Assessment of Pacific mackerel (*Scomber japonicus*) for U.S. management in the 2023-24 and 2024-25 fishing years

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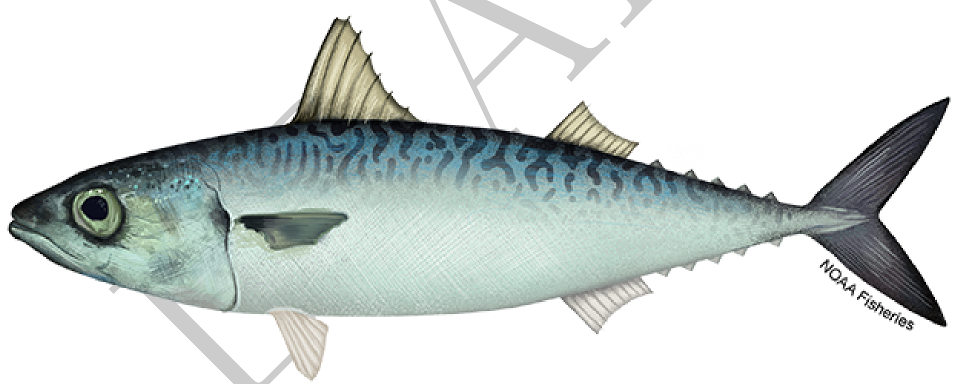

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1 Introduction

1.1 Stock Structure and Management Units

The full range of Pacific mackerel (*Scomber japonicus*, also referred to as chub or blue mackerel) in the northeastern Pacific Ocean is from southeastern Alaska to Banderas Bay (Puerto Vallarta), Mexico, including the Gulf of California (Hart 1971). Although stock structure of this species off the Pacific coast of North America is not known definitively, it is generally hypothesized that three spawning aggregations exist currently: one in the Gulf of California; one in the vicinity of Cabo San Lucas (Baja California, Mexico); and one along the Pacific coast north of Punta Abreojos (Baja California) that extends north to areas off southern California, and even further during favorable oceanographic periods to waters off the U.S. Pacific Northwest. The latter sub-stock is harvested by fishermen in the U.S. and Mexico, and is the population considered in this assessment.

The Pacific Fishery Management Council (PFMC) manages the northeastern Pacific Ocean stock along the Pacific coast of North America as a single unit, with no area- or sector-specific allocations. However, the formal Fishery Management Plan (FMP) harvest control rule does include a stock distribution adjustment, based on a long-term assumption that on average, roughly 70% of this transboundary population resides in U.S. waters in any given year (PFMC 1998).

1.2 Distribution and Movement

Although the northeastern Pacific Ocean stock ranges from southeastern Alaska to southern Baja California, the species is more common from Monterey Bay, CA to Cabo San Lucas, Mexico (Figure 1). Over the last few decades, the stock has been observed to more fully occupy the northernmost portions of its range in response to warmer oceanographic conditions that have persisted in the northeastern Pacific Ocean, being found at times as far north as British Columbia, Canada (Ware and Hargreaves 1993, Hargreaves and Hungar 1995). To date, there exists only a general understanding of the seasonal movement patterns exhibited by this species along the coast of North America (Fry Jr and Roedel 1949, Roedel 1949, Parrish and MacCall 1978, Hill 1999), with northward movement from waters off Baja and southern California beginning in the late spring/summer to feed in productive areas of upwelling off Oregon and Washington (potentially, more extensive geographical range during El Niño events, MBC (1987)); and southerly movement in the late fall/winter back to spawning grounds off southern and Baja California. Pacific mackerel sampled from Pacific Northwest incidental fisheries (e.g., Pacific hake and salmon spp.) during the mid-1990s indicated the fish were generally older and larger than those captured in the southern California fishery (Hill 1999). In recent years, the stock has been observed to be relatively abundant in waters off the Pacific Northwest as documented in cruise reports for the acoustic-trawl (AT) survey, conducted annually since the mid-2000s by the Southwest Fisheries Science

Center (SWFSC), e.g., Stierhoff et al. (2019a) and Zwolinski et al. (2019). Thus, the stock is assumed to be most abundant in U.S. waters during the summer and fall months of each year; however, determination of the exact portion of the population that occupies U.S. waters each summer/fall is necessarily problematic and subject to some level of uncertainty.

It is further hypothesized that the stock exhibits east-west (inshore-offshore) movement along the U.S. Pacific coast, with increased inshore abundance from July to November and increased offshore abundance from March to May (Cannon 1967, Sciences 1987). Pacific mackerel usually occur within 30 km of shore, but have been captured as far as 400 km offshore (Fitch 1969, Frey 1971, Sciences 1987, Allen et al. 1990). Pacific mackerel adults are found in water ranging from 10 to 22.2°C (Sciences 1987) and larvae are found in water around 14°C (Allen et al. 1990). Adult fish are commonly found near shallow banks. Juveniles are found off sandy beaches, around kelp beds, and in open bays. Adults are found from the surface to 300 m depth (Allen et al. 1990). Pacific mackerel often school with other small pelagic species, particularly jack mackerel and Pacific sardine, likely based on size/age attributes as well (Parrish and MacCall 1978).

1.3 Life History

Pacific mackerel found off the Pacific coast of North America are the same species found elsewhere in the Pacific and Indian Oceans (Collette and Nauen 1983). Synopses regarding the biology of Pacific mackerel are presented in Kramer (1969) and Schaefer (1980). Spawning occurs from Point Conception, California to Cabo San Lucas from 3 to over 300 km offshore (Moser et al. 1993). Off California, spawning occurs from March to October (primarily, late April through August) at depths to 100 meters (Knaggs and Parrish 1973). Off central Baja California, spawning can occur year round at some level, peaking from June through October. Around Cabo San Lucas, spawning occurs primarily from late fall to early spring. Pacific mackerel are believed to seldomly spawn north of Point Conception (Fritzsche 1978, Sciences 1987).

As exhibited by similar CPS, Pacific mackerel have indeterminate fecundity and appear to spawn whenever sufficient food is available and favorable oceanographic conditions prevail. Individual fish may spawn eight times or more per year and can release batches of at least 68,000 eggs per spawning. Actively spawning fish appear capable of spawning daily or every other day(Dickerson et al. 1992). Pacific mackerel larvae eat copepods and other zooplankton, including fish larvae (Collette and Nauen 1983, Sciences 1987). Juvenile and adult mackerel feed on small fish (e.g., northern anchovy), fish larvae, squid, and pelagic crustaceans, such as euphausids (Clemmens and Wilby 1961, Turner and Sexsmith 1967, Fitch 1969, Fitch and Lavenberg 1971, Frey 1971, Hart 1971, Collette and Nauen 1983). Pacific mackerel larvae are subject to predation from a number of invertebrate and vertebrate planktivores. Juveniles and adults are eaten by larger fishes, marine mammals, and seabirds. Principal predators include porpoises, California sea lions, pelicans, and large piscivorous fish, such as sharks and tunas. Pacific mackerel likely school as a defense against predation, often with other CPS, such as jack mackerel and Pacific sardine.

Population dynamics of the Pacific mackerel stock off U.S. Pacific coast, particularly California, have been extensively studied in the past and of particular importance was pioneering research conducted during the 1970s and 1980s, e.g., Parrish (1974), Parrish and MacCall (1978), Mallicoate and Parrish (1981), MacCall et al. (1985), and Prager and MacCall (1988). Since the mid-1990s, various age-structured population dynamics models have been used to regularly assess the Pacific mackerel stock for providing management advice (e.g., Jacobson et al. 1994, Hill and Crone 2005, Crone et al. 2009, Crone and Hill 2015), see History of modeling approaches below.

Pacific mackerel experience cyclical periods of notable abundance, a phenomenon exhibited by CPS in general, which are characterized by relatively short life spans and highly variable productivity/abundance driven primarily by large-scale environmental factors (e.g., Pacific Decadal Oscillation (PDO), North Pacific Gyre Oscillation (NPGO), and related oceanographic drivers, such as sea-surface temperature, sea-surface height, upwelling, cholorophyll, etc.). Analysis of mackerel scale-deposition data (Soutar and Isaacs 1974) indicates that periods of high biomass, such as during the 1930s and 1980s, are relatively rare events that might be expected to occur, on average, about once every 60 years (MacCall et al. 1985). Results from the ongoing assessment of this stock generally support past research, with periods of high recruitment success observed no more frequently than every few decades. As presented above, recruitment is generally variable both spatially and temporally in the northeastern Pacific Ocean, and unlikely to be related strongly to spawning stock size (Parrish 1974, Parrish and MacCall 1978).

The largest recorded Pacific mackerel was 63.0 cm in length (FL) and weighed 2.9 kg (Roedel 1938, Hart 1971), but the largest Pacific mackerels taken by commercial fishing (CA) were a 47.8 cm FL fish and a 1.72 kg fish. The oldest recorded age for a Pacific mackerel was 14 years, but most commercially caught Pacific mackerel recorded by CDFW are less than 4 years old, with few living beyond age 8 and larger than 45 cm. Historical data of generally older and larger Pacific mackerel sampled from Pacific Northwest incidental fisheries in the 1990s exists, and have been reported on previously (Hill 1999), but more current data are not available.

As addressed in earlier assessments/reviews, size-at-age relationships by sex and sex ratio data indicated no notable sexual dimorphism in growth or mortality rate is exhibited by this species. Combined sex models have been used in all past and present Pacific mackerel assessments used to advise management.

1.4 Fishery Descriptions

Pacific mackerel are currently harvested by three fisheries (Table 1 and Figure 2): the USA commercial fishery that primarily operates out of southern California, as well as Oregon and

Washington; a sport fishery based largely in southern California; and the Mexico commercial fishery that is based in Ensenada, Baja California and Magdalena Bay, Baja California Sur. In the commercial fisheries, Pacific mackerel are landed by the same boats that catch Pacific sardine, northern anchovy, jack mackerel, and market squid (commonly referred to as the west coast 'wetfish' fleet). In recent years, Oregon and Washington have landed limited amounts of Pacific mackerel, with a combined annual average catch of roughly 500 mt over the last decade. Pacific mackerel are also (incidentally) harvested in small volumes by whiting trawlers and salmon trollers. Available information concerning bycatch and discard mortality of Pacific mackerel, as well as other members of the small pelagic fish assemblage of the California Current, is presented in (PFMC 2021). Limited information from observer programs implemented in the past indicated little bycatch of other species and/or discard of Pacific mackerel in the commercial purse seine fishery off the U.S. Pacific coast.

The history of California's Pacific mackerel fishery has been reviewed by Croker (1933), Croker (1938), Roedel (1952), and Klingbeil (1983). Historically, Pacific mackerel have been landed in moderate amounts, supporting a viable fishery in California during the 1930s and 1940s and more recently, in the 1980s and early 1990s. During the early years of the fishery, Pacific mackerel were taken by lampara and pole-and-line boats, which were replaced in the 1930s by the same purse seine fleet that fished for Pacific sardine. Before 1929, Pacific mackerel were taken incidentally, in relatively small volumes with sardine and sold as a fresh product (Frey 1971). Canning of Pacific mackerel began in the late 1920s and increased as greater processing capacities and more marketable 'packs' were developed. Landings decreased in the early 1930s due to the economic depression and subsequent decline in demand, but increased significantly by the mid-1930s (66,400 mt in 1935-36). During this period, Pacific mackerel were second only to Pacific sardine in total (annual) landings. Subsequently, harvests underwent a long-term decline and for many years, a continued demand for canned mackerel exceeded supply. Supply reached record low levels in the early 1970s, at which time the State of California implemented a 'moratorium' on the directed fishery, allowing only limited amounts of incidental landings.

Following a period of 'recovery' that spanned from the mid to late 1970s, the moratorium was lifted. During the 1980s through mid-1990s, catches of Pacific mackerel by California fishermen supported an economically viable fishery. The market for canned mackerel during the 1980s through early 1990s fluctuated substantially due largely to economic factors. Domestic demand for canned Pacific mackerel eventually waned and the last mackerel cannery in California closed in 1992. Presently, the limited landings of Pacific mackerel caught by U.S. fishermen are used for human consumption (e.g., canned, frozen, fresh) or pet food.

Pacific mackerel are caught by recreational anglers in southern California using commercial passenger fishing vessels (CPFV), private boats, piers, beaches, etc., but not typically considered a target species (Young 1969), with comparatively minimal catches to landings from commercial operations (Table 1). Pacific mackerel are also harvested in California's recreational fishery as bait for directed fishing on larger pelagic species, such as tunas, sharks, and billfishes. Additionally, Pacific mackerel are caught by anglers in central California, Oregon, and Washington, but typically, in only limited amounts. The sport harvest of Pacific mackerel in California comprises a very small fraction of the total landings of Pacific mackerel, e.g., over the last decade, recreational catch is less than 5% of the total weight landed (Table 1). Although some mackerel are likely discarded in some recreational fishing sectors for this non-targeted species, accurate determination of discard magnitude from available creel survey data is not straightforward, potentially subject to problematic sampling biases in the field.

In summary, Pacific mackerel landings in the U.S. have remained low over the last two decades, with total annual landings averaging ~7,000 mt since the late 1990s (Table 1). Relatedly, mackerel catches from fisheries have not realized allowable yields via stipulated harvest guidelines imposed since the late 1990s (see Table 2 and 'Management performance' below).

The Mexico fishery for Pacific mackerel is primarily based in Ensenada and to a lesser extent, Magdalena Bay, Baja California Sur. The Mexico purse seine fleet has slightly larger vessels, but is similar to southern California's fleet with respect to gear (mesh size) and fishing practices. The fleet operates in the vicinity of the nearby ports and also targets other CPS. Demand for Pacific mackerel in Baja California increased after World War II. Mexico landings remained stable for several years, increased to over 10,000 mt in the mid-1950s, declined to under 500 mt during the mid-1970s, and remained relatively low through the late 1980s. Landings of Pacific mackerel in Ensenada peaked during the 1990s, but have remained relatively low over the last two decades. For the most part, the Ensenada fishery has been generally comparable in volume to the southern California fishery since 1990 (averaging ~10,000 mt/yr), with some differences for particular years (Table 1). In Mexico, harvested Pacific mackerel have been canned for human consumption or reduced to fish meal.

1.5 Ecosystem Considerations

Pacific mackerel are part of the CPS assemblage of the northeastern Pacific Ocean, which represents an important forage base in the California Current Ecosystem (CCE). Pacific mackerel does not typically represent a dominant species of this assemblage in any given year, with abundances likely less than more productive CPS, such as northern anchovy and Pacific sardine. However, mackerel population biomass can increase to relatively high levels during periods of favorable oceanographic conditions, which likely occur less regularly than observed for anchovy and sardine stocks. Relatedly, periods of low recruitment success driven by prevailing oceanic phenomena can lead to low population abundance over extended periods of time. Readers should consult Field et al. (2001), PFMC (1998, 2021), and NMFS (2022) for comprehensive information regarding environmental processes generally hypothesized to influence small pelagic species that inhabit the CCE.

1.6 Management History

The state of California first implemented formal management associated with the Pacific mackerel stock in 1970, after the stock was thought to have declined substantially during the mid-1960s. A moratorium was placed on the fishery at this time, with a small allowance for incidental catch in mixed-fish landings. In 1972, legislation was enacted that imposed a quota based on the estimate of age-1+ biomass (>1-yr old fish) generated from formal stock assessments. A couple of very strong year classes in the late 1970s led to a brief period of moderately high stock abundance, which was followed by the fishery being reopened under a quota system in 1977. From 1977 to 1985, various adjustments were made to quotas for the directed harvest of Pacific mackerel and related incidental catch limits. It is important to note that even during the moratorium, substantial allowances were made for incidental catches associated with this species (Parrish and MacCall 1978).

State regulations enacted in 1985 imposed a moratorium on directed fishing when the total biomass was less than 18,200 mt, and limited incidental landings of Pacific mackerel to 18% (~3,000 mt) during such periods. At this time, the 'fishing year' was set to extend from July 1st to June 30th of the following year. In summary, seasonal quotas, equal to 30% of the total biomass in excess of 18,200 mt, were allowed when the biomass was between 18,200 and 136,000 mt, with no quota limitations in effect when the total biomass was estimated to be 136,000 mt or higher.

A federal fishery management plan (FMP) for CPS, including Pacific mackerel, was implemented by the PFMC in January 2000 (PFMC 1998). The FMP's harvest policy for Pacific mackerel, originally implemented by the State of California, was based on simulation analysis conducted during the mid-1980s (MacCall et al. 1985), with the addition of a proration to account nominally for the portion of the assessed stock assumed to inhabit U.S. waters (PFMC 1998). The following maximum sustainable yield (MSY) control rule for Pacific mackerel has been generally used for management from the early 2000s to the present:

$$Harvest = (Biomass - Cutoff)E_{MSY} * Distribution$$

where Harvest is the harvest guideline (HG), Cutoff (18,200 mt) is the lowest level of estimated biomass above which harvest is allowed, EMSY (30%, also referred to as exploitation fraction in earlier PFMC documents) is the proportion of biomass above the Cutoff that can be harvested by fisheries, and Distribution (70%) is the average proportion of total Biomass (ages 1+) assumed to reside in U.S. waters. The HGs under the federal FMP are applied to a July to June fishing year. Detailed description of the current management actions applicable to Pacific mackerel, including quotas and related fishing quantities (e.g., acceptable biological catch-ABC, acceptable catch limit-ACL, overfishing limit-OFL, etc.), can be found in the most recent CPS SAFE document (PFMC 2021). Also, see Harvest Control Rules for U.S. Management (2019-20 and 2020-21).

Total annual harvest of Pacific mackerel by the Mexico fishery is not regulated by quotas, but there has been minimum legal size limits (e.g., 25.5 cm) imposed in the past. International management agreements between the U.S. and Mexico regarding transboundary stocks, such as Pacific mackerel, have not been developed to date (see Research and data needs below).

1.7 Management Performance

From 1985 to 1991, the biomass exceeded 136,000 mt and no state quota restrictions were in effect. State quotas for 1992-00 fishing years averaged roughly 24,000 mt. The HGs averaged roughly 15,000 mt from 2001-06. In 2007, the HG was increased substantially to 40,000 mt and remained at this quota until 2009, when the calculated HG (55,408 mt) was reduced by management to 10,000 mt based on limited landings in recent years, with the quota applicable through the 2010-11 fishing year that included an additional 1,000 mt incidental landing allowance (11,000 mt). Following the full stock assessment conducted in 2011, a harvest guideline of roughly 31,000 mt was implemented for two consecutive fishing years. Catch-based projection assessments were used to set quotas for 2013-14 (~39,000 mt) and 2014-15 (~29,000 mt). Quotas have remained at roughly 20,000-25,000 mt since 2015. Note that from a management context, the CPS fishery has not fully utilized HGs since the late 1990s, with total landings far below recommended catches (see Table 2 for harvest regulations from 2008-18).

2 Data

The available data between 2008 and 2021 are shown in Figure 3. Data for model year 2022 were available but not finalized nor included in this base model.

2.1 Fishery-dependent data

Fishery data for assessing Pacific mackerel included landings from California, Oregon, and Washington commercial fisheries, California recreational fishery, and the Mexico commercial fishery from Ensenada, BC and Magdalena Bay, BCS. Additionally, port sample data (ages, lengths, and weights) from from California's commercial fishery were included.

Since 1929, CDFW has collected biological data for Pacific mackerel landed in the southern California fishery (primarily, San Pedro). Limited samples have also been collected from the Monterey fishery when available. Sample data collected from 2008 through 2022 were incorporated in this assessment (Table 3). There was one fishery sample from San Pedro from August 2022 (model year 2022) that was not included. Biological samples from the commercial fishery generally include whole body weight, fork length, sex, maturity (visual), and otoliths for age determination. Currently, CDFW strives to collect 12 'random' (port) samples per month (typically, 25 fish per sample) to determine length/age compositions, as well as catch-at-age, weight-at-age, etc. for the directed fishery.

Additionally, port sampling data for the commercial fishery in Mexico have been collected by the National Fisheries Institute (INAPESCA) since 1989; however, this information has not been made formally available to date and thus, commercial fishery data from the California purse seine fleet were assumed to be representative of the combined fisheries. Lack of data from the Pacific Northwest and Baja California may not be a serious problem for some years when catches were low. However, in some recent years, Baja California catches have equaled or exceed California catches by volume (Table 1), which necessarily increases the likelihood that potential biases associated with the omission of (and subsequent assumptions concerning) sample data from the Mexico and Pacific Northwest fisheries.

Pacific mackerel are aged by CDFW biologists based on identification of annuli in whole sagittae. Historically, a birth date of May 1st was used to assign year class (Fitch 1951). In 1976, ageing protocols changed to a July 1st birth date, which coincided with an increasing population, resumed fishery sampling, and a change in the management season from a May 1st opening to a July 1st start date. Fishery inputs for this assessment were compiled by 'biological year,' based on the birth dates used to assign age. The biological year used in this assessment is synonymous with the 'fishing year' defined previously, as well as with 'fishing season' as reported in the historical literature (from 1976 onwards). All landings and biological compositions included in this assessment were developed on a fishing year (July – June) basis. Sample sizes associated with biological data used in this assessment are presented in (Table 3).

2.1.1 Landings

The assessment includes commercial and recreational landings from calendar years 2008 to 2022. Catch estimates are based on model years and presented by region in Table 1 and Figure 2. Commercial catch statistics compiled in the CPS assessment data base are from the state fishery agencies CDFW (T. Nguyen, pers. comm.), Oregon Department of Fish and Wildlife (ODFW, C. Schmitt, pers. comm.), and Washington Department of Fish and Wildlife (WDFW, L. Wargo, pers. comm.). California recreational catch (mt) time series from 2008 to the present are based on all sport fishery modes (man-made, beach/bank, party/charter, and private/rental) and obtained from CDFW (K. Lynn, pers. comm.).

As in the last assessment (Crone et al. 2019), commercial and recreational catch have been combined into one fishery, given similar selectivity properties between the two fisheries and the limited sport-related catches. To date, the sport fishery has contributed only limited catches to the overall landings of this species. Discards were assumed to be negligible, as in previous assessments, in both the commercial and recreational fisheries associated with this species. The total values summed across region are shown in Table 4 and Figure 4

Mexico landings reflect catches in Baja California from commercial purse seine fleets operating off Ensenada and in Magdalena Bay. Commercial landings from 2008 to 2022 were taken from the National Commission of Aquaculture and Fishing (CONAPESCA) website that archives Mexico's fishery yearbook statistics e.g. CONAPESCA (2020).

2.1.2 Age compositions

Presently, age data are only available from the California commercial fishery, which typically contributes the majority of fish landed at U.S. Pacific coast ports (Table 1). Biological sampling directed towards Pacific mackerel has recently begun in the states of Oregon and Washington, but only limited information is available at this time. Sample sizes (number of fishing trips) and number of measured individuals (specimens) associated with biological compositions included or considered in this assessment are presented in Table 3.

To determine the appropriate proportion of each age in the total fishery landings, the nominal age composition was weighted by the total monthly landings (no. of fish). The following steps were used to develop the weighted age-composition time series (Figure 5):

1) identified an 'age-plus' group (8+) for combining older fish into a single group;
2) determined the number of individuals measured for each year, month, and age, as well as the number of samples taken (samples=fishing trips=unique combination of day/month/year/sample_id);
3) calculated total and average monthly catch weights, as well as average monthly weight-at-age estimates (in mt to match fishery catch units);
4) average monthly weight-at-age estimates were then multiplied by the number of specimens measured, and the product divided by total monthly catch weight to produce age-group proportions;
5) the age-group proportions calculated in step 4 were then multiplied by the total monthly catch to produce the total weight (mt) of each age group in the fishery catch per month;
6) the numbers of fish per age group by month in the total fishery catch were calculated by taking the result of step 5 and dividing by the average monthly weight of each age group calculated in step 3;
7) the monthly calculations of numbers of fish were then aggregated into fishing years (July-June) to produce the numbers of fish-at-age per fishing year and subsequently, summed across ages to produce the total number of fish landed per fishing year; and
8) dividing the result for step 7 by the total number of fish per year produced the final weighted age-composition time series (in proportion) for each fishing year. For the most part, weighted and un-weighted compositions were generally similar, but in some years, estimated proportions of 0- and 1-yr old fish, which typically compose the majority of the overall composition, varied substantially.

Total numbers of ages measured were divided by 25, which is the typical number of fish collected per sampled fishing load. This calculation was used to set the sample sizes for age composition data included in the assessment model. Age compositions were input as proportions.

2.1.3 Ageing error

Pacific mackerel are routinely aged by fishery biologists at CDFW and the SWFSC based on the number of annuli, defined to be the interface between an inner translucent growth increment (Fitch 1951). Ageing error vectors were based on double-read methods and calculated based on the methodology described in Punt et al. (2008). The two ageing error vectors for calendar years 2015-2016 and 2017-2018 for the fishery-dependent data are shown in Table 5 and Figure 12. Additional details on CDFW ageing methodology can be found in Fitch (1951) and past stock assesment reports.

2.1.4 Empirical weight-at-age

A matrix of empirically derived weight-at-age (WAA) data were used in the model to convert estimated numbers-at-age in the model to biomass-at-age. Additionally, the WAA data were a substitute for directly estimating growth in the base model from available age and length composition data (Figure 6). WAA values for each age and model year were calculated with unweighted averages. A specific WAA value had to be calculated from a minimum of three measured fish. Within a cohort, ages without observations were linearly interpolated. A cohort without observations greater than a specific age were assumed to have constant weight-at-age values. For example, the 2013 cohort (Figure 6) did not have any age 6-8 fish measured, and the WAA value for age 5 was assumed to be constant. The 2020 cohort did not have an age-0 WAA value, and this value was assumed to be the pooled age-0 WAA value across all cohorts.

2.2 Fishery-independent data: Acoustic-trawl survey

2.2.1 Overview

This assessment uses a single time series of biomass from the SWFSC's acoustic-trawl (AT) survey. Acoustic sampling of marine environments for determining abundance of fish populations is a standard practice conducted worldwide that continues to receive more focused research in fisheries science, e.g., see Simmonds and MacLennan (2005) for general theory and application of fisheries acoustics, and ICES (2018) for an example of a long-term program for surveying trans-national, wide-ranging small pelagic fish communities. In February 2018, a second review was held for purposes of critically evaluating the AT survey methods in general, as well as determining the utility of these survey data for informing abundance of CPS in both ongoing and future assessments of the small pelagic fish assemblage of the California Current (PFMC 2018). The panel concluded that AT data represent the best scientific information available on an annual basis for assessing abundance of all members of the CPS assemblage (except Pacific herring), and approved the use of these data for directly (survey-based) or indirectly (model-based) assessing the status of the stock, depending on the species of interest (PFMC 2018).

2.2.2 Index of Abundance

Data from the summer SWFSC AT survey from 2008 and 2012-2021 were used in this assessment. A preliminary value for 2022 is available but has not been approved yet. The time series used here is slightly different than that used in Crone et al. (2019). The previous biomass time series borrowed a target strength value and length-weight relationship from South African Jack mackerel to translate abundance at length to biomass. The borrowed length-weight relationship resulted in AT survey empirical weight-at-age values that were lower than those from the fishery data. As a result, the STAT used a recently published Pacific mackerel length-weight relationship (Palance et al. 2019) which was calculated based on AT survey trawl samples. This Pacific mackerel length-weight relationship was used to convert abundance-at-length data to biomass, and the difference between the two biomass time series was about 9% on average. The one exception was the 2015 observation which had a previously published estimate of 7,146 mt but is now 1,353 mt with the updated length-weight relationship (Figure 7). The CVs associated with each estimate were assumed to be unchanged. The values of abundance by fork length and abundance by age are shown in Tables 6 and 7.

The summer 2008 survey were found in stratum with an area of 49,453 nmi^2 with 22 trawls that observed Pacific mackerel. The biomass was estimated to be 58,511 mt with a CV of 0.38. The previous estimate was 55,000 mt (Demer et al. 2012).

The summer 2012 survey biomass estimate was 119,038 mt with a CV of 0.34. The summer 2013 estimate was 9,168 mt with a CV of 0.61. The previous estimates were 109,951 mt and 8,245 mt, respectively (Zwolinski et al. 2014).

The summer 2014 survey biomass was 9,159 with a CV of 0.56. The previous estimate was 10,423 mt. There is no report associated with this survey but the values vere calculated with the same methods as other cruises (Zwolinski, personal communication). The values for this survey were calculated specifically for the 2019 benchmark (Crone et al. 2019).

The summer 2015 survey spanned roughly Haida Gwaii, British Columbia, Canada to San Diego, CA, USA with 79 east-west transects covering 3150 nmi and 158 Nordic trawls (Stierhoff et al. 2018). The biomass estimate is 1,353 with a CV of 0.52. The previous published biomass estimate is 7,146 mt (Stierhoff et al. 2021). This difference is due to the reanalysis of the echograms and is not related to the update of the length-weight relationship.

The summer 2016 survey spanned roughly Cape Scott, British Columbia, Canada to San Diego, CA, USA with 103 east-west transects covering 4,627 nmi and 118 Nordic trawls (Stierhoff et al. 2018b). The biomass estimate is 35,401 with a CV of 0.52. The previous published biomass estimate is 32,782 mt (Stierhoff et al. 2021b).

The summer 2017 survey spanned roughly Cape Scott, British Columbia, Canada to Point Conception, CA, USA with 105 east-west transects covering 3,540 nmi and 83 Nordic trawls (Stierhoff et al. 2018c). The biomass estimate is 45,319 with a CV of 0.26. The previous published biomass estimate is 41,139 mt (Zwolinski et al. 2019).

The summer 2018 survey spanned Cape Scott, British Columbia, Canada to San Diego, CA with 127 east-west transects covering 6,104 nmi and 169 Nordic trawls (Stierhoff et al. 2019a). The biomass estimate is 31,739 mt with a CV of 0.22. The previous published biomass estimate is 33,351 mt (Stierhoff et al. 2019b).

The summer 2019 survey spanned Cape Scott, British Columbia, Canada to San Diego, CA with 140 east-west transects covering 6,691 nmi and 163 Nordic trawls (Stierhoff et al. 2020). The biomass estimate is 27,750 with a CV of 0.24. The previously published biomass estimate is 26,577, with 24,643 core grid and 1,934 nearshore (Stierhoff et al. 2020b).

The summer 2021 survey survey spanned Cape Flattery, WA to Punta Abreojos, Mexico with 141 east-west transects covering 6,749 nmi (Renfree et al. 2022). The biomass estimate is 23,830 with a CV of 0.24. The previously published biomass estimate is 21,998 mt (Stierhoff et al. 2023). There were an estimated 14,202 mt (65%) in Mexican and 7,796 mt (35%) in US waters [see Figure 8; Stierhoff et al. (2023)]

The full time series is shown in Figure 9.

2.2.3 Age compositions

Age composition data are shown in Figure 10. Estimates of abundance-at-length were converted to abundance-at-age using survey-specific age-length keys for the summer surveys (Figure 11). Age-length keys were constructed using ordinal generalized additive regression models from the R package mgcv (Wood 2017). A generalized additive model with an ordinal categorical distribution fits an ordered logistic regression model in which the linear predictor provides the expected value of a latent variable following sequentially ordered logistic distributions. Unlike previous iterations in which the conditional age-at-length was modeled as a multinomial response function 'multinom' from the R package 'nnet', and hence, disregarding the order of the age classes, the order logistical framework provides a more strict structure for the conditional age-at-length, which might, arguably, be beneficial with small sample sizes. The survey age compositions were weighted (i.e input sample sizes in Stock Synthesis) by the number of positive clusters in each cruise. This is in contrast to the calculation for the fishery age compositions, which considered a sample to be the number of total aged fish / 25.

2.2.4 Ageing error

Ageing error vectors were calculated based on the methodology described in Punt et al. (2008) and Thorson et al. (2012). Further details on the ageing methodology are available in Appendix A. The ageing error vectors are shown in Figure 12. There was one ageing error vector for the AT survey data from 2019-2021 (Table 5 and Figure 12).

2.2.5 Empirical weight-at-age

AT survey weight-at-age time series (Figure 6) were calculated for every survey using the following process: 1) the AT-derived abundance-at-length was converted to biomass-at-length using a time-invariant length-to-weight relationship (Palance et al. 2019); 2) the biomass- and numbers-at-length were converted to biomass-at-age and numbers-at-age, respectively, using the above-mentioned age-length keys; and 3) mean weights-at-age were calculated by dividing biomass-at-age by the respective numbers-at-age. The protocols for filling and interpolating missing values were the same as those described in the empirical weight-at-age section for the fishery data.

In the previous assessment, the AT survey and fishery weight-at-age values were assumed to be the same. This assessment utilizes updated age compositions, produced by the Life History Group at the SWFSC.

2.3 Nearshore sampling

The acoustic-trawl survey has had three methods of extrapolating or observing nearshore biomass: model extrapolation, unmanned surface vehicles, and fishing vessel acoustic-trawl methods (Stierhoff et al. 2020b).

With model extrapolation, the easternmost portions of transects are extrapolated to the 5-m isobath in the unsampled nearshore areas. Thus, the length and species compositions associated with the end of the transects are extrapolated to the 5-m isobath.

Unmanned surface vehicles (USVs) generally cover portions of the coast rather than the entire coast. The ability to collect USV observations has depended on the number of USVs available for use and on local wind conditions. The USVs collect acoustic data but do not collect associated biological samples. As a result, the nearest trawl compositions are assumed to be representative of the nearshore acoustic observations when calculating species-specific biomass values.

Fishing vessel acoustic-trawl methods involve equipping vessels with acoustic echosounders and conducting a maximum of one purse seine set during daylight hours. In the case of abundant coastal pelagic species or an unsuccessful daytime set, a set is conducted at night.

Nearshore biomass estimates for Pacific mackerel are: 5.97 mt in 2015 from model extrapolation (Stierhoff et al. 2021), 3,102 mt in 2016 from model extrapolation (Stierhoff et al. 2021b), 1,105 mt in 2017 from model extrapolation (Zwolinski et al. 2019), 1,320 mt in 2018 from model extrapolation (Stierhoff et al. 2019b), 1,934 mt in 2019 from (Stierhoff et al. 2020b) acoustic-trawl fishing vessels, and 1,507 mt in 2021 from acoustic-trawl fishing vessels (Stierhoff et al. 2023).

2.4 Biological Parameters

2.4.1 Stock Structure

Fishery and survey observations from the west coast of the US (California, Oregon, and Washington) and catch values from Mexico (Baja California and Baja California Sur) were assumed to be part of the same stock. Pacific mackerel are found throughout the Northeast Pacific Ocean as described in the introduction.

2.4.2 Growth

Growth was assumed to not be sexually dimorphic, consistent with the assumptions in previous stock assessments (e.g. Crone et al. 2019). The assessment model used empirical weight-at-age values to account for Pacific mackerel growth. This is approach is also consistent with the assessments of other US coastal pelagic species. Estimating growth internally in the stock assessment may be difficult due to variation in time and space and potential confounding between length-based selectivity, age-based availability to fishing/survey gear, and variable growth parameters.

2.4.3 Maturity

Maturity was modeled with a fixed vector of fecundity multiplied by maturity at age. The equation: $Maturity = \frac{1}{1+exp(slope*age-age_{inflection})}$ was used to estimate maturity at age from 494 female mackerel collected from spring and summer AT surveys from 2010-2021. The fixed maturity-at-age vector used as input for the population is shown in Table 8 and Figure 13

2.4.4 Natural mortality

In past assessments, natural mortality rate (M) was assumed to be 0.5 yr-1 and constant over time for all ages. Parrish and MacCall (1978) estimated natural mortality for Pacific mackerel using early catch curves (M = 0.3-0.5), regression of Z on f (M = 0.5), and comparative studies of maximum age [M = 0.3-0.7; Beverton (1963)] and growth rate [M = 0.4-0.6; Beverton and Holt (1959)]. The above research and overall conclusions considered the regression of Z on f to be the most reliable method, with the estimate M = 0.5 falling within the range of the plausible estimates.

Given past uncertainty associated with assumed rates of M to consider for Pacific mackerel, as well as other members of the small pelagic species assemblage of the CCE, M was estimated in this assessment with a longevity-based prior described in Hamel and Cope (2022). The maximum age assumed for the prior was age-8, which is also the beginning of the plus group assumed in this assessment. The prior on M was lognormal with a mean of -0.393 (0.675 in linear space; 5.40 / 8 the assumed age max) and SD of 0.31 (Hamel and Cope 2022).

2.5 Available Data Sets Not Used in Assessment

The STAT investigated three fishery-independent data sets, that were ultimately not incorporated to this assessment: Investigaciones Mexicanas de la Corriente de California (IMECOCAL), California Cooperative Oceanic Fisheries Investigations (CalCOFI), and the Rockfish Recruitment and Ecosystem Assessment Survey (RREAS). IMECOCAL and CalCOFI seasonally sample eggs and ichthyoplankton in fixed grids in Mexican and US waters, respectively. The challenge with these data sets is that there is not a straightforward method of directly incorporating data from these early life stages, directly into the assessment framework. The RREAS data set has sparse observations for Pacific mackerel (134 individuals observed from 1990-2018).

The 2022 AT survey biomass estimate is available for Pacific mackerel. However, due to logistical constraints, the survey area off Washington, Oregon, and part of northern California had to be conducted with fishing vessel acoustic-purse seine sampling. Acoustic-trawl sampling aboard the SWFSC's R/V *Reuben Lasker* began off northern California and proceeded south. Due to these differences with the preceding AT survey protocols, the 2022 biomass estimate and associated age compositions were not included in this benchmark.

Catch data and biological compositions are available prior to 2008, but the potential benefits of extending the modeling timeframe were not clear.

3 Stock Assessment Model

3.1 History of modeling approaches

Parrish and MacCall (Parrish and MacCall 1978) were the first to provide stock status determinations for Pacific mackerel using an age-structured population model (virtual population analysis, VPA). Beginning in the mid-1990s, the ADEPT model, which was based on the ADAPT VPA and modified for Pacific mackerel (Jacobson 1993, Jacobson et al. 1994), was used to evaluate stock status and establish management quotas for approximately 10 years. The assessment conducted in 2004 (for 2004-05 management) represented the final ADEPT-based analysis for this stock (see Hill and Crone 2004). The forward-simulation model ASAP (Legault and Restrepo 1998) was reviewed and adopted for Pacific mackerel at the STAR conducted in 2004 (Hill and Crone 2004). The ASAP model was used for assessments and management advice from 2005 through 2008. The STAR conducted in 2009 supported decisions to begin using the Stock Synthesis (SS) model for conducting formal stock assessments of Pacific mackerel in the future (Crone et al. 2009, PFMC 2009); the SS model has been used for all assessments since 2009. A full (benchmark) stock assessment and review for this species were conducted in 2011 (Crone et al. 2011), with a harvest guideline (HG) serving for two fishing years. In 2013 and 2014, catch-based projection assessments were conducted and used to set the HGs (Crone 2013, Crone and Hill 2014). In 2015, a benchmark assessment was conducted for purposes of providing management advice that served for two (fishing) years, 2015-16 and 2016-17 (Crone and Hill 2015). A catch-only projection assessment was conducted in May 2017 that provided HGs for managing the Pacific mackerel resource for fishing years 2017-18 and 2018-19 (Crone and Hill 2017). The most recent benchmark assessment was conducted in 2019 (Crone et al. 2019).

3.2 2019 STAR Panel Recommendations

High priority

1. Improve collaboration with fishery researchers from Mexico. As noted in previous assessment reviews, a large fraction of the catch is taken off Mexico, and efforts should be made to obtain length, age and related biological data from the Mexican fisheries. Inclusion of the AT surveys in the assessment has increased the need for comparable surveys within Mexican waters because such information could be used to develop a nearly comprehensive index of the abundance of the transboundary stock of Pacific mackerel. Alternatively, collaborative research extending the AT survey into Mexican waters would also achieve the goal of encompassing the full range of Pacific Mackerel.

- The AT survey began surveying Mexican waters in 2021. This was the result of extensive work by members of the Advanced Survey Technologies and Life History Group at the SWFSC. This achievement was awarded a Department of Commerce Silver Award in 2022 and the data are used in this assessment.

2. Continue to refine the indices of abundance. The Panel considers an AT survey to be an appropriate way to index the abundance of CPS such as Pacific mackerel. The PFMC conducted reviews of the AT survey in 2011 (PFMC 2011) and in 2018 (PFMC 2018).

Some of the recommendations from those reviews have been implemented (e.g. Zwolinski and Demer, 2014). However, most of the recommendations, even those from the 2011 review, have yet to be addressed. The following are a subset of tasks to better realize the potential of the AT survey for Pacific mackerel:

a. Trawl sampling during the day to address the potential for differences in fish represented by the signal from the acoustic sampling during the day versus trawl sampling at night to capture the species, length and age composition of the sampled fish.

- This will be one component of experimental trawling scheduled for summer 2023.

b. Refine the target strength estimates for Pacific mackerel.

- This may be evaluated in the future.

c. Provide separate estimates of age-0 and age-1+ Pacific mackerel biomass from the AT survey. There appears to be more uncertainty in the enumeration of age-0 mackerel than of other age classes due to the spatial distribution and age-specific selectivity patterns.

- This calculation is possible but has not been provided.

3. Standard data processing procedures should be developed for CPS, similar to those developed for groundfish species, and a 'data document' developed that provides, in considerable detail, how the basic data sources (e.g., catches, CPFV indices, etc.) are constructed. Much of this information has been published in the past, but a single (and 'living') document describing the basic data will assist assessment authors and future review panels.

- See this document and Appendix A for documentation

4. Investigate the spatial distribution, especially the range, of the Pacific mackerel population over time and whether this changes with population size and/or environmental conditions. In particular, an environmentally based index of spatial distribution might prove useful for developing priors for AT survey catchability for use in future assessments.

- See response to number 1

5. Improve collection of age data, coordination of ageing laboratories and cross validation efforts to standardize reads between laboratories and develop bias adjustments.

a. Increase support for current port sampling and laboratory analysis programs for CPS, particularly in the Pacific Northwest. Biological (e.g. length, age, sex) data on mackerel caught in the Pacific Northwest should be collected. These data could further assist in understanding whether and to what extent selectivity for the commercial fishery is domeshaped. The aging of Pacific sardine in the Pacific Northwest should be coordinated with laboratories conducting ageing in California.
b. Analysis of data from the multistage approach to age/length composition sampling has indicated that most of the variability occurs between commercial trips as opposed to replicate sampling of a landing within a landing. The number of trips sampled is relatively low due to the infrequent fishing and need to coordinate sampling with industry to increase the effective sample size. Many samples from the Pacific Northwest have not been processed and should be aged with methods consistent with those currently employed by the CDFW from the commercial fishery.
c. Ageing of survey collections for the survey age production laboratory at SWFSC needs increased collaboration to increase precision in reads. Reading of otoliths from the AT survey should be prioritized to alleviate the need for using age length keys to convert lengths to ages with greater potential for bias and imprecision. Production ageing of otoliths from the AT survey needs validation and verification of age reads between observers or laboratories should be conducted to provide reads consistent with those currently provided by CDFW for commercial landings, relying on experienced age readers as the basis for comparison between laboratories.
d. Cross reads should be conducted between laboratories or, preferably, reads simply done by CDFW staff to provide greater consistency and precision. Ageing bias can be identified using cross-reads of the same otoliths among laboratories.

- The SWFSC hired full time staff in the Life History Program to improve the collection and processing of age data, standardize ageing protocols, cross-validate reads, improve ageing precision, and develop bias adjustments. Three SWFSC readers aged 1,762 Pacific mackerel collected from the 2012-2022 AT surveys for this assessment, including samples collected from the Pacific Northwest. The SWFSC readers trained with the best CDFW reader and generated a standardized protocol, and 317 Pacific mackerel were cross-read by all four readers. This collaborative effort significantly improved the quality of age data, as bias among readers was low and precision was high (See Appendix A). A forthcoming Tech Memo will summarize ageing efforts by the SWFSC Life History Program for Pacific mackerel in greater detail. Additionally, there are plans to reach out to Pacific mackerel age reading labs in the Pacific Northwest to examine interagency comparisons.

6. Revisit the harvest control rules and reference points for Pacific mackerel. The basis for the current harvest cutoff are derived from analyses performed by MacCall et al. (1985)

over 30 years ago using data, biological assumptions (e.g. about selectivity and natural mortality), and methods (virtual population analysis) that are not reflected in the current stock assessment. If the underlying data and assumptions used by MacCall et al. (1985) are no longer considered relevant to the current population as reflected in the ALT_19 assessment model, it is likely time to revise the scientific basis for these reference points.

- The harvest control rules have not been revisited. Catches have been below harvest guidelines in the time frame of this model (2008-2021).

Medium priority

1. Examine whether parameters such as growth rate and asymptotic size have changed over time.

- Growth was not modeled internal to the assessment.

2. Conduct a study to update the information used to determine maturity-at-length (and maturity-at-age).

- See Appendix A

Low Priority

1. Explore the feasibility of modeling non-landed mortalities of sublegal-sized fish in the Mexican fishery

- This has not been explored yet.

3.3 Base model description

A number of features have been modified for the 2023 benchmark assessment (Figure 14):

- Use of SS3.30.20 which was the most recent version (v3.30.21 has since been released)
- Extension of main recruitment deviation period to 2021

- Equal weight (lambda=1) for fishery and AT survey age compositions. The previous model downweighted (lambda=0.5) the AT survey age compositions, which were derived from an ALK developed from fishery-dependent data.

- Addition of SR_regime block parameter. Previously the model, which begins in 2008, was assumed to be starting from equilibrium recruitment conditions. Estimation of this additional parameter accounts for the model period beginning in a fished state which more closely matches the reality of the stock's history.

- The 2021 AT survey had observations from both US and Mexican waters, and we assumed Q to be calculated from the data and fixed in this year. Time-varying blocks for Q were added for previous years to better fit the index data. The priors for Q in these blocks were assumed to be centered at the 2021 estimate.

- Time-varying fishery selectivity, modeled to have the random-walk (one selectivity parameter per age; option 17 in SS3) with parameter deviations estimated with the two-dimensional auto-regressive smoother. This treatment was also used in the 2021 anchovy benchmark assessment (Kuriyama et al. 2020).

- Age-specific, time-invariant natural mortality across age 0-8. An average value of M is estimated in SS3, with a longevity-based prior assuming a maximum age of 8 per Hamel and Cope (2022).

3.3.1 Time period and time step

The modeled timeframe begins in 2008 and extends through 2021, to match the availability of the AT survey data (Figure 3). Annual timesteps are used in this assessment and the model year is aligned with the fishing year which spans July of one calendar year to June of the following calendar year. For example model year 2021 represents July, 2021 to June, 2022.

The goal of this assessment is to estimate terminal year stock biomass and forecast biomass levels for the following two fishing years. Extension of this model prior to 2008 may result in different estimates of scaling parameters but may not result in significantly different biomass estimates for recent years.

3.3.2 Forecast

Stock biomass was forecasted for model years 2022, 2023, and 2024. There are 2022 AT survey biomass data available but these were not included due to logistical challenges that limited the survey protocols. The catch values used in the forecast file were data for 2022 and catch values averaged from 2019-2022 for 2023 and 2024. The fishery selectivity pattern in the forecast file was assumed to be the selectivity curve estimated in 2021.

3.3.3 Stock-recruit relationship

Equilibrium recruitment (R_0) and initial recruitment equilibrium offset (SR_{regime}) were estimated in the base model. Steepness (h) and average recruitment variability (σ_R) were fixed at 0.75 and 0.75, respectively. These were the values used in the previous stock assessment (Crone et al. 2019). Recruitment deviations were estimated as separate vectors for the early and main data periods in the model. A recruitment bias adjustment ramp (Methot and Taylor 2011) was applied to the early period and adjusted recruitment in the main period of the model.

3.3.4 Catchability

There is a high degree of variability in the index of abundance that is unlikely to be due to recruitment and natural mortality. For example, in 2012 the AT survey estimate was about 120,000 mt and the biomass estimates from 2013-2015 ranged from 1,353 to 9,168 mt. The STAT assumed that this decrease in biomass was due to a change in catchability (Q) rather than a large mortality event coupled with low recruitment. Pacific mackerel catchability could vary through time due to time-varying availability (i.e. migrations and movement) or due to gear avoidance.

The STAT modeled four blocks (2008-2012, 2013-2015, 2016-2019 and 2021) for Q. The 2021 Q value was assumed to be the base parameter, with the three prior blocks estimated with the block replacement feature in SS3. The 2021 Q value was fixed at 0.357 (-1.030 in log space) based on the biomass observed in the US and Mexico. Additionally, the 2021 Q value was the prior for the other Q blocks. The STAT made this decision as this is the only data value available for Pacific mackerel distributions in the US and Mexico.

3.3.5 Selectivity

Fishery selectivity was estimated to be time-varying with the 2dAR feature in SS3 (Xu et al. 2019). The base selectivity form was estimated as a "random walk" using SS3 terminology. In practice, the "random walk" form estimates a selectivity parameter for each age, and deviations around this base curve are estimated to be autoregressive through time. The goal of this configuration was to capture the year-to-year variability in the fishery age composition data.

AT survey age-0 selectivity was estimated to be time-invariant. Other CPS assessments (e.g. Kuriyama et al. 2020) estimated age-0 selectivity to be time-varying. However, estimating time-varying selectivity for the AT survey resulted in a high estimate of M (roughly 1 for the average value across all ages). Biologically it does not seem possible that M for Pacific mackerel was greater than that for Pacific sardine and northern anchovy and the STAT decided to estimate age-0 selectivity to be time-invariant.

3.3.6 Likelihoods components and model parameters

A complete list of model parameters estimated in the base model is shown in Table 9. The total objective function was based on the likelihood components from fits to the AT survey abundance index and fishery and AT survey age compositions (Table 10).

3.3.7 Bridging analysis

Figure 14 shows the addition of each major feature to the 2019 benchmark model. The additions of the Q blocks and time-varying fishery selectivity resulted in the largest changes in summary biomass estimates.

3.4 Base model results

3.4.1 Likelihoods and quantities of interest

The total likelihood value was 111.69 and the gradient was 9.432e-05. Likelihood values from the age-compositions and parameter deviations constituted a majority of the total likelihood. The forecast summary biomass values for model years 2022, 2023, and 2024 are 41,955, 45,902, and 46,808 mt, respectively.

3.4.2 Selectivity estimates and fits to fishery and survey age-compositions

Time-varying age-based selectivities were estimated for the fishery (Figure 15). Fits to the fishery age-composition data were relatively good, as the flexible 2dAR selectivity captured year-to-year variability (Figures 16 and 17). The fits to the survey age compositions are shown in Figure 18 and 19.

3.4.3 Fit to survey index of abundance

The base model, with time-varying Q values, fit all the AT survey indices of abundance except for in 2015 (Figures 20 and 21). The values of Q are shown in Figure 22, and the values of age-specific M are shown in Figure 23.

3.4.4 Stock-recruitment relationship

Recruitment was modeled using a Beverton-Holt stock-recruitment relationship (Figure 24). The recruitment deviations are presented in Figure 25. Asymptotic standard errors for recruitment deviations are shown in Figure 26 and the recruitment bias adjustment plot is shown in Figure 27. Note steepness and σ_R were both fixed at 0.75.

3.4.5 Population numbers- and biomass-at-age estimates

The population age distributions (by numbers of fish) are shown in Figure 28 and Table 11. Corresponding estimates of population biomass-at-age, total biomass (age-0+, mt) and summary biomass (age-1+, mt) are shown in Table 12.

3.4.6 Biomass and recruitment

Time series of estimated spawning stock biomass (SSB; mt) and associated 95% confidence intervals are presented in Table 13 and Figure 29. The estimated recruitment time series is shown in Table 13 and Figure 30.

Total and summary biomass values are shown in Table 14 and Figure 31. The 2021 summary biomass estimate is 40,024 mt.

3.4.7 Fishing mortality

Estimated fishing mortality (apical F) time series are presented in Figure 32. Exploitation rates are shown in Table 15 and Figure 33.

3.5 Modeling Diagnostics

3.5.1 Convergence

Convergence was evaluated by starting model parameters from values jittered from the maximum likelihood estimates. Starting parameters were jittered by 5% for 50 replicates and 10% for 20 replicates. A lower likelihood was not found, and nearly all the replicates for both scenarios converged to the maximum likelihood value from the base model. The hessian was invertible in the base model.

3.5.2 Retrospective analysis

The base model has a time-varying Q value, and as a result, there is expected to be a strong retrospective pattern. The 2021 Q value was fixed at the observed proportion of biomass in US waters. There was no AT survey in 2020 due to COVID, and the 2019 Q value was estimated with a prior centered at the 2021 Q value. The changes in the time-varying Q will likely have large retrospective patterns due to model configuration. The STAT has not currently conducted the retrospective analysis for this document but will anticipate conducting this sensitivity at the STAR panel review.

3.5.3 Historical analysis

The historical analysis for summary biomass is shown in Figure 34. The assessments shown are from 2005, 2011, 2015, and 2019.

3.5.4 Likelihood profiles

There was not much information in the age compositions nor AT index of abundance to estimate steepness (Table 16 and Figure 35). Steepness was fixed at 0.75 in the base model. There is a relatively weak data conflict between the survey and age compositions as steepness decreases below 0.75.

Neither the age compositions nor survey data seemed to have any information on catchability (Table 17 and Figure 36). Specifically the survey data contained little information to estimate catchability (Figure 36).

The AT survey age compositions seemed to contain the most information to estimate M and all the data sets were in relative agreement (Table 18 and Figure 37.

3.5.5 Sensitivity to alternative data weighting

The base model was run with age compositions reweighted according to the Francis method (Francis 2011) to evaluate model sensitivity to data weighting. The variance adjustment values were 4.161 for the fishery age comps and 0.508 for the AT survey age comps (Table 19). Parameter estimates, biomass estimates, and likelihood values are shown in Table 19 and Figure 38. With Francis reweighting, the 2021 summary biomass value increase from 40,024 in the base model to 43,962.

The base model was also run with downweighted age compositions (lambda = 0.5 rather than 1 in the base model) to evaluate model sensitivity to data weighting. Parameter estimates, biomass estimates, and likelihood values are shown in Table 20 and Figure 39.

4 Harvest Control Rules

Note, this section is just copied and pasted from the 2019 benchmark assessment. This section will be updated with the appropriate values after the STAR panel, once a base model has been finalized.

Since 2000, the Pacific mackerel stock has been managed under a Federal Management Plan (FMP) harvest policy, stipulating that an optimum yield for this species be set according to the following harvest control rule (HCR):

$$Harvest = (Biomass - Cutoff) * E_{MSY} * Distribution$$

where Harvest is the harvest guideline (HG), Biomass is age 1+ stock biomass (mt) in the respective fishing year (71,099 mt in July 2019 and 56,058 mt in July 2020), Cutoff (18,200 mt) is the lowest level of estimated biomass above which harvest is allowed, EMSY (30%, also referred to as Fraction) is the proportion of biomass above the Cutoff that can be harvested by fisheries, and Distribution (70%) is the average proportion of stock biomass (ages 1+) assumed in U.S. waters (PFMC 1998). Harvest stipulations under the federal FMP are applied to a July-June fishing year. The HG estimate associated with final base model ALT_19 for July 2019 was 11,109 mt (Table ES-3a) and 7,950 mt for July 2020 (Table ES-3b). Additional HCR statistics are also included in Tables ES-3a-b for specifying overfishing limits (OFL), as well as a range of acceptable biological catches and limits (ABCs and ACLs) based on different probability levels of overfishing using 'P-star' and associated ABC 'buffer' calculations. Final base model ALT_19 estimates of SSB uncertainty, used for calculating sigma for P-star buffers, were CV=37.6% (σ=0.363) in 2019 and 2020 was based on the assumption that that projected catch for 2019 was similar to estimated landings in 2018 (12,000 mt), with predicted recruitment (i.e., 2019 and 2020 cohorts) for the forecast period estimated directly from the spawner-recruit relationship as recommended in previous reviews. Landings and associated HGs since 2008 are presented in Table 11. Finally, additional HCR statistics are also included in Table 10a-b for specifying overfishing limits (OFLs), as well as a range of acceptable biological catches and limits (ABCs and ACLs) based on different probability levels of overfishing using 'P-star' and associated ABC 'buffer' calculations. Final base model ALT_19 estimates of SSB uncertainty, used for calculating sigma for P-star buffers, were CV=37.6% (σ=0.363) in 2019 and CV=45.4% (σ=0.433) in 2020, so the current default sigma (0.5) was applied to Tier 1 ABCs in Table 10a-b.

5 Research and Data Needs

Extending the AT survey into Mexican waters should continue to be a top priority. The data collected on these surveys are valuable for the stock assessment (see fixed 2021 Q value) and will enable future research into the movement and distribution of Pacific mackerel (and other CPS like Pacific sardine).

Thanks to the full time staff at the SWFSC, the AT survey age data are no longer a major data need. Efforts to coordinate with state agencies and, perhaps in the future, Mexican agencies should continue as age-composition data are crucial for stock assessment.

The harvest control rule utilized in the Pacific mackerel federal CPS-FMP was developed in the mid-1980s based on estimated abundance and spawner-recruit data available at that time. Harvest strategies should be re-examined using updated data and simulation methods.

6 Acknowledgements

Will be filled for final version of the document.

7 Tables

Table 1: Landings (mt) of Pacific mackerel by region and fishing year (1999-2022). Landings values from 2008-2022 were included in the assessment (see horizontal line). Mexican landings were from Magdalena Bay, BCS (MAG) and Ensenada, BC (ENS). US landings are from California (CA), Oregon (OR), Washington (WA). Additionally, California recreational landings are included (CA-REC). The total (TOT) landings are summed across all regions and used as input to the stock assessment. Note that model years include data from two calendar years. For example, model year 1999 includes landings from July 1, 1999 to June 30, 2000 to align with the fishery management timeframes.

Model Year	MAG	ENS	MEX-TOT	CA	OR	WA	CA-REC	USA-TOT	TOT
1999	97	2,524	2,621	3,634	0	0	26	3,660	6,281
2000	0	6,530	6,530	20,936	139	48	325	21,449	27,979
2001	372	3,631	4,003	8,436	303	271	571	9,580	13,584
2002	3,050	7,278	10,328	3,541	128	249	254	4,171	14,499
2003	222	2,396	2,618	5,972	159	53	323	6,508	9,125
2004	83	1,628	1,711	5,012	111	24	544	5,690	7,402
2005	7	3,078	3,085	4,572	314	22	411	5,320	8,405
2006	19	1,967	1,986	7,870	669	42	372	8,953	10,939
2007	28	2,190	2,218	6,208	698	38	310	7,254	9,472
2008	689	114	803	4,198	58	9	279	4,543	5,346
2009	49	0	49	3,279	54	5	269	3,607	3,656
2010	312	1,605	1,917	2,047	48	2	216	2,313	4,229
2011	1,081	1,151	2,232	1,665	202	83	124	2,074	4,306
2012	7,219	171	7,390	3,202	1,588	719	99	5,608	12,998
2013	2,071	482	2,553	11,165	438	173	133	11,909	14,462
2014	2,757	1,342	4,099	3,651	1,215	502	225	5,593	9,692
2015	3,663	5,515	9,179	4,435	7	1	243	4,686	13,865
2016	5,730	5,977	11,707	2,523	4	22	209	2,757	14,464
2017	2,224	585	2,810	1,513	45	4	245	1,808	4,617
2018	3,422	12,330	15,752	2,199	112	10	180	2,501	18,252
2019	16,777	2,297	19,074	3,783	50	5	78	3,916	22,990
2020	26,136	5,232	31,368	500	101	3	87	691	32,060
2021	7,649	1,760	9,409	847	86	0	73	1,007	10,416
2022	7,649	7,361	15,010	543	366	26	56	990	16,000

Table 2: Pacific mackerel US overfishing limits (OFL), allowable biological catches (ABC), allowable catch limits (ACL), harvest guidelines (HG) since 2008. Total US landings (USA-TOT) and the percentage of ACL are also shown. Model year 2008, for example includes landings from July 1, 2008 to June 30, 2009 to align with fishery management timeframes.

Model Year	OFL	ABC	ACL	HG	USA-TOT	PercHG
2008	NA	NA	40,000	NA	4,543	11%
2009	NA	NA	10,000	NA	3,607	36%
2010	NA	NA	11,000	NA	2,313	21%
2011	44,336	42,375	40,514	30,386	2,074	7%
2012	44,336	42,375	40,514	30,386	5,608	18%
2013	57,316	52,358	52,358	39,268	11,909	30%
2014	32,992	30,138	29,170	24,170	5,593	23%
2015	25,291	23,104	21,469	20,469	4,686	23%
2016	24,983	22,822	21,161	20,161	2,757	14%
2017	30,115	27,510	26,293	25,293	1,808	7%
2018	27,662	25,269	23,840	22,840	2,501	11%
2019	14,931	13,169	11,109	10,109	3,916	39%
2020	11,772	10,289	7,950	6,950	691	10%
2021	12,145	9,446	8,323	7,323	1,007	14%
2022	9,644	7,501	5,822	4,822	990	21%

Table 3: Pacific mackerel samples from the California commercial fishery and AT survey. The numbers of samples, ages, and age 8+ fish are shown for the fishery. For the AT survey, there were no age 8+ fish and the number of aged fish are shown. The numbers of lengths and weights are the same as the number of ages.

		FisheryFishery		SurveySurvey
Model year	N samples	N fish	N 8+	N fish
2008	29	725	2	0
2009	17	440	18	0
2010	18	512	15	0
2011	26	775	4	0
2012	48	1,198	3	449
2013	72	1,800	7	9
2014	56	1,396	1	45
2015	18	447	0	26
2016	20	494	0	82
2017	9	222	0	110
2018	6	148	0	371
2019	10	250	0	289
2021	8	200	0	183
2022	1	25	0	198

Table 4: Pacific mackerel catch (mt) by landing year input to the base model. The model year for 2008, for example, includes landings from July 1, 2008 to June 30, 2009. Catch data for 2022 were used in the base model forecast file as the last model year in the assessment was 2021.

Model Year	Catch (mt)
2008	5,346
2009	3,656
2010	4,229
2011	4,305
2012	12,997
2013	14,461
2014	9,691
2015	13,865
2016	14,464
2017	4,617
2018	18,252
2019	22,989
2020	32,059
2021	10,415
2022	16,000

Table 5: Standard deviations of ageing error, arranged by age, for Pacific mackerel. Ageing error from the AT survey and fishery are shown.

Age	Fishery	AT survey
0	0.32	0.00
1	0.32	0.00
2	0.55	0.15
3	0.79	0.23
4	1.04	0.27
5	1.31	0.30
6	1.59	0.31
7	1.88	0.32
8	2.19	0.32

Table 6: Abundance by fork length (cm) for AT summer surveys from 2012 to 2022.

FL (cm)	2012	2013	2014	2015	2016	2017	2018	2019	2021	2022
8	0	0	0	0	4,135,821	0	0	0	0	41,814,427
9	0	0	0	0	0	0	6,743,924	6,743,924	428,113	36,269,442
10	0	0	0	0	4,098,922	0	60,695,315	60,695,315	776,215	25,256,609
11	0	0	0	0	495,151	0	135,203,988	135,203,988	93,942	78,306,355
12	0	0	589,930	0	10,534	0	83,032,095	83,032,095	760,693	36,190,083
13	0	0	0	0	513,877	0	45,019,544	45,019,544	2,200,508	4,934,019
14	0	0	0	0	3,400,322	0	28,271,563	28,271,563	6,707,487	9,970,176
15	0	0	589,930	0	140,120,589	0	102,859,438	102,859,438	6,924,410	17,995,740
16	0	0	2,359,721	0	140,445,041	0	85,131,501	85,131,501	3,858,857	14,103,694
17	0	0	589,930	0	564,583	0	18,780,235	18,780,235	8,936,143	11,092,929
18	0	0	1,179,860	0	222,670	0	17,884,006	17,884,006	11,165,214	14,111,066
19	0	0	1,769,790	0	2,221,024	0	17,589,955	17,589,955	21,076,531	4,113,360
20	0	0	589,930	0	144,282,995	0	1,207,190	1,207,190	19,608,695	1,842,523
21	26,264,946	0	0	0	12,701,738	0	1,235,522	1,235,522	30,395,251	2,727,661
22	4,420,079	4,965	0	67,679	11,239,310	0	16,150,698	16,150,698	26,348,708	1,317,896
23	2,698,532	0	0	184,835	11,193,303	63,950	0	0	23,062,284	976,320
24	43,651,664	0	0	248,469	12,680,136	4,307,611	238,131	238,131	16,299,526	412,623
25	76,410,284	0	0	744,452	4,932,854	15,681,142	1,366,016	1,366,016	5,622,562	501,368
26	162,917,641	4,965	707,811	1,418,233	1,262,309	38,091,584	2,736,261	2,736,261	1,931,577	575,014
27	161,713,912	558,272	0	905,898	792,413	47,794,765	1,954,689	1,954,689	371,503	1,659,187
28	40,953,968	7,264,697	0	1,041,195	557,164	36,028,892	4,451,299	4,451,299	0	693,934
29	20,881,761	8,694,120	1,225,926	462,819	1,034,677	13,328,999	7,394,546	7,394,546	24,672	1,009,929
30	6,088,585	6,907,247	1,663,349	31,089	1,312,437	5,232,239	10,182,669	10,182,669	123,358	30,972
31	1,212,517	1,776,998	5,111,446	4,432	1,617,476	3,708,441	10,542,879	10,542,879	409,107	483,707
32	145,477	2,153,637	6,561,372	0	1,796,604	5,918,203	1,402,458	1,402,458	49,343	46,458
33	246,982	1,233,623	3,435,199	361,579	1,306,108	3,140,715	619,747	619,747	471,483	15,486
34	855,801	0	709,506	8,864	0	1,457,915	76,341	76,341	5,274,991	15,486
35	855,801	156,805	1,375,500	26,657	89,120	860,964	0	0	335,092	46,458
36	0	0	687,750	22,224	178,240	575,634	0	0	496,155	0
37	648,328	0	0	0	0	150,781	0	0	24,672	0
38	0	0	0	0	0	89,099	0	0	1,476,761	152,226
39	0	0	0	0	0	0	0	0	0	0
40	29,529	0	0	0	0	0	0	0	0	0

Table 7: Abundance by age for AT summer surveys from 2012 to 2022.

Age	2012	2013	2014	2015	2016	2017	2018	2019	2021	2022
0	194,517,355	194,517,355	8,114,309	1,796,645	466,835,981	32,409,605	622,895,074	846,230,237	136,466,340	299,590,444
1	311,577,301	311,577,301	3,934,681	2,783,473	28,436,595	93,456,933	10,787,379	35,066,954	48,554,378	5,677,958
2	39,268,492	39,268,492	5,311,950	470,493	4,269,920	44,594,499	24,239,648	12,298,455	2,521,360	786,103
3	3,401,988	3,401,988	6,318,553	265,103	3,263,356	3,231,279	2,577,133	18,454,929	4,454,624	414,419
4	11	11	4,487,425	178,617	6	938,142	134,235	2,198,805	1,649,663	76,865
5	931,954	931,954	980,029	34,098	399,567	1,696,157	136,529	977,360	1,286,213	91,540
6	20	20	2	0	0	104,313	4	10	321,283	27,816
7	NA	298,687	2	0	0	2	4	10	0	0

Table 8: Proportion of mature mackerel by age. The number of mature fish, number of total fish, and predicted proportion of mature fish by age from a binomial GLM are shown.

Age	N mature	Total fish	Predicted
0	16	106	0.12
1	88	189	0.49
2	105	120	0.87
3	66	66	0.98
4	8	8	1.00
5	5	5	1.00
6	-	-	1.00
7	1	1	1.00

Table 9: Parameter estimates in the base model. Estimated values, standard deviations (SDs), bounds (minimum and maximum), estimation phase (negative values indicate that a parameter was not estimated), status (indicates if parameters are near bounds), and prior type information (mean, SD) are shown.

Parameter	Value	Phase	Bounds	Status	SD
NatM_Lorenzen_averageFem_GP_1	0.7845	3	(0.3, 1.1)	OK	0.1034
SR_LN(R0)	13.3308	1	(5, 20)	OK	0.3113
SR_regime_BLK3repl_2007	-0.3046	1	(-15, 15)	OK	0.5456
Early_InitAge_6	-0.0081	3	(-6, 6)	act	0.7476
Early_InitAge_5	-0.0506	3	(-6, 6)	act	0.7269
Early_InitAge_4	-0.0071	3	(-6, 6)	act	0.7323
Early_InitAge_3	0.3299	3	(-6, 6)	act	0.6459
Early_InitAge_2	-0.1272	3	(-6, 6)	act	0.6431
Early_InitAge_1	-0.3552	3	(-6, 6)	act	0.6080
Main_RecrDev_2008	-0.0784	1	(-6, 6)	act	0.4201
Main_RecrDev_2009	-0.5746	1	(-6, 6)	act	0.5162
Main_RecrDev_2010	0.2412	1	(-6, 6)	act	0.3890
Main_RecrDev_2011	0.9952	1	(-6, 6)	act	0.2736
Main_RecrDev_2012	-0.0970	1	(-6, 6)	act	0.2758
Main_RecrDev_2013	-0.3958	1	(-6, 6)	act	0.2902
Main_RecrDev_2014	-0.3262	1	(-6, 6)	act	0.2668
Main_RecrDev_2015	-0.1308	1	(-6, 6)	act	0.2427
Main_RecrDev_2016	0.4416	1	(-6, 6)	act	0.2378
Main_RecrDev_2017	-0.9844	1	(-6, 6)	act	0.3162
Main_RecrDev_2018	0.2346	1	(-6, 6)	act	0.2383
Main_RecrDev_2019	0.6155	1	(-6, 6)	act	0.2561
Main_RecrDev_2020	0.0541	1	(-6, 6)	act	0.3513
Main_RecrDev_2021	0.0050	1	(-6, 6)	act	0.3288
ForeRecr_2022	0.0000	4	(-6, 6)	act	0.7500
ForeRecr_2023	0.0000	4	(-6, 6)	act	0.7500
ForeRecr_2024	0.0000	4	(-6, 6)	act	0.7500
ForeRecr_2025	0.0000	4	(-6, 6)	act	0.7500
LnQ_base_AT(2)_BLK4repl_2008	-0.5701	1	(-4.59, 5.41)	OK	0.3705
LnQ_base_AT(2)_BLK4repl_2013	-2.7647	1	(-4.59, 5.41)	OK	0.3492
LnQ_base_AT(2)_BLK4repl_2016	-0.6979	1	(-4.59, 5.41)	OK	0.2500
AgeSel_P2_FISHERY(1)	1.2519	2	(-5, 9)	OK	0.4611
AgeSel_P3_FISHERY(1)	0.0456	2	(-5, 9)	OK	0.5338
AgeSel_P4_FISHERY(1)	0.2074	2	(-5, 9)	OK	0.7649
AgeSel_P5_FISHERY(1)	-2.7018	2	(-5, 9)	OK	10.9284
AgeSel_P6_FISHERY(1)	2.1511	2	(-5, 9)	OK	12.0947
AgeSel_P7_FISHERY(1)	-3.7949	2	(-5, 9)	OK	25.7656
AgeSel_P8_FISHERY(1)	1.7700	2	(-5, 9)	OK	27.8592
AgeSel_P2_AT(2)	0.1846	2	(0, 9)	OK	0.2807

FISHERY_ARDEV_y2008_A0	0.2538	3	(-10, 10)	act	0.7313
FISHERY_ARDEV_y2008_A1	-0.4885	3	(-10, 10)	act	0.7798
FISHERY_ARDEV_y2008_A2	-0.3045	3	(-10, 10)	act	0.8465
FISHERY_ARDEV_y2008_A3	0.6213	3	(-10, 10)	act	0.8177
FISHERY_ARDEV_y2008_A4	0.0028	3	(-10, 10)	act	1.0009
FISHERY_ARDEV_y2008_A5	-0.0666	3	(-10, 10)	act	0.9598
FISHERY_ARDEV_y2009_A0	-0.6867	3	(-10, 10)	act	0.8029
FISHERY_ARDEV_y2009_A1	0.5020	3	(-10, 10)	act	0.7584
FISHERY_ARDEV_y2009_A2	-0.0891	3	(-10, 10)	act	0.8904
FISHERY_ARDEV_y2009_A3	0.2461	3	(-10, 10)	act	0.8965
FISHERY_ARDEV_y2009_A4	0.0118	3	(-10, 10)	act	1.0121
FISHERY_ARDEV_y2009_A5	0.0172	3	(-10, 10)	act	0.9735
FISHERY_ARDEV_y2010_A0	-0.2139	3	(-10, 10)	act	0.7191
FISHERY_ARDEV_y2010_A1	0.0348	3	(-10, 10)	act	0.7665
FISHERY_ARDEV_y2010_A2	0.1209	3	(-10, 10)	act	0.8079
FISHERY_ARDEV_y2010_A3	0.0935	3	(-10, 10)	act	0.9080
FISHERY_ARDEV_y2010_A4	0.0076	3	(-10, 10)	act	1.0060
FISHERY_ARDEV_y2010_A5	-0.0306	3	(-10, 10)	act	0.9584
FISHERY_ARDEV_y2011_A0	0.8032	3	(-10, 10)	act	0.7044
FISHERY_ARDEV_y2011_A1	0.2375	3	(-10, 10)	act	0.7415
FISHERY_ARDEV_y2011_A2	-0.4445	3	(-10, 10)	act	0.8774
FISHERY_ARDEV_y2011_A3	-0.4833	3	(-10, 10)	act	0.8821
FISHERY_ARDEV_y2011_A4	-0.0159	3	(-10, 10)	act	1.0060
FISHERY_ARDEV_y2011_A5	-0.0865	3	(-10, 10)	act	0.9739
FISHERY_ARDEV_y2012_A0	0.7139	3	(-10, 10)	act	0.6708
FISHERY_ARDEV_y2012_A1	-0.0735	3	(-10, 10)	act	0.6728
FISHERY_ARDEV_y2012_A2	-0.3167	3	(-10, 10)	act	0.7808
FISHERY_ARDEV_y2012_A3	-0.2939	3	(-10, 10)	act	0.8882
FISHERY_ARDEV_y2012_A4	-0.0109	3	(-10, 10)	act	1.0024
FISHERY_ARDEV_y2012_A5	-0.0161	3	(-10, 10)	act	0.9734
FISHERY_ARDEV_y2013_A0	2.0338	3	(-10, 10)	act	0.6571
FISHERY_ARDEV_y2013_A1	-0.8315	3	(-10, 10)	act	0.7246
FISHERY_ARDEV_y2013_A2	-0.6384	3	(-10, 10)	act	0.7294
FISHERY_ARDEV_y2013_A3	-0.5485	3	(-10, 10)	act	0.8256
FISHERY_ARDEV_y2013_A4	-0.0169	3	(-10, 10)	act	1.0051
FISHERY_ARDEV_y2013_A5	-0.0059	3	(-10, 10)	act	0.9505
FISHERY_ARDEV_y2014_A0	1.0761	3	(-10, 10)	act	0.6595
FISHERY_ARDEV_y2014_A1	-0.6101	3	(-10, 10)	act	0.7562
FISHERY_ARDEV_y2014_A2	-0.4639	3	(-10, 10)	act	0.7993
FISHERY_ARDEV_y2014_A3	-0.2672	3	(-10, 10)	act	0.7737
FISHERY_ARDEV_y2014_A4	0.0349	3	(-10, 10)	act	1.0788
FISHERY_ARDEV_y2014_A5	0.2010	3	(-10, 10)	act	1.0617
FISHERY_ARDEV_y2015_A0	0.0600	3	(-10, 10)	act	0.6855
FISHERY_ARDEV_y2015_A1	-0.4113	3	(-10, 10)	act	0.7387
FISHERY_ARDEV_y2015_A2	0.2984	3	(-10, 10)	act	0.8639
FISHERY_ARDEV_y2015_A3	0.0840	3	(-10, 10)	act	0.9088
FISHERY_ARDEV_y2015_A4	0.0049	3	(-10, 10)	act	0.9987
FISHERY_ARDEV_y2015_A5	-0.0324	3	(-10, 10)	act	0.9714
FISHERY_ARDEV_y2016_A0	-1.3973	3	(-10, 10)	act	0.7433
FISHERY_ARDEV_y2016_A1	0.5917	3	(-10, 10)	act	0.7113
FISHERY_ARDEV_y2016_A2	1.0208	3	(-10, 10)	act	0.7941
FISHERY_ARDEV_y2016_A3	-0.0485	3	(-10, 10)	act	0.9722
FISHERY_ARDEV_y2016_A4	-0.0114	3	(-10, 10)	act	1.0016
FISHERY_ARDEV_y2016_A5	-0.1511	3	(-10, 10)	act	0.9718
FISHERY_ARDEV_y2017_A0	0.1441	3	(-10, 10)	act	0.7885
FISHERY_ARDEV_y2017_A1	-0.4177	3	(-10, 10)	act	0.7694
FISHERY_ARDEV_y2017_A2	0.2754	3	(-10, 10)	act	0.8715
FISHERY_ARDEV_y2017_A3	0.0264	3	(-10, 10)	act	0.9783
FISHERY_ARDEV_y2017_A4	-0.0021	3	(-10, 10)	act	0.9992
FISHERY_ARDEV_y2017_A5	-0.0238	3	(-10, 10)	act	0.9841
FISHERY_ARDEV_y2018_A0	-0.5255	3	(-10, 10)	act	0.8272
FISHERY_ARDEV_y2018_A1	0.8976	3	(-10, 10)	act	0.8124
FISHERY_ARDEV_y2018_A2	-0.3810	3	(-10, 10)	act	0.8598
FISHERY_ARDEV_y2018_A3	0.0023	3	(-10, 10)	act	0.9671

FISHERY_ARDEV_y2018_A4	0.0013	3	(-10, 10)	act	1.0007
FISHERY_ARDEV_y2018_A5	0.0039	3	(-10, 10)	act	1.0007
FISHERY_ARDEV_y2019_A0	-0.7641	3	(-10, 10)	act	0.7661
FISHERY_ARDEV_y2019_A1	0.1950	3	(-10, 10)	act	0.7822
FISHERY_ARDEV_y2019_A2	0.1026	3	(-10, 10)	act	1.0136
FISHERY_ARDEV_y2019_A3	0.4322	3	(-10, 10)	act	0.8577
FISHERY_ARDEV_y2019_A4	0.0057	3	(-10, 10)	act	1.0044
FISHERY_ARDEV_y2019_A5	0.0225	3	(-10, 10)	act	1.0062
FISHERY_ARDEV_y2020_A0	-0.1596	3	(-10, 10)	act	0.9332
FISHERY_ARDEV_y2020_A1	0.4909	3	(-10, 10)	act	0.8743
FISHERY_ARDEV_y2020_A2	-0.2155	3	(-10, 10)	act	0.9072
FISHERY_ARDEV_y2020_A3	-0.0901	3	(-10, 10)	act	0.9685
FISHERY_ARDEV_y2020_A4	-0.0148	3	(-10, 10)	act	1.0046
FISHERY_ARDEV_y2020_A5	-0.0115	3	(-10, 10)	act	0.9946
FISHERY_ARDEV_y2021_A0	-1.3377	3	(-10, 10)	act	0.7210
FISHERY_ARDEV_y2021_A1	-0.1169	3	(-10, 10)	act	0.7020
FISHERY_ARDEV_y2021_A2	1.0355	3	(-10, 10)	act	0.7599
FISHERY_ARDEV_y2021_A3	0.2260	3	(-10, 10)	act	0.8904
FISHERY_ARDEV_y2021_A4	0.0028	3	(-10, 10)	act	1.0019
FISHERY_ARDEV_y2021_A5	0.1808	3	(-10, 10)	act	0.9890

Table 10: Likelihood components, parameters, and biomass estimates.

	Description	Value
Likelihood	TOTAL	111.69
	Catch	0
	Equil_catch	0
	Survey	-4.621
	Length_comp	0
	Age_comp	30.159
	Recruitment	-0.401
	InitEQ_Regime	0.064
	Forecast_Recruitment	0
	Parm_priors	4.744
	Parm_softbounds	0.004
	Parm_devs	81.74
	Crash_Pen	0
Parameter	NatM_Lorenzen_averageFem_GP_1	0.784
	SR_LN(R0)	13.331
	SR_BH_steep	0.75
	SR_sigmaR	0.75
	SR_regime_BLK3repl_2007	-0.305
	LnQ_base_AT(2)	-1.03
	LnQ_base_AT(2)_BLK4repl_2008	-0.57
	LnQ_base_AT(2)_BLK4repl_2013	-2.765
	LnQ_base_AT(2)_BLK4repl_2016	-0.698
Biomass (mt)	2020 Age1+	54,025
	2021 Age1+	40,024

Table 11: Pacific mackerel numbers-at-age (thousands of fish) estimated in base model years

Model Year	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8+
VIRG	615,848	203,918	82,223	36,519	17,122	8,293	4,099	2,053	2,116
INIT	454,122	150,368	60,630	26,929	12,626	6,115	3,023	1,514	1,560
2008	471,377	93,774	48,903	35,326	12,176	5,814	2,999	1,514	1,560
2009	272,225	150,696	35,665	20,181	13,182	5,849	2,690	1,499	1,546
2010	587,145	89,415	55,393	15,014	8,628	6,353	2,771	1,346	1,537
2011	1,234,810	189,837	32,400	21,780	6,084	4,142	2,916	1,386	1,449
2012	432,596	397,651	72,431	13,976	9,864	2,936	1,987	1,459	1,433
2013	321,329	131,262	139,537	28,703	5,676	4,717	1,301	993	1,446
2014	336,623	72,764	49,068	56,297	11,824	2,709	2,051	650	1,218
2015	390,743	96,418	26,710	19,450	22,260	5,639	1,145	1,024	933
2016	665,891	114,793	29,943	6,805	5,252	10,419	2,100	569	956
2017	166,038	216,936	30,566	6,825	2,407	2,494	4,448	1,048	758
2018	555,832	53,072	81,532	11,717	2,779	1,155	1,141	2,224	906
2019	790,895	170,138	6,842	25,974	3,015	1,293	404	567	1,515
2020	453,405	248,073	41,853	1,896	5,435	1,410	469	201	1,017
2021	424,981	134,552	48,000	12,723	524	2,534	501	233	594

Table 12: Pacific mackerel biomass-at-age for base model years.

Model year	0	1	2	3	4	5	6	7	8+	Total Age0+	Total Age1+
VIRG	72,188	48,259	27,182	14,766	7,740	3,914	2,091	1,085	1,110	178,335	106,148
INIT	53,231	35,586	20,044	10,888	5,707	2,886	1,542	800	819	131,503	78,273
2008	55,253	22,193	16,167	14,284	5,504	2,743	1,529	800	819	119,293	64,039
2009	31,909	35,664	11,791	8,160	5,959	2,760	1,372	792	811	99,218	67,308
2010	68,823	21,161	18,312	6,070	3,900	2,998	1,414	711	807	124,197	55,374
2011	144,741	44,927	10,711	8,806	2,750	1,954	1,487	732	760	216,869	72,128
2012	80,693	90,148	18,943	5,470	4,334	1,419	1,028	766	752	203,554	122,861
2013	40,758	39,066	45,458	10,304	2,494	2,280	673	521	759	142,312	101,555
2014	42,697	25,222	18,998	23,325	5,443	1,309	1,061	341	640	119,037	76,340
2015	77,182	23,018	10,955	7,874	9,943	2,797	592	538	490	133,390	56,207
2016	40,340	27,524	9,561	2,791	2,219	5,277	1,186	299	502	89,699	49,359
2017	36,386	54,254	8,620	2,269	987	1,112	2,703	663	398	107,392	71,007
2018	15,047	14,714	27,561	4,400	1,077	474	509	1,351	574	65,707	50,659
2019	6,544	36,001	2,508	10,827	1,331	576	166	253	920	59,126	52,582
2020	57,510	34,392	14,494	868	2,850	622	263	82	453	111,536	54,026
2021	39,320	18,780	12,912	6,120	288	1,328	221	131	243	79,343	40,024

Table 13: Spawning stock biomas (SSB) and recruitment (1000s of fish) estimates and asymptotic standard errors for the base model.

Year	SSB	SSB SD	Recruits	Recruits SD
Virgin	86,554	11,842	615,848	191,686
Initial	63,824	36,128	454,122	302,346
2008	56,820	29,474	471,377	282,555
2009	47,493	21,033	272,225	186,470
2010	42,141	17,266	587,145	336,807
2011	47,742	17,876	1,234,810	576,590
2012	74,513	24,053	432,596	201,673
2013	75,667	23,958	321,329	130,435
2014	60,589	18,272	336,623	131,456
2015	42,917	12,188	390,743	137,839
2016	34,088	9,278	665,891	245,197
2017	42,292	10,933	166,038	72,588
2018	39,561	9,884	555,832	190,467
2019	33,741	8,689	790,895	271,485
2020	34,672	8,620	453,405	174,929
2021	28,701	8,027	424,981	173,129

Table 14: Total (age-0+) and summary (age-1+) biomass values (mt) estimated on June 1 of each year.

Year	Age-0+	Age-1+
2008	119,292	64,039
2009	99,217	67,308
2010	124,197	55,373
2011	216,870	72,128
2012	203,554	122,861
2013	142,312	101,555
2014	119,037	76,340
2015	133,390	56,207
2016	89,698	49,358
2017	107,392	71,006
2018	65,706	50,659
2019	59,126	52,581
2020	111,535	54,025
2021	79,343	40,024

Table 15: Annual exploitation rate (calendar year landings / total age-0+ biomass values).

Year	Exploitation rate
2008	0.04
2009	0.06
2010	0.02
2011	0.02
2012	0.05
2013	0.11
2014	0.08
2015	0.09
2016	0.21
2017	0.06
2018	0.26
2019	0.29
2020	0.34
2021	0.12

Table 16: Parameter estimates, summary biomass (age 1+; mt), and total likelihood values associated with fixed values of steepness ranging from 0.25 to 1. The base model steepness value was 0.75.

	Steepness									
	0.25	0.3	0.4	0.5	0.6	0.7	0.75	0.8	0.9	1
NatM_Lorenzen_averageFem_GP_1	0.845	0.837	0.808	0.796	0.790	0.786	0.784	0.783	0.781	0.780
SR_LN(R0)	15.228	14.674	13.896	13.598	13.451	13.363	13.331	13.304	13.262	13.231
SR_regime_BLK3repl_2007	-0.705	-0.758	-0.537	-0.418	-0.356	-0.318	-0.305	-0.293	-0.275	-0.261
LnQ_base_AT(2)	-1.030	-1.030	-1.030	-1.030	-1.030	-1.030	-1.030	-1.030	-1.030	-1.030
LnQ_base_AT(2)_BLK4repl_2008	-1.309	-0.970	-0.712	-0.637	-0.601	-0.578	-0.570	-0.563	-0.552	-0.543
LnQ_base_AT(2)_BLK4repl_2013	-3.166	-2.983	-2.846	-2.804	-2.783	-2.770	-2.765	-2.760	-2.753	-2.748
LnQ_base_AT(2)_BLK4repl_2016	-0.980	-0.858	-0.759	-0.726	-0.710	-0.701	-0.698	-0.695	-0.691	-0.688
2020 Age-1+ bio	63,074	59,799	56,331	55,044	54,446	54,128	54,026	53,947	53,838	53,770
2021 Age-1+ bio	39,539	39,983	39,976	39,903	39,923	39,986	40,024	40,063	40,141	40,215
Total likelihood	116.807	114.342	112.737	112.189	111.913	111.749	111.690	111.641	111.565	111.510

Table 17: Parameter estimates, summary biomass (age 1+; mt), and total likelihood values associated with fixed values of 2021 Log catchability (Q) values. The blocks for Q values prior to 2021 were estimated. The base model fixed Q at 0.36. Column headers show the Q values in linear space.

	Fixed 2021 catchability (Q)										
	0.1	0.2	0.3	0.36	0.4	0.5	0.6	0.7	0.8	0.9	1
NatM_Lorenzen_averageFem_GP_1	0.809	0.797	0.789	0.784	0.782	0.776	0.772	0.769	0.766	0.763	0.761
SR_LN(R0)	13.817	13.545	13.393	13.331	13.291	13.216	13.158	13.111	13.073	13.041	13.013
SR_BH_steep	0.750	0.750	0.750	0.750	0.750	0.750	0.750	0.750	0.750	0.750	0.750
SR_regime_BLK3repl_2007	-0.439	-0.359	-0.320	-0.305	-0.295	-0.279	-0.268	-0.259	-0.252	-0.247	-0.243
LnQ_base_AT(2)	-2.303	-1.609	-1.204	-1.030	-0.916	-0.693	-0.511	-0.357	-0.223	-0.105	0.000
LnQ_base_AT(2)_BLK4repl_2008	-0.807	-0.674	-0.600	-0.570	-0.551	-0.514	-0.486	-0.462	-0.443	-0.427	-0.413
LnQ_base_AT(2)_BLK4repl_2013	-2.980	-2.856	-2.791	-2.765	-2.748	-2.717	-2.693	-2.674	-2.658	-2.645	-2.634
LnQ_base_AT(2)_BLK4repl_2016	-1.102	-0.873	-0.748	-0.698	-0.666	-0.607	-0.562	-0.526	-0.497	-0.473	-0.452
2020 Age-1+ bio	107,681	73,298	59,021	54,026	51,098	46,078	42,633	40,137	38,251	36,777	35,593
2021 Age-1+ bio	115,519	65,698	46,534	40,024	36,251	29,845	25,490	22,347	19,980	18,137	16,661
Total likelihood	112.808	111.727	111.628	111.690	111.762	111.971	112.210	112.459	112.712	112.966	113.218

Table 18: Parameter estimates, summary biomass (age 1+; mt), and total likelihood values associated with fixed values of average age-specific natural mortality (M). Note that for this configuration, steepness was freely estimated. The base model estimated average M to be 0.784 with a fixed steepness at 0.75.

	Average age-specific natural mortality (M)								
	0.3	0.4	0.5	0.6	0.7	0.784	0.8	0.9	1
SR_LN(R0)	11.759	12.075	12.392	12.707	13.008	13.331	13.286	13.555	13.815
SR_BH_steep	1.000	1.000	1.000	1.000	1.000	0.750	1.000	1.000	1.000
SR_regime_BLK3repl_2007	-0.565	-0.535	-0.476	-0.399	-0.317	-0.305	-0.246	-0.170	-0.094
LnQ_base_AT(2)	-1.030	-1.030	-1.030	-1.030	-1.030	-1.030	-1.030	-1.030	-1.030
LnQ_base_AT(2)_BLK4repl_2008	0.256	0.153	-0.034	-0.252	-0.453	-0.570	-0.565	-0.669	-0.764
LnQ_base_AT(2)_BLK4repl_2013	-2.094	-2.228	-2.395	-2.565	-2.706	-2.765	-2.758	-2.803	-2.843
LnQ_base_AT(2)_BLK4repl_2016	-0.212	-0.332	-0.458	-0.574	-0.662	-0.698	-0.695	-0.728	-0.764
2020 Age-1+ bio	35,485	37,506	38,862	39,614	39,902	40,024	40,303	40,779	41,314
2021 Age-1+ bio	54,045	52,366	49,542	46,128	42,991	41,955	42,495	42,188	42,044
Total likelihood	134.481	123.529	117.207	113.501	111.822	111.690	111.379	111.696	112.634

Table 19: Variance adjustment, parameter estimates, summary biomass (age-1+; mt) and total NLL from the base model and a model with Francis reweighting of age compositions.

	Base model	Francis
Fishery age comps	–	4.161
AT Survey age comps	–	0.508
NatM_Lorenzen_averageFem_GP_1	0.784	0.780
SR_LN(R0)	13.331	13.398
SR_BH_steep	0.750	0.750
SR_regime_BLK3repl_2007	-0.305	-0.389
LnQ_base_AT(2)	-1.030	-1.030
LnQ_base_AT(2)_BLK4repl_2008	-0.570	-0.503
LnQ_base_AT(2)_BLK4repl_2013	-2.765	-2.779
LnQ_base_AT(2)_BLK4repl_2016	-0.698	-0.939
2020 Age-1+ bio	54,025	62,504
2021 Age-1+ bio	40,024	43,962
Total likelihood	111.690	112.933

Table 20: Parameter estimates, summary biomass (age-1+; mt) and total NLL from the base model and a model with fishery and AT survey age compositions downweighted. Fishery age compositions had lambda of 0.5 and AT survey age compositions had a lambda of 0.5 for each of the respective runs.

	Base model	Fishery down	AT survey down
NatM_Lorenzen_averageFem_GP_1	0.784	0.778	0.773
SR_LN(R0)	13.331	13.269	13.320
SR_BH_steep	0.750	0.750	0.750
SR_regime_BLK3repl_2007	-0.305	-0.288	-0.345
LnQ_base_AT(2)	-1.030	-1.030	-1.030
LnQ_base_AT(2)_BLK4repl_2008	-0.570	-0.543	-0.481
LnQ_base_AT(2)_BLK4repl_2013	-2.765	-2.708	-2.725
LnQ_base_AT(2)_BLK4repl_2016	-0.698	-0.580	-0.766
2020 Age-1+ bio	54,025	50,531	56,982
2021 Age-1+ bio	40,024	38,207	41,439
Total likelihood	111.690	106.046	100.067

932 # 8 Figures

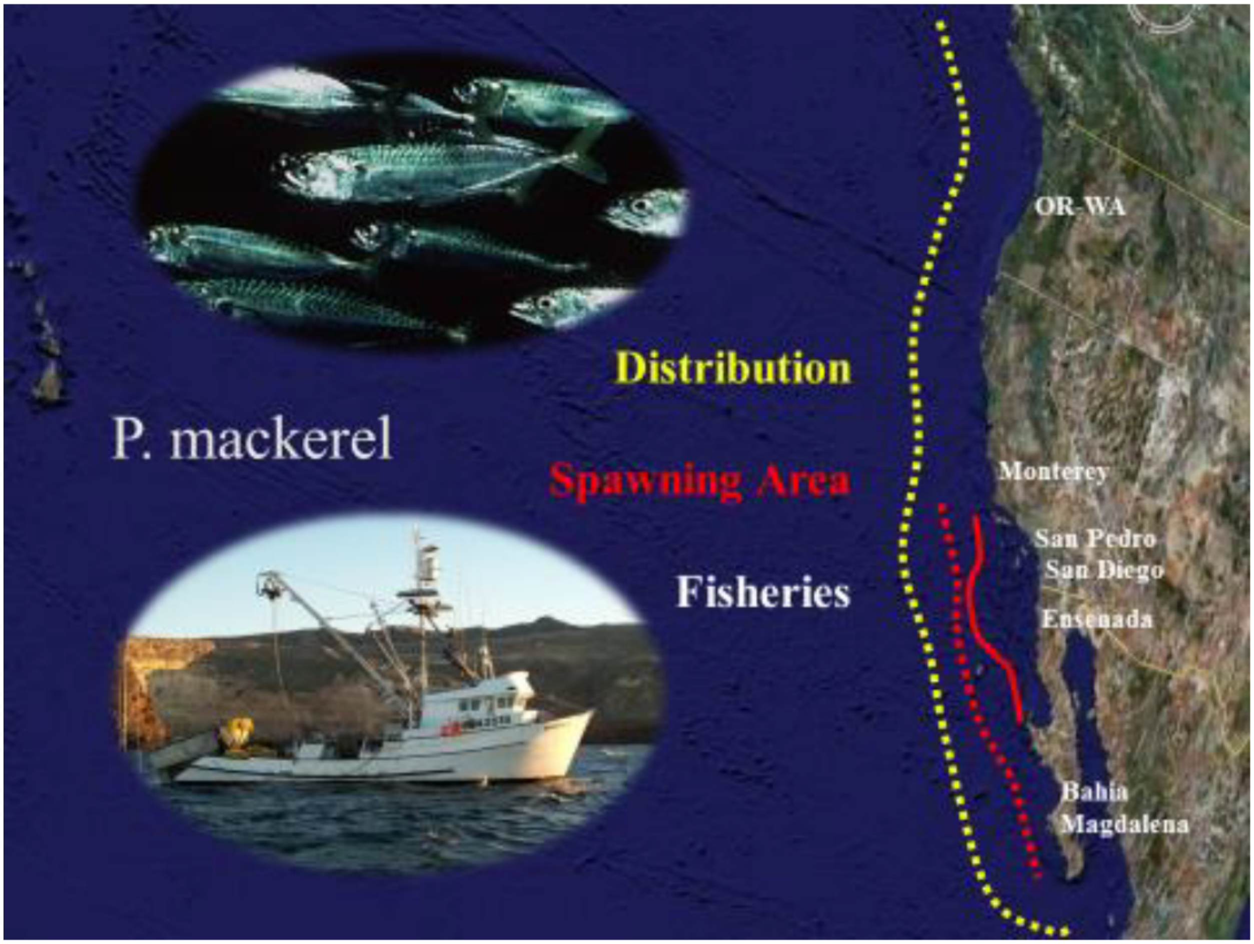

Figure 1: Map of Pacific mackerel stock distribution, spawning range, and fisheries. Created by Paul Crone.

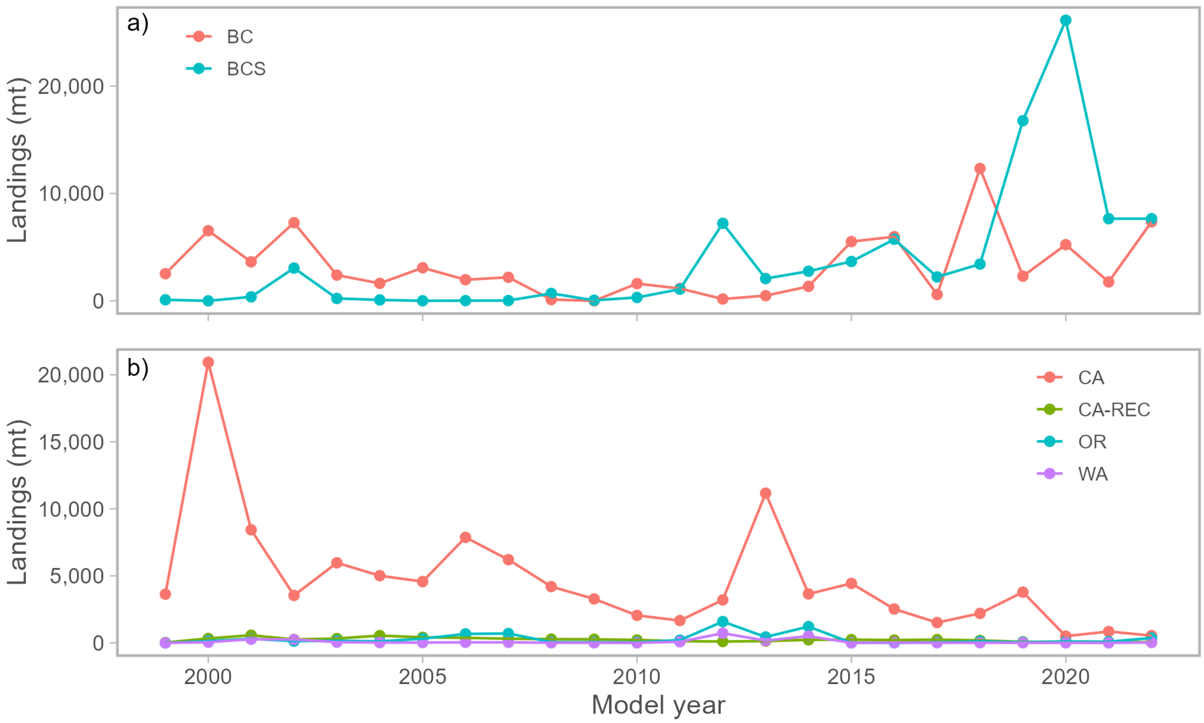

Figure 2: Pacific mackerel landings (mt) by major fishing region in Mexico (a) and USA (b). Landings from Ensenada (BC) and Magdalena Bay (BCS) are shown in the top panel. Landings from California (CA), California recreational sector (CA-REC), Oregon (OR), and Washington (WA) are shown int he bottom panel. Landings were grouped by model year which spans July 1 to June 30 of the following calendar year.

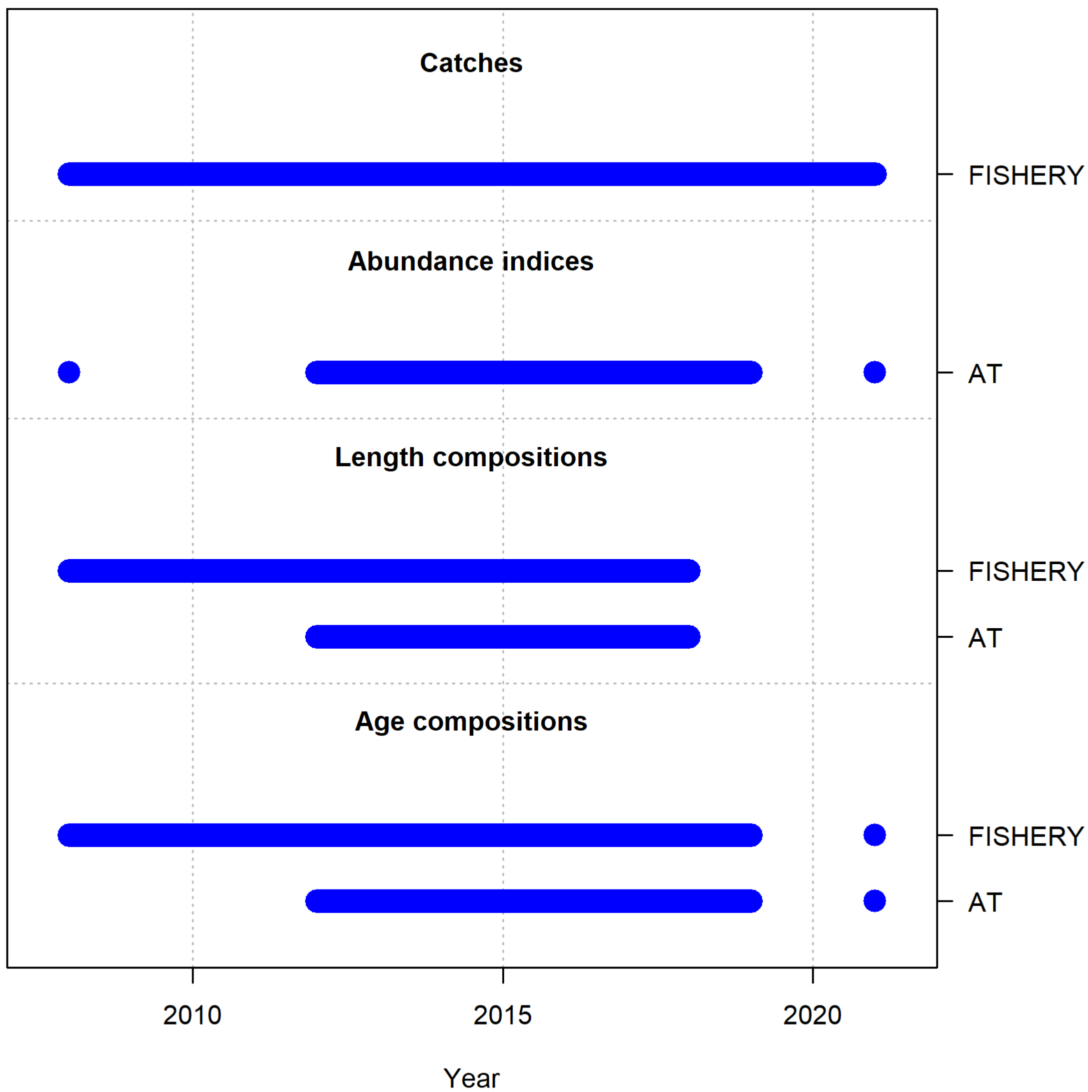

Figure 3: Summary of data sources used in the base model. Note, length compositions were available for the years shown and 2019 and 2021, but the base model was not fit to any length-composition data.

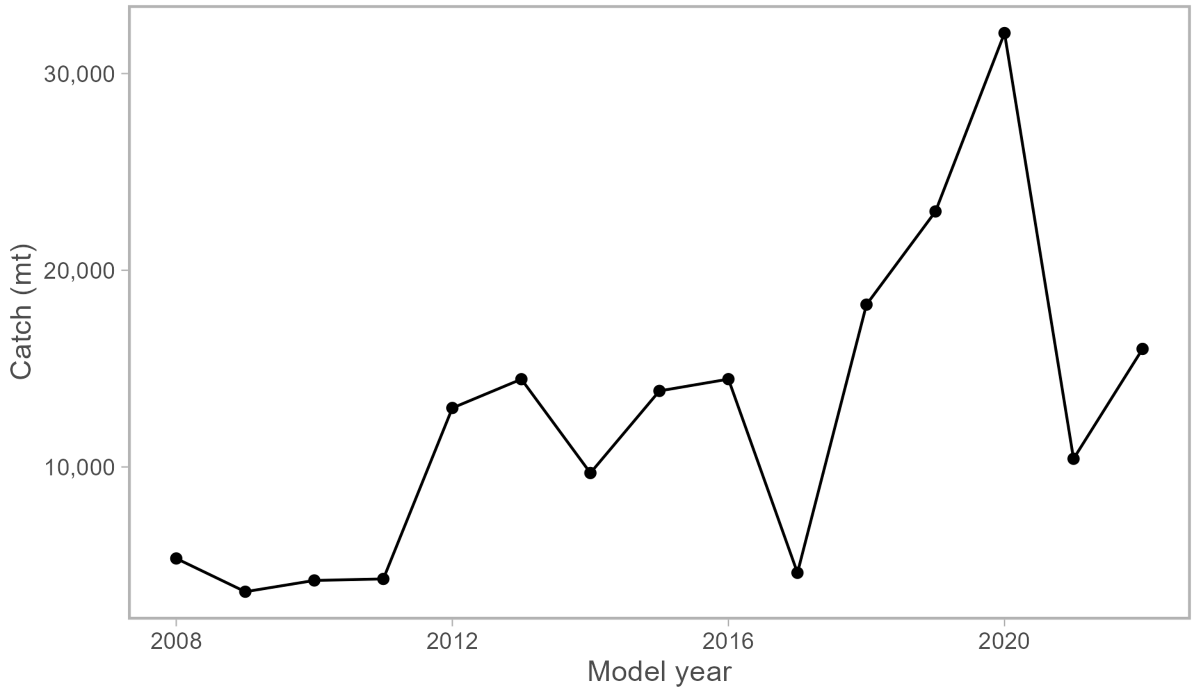

Figure 4: Catch time series input to the stock assessment. Catches from all fishing regions were summed by model year.

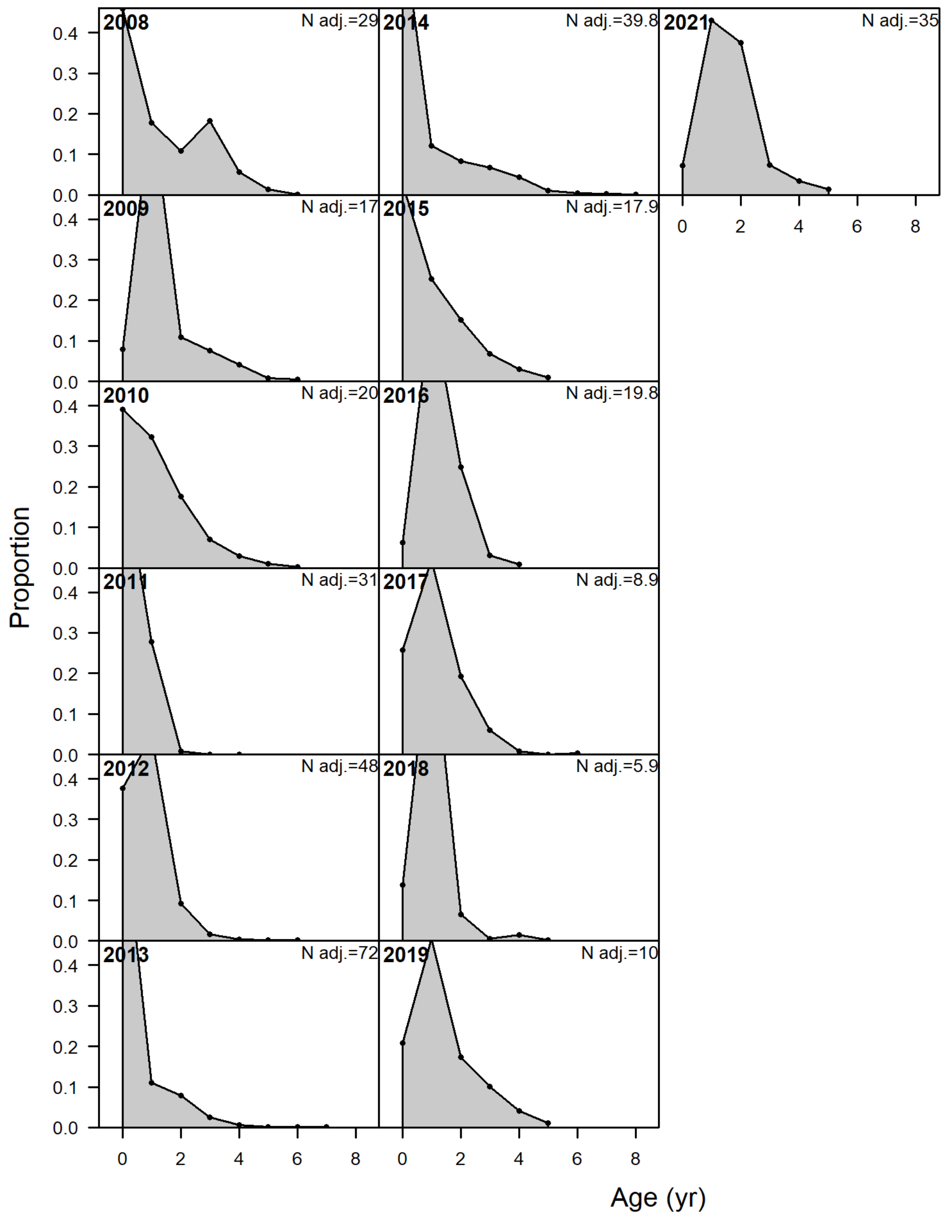

Figure 5: Age composition data for the fishery arranged by model year. The input sample sizes (numbers of measured fish/25) are shown in the top right of each panel. One sample (25 measured fish) was available for model year 2022 but not included in the assessment.

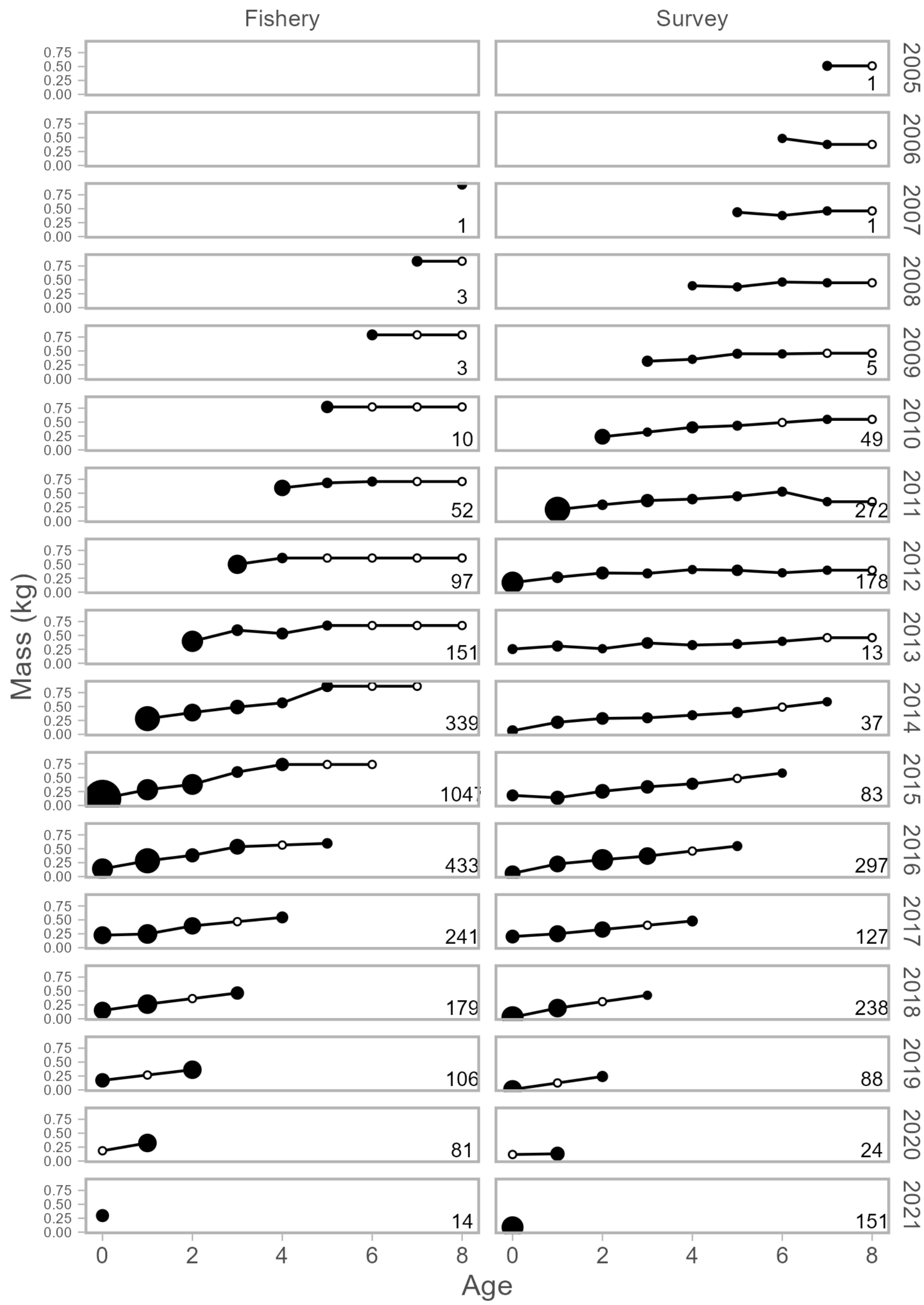

Figure 6: Weight-at-age data for Pacific mackerel arranged by fleet (columns) and cohort model year (rows). Numbers shown in the bottom right are the number of individual fish measured for each cohort. Panels are arranged by cohort because missing weight-at-age values were interpolated as necessary by cohort.

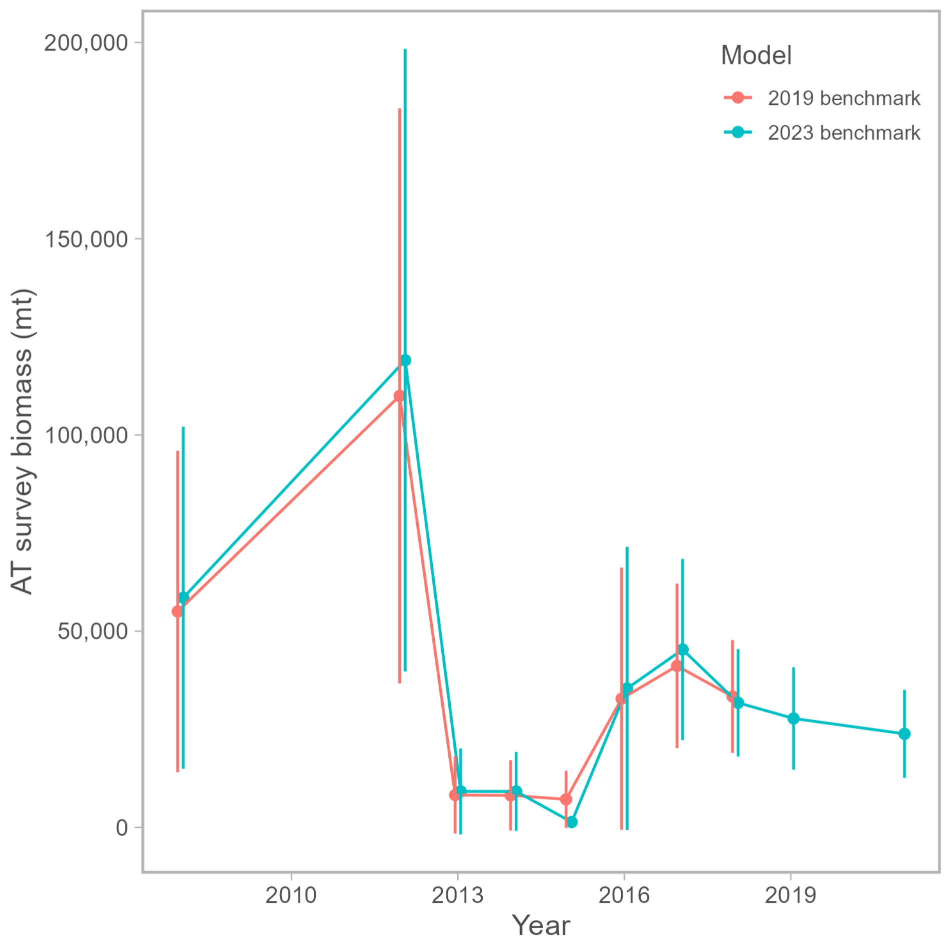

Figure 7: Acoustic-trawl survey biomass time series used in the 2019 benchmark assessment (red) and 2023 benchmark (blue). The differences are due to an updated length-weight relationship for Pacific mackerel, and for the 2015 estimate a reanalysis of the echogram. The 95% CIs are shown as well with the vertical bars.

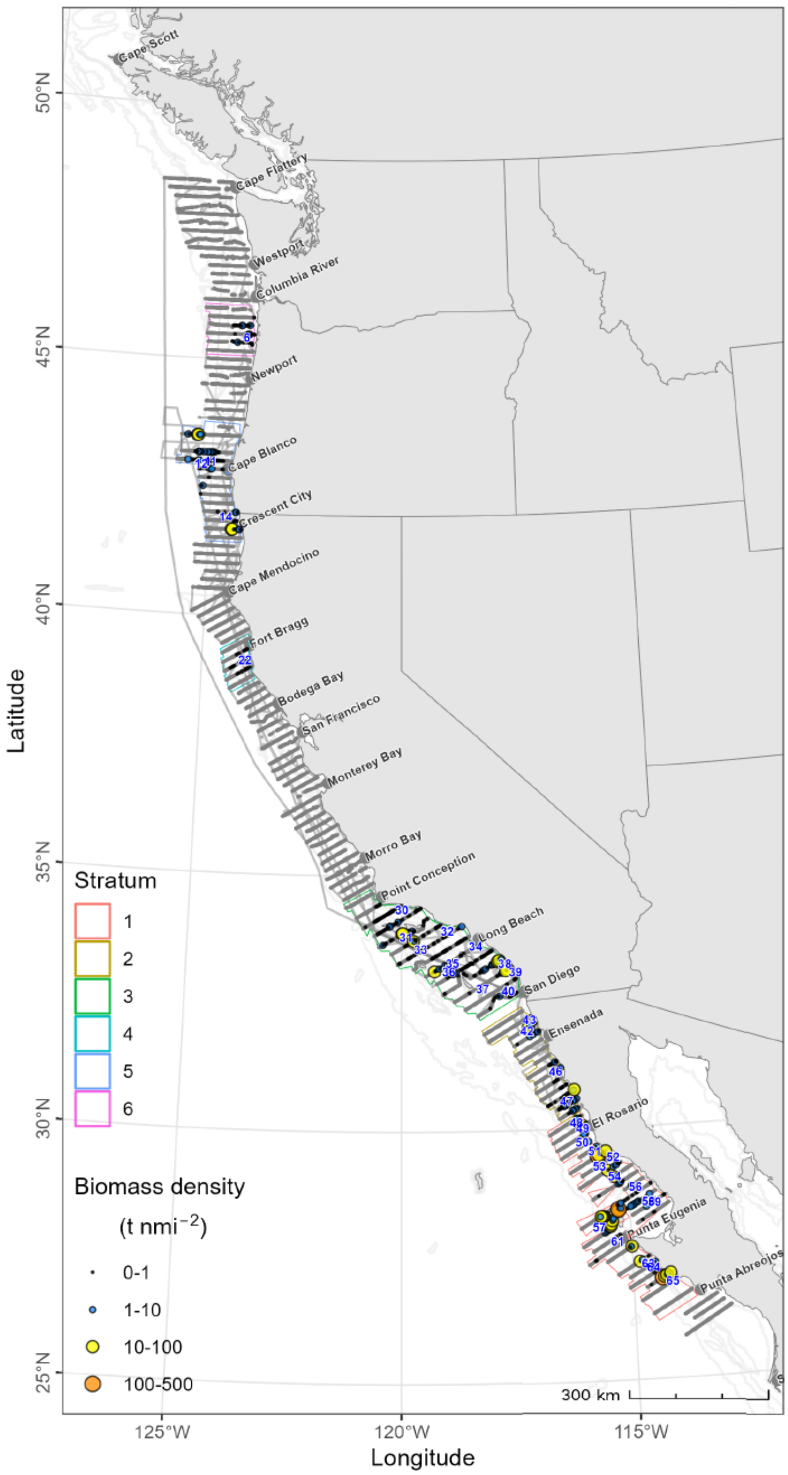

Figure 8: Biomass densities (colored points) of Pacific mackerel, per stratum in the core survey regions from the summer 2021 AT survey. Thick gray lines represent acoustic transects. A majority of the biomass density was observed in Mexican waters (65%).

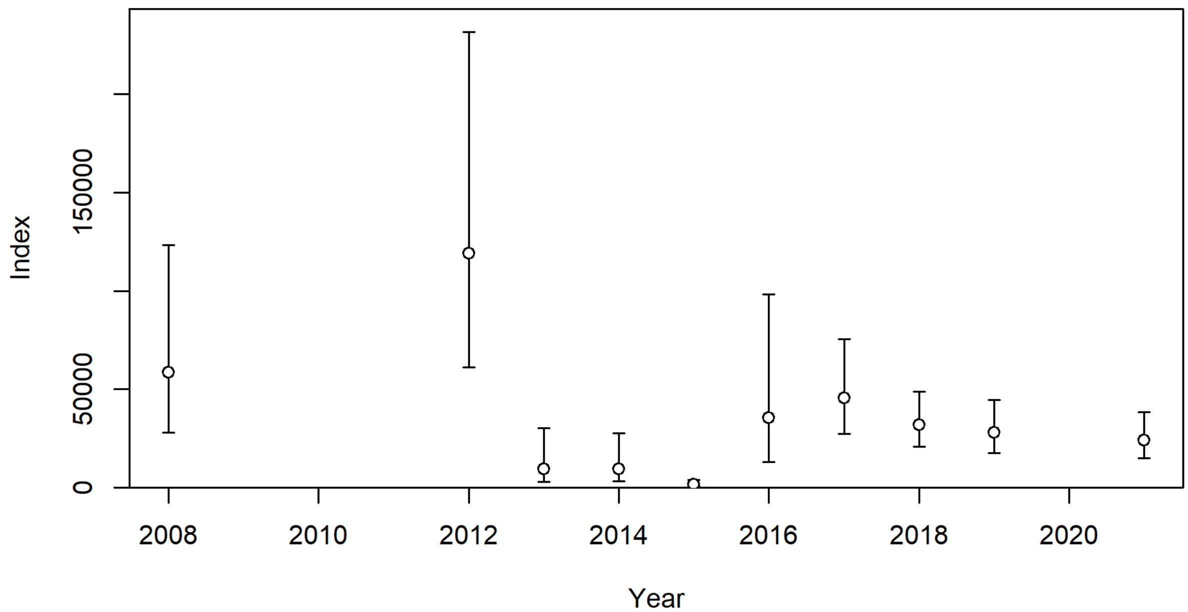

Figure 9: AT survey index of abundance values in untransformed space.

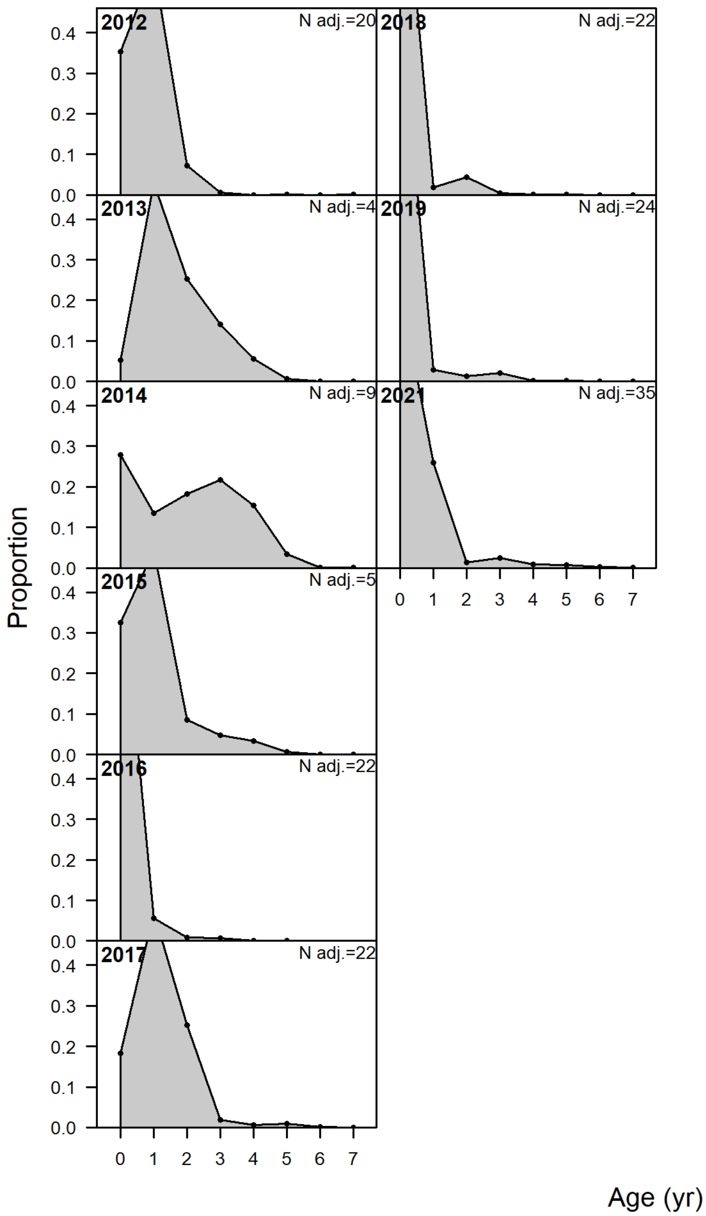

Figure 10: Age composition data for the AT survey arranged by model year. The input sample sizes are the numbers of clusters per model year.

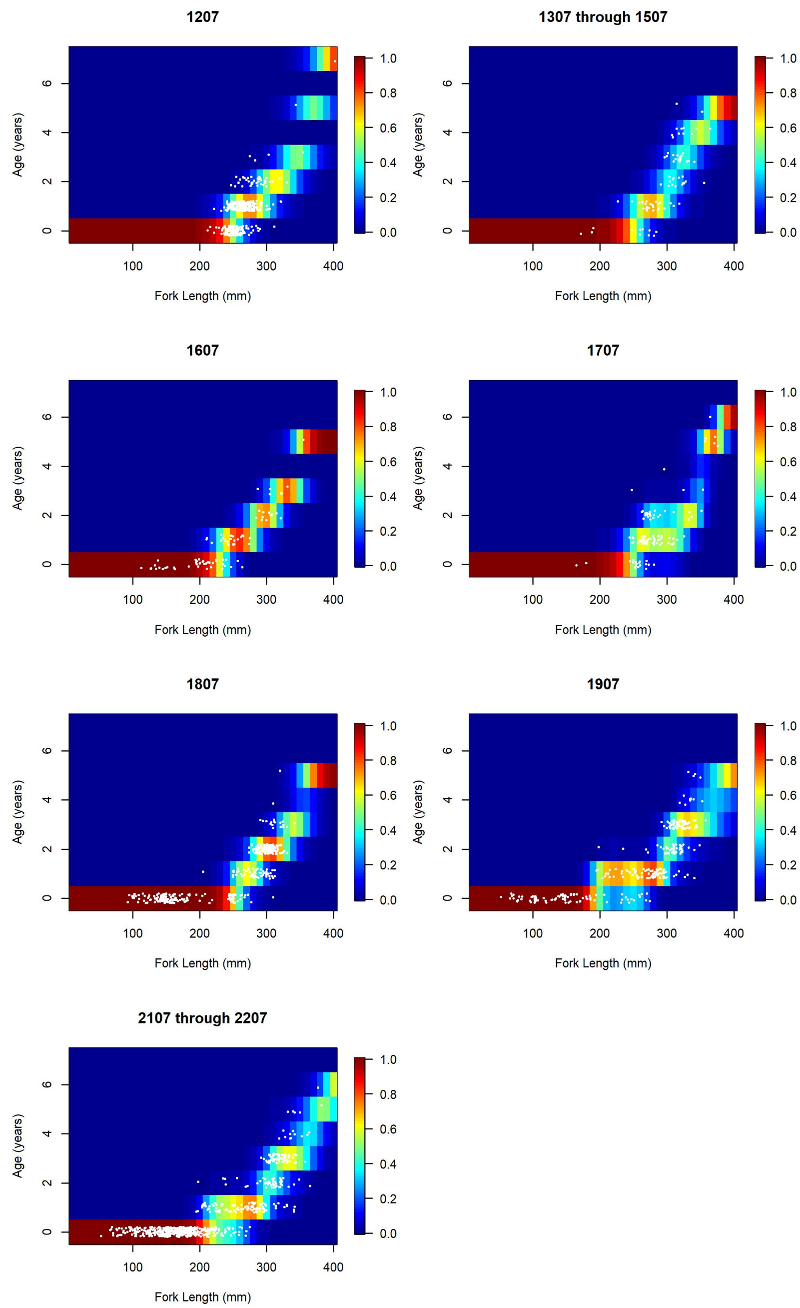

Figure 11: Semi-annual age-length keys derived from summer AT survey samples from 2012 to 2022. There were pooled age-length keys for 2013-2015 and 2021-2022 due to low sample sizes.

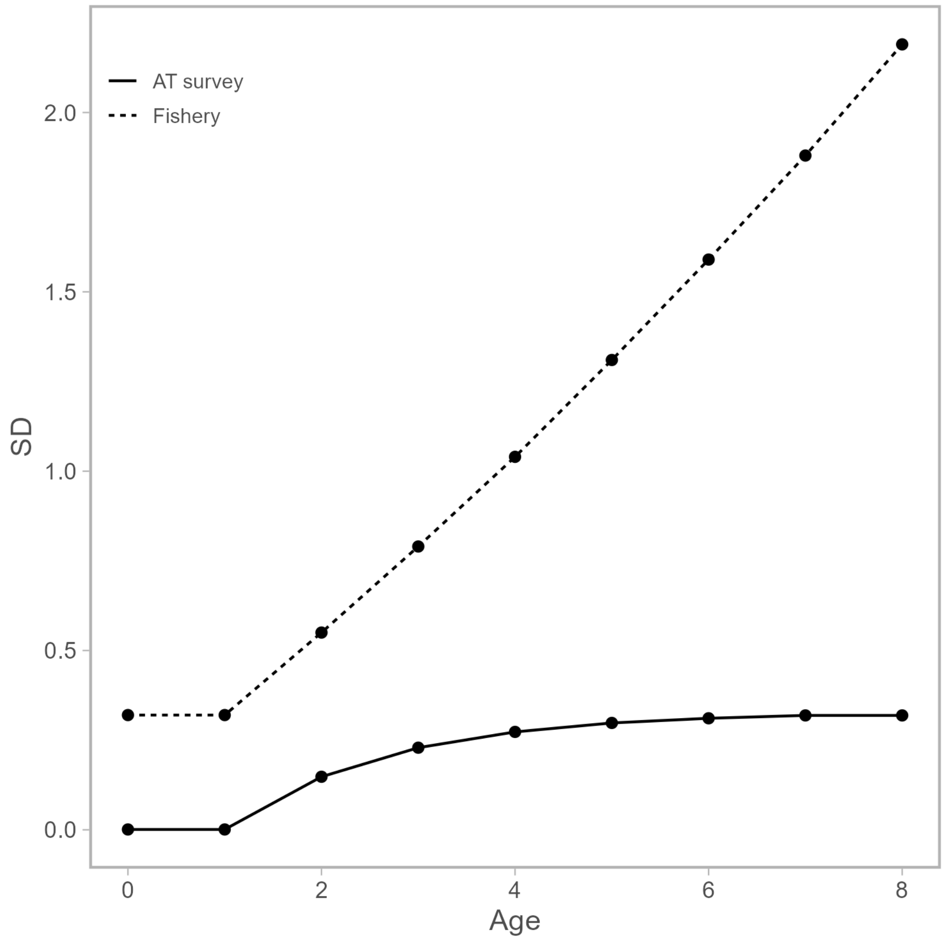

Figure 12: Ageing error estimated for the fishery and AT survey.

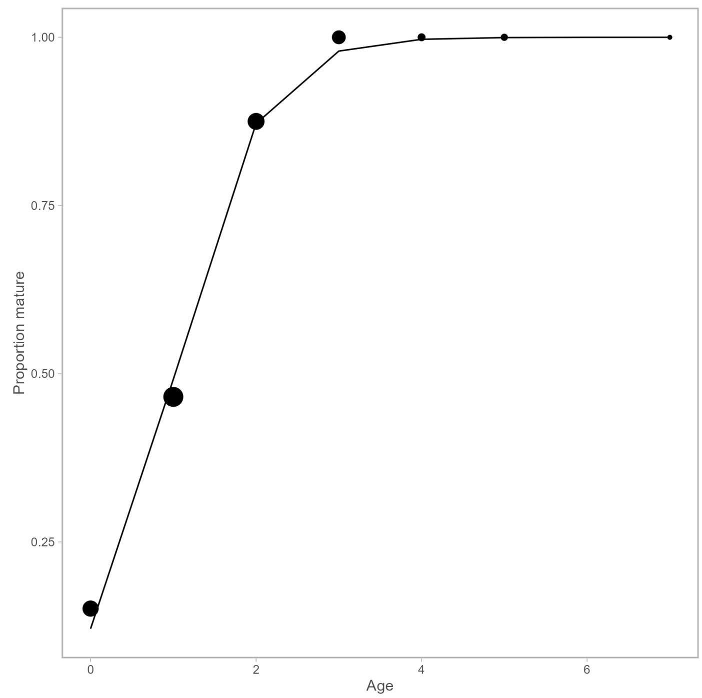

Figure 13: Pacific mackerel maturity-at-age. The observed proportion mature are shown (points; point size represents number of fish) and the predicted proportion mature based on a binomial GLM.

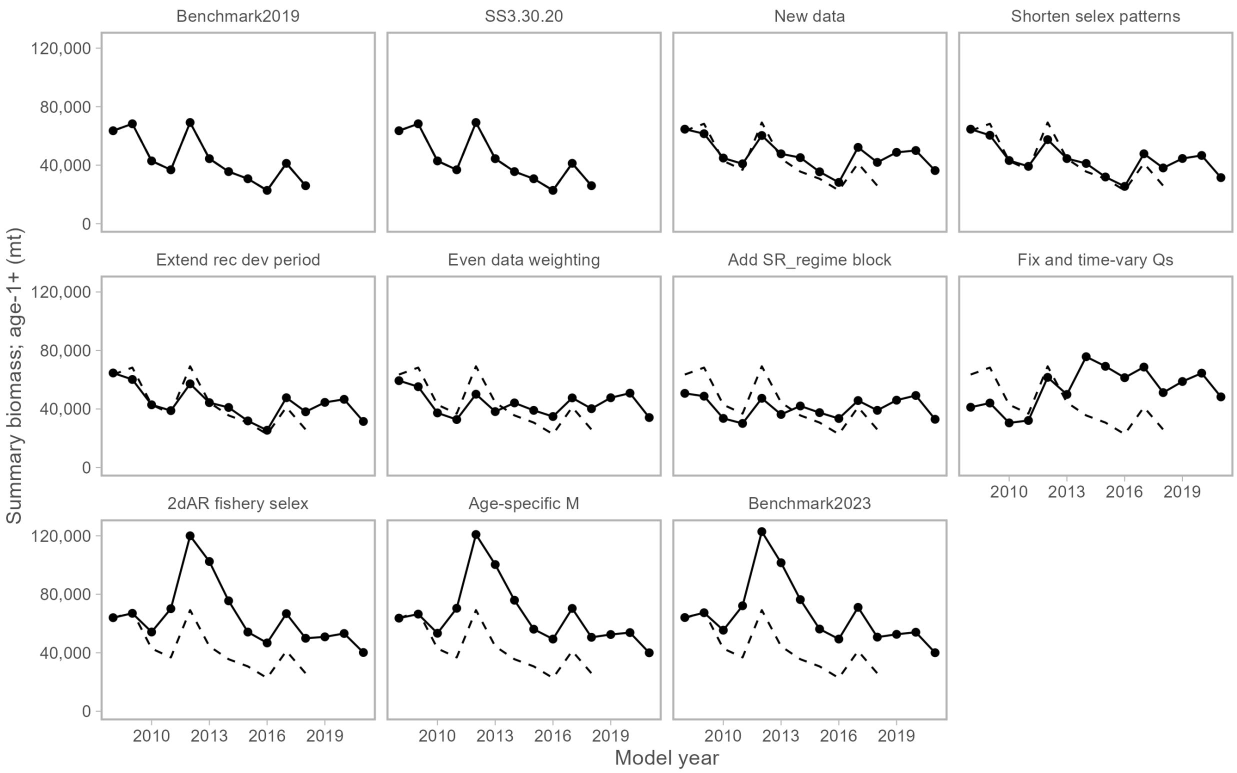

Figure 14: Model bridging between the 2019 (dashed lines) and 2023 benchmark assessments. Features were modified one at a time and added cumulatively.

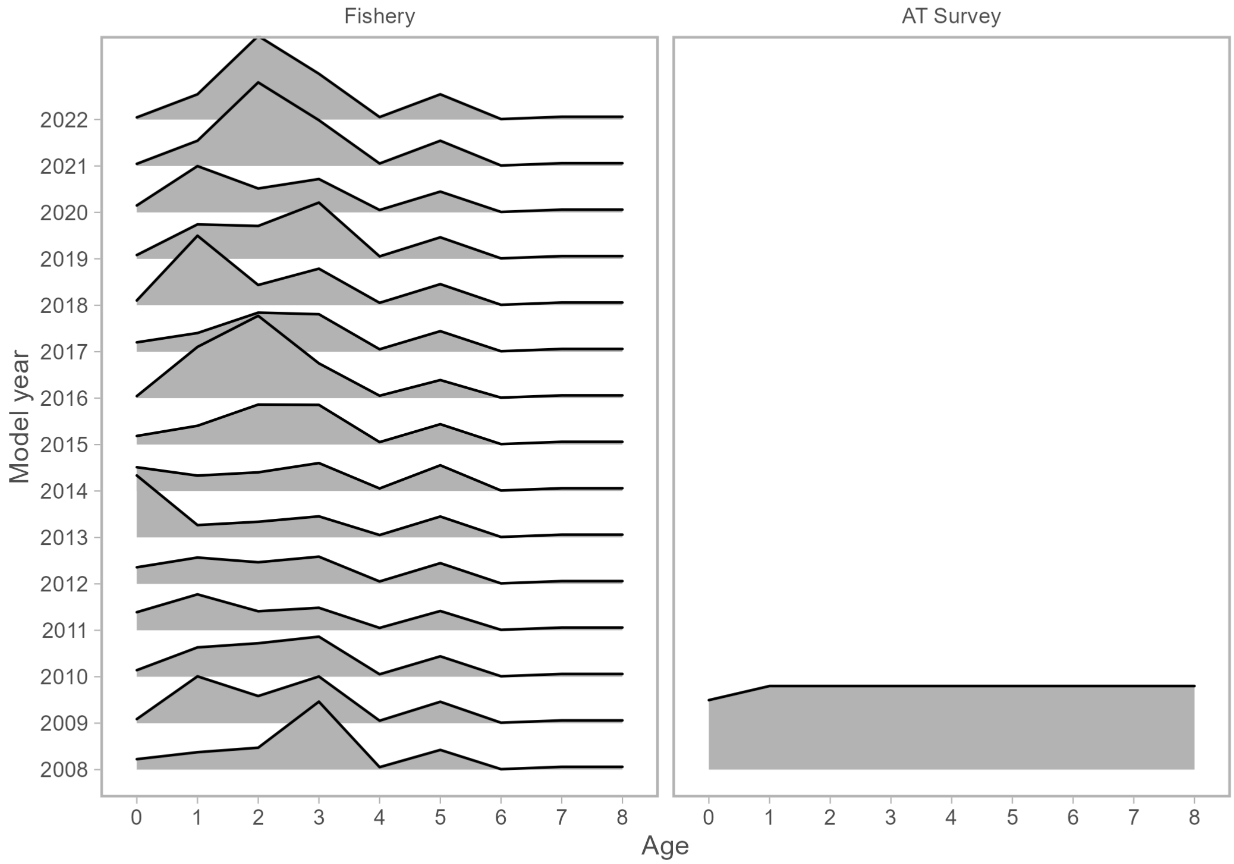

Figure 15: Age-based selectivity patterns for the fishery (time-varying) and AT survey.

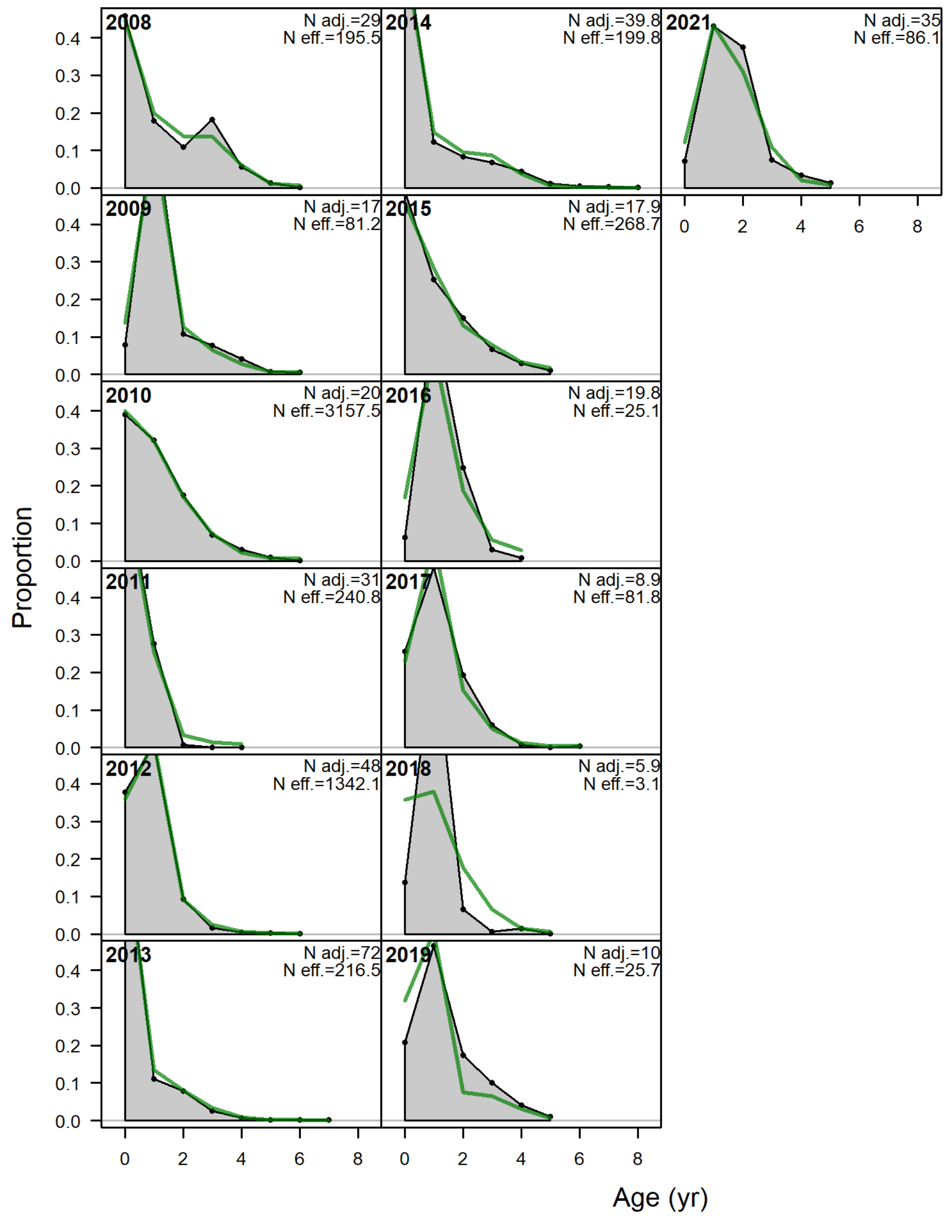

Figure 16: Fits to the age-composition time series for the fishery in the base model. Values in the top right are input sample sizes (N adj) and effective sample size given the statistical fit in the model (N eff).

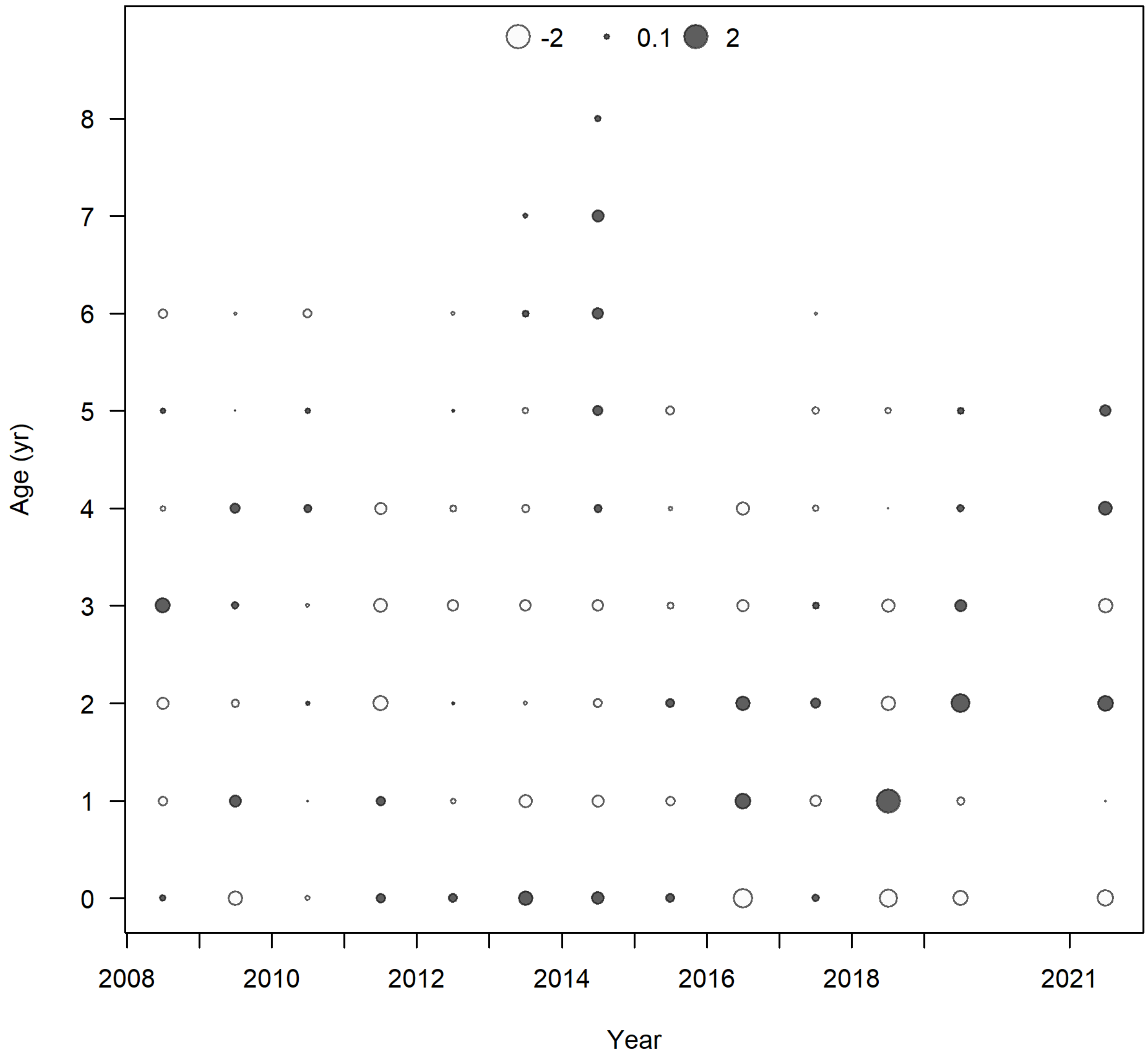

Figure 17: Residuals from the fits to the age-composition time series for the fishery data in the base model.

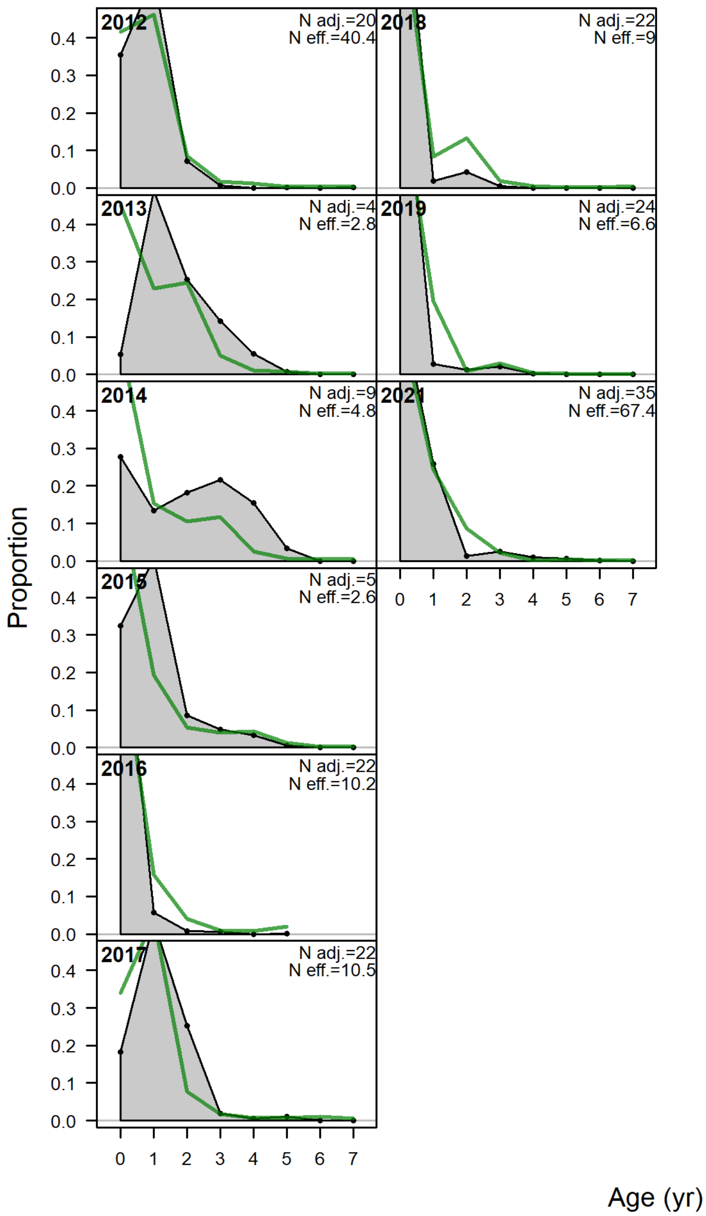

Figure 18: Fits to the age-composition time series for the AT survey in the base model. Values in the top right are input sample sizes (N adj) and effective sample size given the statistical fit in the model (N eff).

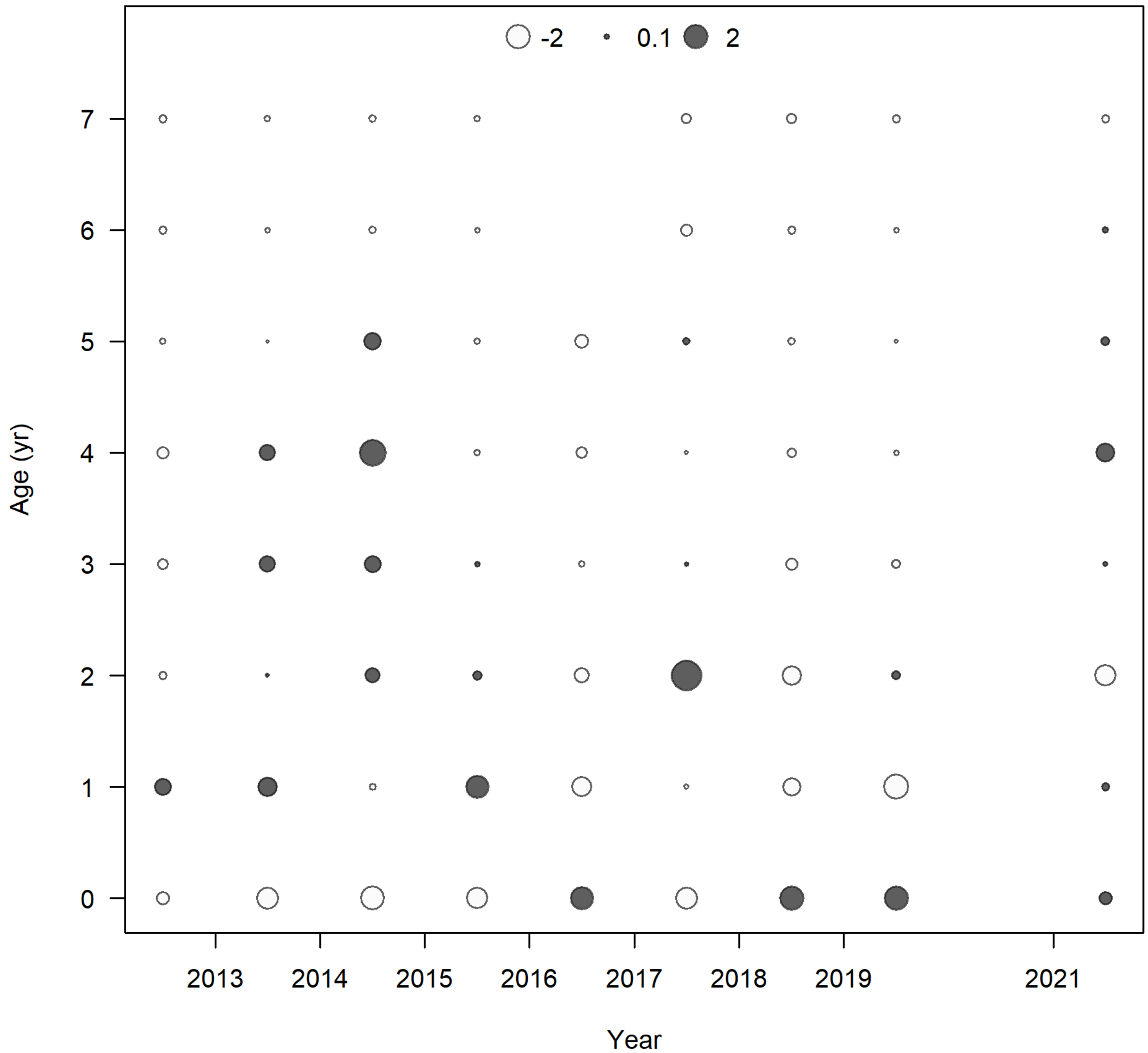

Figure 19: Residuals from the fits to the age-composition time series for the AT survey data in the base model.

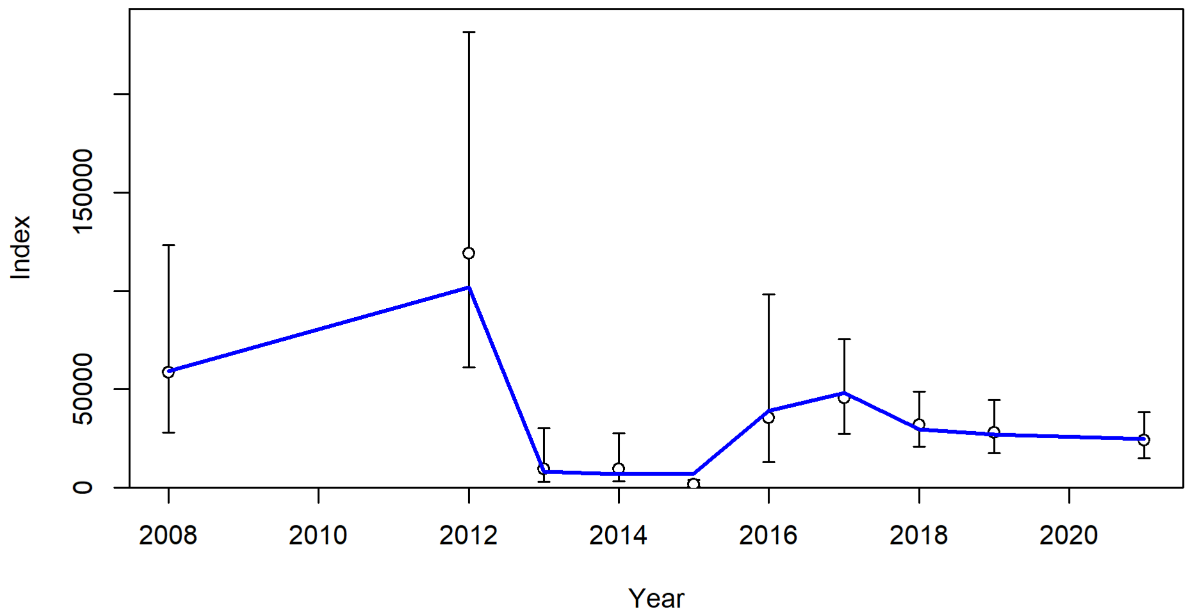

Figure 20: Fit to the index data (blue line) for the AT survey in linear space. Vertical lines indicate 95% uncertainty intervals around index values based on the model assumption of lognormal error.

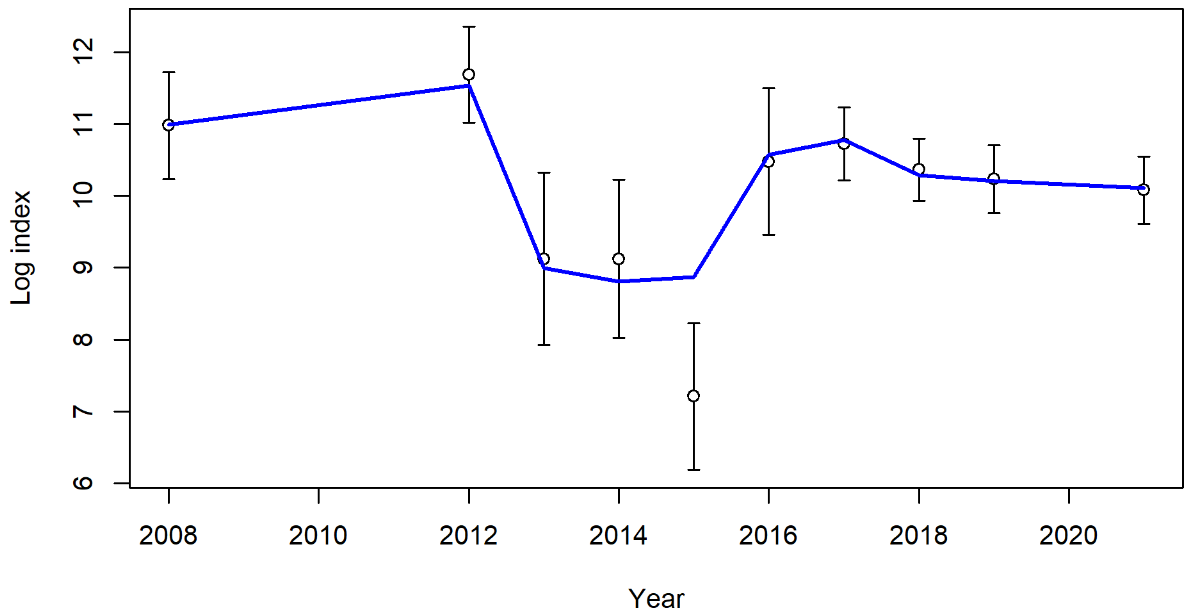

Figure 21: Fit to the index data (blue line) for the AT survey in log space. Vertical lines indicate 95% uncertainty intervals around index values based on the model assumption of lognormal error.

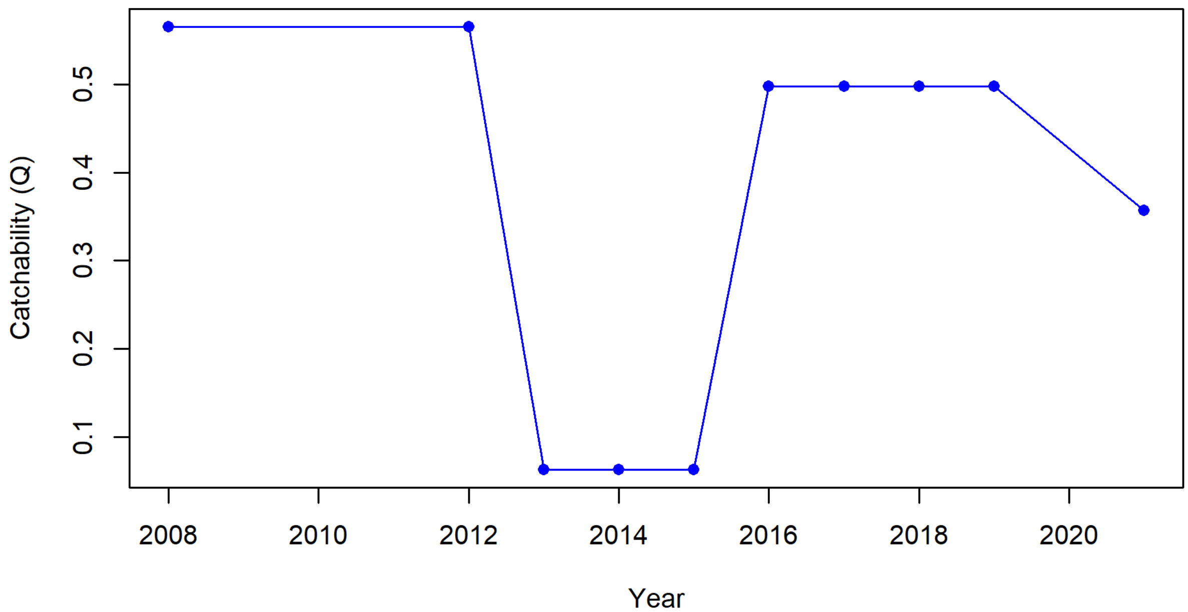

Figure 22: Catchability (Q) values through time. Blocks span the years 2008-2012, 2013-2015, 2016-2019 and 2021. The 2021 Q value was fixed and the other blocks were estimated with a prior centered at the 2021 Q value.

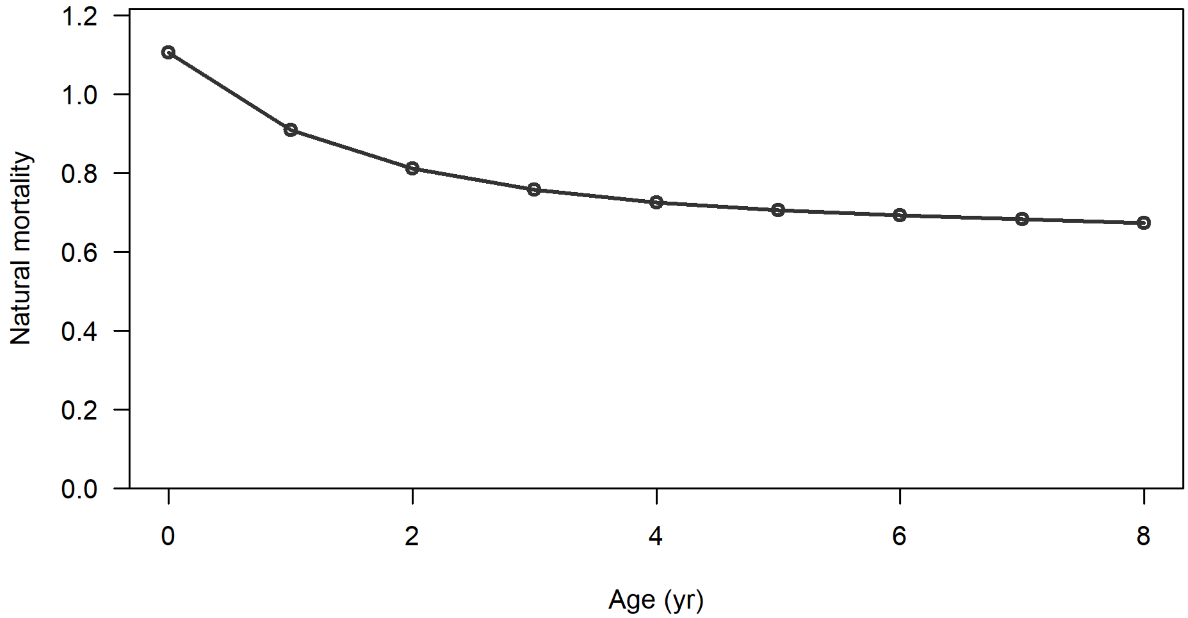

Figure 23: Time-invariant, age-specific natural mortality values.

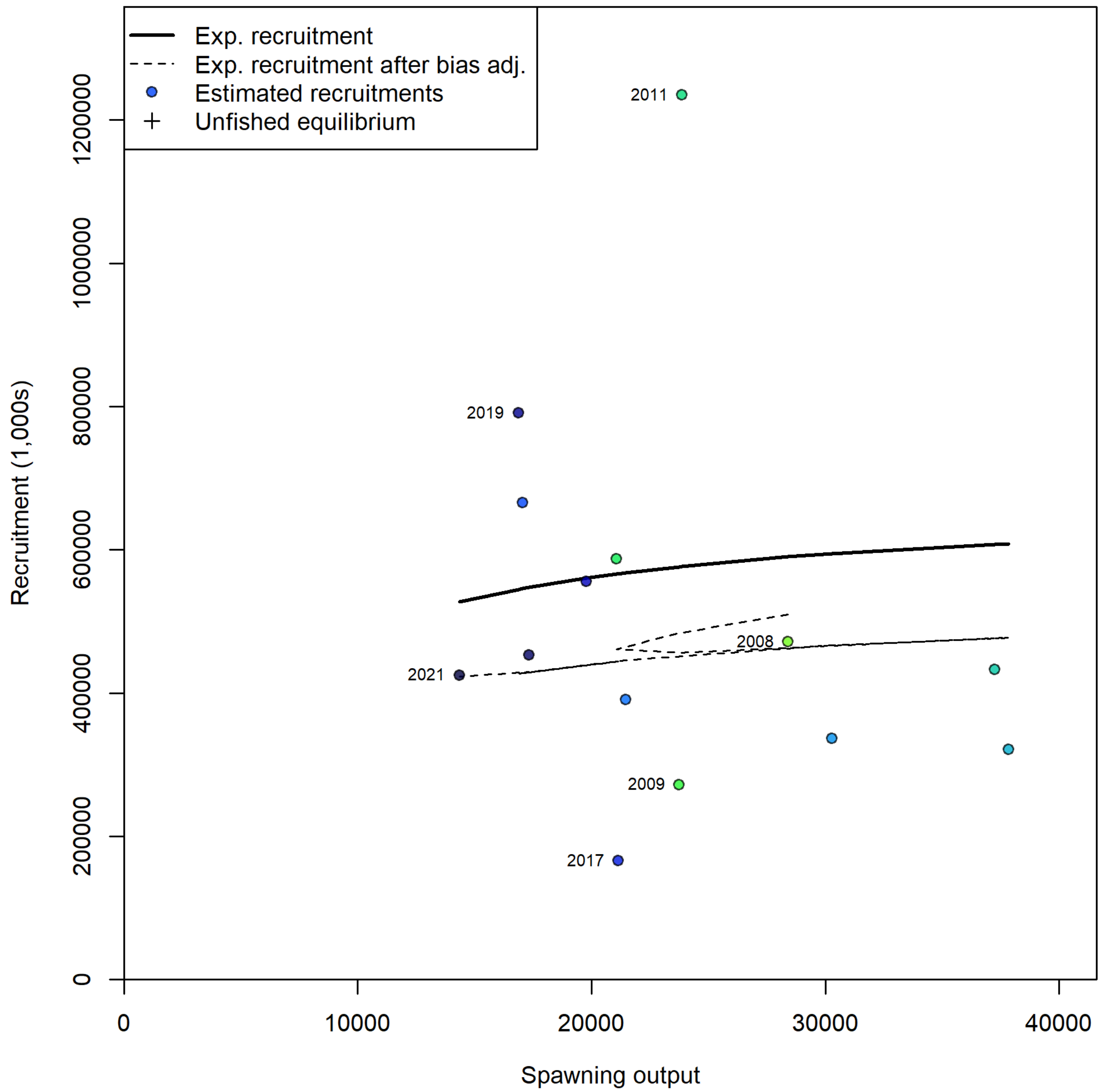

Figure 24: Estimated stock-recruit (Beverton-Holt) relationship with steepness fixed at 0.75. Year numbers indicate the first, last, and years with (log) deviations > 0.5.

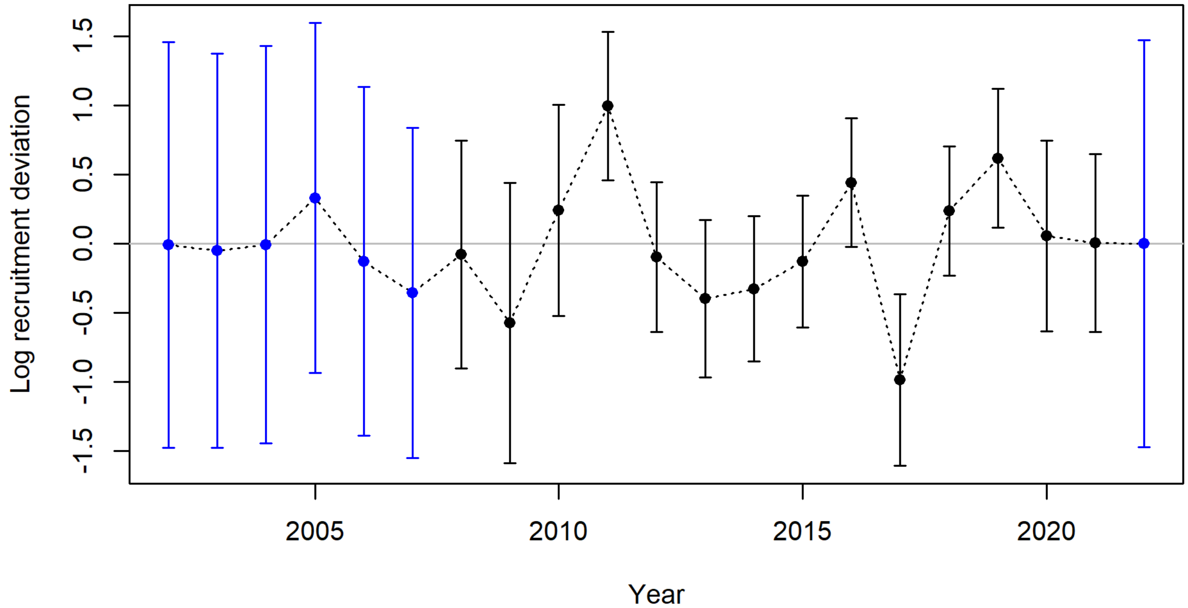

Figure 25: Recruitment deviations with 95% intervals for the base model $\sigma_R = 0.75$.

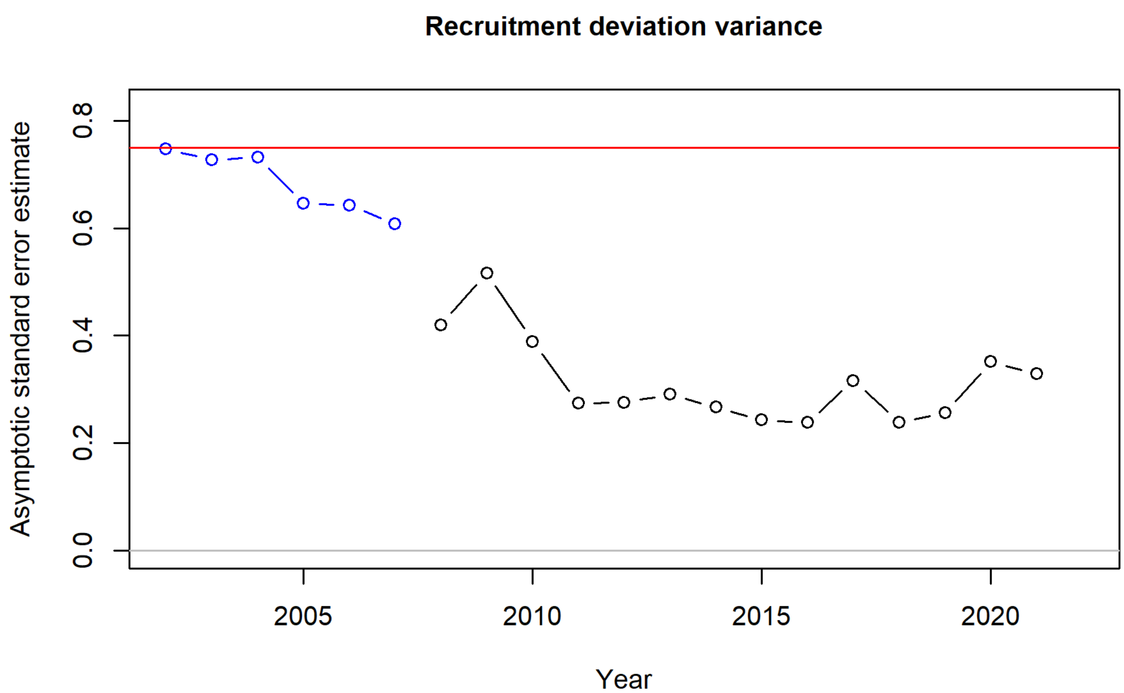

Figure 26: Asymptotic standard errors for the estimated recruitment deviations.

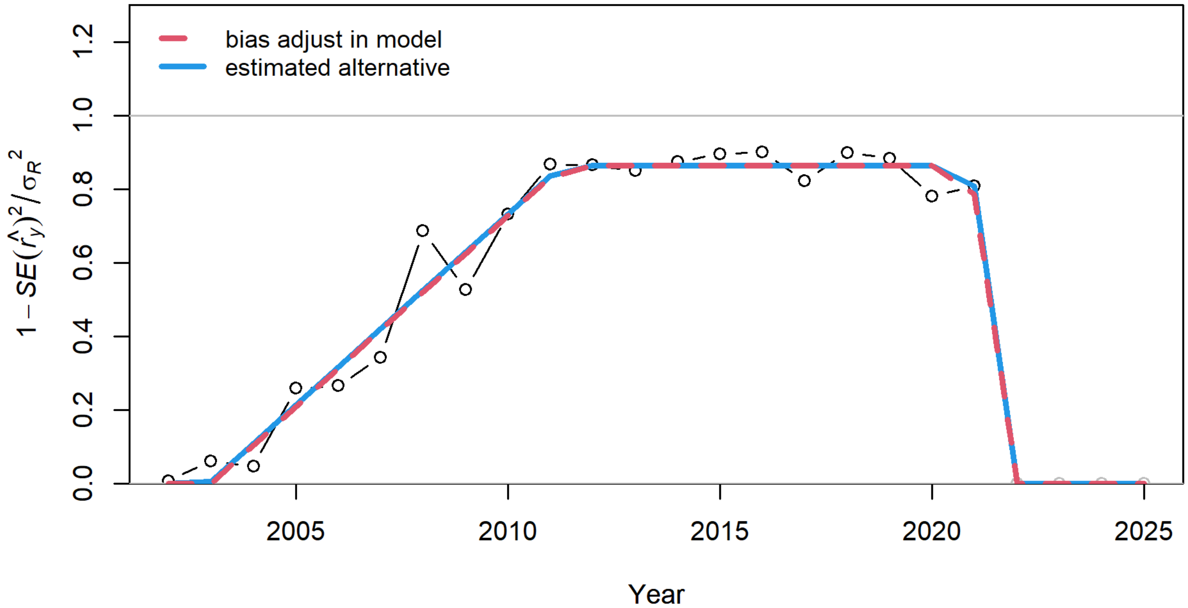

Figure 27: Recruitment bias adjustment plot for early, main, and forecast periods.

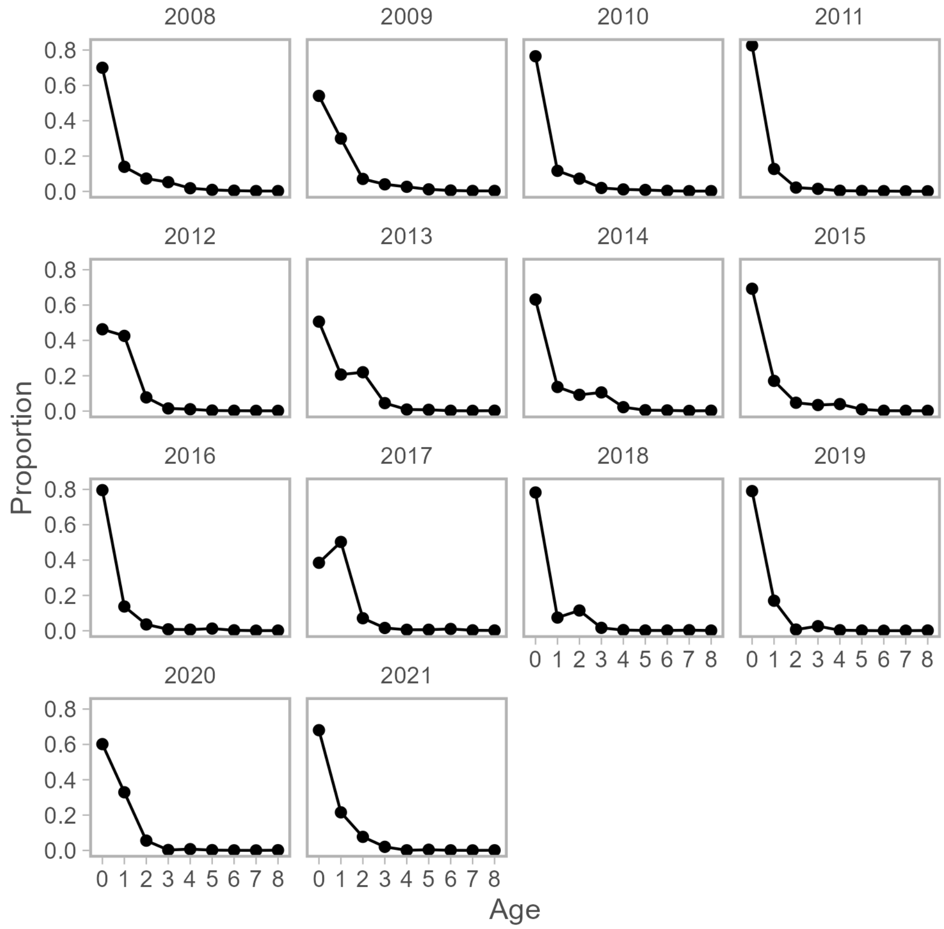

Figure 28: Population numbers at age from the base model.

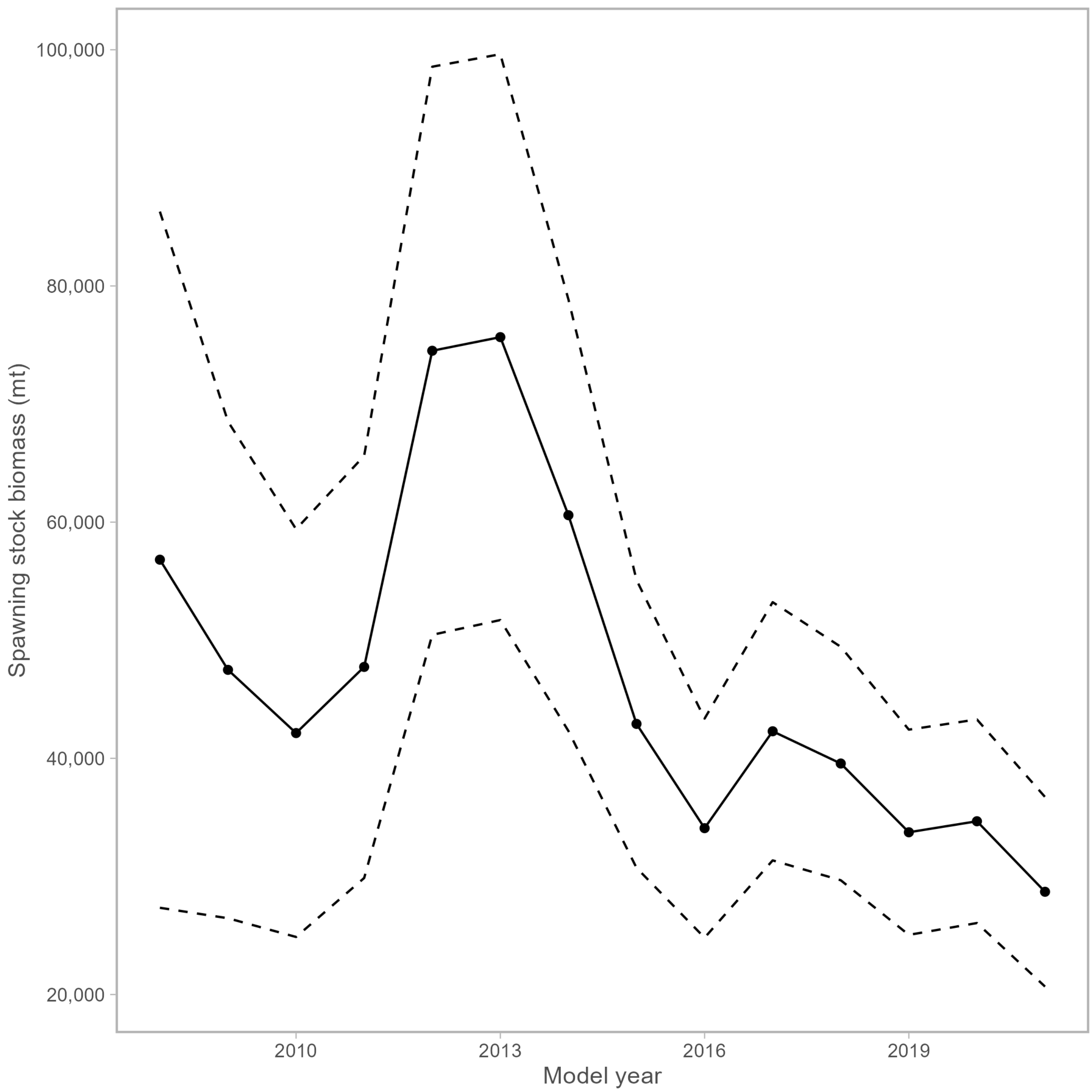

Figure 29: Estimated spawning stock biomass time series (million mt) with 95% confidence intervals (dashed lines).

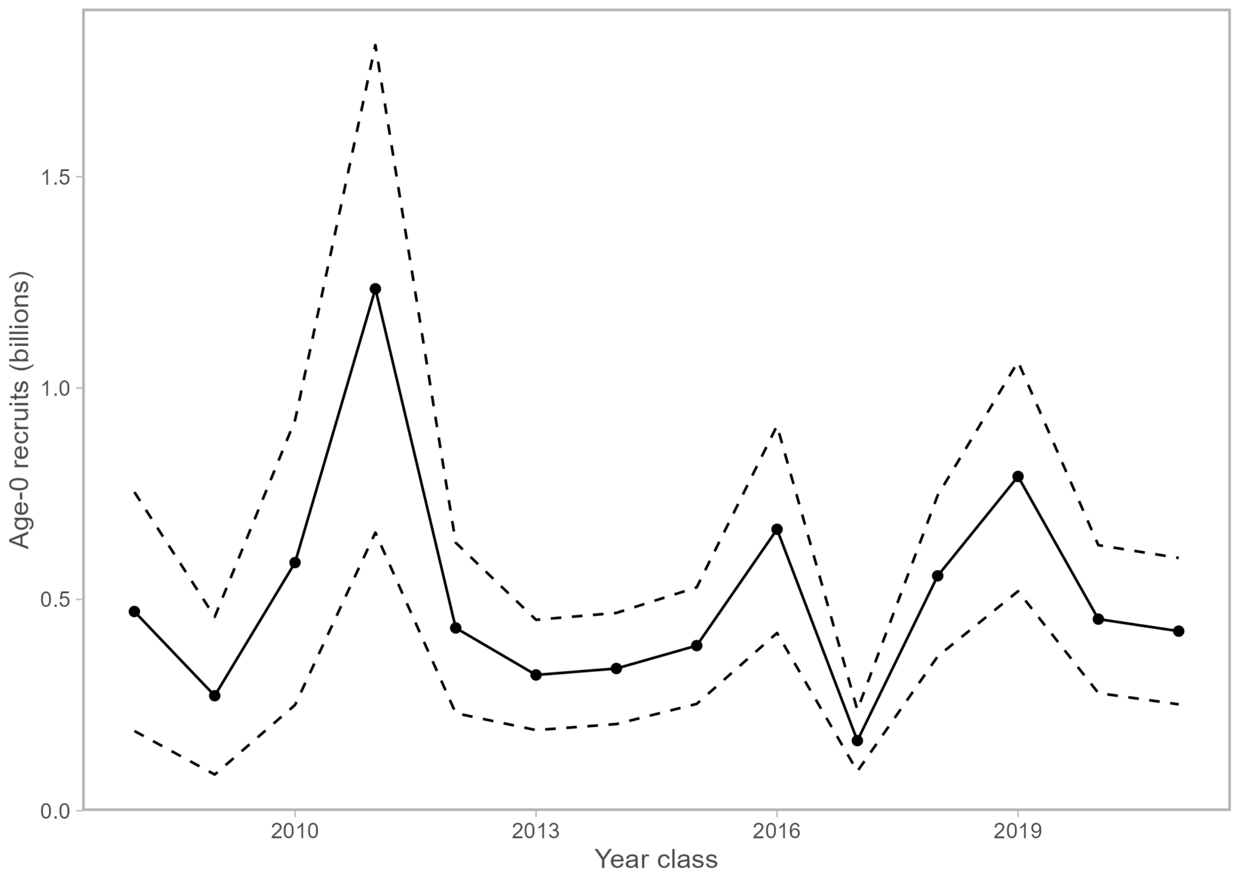

Figure 30: Estimated recruitment time series (billions fish) with 95% confidence intervals (dashed lines).

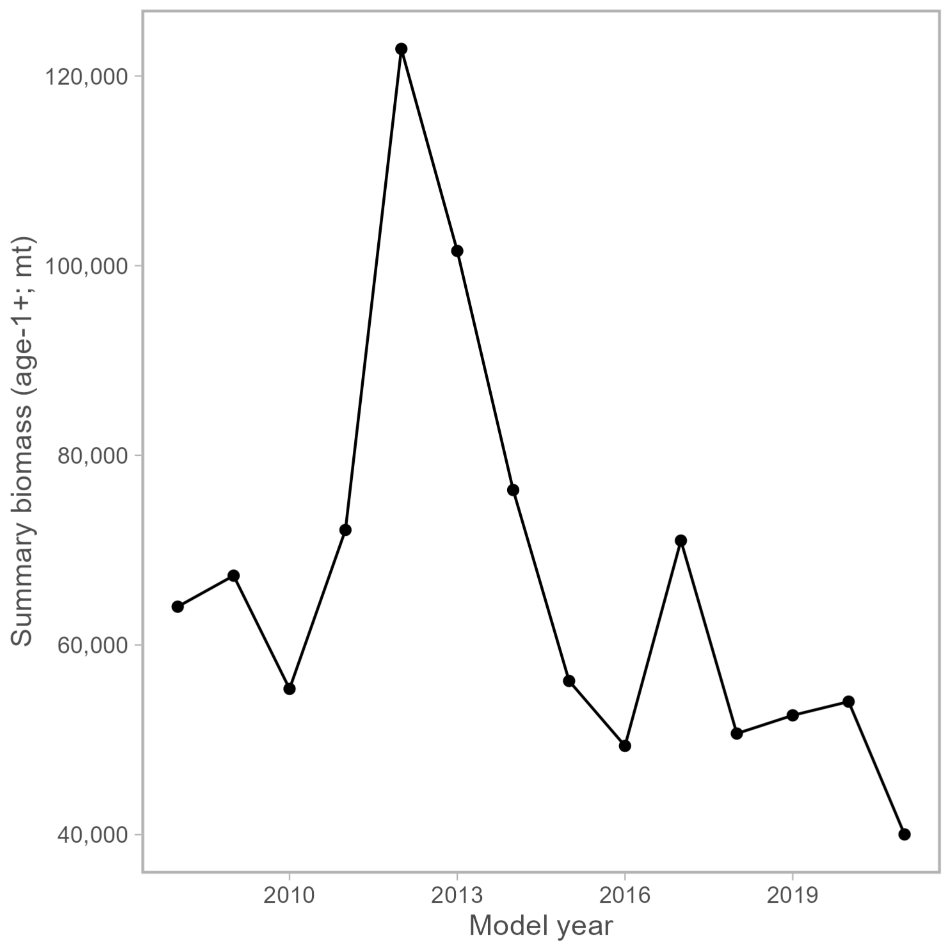

Figure 31: Estimated summary (age-1+) biomass (mt).

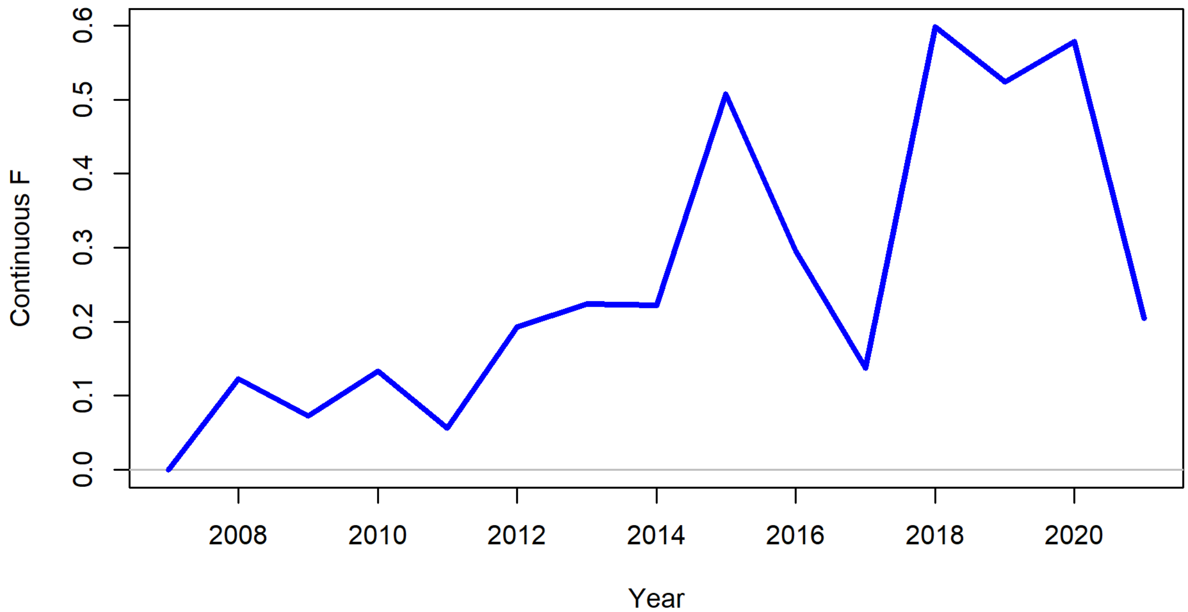

Figure 32: Continuous fishing mortality (F) estimates.

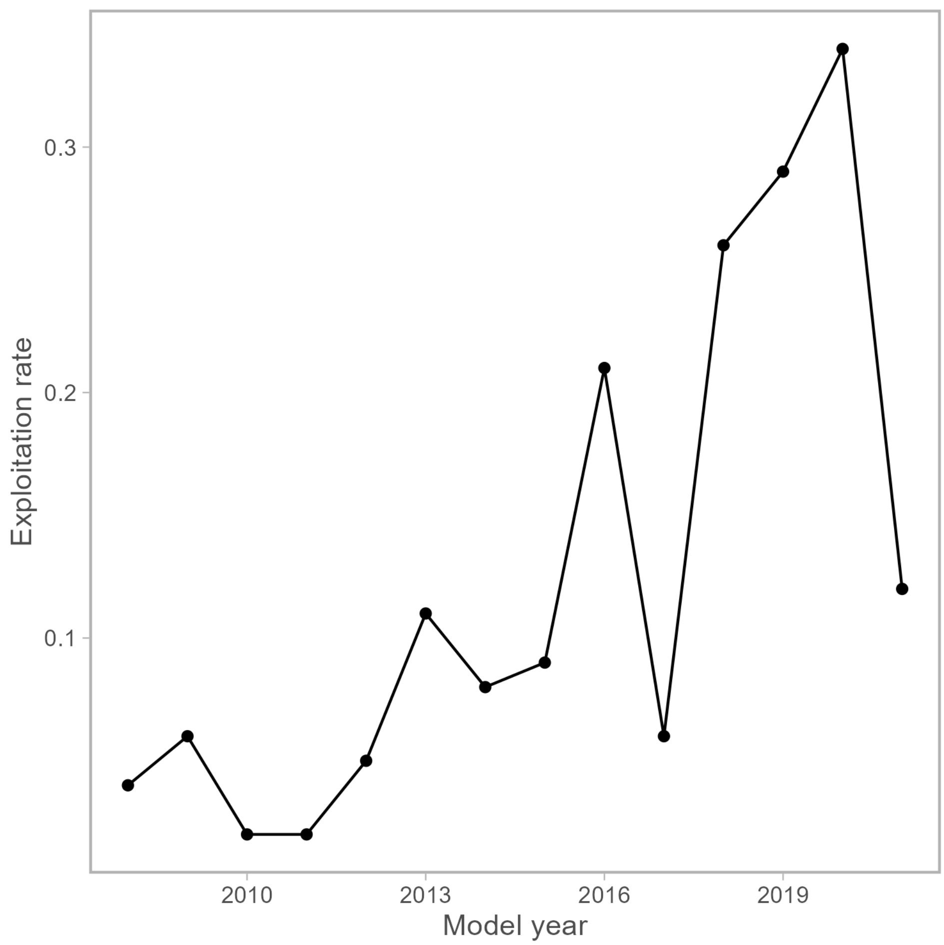

Figure 33: Annual exploitation rates (calendar year landings/ July total biomass).

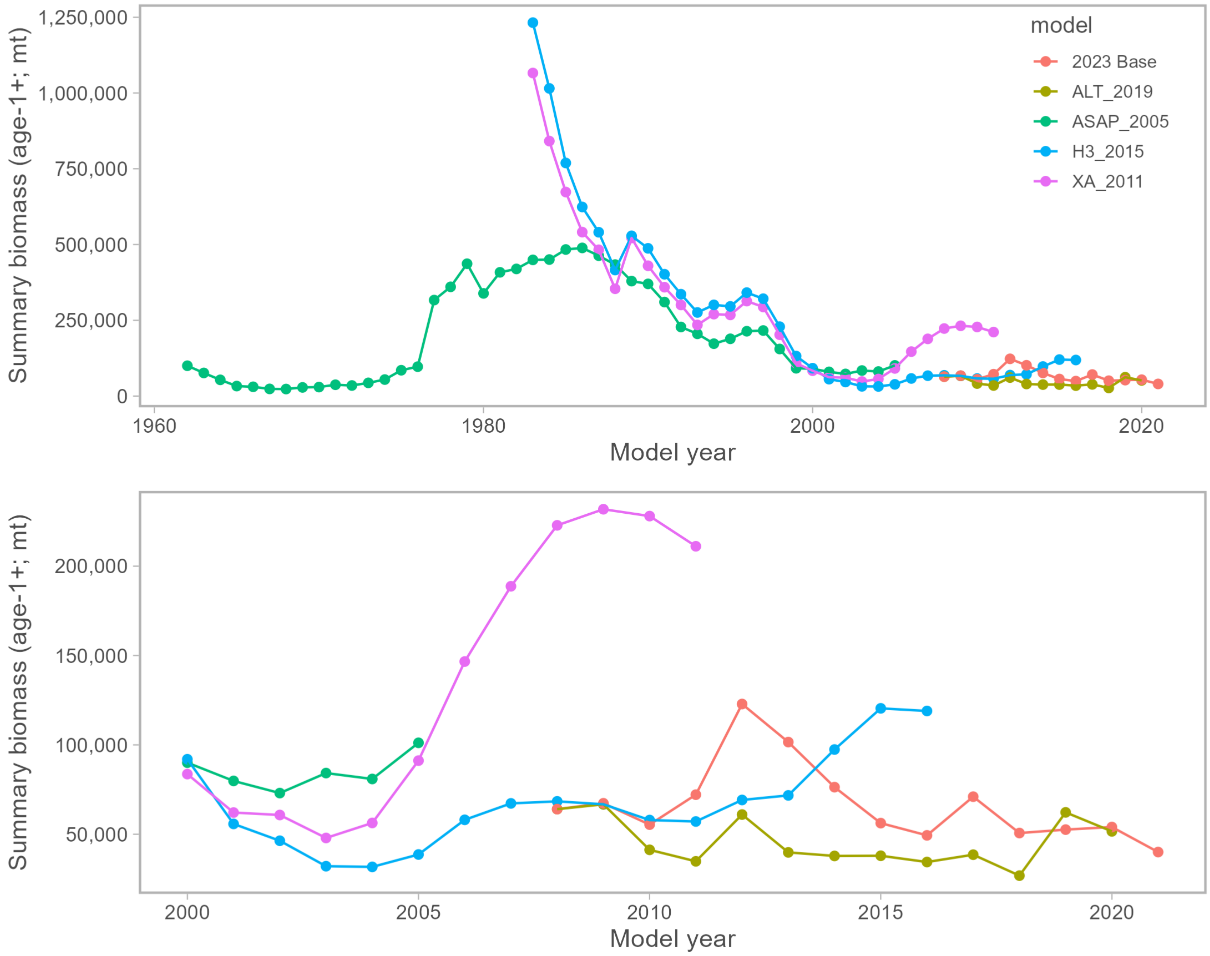

Figure 34: Historical analysis comparing this base model's summary biomass estimate to the 2019 benchmark, and a selection of models dating back to 2005. The top panel shows the longer time series of biomass, and the bottom panel shows time series dating back to 2000.

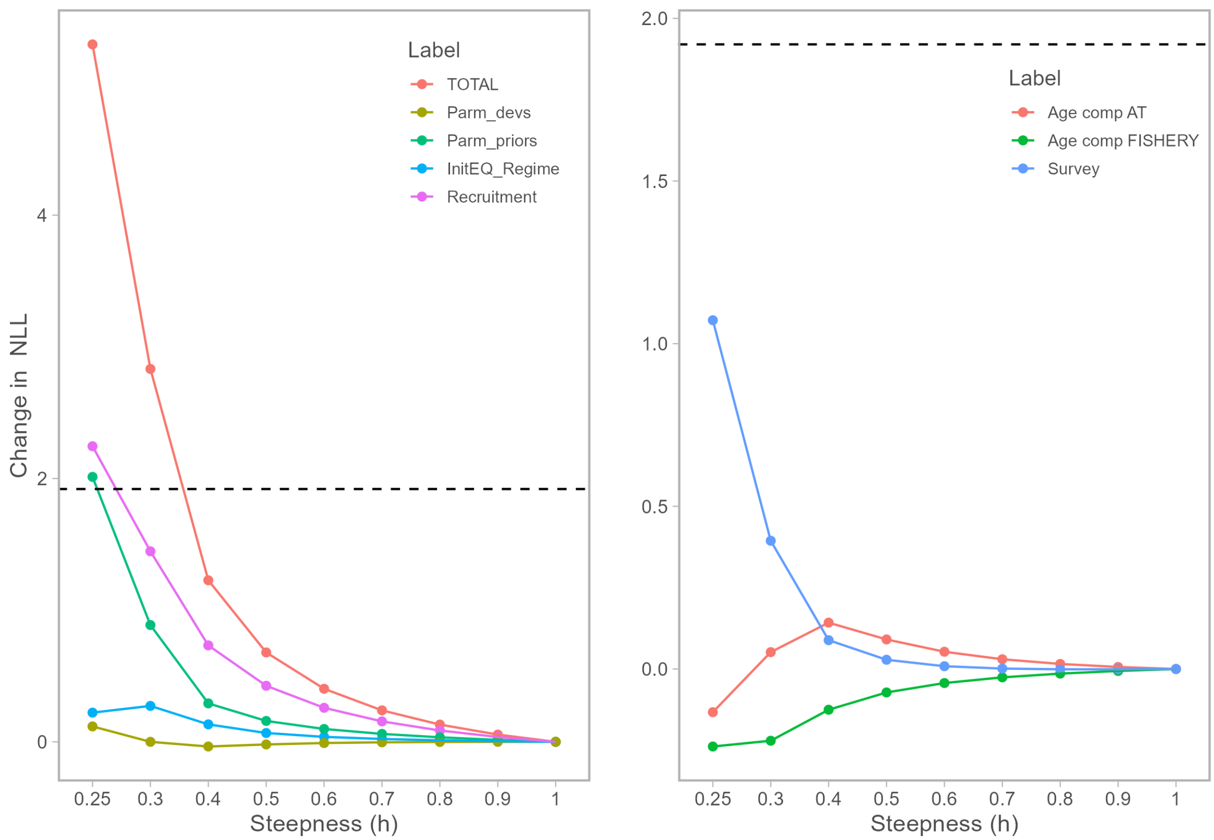

Figure 35: Likelihood profile for values of steepness (h) ranging from 0.25 to 1. Values within 1.92 units of the MLE (dashed horizontal line) are within the 95% confidence interval.

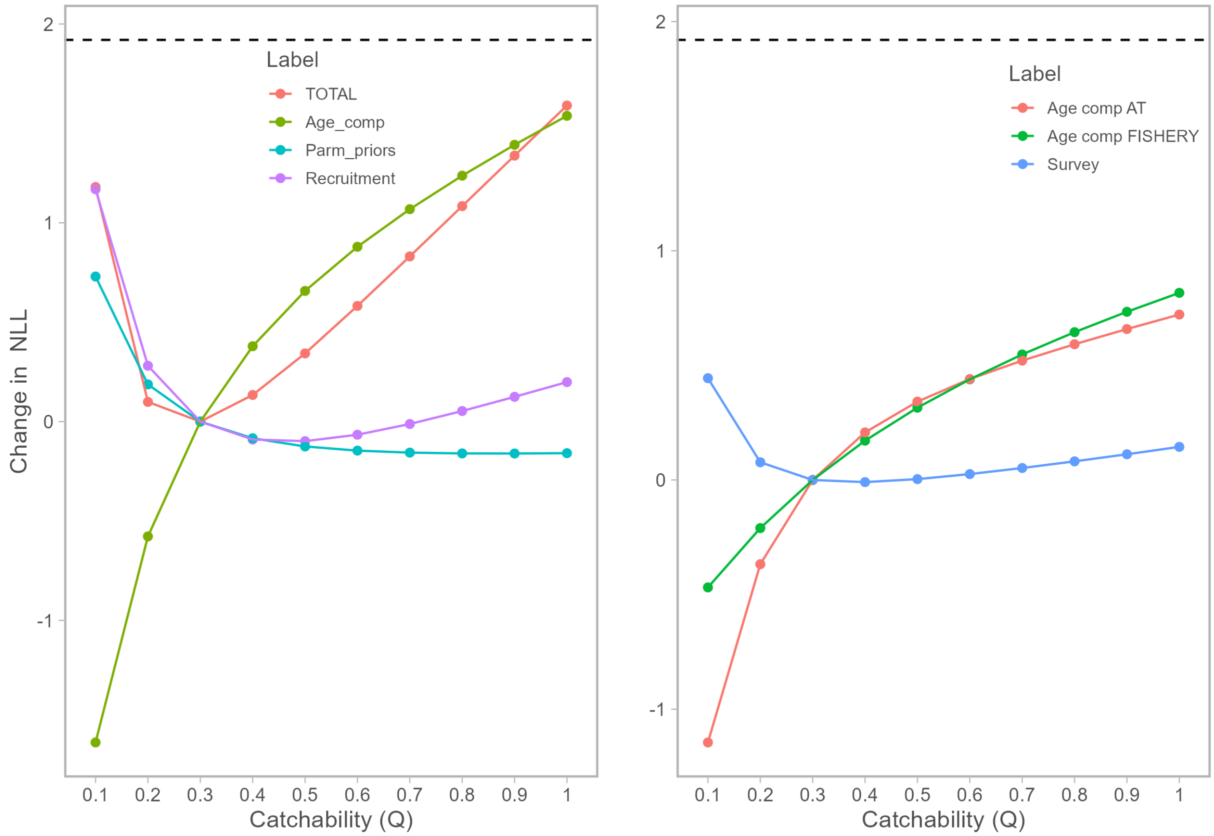

Figure 36: Likelihood profile for values of catchability (Q) ranging from 0.1 to 1. Values within 1.92 units of the MLE (dashed horizontal line) are within the 95% confidence interval. Note that the LnQ values were implemented in SS although the values are shown in linear space here.

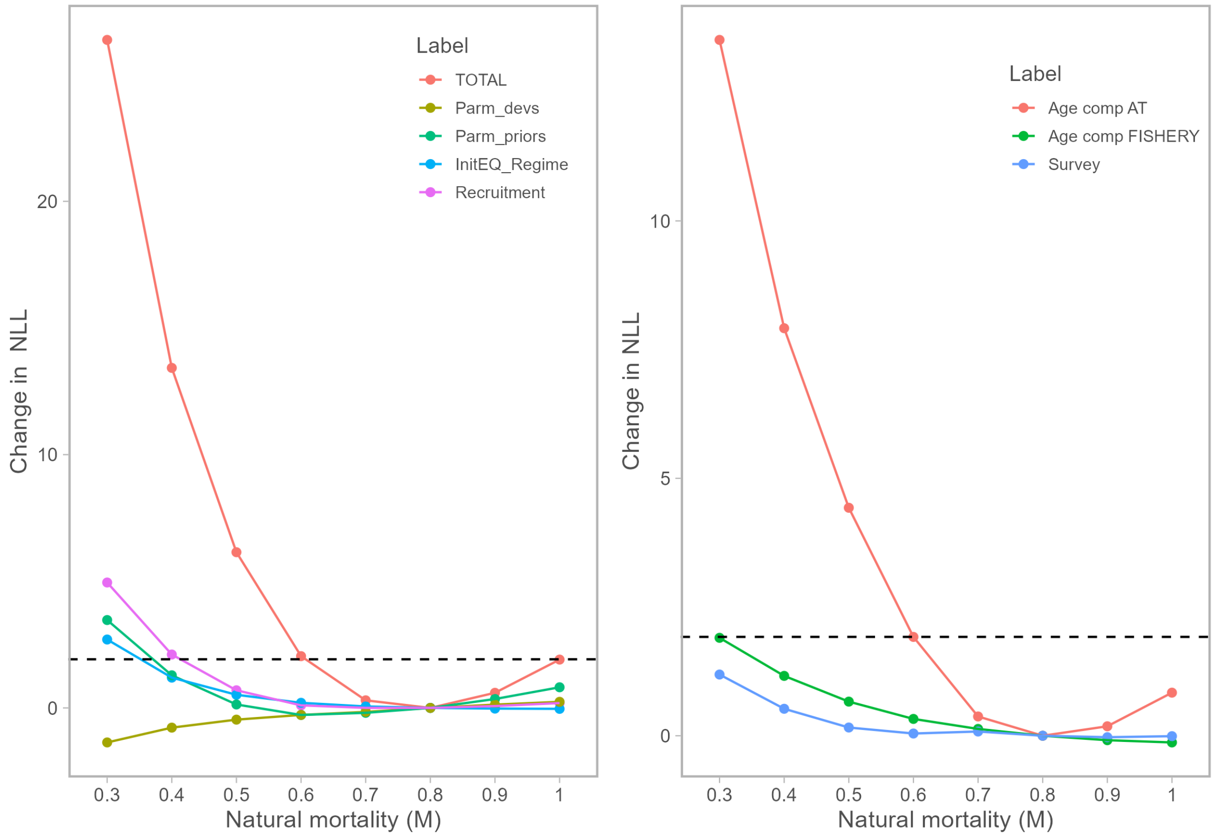

Figure 37: Likelihood profile for values of natural mortality (M) ranging from 0.3 to 1. Values within 1.92 units of the MLE (dashed horizontal line) are within the 95% confidence interval.

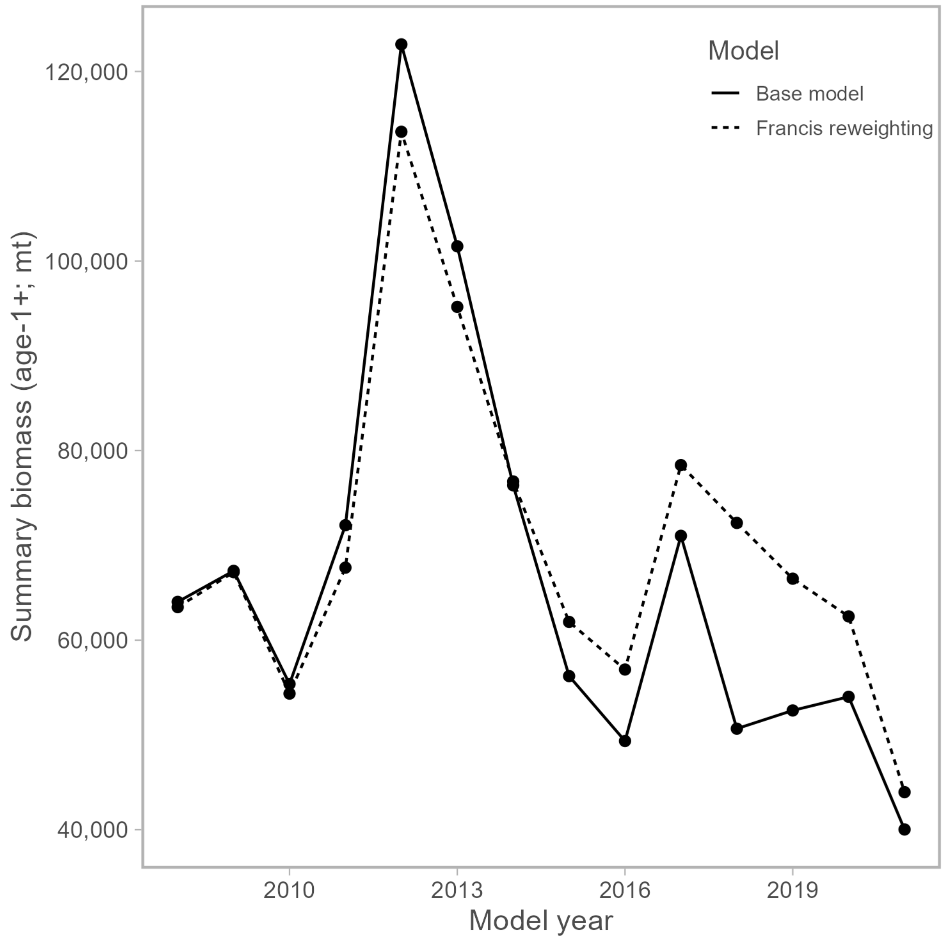

Figure 38: Age-1+ summary biomass (mt) values estimated from the base model (solid line) and the model with Francis reweighting (dashed line) for the age composition from the fishing and AT survey fleets.

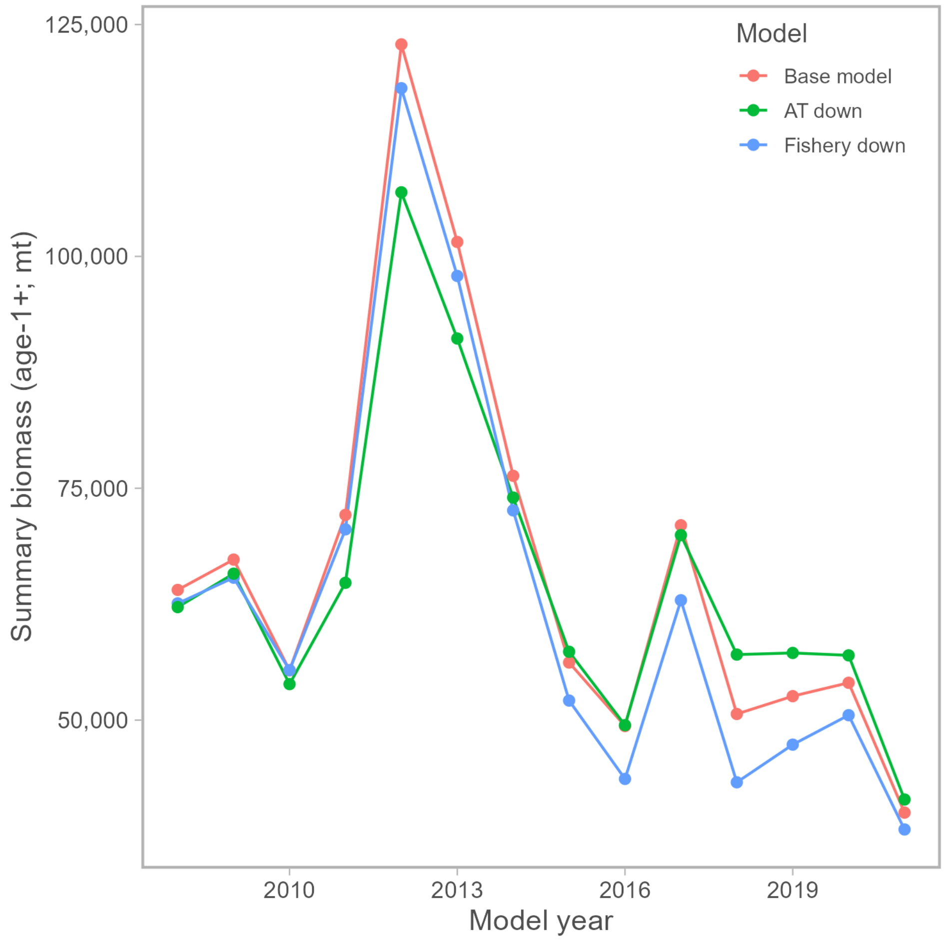

Figure 39: Age-1+ summary biomass (mt) values estimated from the base model and models with AT survey age compositions and fishery age compositions downweighted individually ($\lambda = 0.5$) in the total likelihood calculation.

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10 Appendix A: Age and Maturity Assessment of Pacific mackerel (*Scomber japonicus*)

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Summary

The goal of this report is to provide updated information on age and maturity of Pacific Mackerel (*Scomber japonicus*) for consideration in the 2023 benchmark stock assessment. In section 1, we provide an ageing dataset and estimates of ageing errors for Pacific Mackerel otoliths collected from 2012 to 2022 during fishery-independent surveys. In section 2, we provide an updated estimate of length and age at sexual maturity for Pacific Mackerel based on samples collected from 2010 to 2021 during fishery-independent surveys.

1. Ageing of Pacific Mackerel

Background

Historically, biological samples of Pacific Mackerel were collected solely from commercial fishery landings by the California Department of Fish and Wildlife (CDFW). Consequently, all age data incorporated into assessments were fishery-dependent. The Southwest Fisheries Science Center (SWFSC) began archiving Pacific Mackerel otoliths in 2007 to provide fishery-independent biological samples for consideration in assessments, although this species was not a primary target species. To provide a more robust sample archive to generate length and age compositions for acoustic biomass estimates, Pacific Mackerel became a primary target species in 2012 and were sampled following the same protocol as Pacific Sardine (*Sardinops sagax*) and Northern Anchovy (*Engraulis mordax*) (Dorval et al. 2022).

SWFSC staff produced Pacific Mackerel ages from whole, unpolished otoliths collected during SWFSC surveys. The procedure described by Fitch (1951) was used to estimate ages with the assumption that observable growth increments were deposited during the progression of seasons. An annulus was assigned when “the interface between an inner translucent growth increment and

1156 the successive outer opaque growth increment” (Fitch 1951, Yaremko 1996) was observed. The application of this method was to immerse the otolith in distilled water, view using a stereo microscope, and count the number of annuli observed on the distal side of the otolith in less than three minutes. Although Pacific Mackerel has an extended spawning season, a July 1 birthdate was assigned for all individual Pacific Mackerel collected in U.S. waters, albeit an unknown number of these individual fish could have been born prior to or following this date. After annuli were counted without knowledge of size, sex, or capture date, the birthdate, capture date, and analysis of the most distal pair of growth increments were used to assign final ages by readers (see Yaremko 1996).

Sample Collection

Pacific Mackerel otoliths were collected during SWFSC summer acoustic trawl method (ATM) surveys conducted from July through October (Dorval et al. 2022). Collections spanned from the Canadian-US border to the US-Mexican border (2012-2022) (Figure 1). Pacific Mackerel were randomly subsampled (n = 50) from the larger catch and measured for fork length (FL; mm) and weighed (g). If fewer than 50 were caught, all Pacific Mackerel were measured and weighed. Sagittal otoliths were then extracted from up to 25 Pacific Mackerel and stored dry.

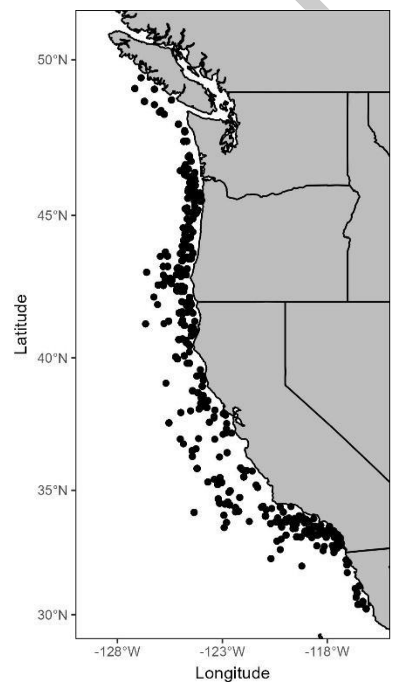

Figure 1. Catch locations for Pacific Mackerel (*Scomber japonicus*) during SWFSC spring and summer trawl surveys (2010-2022).

Age-reading

Whole otoliths were immersed in distilled water with the distal side facing up and then read from the posterior region, using a stereo microscope at 25 X magnification. Three SWFSC age readers, identified as readers 15, 17, and 18, participated in the age determination process, using the conventional technique of otolith age-reading described in Yaremko (1996). All agers used in this study were certified agers. Further, the SWFSC ATM survey age dataset is consistent with fishery ages produced by CDFW for the 2019 and 2023 stock assessments, as the best CDFW age reader was involved in the training process of the three SWFSC readers above.

A total of 1762 ages from 2012 to 2022 were produced by readers 17 and 18. From each summer survey, otolith samples were randomly selected by haul and by length bin (50 mm FL), and approximately 50% of the selected samples were randomly allocated to each of these two readers. This selection scheme maintained the spatial and temporal integrity of the trawl sampling and the distribution of length-at-age in space and time. Due to time constraints, a subset of total otoliths collected were aged from 2013 to 2019 that accounted for length bin, year, and geographic location. Each individual fish was assigned a final age based on the capture date and an assumed July 1 birthdate (see Yaremko 1996) and the analysis of the most distal pair of growth increments.

Further, 36% of the total number of otolith samples aged by readers 17 and 18 were randomly selected and double-read by these two readers and reader 15 to produce a consensus age reading vector identified as reader CA. The CA ageing vector included ages that all three readers agreed upon and additional ages determined from simultaneous onsite readings under the same stereo microscope until they reached 100% agreement. As such, the CA ageing vector was assumed to be the best ages, and accordingly was considered unbiased in the computation of ageing errors. This method was previously reviewed and approved by Pacific Sardine STAR panels in 2011 for ages produced by the Department of Fisheries and Oceans (DFO) laboratory (Hill et al. 2011, Dorval et al. 2013) and in 2020 for ages produced by SWFSC (Kuriyama et al. 2020).

The computation of age-reading errors was based on the method described by Punt et al. (2008), using the nwfscAgeingError R package (Thorson et al. 2012). We computed ageing error matrices based on otoliths that were aged by reader CA, 17, and 18 while assuming that: (1) ageing bias depends on reader and the true age of a fish; (2) the age-reading error standard deviation depends on reader and the true age; and (3) age-reading error is normally distributed around the expected age (see Punt et al. 2008). For the purpose of this report, we were mostly interested in estimating the *SD*s-at-age for age data collected during the 2012-2022 trawl surveys, following similar methods used in the past for Pacific Sardine and Pacific Mackerel assessments (Hill et al. 2011; Dorval et al. 2013; Crone et al. 2019; Kuriyama et al. 2020). We defined various model scenarios, comparing models that assumed equal or unequal *SD*s among readers. As in previous assessments, Model C (Dorval et al. 2013) was selected as the best model, using Akaike Information Criterion with a correction for finite sample sizes. This model assumed that all three readers (CA, 17, and 18) were unbiased and had equal SDs. One dataset set, including age data from 2012 to 2022, was used to compute ageing errors for the trawl surveys. The functional form of random ageing-error precisions was assumed to follow a

1158 curvilinear *SD* and a curvilinear *CV* based on a three-parameters, Hollings-form relationship of *SD* or *CV* with true age (see Punt et al. 2008; Thorson et al. 2012, Dorval et al. 2013). Further, the maximum *SD* allowed in model runs was 40.

Results and Discussion

The length distribution of Pacific Mackerel subsampled and measured during summer trawl surveys from 2012 to 2022 ranged from 53 mm FL to 402 mm FL (Figure 2a)**.** A total of 1,762 fish were aged, with ages ranging from 0 to 7 years (Figure 2b). Aged samples were comprised mostly of young fish, with individuals aged at 0, 1, 2, and 3 years representing 46%, 29%, 16%, and 6% of the total number of otoliths aged, respectively. Older fish (4-7 years in age) made up only 2.3% of the samples aged, and thus these age classes might not have been well represented in the summer trawl surveys. There were large overlaps in length distributions among age classes (Figure 3).

Age-Reading Errors

Age-reading errors for the survey data were computed using 643 otoliths collected from 2012 to 2022. Ages were estimated with high level of precision. Ageing agreement for these 643 otoliths between reader 17 and 18 was 100% from age 0 to age 2, 94% at age 3, 75% at age 4, and 70% at age 5 (Figure 4). Only 2 fish were aged greater than 5 years, but these readers disagreed on the age of these fish. In the consensus ageing vector, one of these fish was assigned an age 5 and the other an age 6. As a result, SDs-at-age estimated from Model C were very low, varying from 0.001 to 0.319 (Table 1).

Pacific Mackerel of ages 4 years and older (Figure 4) were the only ages where readers agreed 75% of the time or less. This age group is more frequent in the Pacific Northwest and/or in offshore waters that are not well covered by current trawl surveys. Only 26 Pacific Mackerel out of 1,762 were in the 4^+ age group. Older age classes generally have lower agreement. Interpreting increments at the edge of older fish otoliths is more challenging, because annuli are much closer together and it is more difficult to differentiate a check from an annulus (Yaremko 1996).

A current drawback is that no age validation has been published for Pacific Mackerel in the eastern North Pacific. The absence of validation of the periodicity of increment formation in each and every age group can lead to systematic bias in age determination (Campana 2001). Shiraishi et al. (2008) confirmed annual periodicity of annuli in Pacific Mackerel from southwest Japan through captive growth of known-age fish up to 2 years old and edge analysis in wild Pacific Mackerel up to 6 years old. SWFSC conducted a captive growth experiment of Pacific Mackerel and preliminary results suggest annual periodicity of annuli in fish up to approximately 2 years old (K.C. James et al. unpublished data). While this research is not for every age class, and there still is a possibility of bias from unvalidated ages, it lends confidence to the accuracy of ages provided to the stock assessment.

1159 While all otolith samples were collected during SWFSC ATM surveys, it is important to note that the entire length range of Pacific Mackerel were not sampled for this study. The ATM survey is designed to produce abundance estimates for multiple coastal pelagic species based on their acoustic signatures. Additionally, trawl net avoidance and rates of capture likely varies by species and fish length.

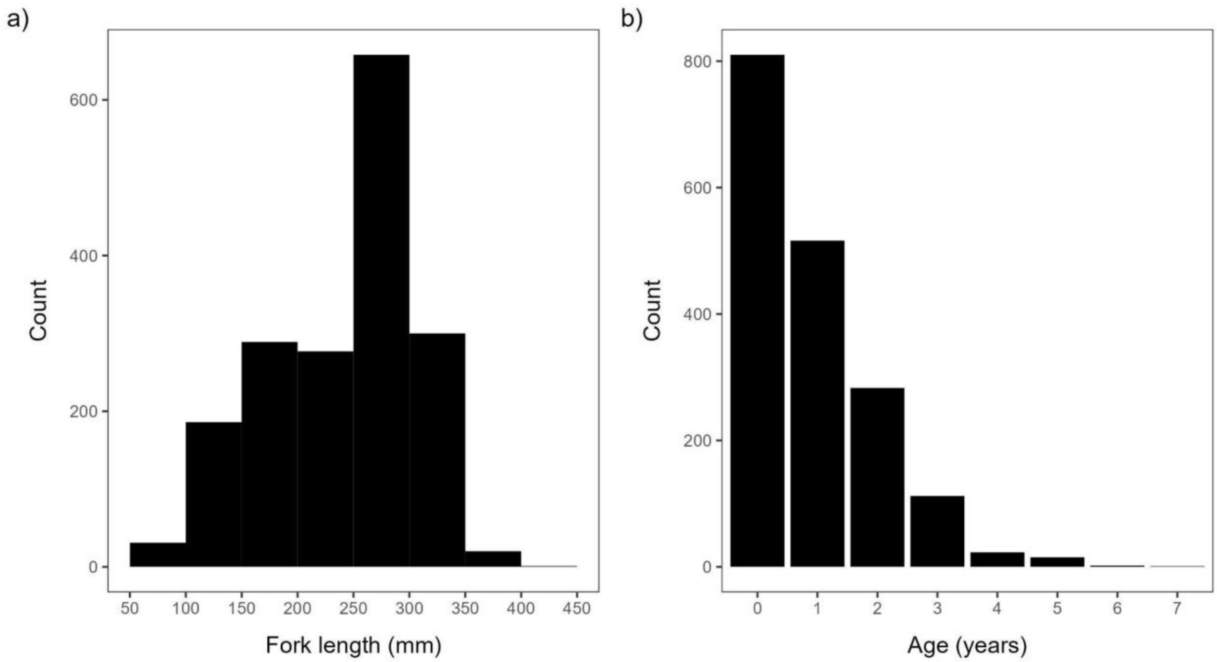

Figure 2. a) Length and b) age distribution of Pacific Mackerel (*Scomber japonicus*) collected from summer SWFSC acoustic trawl surveys (2012-2022).

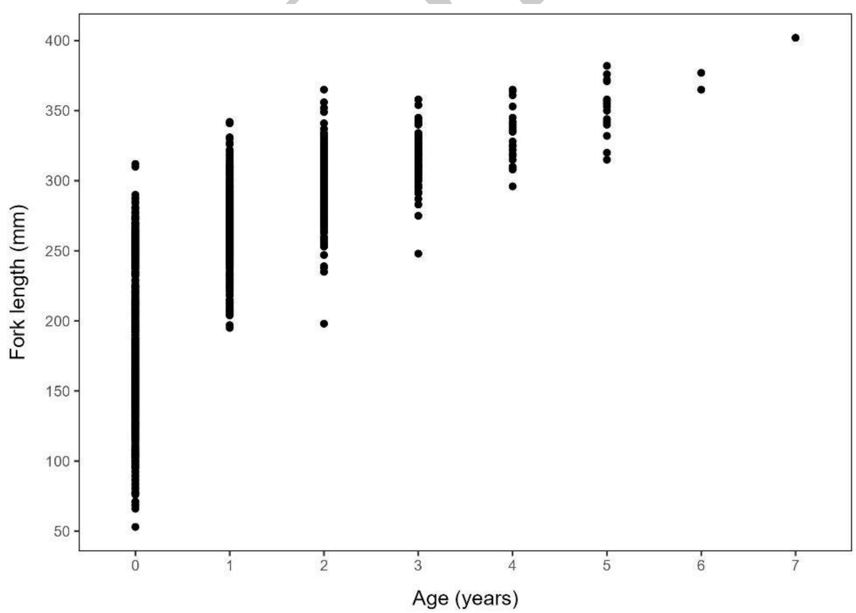

Figure 3. Age-at-length for Pacific Mackerel (*Scomber japonicus*) collected from summer SWFSC acoustic trawl surveys (2012-2022).

Table 1. Coefficient of variation (CV) and standard deviation (SD) at age estimated for Pacific Mackerel (*Scomber japonicus*) collected from summer SWFSC acoustic trawl surveys (2012-2022). All estimates were calculated using the latest version of the nwfscAgeingError R package (Thorson et al. 2012) based on the assumptions that, within the SWFSC laboratory, there was no bias in ageing among readers, and readers had similar SD.

						Agemat model	
Survey	**Collection Year**	**Data set ID**	**Sample size**	**Number of readers**	**Age**	**CV**	**SD**
SFWSC Trawl Survey	2012-2022	1	643	3	0	0.001	0.001
					1	0.001	0.001
					2	0.074	0.148
					3	0.076	0.229
					4	0.068	0.273
					5	0.060	0.298
					6	0.052	0.311
					7	0.046	0.319

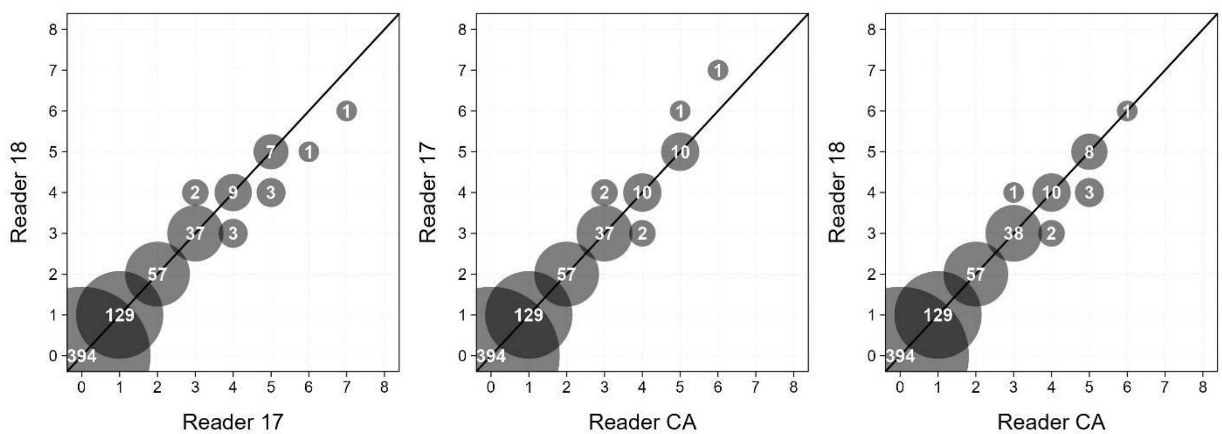

Figure 4. Age bias plots from the Agemat model for readers CA, 17, and 18 for Pacific Mackerel (*Scomber japonicus*) collected from summer SWFSC acoustic trawl surveys (2012-2022).

2. Length and Age at Maturity of Pacific Mackerel

Background

The Pacific Mackerel is a multiple batch spawner with indeterminate fecundity, asynchronous oocyte development, and a relatively high spawning frequency (Knaggs and Parrish 1973; Peña et al. 1986; Asano and Tanaka 1989: Dickerson et al. 1992). In the northeast Pacific, spawning of Pacific Mackerel typically occurs from Point Conception to Cabo San Lucas from 3 to over 300 km offshore (Moser et al. 1993), although small juveniles have been reported off Oregon and Washington in recent years (Stierhoff et al. 2019). Pacific Mackerel have a protracted spawning season throughout their range, with peak spawning off California and central Baja California, Mexico, occurring during the spring through summer months and some spawning occurring during all months of the year (Ahlstrom 1959; Kramer 1969; Knaggs and Parrish 1973; Schaefer 1980; Gluyas-Millán 1994). Similar to other broadcast-spawning marine fishes, both spawning frequency and spawning season duration are believed to increase with female size and age (Knaggs and Parrish 1973; Dickerson et al. 1992).

Recent stock assessments for Pacific Mackerel used maturity schedules from Dickerson et al. (1992), in which the fraction of mature females was estimated by fitting a logistic regression model to maturity data (Crone and Hill 2015; Crone et al. 2019). A more recent study was conducted from 2009 to 2012 for purposes of re-evaluating maturity-at-age for Pacific Mackerel, which used simple logistic regression to estimate 50% maturity at 27 cm FL and 2.2 years of age (Crone and Hill 2015). The results of the more recent study were similar to those based on Dickerson et al. (1992), and consequently, the maturity schedules used in past assessments were again applied in both 2015 and 2020 (Crone and Hill 2015; Crone et al. 2019). Estimated maturity schedules for Pacific Mackerel off California are similar to those reported in Mexico. For example, Gluyas-Millán (1994) concluded that 50% of female Pacific Mackerel off Vizcaino Bay, Mexico, are mature by 293 mm standard length (SL).

Material and Methods

Samples of ovarian tissues were collected from female Pacific Mackerel during SWFSC spring and summer surveys conducted from 2010 through 2021 to generate updated estimates of length and age-at-maturity. Males were not included in this study, because previous studies have concluded there to be no notable differences in growth, maturity, or mortality rate in Pacific Mackerel by sex (see Crone et al. 2019). Consequently, combined sex models have been used in all stock assessments used to advise management in U.S. Pacific waters (Crone et al. 2019). Each gonad sample was placed in a tissue-tek cassette and preserved in 10% neutral buffered formalin in preparation for histological processing and examination. Samples were later embedded in paraffin, sectioned at 6 µm, mounted on slides, stained with Mayer’s haemotoxylin-eosin, and observed under a compound microscope (Humason 1972). Past studies on reproductive development in Pacific Mackerel emphasized the importance of using histological criteria for maturity assessments, as all stages of ovarian development cannot be discerned with the unaided eye (Asano and Tanaka 1989; Dickerson et al. 1992).

Standardized terminology for describing reproductive development in marine fishes (Brown-Peterson et al. 2011) were used to classify each sampled female Pacific Mackerel as either immature (never spawned) or mature (previously spawned or first spawning) (Figure 5). Females with ovaries containing no oocytes undergoing vitellogenesis but numerous oocytes in the cortical alveolar stage of development were classified as mature, because fish sampled at this phase of development usually spawn at some point during the season (Murua and Saborido-Rey

2003; Wright 2007; Lowerre-Barbieri et al. 2011a,b). Additional histological features used to distinguish between immature females and mature, regenerating females included the thickness of the ovarian wall, the presence of muscle bundles or atretic follicles, and the level of organization within the lamellar structure (Lowerre-Barbieri et al. 2011a,b).

Following common practice, the length and age at sexual maturity for Pacific Mackerel was estimated using an analytical method based on logistic, non-linear regression (Hunter et al. 1992; Macewicz et al. 1996; Roa et al. 1999; Lo et al. 2005; Basilone et al. 2006). Specifically, we followed the methods described by McBride (2016), which used a binomial model in R (R Core Team 2022) to the estimate the length and age at 25, 50, and 95% maturity and the uncertainty around the predicted relationship between length or age and percent maturity (Formula: Maturity ~ FL). Maturity data were pooled across all survey years to generate sample sizes across all length and age classes that were sufficient to produce a realistic ogive estimate without sample distribution bias. The use of a pooled maturity data set was consistent with recent stock assessments for Pacific Mackerel, in which age-length keys used to estimate age compositions were comprised of pooled age and length data (see Crone and Hill 2015 and Crone et al. 2019).

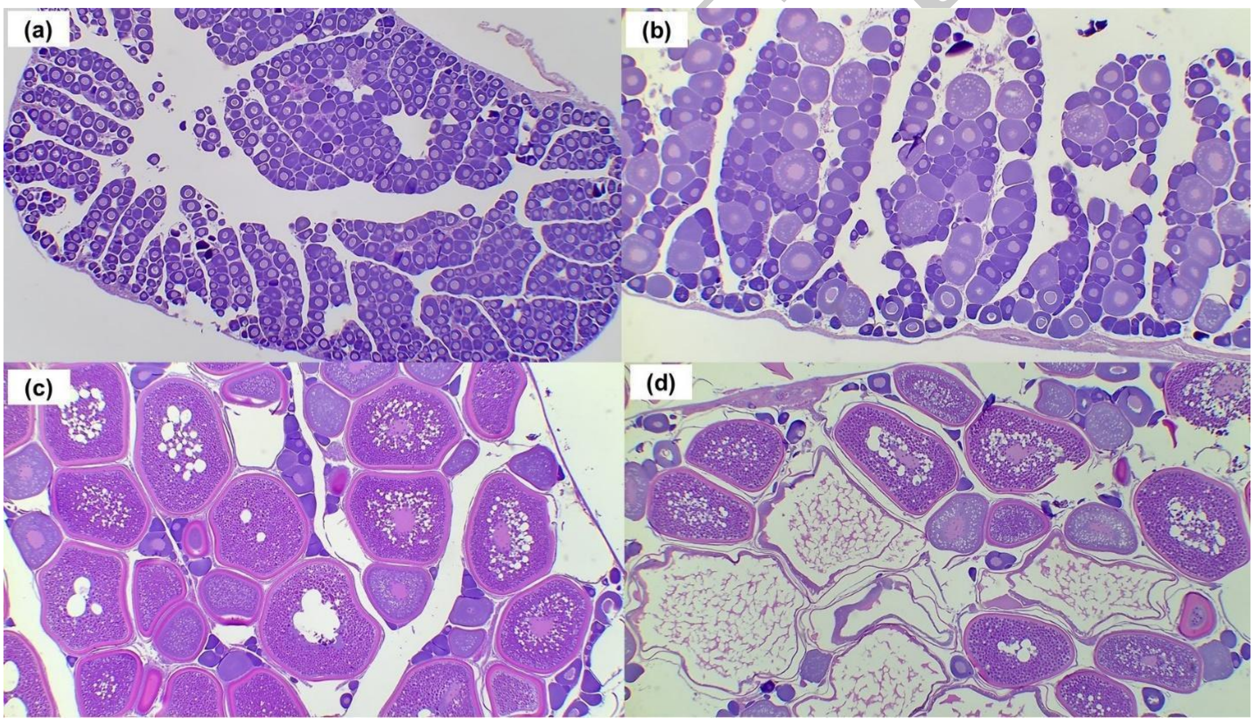

Figure 5. Histological sections of gonads of female Pacific Mackerel (*Scomber japonicus*) collected from SWFSC spring and summer trawl surveys (2010-2021): (a) Immature female with only previtellogenic oocytes; (b) Mature, developing female with numerous oocytes in early cortical alveoli stage; (c) Mature, spawning capable female with numerous vitellogenic oocytes; (d) Mature, actively spawning female with hydrated oocytes.

Results and Discussion

1163 A total of 911 gonad samples of female Pacific Mackerel were examined histologically, classified as either immature (juvenile) or mature (adult), and then used to generate an estimate of length at maturity. Age data were available for 494 of these sampled females to generate an estimate of age at maturity. Females ranged in length from 174 to 402 mm FL and in age from 0 to 7 years (Figure 6a,b). Immature females ranged in length from 174 to 329 mm FL and in age from 0 to 2 years. Mature females were 207-402 mm FL and 0-7 years of age.

The estimated length at maturity (*L*50) for all sampled females (n = 911) was 274 ± 1.26 mm FL with all females (*L*95) larger than 309 ± 2.60 mm FL predicted to be mature (Figure 7a; Table 2). The estimated age at maturity (*A*50) for all sampled females (n = 494) was 1.01 ± 0.06 years with all females older than 2.52 ± 0.15 years predicted to be mature (Figure 7b; Table 3).

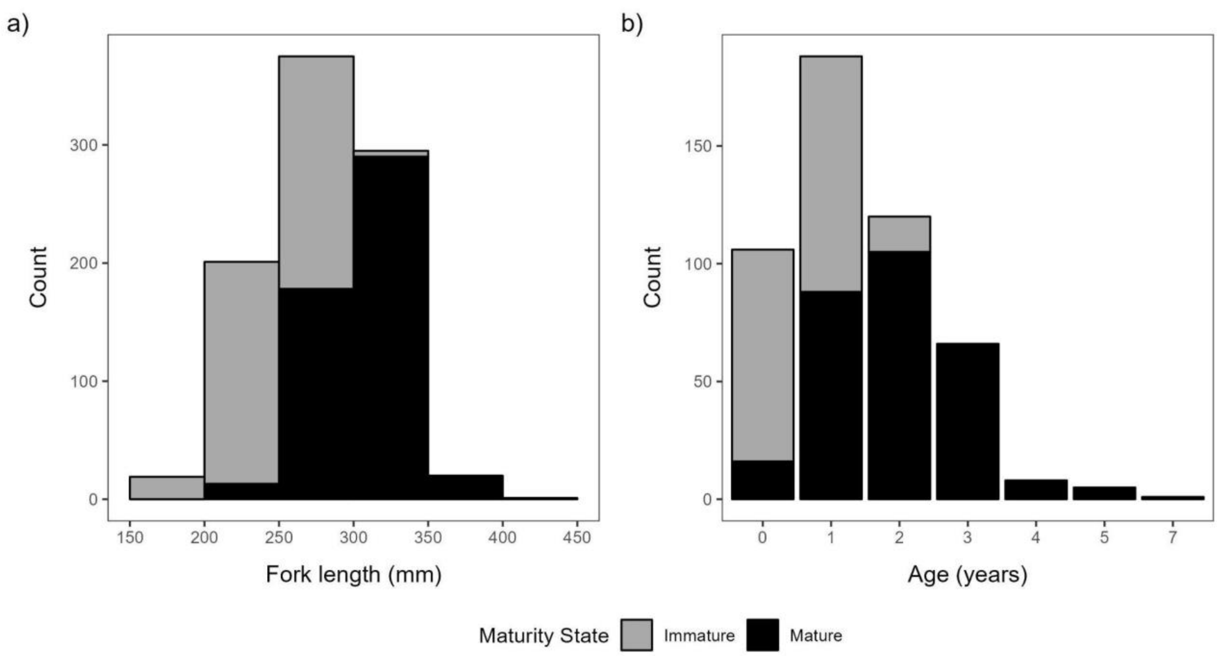

Figure 6. Histograms showing a) length and b) age distribution by maturity state for female Pacific Mackerel (*Scomber japonicus*) collected from SWFSC spring and summer trawl surveys (2010-2021) and analyzed histologically for reproductive condition.

The estimates of length and age at maturity reported here are nearly identical to those used in recent stock assessments for Pacific Mackerel (Dickerson et al. 1992; Crone et al. 2015; Crone et al. 2019). Collectively, the results of this and past studies indicate that maturity schedules in Pacific Mackerel off the U.S. Pacific coast have remained constant over the past several decades.

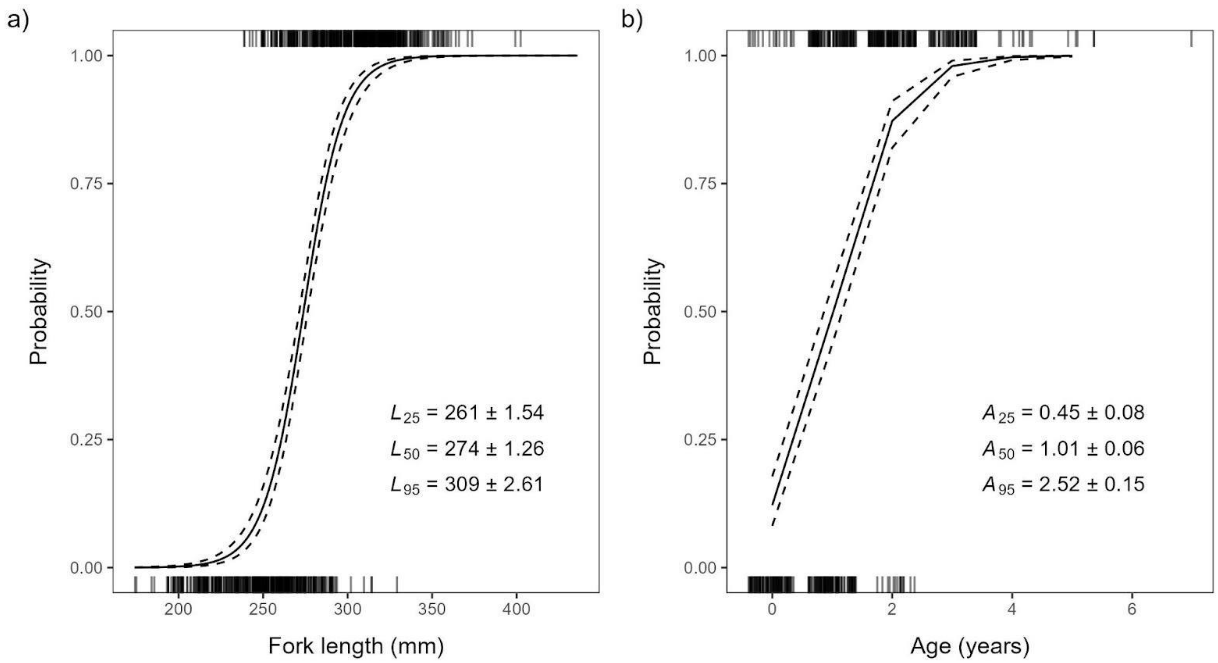

Figure 7. a) Length-based and b) age-based maturity ogives of female Pacific Mackerel (*Scomber japonicus*) based on samples collected from SWFSC spring and summer trawl surveys (2010-2021). Data are shown as jittered tick marks along the lower (immature fish) and upper (mature fish) x-axis. The solid line represents the predicted curve, and the dashed lines depict the 95% confidence intervals.

Table 2. Mean predicted probability of being mature and standard deviation for Pacific Mackerel (*Scomber japonicus*) in 50 mm fork-length bins from the length-based ogive for samples collected from SWFSC spring and summer trawl surveys (2010-2021).

Fork-length bin	Mean predicted probability	Standard deviation
151-200 mm FL	0.00083	5.34e-04
201-250 mm FL	0.03	3.22e-02
251-300 mm FL	0.52	2.54e-01
301-350 mm FL	0.97	2.52e-02
351-400 mm FL	0.99	4.11e-04
401-450 mm FL	0.99	6.32e-06

Table 3. Predicted probability of being mature for each age with 95% confidence intervals for Pacific Mackerel (*Scomber japonicus*) from the age-based ogive for samples collected from SWFSC spring and summer trawl surveys (2010-2021).

Age (years)	Predicted probability	95% confidence interval
0	0.12	0.08-0.17
1	0.49	0.43-0.55
2	0.87	0.82-0.91
3	0.98	0.95-0.99
4	0.99	0.99-0.99
5	0.99	0.99-0.99

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