet dominated by zooplankton, fish, and benthic invertebrates (Yang 1993; Spies et al. 2019). For juveniles (< 20 cm), euphausiids made up nearly 60% of their diet followed by capelin at 24%, whereas adults exhibited a more diverse diet. In the same region and time period, predation by Pacific Cod (*Gadus macrocephalus*), Pacific Halibut (*Hippoglossus stenolepis*), and Steller Sea Lions (*Eumetopias jubatus*) together explained about 10% of adult Arrowtooth mortality, while the flatfish trawl fishery accounted for 2% (Spies et al. 2019). Juvenile Arrowtooth Flounder were preyed on by adult Arrowtooth Flounder, and both adult and juvenile pollock, but the total juvenile mortality from these sources was less than 7% of juvenile Arrowtooth Flounder production (Spies et al. 2019).

Migration patterns are not well known for Arrowtooth Flounder, but there is some indication that larger fish may migrate to deeper water in winter and to shallower water in summer (Rickey 1995; Fargo and Starr 2001). Spawning and hatching occur in deeper waters (> 350 m) along the continental shelf break in fall and winter (Rickey 1995; Blood et al. 2007).

A geostatistical model was used to create an index of changes in body condition (plumpness). Overall, body condition declined slightly since 2014 off the west coast of Vancouver Island but increased in Queen Charlotte Sound around 2013-2015 and remained relatively stable in the other two surveys. There is some evidence of higher condition in the deepest regions, which may explain the higher condition index for the west coast of Haida Gwaii (WCHG) survey. Neither mean bottom temperature at depth nor abundance had a clear correlation with body condition. Beyond body condition, local warming has been associated with increased biomass of immature Arrowtooth Flounder in cooler areas, but declines in biomass across maturity classes in already warmer areas (English et al. 2021).

Taking into account the ecosystem considerations stated above and the known biology of Arrowtooth Flounder, there are no clear indications that current environmental conditions should modify the catch advice in this assessment.

Sources of Uncertainty

There are two major types of uncertainty in the advice presented: (1) uncertainty in model parameters within the assessment; and (2) structural uncertainty arising from processes and data that were not included in the assessment. The first type, parameter uncertainty, is presented in terms of posterior credible intervals for parameters and state variables such as biomass, recruitment, and fishing mortality. This uncertainty was captured in the decision tables and was further explored using sensitivity analyses. The second type, structural uncertainty, was tested through sensitivity tests of model structure and the inclusion/removal of data. Sensitivity runs to assess structural uncertainty included:

- changing the relative magnitude of process (recruitment) and observation errors;
- estimating natural mortality with various priors;
- setting selectivity curves equal to the maturity ogive for all gears;
- estimating time-varying selectivity for the Queen Charlotte Sound synoptic survey in an attempt to improve the survey index fit;
- replacing design-based survey indices with geostatistical model-based survey indices;
- removing the discard CPUE index;
- modifying the maturity ogive to exclude ‘developing’ or ‘resting’ fish;
- fixing selectivity for the discard CPUE index to be equal to the Shoreside fishery selectivity; and
- fixing all survey selectivity to be equal to the Shoreside fishery selectivity.

Most sensitivity runs resulted in similar inferences about relative depletion in 2022 with the following exceptions. Increasing assumed recruitment variance or decreasing assumed index observation error placed the stock close to $0.2B_0$. Although the observation error is informed by survey sampling, the most appropriate degree of recruitment variance is less well known. Estimating female natural mortality or fixing commercial selectivity to equal the maturity ogive placed the stock slightly above $0.4B_0$. Fixing the survey selectivities to match the Shoreside fishery selectivity resulted in an upswing in biomass at the end of the time series that was deemed unrealistic. The model did not fit the Queen Charlotte Sound synoptic survey index as well as other indices—the index declined more slowly after 2015 than the model prediction. The sensitivity run estimating time-varying selectivity for this survey improved the index fit but resulted in poor estimates of selectivity, which were estimated as knife-edged selectivity at age zero for some year ranges and selectivity-at-age of zero for all ages for other year ranges.

The magnitude of catch and discards prior to 1996 is a major source of structural uncertainty in this assessment. All data prior to the introduction of 100% at-sea observer coverage in 1996 were omitted from this assessment on the recommendation of industry advisors and Arrowtooth Flounder Technical Working Group, as was done in the 2015 assessment. Arrowtooth Flounder are known to have been discarded at sea in large quantities due to proteolysis of the flesh if catches were not landed and frozen quickly after capture. Analytical methods to estimate historical discard rates were rejected due to discarding of whole tows and changes to discarding behaviour over time.

The estimation of maturity and selectivity curves is a major source of uncertainty in this assessment that makes it challenging to assess the scale and productivity of the stock. In particular, the relationship between the maturity and the fishery selectivity curves is linked to the estimate of vulnerable biomass (amount of biomass that is vulnerable to the fishery). With selectivity curves estimated to lie far to the right of maturity curves, the fisheries can theoretically harvest all the vulnerable mature fish without compromising population productivity (because a large number of mature fish remain invulnerable to the gear). Additionally, estimation of B_0 is linked to productivity (R_0). There are other approaches to estimation of B_0 that are not presented in this assessment.

CONCLUSIONS AND ADVICE

For the base model, the estimated median spawning biomass at the beginning of 2022 (B_{2022}) was 0.37 of B_0 (0.26-0.51; 5th and 95th percentiles of Bayesian results, respectively). The stock is currently considered to be in the DFO Cautious zone relative to the LRP ($0.2B_0$) and proposed USR ($0.4B_0$), with a probability close to zero of being below the LRP ($P(B_{2022} < 0.2B_0)$) and a probability of 0.66 of being below the proposed USR ($P(B_{2022} < 0.4B_0)$).

The following is a list of key probabilities noted from Tables 1 and 2:

- Biomass projections show that, if the low and declining recruitment observed over the period 2010-2019 continues, a constant catch of 4.4 kt per year (the reference removal rate catch) would result in a long-term spawning biomass value equal to $0.4B_0$ (the proposed USR). This is equivalent to a reference removal rate of 0.105 of the vulnerable population annually.
- There is a probability > 0.5 that the spawning biomass will be below $0.4B_0$ at all catch levels, including zero catch, in 2023.
- In the base model, there is a probability < 0.01 that the spawning biomass will be below $0.2B_0$ (the LRP) at all catch levels in 2023.
- There is a probability > 0.5 that the spawning biomass will decline from 2022 to 2023 for all catch levels greater than 3 kt.
- At a constant annual catch of 15 kt, there is probability of 0.506 that the spawning biomass will be below $0.2B_0$ (the LRP) in 2026.

The assessment model estimates that the Arrowtooth Flounder stock has had below-average recruitment since 2004, that recruitment has become even lower since 2009, and that these declines have coincided with declining survey indices and declines in estimated spawning biomass. It is suggested that this assessment be updated in two years when one additional survey has been run in each area of the coast and that an updated groundfish data synopsis report (Anderson et al. 2019) be consulted in the intervening year to monitor new survey data.

The size of catches and discards prior to 1996, the lack of random-stratified surveys prior to 2005 that together cover the entire coast, the estimation of maturity and selectivity curves, the assumed magnitude of recruitment variability, and the estimation of B_0 are major sources of uncertainty in the assessment that make it challenging to assess the size and productivity of the stock. In the longer term, it is suggested that conducting this assessment using a management procedure approach (e.g., Anderson et al. 2021) could provide management advice that more explicitly handles the uncertainties identified in this system.

Future Research

There is a lack of age structures sampled from the commercial fleets for 2020 and 2021. The absence of these samples would have had a minimal impact on this assessment given that the last year of data was 2021. However, the absence of commercial age data may have an increasingly large impact on the assessment in terms of estimating selectivity, recruitment, and tracking age-cohorts within the composition data. Retrospective analyses could be conducted excluding existing commercial age data to partially evaluate this impact. Simulation analyses, possibly including closed-loop simulation, could also evaluate this impact.

It is suggested that collecting maturity data from winter samples (from commercial fisheries or surveys) could help reconcile the position of the maturity ogives with respect to selectivity curves (Figure 3) because this species is a winter spawner while all the structured surveys operate in the spring/summer/fall months. In addition, future work could investigate various treatments of dynamic B_0 (e.g., Berger 2019).

Future research could evaluate incorporating environmental variables related to climate change into the Arrowtooth Flounder stock advice more explicitly. It is not clear what mechanism this should entail, although options may include linking environmental indices to natural mortality or recruitment processes (e.g., Stock and Miller 2021). Other options would include adjusting target fishing mortality based on ecosystem modelling (Howell et al. 2021) or through closed-loop simulation that aims to find management procedures that are robust to uncertainties about future environmental conditions (e.g., Anderson et al. 2021).

LIST OF MEETING PARTICIPANTS[1]

Last Name	First Name	Affiliation
Anderson	Sean	DFO Science
Anderson	Erika	DFO Centre for Science Advice Pacific
English	Philina	DFO Science
Finn	Deirdre	DFO Fisheries Management
Grandin	Chris	DFO Science
Haggarty	Dana	DFO Science
Haigh	Rowan	DFO Science
Kronlund	Rob	Interface Fisheries Consulting
Mann	Shannon	Mariner Seafoods
Mason	Gwyn	DFO Fisheries Management
Mazur	Mackenzie	DFO Science
Mose	Brian	Commercial Industry Caucus - Trawl
Muirhead-Vert	Yvonne	DFO Centre for Science Advice Pacific
Obradovich	Shannon	DFO Science
Sporer	Chris	Pacific Halibut Management Association
Starr	Paul	Canadian Groundfish Research and Conservation Society
Tadey	Rob	DFO Fisheries Management
Turris	Bruce	Canadian Groundfish Research and Conservation Society

[1] This list of participants includes people who attended on December 5, 2022 when this SAR was drafted. The full list of participants on both October 19-20 and December 5, 2022 is included in the associated Proceedings document.

SOURCES OF INFORMATION

This Science Advisory Report is from the October 19-20 and December 5, 2022 regional peer review on the Arrowtooth Flounder (*Atheresthes stomias*) Stock Assessment for British Columbia in 2021. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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Centre for Science Advice (CSA)
Pacific Region
Fisheries and Oceans Canada
3190 Hammond Bay Road
Nanaimo, BC V9T 6N7

E-Mail: DFO.PacificCSA-CASPacifique.MPO@dfo-mpo.gc.ca
Internet address: www.dfo-mpo.gc.ca/csas-sccs/

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