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

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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 2019 NMFS eastern Bering Sea shelf bottom-trawl survey biomass estimates and standard error were included.
2. The 2018 fishery age composition was included.
3. The 2018 survey age composition was included.
4. Estimates of the retained and discarded portions of the 2018 catch were added.
5. The estimate of the total catch made through the end of 2020 was used. Catch of 150,000 t was assumed for the 2020 and 2021 projections.

Changes in the assessment methods

Two models are considered in this assessment. 1. The model used in the 2018 assessment is referred to as Model 18.1. 2. Model 18.1 used the same natural mortality for males and females, M=0.12. A second model is presented (Model 18.2) that used a fixed value for female natural mortality (M=0.12) and allowed male natural mortality to be estimated by within the model. Model 18.2 was the preferred model.

Summary of Results

A new base model (18.1) and several variants were introduced in 2018, motivated in part by an unexpected 32% decrease in the survey biomass. Model 18.1 includes the survey mean bottom temperature across stations < 100m as a covariate on survey catchability, as in previous years, but adds survey start date as an additional covariate within the model, based on a recent study by Nichol et al. (2018). In 2019 a new model called Model 18.2 that was based on Model 18.1 was introduced that retains female natural mortality fixed at 0.12, but allows the model to estimate male natural mortality.

Although total biomass and spawning biomass have been declining slowly since 1994, spawning biomass estimated by the new model remains high at 1.85 * BMSY. Therefore, Yellowfin Sole continues to qualify for management under Tier 1a. As in recent years, the 1978-2012 age-1 recruitments and the corresponding spawning biomass estimates were used to determine the Tier 1 harvest recommendations. The SSC supports this time period for determining stock productivity and agrees with the authors' and PT's recommendations for ABC and OFL under Tier 1a.

This assessment updates last year's with results and management quantities that are lower than the 2018 assessment primarily due to 1) the 2019 survey biomass point estimate is 32% lower than the 2018 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).

Quantity	As estimated or *specified last* year for: 2019	2020	As estimated or *recommended this* year for: 2020	2021
M (natural mortality rate)	0.12	0.12	0.12, 0.135	0.12,0.135
Tier	1a	1a	1a	1a
Projected total (age 6+) biomass (t)	2,388,000 t	2,331,500 t	2,690,080 t	2,577,430 t
Projected female spawning biomass (t)	827,900 t	796,600 t	1,007,780 t	901,877 t
$B_{100\%}$	1,236,000 t	1,236,000 t	1,500,060 t	1,500,060 t
$B_{MSY\%}$	451,600 t	451,600 t	541,737 t	541,737 t
F_{OFL}	0.118	0.118	0.117	0.117
$maxF_{ABC}$	0.107	0.107	0.108	0.108
F_{ABC}	0.107	0.107	0.108	0.108
OFL	281,800 t	275,100 t	315,785 t	302,561 t
$maxABC$	255,100 t	249,100 t	290,690 t	278,517 t
ABC	255,100 t	249,100 t	290,690 t	278,517 t
Status	2017	2018	2018	2019
Overfishing	No	n/a	No	n/a
Overfished	n/a	No	n/a	No
Approaching overfished	n/a	No	n/a	No

Projections are based on estimated catches of 150,000 t used in place of maximum ABC for 2020 and 2021.

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 2018.

Responses to SSC and Plan Team Comments Specific to this Assessment

1. The SSC encourages further exploration of the way mortality is handled in the model, for example through the use of sex-specific or time-varying mortality and the authors noted that they may be able to explore this more fully in 2019.

Authors' response

In the current assessment, a model was explored that used a fixed value for female natural mortality, and allowed male natural mortality to be estimated by within the model (Model 18.2).

2. Given recent changes in the distribution of other species, the SSC encourages authors to explore variability over time in the proportion of the stock that occurs in the Northern Bering Sea. While the model may account for this portion of the stock through the catchability parameter this assumes that the fraction of the biomass occurring in the NBS has not changed substantially. There is little evidence for a change in the NBS biomass within the area that was surveyed in all three years, but this does not account for the possibly large fraction of Yellowfin Sole in nearshore areas that were not surveyed in 2018. The SSC suggests a few avenues to explore possible changes in distribution of Yellowfin Sole, including a comparison of the full NBS survey area between 2010 and 2017, the application of the VAST model to estimate the proportion of Yellowfin Sole in the NBS over time, and an examination of other available data sources, in particular the ADF&G survey in Norton Sound that has been conducted triennially since 1978 and annually since 2017. The SSC encourages the authors to consider approaches for including the substantial biomass of NBS Yellowfin Sole in the model, with the expectations that NBS surveys will be conducted regularly in the future.

Authors' response

The distribution of Yellowfin Sole in the eastern Bering Sea is shown in Figure 4.1, based on results from the four most recent NBS surveys. There does not appear to be a large shift in distribution since 2010. The distribution of Yellowfin Sole will continue to be monitored and approaches for including the substantial biomass of Yellowfin Sole in the NBS will be considered in future assessments.

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. 49°N) to the Chukchi Sea (about lat. 70°N) and south along the Asian coast off the South Korean coast in the Sea of Japan (to about lat. 35°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 - 2019
Fishery age composition	1964 - 2018
Fishery weight-at-age	Avg wt at age from 2008-16 used for 2008-2019
Survey biomass and standard error	1982 - 2019
bottom temperature	1982 - 2019
Survey age composition	1979 - 2018
Annual length-at-age and weight-at-age from surveys	1979 - 2018
Age at maturity	Combined 1992 and 2012 samples

Fishery Catch and Catch-at-Age

This assessment uses fishery catch data from 1954-2019 (Table 4.1), and fishery catch-at-age (proportions) from 1964-2018 (Table 4.4, 1975-2018). The fishery age composition has always been primarily composed of fish older than 9 years with a large amount of 20+ fish, although the proportion has declined from 90% over age 7 to 70% over age 7 since the 1970's.

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 implementation of the MFCMA in 1977 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).

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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 2019, 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 2019, the fishing season is ongoing. In order to estimate the total 2019 catch for the stock assessment model, the average proportion of the 2011-2018 cumulative catch attained by the 35th week of the year (mid-September) was applied to the 2019 catch amount at the same time period and results in a 2019 catch estimate of 154,200 t (53.05% of the ABC). The size composition of the 2019 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. Maps of the locations where Yellowfin Sole were caught in 2019, by month (through mid-September), are shown in Figure 4.4. The average age of Yellowfin Sole in the 2018 catch is estimated at 13.36 and 12.84 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 2018 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, 2018, and 2019. The trawl surveys conducted in 2010, 2017, and 2019 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. Large shifts in the abundance of Yellowfin Sole into the Bering Sea have not been observed (Figure 4.1), but the spatial distribution will continue to be monitored as shifts may occur under future climate change.

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 was 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 was 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.

Total mortality Z in the model was modeled as 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, $F_{t,a}$, was 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 fishing mortality. Age-specific fishing selectivity s_a was calculated using the logistic equation

$$s_a = \frac{1}{1 + e^{(-\alpha + age\beta)}}.$$

Catch in year t for age a fish $C_{t,a}$ was calculated:

$$C_{t,a} = \frac{F_{t,a}}{Z_{t,a}}(1 - e^{Z_{t,a}})N_{t,a},$$

where $N_{t,a}$ is the number of fish at time t, age a. Total catch in each year C_t was the sum of catch over all ages, $C_t = \sum_a C_{t,a}$, and the proportion at age in catch was $P_{t,a} = \dfrac{C_{t,a}}{C_t}$.

Recruitment from 1956-1975 was modeled as $N_{t,1} = R_t = R_0 e^{\tau_t}, \tau_t \backsim N(0, \sigma_R^2)$, where R_0 is the geometric mean of the modeled age 1 recruitment from 1956-1975, and σ_R is the standard deviation of recruitment.

Recruitment from 1976-2019 was determined using the Ricker stock recruitment curve,

$$R = \alpha S e^{-\beta S}.$$

Parameters α and β were estimated by fitting spawning biomass and recruitment during the period 1976-2013.

The number of fish in year $t+1$ at age a was the number of fish in the previous year subjected to natural and fishing mortality,

$$N_{t+1,a+1} = N_{t,a} e^{-Z_{t,a}}.$$

The number of fish in a "plus group" which included all fish age 20 and older included fish surviving from age 19 as well as those age 20 and higher,

$$N_{t+1,A} = N_{t,a} e^{-Z_{t,A-1}} + N_{t,A} e^{-Z_{t,A}}.$$

Spawning biomass was calculated as the product of weight at age and the number of mature females at each age,

$$S_t = \sum N_{t,a} W_{t,a} \phi_a,$$

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. Survey biomass was assumed to be the product of catchability q, survey selectivity s_a, and the biomass,

$$Biomass_{survey,t} = q \sum N_{t,a} W_{t,a} s_a.$$

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 2019 catch, the fishery and survey age compositions from 2018 and the 2019 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 2020 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

Risk assessment table

Assessment related considerations

The BSAI Yellowfin Sole assessment is based on surveys conducted annually on the EBS shelf from 1982-2018 (no skipped years). Fish ages, derived from otoliths collected during the surveys and the fishery to calculate annual estimates of population and fishery age composition, have been validated. The assessment model exhibits good fits to all compositional and abundance data and converges to a single minima in the likelihood surface. Recruitment estimates track strong year classes that are consistent with the data.

The retrospective pattern from the current assessment model was less than desirable and has been the subject of some concern for the assessment. 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. However, the best retrospective patterns do not occur at the corresponding values of best overall model fit of M and q (which occur at higher levels of M and q). 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.

Population dynamics considerations

Stock assessment 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. 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, although the 2006-2010 year-classes all look about average according to the 2018 stock assessment. The present biomass is estimated at 78% of the peak 1985 level and is at twice the level of BMSY. Projections indicate that the FSB will remain well-above the BMSY level through 2028. Population dynamics are not a concern for this assessment.

Environmental/ecosystem considerations

It is unknown how particular environmental factors affect the sustainability of Yellowfin Sole. It has been demonstrated that the migration to spawning grounds and subsequent spawning occurs sooner in warm years. Somatic growth has also been shown to increase in warmer temperatures. The prey field for this species consists primarily of polycheate worms and clam siphons, species whose distribution and abundance patterns relative to a changing environment are unknown. It is also unknown what effect environmental variability has on the distribution of Yellowfin Sole predators. Given the high level of sustained abundance of this species, there is a low level of concern for a variable environment, at least for the levels observed over the past 40 years. These results are summarized in the table below.

Fishery performance considerations

Recent surveys of the northern Bering sea have not indicated a large shift in the spatial distribution of the eastern Bering Sea stock of Yellowfin Sole. If the stock moves northward out of the eastern Bering Sea under climate change into untrawlable areas in the northern Bering sea, then fisheries would be unable to target the stock in the untrawlable zone. A NOAA Coastal and Oceans Climate Applications proposal will be submitted examine the implications to the fishery and the region of the northern Bering Sea if the stock of Yellowfin Sole shifts northward. At the current time, fishery CPUE is not showing a contrasting pattern from the stock biomass trend, unusual spatial pattern of fishing, or changes in the percent of TAC taken, changes in the duration of fishery openings.

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 2019 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 2020 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 2020 biomass estimate.

The geometric mean of the 2020 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 2020 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 2020 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 2020 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 2020. 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 2018 to 2019.

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	2020 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 2019 numbers at age estimated in the assessment. This vector is then projected forward to the beginning of 2020 using the schedules of natural mortality and selectivity described in the assessment and the best available estimate of total (year-end) catch for 2019. 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 2020, 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 2020. (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 2014-2019 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 2020 and 2021, 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 2032 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 2032 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.

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Tables

Table 4.19: Foreign and domestic datch (t) of Yellowfin Sole 1954-2019. Foreign catches are designated as joint venture processing (JVP) and domestic annual processing (DAP). Catch for 2019 was downloaded October 28, 2019.

		Domestic		
Year	Foreign	JVP	DAP	Total
1954	12,562			12,562
1955	14,690			14,690
1956	24,697			24,697
1957	24,145			24,145
1958	44,153			44,153
1959	185,321			185,321
1960	456,103			456,103
1961	553,742			553,742
1962	420,703			420,703
1963	85,810			85,810
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	156,772	156,772
2015	126,936	126,936
2016	135,345	135,345
2017	132,265	132,265
2018	131,543	131,543
2019	109,620	109,620

Table 4.20: Estimates of retained and discarded (t) Yellowfin Sole caught in Bering Sea fisheries through September 25th, 2019, 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 4.21: Discarded and retained catch of non-CDQ Yellowfin Sole, by fishery, in 2018. 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.

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

Table 4.22: Yellowfin Sole fishery catch-at-age (proportions), 1975-2018 (female), ages 7-17+.

Year	7	8	9	10	11	12	13	14	15	16	17+	Total proportion over age 7
1975	0.1154	0.2903	0.2757	0.1205	0.0536	0.0263	0.0200	0.0235	0.0064	0.0056	0.0035	0.9408
1976	0.0976	0.1620	0.2627	0.2095	0.0920	0.0421	0.0210	0.0160	0.0189	0.0051	0.0045	0.9314
1977	0.1758	0.1966	0.1569	0.1367	0.0739	0.0272	0.0117	0.0057	0.0043	0.0051	0.0014	0.7953
1978	0.0935	0.2054	0.2284	0.1668	0.1339	0.0687	0.0246	0.0104	0.0050	0.0038	0.0045	0.9450
1979	0.0607	0.1432	0.2203	0.1943	0.1283	0.0996	0.0505	0.0180	0.0076	0.0037	0.0028	0.9290
1980	0.0623	0.0697	0.1318	0.1892	0.1706	0.1173	0.0939	0.0486	0.0175	0.0074	0.0036	0.9119
1981	0.0761	0.0987	0.0938	0.1451	0.1738	0.1378	0.0878	0.0673	0.0341	0.0121	0.0051	0.9317
1982	0.0586	0.1356	0.1361	0.0990	0.1261	0.1350	0.1010	0.0626	0.0474	0.0239	0.0085	0.9338
1983	0.0943	0.1015	0.1605	0.1250	0.0804	0.0973	0.1021	0.0759	0.0469	0.0355	0.0179	0.9373
1984	0.0350	0.0957	0.1000	0.1578	0.1234	0.0796	0.0965	0.1014	0.0754	0.0466	0.0353	0.9467
1985	0.0200	0.0570	0.1198	0.1026	0.1470	0.1108	0.0707	0.0853	0.0895	0.0665	0.0411	0.9103
1986	0.0521	0.0531	0.0990	0.1392	0.0948	0.1230	0.0893	0.0562	0.0675	0.0707	0.0525	0.8974
1987	0.0173	0.0484	0.0419	0.0838	0.1309	0.0946	0.1259	0.0923	0.0583	0.0702	0.0735	0.8371
1988	0.0493	0.0442	0.1056	0.0635	0.0911	0.1179	0.0786	0.1013	0.0734	0.0462	0.0555	0.8266
1989	0.0049	0.0783	0.0613	0.1198	0.0624	0.0847	0.1077	0.0714	0.0920	0.0667	0.0419	0.7911
1990	0.0388	0.0229	0.2256	0.0918	0.1107	0.0468	0.0594	0.0742	0.0490	0.0630	0.0456	0.8278
1991	0.0174	0.1029	0.0370	0.2421	0.0810	0.0923	0.0386	0.0489	0.0612	0.0404	0.0519	0.8137
1992	0.0157	0.0398	0.1730	0.0446	0.2319	0.0694	0.0756	0.0311	0.0392	0.0489	0.0322	0.8014
1993	0.0216	0.0249	0.0459	0.1641	0.0398	0.2096	0.0644	0.0717	0.0299	0.0380	0.0475	0.7574
1994	0.0377	0.0555	0.0564	0.0763	0.2003	0.0388	0.1773	0.0504	0.0539	0.0220	0.0277	0.7963
1995	0.0495	0.0911	0.0824	0.0589	0.0684	0.1705	0.0325	0.1480	0.0420	0.0449	0.0184	0.8066
1996	0.0258	0.0781	0.0971	0.0745	0.0516	0.0603	0.1517	0.0291	0.1327	0.0378	0.0404	0.7791
1997	0.0275	0.0376	0.0965	0.1038	0.0724	0.0477	0.0545	0.1357	0.0259	0.1180	0.0335	0.7531
1998	0.0756	0.0528	0.0566	0.1129	0.1016	0.0641	0.0403	0.0449	0.1108	0.0210	0.0957	0.7763
1999	0.0107	0.0441	0.0403	0.0536	0.1189	0.1108	0.0705	0.0443	0.0495	0.1220	0.0232	0.6879
2000	0.0096	0.0276	0.0927	0.0618	0.0606	0.1132	0.0983	0.0611	0.0381	0.0424	0.1045	0.7099
2001	0.0210	0.0423	0.0783	0.1536	0.0666	0.0521	0.0887	0.0746	0.0459	0.0285	0.0317	0.6833
2002	0.0247	0.0254	0.0513	0.0882	0.1590	0.0655	0.0501	0.0845	0.0709	0.0435	0.0271	0.6902
2003	0.0186	0.0932	0.0632	0.0774	0.0913	0.1372	0.0529	0.0396	0.0664	0.0556	0.0341	0.7295
2004	0.0181	0.0441	0.1592	0.0763	0.0744	0.0792	0.1146	0.0437	0.0325	0.0545	0.0456	0.7422
2005	0.0303	0.0404	0.0665	0.1750	0.0704	0.0642	0.0669	0.0963	0.0367	0.0273	0.0458	0.7198
2006	0.1113	0.0913	0.0700	0.0747	0.1503	0.0526	0.0449	0.0455	0.0647	0.0245	0.0182	0.7480
2007	0.0279	0.0750	0.0736	0.0667	0.0775	0.1618	0.0575	0.0493	0.0500	0.0712	0.0270	0.7375
2008	0.0420	0.0562	0.1139	0.0842	0.0638	0.0682	0.1375	0.0482	0.0411	0.0417	0.0592	0.7560
2009	0.0326	0.0768	0.0800	0.1244	0.0797	0.0570	0.0598	0.1197	0.0419	0.0357	0.0362	0.7438
2010	0.0570	0.0671	0.0963	0.0759	0.1085	0.0685	0.0490	0.0515	0.1031	0.0361	0.0308	0.7438
2011	0.0233	0.1021	0.0939	0.1055	0.0716	0.0957	0.0589	0.0418	0.0437	0.0875	0.0306	0.7546
2012	0.0292	0.0469	0.1470	0.1014	0.0971	0.0618	0.0809	0.0494	0.0350	0.0366	0.0731	0.7584
2013	0.0145	0.0340	0.0600	0.1717	0.1054	0.0945	0.0585	0.0757	0.0461	0.0325	0.0340	0.7269
2014	0.0152	0.0452	0.0711	0.0780	0.1679	0.0934	0.0815	0.0501	0.0647	0.0394	0.0278	0.7343
2015	0.0144	0.0283	0.0599	0.0728	0.0726	0.1560	0.0880	0.0775	0.0478	0.0619	0.0377	0.7169
2016	0.0335	0.0487	0.0719	0.1030	0.0859	0.0672	0.1286	0.0693	0.0601	0.0369	0.0476	0.7527
2017	0.0207	0.1153	0.1134	0.1043	0.1031	0.0699	0.0498	0.0920	0.0489	0.0422	0.0258	0.7854
2018	0.0076	0.0293	0.1386	0.1184	0.1009	0.0968	0.0651	0.0462	0.0853	0.0453	0.0391	0.7726

Table 4.23: 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.

Year	Biomass (t)	Lower confidence interval	Upper confidence interval
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
2019	2,006,510	2,006,096	2,006,923

Table 4.24: Yellowfin Sole population numbers-at-age (millions) estimated from the annual EBS bottom trawl surveys, 1982-2019. Numbers-at-age from 1982-1986 come from the standard survey area, and years 1987 forward come from the 'plusnw' extended survey area. Females are presented first, followed by males.

Year	Age (Females)															
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17+
1987	0	0	68	116	781	443	816	250	362	576	341	431	232	259	237	173
1988	0	0	6	341	64	1,354	497	495	163	213	315	186	323	245	196	151
1989	0	0	14	97	715	233	1,333	592	446	74	179	307	234	238	183	82
1990	0	0	69	101	324	1,065	192	1,257	408	481	101	71	107	78	230	126
1991	0	9	126	247	122	404	894	150	1,261	212	524	62	127	86	122	163
1992	0	18	238	461	495	202	273	895	90	789	72	295	123	130	162	103
1993	0	24	99	357	635	434	268	224	1,315	78	867	156	165	68	67	91
1994	0	53	94	221	515	900	552	479	283	1,164	0	513	43	272	141	41
1995	0	18	152	288	181	890	628	275	135	24	634	20	561	104	80	96
1996	0	15	149	787	278	269	419	498	198	140	146	579	112	613	44	28
1997	0	17	323	502	724	255	238	505	228	113	176	183	499	43	313	75
1998	0	9	78	451	399	854	246	193	351	391	350	161	166	251	63	395
1999	0	3	61	188	166	177	699	100	103	236	183	179	69	98	169	101
2000	0	11	54	247	208	304	445	540	190	198	238	220	65	117	145	109
2001	0	1	65	219	474	223	361	369	581	332	73	171	137	113	169	99
2002	0	15	118	162	241	742	323	271	214	431	208	85	289	109	142	136
2003	0	15	113	234	241	276	1,104	217	268	275	241	98	110	162	160	82
2004	10	33	195	438	568	415	217	971	223	212	220	221	107	20	168	186
2005	0	52	166	194	584	412	230	471	873	220	136	183	334	163	50	180
2006	8	67	301	375	276	634	470	176	325	737	132	132	70	156	175	1
2007	0	37	514	346	381	274	502	307	123	226	503	119	137	126	104	76
2008	0	23	114	735	620	542	355	359	195	127	253	353	150	78	85	118
2009	5	37	203	203	1,189	596	491	264	210	218	129	138	196	88	43	1
2010	0	32	327	386	438	895	554	516	329	335	154	166	135	172	99	49
2011	0	14	243	539	706	463	769	410	456	204	226	148	141	144	186	98
2012	9	49	229	394	504	293	243	753	256	334	106	156	36	150	128	149
2013	0	4	88	268	419	531	256	220	408	405	358	119	134	132	132	94
2014	0	0	36	420	383	248	419	231	228	523	340	160	144	228	34	122
2015	0	22	3	167	466	349	307	287	249	149	282	258	134	99	80	67
2016	0	32	71	45	163	743	565	403	363	300	143	244	229	140	162	169
2017	16	78	381	378	121	317	1,001	481	335	377	228	148	202	200	148	117
2018	0	49	181	260	177	91	263	638	325	230	81	76	41	124	99	103

Year	Age (Males)														
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17+
1987	0	4	39	103	813	453	650	427	314	264	201	140	101	135	176	209
1988	0	1	9	410	45	1,079	503	403	77	170	25	161	305	172	25	105
1989	0	2	23	180	783	176	1,301	511	355	134	49	103	53	203	35	38
1990	0	10	47	120	316	888	194	1,144	317	263	39	64	66	23	54	72
1991	0	0	102	353	139	274	1,043	67	1,135	328	243	74	64	60	52	91
1992	0	0	140	425	538	250	214	773	109	869	184	204	11	12	59	37
1993	0	20	52	233	646	393	278	246	1,096	69	842	52	53	50	0	48
1994	4	21	70	165	424	947	652	305	189	817	25	618	45	131	11	36
1995	0	0	168	119	270	667	565	94	179	75	477	13	603	49	24	77
1996	0	73	92	815	236	219	411	332	319	136	134	385	58	433	120	91
1997	0	9	214	425	797	180	183	445	245	194	213	108	514	78	264	30
1998	0	45	66	332	542	791	150	213	192	256	326	141	148	177	106	248
1999	0	5	95	134	214	232	551	140	90	297	258	71	51	27	114	33
2000	0	0	35	218	259	143	511	585	78	215	133	76	92	78	66	152
2001	0	0	80	129	598	307	339	321	509	189	79	143	59	66	128	54
2002	0	55	70	151	295	721	301	313	246	416	182	133	205	149	123	19
2003	0	23	92	172	248	242	1,038	229	351	51	275	167	9	69	55	103
2004	4	63	115	473	451	200	397	998	265	82	196	224	103	47	250	104
2005	0	48	166	178	450	455	238	295	999	122	138	117	130	67	91	125
2006	0	100	172	347	331	504	393	287	298	383	116	154	89	38	11	54
2007	0	57	480	351	405	283	545	209	165	266	334	99	131	69	59	122
2008	0	10	99	661	462	483	344	452	225	144	184	329	62	65	34	103
2009	0	64	144	290	952	464	544	247	249	216	78	31	195	29	28	50
2010	0	77	199	418	370	1,032	462	509	171	188	159	52	116	151	78	53
2011	0	6	149	384	482	357	791	398	224	176	77	80	136	102	156	96
2012	0	69	273	352	345	275	239	426	297	179	98	67	90	34	100	59
2013	0	6	91	365	383	481	210	267	444	199	200	33	88	99	117	18
2014	0	0	8	365	396	285	338	310	250	399	206	192	19	191	94	107
2015	0	28	35	130	426	332	301	312	317	47	179	130	80	0	79	110
2016	0	43	84	20	141	704	544	401	366	125	117	226	180	88	35	91
2017	9	120	231	396	106	260	880	498	310	275	194	107	215	155	37	12
2018	0	39	173	187	227	71	234	520	259	187	95	76	72	74	68	29

Table 4.25: Comparison of likelihood values for survey and fishery age, selectivity, survey biomass, recruitment, and total likelihood for Models 18.1 and 18.2.

Likelihood component	Model 18.1	Model 18.2
Survey age	590.07	560.39
Fishery age	648.68	610.42
Selectivity	64.04	64.07
Survey biomass	91.88	94.94
Recruitment	27	28.15
Total	1421.68	1357.97

Table 4.26: Comparison of reference points using Model 18.1 and Model 18.2.

	Model 18.2		Model 18.1	
Quantity	2020	2021	2020	2021
M (natural mortality rate)	0.12	0.12	0.12, 0.135	0.12, 0.135
Tier	1a	1a	1a	1a
Projected total (age 6+) biomass (t)	2,690,080	2,577,430 t	2,432,260 t	2,311,300 t
Projected female spawning biomass (t)	1,007,780 t	901,877t	818,679 t	723,107 t
$B_{100\%}$	1,500,060	1,500,060	1,270,960 t	1,270,960 t
$B_{MSY\%}$	541,737	541,737	461,791 t	461,791 t
F_{OFL}	0.117	0.117	0.117	0.117
$maxF_{ABC}$	0.108	0.108	0.107	0.107
F_{ABC}	0.108	0.108	0.107	0.107
OFL	315,785	302,561	283,692 t	269,583t
$maxABC$	290,690	278,517	259,250 t	246,358 t
ABC	290,690	278,517	259,250 t	246,358 t
Status	2018	2019	2018	2019
Overfishing	No	n/a	No	n/a
Overfished	n/a	No	n/a	No
Approaching overfished	n/a	No	n/a	No

Projections were based on xxx.

Table 4.26: Comparison of reference points using Model 18.1 and Model 18.2.

	Model 18.2		Model 18.1	
Quantity	2020	2021	2020	2021
M (natural mortality rate)	0.12	0.12	0.12, 0.135	0.12, 0.135
Tier	1a	1a	1a	1a
Projected total (age 6+) biomass (t)	2,690,080 t	2,577,430 t	2,432,260 t	2,311,300 t
Projected female spawning biomass (t)	1,007,780 t	901,877t	818,679 t	723,107 t
$B_{100\%}$	1,500,060	1,500,060	1,270,960 t	1,270,960 t
$B_{MSY\%}$	541,737	541,737	461,791 t	461,791 t
F_{OFL}	0.117	0.117	0.117	0.117
$maxF_{ABC}$	0.108	0.108	0.107	0.107
F_{ABC}	0.108	0.108	0.107	0.107
OFL	315,785	302,561	283,692 t	269,583t
$maxABC$	290,690	278,517	259,250 t	246,358 t
ABC	290,690	278,517	259,250 t	246,358 t
Status	2018	2019	2018	2019
Overfishing	No	n/a	No	n/a
Overfished	n/a	No	n/a	No
Approaching overfished	n/a	No	n/a	No

Projections were based on an assumed catch equal to that of 2018.

Table 4.27: Occurrence of Yellowfin Sole in the Bering Sea trawl survey and collections of length and age structures and the number of otoliths aged from each survey.

Year	Total hauls	Hauls with length	Number of lengths	Hauls with otoliths	Hauls with ages	Number of otoliths	Number of ages
1982	334	246	37023	35	35	744	744
1983	353	256	33924	37	37	709	709
1984	355	271	33894	56	56	821	796
1985	357	261	33824	44	43	810	802
1986	354	249	30470	34	34	739	739
1987	357	224	31241	16	16	798	798
1988	373	254	27138	14	14	543	543
1989	374	236	29672	24	24	740	740
1990	371	251	30257	28	28	792	792
1991	372	248	27986	26	26	742	742
1992	356	229	23628	16	16	606	606
1993	375	242	26651	20	20	549	549
1994	375	269	24448	14	14	526	522
1995	376	254	22116	20	20	654	647
1996	375	247	27505	16	16	729	721
1997	376	262	26034	11	11	470	466
1998	375	310	34509	15	15	575	570
1999	373	276	28431	31	31	777	770
2000	372	255	24880	20	20	517	511
2001	375	251	26558	25	25	604	593
2002	375	246	26309	32	32	738	723
2003	376	241	27135	37	37	699	695
2004	375	251	26103	26	26	725	712
2005	373	251	24658	34	34	644	635
2006	376	246	28470	39	39	428	426
2007	376	247	24790	66	66	779	772
2008	375	238	25848	65	65	858	830
2009	376	235	22018	70	70	784	752
2010	376	228	20619	77	77	841	827
2011	376	228	21665	65	64	784	753
2012	376	242	23519	72	72	993	973
2013	376	232	23261	70	70	821	803
2014	376	219	20229	52	52	799	790
2015	376	223	20830	73	73	878	875
2016	376	242	26674	69	69	884	876
2017	376	258	25767	78	78	896	886
2018	376	255	1830	68	68	724	720
2019	376	270	25669	67		836	

Table 4.28: Total tonnage of Yellowfin Sole caught in resource assessment surveys in the eastern Bering Sea from 1977- 2019 .

Year	Research catch (t)
1977	60
1978	71
1979	147
1980	92
1981	74
1982	158
1983	254
1984	218
1985	105
1986	68
1987	92
1988	138
1989	148
1990	129
1991	118
1992	60
1993	95
1994	91
1995	95
1996	72
1997	76
1998	79
1999	61
2000	72
2001	75
2002	76
2003	78
2004	114
2005	94
2006	74
2007	74
2008	69
2009	60
2010	79
2011	77
2012	64
2013	75
2014	81
2015	64
2016	98
2017	98
2018	67
2019	67

Table 4.29: Mean length and weight at age for Yellowfin Sole (unsmoothed), females presented first, followed by males.

Year	Age (Females)																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1964	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481	590
1965	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481	590
1966	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481	590
1967	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481	590
1968	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481	590
1969	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481	590
1970	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481	590
1971	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481	590
1972	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481	590
1973	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481	590
1974	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481	590
1975	8	20	31	55	84	124	165	217	266	301	341	374	407	428	443	480	483	499	590	590
1976	8	20	31	55	84	124	165	217	266	301	341	374	407	428	443	480	483	499	590	590
1977	8	20	31	55	84	124	165	217	266	301	341	374	407	428	443	480	483	499	590	590
1978	8	20	31	55	84	124	165	217	266	301	341	374	407	428	443	480	483	499	590	590
1979	8	20	31	55	84	124	165	217	266	301	341	374	407	428	443	480	483	499	590	590
1980	8	20	31	55	84	124	165	217	266	301	341	374	407	428	443	480	483	499	590	590
1981	8	20	31	55	84	124	165	217	266	301	341	374	407	428	443	480	483	499	590	590
1982	8	20	42	75	98	139	176	214	233	235	331	359	393	410	436	482	470	476	586	590
1983	10	14	26	60	103	162	185	201	243	255	318	350	391	419	455	503	489	503	605	590
1984	14	26	33	57	110	156	177	222	246	294	318	342	375	418	453	498	492	536	617	590
1985	11	16	28	46	77	177	202	251	286	302	314	341	367	417	450	502	520	556	623	590
1986	14	27	23	41	71	103	173	239	284	338	314	336	366	401	439	490	511	547	628	590
1987	10	14	20	47	55	127	179	256	317	324	331	351	375	411	443	475	519	557	619	590
1988	9	12	16	34	66	85	159	237	286	307	351	364	377	393	418	446	490	528	597	590
1989	12	21	33	67	71	112	133	197	279	339	364	384	402	400	422	445	506	490	570	590
1990	11	17	24	38	65	99	126	197	243	321	389	400	411	405	430	436	475	475	559	590
1991	11	16	23	58	56	100	142	156	238	310	394	421	420	429	446	450	486	481	557	590
1992	12	21	29	55	85	121	177	176	283	305	377	417	430	456	454	464	498	485	562	590
1993	15	28	35	64	93	155	165	232	244	301	368	411	438	469	470	477	506	496	563	590
1994	20	46	53	86	87	125	155	235	276	284	355	405	418	470	472	482	486	504	571	590
1995	12	20	28	60	84	123	160	217	284	332	333	403	412	463	470	478	515	495	575	590
1996	11	16	36	51	108	137	167	202	222	311	322	379	403	448	461	487	509	503	567	590
1997	16	34	33	72	85	157	200	236	260	292	336	383	397	439	457	488	492	514	577	590
1998	10	14	36	51	90	104	177	237	278	279	333	383	391	430	439	478	479	513	576	590
1999	9	12	18	37	67	103	131	239	284	296	331	374	398	417	429	474	484	506	593	590
2000	11	16	33	33	91	81	158	175	237	306	325	360	401	422	423	485	462	506	603	590
2001	6	6	32	41	57	83	148	179	255	305	333	367	410	425	420	463	464	506	611	590
2002	11	18	27	48	65	87	120	224	243	261	330	362	404	413	419	455	479	501	608	590
2003	9	12	31	53	86	124	156	213	289	303	335	369	406	412	425	439	485	486	599	590
2004	9	18	43	63	101	168	172	245	299	346	346	381	426	441	432	439	478	490	592	590
2005	14	26	44	78	114	152	213	238	277	337	353	386	434	445	454	444	464	501	590	590
2006	9	13	40	82	125	153	204	245	319	314	357	385	451	454	465	533	465	504	609	590
2007	11	16	36	66	115	173	198	244	316	311	362	388	459	465	471	542	462	529	620	590
2008	13	24	28	54	98	129	199	226	286	320	364	383	463	472	478	575	481	548	639	590
2009	6	9	18	45	69	127	163	239	306	322	363	385	442	446	483	630	496	546	654	590
2010	8	20	31	55	84	124	165	217	266	301	362	380	436	439	465	622	505	538	646	590
2011	8	18	25	56	80	126	188	205	327	332	361	387	412	435	455	522	507	539	626	590
2012	8	12	26	49	81	144	169	256	313	341	358	404	421	437	458	512	514	522	616	590
2013	8	12	21	35	92	125	182	261	305	364	369	413	425	442	454	507	507	518	608	590
2014	6	8	11	18	34	74	145	203	260	305	370	403	430	441	457	464	496	536	582	590
2015	6	8	11	16	39	53	122	210	273	360	387	414	433	448	462	475	513	541	564	590
2016	6	8	32	50	66	74	112	186	338	372	397	416	449	455	479	499	518	535	560	590
2017	6	9	18	56	65	155	129	156	250	357	402	413	454	459	487	512	521	542	551	590
2018	6	9	24	44	85	102	143	221	226	345	404	417	449	460	503	518	529	543	557	590
2019	6	9	24	44	85	102	143	221	226	345	413	433	456	471	512	521	540	535	571	590

Year	Age (Males)																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1964	0	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481
1965	0	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481
1966	0	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481
1967	0	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481
1968	0	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481
1969	0	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481
1970	0	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481
1971	0	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481
1972	0	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481
1973	0	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481
1974	0	4	15	34	60	91	125	160	195	230	263	294	322	348	372	393	412	429	444	481
1975	4	14	18	32	54	85	120	156	193	225	253	280	303	324	330	344	355	366	390	423
1976	4	14	18	32	54	85	120	156	193	225	253	280	303	324	330	344	355	366	390	423
1977	4	14	18	32	54	85	120	156	193	225	253	280	303	324	330	344	355	366	390	423
1978	4	14	18	32	54	85	120	156	193	225	253	280	303	324	330	344	355	366	390	423
1979	4	14	18	32	54	85	120	156	193	225	253	280	303	324	330	344	355	366	390	423
1980	4	14	18	32	54	85	120	156	193	225	253	280	303	324	330	344	355	366	390	423
1981	4	14	18	32	54	85	120	156	193	225	253	280	303	324	330	344	355	366	390	423
1982	4	11	25	50	83	112	133	142	158	182	242	266	286	309	345	352	361	384	418	420
1983	4	5	5	23	57	95	156	156	155	176	233	256	271	295	331	341	344	385	414	417
1984	4	10	20	31	57	121	150	181	202	193	223	242	259	281	316	325	330	394	394	406
1985	4	11	23	32	51	84	148	186	214	227	218	236	254	269	307	317	340	399	423	399
1986	4	9	18	27	34	61	98	176	217	233	215	225	248	257	293	313	322	389	405	389
1987	4	8	14	17	27	53	97	157	211	226	228	236	266	269	267	294	306	358	364	386
1988	4	7	10	18	45	75	76	138	207	242	238	252	281	278	283	297	314	347	355	381
1989	4	7	10	27	47	72	142	130	179	244	252	279	300	298	295	305	336	325	370	377
1990	4	9	16	22	44	64	98	120	175	197	261	295	312	309	305	301	324	318	332	377
1991	4	9	17	29	51	75	100	132	180	212	266	302	323	328	319	308	341	315	378	379
1992	4	9	17	28	53	86	97	125	174	208	262	302	322	368	345	329	349	328	394	373
1993	4	9	18	45	56	93	135	145	206	209	257	294	339	369	347	341	362	335	397	372
1994	4	23	32	53	76	92	116	182	198	207	255	291	334	367	353	362	355	369	394	387
1995	4	10	19	32	59	88	110	154	177	207	250	278	333	361	349	380	359	375	406	399
1996	4	10	19	32	54	107	134	163	184	215	241	277	324	349	347	374	355	398	365	410
1997	4	8	14	37	64	75	149	174	185	239	240	274	315	308	335	362	363	400	353	427
1998	4	10	20	27	49	79	113	156	208	207	244	274	296	308	324	356	354	401	354	429
1999	4	6	7	18	37	63	95	123	170	171	241	263	287	292	324	340	362	375	355	434
2000	4	10	20	36	32	64	88	133	161	284	238	265	280	285	318	331	359	368	349	421
2001	4	9	16	27	38	51	91	152	161	198	247	260	280	285	314	330	361	356	370	421
2002	4	9	18	21	57	59	81	134	188	204	249	260	282	286	305	331	351	343	374	415
2003	4	11	22	39	53	83	109	161	179	251	247	269	277	319	313	333	346	340	375	418
2004	4	7	20	40	64	94	157	157	213	266	265	275	282	337	315	334	344	353	393	417
2005	4	11	24	44	77	110	136	170	201	262	274	287	295	347	323	338	349	352	388	427
2006	4	10	19	36	71	124	139	180	207	237	267	302	305	364	341	363	354	348	379	418
2007	4	10	19	36	63	107	140	181	208	248	277	309	313	370	356	363	358	361	390	421
2008	4	8	13	29	50	91	113	181	194	252	280	306	322	350	363	369	371	368	403	436
2009	4	7	11	20	39	74	112	133	194	273	267	305	332	343	367	365	375	359	392	439
2010	4	14	18	32	54	85	120	156	193	225	262	294	320	346	367	364	371	363	400	437
2011	4	14	17	25	47	81	134	164	174	305	272	297	312	339	356	344	375	369	399	439
2012	4	14	12	27	48	83	126	181	214	249	268	299	309	339	350	352	380	372	394	433
2013	4	14	13	21	40	72	122	179	227	259	272	306	302	342	348	354	387	376	384	417
2014	4	8	11	44	34	75	150	195	246	296	280	308	298	333	349	367	386	397	393	405
2015	4	8	11	44	34	75	150	195	246	296	300	324	306	336	355	370	393	427	424	420
2016	4	8	43	57	63	82	116	171	253	319	308	324	323	341	369	380	400	433	421	440
2017	4	9	26	58	76	94	103	149	207	291	316	336	338	343	380	376	424	433	421	460
2018	4	9	32	47	86	88	154	174	216	286	323	346	357	349	388	371	419	430	457	480
2019	4	9	32	47	86	88	154	174	216	286	324	357	365	376	392	364	415	409	480	500

Table 4.30: 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 4.1: Key equations used in the population dynamics model.

Figures

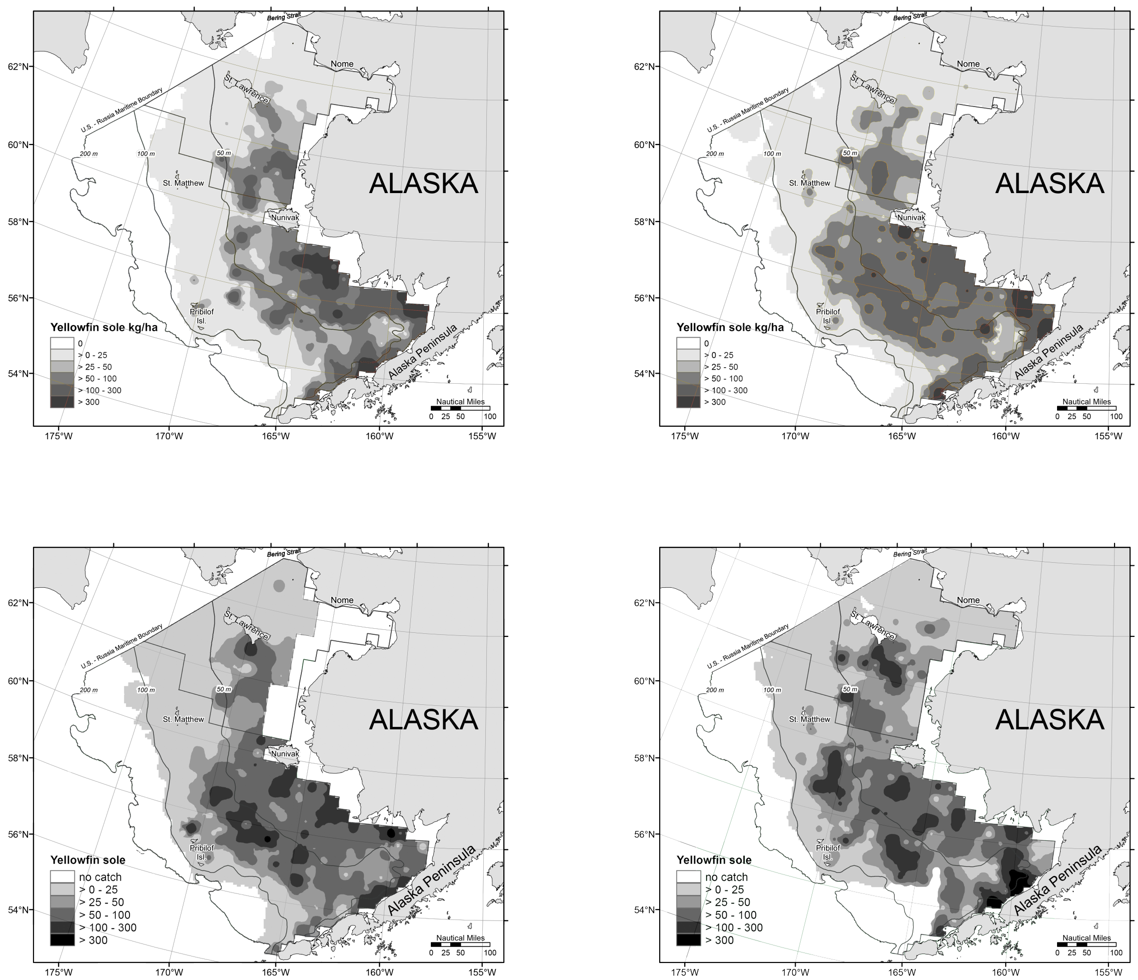


Figure 4.23: Distribution of Yellowfin Sole in the eastern and northern Bering sea based on surveys conducted in 2010 (upper left), 2017 (upper right), 2018 (lower left), and 2019 (lower right).

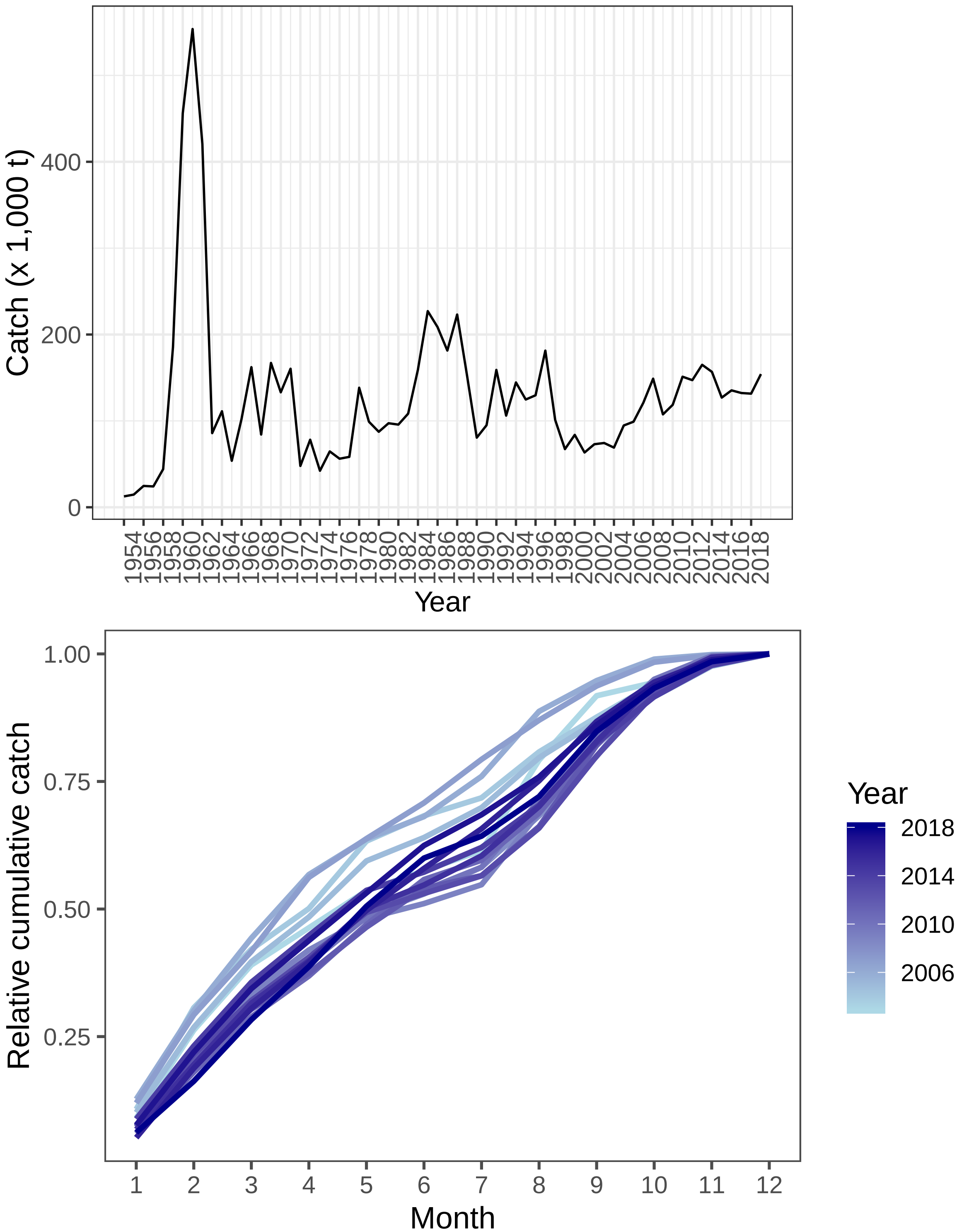


Figure 4.1: Yellowfin Sole annual total catch (1,000s t) in the Eastern Bering Sea from 1954-2019 (upper panel). Yellowfin Sole annual cumulative catch by month and year (non CDQ) 2003-2018 (lower panel).

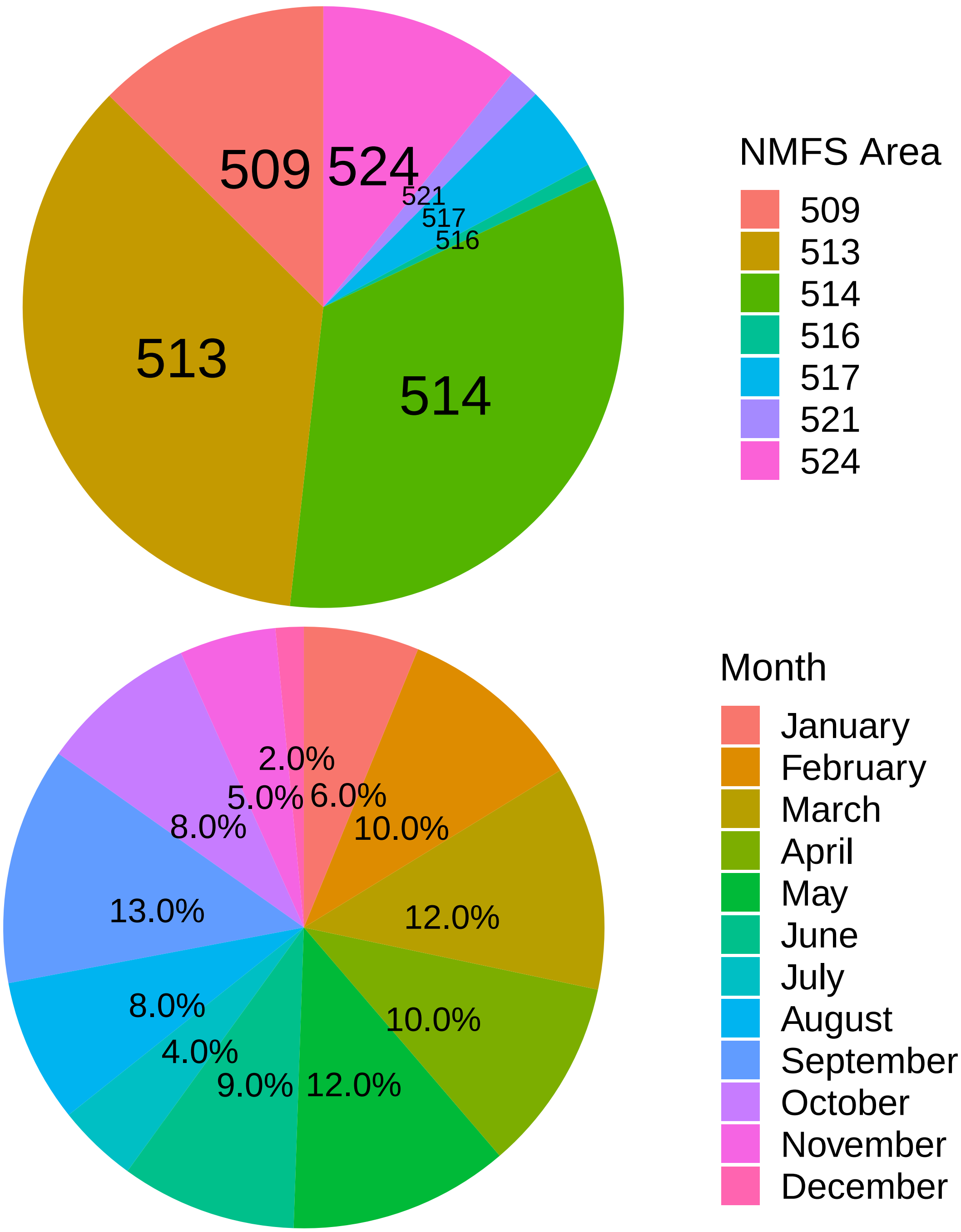


Figure 4.3: Yellowfin Sole catch proportion by area (upper panel) and by month (lower panel) in the Eastern Bering Sea in 2019 .

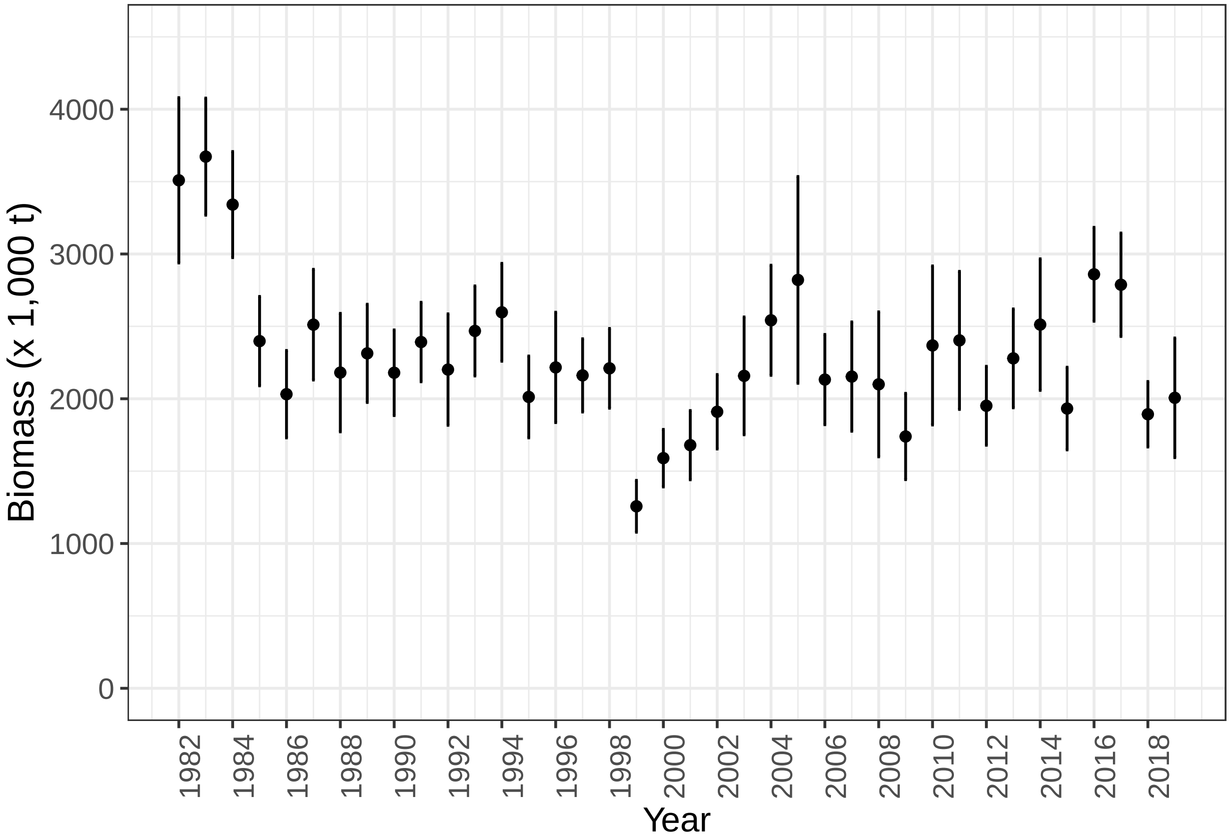


Figure 4.5: Annual eastern Bering Sea bottom trawl survey biomass point-estimates and 95% confidence intervals for Yellowfin Sole, 1982-2019.

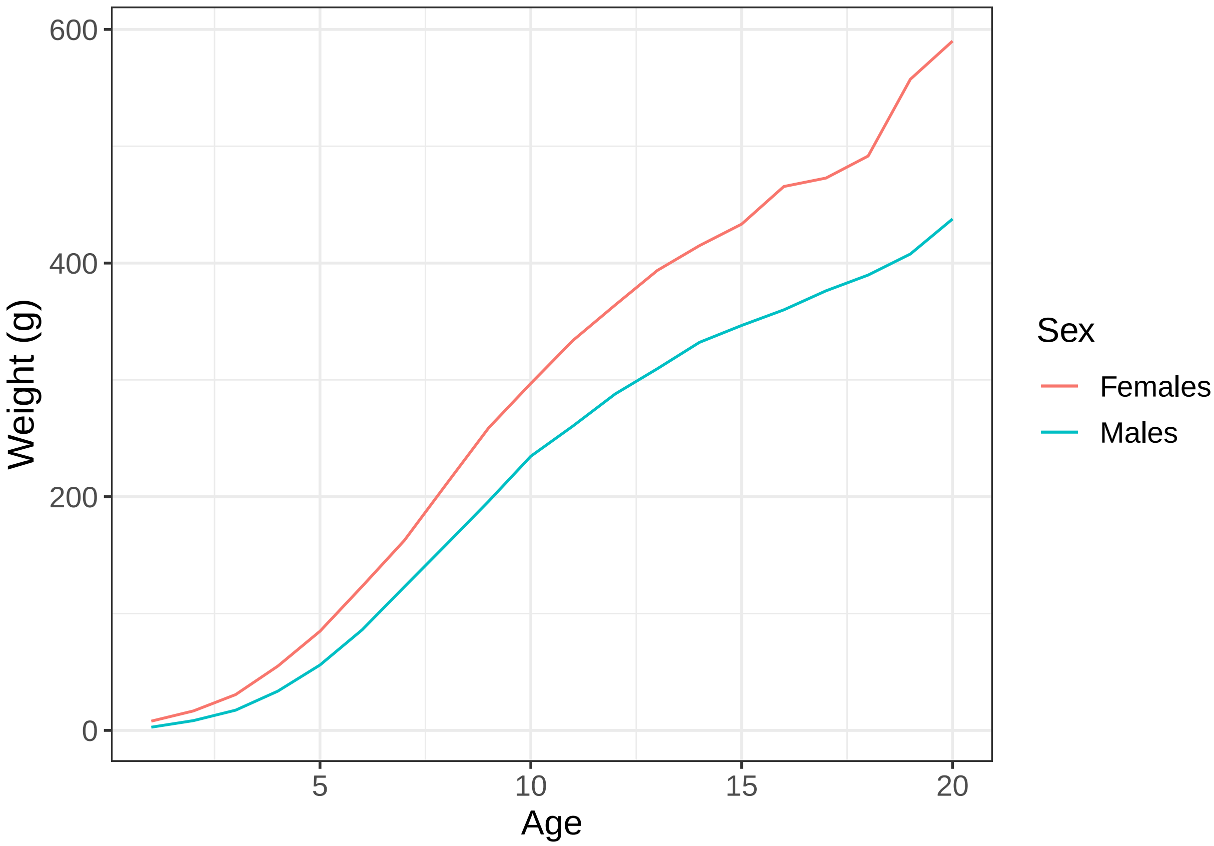


Figure 4.7: Average Yellowfin Sole weight-at-age (g) from trawl survey observations.

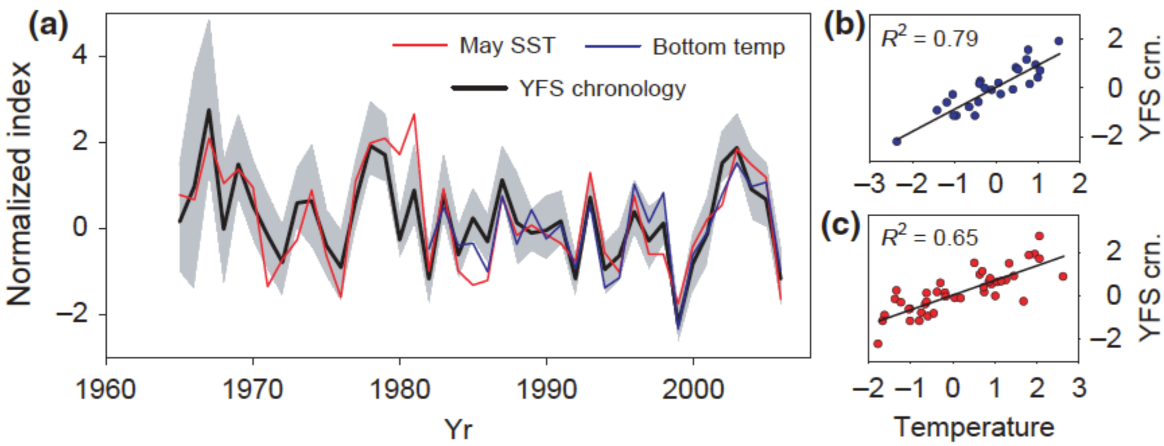


Figure 4.8: Master chronology for Yellowfin Sole and time series of mean summer bottom temperature and May sea surface temperature for the southeastern Bering Sea (Panel A). All data re normalized to a mean of 0 and standard deviation of 1. Correlations of chronologies with bottom temperature and sea surface temperature are shown in panels B and C, respectively (Matta et al. 2010).

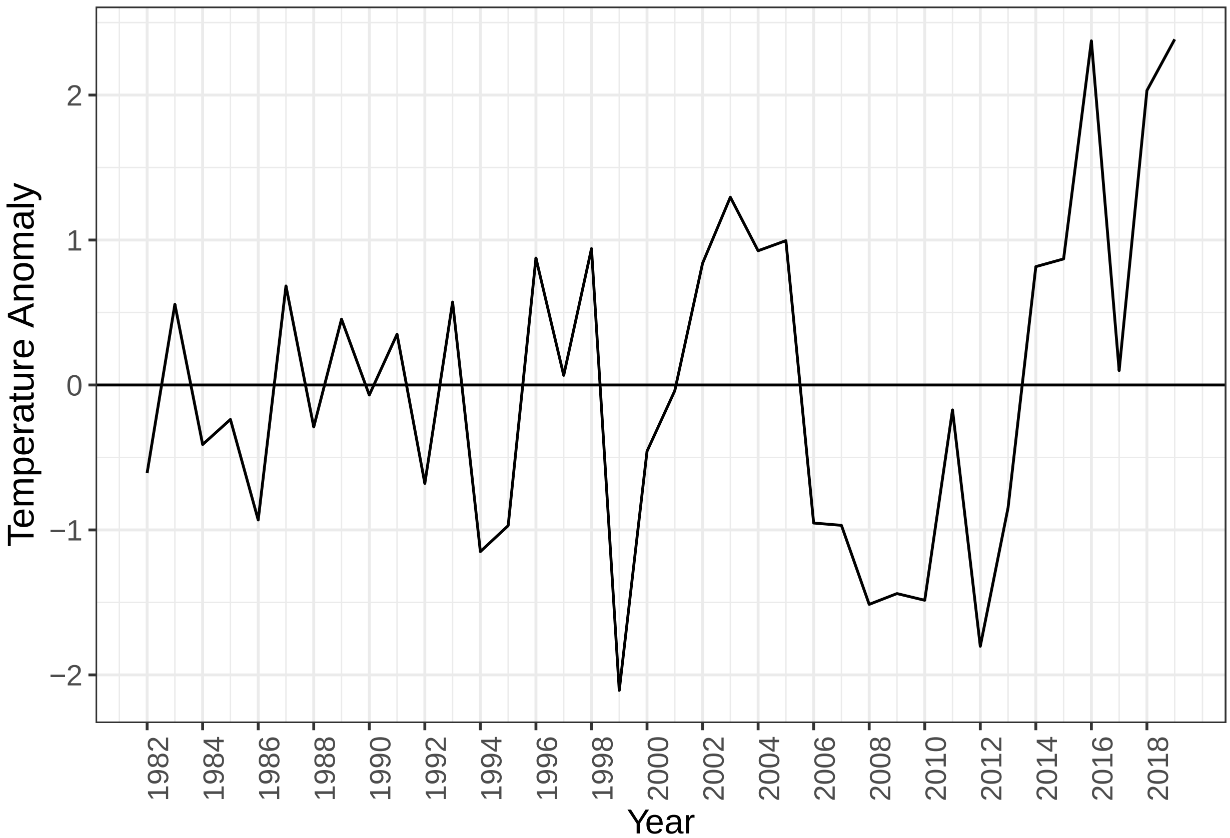
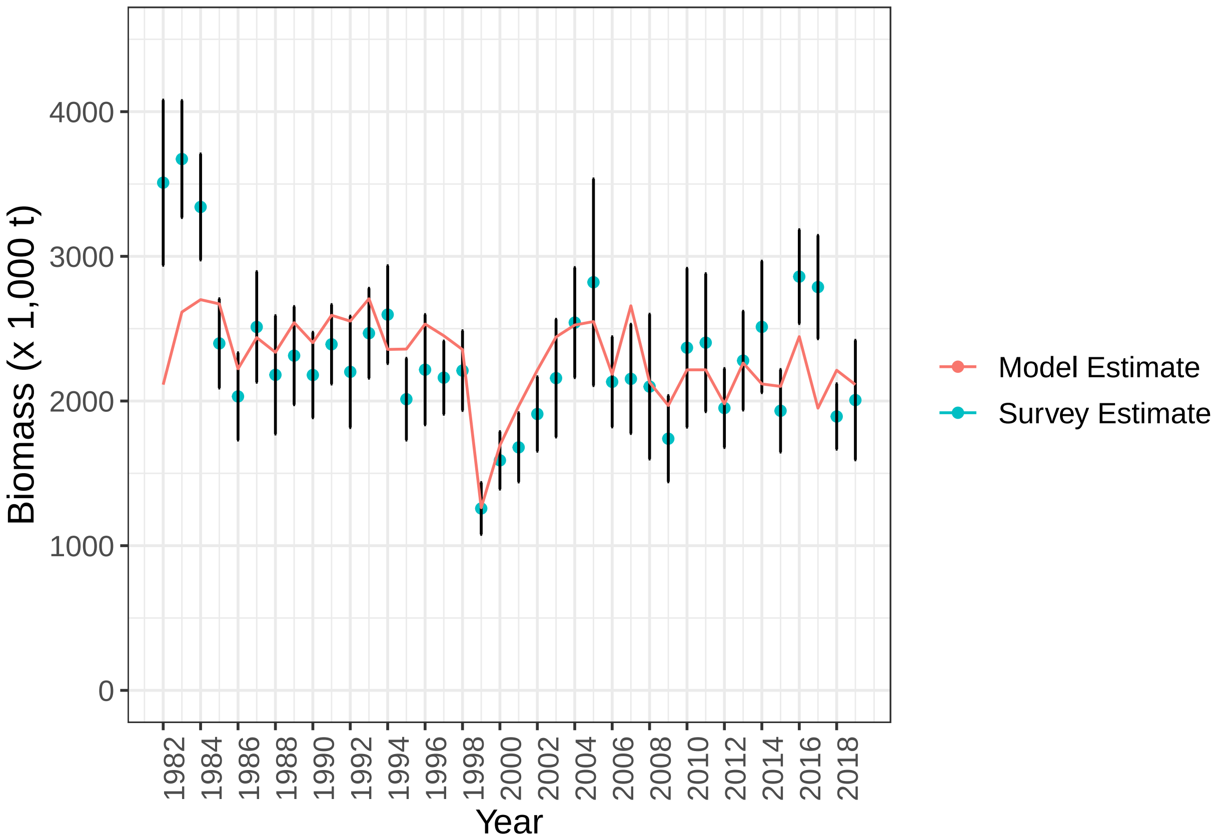
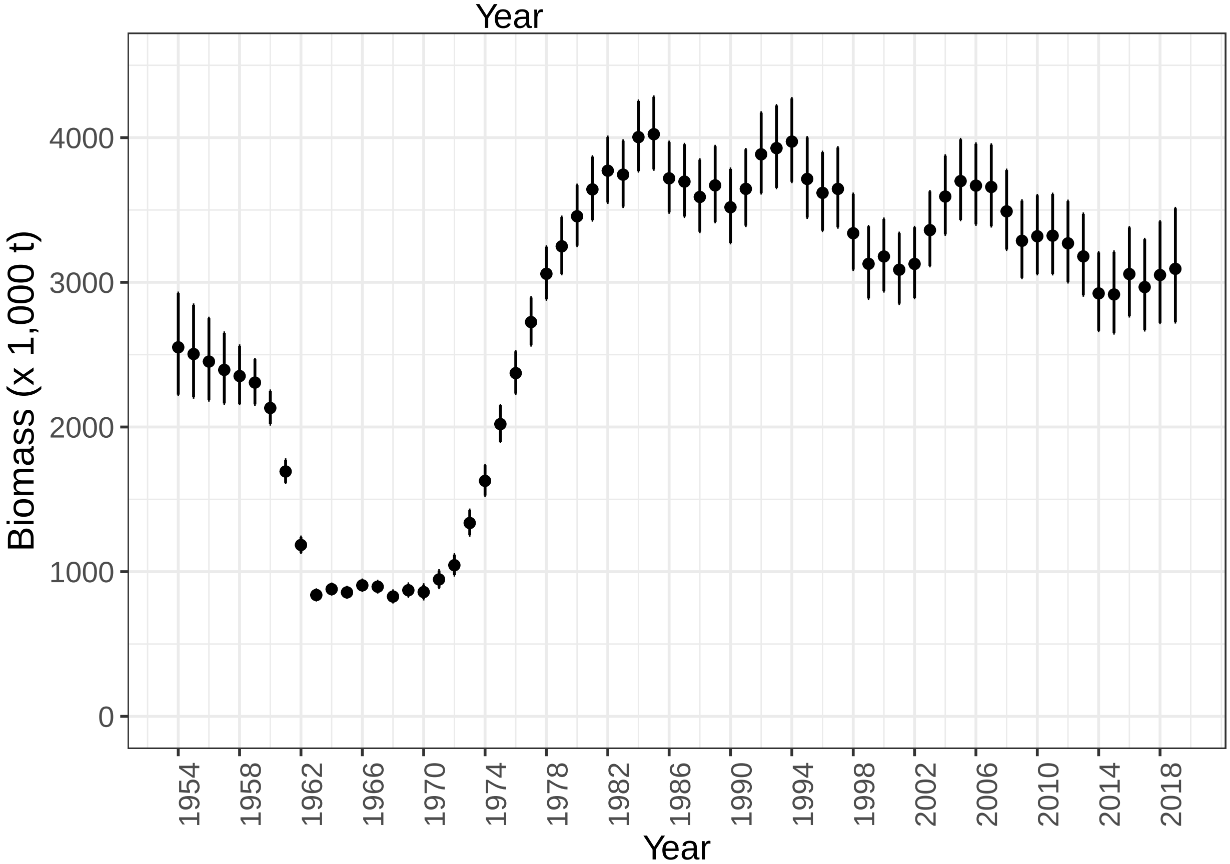


Figure 4.9: Yellowfin Sole length-at-age anomalies, for males and females, and bottom temperature anomalies. Correspondence in these residuals is apparent with a 2-3 year lag effect from the mid-1990s to 2017. Late 1980s and early 1990s pattern may be a density-dependent response in growth from the large 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

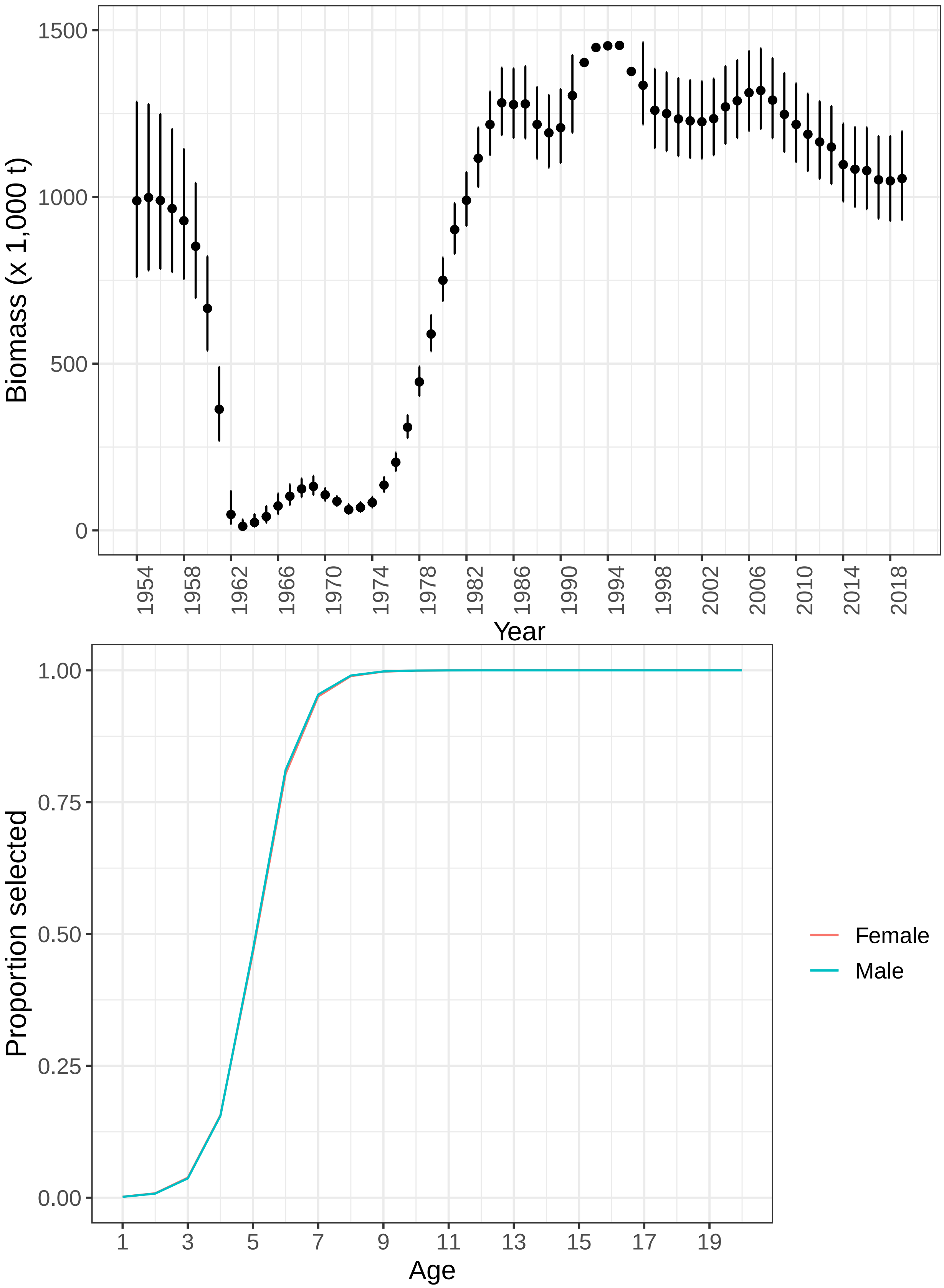


Figure 4.15: Model fit to the survey biomass estimates (top left panel), model estimate of the full selection

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).

Nichol, D.G., Kotwicki, S., Wilderbuer, T.K., Lauth, R.R. and Ianelli, J.N., 2019. Availability of yellowfin sole Limanda aspera to the eastern Bering Sea trawl survey and its effect on estimates of survey biomass. Fisheries Research, 211, pp.319-330.