Assessment of the Yellowfin Sole Stock in the Bering Sea and Aleutian Islands

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27 September, 2019

Executive summary

Summary of changes in assessment inputs

Relative to last year's BSAI SAFE report, the following substantive changes have been made in the BSAI Yellowfin Sole assessment.

Changes in the data

1. The 2017 NMFS bottom-trawl survey biomass estimates were included.
2. The 2017 fishery age composition.
3. The 2018 survey age composition.
4. The estimates of the retained and discarded portions of the 2017 catch.
5. The estimate of the total catch made through the end of 2019. Catch of 150,000 t was assumed for the 2019 and 2020 projections.

Changes in the assessment methods

Explored incorporating survey start date and its interaction term with annual bottom water temperature in the survey catchability equation.

Summary of Results

The assessment updates last year's with results and management quantities that are lower than the 2017 assessment primarily due to 1) the 2018 survey biomass point estimate is 32% lower than the 2017 estimate and 2) the assessment model estimated a slightly lower survey catchability. Yellowfin sole continue to be well-above B_{MSY} and the annual harvest remains below the ABC level. The female spawning stock is in a slow downward trend. Management quantities are given below for the current base model (Model 14_1) and a new base model (Model 18_1).

Projections are based on estimated catches of 150,000 t used in place of maximum ABC for 2019 and 2020.

Responses to SSC and Plan Team Comments on Assessments in General

In this section, we list new or outstanding comments on assessments in general from the last full assessment in 2017.

"The SSC recommends that, for those sets of environmental and fisheries observations that support the inference of an impending severe decline in stock biomass, the issue of concern be brought to the SSC, with an integrated analysis of the indices in future stock assessment cycles. To be of greatest value, to the extent possible, this information should be presented at the October Council meeting so that there is sufficient time for the Plan Teams and industry to react to the possible reduction in fishing opportunity." (SSC October 2017)

Quantity	As estimated or *specified last* year for: 2018	2019	As estimated or *recommended this* year for: 2019	2020
M (natural mortality rate, ages 3+)	0.3	0.3	0.3	0.3
Tier	1a	1a	1a	1a
Projected total (age 3+) biomass (t)	10,965,000 t	10,117,000 t	0.10665 t	0.10665 t
Projected female spawning biomass (t)	3,678,000 t	3,365,000 t	0.10665 t	0.10665 t
B_0	5,394,000 t	5,394,000 t	0.10665,000 t	0.10665,000 t
B_{msy}	2,042,000 t	2,042,000 t	0.10665,000 t	0.10665,000 t
F_{OFL}	0.621	0.621	0.107	0.107
$maxF_{ABC}$	0.466	0.466	0.107	0.107
F_{ABC}	0.336	0.336	0.10665	0.10665
OFL	4,797,000 t	4,592,000 t	0.10665 t	0.10665 t
$maxABC$	3,603,000 t	3,448,000 t	0.10665 t	0.10665 t
ABC	2,592,000 t	2,467,000 t	0.10665 t	0.10665 t
Status	2016	2017	2017	2018
Overfishing	No	n/a	No	n/a
Overfished	n/a	No	n/a	No
Approaching overfished	n/a	No	n/a	No

To facilitate a coordinated response to this request, the co-chairs and coordinators of the BSAI and GOA Groundfish Plan Teams, with concurrence from stock assessment program leadership at the AFSC, have suggested that authors address it by using the previous year's Ecosystem Status Report (ESR) as follows:

"No later than the summer of each year, the lead author of each assessment should review the previous year's ESR and determine whether any factor or set of factors described in that ESR implies an impending severe decline in stock/complex biomass, where "severe decline" means a decline of at least 20% (or any alternative value that may be established by the SSC), and where biomass is measured as spawning biomass for Tiers 1-3 and survey biomass as smoothed by the standard Tier 5 random effects model for Tiers 4-5. If an author determines that an impending severe decline is likely and if that decline was not anticipated in the most recent stock assessment, he or she should summarize that evidence in a document that will be reviewed by the respective Team in September of that year and by the SSC in October of that year, including a description of at least one plausible mechanism linking the factor or set of factors to an impending severe decline in biomass, and also including an estimate or range of estimates regarding likely impacts on ABC. In the event that new survey or relevant ESR data become available after the document is produced but prior to the October Council meeting of that year, the document should be amended to include those data prior to its review by the SSC, and the degree to which they corroborate or refute the predicted severe decline should be noted, with the estimate or range of estimates regarding likely impacts on ABC modified in light of the new data as necessary."

"Stock assessment authors are encouraged to work with ESR analysts to identify a small subset of indicators prior to analysis, and preferably based on mechanistic hypotheses." (SSC October 2018)

It has been demonstrated that annual bottom water temperature is at least a partial determinate of yellowfin sole late spring/summertime distribution. However it is unclear how temperature is related to the productivity of the stock. This species does not rely on ocean/atmosphere advective properties but instead migrates directly to nursery areas to spawn, so may be more resilient to changing ocean conditions. We also know that somatic growth is positively related to bottom temperature that may result in increased fecundity. Stock assessment authors would welcome the chance to work with an ESR analysist to think about indicators.

"The SSC also recommends explicit consideration and documentation of ecosystem and stock assessment status for each stock ... during the December Council meeting to aid in identifying stocks of concern." (SSC October 2017)

Clarification during December 2017 SSC meeting and then re-clarified during June 2018 SSC meeting. In the interest of efficiency, the clarification from the December 2017 minutes is not included here. The relevant portion of the clarification from the June 2018 minutes reads as follows:

"This request was recently clarified by the SSC by replacing the terms 'ecosystem status' and 'stock assessment status' with 'Ecosystem Status Report information' and 'Stock Assessment Information,' where the potential determinations for each will consist of 'Okay' and 'Not Okay,' and by issuing the following guidance:

** The SSC clarifies that 'stock assessment status' is a fundamental requirement of the SAFEs and is not really very useful to this exercise, because virtually all stocks are never overfished nor is overfishing occurring. * Rather the SSC suggests that recent trends in recruitment and stock abundance could indicate warning signs well before a critical official status determination is reached. It may also be useful to consider some sort of ratio of how close a stock is to a limit or target reference point (e.g., B/B35). Thus, additional results for the stock assessments will need to be considered to make the 'Okay' or 'Not Okay' determinations. * The SSC retracts its previous request for development of an ecosystem status for each stock/complex. Instead, while considering ecosystem status report information, it may be useful to attempt to develop thresholds for action concerning broad-scale ecosystem changes that are likely to impact multiple stocks/complexes. * Implementation of these stock and ecosystem determinations will be an iterative process and will require a dialogue between the stock assessment authors, Plan Teams, ecosystem modelers, ESR editors, and the SSC."*

"The Teams recommend that the terms 'current and future ecosystem condition' and 'current and future stock condition' be used in place of 'ESR information' and 'stock assessment information'." (Plan Team September 2018)

"The SSC recognized that because formal criteria for these categorizations have not been developed by the PT, they will not be presented in December 2018." (SSC October 2018)

The iterative process described in the final bullet above was scheduled to begin at the September 2018 meeting of the Joint BSAI and GOA Plan Teams. However, no formal criteria for these categorizations were developed by the Plan Teams in September 2018. As specified by the SSC in October, we will not provide determinations for yellowfin sole at this time and will provide determinations when formal criteria are established.

"The Team recommended that the authors simply report in words or a table whether catches exceed ABC as an indicator for "partial update" stocks. (Plan Team November 2017)

Does not apply to yellowfin sole SAFE report since it is not a "partial update stock".

"The SSC reminds authors of the need to balance the desire to improve model fit with increased risk of model misspecification." (SSC December 2017)

Clarification: *"In the absence of strict objective guidelines, the SSC recommends that thorough documentation of model evaluation and the logical basis for changes in model complexity be provided in all cases."* (SSC June 2018)

Important point as the 2018 yellowfin sole assessment has increased the number of parameters estimated by 2 to improve fit to survey biomass. Hopefully our model evaluation is sound by providing a mechanism for the increased complexity from a new paper on availability/temperature correlations.

"Report a consistent metric (or set of metrics) to describe fish condition among assessments and ecosystem documents where possible." (SSC December 2017)

We do not yet report fish condition for yellowfin sole. However, if we do report this metric in the future then we will be consistent with the weight-length residual approach to report fish condition as described in the Ecosystem Status Report.

"Projections . . . clearly illustrate the lack of uncertainty propagation in the 'proj' program used by assessment authors. The SSC encourages authors to investigate alternative methods for projection that incorporate uncertainty in model parameters in addition to recruitment deviations. Further, the SSC noted that projections made on the basis of fishing mortality rates (Fs) only will tend to underestimate the uncertainty (and perhaps introduce bias if the population distribution is skewed). Instead, a two-stage approach that first includes a projection using F to find the catch associated with that F and then a second projection using that fixed catch may produce differing results that may warrant consideration." (SSC December 2017)

Please see model evaluation section for alternative Tier 1 projection with uncertainty in F.

"The Teams recommend that the appropriate use, or non-use, of new model based estimates in this assessment cycle be left to individual authors' discretion. The Teams further recommend that, if an author chooses to incorporate these into the assessment, the assessment should also contain appropriate comparative models and a full set of diagnostics." (Plan Team September 2018)

"The SSC supports the PT recommendation to make the use of model-based survey estimates at the individual author's discretion for 2018." (SSC October 2018)

This assessment did not utilize any model based survey estimates. In the future, model-based estimates produced by the Groundfish Assessment Program (GAP) will be used to fit the assessment model as a contrast to the current use of survey estimates. A working group was formed to investigate criteria for use of the model-based estimates in a variety of groundfish life histories. We will consult the guidelines from this working group for determining the usefulness of the model-based estimates for yellowfin sole when they become available.

"The SSC also noted that, in order to save resources, authors should not conduct additional assessments beyond the prioritized schedule unless they specifically trigger one or more of the criteria identified." (SSC October 2018)

Yellowfin sole is a Tier 1 stock assessment conducted every year and as such it's frequency for completion is not determined by a specific external criteria.

Responses to SSC and Plan Team Comments Specific to this Assessment

The Team recommends plotting the estimated spawning biomass trajectory with a fixed pair of M and q values that reduces the retrospective pattern (e.g., M=0.09 and q=1.0) on top of the estimated spawning biomass trajectory, with confidence intervals, from the base model run. This comparison will help to determine if the different combination of M and q values is within the estimated uncertainty of the base model, or is describing a completely different population size.

Please see Retrospective Analysis section of this report.

The M=0.09 and q=1.0 retrospective model runs are outside the confidence intervals of the assessment model spawning biomass trajectory for about a 17 year period from 1978-1995. Otherwise it is generally within the uncertainty of the assessment model results.

The Team recommends continuing to explore the retrospective patterns in relation to values of M and q, with fixed values of M and fixed values of q, reporting values of Mohn's rho for each combination (range to be decided by the authors). Additionally, using those same model runs, report the total likelihood for each combination to create a bivariate likelihood profile for those parameters. Realizing that this will require a considerable number of model runs, the Team leaves it up to the authors to decide whether using the model runs done for the 2017 assessment will suffice, or if important differences arise from a 2018 model that warrant redoing those model runs.

One ongoing concern with the assessment is a strong retrospective pattern in female spawning biomass, whereby more recent assessments tend to yield higher biomass estimates (Figure 4.21). Pursuant to requests by the Plan Team and SSC, the authors explored the effects of M and q on these patterns. Lower values of q and M resulted in better retrospective patterns and lower Mohn's test statistics. The SSC supports the Plan Team's recommendation to select a parameterization (e.g., M=0.09 and q=1.0) that reduces the retrospective pattern and to determine whether spawning biomass projections from this parameterization fall within the uncertainty of the base model or if it describes different population trends. The SSC also endorses the Plan Team's recommendation to continue to explore effects of M and q on the retrospective patterns in biomass.

The M-q analysis of 2017 was repeated in 2018 but focused on the pattern of model fit (-log likelihood) instead of Mohn's test statistic and indicated that the best fit to the stock assessment model occurs at M and q values higher than where the best retrospective pattern occurs.

The SSC notes that potential improved performance of the model with lower values of M are interesting, given that M appears to have been well specified both outside the model (based on multiple methods of estimation, including analysis of old Japanese pair trawl effort data) as well as inside the model (profile of M over a range of values). A natural mortality value of 0.12 is used for both sexes in the base model. Pending the outcome of efforts to explore effects of M and q on the retrospective pattern, the SSC recommends that the authors reexamine alternative methods and data available to estimate M independent of the model in attempts to independently "validate" the plausibility of the results.

Natural mortality modeling was not attempted in 2018 but can be done in 2019, for both sex-specific M and also time-varying M.

The SSC notes that there appears to be a strong time trend in the proportion of fish in the final age bin (age 17+) in the fishery catch at age data for both males and females (Table 4.4). Prior to 1980, there were no fish in this category. This proportion has generally increased from the mid 1980s to a maximum of 19% for males in 2004 and 23% for females in 1999, and fluctuated at relatively high levels through 2016. Such a pattern could be consistent with time-varying M, although there may be other explanations. For next year's assessment, the SSC recommends that the assessment authors consider the evidence for time-varying M and evaluate the ability of time-varying M to address the retrospective biomass pattern in an alternative model.

The pattern of increasing proportion of fish in the plus group for our time-series can also be explained by overfishing the stock in the early 1960s by foreign fleets where the yellowfin sole stock was reduced to very low levels and the larger fish were mostly gone. By 1980 the age 15+ fish were beginning to accumulate in the population again and increased thereafter (to the present) with more prudent management.

Introduction

The yellowfin sole (*Limanda aspera*) is one of the most abundant flatfish species in the eastern Bering Sea (EBS) and currently is the target of the largest flatfish fishery in the world. They inhabit the EBS shelf and are considered one stock. Abundance in the Aleutian Islands region is negligible. Yellowfin sole are distributed in North American waters from off British Columbia, Canada, (approx. lat. 49o N) to the Chukchi Sea (about lat. 70o N) and south along the Asian coast off the South Korean coast in the Sea of Japan (to about lat. 35o N). Adults exhibit a benthic lifestyle and occupy separate winter, spawning and summertime feeding distributions on the eastern Bering Sea shelf. From over-winter grounds near the shelf margins, adults begin a migration onto the inner shelf in April or early May each year for spawning and feeding. The directed fishery historically occurred from winter through autumn (Wilderbuer et al. 1992). Yellowfin sole are managed as a single stock in the BSAI management area as there is presently no direct evidence of stock structure.

Data

The data used in this assessment include estimates of total catch, bottom trawl survey biomass estimates and their attendant 95% confidence intervals, catch-at-age from the fishery, and population age composition estimates from the bottom trawl survey. Weight-at-age and proportion mature-at-age are also available from studies conducted during the bottom trawl surveys.

Data source	Year
Fishery catch	1954 - 2018
Fishery age composition	1964 - 2017
Fishery weight-at-age	Avg wt at age from 2008-16 used for 2008-2018
Survey biomass and standard error	1982 - 2018
bottom temperature	1982 - 2018
Survey age composition	1979 - 2017
Annual length-at-age and weight-at-age from surveys	1979 - 2017
Age at maturity	Combined 1992 and 2012 samples

Fishery Catch and Catch-at-Age

This assessment uses fishery catch data from 1955-2018 (shown for 1964-2018 in Table 4.1), including an estimate of the 2018 catch, and fishery catch-at-age (proportions) from 1964-2017 (Table 4.4, 1975-2017). The 2017 fishery age composition was primarily composed of fish older than 9 years with a large amount of 20+ fish.

Age Determination

Yellowfin sole ages have been determined at the AFSC by using the break and burn method on otoliths collected in surveys and from fisheries since 1979. In 2016 the age determination methods for yellowfin sole were validated using the bomb-produced uptake measurement of 14C method (Kastelle et al. 2016).

Length and Weight-at-Age

Past assessments of yellowfin sole have used sex-specific, time-invariant growth based on the average length-at-age and weight-at-length relationships from the time-series of survey observations summed over all years since 1982. These weight-at-age estimates were estimated from the von Bertalanffy growth curve.

Parameters of the von Bertalanffy growth curve have been estimated for yellowfin sole, by sex, from the trawl survey database as follows:

Sex	L_{inf}	K	t_0	n
Males	33.7	0.161	-0.111	656
Females	37.8	0.137	0.112	709

A sex-specific length-weight relationship was also calculated from the survey database using the power function, $Weight(g) = a * Length(cm)^b$, where a and b are parameters estimated to provide the best fit to the data (Fig. 4.8).

Sex	a	b	n
Males	0.00854	3.081	2,701
Females	0.0054	3.227	3,662

These estimates of weight at length were applied to the annual trawl survey estimates of population length at age, by sex, to calculate the weight at each age (Fig. 4.8). Since the resulting estimates of annual weight-at-age were highly variable for fish older than 11 years, ages 11-20 were smoothed using a five year average smoothing method for 1982-2018.

Applications of dendrochronology (tree-ring techniques) have been used to develop biochronologies from the otolith growth increments of northern rock sole (*Lepidopsetta polyxystra*), yellowfin sole and Alaska plaice (*Pleuronectes quadrituberculatus*) in the eastern Bering Sea. These techniques ensure that all growth increments are assigned the correct calendar year, allowing for estimation of somatic growth by age and year for chronologies that span approximately 25 years (Matta et al. 2010). The analysis indicated that yellowfin sole somatic growth exhibits annual variability and has a strong positive correlation with May bottom water temperature in the Bering Sea (Fig. 4.9).

The relationship between temperature and growth was further explored by reanalyzing yellowfin sole growth by age and year. Length-weight data collected when obtaining otolith (age) samples in RACE surveys (n=7,000 from 1987, 1994 and 1999-2009) also indicate that weight at age exhibits annual variability and is highly correlated with summer bottom water temperature observations with a lag of 2-3 years for the temperature effect to be seen (shown for age 5 fish in figure 4.10) . These observations were then extended back to 1979 using survey population length-at-age estimates (since weight-at-age is a power function of the length-at-age, Clark et al. 1999, Walters and Wilderbuer 2000).

In order to incorporate time-varying (year effect on growth) and temperature-dependent growth functions into the age-structured stock assessment model we used the annual observed population mean weight-at-age (time-varying) from the trawl survey. These empirical data indicate good somatic growth correspondence with annual bottom temperature anomalies from 1982-2017 (Fig. 4.11). Fishery weight at age data available from 2008-2016 were averaged across years for each age to provide updated estimates for the fishery

Maturity-at-age

Maturity information collected from yellowfin sole females during the 1992 and 1993 eastern Bering Sea trawl surveys have been used in this assessment for the past 20 years (Table 4.10). Nichol (1995) estimated the age of 50% maturity at 10.5 years based on the histological examination of 639 ovaries. Maturity has recently been re-evaluated from a histological analysis of ovaries collected in 2012 (Table 4.10). Results were very similar to the earlier study with only a 2% difference in estimates of yellowfin sole female spawning biomass (TenBrink and Wilderbuer 2015). In addition, the SSC requested that the assessment use a maturity schedule that uses estimates derived from both the 1992 and the 2012 collections (Table 4.10). For yellowfin sole sexual maturity occurs well after the age of entry into the fishery. Yellowfin sole females are 82% selected to the fishery by age 10 whereas they have been found to be only 40% mature at this age.

Fishery

Yellowfin sole have annually been caught with bottom trawls on the Bering Sea shelf since the fishery began in 1954 and were overexploited by foreign fisheries in 1959-62 when catches averaged 404,000 t annually (Fig. 4.1, top panel). As a result of reduced stock abundance, catches declined to an annual average of 117,800 t from 1963-71 and further declined to an annual average of 50,700 t from 1972-77. The lower yield in this latter period was partially due to the discontinuation of the U.S.S.R. fishery. In the early 1980s, after the stock condition had improved, catches again increased reaching a peak of over 227,000 t in 1985.

During the 1980s, there was also a major transition in the characteristics of the fishery. Yellowfin sole were traditionally taken exclusively by foreign fisheries and these fisheries continued to dominate through 1984. However, U.S. fisheries developed rapidly during the 1980s in the form of joint ventures, and during the last half of the decade began to dominate and then take all of the catch as the foreign fisheries were phased out of the EBS. Since 1990, only domestic harvesting and processing has occurred.

The management of the yellowfin sole fishery changed significantly in 2008 with the implementation of Amendment 80 to the BSAI Fisheries Management Plan. The Amendment directly allocated fishery resources among BSAI trawl harvesters in consideration of their historic harvest patterns and future harvest needs in order to improve retention and utilization of fishery resources by the non-AFA trawl catcher/processor fleet. This was accomplished by extending the groundfish retention standards to all H&G vessels and also by providing the ability to form cooperatives within the newly formed Amendment 80 sector. In addition, Amendment 80 also mandated additional monitoring requirements which included observer coverage on all hauls, motion-compensating scales for weighing samples, flow scales to obtain accurate catch weight estimates for the entire catch, no mixing of hauls and no on-deck sorting. The partitioning of TAC and PSC (prohibited species catch) among cooperatives has significantly changed the way the annual catch has accumulated (Fig 4.1, bottom panel) and the rate of target catch per bycatch ton. There is now a more even and slow attainment of the annual catch relative to the pre-Amendment 80 fishing behavior.

Yellowfin sole are usually headed and gutted, frozen at sea, and then shipped to Asian countries for further processing (AFSC 2016). The first wholesale value of Alaska yellowfin sole totaled $97.8 million in 2014. From 2016 to 2017 the first wholesale price of all Bering Sea flatfish fisheries increased 16% to $192.9 million t and yellowfin sole price increased 19% year over year. In 2010, following a comprehensive assessment process, the yellowfin sole fishery was certified under the Marine Stewardship Council environmental standard for sustainable and well-managed fisheries. The certification also applies to all the major flatfish fisheries in the BSAI and GOA. The total annual catch (t) since 1964 is shown in Table 4.1.

In 2011, federally permitted vessels using non-pelagic trawl gear whose harvest resulted in flatfish retained catch that was greater than any other retained fishery category were required to use modified trawl gear. The modifications required the use of elevating devices to raise the section of the trawl warps between the doors and the trawl wing tips by 2.5 inches off the seafloor. The purpose of the management action was to reduce damage of non-target animals, particularly those that form habitat structure or support other fisheries while not substantially reducing flatfish catch rates or causing gear handling problems (Rose et al. 2010).

The 1997 catch of 181,389 t (retained and discards) was the largest since the fishery became completely domestic, but decreased from 1998–2010, averaging 94,004 t (Table 4.2). From 2011-2014 the catch increased, averaging 155,000 t. The 2013 catch totaled 165,000 t (73% of the ABC), the highest annual catch in the past 19 years. For 2018, the catch distribution has been spread out from January through May with the majority coming from four BSAI management areas (509, 513, 514, 517). As of mid-September 2018, the fishing season is ongoing. In order to estimate the total 2018 catch for the stock assessment model, the average proportion of the 2010-2017 cumulative catch attained by the 35th week of the year (mid-September) was applied to the 2018 catch amount at the same time period and results in a 2018 catch estimate of 146,500 t (53% of the ABC). The size composition of the 2018 catch for both males and females, from observer sampling, are shown in Figure 4.2, the catch proportions by month and area are shown in Figure 4.3, and maps of the locations where yellowfin sole were caught in 2018, by month (through mid-September), are shown in Figure 4.4. The average age of yellowfin sole in the 2017 catch is estimated at 12.6 and 13.5 years for females and males, respectively.

The time-series of catch in Table 4.1 also includes yellowfin sole that were discarded in domestic fisheries from 1987 to the present. Annual discard estimates were calculated from at-sea sampling (Table 4.2). The rate of discard has ranged from a low of 2% of the total catch in 2012 (and 2015) to 30% in 1992 and is estimated at 3% in the 2017 fishery. The trend has been toward fuller retention of the catch in recent years, and with the advent of the Amendment 80 harvest practices, discarding is at its lowest level since these estimates have become available. Historically, discarding primarily occurred in the yellowfin sole directed fishery, with lesser amounts in the Pacific cod, Pollock, rock sole, flathead sole, and "other flatfish" fisheries (Table 4.3).

Survey

Survey Biomass Estimates and Population Age Composition Estimates

Indices of relative abundance available from AFSC surveys showed a major increase in the abundance of yellowfin sole during the late 1970s, increasing from 21 kg/ha in 1975 to 51 kg/ha in 1981 (Fig. 4.2 in Bakkala and Wilderbuer 1990). These increases have also been documented through Japanese commercial pair trawl data and catch-at-age modeling in past assessments (Bakkala and Wilderbuer 1990).

Since 1981, the survey CPUEs have fluctuated widely (Fig. 4.5). Biomass estimates for yellowfin sole from the annual bottom trawl survey on the eastern Bering Sea shelf are shown in Table 4.5 and Figure 4.6. The data show a doubling of survey biomass between 1975 and 1979 with a further increase to over 3.3 million t in 1981. Total survey abundance estimates fluctuated erratically from 1983 to 1990 with biomass ranging from as high as 3.5 million t in 1983 to as low as 1.9 million t in 1986. Biomass estimates since 1990 indicate an even trend at high levels of abundance for yellowfin sole, with the exception of the results from the 1999 and 2000 summer surveys, which were at lower levels. Surveys from 2001-2005 estimated an increase each year but the estimates since 2006 indicate a stable level with some annual variability. However, the 2012 estimate is a 19% decrease from 2011 and the 2013 and 2014 surveys have estimated a 17% increase over 2012. Similarly, there was a 24% decrease from 2014 to 2015 followed by a 48% increase from 2015 to 2016, the highest biomass estimate since 1984. Fluctuations of the magnitude shown between 1980 and 1990, 1998 and 1999, 2008 and 2009, 2011 and 2012, 2014 and 2015, and 2015 and 2016 are unreasonable considering the elements of slow growth and long life span of yellowfin sole combined with low to moderate exploitation rate, characteristics which should produce more gradual changes in abundance.

Variability of yellowfin sole survey biomass estimates (Fig. 4.6) is in part due to the availability of yellowfin sole to the survey area (Nichol 1998). Yellowfin sole are known to undergo annual migrations from wintering areas off the shelf-slope break to near shore waters where they spawn throughout the spring and summer months (Nichol, 1995; Wakabayashi, 1989; Wilderbuer et al., 1992). Exploratory survey sampling in coastal waters of the eastern Bering Sea during early summer indicate that yellowfin sole concentrations can be greater in these shallower areas not covered by the standard AFSC survey than in the survey proper. Commercial bottom trawlers have commonly found high concentrations of yellowfin sole in areas such as near Togiak Bay

(Low and Narita, 1990) and in more recent years from Kuskokwim Bay to just south of Nunivak Island. The coastal areas are sufficiently large enough to offer a substantial refuge for yellowfin sole from the current survey.

Over the past 18 years, survey biomass estimates for yellowfin sole have shown a positive correlation with shelf bottom temperatures (Nichol, 1998); estimates have generally been lower during cold years. The 1999 survey, which was conducted in exceptionally cold waters, indicated a decline in biomass that was unrealistic. The bottom temperatures during the 2000 survey were much warmer than in 1999, and the biomass increased, but still did not approach estimates from earlier years. Average bottom temperature and biomass both increased again during the period 2001 – 2003, with the 2003 value the highest temperature and biomass observed over the 22 year time series up to that time. Given that both the 1999 and 2000 surveys were conducted two weeks earlier than previous surveys, it is possible that the time difference may also have also affected the availability of yellowfin sole to the survey. If, for example, the timing of peak yellowfin sole spawning in nearshore waters corresponded to the time of the survey, a greater proportion of the population would be unavailable to the standard survey area. This pattern was observed again in 2009 and 2012 when the temperatures and the bottom trawl survey point estimates were lower. Summer shelf bottom temperatures in 2012 were the 2nd coldest recorded by the survey and the time-series and resulted in a 19% decline from 2011. In 2016 the Bering Sea had the highest recorded bottom temperature since measurements began in 1982 and the 2016 estimate of biomass was the highest in 32 years and 48% higher than the 2015 estimate. The 2017 survey estimate of 2,787,700 t was 3% lower than 2016, but the 2018 estimate of 1,892,925 (another warm year) was down 32% from 2017. We propose two possible reasons why survey biomass estimates are lower during years when bottom temperatures are low. First, catchability may be lower because yellowfin sole may be less active when cold. Less active fish may be less susceptible to herding, and escapement under the footrope of survey gear may increase if fish are less active. Secondly, bottom temperatures may influence the timing of the inshore spawning migrations of yellowfin sole and therefore affect their availability to the survey area (Nichol et al. in review). Because yellowfin sole spawning grounds include nearshore areas outside the survey area, availability of fish within the survey area can vary with the timing of this migration and the timing of the survey. In the case of 2016, a very warm year in the Bering Sea, it appears that a higher portion of the adult biomass was distributed on the shelf (outside of the spawning areas) relative to the average of all previous survey years, indicating earlier spawning migration (Fig 4.7).

Yellowfin sole population numbers-at-age estimated from the annual bottom trawl surveys are shown in Table 4.6 and their occurrence in trawl survey hauls and associated collections of lengths and age structures since 1982 are shown in Table 4.7. Their total tonnage caught in the resource assessment surveys since 1982 are listed in Table 4.8 and also in an appendix table with IPHC survey catches.

Northern Bering Sea survey

Trawl survey sampling was extended to the northern Bering Sea in 2010, 2017 and 2018. The trawl surveys conducted in 2010 and 2017 occupied the same areas with similar sampling densities. The 2018 survey was a reduced effort and only sampled a subset of the northern Bering Sea. Stations in 2018 were 30 nautical miles apart (instead of 20 nm) and excluded Norton Sound and inshore areas north of Nunivak Island. For comparison among years (2010, 2017, 2018), biomass estimates were derived by truncating the areal coverage of the 2010 and 2017 surveys to include only the area covered in 2018 that was common to all three surveys, and this was treated as a single stratum (Table 4.5). This truncated area is 158,286 square kilometers (compared to 200,207 square kilometers in 2010 & 2017). There was a small increase in the estimate of yellowfin sole in the truncated survey area from the 3 surveys. Since yellowfin sole fishing is presently prohibited in the northern Bering Sea, the biomass from this area is not included in the stock assessment model.

Analytic Approach

General Model Structure

The abundance, mortality, recruitment and selectivity of yellowfin sole were assessed with a stock assessment model using the AD Model Builder language (Fournier et al. 2012; Ianelli and Fournier 1998). The conceptual

model is a separable catch-age analysis that uses survey estimates of biomass and age composition as auxiliary information (Fournier and Archibald 1982). The assessment model simulates the dynamics of the population and compares the expected values of the population characteristics to the characteristics observed from surveys and fishery sampling programs. This is accomplished by the simultaneous estimation of the parameters in the model using the maximum likelihood estimation procedure. The fit of the simulated values to the observable characteristics is optimized by maximizing a log(likelihood) function given some distributional assumptions about the observed data.
The model starts at age one and fish older than twenty are allowed to accumulate into a plus group. Since the sex-specific weight-at-age for yellowfin sole diverges after age of maturity (about age 10 for 40% of the stock) with females growing larger than males, the current assessment model is coded to accommodate the sex-specific aspects of the population dynamics of yellowfin sole. The model allows for the input of sex-specific estimates of fishery and survey age composition and weight-at-age and provides sex-specific estimates of population numbers, fishing mortality, selectivity, fishery and survey age composition and allows for the estimation of sex-specific natural mortality and catchability. The model retains the utility to fit combined sex data inputs. The suite of parameters estimated by the model are classified by three likelihood components:

Data component	Distributional assumption
Trawl fishery catch-at-age	Multinomial
Trawl survey population age composition	Multinomial
Trawl survey biomass estimates and S.E.	Log-normal

The total log likelihood is the sum of the likelihoods for each data component (Table 4.11). The likelihood components may be weighted by an emphasis factor, however, equal emphasis was placed on fitting each likelihood component in the yellowfin sole assessment except for the catch. The AD Model Builder software fits the data components using automatic differentiation (Griewank and Corliss 1991) software developed as a set of libraries (AUTODIFF C++ library). Table 4.11 also presents the key equations used to model the yellowfin sole population dynamics in the Bering Sea and Table 4.12 provides a description of the variables used in Table 4.11. Sharp increases in trawl survey abundance estimates for most species of Bering Sea flatfish between 1981 and 1982 indicate that the 83-112 trawl was more efficient for capturing these species than the 400-mesh eastern trawl used in 1975, and 1979-81. Allowing the model to tune to these early survey estimates would most likely underestimate the true pre-1982 biomass, thus exaggerating the degree to which biomass increased during that period. Although this underestimate would have little effect on the estimate of current yellowfin sole biomass, it would affect the spawner and recruitment estimates for the time-series. Hence, the pre-1982 survey biomass estimates were omitted from the analysis. The model of yellowfin sole population dynamics was evaluated with respect to the observations of the time-series of survey and fishery age compositions and the survey biomass trend since 1982.

Description of Alternative Models

Parameters Estimated Outside the Assessment Model

Natural mortality (M) was initially estimated by a least squares analysis where catch at age data were fitted to Japanese pair trawl effort data while varying the catchability coefficient (q) and M simultaneously. The best fit to the data (the point where the residual variance was minimized) occurred at a M value of 0.12 (Bakkala and Wespestad 1984). This was also the value which provided the best fit to the observable population characteristics when M was profiled over a range of values in the stock assessment model using data up to 1992 (Wilderbuer 1992). Since then, natural mortality has been estimated as a free parameter in some of the stock assessment model runs which have been evaluated the past five years. A natural mortality value of 0.12 is used for both sexes in the base model presented in this assessment.

Yellowfin sole maturity schedules were estimated from in-situ observations from two studies as discussed in a previous section (Table 4.10).

Parameter Estimates

(Use the above heading for Tiers 4-6) List of parameters that are estimated independently of others (e.g., the natural mortality rate, parameters governing the maturity schedule, parameters governing growth [length at age, weight at length or age]—if not estimated inside the assessment model) Description of how these parameters are estimated (methods do not necessarily have to be statistical; e.g., M could be estimated by referencing a previously published value)

Parameters Estimated Inside the Assessment Model

The parameters estimated by the model are presented below:

Fishing mortality	Selectivity	Survey catchability	Year-class strength	Spawner-recruit	Total
66	268	4	105	2	445

The increase in the number of parameters estimated in this assessment compared to last year (8) can be accounted for by the input of another year of fishery data and the entry of another year class into the observed population, four more sex-specific fishery selectivity parameters and 2 additional catchability parameters.

Year Class Strengths

The population simulation specifies the numbers-at-age in the beginning year of the simulation, the number of recruits in each subsequent year, and the survival rate for each cohort as it moves through the population over time using the population dynamics equations given in Table 4.11.

Selectivity

Fishery and survey selectivity was modeled separately for males and females using the two parameter formulation of the logistic function (Table 4.11). The model was run with an asymptotic selectivity curve for the older fish in the fishery and survey, but still was allowed to estimate the shape of the logistic curve for young fish. The oldest year classes in the surveys and fisheries were truncated at 20 and allowed to accumulate into the age category 20+ years. A single selectivity curve, for both males and females, was fit for all years of survey data.

Given that there have been annual changes in management, vessel participation and most likely gear selectivity, time-varying fishing selectivity curves were estimated. A logistic equation was used to model fishery selectivity and is a function of time-varying parameters specifying the age and slope at 50% selection, φ_t and η_t , respectively. The fishing selectivity (S^f) for age a and year t is modeled as,

$$S^f_{a,t} = [1 + e^{\eta_t(a-\varphi_t)}]^{-1}, \tag{1}$$

where φ_t and η_t are time-varying and partitioned (for estimation) into parameters representing the mean and a vector of deviations (log-scale) conditioned to sum to zero. The deviations are constrained by a lognormal prior with a variance that was iteratively estimated. The process of iterating was to first set the variance to a high value (diffuse prior) of 0.5^2 and estimate the deviations. The next step was to compare the variability of model estimates. The variance of the model estimates were then rounded up slightly and fixed for subsequent runs. The 2016 values were fixed as the average of the 3 most recent years.

Fishing Mortality The fishing mortality rates (F) for each age and year are calculated to approximate the catch weight by solving for F while still allowing for observation error in catch measurement. A large emphasis (300) was placed on the catch likelihood component to force the model to closely match the observed catch.

Survey Catchability A past assessment (Wilderbuer and Nichol 2001) first examined the relationship between estimates of survey biomass and bottom water temperature. To better understand how water temperature may affect the catchability of yellowfin sole to the survey trawl, catchability was estimated for each year in the stock assessment model as:

$$q = e^{-\alpha+\beta T}, \tag{2}$$

where q is catchability, T is the average annual bottom water temperature anomaly at survey stations less than 100 m, and α and β are parameters estimated by the model. The catchability equation has two parts. The $e^{-}\alpha$ term is a constant or time-independent estimate of q. The second term, $e^{\beta * T}$ is a time-varying (annual) q which responds to metabolic aspects of herding or distribution (availability) which can vary annually with bottom water temperature. The result of incorporating bottom temperature to estimate annual q has resulted in an improved fit to the survey (shown in Figure 4.12 for the base model).

In this assessment we introduce a revised survey catchability model (Model 18_1) where survey start date (expressed as deviation in days (- and +) from the average survey start date of June 4th) and its interaction with annual bottom water temperature is added to the catchability equation as:

$$q = e^{-\alpha+\beta T+\gamma S+\mu T:S}, \tag{3}$$

where T=survey bottom temperature (averaged per year for all stations <100 m), S=survey start date, and $T:S$=interaction of T and S. Earlier survey start dates usually encounter colder water and since the timing of the survey start date is positively correlated with bottom water temperature, improvement in fitting the survey biomass estimates can be gained by estimating two new parameters (μ and γ). Akaike information criterion (AIC) were used to determine if the additional variables (S and $T:S$) improved the regression fit. The improvement in fit was more than offset by the additional two parameters (Nichol et al. In review).

Spawner-Recruit Estimation

Annual recruitment estimates from 1978-2012 were constrained to fit a Ricker (1958) form of the stock recruitment relationship as follows:

$$R = \alpha S e^{-\beta S}, \tag{4}$$

where R is age 1 recruitment, S is female spawning biomass in metric tons the previous year, and α and β are parameters estimated by the model. The spawner-recruit fitting is estimated in a later phase after initial estimates of survival, numbers-at-age and selectivity are obtained.

Results

Model Evaluation

The model evaluation for this stock assessment involved a two-step process. The first step was to evaluate the productivity of the yellowfin sole stock by an examination of which sets of years to include for spawner-recruit fitting (increased from 1978-2010 to 1978-2012 in this assessment). The second step evaluated various hypothesized states of nature by fitting natural mortality and catchability estimates in various combinations.

The SSC determined in December 2006 that yellowfin sole would be managed under the Tier 1 harvest guidelines, and therefore future harvest recommendations would be based on maximum sustainable yield MSY and the associated fishing effort F_{MSY} values calculated from a spawner-recruit relationship. MSY is an equilibrium concept and its value is dependent on both the spawner-recruit estimates which are assumed to represent the equilibrium stock size-recruitment relationship and the model used to fit the estimates. In the yellowfin sole stock assessment model, a Ricker form of the stock-recruit relationship was fit to various combinations of these data and estimates of F_{MSY} and B_{MSY} were calculated, assuming that the fit to the stock-recruitment data represents the long-term productivity of the stock.

For this assessment, two different stock-recruitment time-series were investigated: the full time-series 1955-2012 (Model 14_2) and the post-regime shift era, 1978-2012 (Model 14_1) (Fig. 4.13) (see Joint Plan Team recommendations for September 2012). Very different estimates of the long-term sustainability of the stock (F_{MSY} and B_{MSY}) are obtained depending on which years of stock-recruitment data are included in the fitting procedure (Table 4.13). When the entire time-series from 1955-2012 was fit, the large recruitments that occurred at low spawning stock sizes in the 1960s and early 1970s determined that the yellowfin sole stock was most productive at a smaller stock size with the result that F_{MSY} (0.208) is higher than $F_{35\%}$ ($F_{35\%} = 0.17$) and B_{MSY} is 314,800 t (Model 14_2). If we limit the analysis to consider only recruitments which occurred after the well-documented regime shift in 1977 (Model 14_1), a lower value of F_{MSY} is obtained (0.118) and B_{MSY} is 451,600 t. Table 4.13 indicates that the ABC values from the Model 14_2 harvest scenario for 2019 would be 239,560 t higher than Model 14_1. Posterior distributions of FMSY for these models indicate that this parameter is estimated with less uncertainty for Model 14_1 resulting in the reduced buffer between ABC and OFL relative to Model 14_2 (9% for Model 14_1 versus 1% for Model 14_2, Table 4.13 and Fig 4.14).

It is important for the Tier 1 calculations to identify which subset of the stock recruitment data is used. Using the full time series to fit the spawner recruit curve estimates that the stock is most productive at a small stock size. Thus MSY and F_{MSY} are relatively high values and B_{MSY} is a lower value. If the stock was productive in the past at a small stock size because of non density-dependent factors (environment), then reducing the stock size to low levels could be detrimental to the long-term sustainability of the stock if the environment, and thus productivity, have changed from the earlier period. Since observations of yellowfin sole recruitment at low stock sizes are not available from multiple time periods, it is uncertain if future recruitment events at low stock conditions would be as productive as during the late 1960s-early 1970s.

Given the uncertainty of the productivity of yellowfin sole at low spawning stock sizes, and because the AFSC policy for reference point time-series selection is to use the post 1977 regime shift values unless there is a compelling reason to do otherwise, the productivity of yellowfin sole in this assessment is estimated by fitting the 1977-2012 spawner-recruit data in the model (Model 14_1).

The second step in the model evaluation for this assessment entailed the use of a single structural model to consider the uncertainty in the key parameters natural mortality M and catchability. Model 14_1 has been the preferred model for the past 5 assessments, and operates by fixing M at 0.12 for both sexes and estimating q using the relationship between survey catchability and the annual average water temperature at the sea floor (from survey stations at less than 100 m). The other models used in the evaluation represented various combinations of estimating M or q as free parameters with different amounts of uncertainty in the parameter estimates (Wilderbuer et al. 2010). The results are detailed in those assessments and are not repeated here except for the following observations. The introduction of survey start date as a variable within the q parameter calculation of the stock assessment model (Model 18_1), similarly improved overall model fits to the survey biomass data with the full model ($q = e^{-\alpha+\beta*T+\gamma*S+\mu*T:S}$) providing the best fit to the survey biomass data compared to models where either annual bottom temperature or start date variable (i.e., constant q across years) were not included, or models with only a bottom temperature variable ($q = e^{-\alpha+\beta*T}$) (Nichol et. al 2018). In particular, inclusion of the start date in the model improved model fits for years 1999 to 2003, years for which the more reduced models clearly overestimated survey biomass. (Panel A constant q, Panel B bottom temperature only, and Panel C survey start date, bottom temperature and interaction term.)

FIGURE

Given these results and the AIC evidence (Nichol et al. 2018), Model 18_1 is the model of choice for estimating the yellowfin sole stock size and management quantities for the 2019 fishing season.

Experiments examining the bridle efficiency of the Bering Sea survey trawl indicate that yellowfin sole are herded into the trawl path from an area between the wing tips of the net and the point where the bridles contact the seafloor (Somerton and Munro 2001). The herding experiments suggest that the survey trawl vulnerability (a component of catchability) is greater than 1.0. The likelihood profile of q from the model indicated a small variance with a narrow range of likely values with a low probability of q being equal to the value of 1.0 in a past assessment (Wilderbuer and Nichol 2003).

A model that allows M to be estimated as a free parameter for males with females fixed at 0.12 provided a better fit to the sex ratio estimated from the annual trawl survey age compositions than did the base model (both sexes fixed at $M = 0.12$). However, since the population sex ratio annually observed at the time of the survey is a function of the timing of the annual spawning in adjacent inshore areas, it is questionable that providing the best fit to these observations is really fitting the population sex ratio better. Thus, the model configuration which utilizes the relationship between annual seafloor temperature and survey start date to estimate survey catchability with M fixed at 0.12 for both sexes (Model 18_1) is the preferred model used to base the assessment of the condition of the Bering Sea yellowfin sole resource for the 2018 fishing season.

Time Series Results

A brief consideration of the inputs and changes to the assessment methodology relative to last year (Model 14_1) is given before presenting the preferred model results. Primary updates in going from Model 14_1 to Model 18_1 were the 2018 catch, the fishery and survey age compositions from 2017 and the 2018 survey biomass (32% lower than 2017) and standard error estimates. The fishery and survey weights-at-age were also changed in a small amount to include the latest year of data. In their totality, these changes produced Model 18_1 ABC and OFL estimates for 2019 that were 2% lower than the 2017 assessment (Model 14_1) projections for 2019.

As expected, this small increase produced very similar spawner-recruit curves.

FIGURE The 2018 overall estimate (1982 – 2018) of trawl survey catchability decreased from 0.9 to 0.88. This resulted in slightly higher model estimates of population numbers at age and biomass for the time-series back to 1992 relative to last year's assessment and increased the estimated level of female spawning biomass. The model results indicate the stock has been in a slowly declining condition since 1994. The estimates of total biomass and ABC are a bit lower than those used to manage the stock in 2018. Seven of the past 11 years have had negative bottom temperature anomalies in the Bering Sea but the last four years have been above the mean. The temperature-dependent q adjustment for 2017 was 0.92.

Fishing Mortality and Selectivity

The assessment model estimates of the annual fishing mortality in terms of age-specific annual F and on fully selected ages are given in Tables 4.14 and 4.15, respectively. The full-selection F has averaged 0.07 over the period of 1978-2018 with a maximum of 0.11 in 1978 and a minimum of 0.04 in 2001. Model estimated selectivities (Table 4.16, Fig. 4.15) indicate that both sexes of yellowfin sole are 50% selected by the fishery at about age 9 and nearly fully selected by age 13, with annual variability.

Abundance Trends

The model estimates q at an average value of 0.88 for the period 1982-2018 which results in the model estimate of the 2018 age 2+ total biomass at 2,786,300 t (Table 4.17). Model results indicate that yellowfin sole total biomass (age 2+) was at low levels during most of the 1960s and early 1970s (700,000-1,000,000 t) after a period of high exploitation (Table 4.17, Fig. 4.16, center left panel). Sustained above average recruitment from 1967-76 combined with light exploitation resulted in a biomass increase to a peak of 3.6 million t by 1985. The population biomass has since been in a slow decline as the strong 1981 and 1983 year-classes have passed through the population, with only the 1991, 1995 and 2003 year-classes at levels observed during the 1970s. The present biomass is estimated at 78% of the peak 1985 level.

The female spawning biomass has also declined since the peak in 1994, with a 'r thisyr' estimate of 854,800 t (27% decline). The spawning biomass has been in a gradual decline for the past 22 years and is 36% above the B40% level and 1.9 times the B_{MSY} level (Fig. 4.16). The model estimate of yellowfin sole population numbers at age for all years is shown in Table 4.18 and the resulting fit to the observed fishery and survey age compositions input into the model are shown in the Figure 4.17. The fit to the trawl survey biomass estimates are shown in Figure 4.16. Allowing q to be correlated with annual bottom temperature and survey start date provides a better fit to the bottom trawl survey estimates than using a q fixed at the average value

(Fig. 4.18). Table 4.19 lists the numbers of female spawners estimated by the model for all ages and years. The estimated average age of yellowfin sole in the population is 6.5 years for males and females.

Both the trawl survey and the stock assessment model indicate that the yellowfin sole resource (total biomass) increased during the 1970s and early 1980s to a peak level during the mid-1980s. The yellowfin sole population biomass slowly decreased over the 23 years since the mid-1990s as the majority of year-classes during those years were below average strength. Average to above average recruitment from 2006 to 2009 is expected to maintain the abundance of yellowfin sole at a level above B_{MSY} in the near future. The stock assessment projection model indicates a mildly decreasing trend in female spawning biomass through 2023 if the fishing mortality rate continues at the same level as the average of the past 5 years (Fig. 4.22).

Recruitment Trends

The primary reason for the sustained increase in abundance of yellowfin sole during the 1970s and early 1980s was the recruitment of a series of stronger than average year classes spawned in 1967-76 (Figure 4.19 and Table 4.20). The 1981 year class was the strongest observed (and estimated) during the 47 year period analyzed and the 1983 year class was also very strong. Survey age composition estimates and the assessment model also estimate that the 1987 and 1988 year classes were average and the 1991 and 1995 year classes were above average. With the exception of these 4 year classes, recruitment from 15 of the following 19 years estimated from 1984-2005 (since the strong 1983 year-class) were below the 48 year average, which caused the population to gradually decline. The 2003 year-class has now been observed multiple times in the age compositions and is clearly a strong year class, similar to some of the strong recruitment mentioned above and have contributed to the reservoir of spawning fish in the current population. In addition, recruitment from 2006-2009 appear also to be average to above average.

Historical Exploitation Rates

Based on results from the stock assessment model, annual average exploitation rates of yellowfin sole since 1977 ranged from 3% to 7% of the total biomass, and have averaged 4% (Table 4.15). Posterior distributions of selected parameters from the preferred stock assessment model used in the assessment are shown in Figure 4.20. The values and standard deviations of some selected model parameters are listed in Table 4.21.

Retrospective Analysis

A within-model retrospective analysis is also included for the recommended assessment model (Model 18_1) where retrospective female spawning biomass is calculated by working backwards in time dropping data one year at a time and then comparing the "peeled" estimate to the reference stock assessment model used in the assessment (Fig. 4.21). The resulting pattern from the current assessment model was less than desirable.

Peculiar to the yellowfin sole assessment, in comparison to the northern rock sole and Alaska plaice assessments (that have nice patterns), is the large amount of variability in the annual survey biomass assessments for this stock due to the temperature-influenced availability to the survey. This large variability in the annual estimates can contribute to undesirable patterns since the earlier years are not fitting the same highly variable information as the current year.

In the 2017 assessment it was demonstrated that low values of Mohn's rho and desirable retrospective patterns of female spawning biomass were obtainable if lower values of M and q were used relative to the base model. The Plan Team (and SSC concurred) requested a plot of the model-estimated female spawning biomass trajectory that reduces the retrospective pattern using M fixed at 0.09 and q=1.0 on top of the estimated female spawning biomass trajectory with confidence interval from the assessment. This comparison is plotted below and indicates the retrospective model runs are outside the confidence intervals of the assessment model spawning biomass trajectory for about a 17 year period from 1978-1995. Otherwise it is within the uncertainty of the assessment model estimate of female spawning biomass.

FIGURE

The Plan Team recommended that the assessment continue to explore the retrospective patterns in relation to M and q by profiling over a range of combinations of M and q and recording the resulting values of Mohn's rho and also total likelihood. This was accomplished using data through 2018 and yielded the following results.

FIGURE

Natural mortality (M) and catchability (q) profile. Top panel is Mohn's rho values and bottom panel is log(likelihood).

The best retrospective patterns (lower values of M and q in top panel) did not occur at corresponding best model fit values (single digit numbers in the bottom panel) of M and q (higher values). The retrospective technique may not always be the best tool for model selection, at least for BSAI yellowfin sole as there is tension between model fit and good retrospective pattern over the range of parameterization examined.

Figures of yellowfin sole spawning biomass for selected retrospective M-q combinations: RETROSPECTIVE FIGURES

Harvest Recommendations

Scenario Projections and Two-Year Ahead Overfishing Level

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. The 2018 numbers at age from the stock assessment model are projected to 2019 given the 2018 catch and then a 2019 catch of 150,000 t is applied to the projected 2019 population biomass to obtain the 2020 OFL.

The SSC has determined that yellowfin sole qualify as a Tier 1 stock and therefore the 2019 ABC is calculated using Tier 1 methodology. The Tier 1 harvest level is calculated as the product of the harmonic mean of F_{MSY} and the geometric mean of the 2019 biomass estimate.

The geometric mean of the 2019 biomass estimate, B_{gm}, is estimated using the equation

$$B_{gm} = e^{ln(B)-(cv^2/2)}$$

, where B is the point estimate of the 2019 biomass from the stock assessment model and cv^2 is the coefficient of variation of the point estimate (a proxy for sigma). The harmonic mean of F_{MSY}, F_{har} is estimated as $F_{har} = e^{ln(F_{MSY}-(ln(sd^2)/2)}$, where F_{MSY} is the peak mode of the F_{MSY} distribution and sd^2 is the square of the standard deviation of the F_{MSY} distribution.

In 2006 the SSC selected the 1978-2001 data set for the Tier 1 harvest recommendation. Using this approach again for the 2019 harvest (now the 1978-2012 time-series) recommendation (Model 18_1 in Table 4.13), the $F_{ABC} = F_{harmonic_mean} = 0.107$. The estimate of age 6+ total biomass for 2019 is 2,462,440 t. The calculations outlined above give a Tier 1 ABC harvest recommendation of 263,200 t and an OFL of 289,900 t for 2019. This results in a 9% (26,200 t) buffer between ABC and OFL. The ABC value is 5% lower than last year, primarily due to the 32% decline in the survey estimate from 2017 to 2018.

The stock assessment analysis must also consider harvest limits, usually described as overfishing fishing mortality levels with corresponding yield amounts. Amendment 56 to the BSAI FMP sets the Tier 1 harvest limit at the F_{MSY} fishing mortality value. The overfishing fishing mortality values, ABC fishing mortality values and their corresponding yields are given as follows:

Harvest level	F value	2019 Yield
Tier 1 $F_{OFL} = F_{MSY}$	0.117	289,900 t
Tier 1 $F_{ABC} = F_{harmonic_mean}$	0.107	263,200 t

Status Determination

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 Policy Act, and the 1977 Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA).

For each scenario, the projections begin with the vector of 2018 numbers at age estimated in the assessment. This vector is then projected forward to the beginning of 2019 using the schedules of natural mortality and selectivity described in the assessment and the best available estimate of total (year-end) catch for 2018. 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 to obtain distributions of possible future stock sizes, fishing mortality rates, and catches.

Five of the seven standard scenarios will be used in an Environmental Assessment prepared in conjunction with the final SAFE. These five scenarios, which are designed to provide a range of harvest alternatives that are likely to bracket the final TAC for 2019, are as follows (max F_{ABC} refers to the maximum permissible value of F_{ABC} under Amendment 56):

- 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 all future years, F is set equal to a constant fraction of max F_{ABC}, where this fraction is equal to the ratio of the FABC value for 2019 recommended in the assessment to the max F_{ABC} for 2019. (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.)
- Scenario 3: In all future years, F is set equal to the 2014-2018 average F. (Rationale: For some stocks, TAC can be well below ABC, and recent average F may provide a better indicator of F_{TAC} than F_{ABC}.)
- Scenario 4: In all future years, the upper bound on F_{ABC} is set at F60%. (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.)
- 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 expected to be above its MSY level in 2016 and above its MSY level in 2030 under this scenario, then the stock is not overfished.)
- Scenario 7: In 2019 and 2020, F is set equal to max F_{ABC}, and in all subsequent years, F is set equal to FOFL. (Rationale: This scenario determines whether a stock is approaching an overfished condition. If the stock is expected to be above its MSY level in 2031 under this scenario, then the stock is not approaching an overfished condition.)

Simulation results shown in Table 4.22 indicate that yellowfin sole are not currently overfished and are not approaching an overfished condition. The projection of yellowfin sole female spawning biomass through 2031 is shown in Figure 4.22 and a phase plane figure of the estimated time-series of yellowfin sole female spawning biomass relative to the harvest control rule is shown in Figure 4.23.

Year	Catch	SSB	Geom. mean 6+ biomass	ABC	OFL
2019	150,000	850,600	2,462,400	263,200	290,000
2020	150,000	821,500	2,411,700	257,800	284,000

Ecosystem Considerations

(Authors are encouraged to use information contained in the Ecosystem Considerations chapter to assist them in developing stock-specific analyses and to recommend new information for inclusion in future versions of the Ecosystem Considerations chapter. Time series currently contained in the Ecosystem Considerations chapter may simply be referenced rather than duplicated here. In cases where stock-specific time series or relationships are used, this information should be included here rather than in the Ecosystem Considerations chapter.)

Ecosystem Effects on the Stock

The following factors should be discussed: Prey availability/abundance trends (historically, in the present, and in the foreseeable future). These prey trends could affect growth or survival of a target stock.

1) Predator population trends (historically, in the present, and in the foreseeable future). These trends could affect stock mortality rates over time.
2) Changes in habitat quality (historically, in the present, and in the foreseeable future). Changes in the physical environment such as temperature, currents, or ice distribution could affect stock migration and distribution patterns, recruitment success, or direct effects of temperature on growth.

Fishery Effects on the Ecosystem

The following factors should be discussed:

1) Fishery-specific contribution to bycatch of prohibited species, forage (including herring and juvenile pollock), HAPC biota (in particular, species common to the target fishery), marine mammals, birds, and other sensitive non-target species (including top predators such as sharks, expressed as a percentage of the total bycatch of that species.
2) Fishery-specific concentration of target catch in space and time relative to predator needs in space and time (if known) and relative to spawning components.
3) Fishery-specific effects on amount of large-size target fish.
4) Fishery-specific contribution to discards and offal production.
5) Fishery-specific effects on age at maturity and fecundity of the target species.
6) Fishery-specific effects on EFH non-living substrate (using gear specific fishing effort as a proxy for amount of possible substrate disturbance).

Data Gaps and Research Priorities

List areas where a significant improvement in the amount of available information would likely result in a significant improvement in the quality of the assessment and the estimates of critical parameters.

Literature Cited

List all references cited in the assessment (and make sure that the current assessment cites appropriate previous assessments containing any analyses that are still mentioned but no longer included in the current assessment). Omit all references not cited in the assessment (i.e., vestigial references from previous assessments).

Tables

Table 4.1: Foreign and domestic datch (t) of yellowfin sole 1964-2018. Foreign catches are designated as joint venture processing (JVP) and domestic annual processing (DAP). Catch for 2018 is an estimate through the end of the year.

		Domestic		
Year	Foreign	JVP	DAP	Total
1964	111,777			111,777
1965	53,810			53,810
1966	102,353			102,353
1967	162,228			162,228
1968	84,189			84,189
1969	167,134			167,134
1970	133,079			133,079
1971	160,399			160,399
1972	47,856			47,856
1973	78,240			78,240
1974	42,235			42,235
1975	64,690			64,690
1976	56,221			56,221
1977	58,373			58,373
1978	138,433			138,433
1979	99,019			99,019
1980	77,768	9,623		87,391
1981	81,255	16,046		97,301
1982	78,331	17,381		95,712
1983	85,874	22,511		108,385
1984	126,762	32,764		159,526
1985	100,706	126,401		227,107
1986	57,197	151,400		208,597
1987	1,811	179,613	4	181,428
1988		213,323	9,833	223,156
1989		151,501	1,664	153,165
1990		69,677	14,293	83,970
1991			115,842	115,842
1992			149,569	149,569
1993			106,101	106,101
1994			144,544	144,544
1995			124,740	124,740
1996			129,659	129,659
1997			181,389	181,389
1998			101,201	101,201
1999			67,320	67,320
2000			83,850	83,850
2001			63,395	63,395
2002			73,000	73,000
2003			74,418	74,418
2004			69,046	69,046
2005			94,383	94,383
2006			99,068	99,068
2007			121,029	121,029
2008			148,894	148,894

2009	107,528	107,528
2010	118,624	118,624
2011	151,164	151,164
2012	147,183	147,183
2013	164,944	164,944
2014	156,778	156,778
2015	126,933	126,933
2016	135,353	135,353
2017	132,297	132,297
2018	146,500	146,500

Table 4.2: Estimates of retained and discarded (t) yellowfin sole caught in Bering Sea fisheries through September 25th, 2018, and the proportion discarded.

Year	Retained (mt)	Discarded (mt)	Proportion discarded
1991	88,967	28,337	0.24
1992	102,542	42,843	0.29
1993	76,798	29,012	0.27
1994	104,918	35,132	0.25
1995	96,770	27,982	0.22
1996	101,324	28,335	0.22
1997	150,745	32,069	0.18
1998	80,267	20,888	0.21
1999	56,604	12,629	0.18
2000	69,971	14,100	0.17
2001	54,918	8,661	0.14
2002	63,625	11,361	0.15
2003	68,832	10,974	0.14
2004	62,746	12,765	0.17
2005	85,311	9,074	0.1
2006	90,592	8,568	0.09
2007	109,004	11,960	0.1
2008	141,235	7,659	0.05
2009	100,642	6,871	0.06
2010	113,244	5,380	0.05
2011	146,418	4,749	0.03
2012	142,132	5,055	0.03
2013	158,781	6,163	0.04
2014	152,167	4,606	0.03
2015	123,065	3,871	0.03
2016	131,203	4,143	0.03
2017	128,665	3,600	0.03
2018	127,331	4,213	0.03
2019	99,754	2,303	0.02

Table 4.3: Discarded and retained catch of non-CDQ yellowfin sole, by fishery, in 2017. Gear types include longline (HAL), bottom trawl (NPT), pot (POT), and pelagic trawl (PTR). Catch was non-zero for all target-gear combinations shown, but may appear as zero as results were rounded to the nearest metric ton (mt). Source: NMFS AKRO BLEND/Catch Accounting System.

Trip target name	Gear type	Discarded (mt)	Retained (mt)
Greenland.Turbot...BSAI	HAL	0	0
Other.Species	HAL	1	0
Pacific.Cod	HAL	1,808	154
Alaska.Plaice...BSAI	NPT	0	0
Atka.Mackerel	NPT	0	0
Kamchatka.Flounder...BSAI	NPT	21	107
No.retained.catch	NPT	3	375
Other.Species.1	NPT	224	13,362
Pacific.Cod.1	NPT	1	3
Pollock...bottom	NPT	0	0
Pollock...midwater	NPT	1,606	108,226
Atka.Mackerel.1	POT	333	67
Yellowfin.Sole...BSAI	POT	0	10
Alaska.Plaice...BSAI.1	PTR	147	253

Table 4.4: Yellowfin sole fishery catch-at-age (proportions), 1975-2017 (female).

7	8	9	10	11	12	13	14	15	16	17+
0.0164	0.0424	0.0427	0.0191	0.0098	0.0049	0.0037	0.0044	0.0012	0.0009	0.0004
0.0134	0.0222	0.0372	0.0309	0.0136	0.0072	0.0036	0.0028	0.0033	0.0009	0.0007
0.0338	0.0376	0.0304	0.0275	0.0153	0.0056	0.0028	0.0014	0.0010	0.0012	0.0003
0.0318	0.0698	0.0779	0.0580	0.0488	0.0260	0.0093	0.0045	0.0022	0.0017	0.0020
0.0136	0.0320	0.0488	0.0429	0.0288	0.0234	0.0123	0.0044	0.0021	0.0010	0.0008
0.0133	0.0149	0.0281	0.0400	0.0360	0.0252	0.0210	0.0113	0.0041	0.0020	0.0010
0.0155	0.0202	0.0191	0.0292	0.0347	0.0274	0.0178	0.0143	0.0075	0.0027	0.0013
0.0110	0.0254	0.0252	0.0181	0.0227	0.0241	0.0180	0.0114	0.0090	0.0047	0.0017
0.0208	0.0222	0.0346	0.0267	0.0170	0.0204	0.0212	0.0158	0.0099	0.0079	0.0041
0.0099	0.0272	0.0284	0.0444	0.0345	0.0221	0.0265	0.0276	0.0205	0.0129	0.0103
0.0075	0.0215	0.0456	0.0393	0.0563	0.0423	0.0268	0.0321	0.0335	0.0249	0.0157
0.0189	0.0195	0.0367	0.0513	0.0346	0.0445	0.0321	0.0200	0.0238	0.0248	0.0184
0.0048	0.0136	0.0119	0.0237	0.0368	0.0263	0.0347	0.0252	0.0158	0.0189	0.0196
0.0172	0.0155	0.0378	0.0231	0.0331	0.0425	0.0280	0.0357	0.0257	0.0160	0.0191
0.0012	0.0188	0.0149	0.0292	0.0151	0.0203	0.0255	0.0167	0.0213	0.0153	0.0096
0.0051	0.0030	0.0300	0.0120	0.0143	0.0060	0.0075	0.0093	0.0061	0.0077	0.0056
0.0027	0.0160	0.0058	0.0371	0.0123	0.0139	0.0057	0.0072	0.0089	0.0058	0.0074
0.0039	0.0101	0.0443	0.0115	0.0597	0.0178	0.0194	0.0079	0.0099	0.0122	0.0080
0.0037	0.0042	0.0078	0.0279	0.0067	0.0350	0.0107	0.0119	0.0049	0.0062	0.0076
0.0088	0.0130	0.0132	0.0178	0.0464	0.0089	0.0405	0.0115	0.0123	0.0050	0.0062
0.0103	0.0192	0.0171	0.0120	0.0139	0.0344	0.0065	0.0294	0.0083	0.0089	0.0036
0.0054	0.0164	0.0202	0.0154	0.0106	0.0123	0.0309	0.0059	0.0267	0.0076	0.0081
0.0077	0.0106	0.0272	0.0293	0.0205	0.0135	0.0154	0.0382	0.0072	0.0328	0.0093
0.0131	0.0091	0.0097	0.0192	0.0171	0.0107	0.0067	0.0074	0.0182	0.0034	0.0155
0.0011	0.0046	0.0042	0.0056	0.0121	0.0111	0.0070	0.0044	0.0048	0.0119	0.0022
0.0012	0.0035	0.0118	0.0078	0.0075	0.0138	0.0118	0.0073	0.0045	0.0050	0.0123
0.0023	0.0046	0.0085	0.0163	0.0069	0.0054	0.0091	0.0076	0.0046	0.0029	0.0032
0.0027	0.0029	0.0059	0.0098	0.0170	0.0068	0.0052	0.0086	0.0072	0.0044	0.0027
0.0021	0.0108	0.0073	0.0088	0.0101	0.0149	0.0057	0.0042	0.0071	0.0059	0.0036
0.0020	0.0050	0.0179	0.0084	0.0080	0.0084	0.0120	0.0045	0.0034	0.0056	0.0046
0.0046	0.0062	0.0102	0.0263	0.0104	0.0093	0.0095	0.0136	0.0051	0.0038	0.0063
0.0208	0.0167	0.0126	0.0134	0.0267	0.0092	0.0077	0.0077	0.0109	0.0041	0.0030
0.0054	0.0147	0.0142	0.0126	0.0145	0.0299	0.0104	0.0088	0.0088	0.0124	0.0047
0.0093	0.0124	0.0252	0.0182	0.0136	0.0144	0.0287	0.0099	0.0083	0.0083	0.0117
0.0053	0.0126	0.0128	0.0199	0.0125	0.0089	0.0092	0.0183	0.0063	0.0053	0.0053
0.0099	0.0117	0.0165	0.0126	0.0180	0.0111	0.0079	0.0082	0.0163	0.0056	0.0047
0.0050	0.0228	0.0206	0.0227	0.0150	0.0202	0.0122	0.0086	0.0089	0.0176	0.0061
0.0065	0.0101	0.0321	0.0214	0.0200	0.0124	0.0163	0.0098	0.0068	0.0071	0.0141
0.0035	0.0083	0.0142	0.0407	0.0241	0.0213	0.0128	0.0167	0.0100	0.0070	0.0073
0.0033	0.0104	0.0163	0.0170	0.0370	0.0201	0.0173	0.0104	0.0135	0.0081	0.0057
0.0025	0.0050	0.0110	0.0133	0.0126	0.0276	0.0153	0.0133	0.0080	0.0105	0.0063
0.0064	0.0097	0.0144	0.0213	0.0173	0.0127	0.0245	0.0129	0.0110	0.0066	0.0086
0.0043	0.0252	0.0259	0.0236	0.0237	0.0154	0.0103	0.0190	0.0098	0.0084	0.0050

Table 4.5: Yellowfin sole biomass estimates (t) from the annual Bering Sea shelf bottom trawl survey (top table) and northern Bering Sea surveys (bottom table) with upper and lower 95% confidence intervals.

1982	3,509,130	3,508,559	3,509,700
1983	3,672,420	3,672,015	3,672,824
1984	3,341,320	3,340,953	3,341,686
1985	2,398,080	2,397,771	2,398,388
1986	2,031,600	2,031,298	2,031,901
1987	2,511,840	2,511,457	2,512,222
1988	2,180,750	2,180,341	2,181,158
1989	2,313,620	2,313,280	2,313,959
1990	2,179,610	2,179,314	2,179,905
1991	2,391,860	2,391,585	2,392,134
1992	2,201,520	2,201,135	2,201,904
1993	2,468,430	2,468,119	2,468,740
1994	2,597,190	2,596,851	2,597,528
1995	2,012,400	2,012,117	2,012,682
1996	2,216,500	2,216,118	2,216,881
1997	2,161,400	2,161,147	2,161,652
1998	2,210,180	2,209,904	2,210,455
1999	1,257,180	1,257,000	1,257,359
2000	1,589,780	1,589,581	1,589,978
2001	1,679,520	1,679,280	1,679,759
2002	1,910,070	1,909,812	1,910,327
2003	2,158,130	2,157,723	2,158,536
2004	2,542,070	2,541,689	2,542,450
2005	2,820,840	2,820,125	2,821,554
2006	2,132,480	2,132,168	2,132,791
2007	2,153,090	2,152,712	2,153,467
2008	2,099,670	2,099,169	2,100,170
2009	1,739,430	1,739,132	1,739,727
2010	2,368,260	2,367,710	2,368,809
2011	2,403,220	2,402,743	2,403,696
2012	1,951,410	1,951,137	1,951,682
2013	2,279,020	2,278,678	2,279,361
2014	2,512,260	2,511,805	2,512,714
2015	1,932,350	1,932,064	1,932,635
2016	2,859,810	2,859,485	2,860,134
2017	2,787,520	2,787,162	2,787,877
2018	1,892,920	1,892,693	1,893,146

Table 4.8: Total tonnage of yellowfin sole caught in resource assessment surveys in the eastern Bering Sea from 1977-2018.

2006	0
2007	5
2010	118m616
2011	100m987
2012	83m402
2013	75m077
2014	82m575
2015	64m981
2016	97m871
2017	112m159

Table 4.10: Female yellowfin sole proportion mature at age from Nichol (1995) and TenBrink and Wilderbuer (2015).

Age	1992, 1993 samples	2012 samples	Combined
1	0.000	0.00	0.00
2	0.000	0.00	0.00
3	0.001	0.00	0.00
4	0.004	0.00	0.00
5	0.008	0.00	0.00
6	0.020	0.01	0.01
7	0.046	0.03	0.04
8	0.104	0.09	0.10
9	0.217	0.21	0.21
10	0.397	0.43	0.41
11	0.612	0.68	0.65
12	0.790	0.86	0.83
13	0.899	0.94	0.92
14	0.955	0.98	0.97
15	0.981	0.99	0.99
16	0.992	1.00	1.00
17	0.997	1.00	1.00
18	1.000	1.00	1.00
19	1.000	1.00	1.00
20	1.000	1.00	1.00

Table 4.11: Key equations used in the population dynamics model.

Total mortality Z in the model is the sum of fishing mortality F and natural mortality M, such that total mortality in year t at age a is $Z_{t,a} = F_{t,a} + M$. Fishing mortality at each year and age $F_{t,a}$ is the product of age-specific fishing gear selectivity s_a and the median year-effect of fishing mortality μ^F, with normally distributed error, $F_{t,a} = s_a \mu^F e^{\epsilon_t^F}, \epsilon_t^F \backsim N(0, \sigma_F^2)$, where ϵ_t^F is the residual year-effect of fishing mortality and σ_F is the standard deviation of the residual year-effect of fishing mortality.

Recruitment 1956-1975: $N_{t,1} = R_t = R_0 e^{\tau_t}, \tau \backsim N(0, \delta_R^2)$, where R_0 is the geometric mean of age 1 recruitment, 1956-1975.

Recruitment 1976-2018 was determined using the Ricker stock recruitment curve, $R = \alpha S e^{-\beta S}$, with parameters determined using data from the period 1976-2012.

$N_{t,1} = R_t = R_\gamma e^{\tau_t}$, where R_γ is the geometric mean value of age 1 recruitment, 1976-2014.

Catch in year t for age a fish: $C_{t,a} = \dfrac{F_{t,a}}{Z_{t,a}}(1 - e^{Z_{t,a}})N_{t,a}$, where C is catch, F is instantaneous annual fishing mortality, Z is instantaneous total mortality, and N is the number of fish.

Number of fish in year $t+1$ at age a: $N_{t+1,a+1} = N_{t,a} e^{-Z_{t,a}}$.

Number of fish in the "plus group": $N_{t+1,A} = N_{t,a} e^{-Z_{t,A-1}} + N_{t,A} e^{-Z_{t,A}}$.

Spawning biomass: $S_t = \sum N_{t,a} W_{t,a} \phi_a$, where ϕ_a is the proportion of mature females at age a and $W_{a,t}$ is the mean body weight in kg of fish age a in year t.

The age-specific fishing selectivity

$Length = \dfrac{S_{inf}}{1 + e^{-K*(age - t_0))}}$.

Figures

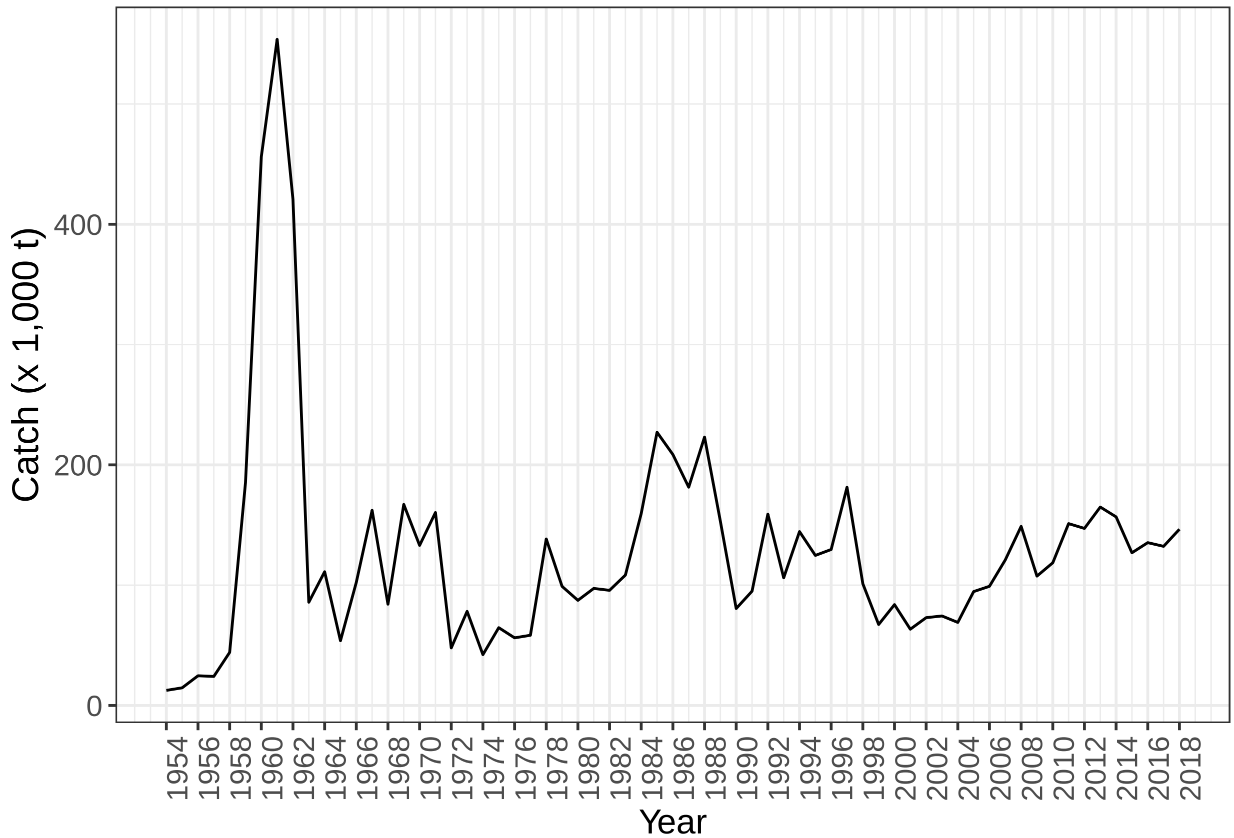


Figure 4.1: Yellowfin sole annual catch (1,000s t) in the Eastern Bering Sea from 1954-2018 (top panel) and catch by week (non CDQ) in 2018 through mid-September (bottom panel).

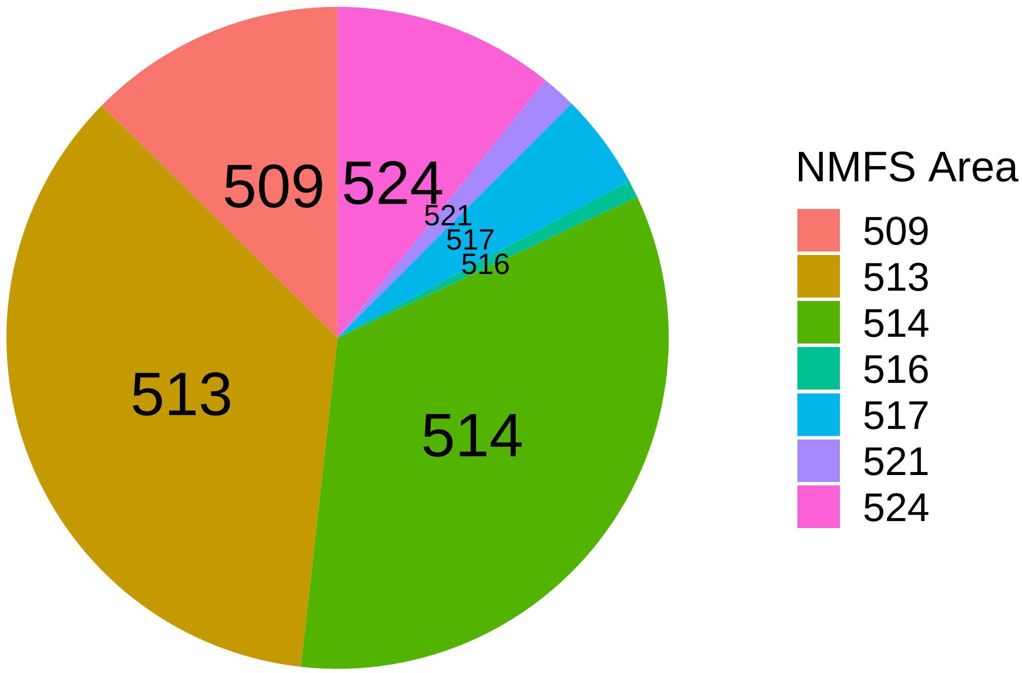


Figure 4.3: Yellowfin sole catch by month and area in the Eastern Bering Sea in 2018.

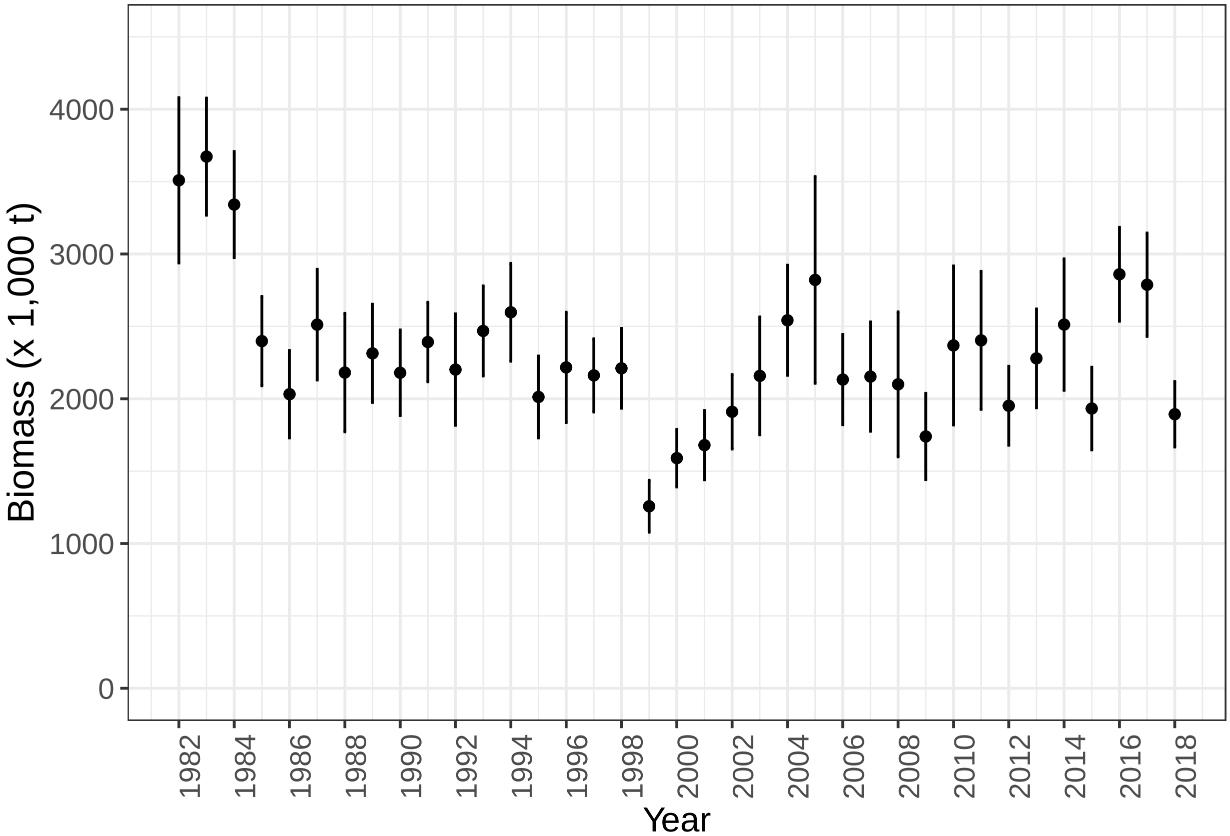


Figure 4.6: Annual eastern Bering Sea bottom trawl survey biomass point-estimates and 95% confidence intervals for yellowfin sole, 1982-2018.

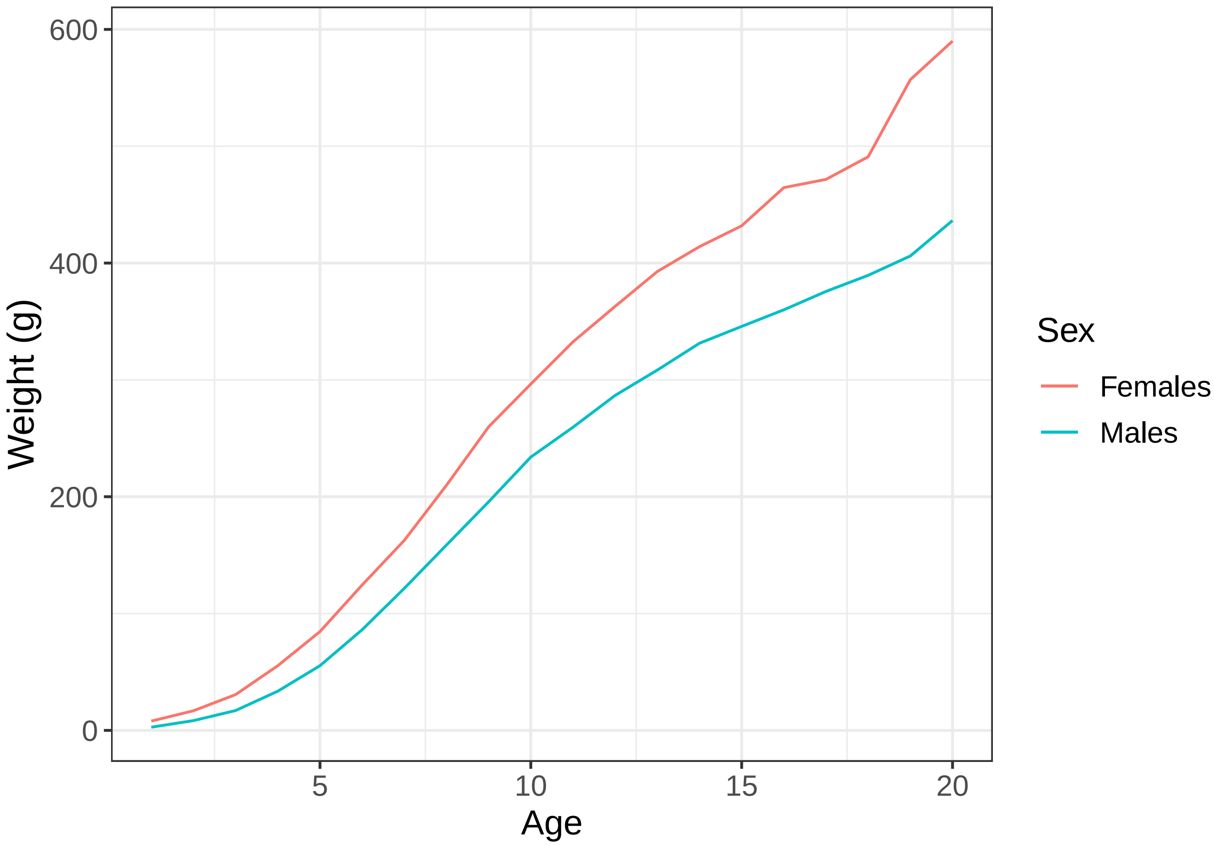


Figure 4.8: Average yellowfin sole weight-at-age (g) from trawl survey observations.

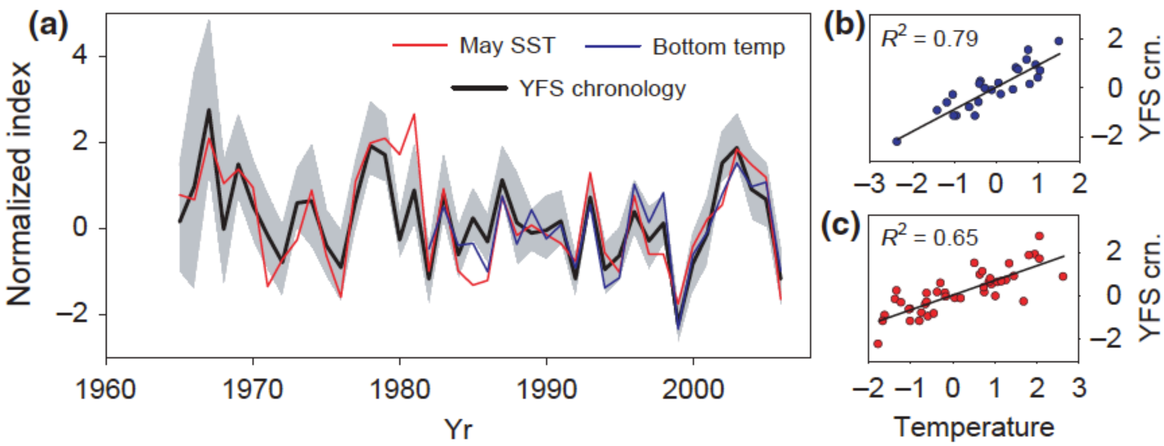


Figure 4.9: Master chronology for yellowfin sole and time series of mean summer bottom temperature and May sea surface temperature for the southeastern Bering Sea (Panel A). All data re normalized to a mean of 0 and standard deviation of 1. Correlations of chronologies with bottom temperature and sea surface temperature are shown in panels B and C, respectively (Matta et al. 2010)

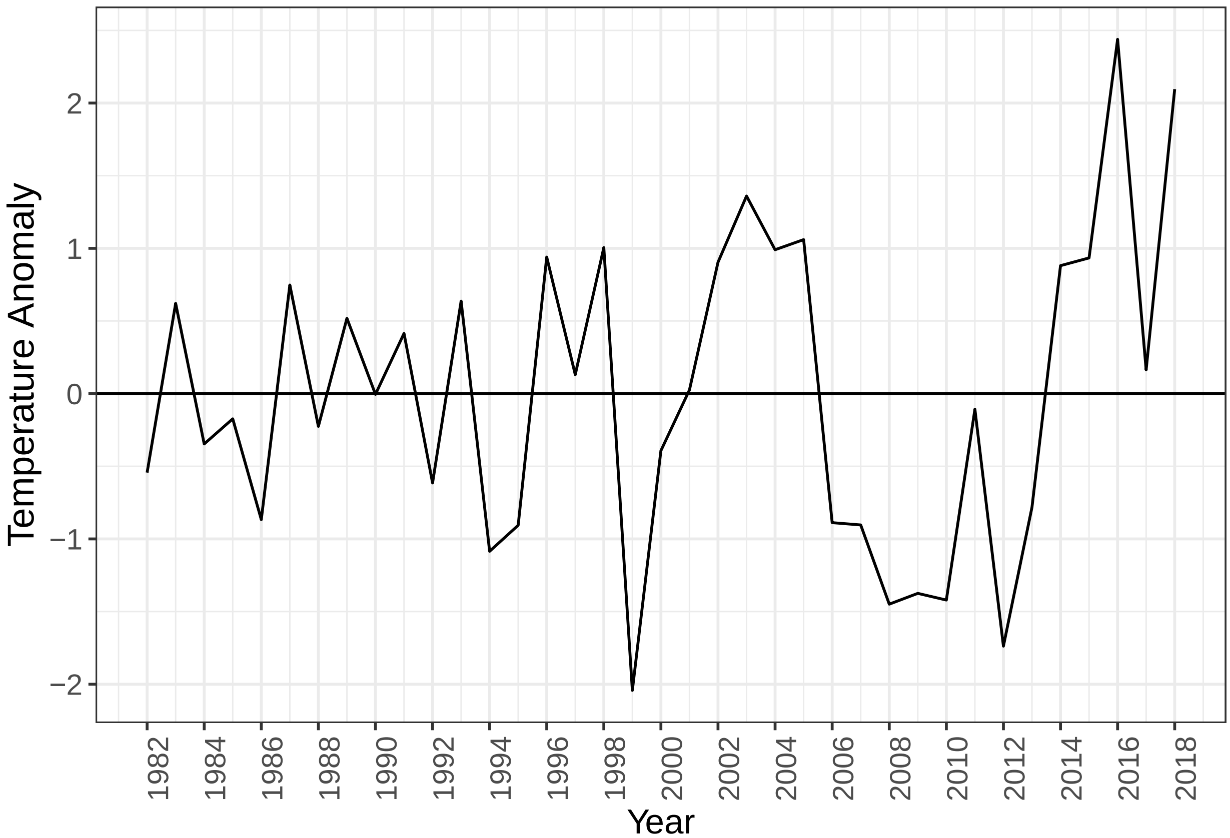
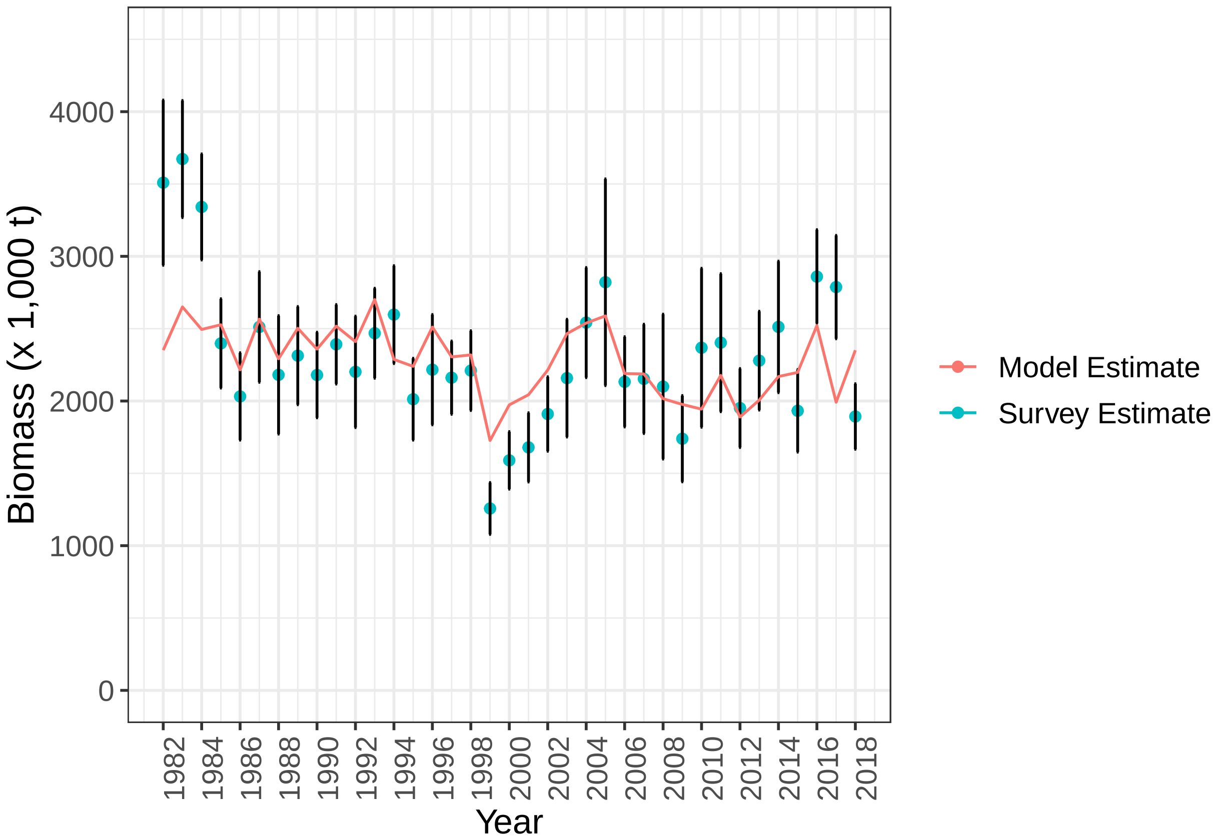
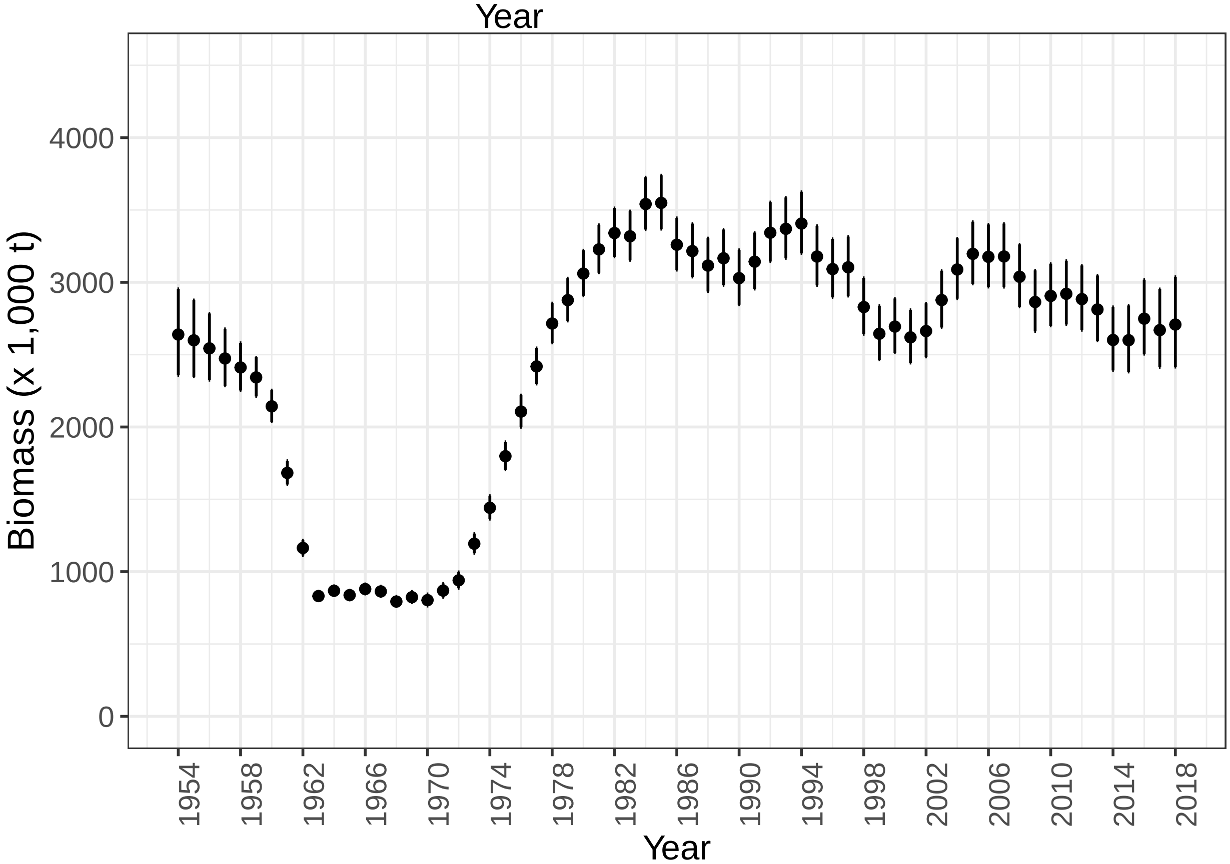


Figure 4.10: Yellowfin sole length-at-age anomalies, for males and females, and bottom temperature anomalies. Correspondence in these residuals is apparent with a 2-3 year lag effect from the mid-1990s to 2017. Late 1980s and early 1990s pattern may be a density-dependent response in growth from the large 1981 and 1983 year-classes.


Biomass (x 1,000 t)
4000
3000
2000
1000
0
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
Year
Model Estimate
Survey Estimate


Biomass (x 1,000 t)
4000
3000
2000
1000
0
1954
1958
1962
1966
1970
1974
1978
1982
1986
1990
1994
1998
2002
2006
2010
2014
2018
Year

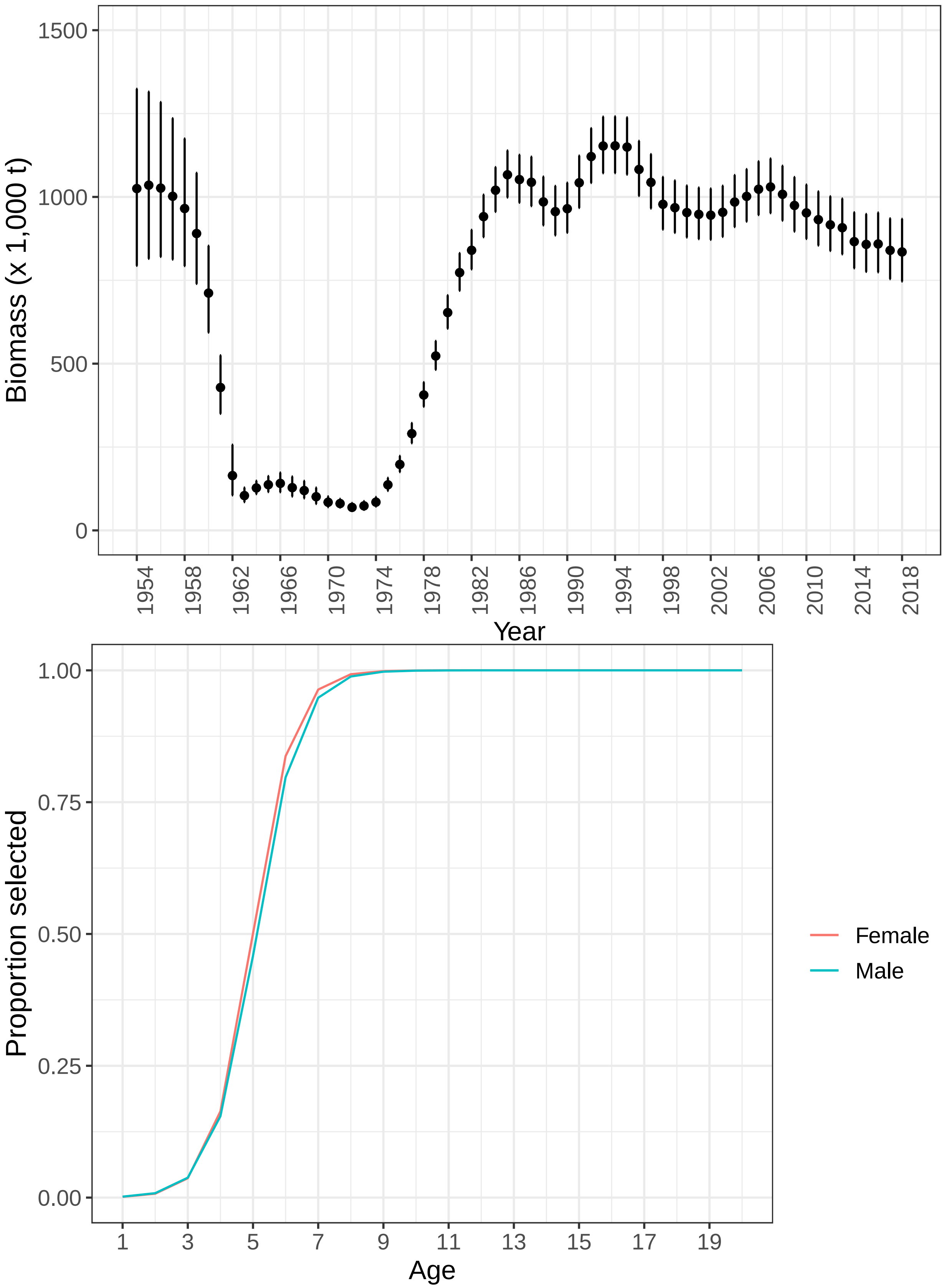


Figure 4.16: Model fit to the survey biomass estimates (top left panel), model estimate of the full selection

fishing mortality rate throughout the time-series (top right panel), model estimate of total biomass (middle left panel), the model estimate of survey selectivity (middle right panel) and the estimate of female spawning biomass (bottom left panel).