# Assessment of the Pacific sardine resource (*Sardinops sagax*) in 2024 for U.S. management in 2024-2025

Peter T. Kuriyama[1], Caitlin Allen Akselrud[1], Juan P. Zwolinski[1,2], and Kevin T. Hill[1]

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[1] Fisheries Resources Division, Southwest Fisheries Science Center, NOAA National Marine Fisheries Service, 8901 La Jolla Shores Drive, La Jolla, CA 92037, USA
[2] Institute of Marine Sciences University of California Santa Cruz, Earth and Marine Sciences Building, Santa Cruz, CA 95064, USA

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# 1 Introduction

## 1.1 Distribution, Migration, Stock Structure, Management Units

Information regarding Pacific sardine (*Sardinops sagax*) biology and population dynamics is available in (Clark and Marr 1955; Ahlstrom 1960; Murphy 1966; MacCall 1979; Leet *et al.* 2001), as well as references cited below.

The Pacific sardine has at times been the most abundant fish species in the California Current Ecosystem (CCE). When the population is large, it is abundant from the tip of Baja California (23°N latitude) to southeastern Alaska (57°N latitude) and throughout the Gulf of California. Occurrence tends to be seasonal in the northern extent of its range. When abundance was low during the 1960-70s, sardines did not generally occur in significant quantities north of Baja California.

Sardines off the west coast of North America have been modeled to represent three subpopulations (see review by Smith 2005): a northern subpopulation ('NSP'; northern Baja California to Alaska; Figure 8.1), a southern subpopulation ('SSP'; outer coastal Baja California to southern California), and a Gulf of California subpopulation. These populations were originally distinguished on the basis of serological techniques (Vrooman 1964) and in studies of oceanography as pertaining to temperature at capture (Felix-Uraga *et al.* 2004, 2005; Garcia-Morales *et al.* 2012; Demer and Zwolinski 2014). An electrophoretic study (Hedgecock *et al.* 1989) showed, however, no genetic variation among sardines from central and southern California, the Pacific coast of Baja California, or the Gulf of California. Although the ranges of the northern and southern subpopulations can overlap within the Southern California Bight, the adult spawning stocks likely move north and south in synchrony and do not occupy the same space simultaneously to a significant extent (Garcia-Morales *et al.* 2012). The 2014 assessment (Hill *et al.* 2014) addressed the above stock structure hypotheses in a more explicit manner, by partitioning southern (Ensenada and Southern California ports) fishery catches and composition data using a habitat model initially described by Demer and Zwolinski (2014), and recently updated (Zwolinski and Demer 2023). This subpopulation hypothesis is carried forward in the following assessment. The NSP is exploited by fisheries off Canada, the U.S., and northern Baja California (Figure 8.1), and represents the stock included in the CPS Fishery Management Plan (PFMC 1998). The CPS-FMP Amendment 8 (PFMC 1998) specified management for NSP Pacific sardine along the US West Coast, thus this assessment addresses this portion of the population, rather than the full extent of the multi-national stock distribution.

Pacific sardine migrate extensively when abundance is high, moving as far north as British Columbia in the summer and returning to southern California and northern Baja California in the fall. Early tagging studies indicated that the older and larger fish moved farther north (Jr. 1938; Clark and Jr. 1945). Movement patterns were probably complex, and the timing and extent of movement were affected by oceanographic conditions (Hart 1973) and stock biomass levels. During the 1950s to 1970s, a period of reduced stock size and unfavorably cold sea-surface temperatures together likely caused the stock to abandon the northern portion of its range. From the 1990s through the early 2010s, the combination of increased stock size and warmer sea surface temperatures resulted in the stock re-occupying areas off Central California, Oregon, Washington, and British Columbia, as well as distant offshore waters off California. During a cooperative U.S.-

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U.S.S.R. research cruise for jack mackerel in 1991, several tons of sardine were collected 300 nm west of the Southern California Bight (Macewicz and Abramenkoff 1993). Resumption of seasonal movement between the southern spawning habitat and the northern feeding habitat has been inferred by presence/absence of size classes in focused regional surveys (Lo *et al.* 2011) and measured directly using the acoustic-trawl method (Demer *et al.* 2012).

Japanese sardine (*Sardinops melanostictus*) have been observed with genetic analysis off the US west coast. SWFSC staff have analyzed samples collected from 2014-2023, and found occurrence of Japanese sardine only in 2022 and 2023, although one individual Japanese sardine was observed in 2014 (Longo and Craig in prep). Genetic samples collected from the 2022 AT survey were not collected in such a way as to be able to separate Japanese sardine out of the AT survey biomass estimate. 2023 AT survey genetic samples were collected to be able to separate out Japanese sardine biomass, but not all samples have been processed yet. After the 2023 genetic samples have all been analyzed, Japanese sardine can be separated from Pacific sardine in the AT biomass estimate. See Appendix C for a model sensitivity accounting for the presence of Japanese sardine.

## 1.2 Life History Features Affecting Management

Pacific sardine may reach 41 cm in length (Eschmeyer *et al.* 1983), but are seldom longer than 30 cm in fishery catches and survey samples. The heaviest sardine on record weighed 0.323 kg. The oldest recorded age of sardine is 15 years, but fish in California commercial catches are usually younger than five years and fish in the PNW are less than 10 years old. Sardine are typically larger and two to three years older in regions off the Pacific Northwest than observed further south in waters off California. There is evidence for regional variation in size-at-age, with size increasing from south to north and from inshore to offshore (Phillips 1948; Hill 1999). McDaniel et al. (2016) analyzed recent fishery and survey data and found evidence for age-based (as opposed to size-based) movement from inshore to offshore and from south to north.

Historically, sardines fully recruited to the fishery when they were ages three and older (MacCall 1979). Recent fishery data indicate that sardines begin to recruit to the SCA fishery at age zero during the late winter-early spring. Age-dependent availability to the fishery depends upon the location of the fishery, with young fish unlikely to be fully available to fisheries located in the north and older fish less likely to be fully available to fisheries south of Point Conception.

Sardines spawn in loosely aggregated schools in the upper 50 meters of the water column. Sardines are oviparous, multiple-batch spawners, with annual fecundity that is indeterminate, and age- or size-dependent (Macewicz *et al.* 1996). Spawning of the northern subpopulation typically begins in January off northern Baja California and ends by August off the Pacific Northwest (Oregon, Washington, and Vancouver Island), typically peaking off California in April. Sardine eggs are most abundant at sea-surface temperatures of 13 to 15 °C, and larvae are most abundant at 13 to 16 °C. The spatial and seasonal distribution of spawning is influenced by temperature. During warm ocean conditions, the center of sardine spawning shifts northward and spawning extends over a longer period of time (Ahlstrom 1960; Butler 1987; Dorval *et al.* 2013, 2016). Spawning is typically concentrated in the region offshore and north of Point Conception (Lo *et al.* 1996, 2005) to areas off San Francisco. However, during April 2015 and 2016 spawning was observed in areas north of Cape Mendocino to central Oregon (Dorval *et al.* 2013, 2016).

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## 1.3 Ecosystem Considerations

Pacific sardine represent an important forage base in the California Current Ecosystem (CCE). At times of high abundance, Pacific sardine can compose a substantial portion of biomass in the CCE. However, periods of low recruitment success driven by prevailing oceanographic conditions can lead to low population abundance over extended periods of time. Readers should consult PFMC (1998), PFMC (2017), and NMFS (2019a,b) for comprehensive information regarding environmental processes generally hypothesized to influence small pelagic species that inhabit the CCE. Recent modeling work by Koenigstein et al. (2022) reproduced the lack of recovery since 2014 using a low food availability scenario. They also note that risks to the stock include future years of low food abundance, as well as passing unknown thermal thresholds in a changing climate. Smith et al. (2021) developed a simulation framework to assess the shifts in spatial distributions of sardine using earth system models. While total landings were uncertain, the simulation indicated a northward shift of the NSP, with generally decreased landings in southern ports and increased landings in northern ports.

## 1.4 Abundance, Recruitment, and Population Dynamics

Extreme natural variability is characteristic of clupeid stocks, such as Pacific sardine (Cushing 1971). Estimates of sardine abundance from as early as 300 AD through 1970 have been reconstructed from the deposition of fish scales in sediment cores from the Santa Barbara basin off SCA (Soutar and Isaacs 1969, 1974; Baumgartner *et al.* 1992; McClatchie *et al.* 2017). Sardine populations existed throughout the period, with abundance varying widely on decadal time scales. Both sardine and anchovy populations tend to vary over periods of roughly 60 years, although sardines have varied more than anchovies. Declines in sardine populations have generally lasted an average of 36 years and recoveries an average of 30 years.

Pacific sardine spawning biomass (age 2+), estimated from virtual population analysis methods, averaged 3.5 mmt from 1932 through 1934, fluctuated from 1.2 to 2.8 mmt over the next ten years, then declined steeply from 1945 to 1965, with some short-term reversals following periods of strong recruitment success (Murphy 1966; MacCall 1979). During the 1960s and 1970s, spawning biomass levels were as low as 10,000 mt (Barnes *et al.* 1992). The sardine stock began to increase by an average annual rate of 27% in the early 1980s (Barnes *et al.* 1992). As exhibited by many members of the small pelagic fish assemblage of the CCE, Pacific sardine recruitment is highly variable, with large fluctuations observed over short timeframes. Analyses of the sardine stock-recruitment relationship have resulted in inconsistent findings, with some studies showing a strong density-dependent relationship (production of young sardine declines at high levels of spawning biomass) and others, concluding no relationship (Clark and Marr 1955; Murphy 1966; MacCall 1979). Jacobson and Maccall (1995) found both density-dependent and environmental factors to be important, as was also agreed during a sardine harvest control rule workshop held in 2013 (Council 2013).

## 1.5 Relevant History of the Fishery and Important Features of the Current Fishery

The sardine fishery was first developed in response to demand for food during World War I. Landings increased rapidly from 1916 to 1936, peaking at over 700,000 mt. Pacific sardine

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supported the largest fishery in the western hemisphere during the 1930s and 1940s, with landings in Mexico to Canada. The population and fishery soon declined, beginning in the late 1940s and with some short-term reversals, to extremely low levels in the 1970s. There was a southward shift in catch as the fishery collapsed, with landings ceasing in the Pacific Northwest in 1947 through 1948 and in San Francisco, from 1951 through 1952. The San Pedro fishery closed in the mid-1960s. Sardines were primarily reduced to fish meal, oil, and canned food, with small quantities used for bait. In the early 1980s, sardines were taken incidentally with Pacific and jack mackerel in the SCA mackerel fishery. As sardine continued to increase in abundance, a directed purse-seine fishery was re-established. The incidental fishery for sardines ceased in 1991 when the directed fishery was offered higher quotas. The renewed fishery initiated in Ensenada and Southern California, expanded to Central California, and by the early 2000s, substantial quantities of Pacific sardine were landed at OR, WA, and BC. Volumes have reduced dramatically in the past several years. Harvest by the Mexican (Ensenada) fishery is not currently regulated by quotas, but there is a minimum legal size limit of 150 mm SL. The Canadian fishery failed to capture sardine in summer 2013, and has been under a moratorium since summer 2015. The U.S. directed fishery has been subject to a moratorium since July 1, 2015.

## 1.6 Recent Management Performance

Management authority for the U.S. Pacific sardine fishery was transferred to the PFMC in January 2000. The Pacific sardine was one of five species included in the federal CPS-FMP (PFMC 1998). The CPS-FMP includes harvest control rules intended to prevent Pacific sardines from being overfished and to maintain relatively high and consistent, long-term catch levels. Harvest control rules for Pacific sardine are described at the end of this report. A thorough description of PFMC management actions for sardines, including HG values, may be found in the most recent CPS SAFE document (PFMC 2017). U.S. harvest specifications and landings since 2005 are displayed in Table 7.1. Harvests in major fishing regions from ENS to BC are provided in Table 7.2 and Figure 8.2.

# 2 Data

Data used in the Pacific sardine assessment are summarized in Figure 8.3. The data updated for this assessment are:

- Fishery catches, updated based on the revised habitat model through 2023
- Model-based fishery weight-at-age values
- AT survey index of abundance, updated through 2023 (although 2023 values are preliminary)
- AT survey age compositions, updated through 2023
- AT survey weight-at-age values and age compositions through 2023 (for summer surveys only)

## 2.1 Fishery-Dependent Data

Available fishery data include commercial landings and biological samples from six regional fisheries: Ensenada (ENS); Southern California (SCA); Central California (CCA); Oregon (OR);

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Washington (WA); and British Columbia (BC). Standard biological samples include individual weight (kg), standard length (cm), sex, maturity, and otoliths for age determination (not in all cases). A complete list of available port sample data by fishing region, model year, and season is provided in (Table 7.3).

All fishery catches and compositions were compiled based on the sardine's biological year ('model year') to match the July 1st birth-date assumption used in age assignments (Table 7.2). Each model year begins in the last half of a calendar year. For example, model year 2005 includes data from July 1, 2005 to June 30, 2006. Further, each model year has two six-month seasons, including 'S1'=Jul-Dec and 'S2'=Jan-Jun. Major fishery regions were pooled to represent a southern 'MexCal' fleet (ENS+SCA+CCA) and a northern Pacific Northwest 'PNW' fleet (OR+WA+BC). The MexCal fleet was treated with semester-based selectivities ('MexCal_S1' and 'MexCal_S2'). The rationale for this fleet design is provided in (Hill *et al.* 2011).

### 2.1.1 Landings

West Coast landings of NSP sardine were compiled from regional agency sources and pooled by year and semester to form the MexCal and PNW catches. Given that catches off Ensenada and Southern California can be composed of one of two sardine subpopulations (NSP or SSP, depending on prevailing habitat), the newly-revised sardine habitat model (Zwolinski and Demer 2023) was applied to monthly catch to exclude purported SSP catch from the assessment model.

Mexico's monthly landings (2005-2022) were taken from CONAPESCA's web archive of Mexican fishery yearbook statistics (CONAPESCA (2022)). Preliminary monthly landings for 2023 were provided by INAPESCA staff (Dr. Concepcion Enciso-Enciso, pers. comm.). When the newly revised habitat model was applied to fishing areas off Ensenada, considerably less catch was ascribed to the NSP than in previous assessments. According to the updated habitat model (Zwolinski and Demer 2023), there has only been one month (Jan 2022) of NSP habitat off Ensenada since 2012, resulting in approximately 11,000 mt of NSP catch in semester 2 of model year 2021 (Table 7.2).

United States landings of NSP sardine were obtained from the PacFIN database (2005-2023). The NSP sardine habitat model was applied to data from Southern California and catches were filtered to exclude SSP. The change in the habitat model resulted in slightly less catch being ascribed to NSP than in previous assessments. California landings were pooled with Ensenada landings to comprise the MexCal fleet catch. Oregon (OR) and Washington (WA) landings (2005-2023) were also obtained from PacFIN and pooled with British Columbia (BC) monthly landings (2005-2012; provided by Linnea Flostrand, Department of Fisheries and Oceans, pers. comm.) to comprise the PNW fleet catch. Note that sardine have not been landed in Canada since 2012.

Landings data for all fisheries are complete through December 2023 (model year-semester 2023-1). NSP landings by model year-semester for each fishing region (ENS and SCA) are presented in Table 7.2 and Figure 8.2. Landings aggregated by model year-semester and the three fleets are presented in Table 7.4 and Figure 8.6.

### 2.1.2 Discards

Available information concerning bycatch and discard mortality of Pacific sardine, as well as other members of the small pelagic fish assemblage of the California Current Ecosystem, is presented

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in NMFS (2019a). Limited information from observer programs implemented in the past indicated minimal discard of Pacific sardine in the commercial purse seine fishery that targets the small pelagic fish assemblage on the USA Pacific coast. It is generally acknowledged that the small purse seine fishery for coastal pelagic fishes discards negligible volumes of sardine.

### 2.1.3 Weight-at-age

Fishery-dependent weight-at-age values were input to models that estimate partial correlations across ages, years, and cohorts with residual variation (Cheng *et al.* 2023). There are generally missing values and ages with few samples in the data. In previous assessments, cohort-specific linear interpolation according to a set of defined rules was used to fill missing values. The current approach used model output from the model with the best fit to each fleet-specific data set. More details on the approach are described in Appendix B: Weight-at-age.

### 2.1.4 Age compositions

Age compositions for each fleet and season were the sums of catch-weighted age observations, with monthly landings (number of fish) within each port and season serving as the weighting unit. As indicated above, environmental criteria used to assign landings to subpopulations (Zwolinski and Demer 2023) were also applied to monthly port samples to categorize NSP-based biological compositions.

The nominal age compositions were weighted by the total monthly landings ($L_m$). Port samplers biologically sample 25 individual fish per landed haul. The following steps were used to develop the weighted age-composition time series (Figures 8.7-8.9):

- identified an ‘age-plus’ group (8+) for combining older fish into a single group and enumerate the number of individual fish ($n$) sampled in each month ($m$), age ($a$), and calendar year ($y$)

$$n_{m,a,y}$$

- Sum total biological sample weight ($B$) by $m$ and $y$ and calculate mean weight (w) of sampled fish by $m, a, y$:

$$B_{m,y}$$

$$\bar{w}_{m,a,y}$$

- Calculate proportions ($A$) in the biological samples by $m, a, y$

$$A_{m,a,y} = \left(\bar{w}_{m,a,y} * n_{m,a,y}\right)/B_{m,y}$$

- Calculate the total landings $L$ by $m, a, y$

$$L_{m,a,y} = A_{m,a,y} * L_{m,y}$$

- The number of fish ($F$) in the catch were then calculated $m, a, y$

$$F_{m,a,y} = L_{m,a,y}/\bar{w}_{m,a,y}$$

and summed by $a$ and model year ($MY$). Model years span July of year y to June of $y + 1$.

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$$F_{a,MY} = \sum_{z=July,y}^{June,y+1} F_{a,z}$$

- The final proportion $P$ at $a$ and $MY$ is

$$P_{a,MY} = F_{a,MY} / \sum_{a=0}^{8} F_{MY}$$

.

Age compositions were input as proportions. Age-composition time series are presented in Figures 8.7-8.9.

Oregon and Washington fishery ages from season 2 (S2, Jan-Jun), were omitted from all models due to inter-laboratory inconsistencies in the application of birth-date criteria during this semester (noting that OR and WA landings and associated samples during S2 are typically trivial). Age data were not available for the BC or ENS fisheries, so PNW and MexCal fleet compositions only represent catch-at-age by the OR-WA and CA fisheries, respectively.

While no directed fishery samples have been available since July 2015, CDFW has continued limited sampling of sardine taken incidental to other CPS finfish, e.g. northern anchovy in Monterey Bay. These few samples represent a relative small portion of incidental removals, e.g. 35-250 mt per semester.

CDFW has also collected and aged samples under exempted fishing permits for the 2021 and 2023 calendar years. Identical methods have been used to weight these age compositions by monthly catch amounts.

### 2.1.5 Ageing error

Sardine ageing using otolith methods was first described by Walford and Mosher (1943) and extended by Yaremko (1996). Pacific sardines are routinely aged by fishery biologists in CDFW, WDFW, and SWFSC using annuli enumerated in whole sagittae. A birth date of July 1st is assumed when assigning ages. Details on the most recent age readings is included in Appendix C: Biological data.

Ageing-error vectors for fishery data were unchanged from the previous stock assessments e.g. Hill et al. (2017) and Kuriyama et al. (2020). Ageing error vectors (SD at true age) were linked to fishery-specific age-composition data (Figure 8.10). For additional details regarding age-reading data sets, model development and assumptions, see Appendix 2 in Hill et al. (2011), as well as Dorval et al. (2013).

## 2.2 Fishery-Independent Data: Acoustic-Trawl Survey

This assessment uses a 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 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

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acoustics, and ICES (2015) 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).

### 2.2.1 Index of abundance

Indices from the spring and summer AT surveys from calendar years 2005-2023 (2023 values are preliminary) were used in this assessment. The acoustic-trawl biomass estimate was derived using nautical area scattering coefficients (NASC) from putative coastal pelagic fishes (CPS) integrated from 10-350 m depth. By extending beyond the typical depth-range of the CPS, these vertically integrated values included backscatter from non-CPS species with swimbladders, e.g., rockfishes and hake. Because the proportion of the integrated backscatter attributed to a given CPS species is a function of all species found in the corresponding cluster, eq. 14 in (Zwolinski *et al.* 2019) applies modifications to the biomass of one of the species, which will change according to the acoustic proportion of the remaining species.

The acoustic-trawl survey has had three methods for extrapolating or observing nearshore biomass where it is too shallow to navigate NOAA ships safely. The methods are model extrapolation from the nearest portion of the core survey area, unmanned surface vehicles, and combined fishing vessel acoustic and purse seine methods (Stierhoff *et al.* 2020). 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-purse seine 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.

In summer 2022, R/V *Reuben Lasker* had logistical challenges that resulted in a loss of about half the scheduled sea days (Stierhoff *et al.* 2023). The *Lisa Marie* was chartered to survey *Lasker*'s transects between Cape Flattery, WA and Cape Mendocino, CA while also extending into the nearshore region to about ~5m depth. Both *Lisa Marie* and *Lasker* sampled in the area between Cape Mendocino and Bodega Bay, and then *Lasker* sampled farther south, ending at Punta Baja. North of Cape Mendocino, where *Lasker* did not sample, species composition and CPS length distributions were estimated from *Lisa Marie*'s daytime purse-seine catches, but adjusted to reflect the associations between Pacifc Sardine and Jack Mackerel in this region during summer 2018-2021 (see Section 3.5.1 of Stierhoff et al. 2023). Between Cape Mendocino and Punta Baja, species

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composition and CPS length distributions were estimated, as usual, by the catches from nighttime surface trawls.

There are three main components to the summer 2022 survey, and a description for handling these values is in the Q section later in the assessment document. The three values are core *Lasker* biomass estimate (which spanned most of the coast off CA; 10,794 mt and CV=0.28), the *Lisa Marie* core survey biomass estimate (coasts of northern CA, OR, and WA; 42,946 mt and CV=0.32) and the nearshore biomass estimate (15,765 mt and CV=0.23).

The full time series is shown in Figure 8.12 and Table 7.6.

### 2.2.2 Age compositions

Estimates of abundance-at-length were converted to abundance-at-age using summer survey-specific age-length keys (Figure 8.13). ALKs from 2021, 2022, and 2023 are shown in Figures 8.14 to 8.16. For 2022, the ALKS from *Lisa Marie* and *Lasker* seemed to sample different ages (Figure 8.15), and were modeled as separate fleets in the assessment. Age-length keys were constructed using ordinal generalized additive regression models from the R package mgcv (Wood 2017). More details are in Kuriyama et al. (2020), Appendix A. 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.

### 2.2.3 Ageing error

There were two ageing error vectors for age data from 2005-2016 and 2017-2018. The standard deviations for 2017-2018 data were applied to survey age-composition time series from 2017-2023 (Figure 8.10). The *Lisa Marie* ages were read by the same reader that aged PNW fishery samples, and the PNW ageing error vector was applied to the 2022 *Lisa Marie* age data.

*Note, PTK realized night of Feb 7, 2024 that the base model has not included the 2021-2022 ageing error vector described in the Biological Data Appendix. This will be amended for the STAR panel and is unlikely to qualitatively affect the base model results and associated sensitivities.*

## 2.3 Fishery-Independent Data: Aerial Survey

Relating the aerial survey estimates to the length compositions was difficult due to the temporal and spatial mismatches, i.e. the point sets represent a small fraction of the overall aerial footprint. There was insufficient biological sampling to relate length compositions to age compositions for explicit integration into the base model. Additional details in Section 3.5.5 and in Lynn et al. (2020).

Aerial survey data are available for springs and summers in calendar years 2022 and 2023. The summer 2022 and 2023 aerial estimates could be compared to the corresponding AT survey estimates (as done in 2019 for example). However, based on the updated habitat model, a majority

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of the aerial estimates in summer 2022 and 2023 were attributed to southern subpopulation sardine. As a result, these aerial estimates were not used in adjusting catchability values.

## 2.4 Biological Parameters

### 2.4.1 Stock structure

We presume to model the northern sub-population of Pacific sardine (NSP) that, at times, ranges from northern Baja California, México to British Columbia, Canada. As mentioned above, it is likely that catches landed in ENS and SCA likely represent a mixture of SSP (during warm months) and NSP (cool months) (Felix-Uraga *et al.* 2004, 2005; Zwolinski *et al.* 2011; Garcia-Morales *et al.* 2012; Demer and Zwolinski 2014; Zwolinski and Demer 2023) (Figure 8.1). The current approach involves analyzing satellite oceanographic data to objectively partition monthly catches and biological compositions from ENS and SCA ports to exclude data from the SSP (Demer and Zwolinski 2014), and has been recently updated (see Zwolinski and Demer (2023)). This approach was first adopted in the 2014 full assessment (Hill *et al.* 2014; STAR 2014) and has carried forward each year, including this assessment.

### 2.4.2 Growth

Previous analysis of size-at-age from fishery samples (1993-2013) provided no indication of sexual dimorphism related to growth (Hill et al. 2014), so combined sexes were included in the present assessment model.

Past Pacific sardine stock assessments conducted with the CANSAR and ASAP statistical catch-at-age models accounted for growth using empirical weight-at-age time series as fixed model inputs (e.g., Hill *et al.* 2006b, 2009). Stock synthesis models used for management from 2007 through 2016 estimated growth internally using conditional age-at-length compositions and a fixed length-weight relationship (e.g., Hill *et al.* 2016). Disadvantages to estimating growth internally within the stock assessment include: 1) inability to account for regional differences in age-at-size due to age-based movements (McDaniel *et al.* 2016); 2) difficulty in modeling cohort-specific growth patterns; 3) potential model interactions between growth estimation and selectivity; and 4) models using conditional age-at-length data require more estimable model parameters than the empirical weight-at-age approach. For these reasons, the 2020 base model was constructed to bypass growth estimation internally in SS, instead opting for use of empirical weight-at-age time series. The current base model further updates this method by applying a state-space model conditional on year, age, and cohort (See Appendix B: Weight-at-age for details).

*Fishery-dependent weight-at-age*

Fishery-dependent weight-at-age values were input to models that estimate partial correlations across ages, years, and cohorts with residual variation (Cheng *et al.* 2023). There are generally missing values and ages with few samples in the data. In previous assessments, cohort-specific linear interpolation according to a set of defined rules was used to fill missing values. The current approach used model output from the model with the best fit to each fleet-specific data set. More details on the approach are described in Appendix B: Weight-at-age. Fishery-dependent weight-at-age vectors are displayed by cohorts in (Figures 8.17, 8.18, and 8.19).

*Fishery-independent weight-at-age*

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AT survey weight-at-age time series (Figure 8.20) 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; 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.

Weight-at-age data were included as fixed inputs in the base model. Weight-at-age models require population weight-at-age vectors to convert population number-at-age to biomass-at-age. The 2017 benchmark assessment (Hill *et al.* 2017) used population weight-at-age vectors that were derived from growth parameter estimates for the beginning and middle of each semester. For the 2020 benchmark assessment, the weight-at-age vectors derived from growth estimates were replaced with empirical weight-at-age values from the AT survey. Beginning and middle semester values were identical, and the assumption was that there is no within-semester variability in weight-at-age values. This change in the 2020 benchmark assessment prioritized recent empirical values over time-invariant estimates of growth. The current benchmark assessment maintains the 2020 benchmark structure.

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### 2.4.3 Maturity

Maturity was modeled using a fixed vector of fecundity × maturity by age. The vector was derived from the 2016 assessment model after it was updated with newly available information (Hill *et al.* 2017). In addition to other data sources, the 2020 benchmark was updated with new parameters for the logistic maturity-at-length function using female sardine sampled from survey trawls conducted from 1994 to 2016 (n=4,561 Hill *et al.* 2017). Reproductive state was primarily established through histological examination, although some immature individuals were simply identified through gross visual inspection. Parameters for the logistic maturity function were estimated as follows:

$$Maturity = \frac{1}{1 + exp\left(slope * L - L_{inflection}\right)}$$

where slope = -0.9051 and $L_{inflection} = 16.06$ cm-SL. Maturity-at-length parameters were fixed in the updated assessment model (T_2017) and fecundity was fixed at 1 egg/gram body weight. The fecundity × maturity-at-age vector was extracted and used in the 2020 benchmark and in the current base model.

### 2.4.4 Natural mortality

Natural mortality *M* was estimated in this assessment with an age-specific, time-invariant natural mortality across ages 0-8, 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). The single value of *M* was adjusted to have age-specific values, called Lorenzen *M* in SS3 from Lorenzen (1996).

The prior on M is generally consistent with values (either fixed or estimated) in previous assessments and studies. The adult natural mortality rate has been estimated to be M=0.4-0.8 $yr^{-1}$

(Murphy 1966; MacCall 1979) and 0.51 $yr^{-1}$ (Clark and Marr 1955). Murphy's (1966) virtual population analysis of the Pacific sardine used M=0.4 $yr^{-1}$ to fit data from the 1930s and 1940s, but M was doubled to 0.8 $yr^{-1}$ from 1950 to 1960 to better fit the trend in CalCOFI egg and larval data (Murphy 1966). Zwolinski and Demer (2013) studied natural mortality using trends in abundance from the acoustic-trawl method (AT) surveys (2006-2011), accounting for fishery removals, and estimated M=0.52 $yr^{-1}$. Age-specific mortality estimates are available for the entire suite of life history stages (Butler *et al.* 1993). Mortality is high at the egg and yolk sac larvae stages (instantaneous rates in excess of 0.66 d-1). Until 2017, Pacific sardine stock assessments for PFMC management used M=0.4 yr-1. The 2017 benchmark assessment (Hill *et al.* 2017) used M=0.6 $yr^{-1}$, which translated to an annual death rate of 45% in adult sardine stock.

## 2.5 Available Data Sets Not Used in Assessment

Past sardine stock assessments have included a time series of daily egg production method (DEPM) spawning stock biomass (SSB). The time series was included in the assessments as an index of relative female SSB (Q estimated) and has always been considered an underestimate of true SSB (Deriso *et al.* 1996). The DEPM time series has been described in numerous publications and stock assessment reports. The DEPM time series was excluded from this benchmark assessment. As indicated in past assessments, exclusion of the DEPM time series continues to have negligible impact on the stock assessment outcome. Nonetheless, DEPM estimates are still considered useful to corroborate/refute results from the AT survey.

# 3 Assessment

## 3.1 History of Modeling Approaches

The population's dynamics and status of Pacific sardine prior to the collapse in the mid-1900s was first modeled by Murphy (1966). MacCall (1979) refined Murphy's virtual population analysis (VPA) model using additional data and prorated portions of Mexican landings to exclude the southern subpopulation. Deriso et al. (1996) modeled the recovering population (1982 forward) using CANSAR, a modification of Deriso's (1985) CAGEAN model. The CANSAR was subsequently modified by Jacobson (Hill *et al.* 1999) into a quasi, two-area model CANSAR-TAM to account for net losses from the core model area. The CANSAR and CANSAR-TAM models were used for annual stock assessments and management advice from 1996 through 2004 (e.g. Hill *et al.* 1999; Conser *et al.* 2003). In 2004, a STAR Panel endorsed the use of an Age Structured Assessment Program (ASAP) model for routine assessments. The ASAP model was used for sardine assessment and management advice from 2005 to 2007 (Conser *et al.* 2003, 2004; Hill *et al.* 2006a,b). In 2007, a STAR Panel reviewed and endorsed an assessment using Stock Synthesis (SS) 2 (Methot 2005), and the results were adopted for management in 2008 (Hill *et al.* 2007), as well as an update for 2009 management (Hill *et al.* 2008). The sardine model was transitioned to SS version 3.03a in 2009 (Methot 2009) and was again used for an update assessment in 2010 (Hill *et al.* 2009, 2010). Stock Synthesis version 3.21d was used for the 2011 full assessment (Hill *et al.* 2011), the 2012 update assessment (Hill *et al.* 2012). The 2014 sardine full assessment (Hill *et al.* 2014), 2015 update assessment (Hill *et al.* 2015), and 2016 update assessment (Hill *et al.* 2016) were based on SS version 3.24s.

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The 2017 full assessment (Hill *et al.* 2017), 2018 (Hill *et al.* 2018), and 2019 (Hill *et al.* 2019) update assessments were based on SS version 3.24aa. SS version 3.24aa corrected errors associated with empirical weight-at-age models having multiple seasons. These past assessments relied solely on the AT survey to provide an index of abundance and did not incorporate daily egg-production time series. As a result, the modeled time frame was shortened to begin in 2005, which coincides with the first available biomass estimate from the AT survey. Natural mortality was fixed at 0.6 and catchability was freely estimated. AT survey age compositions were derived using pooled, seasonal age-length keys, but survey weight-at-age values used a state-space model with the option for correlations between year, age, and cohort as described in Appendix B. Selectivity was age-based and estimated with a flexible selectivity pattern which is based on age-specific estimated selectivity parameters rather than fitting a dome-shaped functional form (e.g. 'double-normal'). See section 3.5.4 for a deeper explanation.

## 3.2 2020 STAR Panel Recommendations

Below are the recommendations from the STAR panel review of the 2020 benchmark assessment. Responses to comments are below.

***High Priority***

A. The final base model relies on the 2019 CCPSS estimate of biomass as the basis for recent Q. However, the ideal is to integrate these data into the assessment. Increased collaboration between SWFSC and CDFW scientists (and ideally inclusion of a CDFW scientist on the next STAT) is needed to achieve this goal.

*Response: The recent CCPSS estimates of biomass have been considered but ultimately not included in this assessment due to the updated habitat model results. The data challenges associated with incorporating CCPSS data directly as a separate survey fleet in the assessment remain.*

B. Purse seine nets used in nearshore areas should utilize a mesh size that can catch sardine effectively without leading to biased estimates of species composition.

*Response: Purse seine nets currently used in nearshore areas are unlikely to catch sardine effectively; until such time as the nets can do this and/or the bias in species composition is quantified CCPSS estimates cannot be integrated into the assessment.*

C. The approach to estimating the variance of the CCPSS based on between-band variance will be flawed if the steep gradient in biomass from band 1 and 2 is confirmed by future surveys. Consideration should be given to estimating variance by temporal replication.

*Response: This request cannot be completed by the STAT, and must be addressed by CDFW survey teams.*

D. More biological samples should be collected during the CCPSS to allow length and age compositions to be estimated and these data included in a future assessment. It is more desirable that the CCPSS and AT results be combined to provide a more spatially complete index of total stock abundance at length and/or age.

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*Response: This request cannot be completed by the STAT, and must be addressed by CDFW survey teams.*

E. Examine information on the attribution of catch and biomass between the northern and southern subpopulations based on the habitat model. It will be necessary to conduct a Methodology Review if this leads to a substantial change to the methodology used to conduct this split.

*Response: A sardine stock structure workshop was held in November 2022, resulting in an updated habitat model Zwolinski and Demer (2023). This updated habitat model was applied to the data for the current assessment.*

F. The approach of basing OFLs, ABCs and HGs for the current year on the previous year's biomass estimate from the AT survey should be examined using MSE so the anticipated effects of larger CVs and a possible time-lag between when the survey was conducted and when catch limits are implemented on risk, catch and catch variation statistics can be quantified. The survey projection method proposed during the 2017 assessment should be developed further.

*Response: This study has not yet been conducted.*

G. Investigate alternative approaches for dealing with highly uncertain estimates of recruitment that have an impact on the most recent estimate of age-1+ biomass given its importance for management.

*Response: Uncertain estimates of recruitment in the final years of the assessment are to be expected as age-0 fish are modeled to have time-varying availability to AT survey gear.*

H. Modify Stock Synthesis so that the standard errors of the logarithms of age-1+ biomass can be reported. These biomasses are used when computing OFLs, ABCs and HGs, but the CV used when applying the ABC control rule is currently that associated with spawning biomass and not age-1+ biomass.

*Response: This feature has been implemented in SS3.*

I. The assessment would benefit not only from data from Mexico and Canada, but also from joint assessment activities, which would include assessment team members from both countries during assessment development.

*Response: Multilateral science, including stock assessments, has long been considered a worthwhile goal. Completion of multilateral science faces many obstacles, many of which are beyond the STAT or even the SWFSC control. As an example, synoptic CPS surveys are discussed each year at the Trinational Sardine Forum and U.S.-Mexico bilateral meetings. An extension of the AT Survey into Mexican waters was completed in 2021, 2022, and 2023 but has come with operational challenges that evolve over time. As this assessment focuses on Pacific sardine in US waters, there has not been a fishery in Canada since 2015, and Mexico's fisheries do not fish on this stock, there is little interest from these countries in participating in joint assessments.*

J. Reduce ageing error and bias by coordinating and standardizing ageing techniques and performing an ageing exchange (double blind reading) to validate ageing and estimate error. Standardization might include establishing a standard "birth month" and criteria for establishing the presence of an outer annuli. If this has already been established, identify labs, years, or sample

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lots where there is deviation from the criteria. The outcome of comparative studies should be provided with every assessment.

*Response: Ageing error is addressed in Biological Data Appendix.*

K. Add a bycatch fleet for MexCal S2 that has zero catch for all but the last two years, where catch is a function of the fishing mortality rate in the last year with data so that the 2019 fishing mortality rate is a function of the data.

*Response: This issue is likely resolved by the updated habitat model.*

L. Evaluate the model sensitivity to the input weight-at-age, and/or to have a deeper think on how uncertainty in the input weight-at-age could/should be characterized because these data are from the AT trawl samples.

*Response: Weight-at-age data from both the fisheries were modeled using a state-space model, conditional on year, age, and cohort. The methods follow those established in by Cheng et al. (2023), and details are included in Appendix B: Weight-at-age.*

***Medium Priority***

A. Further investigate the catch data from Ensenada to (a) quantify uncertainty in the estimates of northern subpopulation catches, (b) examine how sensitive the estimates of northern subpopulation catch are to how the habitat model is applied.

*Response: See above (E) regarding the stock structure workshop and updated habitat model.*

B. Obtain ageing data for northern subpopulation fish from the Ensenada fishery to allow testing of the hypothesis that the age-structure of the Ensenada catch matches that of the catches off California. Care should be taken to ensure that a common ageing protocol is followed for ageing of fish off Ensenada and California.

*Response: This is likely resolved with the updated habitat model. Additionally, there is not much catch of NSP. Mexico doesn't apply the July 1 birthdate assumption and thus data could not be directly compared.*

C. Continue to explore possible additional fishery-independent data sources such as the SWFSC juvenile rockfish survey. Inclusion of a substantial new data source would likely require review, which would not be easily accomplished during a standard STAR Panel meeting and would likely need to be reviewed during a Council-sponsored Methodology Review.

*Response: While other potential fishery-independent data sources may exist for Pacific sardine, none have been vetted through a Council-sponsored methodology review. The SWFSC juvenile rockfish survey does catch CPS incidentally but in a much smaller spatial area and a different time of year than the targeted, range-wide SWFSC AT survey. The STAT continues to support and promote use of the single, most objective survey tool available for estimating abundance of CPS, which has been approved by multiple Council-sponsored methodology reviews.*

D. Consider spatial models for Pacific sardine that can be used to explore the implications of regional recruitment patterns and region-specific biological parameters. These models could be used to identify critical biological data gaps as well as better represent the latitudinal variation in

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size-at-age; this should include an analysis of age-structure on the mean distribution of sardine in terms of inshore-offshore (especially if industry partner-derived data were available).

*Response: No progress has been made toward spatial modeling. Some of the concerns raised regarding spatial structure have been accounted for with area-specific fishing fleets with time-varying selectivity curves.*

E. Consider a model that has separate fleets for Mexico, California, Oregon-Washington and Canada.

*Response: In the past, the STAT has modeled each of these regional fisheries as individual fleets, which resulted in an unstable, over-parameterized model. That is, the goal of current model development is to construct a parsimonious assessment model that meets the overriding management objective using/emphasizing the highest quality data available (AT survey abundance time series) in the most straightforward manner (not developed around fine-scale fishery catch and selectivity data).*

F. Compare the annual length-composition data for the Oregon-Washington catches with those from the British Columbia fishery to evaluate the assumption that the age-structure of the historical catches of British Columbia matches those off Washington. This is particularly important if a future age data/age-based selectivity model scenario is further developed and presented for review.

*Response: Catch data from British Columbia was last collected in 2012, with the fishery closed since 2015. It is unlikely this would affect current biomass estimates or projections.*

## 3.3 Changes between 2020 and the 2024 Base Model

- Updated habitat model for the catch data
- Updated AT survey data through 2023 (although 2023 data are preliminary)
- Steepness fixed at 0.65
- Added Lorenzen M
- Updated the prior on M to the Hamel prior
- Empirical weight-at-age data are now model derived for the fisheries
- Updated to 2D-AR selectivity for time-varying estimates of MexCalS1 and MexCalS2 selectivities

## 3.4 Model Description

### 3.4.1 Time period and time step

The modeled timeframe begins in 2005, just as in the 2020 benchmark model, and extends through 2023. Time steps remain based on two, six-month semester blocks for each fishing year (semester 1= July-December and semester 2=January-June). The need for an extended time period in the model is not supported by the management goal, given that years prior to the start of the AT survey time series provide limited additional information for evaluating terminal stock biomass in the integrated model. Further, although a longer time series of catch may be helpful in a model for accurately determining the scale in estimated quantities of interest, estimated trend and scale were not sensitive to changes in start year for the base model. Finally, Pacific sardine biology (relatively few fish >5 years old observed in fisheries or surveys) further negates the utility of an extended

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time period in a population dynamics model employed for estimating terminal stock biomass of a short-lived species.

### 3.4.2 Surveys

The base model uses the spring and summer AT survey indices of abundance. The spring survey age compositions were not used in the base model, consistent with the previous assessment.

The 2022 survey was modeled as two separate fleets. The 2022 survey had three components: the *Lasker* core survey which spanned waters off Baja California to northern California, the *Lisa Marie* core survey which spanned waters off northern California, Oregon, and Washington, and the nearshore survey. As mentioned in previous sections, a number of logistical challenges resulted in lost sea days and the decision to contract *Lisa Marie* to conduct the survey in the core survey area. Age composition data collected from both *Lasker* and *Lisa Marie*, but the age compositions seem to catch younger and older fish, respectively. There is likely a difference in selectivity between the trawl gear and purse seine gear, but a strong assumption regarding gear selectivities must be made to relate acoustic and net observations. The STAT decided to combine the *Lasker* core survey and nearshore biomass values, similar to the approach used in the previous benchmark assessment. The *Lisa Marie* fleet was modeled separately as it seemed to sample a different portion of the population both in space and available ages. Qs for each fleet were calculated based on the biomass ratios for each and sum to 1.

The STAT considered alternative modeling options, although alternatives would require different assumptions. One option was to combine all the data together and model it as one fleet. This would result in bimodal age composition data, and it was difficult to conclude the two gear types had the same selectivities. The STAT anticipates evaluating different configurations of this survey at the STAR panel.

### 3.4.3 Fisheries

Fishery structure in the base model is the same as implemented in recent assessments. Three fisheries are included in the model, including two Mexico-California fleets separated into semesters (MexCal S1 and MexCal S2) and one fleet representing Pacific Northwest fisheries (Canada-WA-OR, PNW). Also, because the California live bait industry currently reflects the only active sector in the U.S. sardine fishery, minor amounts of live bait landings were included in the current assessment.

Data from major fishing regions are aggregated to represent southern and northern fleets (fisheries). The southern 'MexCal' fleet includes data from three major fishing areas at the southern end of the stock's distribution: northern Baja California (Ensenada, Mexico), southern California (Los Angeles to Santa Barbara), and central California (Monterey Bay). Fishing can occur throughout the year in the southern region, however, availability-at-size/age changes due to migration. Selectivity for the southern MexCal fleet was modeled separately for seasons 1 and 2 (semesters, S1 and S2).

The 'PNW' fleet (fishery) includes data from the northern range of the stock's distribution, where sardine are typically abundant between late spring and early fall. The PNW fleet includes aggregate data from Oregon, Washington, and Vancouver Island (British Columbia, Canada). The majority of fishing in the northern region typically occurs between July and October (S1).

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## 3.5 Model Parameters

### 3.5.1 Longevity and natural mortality

Assumptions regarding the biology of Pacific sardine in the 2024 base model were similar to those used in past models. There were 9 age bins, representing ages 0 to 8+. The prior for natural mortality (M) was calculated with the updated Hamel and Cope method (Hamel and Cope 2022) which assumed a maximum age of 8 (see Figure 8.21). Additionally, natural mortality was time-invariant and age-specific (Lorenzen 1996; Lorenzen 2022).

### 3.5.2 Growth

Weight-at-age estimates by year/semester were generated outside the model and used in the base model to translate derived numbers-at-age into biomass-at-age for both input data (catch time series) and output estimates (population numbers-at-age). Treatment of growth using weight-at-age matrices associated with the fisheries, survey, and population greatly simplifies the overall assessment, while allowing growth to vary across time and minimizing potential conflicts with selectivity parameterizations. Appendix B contains details on weight-at-age calculations for the fishing fleets.

### 3.5.3 Stock-recruitment relationship

In the 2020 benchmark model, equilibrium recruitment ($R_0$) and initial equilibrium offset ($SR_{regime}$) were estimated, and steepness (h) was fixed at 0.65. Steepness is difficult to estimate from available data, although the likelihood profile suggests that values ranging between 0.25 and about 0.65 are supported by the data. As a result, steepness was fixed at 0.65. It seems biologically implausible for steepness to be low given the characteristic large fluctuations in sardine over time.

Following recommendations from past assessment reviews, the estimate of average recruitment variability ($\sigma_R$) assumed in the stock-recruitment (S-R) relationship was set to 1.2. The 2020 assessment model used a value of 1.2, which was increased as part of the model tuning process from 0.75. Specifically, $\sigma_R$ was increased to reflect the estimated root mean square error values in the modeled recruitment deviations. Recruitment deviations were estimated as separate vectors for the early and main data periods in the overall model. Early recruitment deviations for the initial population were estimated from 1999-2004 (six years before the start of the model). A recruitment bias adjustment ramp (Methot and Taylor 2011) was applied to the early period and bias-adjusted recruitment estimated in the main period of the model. Main period recruitment deviations were advanced one year from that used in the last assessment, i.e., estimated from 2005-22 (S2 of each model year), which translated to the 2023 year class being freely estimated in the model. The STAT is prepared to evaluate sensitivities to $\sigma_R$ at the STAR panel.

Pacific sardines are believed to have a broad spawning season, beginning in January off northern Baja California and ending by July off the Pacific Northwest. In the semester-based model, spawning stock biomass (SSB) is calculated at the beginning of S2 (January). Recruitment was specified to occur in S1 of the following model year (consistent with the July 1st birth-date assumption). In earlier assessments, a Ricker stock-recruitment (S-R) relationship had been assumed following Jacobson and MacCall (1995), however, following recommendations from past reviews, a Beverton-Holt S-R has been implemented in all assessments since 2014.

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It is important to note that there exists little data available to directly evaluate recent recruitment strength (e.g., absolute numbers of age-0, 6-9 cm fish in the most recent year). In past years the MexCal fleets have caught age-0 fish, particularly in the spring of calendar years. Data from the PNW fishery have no records of age-0 fish. In some years, the AT survey can observe relatively high amounts of age-0 fish, thus the AT survey selectivity is modeled to have time-varying age-0 selectivity (see below section).

### 3.5.4 Selectivity

The base model assumed selectivity was an age-based process. Age-based selectivity was adopted as the assessments began to rely on empirical weight-at-age rather than internal growth estimation from age and length data. Time-varying selectivity was generally implemented in the base model for both the fisheries and survey, whereas, selectivity in models prior to the 2020 benchmark were time invariant. Pacific sardine migrate north in summer, and then back to southern waters in late fall and winter to spawning grounds (McDaniel *et al.* 2016). Time-varying selectivity better captures interannual variations in these migrations and to provide better model fits to age compositions from the fisheries and AT survey.

MexCal S1 and MexCal S2 fishery selectivitities were estimated to be time-varying with the two-dimensional auto-regressive (2dAR) feature in SS3 (Xu *et al.* 2019). The base selectivity form for both fleets 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 temporally independent. For MexCal S1, ages 0-3 were time-varying and ages 4-8+ were not estimated with the 2dAR feature. Because of the random walk parameterization, selectivities for ages 4-8 can be time-varying without directly being estimated as such. For MexCal S2, ages 0-4 were time-varying and 5-8+ were time-invariant. Both fleets had time-varying estimation for the years 2006-2022.The SE value for the deviations was 1.0 in the base model, and values of 0.5 and 1.5 were explored in model development. Decreasing the SE values resulted in smoother curves but poorer fits to the age composition data. Increasing the SE values resulted in improved fits to the age composition data but a higher values associated with parameter deviations in the total likelihood calculations. The goal of this configuration was to capture the year-to-year variability in the fishery age composition data.

The PNW fleet was modeled using a two-parameter logistic selectivity form as implemented in past models. Asymptotic selectivity captured the stock’s biology and evidence that larger, older sardines typically migrate to northern feeding habitats each summer (McDaniel *et al.* 2016). The age-at-inflection estimate was modeled as a time-varying parameter. The block treatment was the same as for the MexCal fleets, in that annual blocks were used from 2005-2014, and the 2014 pattern was constant through 2023 (although there were no associated catch values to remove fish from the population).

The AT survey selectivity was modeled with time-varying age-0 selectivity and time-invariant full selectivity for age 1+ fish. There are three main selectivity components to consider in the AT survey data: 1) fish availability in the survey area; 2) vulnerability of fish to the acoustic sampling gear; and 3) vulnerability of fish to the mid-water trawl (avoidance and/or extrusion). No evidence exists that sardine with fully-developed swim bladders (i.e., greater than age-0) are missed by the acoustic equipment, further supporting the assumption that age-1+ fish are fully-selected by the

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survey in any given year. Selectivity for the *Lisa Marie* in 2022 was estimated for age-0 and assumed to be 1 for ages 1+ (consistent with the estimation for the AT survey data).

### 3.5.5 Catchability

Previous stock assessments have estimated catchability ($Q$) with a prior and treated it as fixed. Estimating $Q$ without a prior has resulted in values greater than 1, suggesting that the survey somehow concentrates sardine biomass. Estimating $Q$ with a prior, requires defining a prior which historically has been centered at 1. The basis for this assumption is that the survey is designed to sample all potential habitat of NSP Pacific sardine.

In recent years, the uncertainties associated with nearshore biomass have been a significant topic of discussion as sardine availability is likely to be density-dependent. Biomass has been low, and while AT survey nearshore methods did not observe much biomass, the CCPSS aerial survey observed relatively high amounts of biomass.

At the 2020 STAR panel meeting, the STAT considered several approaches related to accounting for the biomass inshore of the AT survey including: (a) ignoring it; (b) adding the estimate of biomass from the 2019 CCPSS survey to the estimate of biomass from the assessment; (c) specifying a change in $Q$ for recent years using the estimates of AT and aerial survey biomass for 2019; and (d) fully integrating the CCPSS data into the assessment. The first of these options would ignore observed biomass not surveyed acoustically, while the second would lead to difficulties when conducting projections for rebuilding analyses. The fourth option is ideal in principle, but there remains considerable uncertainty about how to achieve this given there are only estimates of biomass from the CCPSS for 2017 and 2019 and uncertainty about what selectivity pattern to assume for the CCPSS data were it to be fit as a separate fleet.

The 2020 benchmark model therefore specified Q for two periods 2005-2014 and 2015-2019, with Q for the first period set to 1 and that for second period set to 0.733 to account for an increase in the proportion of sardine biomass inshore of the AT survey since 2015. The value of 0.733 was calculated from the 2019 AT survey estimate (33,632 mt) and 2019 aerial survey estimate (12,279 mt), specifically $\frac{33{,}632}{33{,}632+12{,}279}$ (Table 7.6). The STAT has kept the $Q$ configuration for 2005-2014 and 2015-2019, as there has been no new analysis to suggest that this approach would need to be revisited.

The $Q$ values for 2020 and 2021 were calculated with the same assumption that $Q$ for the AT survey is $\frac{ATcore+ATnearshore}{ATcore+ATnearshore+aerial}$, resulting in values of 0.589 and 0.733, respectively (Table 7.6).

The 2022 AT survey had logistical challenges that resulted in the waters off northern California, Oregon, and Washington being surveyed by the fishing vessel *Lisa Marie*. Data from the fishing vessel were modeled as a separate survey fleet, and a $Q$ value was calculated based on the ratio of biomass observations between the AT survey and *Lisa Marie*. The *Lisa Marie* observed a majority of the sardine biomass and had a $Q$=0.616, and the AT survey had a $Q$=0.384 (Table 7.6).

The STAT chose to calculate $Q$ based on available data rather than estimating values in the assessment model. This approach has been utilized in the previous assessment of Pacific sardine,

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Pacific mackerel, and northern anchovy. The STAT will be prepared to consider alternative handlings of $Q$ at the STAR panel.

### 3.5.6 Likelihood components and model parameters

A complete list of model parameters for the base model is presented in Table 7.12. The total objective function was based on the following individual likelihood components: 1) fits to catch time series; 2) fits to the AT survey abundance index; 3) fits to age compositions from the three fleets and AT survey; 4) estimated parameters and deviations associated with the stock-recruitment relationship; and 5) minor contributions from soft-bound penalties associated with particular estimated parameters.

### 3.5.7 Initial population and fishing conditions

Given the Pacific sardine stock has been exploited since the early 20th Century (i.e., well before the start year used in the model), further information is needed to address equilibrium assumptions related to initial population dynamics conditions in the assessment model.

Pacific sardine have been exploited since the early 20th century, well before the start year used in the assessment model. As a result, parameters associated with equilibrium conditions (such as $R_0$) are estimated, the model is assumed to begin at an exploited state. This required the estimating additional parameters, such as a recruitment regime offset and initial fishing mortality.

The initial population was defined by estimating 'early' recruitment deviations from 1999-2004, i.e., six years prior to the start year in the model. Initial fishing mortality (F) was estimated for the MexCal S1 fishery and fixed at 0 for MexCal S2 and PNW fisheries, noting that results were robust to different combinations of estimated vs. fixed initial F for the three fisheries.

In effect, the initial equilibrium age composition in the model is adjusted via application of early recruitment deviations prior to the start year of the model, whereby the model applies the initial F level to an equilibrium age composition to get a preliminary number-at-age time series, then applies the recruitment deviations for the specified number of younger ages in this initial vector. If the number of estimated ages in the initial age composition is less than the total number of age groups assumed in the model (as is the case here), then the older ages will retain their equilibrium levels. Because the older ages in the initial age composition will have progressively less information from which to estimate their true deviation, the start of the bias adjustment was set accordingly (Methot 2011; Methot and Wetzel 2013). Ultimately, this approach reflects a non-equilibrium analysis or rather, allows for a relaxed equilibrium assumption of the virgin (unfished) age

structure at the start of the model as implied by the assumed natural mortality rate (M). Finally, an equilibrium 'offset' from the stock-recruitment relationship ($R_1$) was estimated (with no contribution to the likelihood) and along with the early recruitment deviation estimates, allowed the most flexibility for matching the population age structure to the initial age-composition data at the start of the modeled time period.

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### 3.5.8 Assessment program with last revision date

For the base model, the stock assessment team (STAT) transitioned from Stock Synthesis (SS) version 3.30.14 to version 3.30.22. The SS model is comprised of three sub-models: (1) a population dynamics sub-model, where abundance, mortality, and growth patterns are incorporated to create a synthetic representation of the true population; (2) an observation sub-model that defines various processes and filters to derive expected values for different types of data; and (3) a statistical sub-model that quantifies the difference between observed data and their expected values and implements algorithms to search for the set of parameters that maximizes goodness of fit. The modeling framework allows for the full integration of both population size and age structure, with explicit parameterization both spatially and temporally. The model incorporates all relevant sources of variability and estimates goodness of fit in terms of the original data, allowing for final estimates of precision that accurately reflect uncertainty associated with the sources of data used as input in the modeling effort.

### 3.5.9 Bridging analysis

The exploration of models began by bridging the 2020 benchmark model to Stock Synthesis version 3.30.22. This exercise resulted in differences in estimated parameter values, as well as biomass estimates and likelihood values. The STAT worked with software authors to track the changes to a bug in the seasonal model of the previous version (3.30.14) that was corrected in the new version (3.30.22). Details of the bridging process are documented in Appendix A.

Results from a bridging analysis that adds each feature of the assessment model is shown in Figure 8.23 and 8.22.

### 3.5.10 Convergence criteria and status

The iterative process for determining numerical solutions in the model was continued until the difference between successive likelihood estimates was <0.00001. The total likelihood and final gradient estimates for the base model were 285.235 and 7.58e-06, respectively.

## 3.6 Base Model Results

### 3.6.1 Likelihoods and derived quantities of interest

The base model total likelihood was 285.235 (Table 7.11). Likelihood values from the AT survey and PNW fishery age compositions made up the majority of the total likelihood. The forecasted stock biomass for July 2024 was 55,494 (age 1+; mt).

### 3.6.2 Parameter estimates and errors

Parameter estimates and standard errors for the 2024 base model are presented in Table 7.12.

### 3.6.3 Growth

Growth parameters were not estimated in the 2024 base model. Rather, weight-at-age estimates by year were used to convert estimated numbers into weight of fish for calculating biomass quantities relevant to management (Figures 8.17 to 8.19).

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### 3.6.4 Selectivity estimates and fits to fishery and survey age compositions

Time-varying age-based selectivities were estimated for the three fisheries (Figures 8.24) and AT survey (Figure 8.25). Time-varying selectivities resulted in good fits to fishery age compositions (Figures 8.26, 8.27, and 8.28), and residuals of the fits to age compositions had a maximum absolute scale of about two (Figures 8.29, 8.30, and 8.31).

Time-varying age-0 parameters resulted in adequate fits to age composition data in some years, and some poor fits in other years (Figures 8.32 and 8.33)

### 3.6.5 Fit to survey index of abundance

Model fits to the AT survey abundance index in arithmetic and log scale are presented in Figures 8.34 and 8.35 for the AT survey and in Figure 8.38 for the 2022 *Lisa Marie* survey. The predicted fit to the survey index was generally good (near mean estimates and within error bounds).

### 3.6.6 Stock-recruitment relationship

Recruitment was modeled using a Beverton-Holt stock-recruitment relationship (Figure 8.39. The assumed level of underlying recruitment deviation error was fixed ($\sigma_R$=1.2), equilibrium recruitment was estimated ($log(R_0)$= 14.532 and steepness (h) was fixed at 0.65. Recruitment deviations for the early (1999-2004), main (2005-2023), and forecast (2024-2025) periods in the model are presented in Figure 8.40. Asymptotic standard errors for recruitment deviations are shown in Figure 8.41, and the recruitment bias adjustment plot for the three periods are shown in Figure 8.42.

### 3.6.7 Population number- and biomass-at-age estimates

Population number-at-age estimates for the base model are presented in Table 7.13. Corresponding estimates of population biomass-at-age, total biomass (age-0+, mt) and stock biomass (age-1+ fish, mt) are shown in Table 7.14. Age 0-3 fish have comprised about a majority of the total population biomass from 2005-2023.

### 3.6.8 Spawning stock biomass

Time series of estimated spawning stock biomass (SSB; mt) and associated 95% confidence intervals are presented in Table 7.15. The initial level of SSB was estimated to be 451,625 mt. The SSB has continually declined since 2005-2006, reaching low levels in recent years (2014-present). The SSB was projected to be 42,393 mt in January 2024.

### 3.6.9 Recruitment

Time series of estimated recruitment abundance are presented in Tables 7.13 and 7.15 and Figure 8.43. The equilibrium level of recruitment $R_0$ was estimated to be 2,047,233 x1000 age-0 fish. As indicated for SSB above, recruitment has declined since 2005-2006 with the exception of a brief period of modest recruitment success in 2009-2010. In particular, the 2011-2018 year classes have been among the weakest in recent history.

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### 3.6.10 Stock biomass for PFMC management

Stock biomass, used for calculating annual harvest specifications, is defined as the sum of the biomass for sardine ages one and older (age 1+) at the start of the management year (July). Time series of estimated stock biomass are presented in Table 7.14 and Figure 8.44. As discussed above for both SSB and recruitment, a similar trend of declining stock biomass has been observed since 2005-2006, peaking in 2006, and plateauing at recent low levels since 2014. The base model stock biomass is projected to be 52,357 mt in July 2023. Pacific sardine NSP biomass is near the 50,000 mt minimum stock size threshold as defined in the CPS-FMP.

### 3.6.11 Fishing mortality

Estimated fishing mortality (apical F) time series by fishery are presented in Figure 8.45. In recent years (2015-2023), fishing mortality estimates have been relatively low, with the exception of 2021 (due to high harvest on NSP sardine in Ensenada). Exploitation rate increased to around 20% for calendar year 2021 but has been relatively low since calendar year 2016 (Table 7.17 and Figure 8.46).

## 3.7 Modeling Diagnostics

### 3.7.1 Convergence

Convergence was evaluated by starting model parameters from values jittered from the maximum likelihood estimates. Starting parameters were jittered by 10% for 50 replicates, and a better minimum was not found (Table 7.18). Rephasing of parameter estimation order did not result in a better fit to the data. There were no difficulties in inverting the Hessian to obtain estimates of variability, and the STAT feels that the base model represents the best fit to the data given the modeling assumptions.

### 3.7.2 Historical analysis

Estimates of stock biomass (Figure 8.47; age 1+ fish, mt) and recruitment (Figure 8.48; age-0 fish, billions) for the 2024 base model were compared to recently conducted assessments. Full and updated stock assessments since 2014 (Hill et al. 2014-2019) are included in the comparison. Stock biomass and recruitment trends were generally similar, with notable differences in scale between particular years. It is important to note that previous (2014-16) assessments were structured very similarly (e.g., similar model dimensions, data, assumptions, and parameterizations). Whereas, the benchmark model reflects much simpler versions of past assessments models, which necessarily confounds direct comparisons between results from this year's model with past assessments. It is not possible to compare estimates of uncertainty, as SS3 only relatively recently calculated uncertainty for stock biomass.

### 3.7.3 Likelihood profiles

Likelihood profiles were conducted for steepness, natural mortality (with steepness estimated), catchability adjusted by percentages, and 2023 survey index biomass. The 2023 survey index biomass value was included as an additional survey fleet in the model (which uses preliminary 2023 estimates for the AT survey). Technically this fleet was weighted heavily (lambda=10) in the model sensitivities.

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Recruitment estimates support low values of steepness (Figure 8.49). There is relatively little information on steepness in the age compositions. One explanation for the low steepness values is the timeframe of the assessment. From 2005-present, the fishery has undergone a “one-way trip”, in which the population has declined. As a result, it follows that estimates of steepness are low given that the biomass has declined by orders of magnitude without any notable increases in the time period. Increasing values of steepness had relatively small changes on 2023 and 2024 forecast stock biomasses (Table 7.19). Estimates of summary biomass across fixed values of steepness are all relatively similar (Figure 8.50).

Natural mortality estimates between 0.5 and 0.6 (Figure 8.51) were supported by profiles. There seems to be a small data conflict between the AT survey age compositions and AT survey index of abundance (Figure 8.51). The changes in select parameter estimates and stock biomass estimates at fixed values of natural mortality are shown in Table 7.20. Generally, increases in natural mortality values resulted in decreased estimates of initial F, catchability (Q), and $R_0$ (Table 7.20). Stock biomass values in 2019 and 2020 increased with increasing natural mortality, due to the negative correlation with catchability (Table 7.20 and Figure 8.52).

Data from the AT survey and PNW fishery (to a lesser extent) support higher $Q$ values than those used in the 2020 benchmark model (Figure 8.53). Percentage increases in catchability values resulted in increased estimates of initial F and decreased estimates of natural mortality and $R_0$ (Table 7.22). Increased catchability values resulted in decreased forecast stock biomass estimates (Figure 8.54).

Biomass values between 40,000-110,000 mt were consistent with the other data sets (Figure 8.55), and this was largely driven by the AT survey index of abundance and survey age composition data. This range of terminal year biomass values resulted in forecast 2024 stock biomass values shown in Table 7.21 and Figure 8.56.

### 3.7.4 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 are shown in Table 7.23. Parameter estimates, biomass estimates, and likelihood values are shown in Table 7.23 and Figure 8.57. The STAT anticipates evaluating other data weighting methods such as McAllister-Ianelli at the STAR panel meeting.

### 3.7.5 Retrospective analysis

There was a retrospective pattern when re-running the model with one year of data dropped at a time (Figure 8.58). Pacific sardine and CPS more generally have recruitment variability which partly explains the retrospective pattern. The base model has a fixed and time-varying Q value which may be another source of the retrospective pattern.

# 4 Harvest Control Rules

Additional details will be available for the briefing book draft after the STAR Panel.

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# 5 Research and Data Needs

In previous assessments there were two notable sources of uncertainty: estimates of nearshore biomass and values of recent Mexican catches. The nearshore component of the AT survey has developed and now routinely involves F/V acoustic-trawl methods. The habitat model used to separate NSP sardine from SSP has been updated, resulting in a biologically plausible time series of catch values. Survey methods will continue to be revisited and adapted to support the best available science.

The presence of Japanese sardine (*Sardinops melanostictus*) mixed with the Pacific sardine population is indicated in preliminary genetics results from the 2022 and 2023 surveys. At the time of this report, it is unclear how much of the total biomass estimate is attributable to Japanese sardine, as research is still ongoing. Results from the genetics research regarding the sample identification, total numbers, and locations of Japanese sardine will be crucial to making any adjustments to the assessment requested by the Council. The data sets that will be affected in particular include: The AT survey index, the survey age composition data (including ageing uncertainty), and the survey weights-at-age.

# 6 Acknowledgements

Section forthcoming

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# 7 Tables

Table 7.1: U.S. Pacific sardine harvest specifications and landings (mt) since the onset of federal management. US. harvest limits and closures are based on total catch, regardless of subpopulation source. Landings for the 2019-20 management year are preliminary and incomplete.

| Mgmt. Year | OFL | ABC | HG or ACL | Tot. Landings | NSP Landings |
|---|---|---|---|---|---|
| 2000 | - | - | 186,791 | 73,766 | 67,691 |
| 2001 | - | - | 134,737 | 79,746 | 57,019 |
| 2002 | - | - | 118,442 | 103,134 | 82,529 |
| 2003 | - | - | 110,908 | 77,728 | 65,692 |
| 2004 | - | - | 122,747 | 96,513 | 78,430 |
| 2005 | - | - | 136,179 | 95,786 | 73,104 |
| 2006 | - | - | 118,937 | 107,471 | 86,952 |
| 2007 | - | - | 152,564 | 125,145 | 104,716 |
| 2008 | - | - | 89,093 | 83,797 | 74,424 |
| 2009 | - | - | 66,932 | 72,847 | 61,220 |
| 2010 | - | - | 72,039 | 60,862 | 49,751 |
| 2011 | 92,767 | 84,681 | 50,526 | 55,017 | 43,725 |
| 2012 | 154,781 | 141,289 | 109,409 | 86,230 | 76,410 |
| 2013 | 103,284 | 94,281 | 66,495 | 69,833 | 63,832 |
| 2014 (1) | 59,214 | 54,052 | 6,966 | 6,806 | 6,121 |
| 2014-15 | 39,210 | 35,792 | 23,293 | 23,113 | 19,969 |
| 2015-16 | 13,227 | 12,074 | 7,000 | 1,919 | 75 |
| 2016-17 | 23,085 | 19,236 | 8,000 | 1,885 | 602 |
| 2017-18 | 16,957 | 15,479 | 8,000 | 1,775 | 351 |
| 2018-19 | 11,324 | 9,436 | 7,000 | 2,278 | 525 |
| 2019-20 | 5,816 | 4,514 | 4,000 | 2,062 | 627 |
| 2020-21 | 5,525 | 4,288 | 4,000 | 2,276 | 657 |
| 2021-22 | 5,525 | 3,329 | 3,000 | 1,772 | 298 |
| 2022-23 | 5,506 | 4,274 | 3,800 | 1,619 | 517 |
| 2023-24 | 5,506 | 3,953 | 3,600 | 1,206 | 154 |

Table 7.2: Pacific sardine landings (mt) for major fishing regions off northern Baja California (Ensenada, Mexico), the United States, and British Columbia (Canada). ENS and SCA landings are presented as totals and northern subpopulation (NSP) portions. Y-S stands for year-semester for calendar and model values.

| Calendar Y-S | Model Y-S | ENS Total | ENS NSP | SCA Total | SCA NSP | CCA | OR | WA | BC |
|---|---|---:|---:|---:|---:|---:|---:|---:|---:|
| 2005-2 | 2005-1 | 38,000 | 4,397 | 16,615 | 1,581 | 7,825 | 44,316 | 6,605 | 3,231 |
| 2006-1 | 2005-2 | 17,601 | 2,710 | 18,290 | 10,643 | 2,033 | 102 | 0 | 0 |
| 2006-2 | 2006-1 | 39,636 | 0 | 18,556 | 5,016 | 15,710 | 35,546 | 4,099 | 1,575 |
| 2007-1 | 2006-2 | 13,981 | 5,800 | 27,546 | 20,567 | 6,013 | 0 | 0 | 0 |
| 2007-2 | 2007-1 | 22,866 | 11,928 | 22,047 | 5,531 | 28,769 | 42,052 | 4,662 | 1,522 |
| 2008-1 | 2007-2 | 23,488 | 0 | 25,099 | 21,186 | 2,515 | 0 | 0 | 0 |
| 2008-2 | 2008-1 | 43,378 | 5,930 | 8,980 | 124 | 24,196 | 22,940 | 6,435 | 10,425 |
| 2009-1 | 2008-2 | 25,783 | 5,339 | 10,167 | 9,650 | 11,080 | 0 | 0 | 0 |
| 2009-2 | 2009-1 | 30,128 | 0 | 5,214 | 109 | 13,936 | 21,482 | 8,025 | 15,334 |
| 2010-1 | 2009-2 | 12,989 | 2,781 | 20,334 | 13,812 | 2,909 | 437 | 511 | 422 |
| 2010-2 | 2010-1 | 43,832 | 0 | 11,261 | 384 | 1,404 | 20,415 | 11,870 | 21,801 |
| 2011-1 | 2010-2 | 18,514 | 0 | 13,192 | 12,959 | 2,720 | 0 | 0 | 0 |
| 2011-2 | 2011-1 | 51,823 | 17,330 | 6,499 | 0 | 7,359 | 11,023 | 8,008 | 20,719 |
| 2012-1 | 2011-2 | 10,534 | 3,166 | 12,649 | 7,856 | 3,673 | 2,874 | 2,932 | 0 |
| 2012-2 | 2012-1 | 48,535 | 0 | 8,621 | 930 | 598 | 39,744 | 32,510 | 19,172 |
| 2013-1 | 2012-2 | 13,609 | 0 | 3,102 | 973 | 84 | 149 | 1,421 | 0 |
| 2013-2 | 2013-1 | 37,804 | 0 | 4,997 | 0 | 811 | 27,599 | 29,619 | 0 |
| 2014-1 | 2013-2 | 12,930 | 0 | 1,495 | 491 | 4,403 | 0 | 908 | 0 |
| 2014-2 | 2014-1 | 77,466 | 0 | 1,601 | 0 | 1,831 | 7,788 | 7,428 | 0 |
| 2015-1 | 2014-2 | 16,497 | 0 | 1,543 | 0 | 728 | 2,131 | 63 | 0 |
| 2015-2 | 2015-1 | 20,972 | 0 | 1,421 | 0 | 6 | 0 | 66 | 0 |
| 2016-1 | 2015-2 | 23,537 | 0 | 423 | 0 | 1 | 1 | 0 | 0 |
| 2016-2 | 2016-1 | 42,532 | 0 | 964 | 49 | 234 | 3 | 170 | 0 |
| 2017-1 | 2016-2 | 30,496 | 0 | 513 | 145 | 0 | 0 | 0 | 0 |
| 2017-2 | 2017-1 | 99,967 | 0 | 1,205 | 0 | 170 | 1 | 0 | 0 |
| 2018-1 | 2017-2 | 25,721 | 0 | 395 | 177 | 0 | 2 | 0 | 0 |
| 2018-2 | 2018-1 | 38,049 | 0 | 1,424 | 0 | 35 | 6 | 2 | 0 |
| 2019-1 | 2018-2 | 30,119 | 0 | 750 | 421 | 58 | 2 | 0 | 0 |
| 2019-2 | 2019-1 | 64,295 | 0 | 870 | 49 | 174 | 8 | 0 | 0 |
| 2020-1 | 2019-2 | 74,817 | 0 | 681 | 67 | 328 | 0 | 0 | 0 |
| 2020-2 | 2020-1 | 74,687 | 0 | 1,204 | 0 | 429 | 0 | 0 | 0 |
| 2021-1 | 2020-2 | 48,988 | 0 | 603 | 187 | 37 | 3 | 0 | 0 |
| 2021-2 | 2021-1 | 74,710 | 0 | 1,093 | 90 | 3 | 9 | 3 | 0 |
| 2022-1 | 2021-2 | 73,385 | 10,979 | 663 | 192 | 2 | 0 | 0 | 0 |
| 2022-2 | 2022-1 | 79,533 | 0 | 988 | 52 | 116 | 7 | 2 | 0 |
| 2023-1 | 2022-2 | 46,179 | 0 | 493 | 326 | 13 | 0 | 0 | 0 |
| 2023-2 | 2023-1 | 106,035 | 0 | 1,052 | 0 | 152 | 1 | 0 | 0 |

Table 7.3: Pacific sardine length and age samples available for major fishing regions off northern Baja California (Mexico), the United States, and Canada. Samples from model year-semester 2015-1 onward were from incidental catches so were not included in the model. Values shown are number of sample lengths-number of sample ages. Note, one sample corresponds to 25 fish (e.g., a sample size of 3 corresponds to 75 fish).

| Calendar Y-S | Model Y-S | ENS | SCA | CCA | OR | WA | BC |
|---|---|---|---|---|---|---|---|
| 2005-2 | 2005-1 | 115-0 | 73-72 | 24-23 | 14-14 | 54-27 | 65-0 |
| 2006-1 | 2005-2 | 53-0 | 67-66 | 32-31 | 0-0 | 0-0 | 0-0 |
| 2006-2 | 2006-1 | 46-0 | 61-61 | 58-58 | 12-12 | 15-15 | 0-0 |
| 2007-1 | 2006-2 | 22-0 | 74-72 | 47-46 | 3-3 | 0-0 | 0-0 |
| 2007-2 | 2007-1 | 46-0 | 72-72 | 68-68 | 80-80 | 10-10 | 23-0 |
| 2008-1 | 2007-2 | 43-0 | 53-53 | 15-15 | 0-0 | 0-0 | 0-0 |
| 2008-2 | 2008-1 | 83-0 | 25-25 | 30-30 | 80-80 | 14-14 | 229-0 |
| 2009-1 | 2008-2 | 50-0 | 20-20 | 20-20 | 0-0 | 0-0 | 0-0 |
| 2009-2 | 2009-1 | 0-0 | 13-12 | 23-23 | 82-81 | 12-12 | 285-0 |
| 2010-1 | 2009-2 | 0-0 | 62-62 | 37-36 | 3-1 | 2-2 | 2-0 |
| 2010-2 | 2010-1 | 0-0 | 25-25 | 13-13 | 64-26 | 8-8 | 287-0 |
| 2011-1 | 2010-2 | 0-0 | 22-21 | 11-11 | 0-0 | 0-0 | 0-0 |
| 2011-2 | 2011-1 | 0-0 | 22-22 | 22-22 | 34-33 | 10-10 | 362-0 |
| 2012-1 | 2011-2 | 0-0 | 48-47 | 16-16 | 8-8 | 8-8 | 0-0 |
| 2012-2 | 2012-1 | 0-0 | 44-41 | 18-17 | 83-82 | 37-37 | 106-0 |
| 2013-1 | 2012-2 | 0-0 | 16-16 | 2-2 | 0-0 | 3-3 | 0-0 |
| 2013-2 | 2013-1 | 0-0 | 39-39 | 5-5 | 75-74 | 66-65 | 0-0 |
| 2014-1 | 2013-2 | 0-0 | 27-26 | 14-13 | 0-0 | 1-1 | 0-0 |
| 2014-2 | 2014-1 | 0-0 | 8-8 | 6-6 | 27-27 | 24-23 | 0-0 |
| 2015-1 | 2014-2 | 0-0 | 18-18 | 14-14 | 15-15 | 1-0 | 0-0 |
| 2015-2 | 2015-1 | 0-0 | 0-0 | 2-2 | 0-0 | 1-0 | 0-0 |
| 2016-1 | 2015-2 | 0-0 | 8-8 | 0-0 | 4-0 | 0-0 | 0-0 |
| 2016-2 | 2016-1 | 0-0 | 3-3 | 4-3 | 4-0 | 0-0 | 0-0 |
| 2017-1 | 2016-2 | 0-0 | 3-3 | 0-0 | 0-0 | 0-0 | 0-0 |
| 2017-2 | 2017-1 | 0-0 | 1-1 | 4-4 | 0-0 | 0-0 | 0-0 |
| 2018-1 | 2017-2 | 0-0 | 2-2 | 0-0 | 0-0 | 0-0 | 0-0 |
| 2018-2 | 2018-1 | 0-0 | 2-2 | 4-4 | 0-0 | 0-0 | 0-0 |
| 2019-1 | 2018-2 | 0-0 | 1-0 | 6-0 | 0-0 | 0-0 | 0-0 |
| 2019-2 | 2019-1 | 0-0 | 1-0 | 2-0 | 0-0 | 0-0 | 0-0 |
| 2020-1 | 2019-1 | 0-0 | 0-0 | 0-0 | 0-0 | 0-0 | 0-0 |
| 2020-2 | 2020-1 | 0-0 | 0-0 | 0-0 | 0-0 | 0-0 | 0-0 |
| 2021-1 | 2020-2 | 0-0 | 6-6 | 3-3 | 0-0 | 0-0 | 0-0 |
| 2021-2 | 2021-1 | 0-0 | 6-6 | 0-0 | 0-0 | 0-0 | 0-0 |
| 2022-1 | 2021-2 | 0-0 | 0-0 | 0-0 | 0-0 | 0-0 | 0-0 |
| 2022-2 | 2022-1 | 0-0 | 0-0 | 0-0 | 0-0 | 0-0 | 0-0 |
| 2023-1 | 2022-2 | 0-0 | 6-6 | 0-0 | 0-0 | 0-0 | 0-0 |
| 2023-2 | 2023-1 | 0-0 | 5-5 | 6-6 | 0-0 | 0-0 | 0-0 |

Table 7.4: Pacific sardine NSP landings (mt) by year-semester and fleet for the 2024 base model. For forecast model year-semesters (2024-1, 2024-2), fishing mortality values estimated from 2023-1 and 2023-2 landings were used.

| Calendar Y-S | Model Y-S | MexCal S1 | MexCal S2 | PNW |
|---|---|---|---|---|
| 2005-2 | 2005-1 | 13,803 | 0 | 54,153 |
| 2006-1 | 2005-2 | 0 | 15,386 | 102 |
| 2006-2 | 2006-1 | 20,726 | 0 | 41,221 |
| 2007-1 | 2006-2 | 0 | 32,381 | 0 |
| 2007-2 | 2007-1 | 46,228 | 0 | 48,237 |
| 2008-1 | 2007-2 | 0 | 23,701 | 0 |
| 2008-2 | 2008-1 | 30,249 | 0 | 39,800 |
| 2009-1 | 2008-2 | 0 | 26,069 | 0 |
| 2009-2 | 2009-1 | 14,045 | 0 | 44,841 |
| 2010-1 | 2009-2 | 0 | 19,502 | 1,370 |
| 2010-2 | 2010-1 | 1,787 | 0 | 54,086 |
| 2011-1 | 2010-2 | 0 | 15,679 | 0 |
| 2011-2 | 2011-1 | 24,689 | 0 | 39,751 |
| 2012-1 | 2011-2 | 0 | 14,694 | 5,806 |
| 2012-2 | 2012-1 | 1,528 | 0 | 91,426 |
| 2013-1 | 2012-2 | 0 | 1,057 | 1,571 |
| 2013-2 | 2013-1 | 811 | 0 | 57,218 |
| 2014-1 | 2013-2 | 0 | 4,894 | 908 |
| 2014-2 | 2014-1 | 1,831 | 0 | 15,217 |
| 2015-1 | 2014-2 | 0 | 728 | 2,194 |
| 2015-2 | 2015-1 | 6 | 0 | 66 |
| 2016-1 | 2015-2 | 0 | 1 | 1 |
| 2016-2 | 2016-1 | 284 | 0 | 173 |
| 2017-1 | 2016-2 | 0 | 145 | 0 |
| 2017-2 | 2017-1 | 170 | 0 | 1 |
| 2018-1 | 2017-2 | 0 | 177 | 2 |
| 2018-2 | 2018-1 | 35 | 0 | 8 |
| 2019-1 | 2018-2 | 0 | 479 | 3 |
| 2019-2 | 2019-1 | 224 | 0 | 8 |
| 2020-1 | 2019-2 | 0 | 395 | 0 |
| 2020-2 | 2020-1 | 429 | 0 | 0 |
| 2021-1 | 2020-2 | 0 | 224 | 3 |
| 2021-2 | 2021-1 | 93 | 0 | 11 |
| 2022-1 | 2021-2 | 0 | 11,172 | 0 |
| 2022-2 | 2022-1 | 168 | 0 | 9 |
| 2023-1 | 2022-2 | 0 | 340 | 0 |
| 2023-2 | 2023-1 | 152 | 0 | 1 |
| 2024-1 | 2023-2 | 0 | 0 | 0 |

Table 7.5: Pacific sardine NSP catch values from the 2020 benchmark assessment and the current assessment. Nonzero differences in catch values as a result of the updated habitat model are shown.

| Fleet name | Model Y-S | 2020 values | 2024 values | Difference |
|---|---|---:|---:|---:|
| MexCal_S1 | 2010-1 | 11,274.00 | 1,787.27 | -9,486.73 |
| | 2011-1 | 24,871.40 | 24,688.90 | -182.50 |
| | 2013-1 | 921.56 | 811.29 | -110.27 |
| | 2020-1 | 542.27 | 428.79 | -113.48 |
| MexCal_S2 | 2005-2 | 30,364.20 | 15,385.50 | -14,978.70 |
| | 2006-2 | 39,900.30 | 32,380.80 | -7,519.50 |
| | 2007-2 | 42,910.10 | 23,701.30 | -19,208.80 |
| | 2008-2 | 41,198.50 | 26,068.60 | -15,129.90 |
| | 2009-2 | 31,146.50 | 19,501.50 | -11,645.00 |
| | 2010-2 | 27,267.60 | 15,679.10 | -11,588.50 |
| | 2011-2 | 23,189.90 | 14,694.20 | -8,495.70 |
| | 2012-2 | 13,884.90 | 1,057.01 | -12,827.89 |
| | 2013-2 | 5,625.03 | 4,894.48 | -730.55 |
| | 2015-2 | 185.82 | 1.05 | -184.77 |
| | 2016-2 | 7,080.53 | 144.72 | -6,935.81 |
| | 2017-2 | 6,229.43 | 176.70 | -6,052.73 |
| | 2018-2 | 11,819.40 | 478.89 | -11,340.51 |
| | 2019-2 | 33,070.20 | 395.43 | -32,674.77 |
| | 2020-2 | 48,312.20 | 224.36 | -48,087.84 |
| | 2021-2 | 48,312.20 | 11,172.00 | -37,140.20 |
| PNW | 2021-2 | 2.93 | 0.21 | -2.72 |

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Table 7.6: Fishery-independent indices of abundance for Pacific sardine from the AT survey, nearshore component of the AT survey, and aerial biomass estimates. The nearshore methods include model extrapolation (Ext), unmanned surface vehicles (USV), and fishing vessel acoustic purse-seine methods (F/V). The model year-semester 2023-1 (*) survey values are preliminary. Values from the AT survey core and nearshore components (and nearshore method) are shown. Additionally, aerial biomass estimates and the associated Q values are shown.

| Calendar Y-S | Model Y-S | AT Core | CV | AT Nearshore | Method | AT Total | Aerial | Qadj |
|---|---|---|---|---|---|---|---|---|
| 2006-1 | 2005-2 | 1,947,060 | 0.3 | -- | -- | 1,947,060 | -- | 1 |
| 2006-2 | 2006-1 | -- | -- | -- | -- |  | -- | -- |
| 2007-1 | 2006-2 | -- | -- | -- | -- |  | -- | -- |
| 2007-2 | 2007-1 | -- | -- | -- | -- |  | -- | -- |
| 2008-1 | 2007-2 | 751,075 | 0.09 | -- | -- | 751,075 | -- | 1 |
| 2008-2 | 2008-1 | 801,000 | 0.3 | -- | -- | 801,000 | -- | 1 |
| 2009-1 | 2008-2 | -- | -- | -- | -- |  | -- | -- |
| 2009-2 | 2009-1 | -- | -- | -- | -- |  | -- | -- |
| 2010-1 | 2009-2 | 357,006 | 0.41 | -- | -- | 357,006 | -- | 1 |
| 2010-2 | 2010-1 | -- | -- | -- | -- |  | -- | -- |
| 2011-1 | 2010-2 | 493,672 | 0.3 | -- | -- | 493,672 | -- | 1 |
| 2011-2 | 2011-1 | -- | -- | -- | -- |  | -- | -- |
| 2012-1 | 2011-2 | 469,480 | 0.28 | -- | -- | 469,480 | -- | 1 |
| 2012-2 | 2012-1 | 340,831 | 0.33 | -- | -- | 340,831 | -- | 1 |
| 2013-1 | 2012-2 | 305,146 | 0.24 | -- | -- | 305,146 | -- | 1 |
| 2013-2 | 2013-1 | 306,191 | 0.293 | -- | -- | 306,191 | -- | 1 |
| 2014-1 | 2013-2 | 35,339 | 0.38 | -- | -- | 35,339 | -- | 1 |
| 2014-2 | 2014-1 | 26,279 | 0.697 | -- | -- | 26,279 | -- | 1 |
| 2015-1 | 2014-2 | 29,048 | 0.29 | -- | -- | 29,048 | -- | 1 |
| 2015-2 | 2015-1 | 16,375 | 0.94 | 452 | Ext | 16,375 | -- | 0.733 |
| 2016-1 | 2015-2 | 83,030 | 0.47 | -- | -- | 83,030 | -- | 0.733 |
| 2016-2 | 2016-1 | 72,867 | 0.497 | 1,403 | Ext | 72,867 | -- | 0.733 |
| 2017-1 | 2016-2 | -- | -- | -- | -- | -- | -- | -- |
| 2017-2 | 2017-1 | 14,103 | 0.3 | 146 | Ext | 14,103 | -- | 0.733 |
| 2018-1 | 2017-2 | -- | -- | -- | -- | -- | -- | -- |
| 2018-2 | 2018-1 | 25,148 | 0.67 | 308 | USV/Ext | 25,148 | -- | 0.733 |
| 2019-1 | 2018-2 | -- | -- | -- | -- | -- | -- | -- |
| 2019-2 | 2019-1 | 33,632 | 0.19 | 494 | F/V | 33,632 | 12,279 | 0.733 |
| 2020-1 | 2019-2 | -- | -- | -- | -- | -- | -- | -- |
| 2020-2 | 2020-1 | -- | -- | -- | -- | -- | -- | -- |
| 2021-1 | 2020-2 | 1,409 | 0.4 | 24,960 | F/V | 26,639 | 18,409 | 0.589 |
| 2021-2 | 2021-1 | 40,528 | 0.37 | 443 | F/V | 40,983 | 14,942 | 0.733 |
| 2022-1 | 2021-2 | -- | -- | -- | -- | -- | -- | -- |
| 2022-1 | 2022-1 | 10,795 | 0.32 | 15,765 | F/V | 26,468 | -- | 0.384 |
| 2022-2 | 2022-1 | 42,496 | 0.32 | -- | L.M. |  | -- | 0.616 |
| 2023-1 | 2022-2 | -- | -- | -- | -- | -- | -- | -- |
| 2023-2 | 2023-1* | 49,643 | 0.79 | 27,610 | F/V | 77,252 | -- | 1 |

Table 7.7: Abundance by standard length (cm) for AT summer surveys 2017-2022.

| SL (cm) | 2017 | 2018 | 2019 | 2021 | 2022 |
|---:|---:|---:|---:|---:|---:|
| 4 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 |
| 6 | 938,376 | 0 | 0 | 0 | 0 |
| 7 | 1,407,563 | 0 | 0 | 0 | 0 |
| 8 | 1,407,563 | 1,003,181 | 0 | 0 | 0 |
| 9 | 37,458,127 | 2,161,093 | 0 | 0 | 0 |
| 10 | 37,458,127 | 19,630,447 | 0 | 0 | 1,924,590 |
| 11 | 0 | 36,669,350 | 0 | 0 | 1,829,922 |
| 12 | 0 | 31,232,681 | 0 | 0 | 857,501 |
| 13 | 0 | 9,479,509 | 0 | 0 | 1,256,042 |
| 14 | 0 | 0 | 4,739,631 | 0 | 17,794,718 |
| 15 | 0 | 9,445,972 | 41,539,498 | 0 | 109,287,253 |
| 16 | 0 | 17,575,747 | 59,579,268 | 194,200 | 269,132,435 |
| 17 | 90 | 17,297,285 | 90,576,517 | 398,801 | 219,060,920 |
| 18 | 2,646,754 | 2,571,115 | 32,295,316 | 3,386,512 | 47,780,802 |
| 19 | 1,155,073 | 488,532 | 14,385,176 | 0 | 13,512,376 |
| 20 | 10,902,914 | 257,930 | 6,519,870 | 6,967,224 | 20,697,317 |
| 21 | 19,682,611 | 663,480 | 6,730,283 | 1,324,466 | 10,464,452 |
| 22 | 32,775,963 | 1,151,296 | 2,482,943 | 7,015,700 | 11,311,389 |
| 23 | 16,389,747 | 13,531,991 | 9,275,903 | 21,157,661 | 20,900,885 |
| 24 | 2,446,053 | 41,917,903 | 30,709,103 | 34,878,971 | 16,335,566 |
| 25 | 2,597,826 | 37,951,826 | 30,803,378 | 29,192,426 | 13,274,355 |
| 26 | 4,135,409 | 8,601,750 | 10,187,719 | 41,022,803 | 7,290,532 |
| 27 | 292,821 | 246,290 | 2,374,336 | 39,465,499 | 4,915,285 |
| 28 | 0 | 1,588,705 | 907,076 | 6,989,348 | 0 |
| 29 | 0 | 0 | 9,303 | 815,726 | 0 |
| 30 | 0 | 0 | 0 | 0 | 0 |

Table 7.8: Abundance by age for AT summer surveys 2017-2022.

| Age | 2017 | 2018 | 2019 | 2021 | 2022 |
|---|---:|---:|---:|---:|---:|
| 0 | 73,396,745 | 99,944,046 | 6,691,458 | 6,564 | 5,030,061 |
| 1 | 14,901,610 | 45,052,881 | 170,804,789 | 5,413,500 | 156,036,703 |
| 2 | 51,900,132 | 31,015,046 | 64,803,847 | 30,072,508 | 481,807,397 |
| 3 | 18,842,033 | 52,569,410 | 31,729,973 | 61,722,258 | 64,312,780 |
| 4 | 4,891,566 | 9,776,712 | 43,653,627 | 33,716,271 | 46,758,480 |
| 5 | 3,080,789 | 3,941,948 | 13,763,278 | 37,877,743 | 14,131,981 |
| 6 | 3,274,101 | 4,647,299 | 5,468,442 | 21,917,046 | 10,127,995 |
| 7 | 1,408,040 | 5,233,944 | 2,361,582 | 1,071,118 | 6,358,176 |
| 8+ | 0 | 1,284,797 | 3,838,323 | 1,012,329 | 3,062,767 |

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Table 7.9: Differences between 2020 and 2024 base models.

| | | 2020 Base | 2024 Base |
|---|---|---|---|
| Time period | | 2005-2019 | 2005-2023 |
| Fisheries (no., type) | | 3, commercial | 3, commercial |
| Surveys (no., type) | | 1, AT | 1, AT |
| Natural mortality (M) | | Estimated (prior) | Estimated (prior) |
| Growth | | Fixed (WAA) | Fixed (WAA) |
| Spawner-recruit relationship | | Beverton-Holt | Beverton-Holt |
| | Equilibrium recruitment ($R_0$) | Estimated | Estimated |
| | Steepness (h) | Fixed (0.3) | Fixed (0.65) |
| | Tot. recruitment variability ($\sigma_R$) | Fixed (1.2) | Fixed (1.2) |
| | Init. Equilibrium recruitment offset | Estimated (now called SR regime) | Estimated (now called SR regime) |
| Catchability (Q) | | Fixed (1 for 2005-2014; 0.73 for 2015-2019) | Fixed (1 for 2005-2014; 0.73 for 2015-2019; variable 2020-2023) |
| Selectivity (age-based) | | Estimated | Estimated |
| Fishery selectivity | | Dome-shaped and asymptotic | Dome-shaped and asymptotic |
| | Age composition | Yes | Yes |
| | Form | Age-specifc, random walk (MexCal) / Logistic (PNW) | Age-specifc, random walk (MexCal) / Logistic (PNW) |
| | Time-varying | Yes (blocks) | Yes (2dAR) |
| Survey selectivity | | Asymptotic | Asymptotic |
| | Age Composition | Yes | Yes |
| | Form | Age-specific, asymptotic | Age-specific, asymptotic |
| | Time-varying | Yes (age-0) | Yes (age-0) |
| Fishery selectivity | | Random walk (option 17) | Random walk (option 17) |
| Data weighting | | No | No |

Table 7.10: Model structure (data and processes) and results (likelihood and final stock biomass) from the benchmark to the base model. The addition of features was cumulative. This table will be updated for the STAR panel.

| Model description | # pars | Likelihood | Terminal year | Age 1+ biomass (mt) |
|---|---:|---:|---|---:|
| A: Benchmark 2020 | 140 | 91.69 | 2019 | 35,186 |
| B: 2020 w/ SS update | 140 | 84.79 | 2019 | 38,827 |
| C: catch 2020 habitat model | 140 | 80.69 | 2019 | 41,092 |
| D: catch and comps 2023 | 144 | 83.08 | 2023 | 79,720 |
| E: index and comps 2023 | 144 | 93.76 | 2023 | 35,824 |
| F: index fleet: Lisa Marie | 144 | 100.97 | 2023 | 40,341 |
| G: waa | 144 | 101.94 | 2023 | 30,965 |
| H: update blocking | 73 | 214.62 | 2023 | 40,094 |
| I: Lorenzen M | 73 | 218.72 | 2023 | 36,792 |
| J: Hamel prior M | 73 | 218.97 | 2023 | 36,560 |
| K: steepness | 73 | 221.22 | 2023 | 38,962 |
| L: SR sd prior and rec devs | 73 | 221.35 | 2023 | 39,260 |
| M: bias adj | 73 | 221.47 | 2023 | 37,081 |
| N: 2dAR selex | 226 | 284.92 | 2023 | 36,721 |
| O: base 2024 | 226 | 284.92 | 2023 | 36,721 |

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Table 7.11: Likelihood components, parameters, and stock biomass (age-1+; mt) estimates for the base model. Total age-composition likelihoods and age-composition likelihoods by fleet are shown.

| Type | Component | Value |
|---|---|---|
| Likelihoods | TOTAL | 285.235 |
| | Parm_devs | 159.591 |
| | Age_comp | 113.069 |
| | Recruitment | 13.413 |
| | Parm_priors | 0.232 |
| | Parm_softbounds | 0.043 |
| | Catch | 0.000 |
| | Survey | -1.115 |
| Fleet likelihoods | AT_Survey Age_like | 58.343 |
| | PNW Age_like | 21.064 |
| | MexCal_S1 Age_like | 20.044 |
| | MexCal_S2 Age_like | 11.645 |
| | Lisa_Marie Age_like | 1.974 |
| | Lisa_Marie Surv_like | -0.538 |
| | AT_Survey Surv_like | -0.577 |
| Parameters | NatM_Lorenzen_averageFem_GP_1 | 0.546 |
| | SR_LN(R0) | 14.532 |
| | SR_regime_BLK1repl_2004 | 2.567 |
| | InitF_seas_1_flt_1MexCal_S1 | 2.285 |
| Summary biomass | 2021 | 104,944 |
| | 2022 | 48,827 |
| | 2023 | 52,357 |
| | 2024 | 55,494 |

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Table 7.12: Parameter estimates in the base model. Estimated values, standard deviations (SDs), bounds (minimum and maximum), estimation phase (negative values not included), status (indicates if parameters are near bounds), and prior type information (mean, SD) are shown.

| Parameter | Value | Phase | Bounds | Status | SD | Prior (Exp.Val, SD) |
|---|---|---|---|---|---|---|
| NatM_Lorenzen_averageFem_GP_1 | 0.5465 | 2 | (0.2,0.94) | OK | 0.0392 | Log_Norm(-0.393,0.31) |
| SR_LN(R0) | 14.5320 | 1 | (3,25) | OK | 0.1948 | |
| SR_regime_BLK1repl_2004 | 2.5674 | 4 | (-15,15) | OK | 0.2089 | |
| Early_InitAge_6 | -0.3271 | 2 | (-5,5) | act | 0.7875 | |
| Early_InitAge_5 | -0.3858 | 2 | (-5,5) | act | 0.6978 | |
| Early_InitAge_4 | -0.1738 | 2 | (-5,5) | act | 0.5421 | |
| Early_InitAge_3 | -0.2510 | 2 | (-5,5) | act | 0.5069 | |
| Early_InitAge_2 | 0.8914 | 2 | (-5,5) | act | 0.2017 | |
| Early_InitAge_1 | 0.5155 | 2 | (-5,5) | act | 0.1763 | |
| Main_RecrDev_2005 | 2.1705 | 1 | (-5,5) | act | 0.2111 | |
| Main_RecrDev_2006 | 1.4560 | 1 | (-5,5) | act | 0.2050 | |
| Main_RecrDev_2007 | 1.0072 | 1 | (-5,5) | act | 0.2283 | |
| Main_RecrDev_2008 | 1.4632 | 1 | (-5,5) | act | 0.1849 | |
| Main_RecrDev_2009 | 1.8011 | 1 | (-5,5) | act | 0.1789 | |
| Main_RecrDev_2010 | -0.9227 | 1 | (-5,5) | act | 0.3977 | |
| Main_RecrDev_2011 | -2.2276 | 1 | (-5,5) | act | 0.5541 | |
| Main_RecrDev_2012 | -1.9523 | 1 | (-5,5) | act | 0.4606 | |
| Main_RecrDev_2013 | -0.7155 | 1 | (-5,5) | act | 0.3710 | |
| Main_RecrDev_2014 | -0.0076 | 1 | (-5,5) | act | 0.2588 | |
| Main_RecrDev_2015 | -1.2365 | 1 | (-5,5) | act | 0.3994 | |
| Main_RecrDev_2016 | -0.6804 | 1 | (-5,5) | act | 0.4081 | |
| Main_RecrDev_2017 | 0.0057 | 1 | (-5,5) | act | 0.3347 | |
| Main_RecrDev_2018 | -0.1961 | 1 | (-5,5) | act | 0.5527 | |
| Main_RecrDev_2019 | 0.6166 | 1 | (-5,5) | act | 0.3124 | |
| Main_RecrDev_2020 | 0.3175 | 1 | (-5,5) | act | 0.3679 | |
| Main_RecrDev_2021 | -0.5436 | 1 | (-5,5) | act | 0.5359 | |
| Main_RecrDev_2022 | -0.4460 | 1 | (-5,5) | act | 0.9409 | |
| Main_RecrDev_2023 | 0.0907 | 1 | (-5,5) | act | 1.1698 | |
| ForeRecr_2024 | 0.0000 | 5 | (-5,5) | act | 1.2000 | |
| InitF_seas_1_flt_1MexCal_S1 | 2.2850 | 1 | (0,3) | OK | 0.5218 | |
| AgeSel_P1_MexCal_S1(1) | 1.0001 | 3 | (-7,9) | OK | 178.8820 | |
| AgeSel_P2_MexCal_S1(1) | 2.5835 | 3 | (-7,9) | OK | 0.5590 | |
| AgeSel_P3_MexCal_S1(1) | 1.0688 | 3 | (-7,9) | OK | 0.3212 | |
| AgeSel_P4_MexCal_S1(1) | -1.3824 | 3 | (-7,9) | OK | 0.5267 | |
| AgeSel_P5_MexCal_S1(1) | -0.3427 | 3 | (-7,9) | OK | 0.7132 | |
| AgeSel_P6_MexCal_S1(1) | -1.0407 | 3 | (-7,9) | OK | 1.9958 | |
| AgeSel_P7_MexCal_S1(1) | 0.0412 | 3 | (-7,9) | OK | 2.7585 | |
| AgeSel_P8_MexCal_S1(1) | -1.7151 | 3 | (-7,9) | OK | 6.0134 | |
| AgeSel_P9_MexCal_S1(1) | -0.3541 | 3 | (-7,9) | OK | 7.3679 | |
| AgeSel_P2_MexCal_S2(2) | 0.5184 | 3 | (-7,9) | OK | 0.2629 | |
| AgeSel_P3_MexCal_S2(2) | -0.5291 | 3 | (-7,9) | OK | 0.3383 | |
| AgeSel_P4_MexCal_S2(2) | -0.7904 | 3 | (-7,9) | OK | 0.5703 | |
| AgeSel_P5_MexCal_S2(2) | -0.1854 | 3 | (-7,9) | OK | 0.7508 | |

| Parameter | Value | Phase | Bounds | Status | SD | Prior (Exp.Val, SD) |
|---|---|---|---|---|---|---|
| AgeSel_P6_MexCal_S2(2) | 0.4017 | 3 | (-7,9) | OK | 0.7444 | |
| AgeSel_P7_MexCal_S2(2) | -0.7698 | 3 | (-7,9) | OK | 1.0275 | |
| AgeSel_P8_MexCal_S2(2) | -0.0762 | 3 | (-7,9) | OK | 1.6875 | |
| AgeSel_P9_MexCal_S2(2) | -1.8795 | 3 | (-7,9) | OK | 4.5502 | |
| Age_inflection_PNW(3) | 2.4062 | 4 | (0,10) | OK | 0.1646 | |
| Age_95%width_PNW(3) | 0.6396 | 4 | (-5,15) | OK | 0.1582 | |
| AgeSel_P2_AT_Survey(4) | 0.0009 | 4 | (0,9) | LO | 0.0300 | |
| AgeSel_P2_Lisa_Marie(5) | 8.1542 | 4 | (0,9) | OK | 20.1129 | |
| Age_inflection_PNW(3)_BLK3repl_2006 | 3.1794 | 4 | (0,10) | OK | 0.1974 | |
| Age_inflection_PNW(3)_BLK3repl_2007 | 3.0876 | 4 | (0,10) | OK | 0.1268 | |
| Age_inflection_PNW(3)_BLK3repl_2008 | 3.5674 | 4 | (0,10) | OK | 0.1961 | |
| Age_inflection_PNW(3)_BLK3repl_2009 | 4.1412 | 4 | (0,10) | OK | 0.1201 | |
| Age_inflection_PNW(3)_BLK3repl_2010 | 3.9530 | 4 | (0,10) | OK | 0.2723 | |
| Age_inflection_PNW(3)_BLK3repl_2011 | 3.2149 | 4 | (0,10) | OK | 0.2103 | |
| Age_inflection_PNW(3)_BLK3repl_2012 | 2.2163 | 4 | (0,10) | OK | 0.0978 | |
| Age_inflection_PNW(3)_BLK3repl_2013 | 2.8442 | 4 | (0,10) | OK | 0.1741 | |
| Age_inflection_PNW(3)_BLK3repl_2014 | 3.5581 | 4 | (0,10) | OK | 0.3391 | |
| AgeSel_P2_AT_Survey(4)_BLK2repl_2007 | 2.5299 | 4 | (0,9) | OK | 7.8468 | |
| AgeSel_P2_AT_Survey(4)_BLK2repl_2008 | 2.3518 | 4 | (0,9) | OK | 1.7277 | |
| AgeSel_P2_AT_Survey(4)_BLK2repl_2009 | 6.5159 | 4 | (0,9) | OK | 47.9241 | |
| AgeSel_P2_AT_Survey(4)_BLK2repl_2010 | 0.0044 | 4 | (0,9) | LO | 0.1389 | |
| AgeSel_P2_AT_Survey(4)_BLK2repl_2011 | 0.0045 | 4 | (0,9) | LO | 0.1453 | |
| AgeSel_P2_AT_Survey(4)_BLK2repl_2012 | 7.4888 | 4 | (0,9) | OK | 31.8811 | |
| AgeSel_P2_AT_Survey(4)_BLK2repl_2013 | 8.1073 | 4 | (0,9) | OK | 21.0056 | |
| AgeSel_P2_AT_Survey(4)_BLK2repl_2014 | 8.5844 | 4 | (0,9) | OK | 11.1169 | |
| AgeSel_P2_AT_Survey(4)_BLK2repl_2015 | 0.0003 | 4 | (0,9) | LO | 0.0133 | |
| AgeSel_P2_AT_Survey(4)_BLK2repl_2016 | 8.1522 | 4 | (0,9) | OK | 20.1496 | |
| AgeSel_P2_AT_Survey(4)_BLK2repl_2017 | 0.4059 | 4 | (0,9) | OK | 0.6312 | |
| AgeSel_P2_AT_Survey(4)_BLK2repl_2018 | 1.1399 | 4 | (0,9) | OK | 0.6185 | |
| AgeSel_P2_AT_Survey(4)_BLK2repl_2019 | 8.4368 | 4 | (0,9) | OK | 14.3571 | |
| AgeSel_P2_AT_Survey(4)_BLK2repl_2021 | 8.5390 | 4 | (0,9) | OK | 12.1327 | |
| AgeSel_P2_AT_Survey(4)_BLK2repl_2022 | 4.7590 | 4 | (0,9) | OK | 5.7092 | |
| AgeSel_P2_AT_Survey(4)_BLK2repl_2023 | 2.3982 | 4 | (0,9) | OK | 1.6108 | |
| MexCal_S1_ARDEV_y2006_A0 | -0.5384 | 3 | (-10,10) | act | 0.8405 | |
| MexCal_S1_ARDEV_y2006_A1 | 0.9243 | 3 | (-10,10) | act | 0.6323 | |
| MexCal_S1_ARDEV_y2006_A2 | -0.2046 | 3 | (-10,10) | act | 0.6498 | |
| MexCal_S1_ARDEV_y2006_A3 | -0.1072 | 3 | (-10,10) | act | 0.7892 | |
| MexCal_S1_ARDEV_y2007_A0 | 0.3151 | 3 | (-10,10) | act | 0.7695 | |
| MexCal_S1_ARDEV_y2007_A1 | -0.0175 | 3 | (-10,10) | act | 0.6009 | |
| MexCal_S1_ARDEV_y2007_A2 | 0.2969 | 3 | (-10,10) | act | 0.5701 | |
| MexCal_S1_ARDEV_y2007_A3 | 0.2513 | 3 | (-10,10) | act | 0.7626 | |
| MexCal_S1_ARDEV_y2008_A0 | 0.2385 | 3 | (-10,10) | act | 1.0011 | |
| MexCal_S1_ARDEV_y2008_A1 | 0.5104 | 3 | (-10,10) | act | 0.7404 | |
| MexCal_S1_ARDEV_y2008_A2 | 0.7987 | 3 | (-10,10) | act | 0.6250 | |
| MexCal_S1_ARDEV_y2008_A3 | -0.6322 | 3 | (-10,10) | act | 0.8192 | |
| MexCal_S1_ARDEV_y2009_A0 | -0.3534 | 3 | (-10,10) | act | 0.8774 | |
| MexCal_S1_ARDEV_y2009_A1 | -0.1210 | 3 | (-10,10) | act | 0.8308 | |

| Parameter | Value | Phase | Bounds | Status | SD | Prior (Exp.Val, SD) |
|---|---|---|---|---|---|---|
| MexCal_S1_ARDEV_y2009_A2 | 1.6597 | 3 | (-10,10) | act | 0.6685 | |
| MexCal_S1_ARDEV_y2009_A3 | -0.1597 | 3 | (-10,10) | act | 0.9147 | |
| MexCal_S1_ARDEV_y2010_A0 | -0.3697 | 3 | (-10,10) | act | 0.8666 | |
| MexCal_S1_ARDEV_y2010_A1 | 1.1664 | 3 | (-10,10) | act | 0.6757 | |
| MexCal_S1_ARDEV_y2010_A2 | -0.0908 | 3 | (-10,10) | act | 0.7572 | |
| MexCal_S1_ARDEV_y2010_A3 | -0.0759 | 3 | (-10,10) | act | 0.9152 | |
| MexCal_S1_ARDEV_y2011_A0 | -0.1124 | 3 | (-10,10) | act | 0.9517 | |
| MexCal_S1_ARDEV_y2011_A1 | -0.5088 | 3 | (-10,10) | act | 0.6419 | |
| MexCal_S1_ARDEV_y2011_A2 | 0.0414 | 3 | (-10,10) | act | 0.6357 | |
| MexCal_S1_ARDEV_y2011_A3 | 1.1912 | 3 | (-10,10) | act | 0.7540 | |
| MexCal_S1_ARDEV_y2012_A0 | -0.0276 | 3 | (-10,10) | act | 0.9749 | |
| MexCal_S1_ARDEV_y2012_A1 | 0.3842 | 3 | (-10,10) | act | 0.7604 | |
| MexCal_S1_ARDEV_y2012_A2 | -1.1196 | 3 | (-10,10) | act | 0.6569 | |
| MexCal_S1_ARDEV_y2012_A3 | 0.8396 | 3 | (-10,10) | act | 0.7242 | |
| MexCal_S1_ARDEV_y2013_A0 | -0.0069 | 3 | (-10,10) | act | 0.9224 | |
| MexCal_S1_ARDEV_y2013_A1 | -0.4211 | 3 | (-10,10) | act | 0.8455 | |
| MexCal_S1_ARDEV_y2013_A2 | -0.6830 | 3 | (-10,10) | act | 0.7541 | |
| MexCal_S1_ARDEV_y2013_A3 | -0.8130 | 3 | (-10,10) | act | 0.7669 | |
| MexCal_S1_ARDEV_y2014_A0 | -0.5566 | 3 | (-10,10) | act | 0.8485 | |
| MexCal_S1_ARDEV_y2014_A1 | -0.8463 | 3 | (-10,10) | act | 0.8082 | |
| MexCal_S1_ARDEV_y2014_A2 | -0.8780 | 3 | (-10,10) | act | 0.8262 | |
| MexCal_S1_ARDEV_y2014_A3 | -0.2533 | 3 | (-10,10) | act | 0.8771 | |
| MexCal_S1_ARDEV_y2015_A0 | 0.0002 | 3 | (-10,10) | act | 1.0001 | |
| MexCal_S1_ARDEV_y2015_A1 | -0.0001 | 3 | (-10,10) | act | 1.0000 | |
| MexCal_S1_ARDEV_y2015_A2 | -0.0005 | 3 | (-10,10) | act | 0.9999 | |
| MexCal_S1_ARDEV_y2015_A3 | 0.0000 | 3 | (-10,10) | act | 1.0000 | |
| MexCal_S1_ARDEV_y2016_A0 | -0.0001 | 3 | (-10,10) | act | 1.0000 | |
| MexCal_S1_ARDEV_y2016_A1 | -0.0076 | 3 | (-10,10) | act | 0.9991 | |
| MexCal_S1_ARDEV_y2016_A2 | 0.0074 | 3 | (-10,10) | act | 0.9998 | |
| MexCal_S1_ARDEV_y2016_A3 | -0.0017 | 3 | (-10,10) | act | 0.9992 | |
| MexCal_S1_ARDEV_y2017_A0 | 0.0007 | 3 | (-10,10) | act | 1.0003 | |
| MexCal_S1_ARDEV_y2017_A1 | -0.0047 | 3 | (-10,10) | act | 0.9981 | |
| MexCal_S1_ARDEV_y2017_A2 | 0.0005 | 3 | (-10,10) | act | 0.9999 | |
| MexCal_S1_ARDEV_y2017_A3 | 0.0031 | 3 | (-10,10) | act | 1.0013 | |
| MexCal_S1_ARDEV_y2018_A0 | 0.0005 | 3 | (-10,10) | act | 1.0002 | |
| MexCal_S1_ARDEV_y2018_A1 | 0.0011 | 3 | (-10,10) | act | 1.0002 | |
| MexCal_S1_ARDEV_y2018_A2 | -0.0028 | 3 | (-10,10) | act | 0.9996 | |
| MexCal_S1_ARDEV_y2018_A3 | 0.0007 | 3 | (-10,10) | act | 1.0002 | |
| MexCal_S1_ARDEV_y2019_A0 | 0.0008 | 3 | (-10,10) | act | 1.0004 | |
| MexCal_S1_ARDEV_y2019_A1 | 0.0035 | 3 | (-10,10) | act | 1.0003 | |
| MexCal_S1_ARDEV_y2019_A2 | -0.0034 | 3 | (-10,10) | act | 0.9997 | |
| MexCal_S1_ARDEV_y2019_A3 | -0.0013 | 3 | (-10,10) | act | 0.9994 | |
| MexCal_S1_ARDEV_y2020_A0 | 0.0011 | 3 | (-10,10) | act | 1.0005 | |
| MexCal_S1_ARDEV_y2020_A1 | 0.0072 | 3 | (-10,10) | act | 1.0019 | |
| MexCal_S1_ARDEV_y2020_A2 | -0.0037 | 3 | (-10,10) | act | 1.0004 | |
| MexCal_S1_ARDEV_y2020_A3 | -0.0028 | 3 | (-10,10) | act | 0.9988 | |
| MexCal_S1_ARDEV_y2021_A0 | 0.3380 | 3 | (-10,10) | act | 0.9285 | |

| Parameter | Value | Phase | Bounds | Status | SD | Prior (Exp.Val, SD) |
|---|---|---|---|---|---|---|
| MexCal_S1_ARDEV_y2021_A1 | 0.4134 | 3 | (-10,10) | act | 0.8157 | |
| MexCal_S1_ARDEV_y2021_A2 | -0.5070 | 3 | (-10,10) | act | 0.8538 | |
| MexCal_S1_ARDEV_y2021_A3 | -0.1692 | 3 | (-10,10) | act | 0.9282 | |
| MexCal_S1_ARDEV_y2022_A0 | 0.0002 | 3 | (-10,10) | act | 1.0001 | |
| MexCal_S1_ARDEV_y2022_A1 | 0.0025 | 3 | (-10,10) | act | 1.0007 | |
| MexCal_S1_ARDEV_y2022_A2 | -0.0042 | 3 | (-10,10) | act | 1.0008 | |
| MexCal_S1_ARDEV_y2022_A3 | 0.0007 | 3 | (-10,10) | act | 1.0003 | |
| MexCal_S2_ARDEV_y2006_A0 | -0.3896 | 3 | (-10,10) | act | 0.5987 | |
| MexCal_S2_ARDEV_y2006_A1 | 0.4635 | 3 | (-10,10) | act | 0.5872 | |
| MexCal_S2_ARDEV_y2006_A2 | 0.2738 | 3 | (-10,10) | act | 0.6209 | |
| MexCal_S2_ARDEV_y2006_A3 | -0.2288 | 3 | (-10,10) | act | 0.7949 | |
| MexCal_S2_ARDEV_y2006_A4 | -0.0514 | 3 | (-10,10) | act | 0.9763 | |
| MexCal_S2_ARDEV_y2007_A0 | 0.8186 | 3 | (-10,10) | act | 0.5637 | |
| MexCal_S2_ARDEV_y2007_A1 | 0.3404 | 3 | (-10,10) | act | 0.5676 | |
| MexCal_S2_ARDEV_y2007_A2 | -0.4882 | 3 | (-10,10) | act | 0.6399 | |
| MexCal_S2_ARDEV_y2007_A3 | -0.2313 | 3 | (-10,10) | act | 0.8007 | |
| MexCal_S2_ARDEV_y2007_A4 | -0.3691 | 3 | (-10,10) | act | 0.8722 | |
| MexCal_S2_ARDEV_y2008_A0 | -0.1259 | 3 | (-10,10) | act | 0.6423 | |
| MexCal_S2_ARDEV_y2008_A1 | 1.2573 | 3 | (-10,10) | act | 0.5804 | |
| MexCal_S2_ARDEV_y2008_A2 | 0.4468 | 3 | (-10,10) | act | 0.7032 | |
| MexCal_S2_ARDEV_y2008_A3 | -0.3665 | 3 | (-10,10) | act | 0.8158 | |
| MexCal_S2_ARDEV_y2008_A4 | -0.4813 | 3 | (-10,10) | act | 0.8553 | |
| MexCal_S2_ARDEV_y2009_A0 | 0.9866 | 3 | (-10,10) | act | 0.5154 | |
| MexCal_S2_ARDEV_y2009_A1 | 1.5493 | 3 | (-10,10) | act | 0.5581 | |
| MexCal_S2_ARDEV_y2009_A2 | 0.5562 | 3 | (-10,10) | act | 0.7762 | |
| MexCal_S2_ARDEV_y2009_A3 | -0.5983 | 3 | (-10,10) | act | 0.8255 | |
| MexCal_S2_ARDEV_y2009_A4 | -0.8598 | 3 | (-10,10) | act | 0.8019 | |
| MexCal_S2_ARDEV_y2010_A0 | -0.9892 | 3 | (-10,10) | act | 0.5252 | |
| MexCal_S2_ARDEV_y2010_A1 | -0.8958 | 3 | (-10,10) | act | 0.5533 | |
| MexCal_S2_ARDEV_y2010_A2 | -0.8191 | 3 | (-10,10) | act | 0.7312 | |
| MexCal_S2_ARDEV_y2010_A3 | 0.2336 | 3 | (-10,10) | act | 0.7970 | |
| MexCal_S2_ARDEV_y2010_A4 | 0.7859 | 3 | (-10,10) | act | 0.7587 | |
| MexCal_S2_ARDEV_y2011_A0 | 0.1614 | 3 | (-10,10) | act | 0.6006 | |
| MexCal_S2_ARDEV_y2011_A1 | -1.5512 | 3 | (-10,10) | act | 0.4989 | |
| MexCal_S2_ARDEV_y2011_A2 | -0.2196 | 3 | (-10,10) | act | 0.5387 | |
| MexCal_S2_ARDEV_y2011_A3 | 0.6232 | 3 | (-10,10) | act | 0.6900 | |
| MexCal_S2_ARDEV_y2011_A4 | 0.5230 | 3 | (-10,10) | act | 0.7874 | |
| MexCal_S2_ARDEV_y2012_A0 | -0.2976 | 3 | (-10,10) | act | 0.8841 | |
| MexCal_S2_ARDEV_y2012_A1 | -0.0369 | 3 | (-10,10) | act | 0.8051 | |
| MexCal_S2_ARDEV_y2012_A2 | -0.1234 | 3 | (-10,10) | act | 0.7283 | |
| MexCal_S2_ARDEV_y2012_A3 | 0.6052 | 3 | (-10,10) | act | 0.8720 | |
| MexCal_S2_ARDEV_y2012_A4 | 0.0796 | 3 | (-10,10) | act | 0.9786 | |
| MexCal_S2_ARDEV_y2013_A0 | -1.4006 | 3 | (-10,10) | act | 0.7497 | |
| MexCal_S2_ARDEV_y2013_A1 | -0.7156 | 3 | (-10,10) | act | 0.7716 | |
| MexCal_S2_ARDEV_y2013_A2 | 0.2154 | 3 | (-10,10) | act | 0.7260 | |
| MexCal_S2_ARDEV_y2013_A3 | 0.2939 | 3 | (-10,10) | act | 0.6698 | |
| MexCal_S2_ARDEV_y2013_A4 | 0.9663 | 3 | (-10,10) | act | 0.7854 | |

| Parameter | Value | Phase | Bounds | Status | SD | Prior (Exp.Val, SD) |
|---|---|---|---|---|---|---|
| MexCal_S2_ARDEV_y2014_A0 | -0.6253 | 3 | (-10,10) | act | 0.7052 | |
| MexCal_S2_ARDEV_y2014_A1 | 1.0091 | 3 | (-10,10) | act | 0.7345 | |
| MexCal_S2_ARDEV_y2014_A2 | 0.4746 | 3 | (-10,10) | act | 0.8721 | |
| MexCal_S2_ARDEV_y2014_A3 | -0.2671 | 3 | (-10,10) | act | 0.9086 | |
| MexCal_S2_ARDEV_y2014_A4 | -0.5550 | 3 | (-10,10) | act | 0.8409 | |
| MexCal_S2_ARDEV_y2015_A0 | 0.0001 | 3 | (-10,10) | act | 1.0000 | |
| MexCal_S2_ARDEV_y2015_A1 | -0.0001 | 3 | (-10,10) | act | 1.0000 | |
| MexCal_S2_ARDEV_y2015_A2 | 0.0000 | 3 | (-10,10) | act | 1.0000 | |
| MexCal_S2_ARDEV_y2015_A3 | 0.0000 | 3 | (-10,10) | act | 1.0000 | |
| MexCal_S2_ARDEV_y2015_A4 | 0.0000 | 3 | (-10,10) | act | 1.0000 | |
| MexCal_S2_ARDEV_y2016_A0 | 0.0006 | 3 | (-10,10) | act | 1.0002 | |
| MexCal_S2_ARDEV_y2016_A1 | -0.0048 | 3 | (-10,10) | act | 1.0005 | |
| MexCal_S2_ARDEV_y2016_A2 | 0.0023 | 3 | (-10,10) | act | 1.0008 | |
| MexCal_S2_ARDEV_y2016_A3 | -0.0006 | 3 | (-10,10) | act | 0.9997 | |
| MexCal_S2_ARDEV_y2016_A4 | -0.0002 | 3 | (-10,10) | act | 0.9999 | |
| MexCal_S2_ARDEV_y2017_A0 | 0.0128 | 3 | (-10,10) | act | 1.0025 | |
| MexCal_S2_ARDEV_y2017_A1 | -0.0154 | 3 | (-10,10) | act | 0.9956 | |
| MexCal_S2_ARDEV_y2017_A2 | -0.0025 | 3 | (-10,10) | act | 0.9996 | |
| MexCal_S2_ARDEV_y2017_A3 | 0.0028 | 3 | (-10,10) | act | 1.0012 | |
| MexCal_S2_ARDEV_y2017_A4 | -0.0001 | 3 | (-10,10) | act | 0.9999 | |
| MexCal_S2_ARDEV_y2018_A0 | 0.0246 | 3 | (-10,10) | act | 1.0005 | |
| MexCal_S2_ARDEV_y2018_A1 | -0.0066 | 3 | (-10,10) | act | 0.9986 | |
| MexCal_S2_ARDEV_y2018_A2 | -0.0169 | 3 | (-10,10) | act | 0.9929 | |
| MexCal_S2_ARDEV_y2018_A3 | -0.0026 | 3 | (-10,10) | act | 0.9989 | |
| MexCal_S2_ARDEV_y2018_A4 | 0.0006 | 3 | (-10,10) | act | 1.0003 | |
| MexCal_S2_ARDEV_y2019_A0 | 0.0082 | 3 | (-10,10) | act | 1.0015 | |
| MexCal_S2_ARDEV_y2019_A1 | -0.0024 | 3 | (-10,10) | act | 0.9999 | |
| MexCal_S2_ARDEV_y2019_A2 | -0.0044 | 3 | (-10,10) | act | 0.9983 | |
| MexCal_S2_ARDEV_y2019_A3 | -0.0018 | 3 | (-10,10) | act | 0.9992 | |
| MexCal_S2_ARDEV_y2019_A4 | -0.0009 | 3 | (-10,10) | act | 0.9996 | |
| MexCal_S2_ARDEV_y2020_A0 | -0.0620 | 3 | (-10,10) | act | 0.7490 | |
| MexCal_S2_ARDEV_y2020_A1 | 0.4426 | 3 | (-10,10) | act | 0.7940 | |
| MexCal_S2_ARDEV_y2020_A2 | -0.2082 | 3 | (-10,10) | act | 0.8667 | |
| MexCal_S2_ARDEV_y2020_A3 | -0.0288 | 3 | (-10,10) | act | 0.9664 | |
| MexCal_S2_ARDEV_y2020_A4 | -0.0265 | 3 | (-10,10) | act | 0.9872 | |
| MexCal_S2_ARDEV_y2021_A0 | 0.7109 | 3 | (-10,10) | act | 0.9512 | |
| MexCal_S2_ARDEV_y2021_A1 | -0.7365 | 3 | (-10,10) | act | 0.8716 | |
| MexCal_S2_ARDEV_y2021_A2 | 0.0071 | 3 | (-10,10) | act | 1.0016 | |
| MexCal_S2_ARDEV_y2021_A3 | 0.0149 | 3 | (-10,10) | act | 1.0059 | |
| MexCal_S2_ARDEV_y2021_A4 | 0.0020 | 3 | (-10,10) | act | 1.0008 | |
| MexCal_S2_ARDEV_y2022_A0 | 0.8462 | 3 | (-10,10) | act | 0.8161 | |
| MexCal_S2_ARDEV_y2022_A1 | -0.3343 | 3 | (-10,10) | act | 0.8475 | |
| MexCal_S2_ARDEV_y2022_A2 | -0.3712 | 3 | (-10,10) | act | 0.8807 | |
| MexCal_S2_ARDEV_y2022_A3 | -0.0645 | 3 | (-10,10) | act | 0.9716 | |
| MexCal_S2_ARDEV_y2022_A4 | -0.0432 | 3 | (-10,10) | act | 0.9800 | |

Table 7.13: Pacific sardine numbers-at-age (thousands) for model year-semesters.

| Calendar Y-S | Model Y-S | Age0 | Age1 | Age2 | Age3 | Age4 | Age5 | Age6 | Age7 | Age8 | Age9 | Age10+ |
|---|---|---:|---:|---:|---:|---:|---:|---:|---:|---:|---:|---:|
| -- | VIRG | 2,047,300 | 858,915 | 444,274 | 252,742 | 151,048 | 92,869 | 58,093 | 36,738 | 23,396 | 14,968 | 26,966 |
| -- | VIRG | 1,295,830 | 613,345 | 335,118 | 195,971 | 118,960 | 73,832 | 46,458 | 29,491 | 18,828 | 12,065 | 21,774 |
| -- | INIT | 26,679,800 | 10,866,300 | 3,796,420 | 688,989 | 309,117 | 155,052 | 90,263 | 52,962 | 33,277 | 21,089 | 37,006 |
| -- | INIT | 16,393,800 | 5,241,170 | 913,552 | 401,049 | 198,613 | 114,717 | 66,974 | 41,946 | 26,527 | 16,838 | 29,599 |
| 2005-2 | 2005-1 | 26,679,800 | 9,410,570 | 4,787,820 | 291,797 | 150,779 | 65,223 | 42,928 | 52,962 | 33,277 | 21,089 | 37,006 |
| 2006-1 | 2005-2 | 16,871,100 | 6,633,500 | 3,268,990 | 142,934 | 73,068 | 32,027 | 21,202 | 26,307 | 16,572 | 10,520 | 18,491 |
| 2006-2 | 2006-1 | 10,391,200 | 11,015,900 | 4,685,220 | 2,428,610 | 109,287 | 56,645 | 24,956 | 16,678 | 20,767 | 13,150 | 23,074 |
| 2007-1 | 2006-2 | 6,573,820 | 7,647,620 | 3,435,500 | 1,654,930 | 57,873 | 30,126 | 13,348 | 8,970 | 11,198 | 7,102 | 12,485 |
| 2007-2 | 2007-1 | 5,118,170 | 4,288,210 | 5,201,240 | 2,512,660 | 1,264,870 | 44,804 | 23,394 | 10,492 | 7,076 | 8,895 | 15,596 |
| 2008-1 | 2007-2 | 3,229,270 | 2,971,360 | 3,474,410 | 1,727,640 | 783,012 | 28,193 | 14,804 | 6,696 | 4,529 | 5,702 | 10,015 |
| 2008-2 | 2008-1 | 3,258,840 | 1,967,450 | 1,971,510 | 2,561,870 | 1,314,100 | 605,446 | 21,728 | 11,595 | 5,265 | 3,596 | 12,508 |
| 2009-1 | 2008-2 | 2,057,350 | 1,343,300 | 1,249,060 | 1,939,070 | 855,928 | 392,271 | 14,154 | 7,614 | 3,467 | 2,372 | 8,264 |
| 2009-2 | 2009-1 | 5,104,120 | 1,310,410 | 745,176 | 878,443 | 1,473,710 | 661,278 | 300,980 | 11,063 | 5,975 | 2,752 | 8,463 |
| 2010-1 | 2009-2 | 3,227,830 | 922,291 | 437,591 | 673,167 | 1,037,770 | 389,902 | 177,491 | 6,565 | 3,555 | 1,640 | 5,053 |
| 2010-2 | 2010-1 | 7,054,870 | 1,959,280 | 515,425 | 311,863 | 514,638 | 802,299 | 297,317 | 137,329 | 5,099 | 2,786 | 5,257 |
| 2011-1 | 2010-2 | 4,464,430 | 1,381,600 | 384,737 | 240,171 | 335,431 | 455,807 | 169,453 | 78,612 | 2,926 | 1,601 | 3,027 |
| 2011-2 | 2011-1 | 454,991 | 2,866,320 | 943,638 | 279,516 | 176,336 | 244,126 | 341,921 | 131,069 | 61,101 | 2,319 | 3,677 |
| 2012-1 | 2011-2 | 286,706 | 1,967,280 | 582,043 | 169,449 | 97,974 | 138,814 | 195,455 | 75,988 | 35,535 | 1,351 | 2,146 |
| 2012-2 | 2012-1 | 121,228 | 160,735 | 1,354,500 | 391,886 | 113,572 | 64,968 | 93,548 | 138,141 | 54,025 | 26,060 | 2,570 |
| 2013-1 | 2012-2 | 76,678 | 112,972 | 834,389 | 148,610 | 43,388 | 25,125 | 36,389 | 54,015 | 21,179 | 10,232 | 1,011 |
| 2013-2 | 2013-1 | 148,780 | 50,399 | 80,340 | 619,451 | 111,108 | 32,992 | 19,223 | 28,075 | 41,818 | 16,469 | 8,756 |
| 2014-1 | 2013-2 | 94,032 | 35,527 | 58,051 | 295,434 | 42,575 | 12,801 | 7,501 | 11,031 | 16,474 | 6,498 | 3,461 |
| 2014-2 | 2014-1 | 440,649 | 60,393 | 23,169 | 37,405 | 207,922 | 28,724 | 9,188 | 5,622 | 8,314 | 12,770 | 7,735 |
| 2015-1 | 2014-2 | 277,848 | 41,531 | 15,708 | 26,739 | 105,834 | 14,452 | 4,644 | 2,892 | 4,291 | 6,601 | 4,006 |
| 2015-2 | 2015-1 | 709,515 | 180,477 | 25,274 | 11,155 | 20,189 | 74,515 | 9,999 | 3,266 | 2,042 | 3,059 | 7,577 |
| 2016-1 | 2015-2 | 449,074 | 128,839 | 19,048 | 8,645 | 15,851 | 59,040 | 7,969 | 2,613 | 1,637 | 2,458 | 6,098 |
| 2016-2 | 2016-1 | 195,692 | 297,650 | 93,319 | 14,365 | 6,663 | 12,373 | 46,450 | 6,302 | 2,073 | 1,302 | 6,818 |
| 2017-1 | 2016-2 | 123,796 | 211,049 | 68,931 | 11,070 | 5,170 | 9,699 | 36,624 | 4,993 | 1,646 | 1,036 | 5,434 |
| 2017-2 | 2017-1 | 349,790 | 81,693 | 151,746 | 51,759 | 8,516 | 4,029 | 7,613 | 28,929 | 3,957 | 1,309 | 5,156 |
| 2018-1 | 2017-2 | 221,333 | 58,111 | 113,173 | 40,018 | 6,693 | 3,201 | 6,083 | 23,216 | 3,184 | 1,055 | 4,163 |
| 2018-2 | 2018-1 | 682,832 | 145,700 | 41,622 | 84,783 | 30,750 | 5,210 | 2,508 | 4,800 | 18,384 | 2,530 | 4,156 |
| 2019-1 | 2018-2 | 432,153 | 103,908 | 31,278 | 65,673 | 24,186 | 4,138 | 2,004 | 3,850 | 14,782 | 2,037 | 3,354 |
| 2019-2 | 2019-1 | 554,469 | 282,243 | 73,477 | 23,261 | 50,292 | 18,775 | 3,229 | 1,578 | 3,043 | 11,743 | 4,292 |
| 2020-1 | 2019-2 | 350,795 | 200,377 | 54,499 | 17,959 | 39,468 | 14,901 | 2,578 | 1,266 | 2,447 | 9,458 | 3,463 |
| 2020-2 | 2020-1 | 1,296,340 | 230,271 | 142,820 | 40,714 | 13,783 | 30,701 | 11,662 | 2,033 | 1,002 | 1,945 | 10,287 |
| 2021-1 | 2020-2 | 820,002 | 163,086 | 105,205 | 31,381 | 10,808 | 24,370 | 9,311 | 1,632 | 806 | 1,567 | 8,305 |
| 2021-2 | 2021-1 | 1,021,860 | 541,747 | 117,062 | 79,120 | 24,146 | 8,425 | 19,134 | 7,355 | 1,293 | 641 | 7,867 |

| Calendar Y-S | Model Y-S | Age0 | Age1 | Age2 | Age3 | Age4 | Age5 | Age6 | Age7 | Age8 | Age9 | Age10+ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2022-1 | 2021-2 | 646,689 | 386,095 | 88,092 | 61,268 | 18,994 | 6,693 | 15,290 | 5,901 | 1,040 | 516 | 6,348 |
| 2022-2 | 2022-1 | 501,355 | 310,189 | 246,129 | 56,710 | 43,926 | 13,973 | 4,820 | 11,605 | 4,507 | 822 | 5,441 |
| 2023-1 | 2022-2 | 317,280 | 221,043 | 184,531 | 43,889 | 34,544 | 11,100 | 3,852 | 9,312 | 3,625 | 662 | 4,391 |
| 2023-2 | 2023-1 | 734,804 | 207,437 | 158,982 | 138,612 | 33,745 | 26,911 | 8,705 | 3,041 | 7,377 | 2,881 | 4,028 |
| 2024-1 | 2023-2 | 465,004 | 147,766 | 119,066 | 107,280 | 26,541 | 21,384 | 6,958 | 2,441 | 5,936 | 2,322 | 3,252 |
| 2024-2 | 2024-1 | 1,678,330 | 308,218 | 107,034 | 89,798 | 82,688 | 20,720 | 16,826 | 5,502 | 1,937 | 4,719 | 4,442 |
| 2025-1 | 2024-2 | 1,062,160 | 219,719 | 80,333 | 69,540 | 65,064 | 16,467 | 13,451 | 4,417 | 1,558 | 3,804 | 3,586 |

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Table 7.14: Pacific sardine biomass-at-age for the base model year-semesters.

| Calendar Y-S | Model Y-S | Age0 | Age1 | Age2 | Age3 | Age4 | Age5 | Age6 | Age7 | Age8 | Age9 | Age10+ | Total Age0+ | Total Age1+ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -- | VIRG | 25,591 | 38,222 | 32,610 | 32,300 | 21,796 | 15,565 | 10,329 | 7,054 | 4,686 | 2,907 | 5,380 | 196,440 | 170,849 |
| -- | VIRG | 75,676 | 41,524 | 25,335 | 17,618 | 12,646 | 9,458 | 7,508 | 5,892 | 3,675 | 2,062 | 3,721 | 205,114 | 129,438 |
| -- | INIT | 333,497 | 483,551 | 278,657 | 88,053 | 44,606 | 25,987 | 16,049 | 10,169 | 6,665 | 4,096 | 7,383 | 1,298,711 | 965,214 |
| -- | INIT | 957,400 | 354,827 | 69,064 | 36,054 | 21,113 | 14,695 | 10,823 | 8,381 | 5,178 | 2,878 | 5,058 | 1,485,472 | 528,072 |
| 2005-2 | 2005-1 | 333,497 | 418,770 | 351,426 | 37,292 | 21,758 | 10,931 | 7,633 | 10,169 | 6,665 | 4,096 | 7,383 | 1,209,618 | 876,121 |
| 2006-1 | 2005-2 | 985,274 | 449,088 | 247,136 | 12,850 | 7,767 | 4,103 | 3,426 | 5,256 | 3,235 | 1,798 | 3,160 | 1,723,093 | 737,819 |
| 2006-2 | 2006-1 | 129,890 | 620,196 | 351,392 | 198,417 | 14,349 | 8,531 | 4,377 | 3,074 | 3,993 | 2,634 | 4,603 | 1,341,457 | 1,211,567 |
| 2007-1 | 2006-2 | 383,911 | 517,744 | 259,724 | 148,778 | 6,152 | 3,859 | 2,157 | 1,792 | 2,186 | 1,214 | 2,134 | 1,329,651 | 945,740 |
| 2007-2 | 2007-1 | 63,977 | 193,398 | 366,687 | 243,477 | 125,981 | 6,040 | 3,671 | 1,934 | 1,347 | 1,727 | 3,124 | 1,011,362 | 947,385 |
| 2008-1 | 2007-2 | 226,695 | 239,492 | 319,646 | 194,878 | 100,147 | 3,860 | 2,148 | 1,033 | 905 | 1,113 | 1,473 | 1,091,389 | 864,694 |
| 2008-2 | 2008-1 | 49,860 | 173,726 | 205,234 | 318,697 | 177,403 | 85,126 | 3,055 | 1,630 | 996 | 684 | 2,429 | 1,018,841 | 968,981 |
| 2009-1 | 2008-2 | 144,426 | 108,270 | 114,914 | 218,727 | 109,473 | 53,702 | 2,054 | 1,174 | 530 | 474 | 1,613 | 755,357 | 610,931 |
| 2009-2 | 2009-1 | 63,802 | 58,444 | 66,321 | 103,832 | 185,246 | 83,586 | 41,174 | 1,711 | 1,137 | 534 | 1,688 | 607,475 | 543,674 |
| 2010-1 | 2009-2 | 128,790 | 81,530 | 52,380 | 92,964 | 152,241 | 59,421 | 28,026 | 1,078 | 581 | 261 | 1,010 | 598,282 | 469,492 |
| 2010-2 | 2010-1 | 88,186 | 94,046 | 36,492 | 33,931 | 69,373 | 109,754 | 41,684 | 20,091 | 970 | 541 | 1,049 | 496,117 | 407,931 |
| 2011-1 | 2010-2 | 271,884 | 88,975 | 26,316 | 33,036 | 41,191 | 67,687 | 27,706 | 13,718 | 507 | 266 | 503 | 571,788 | 299,904 |
| 2011-2 | 2011-1 | 5,960 | 206,375 | 103,895 | 32,955 | 21,584 | 33,421 | 48,518 | 18,206 | 8,799 | 441 | 714 | 480,868 | 474,907 |
| 2012-1 | 2011-2 | 22,707 | 199,875 | 67,168 | 23,113 | 15,225 | 23,168 | 34,302 | 13,883 | 6,460 | 240 | 380 | 406,521 | 383,814 |
| 2012-2 | 2012-1 | 1,588 | 18,075 | 157,122 | 47,497 | 14,526 | 9,823 | 15,538 | 22,489 | 9,584 | 4,657 | 489 | 301,388 | 299,800 |
| 2013-1 | 2012-2 | 8,749 | 13,997 | 107,970 | 20,597 | 6,460 | 3,982 | 6,164 | 9,885 | 3,835 | 1,764 | 174 | 183,579 | 174,830 |
| 2013-2 | 2013-1 | 1,949 | 5,667 | 12,035 | 94,280 | 17,200 | 5,998 | 3,754 | 4,680 | 7,218 | 2,655 | 1,412 | 156,848 | 154,899 |
| 2014-1 | 2013-2 | 14,631 | 5,660 | 9,398 | 49,160 | 7,268 | 2,230 | 1,334 | 2,007 | 2,987 | 1,161 | 619 | 96,454 | 81,823 |
| 2014-2 | 2014-1 | 4,274 | 10,611 | 4,138 | 6,838 | 38,382 | 5,552 | 1,881 | 1,129 | 1,670 | 2,565 | 1,554 | 78,596 | 74,321 |
| 2015-1 | 2014-2 | 25,395 | 6,462 | 2,708 | 3,845 | 19,357 | 2,825 | 936 | 595 | 881 | 1,337 | 812 | 65,154 | 39,758 |
| 2015-2 | 2015-1 | 2,838 | 22,902 | 3,935 | 2,205 | 4,157 | 15,477 | 2,047 | 657 | 427 | 640 | 1,586 | 56,872 | 54,034 |
| 2016-1 | 2015-2 | 16,122 | 13,597 | 2,964 | 1,490 | 2,940 | 12,074 | 1,703 | 574 | 358 | 529 | 1,313 | 53,664 | 37,542 |
| 2016-2 | 2016-1 | 9,080 | 20,836 | 12,635 | 2,280 | 1,293 | 2,424 | 9,392 | 1,424 | 454 | 290 | 1,427 | 61,534 | 52,454 |
| 2017-1 | 2016-2 | 4,444 | 8,948 | 7,762 | 1,481 | 959 | 1,983 | 7,827 | 1,096 | 360 | 223 | 1,170 | 36,254 | 31,810 |
| 2017-2 | 2017-1 | 3,743 | 8,896 | 19,105 | 7,448 | 1,377 | 767 | 1,631 | 6,842 | 936 | 310 | 1,220 | 52,274 | 48,531 |
| 2018-1 | 2017-2 | 7,946 | 2,464 | 7,220 | 5,354 | 1,241 | 655 | 1,300 | 5,098 | 697 | 227 | 896 | 33,099 | 25,153 |
| 2018-2 | 2018-1 | 13,315 | 7,999 | 7,442 | 16,355 | 6,012 | 1,065 | 552 | 1,086 | 5,486 | 755 | 1,240 | 61,307 | 47,991 |
| 2019-1 | 2018-2 | 15,514 | 4,406 | 1,996 | 8,787 | 4,486 | 846 | 428 | 846 | 3,236 | 439 | 722 | 41,706 | 26,191 |
| 2019-2 | 2019-1 | 24,341 | 16,539 | 5,467 | 3,429 | 9,631 | 3,862 | 594 | 345 | 785 | 3,027 | 1,107 | 69,127 | 44,786 |
| 2020-1 | 2019-2 | 12,594 | 8,496 | 3,477 | 2,403 | 7,321 | 3,047 | 551 | 278 | 536 | 2,036 | 746 | 41,484 | 28,891 |
| 2020-2 | 2020-1 | 56,909 | 13,494 | 10,626 | 6,001 | 2,639 | 6,315 | 2,146 | 445 | 258 | 501 | 2,652 | 101,987 | 45,078 |
| 2021-1 | 2020-2 | 29,438 | 6,915 | 6,712 | 4,199 | 2,005 | 4,984 | 1,990 | 358 | 176 | 337 | 1,788 | 58,903 | 29,464 |

| Calendar Y-S | Model Y-S | Age0 | Age1 | Age2 | Age3 | Age4 | Age5 | Age6 | Age7 | Age8 | Age9 | Age10+ | Total Age0+ | Total Age1+ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2021-2 | 2021-1 | 54,874 | 52,712 | 20,018 | 15,057 | 5,781 | 2,180 | 4,785 | 1,972 | 322 | 159 | 1,958 | 159,818 | 104,944 |
| 2022-1 | 2021-2 | 23,216 | 16,370 | 5,620 | 8,198 | 3,523 | 1,369 | 3,267 | 1,296 | 228 | 111 | 1,367 | 64,565 | 41,349 |
| 2022-2 | 2022-1 | 12,083 | 16,533 | 15,678 | 4,316 | 4,441 | 2,456 | 878 | 2,231 | 948 | 176 | 1,170 | 60,909 | 48,826 |
| 2023-1 | 2022-2 | 11,390 | 9,372 | 11,773 | 5,872 | 6,408 | 2,270 | 823 | 2,045 | 794 | 143 | 945 | 51,836 | 40,445 |
| 2023-2 | 2023-1 | 6,172 | 13,732 | 13,227 | 12,198 | 3,280 | 4,230 | 1,631 | 662 | 1,754 | 685 | 958 | 58,530 | 52,357 |
| 2024-1 | 2023-2 | 16,694 | 6,265 | 7,596 | 14,354 | 4,923 | 4,373 | 1,487 | 536 | 1,299 | 500 | 700 | 58,728 | 42,034 |
| 2024-2 | 2024-1 | 14,098 | 20,404 | 8,905 | 7,902 | 8,037 | 3,257 | 3,151 | 1,197 | 461 | 1,122 | 1,056 | 69,592 | 55,494 |
| 2025-1 | 2024-2 | 38,131 | 9,316 | 5,125 | 9,304 | 12,069 | 3,368 | 2,875 | 970 | 341 | 819 | 772 | 83,091 | 44,959 |

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Table 7.15: Spawning stock biomas (SSB) and recruitment (1000s of fish) estimates and asymptotic standard errors for base model. SSB estimates were calculated at the beginning of semester 2 of each model year (January). Recruits were age-0 fish calculated at the beginning of each model year (July).

| Calendar Y-S | Model Y-S | SSB | SSB sd | Recruits | Recruits sd |
|---|---|---:|---:|---:|---:|
| -- | VIRG-1 | 0 | 0 | 0 | 0.0 |
| -- | VIRG-2 | 124,883 | 20,119 | 2,047,300 | 398,736.0 |
| -- | INIT-1 | 0 | 0 | 0 | 0.0 |
| -- | INIT-2 | 451,625 | 111,001 | 0 | 0.0 |
| 2005-2 | 2005-1 | 0 | 0 | 26,679,800 | 6,522,470.0 |
| 2006-1 | 2005-2 | 612,081 | 98,371 | 0 | 0.0 |
| 2006-2 | 2006-1 | 0 | 0 | 10,391,200 | 2,561,910.0 |
| 2007-1 | 2006-2 | 770,405 | 105,531 | 0 | 0.0 |
| 2007-2 | 2007-1 | 0 | 0 | 5,118,170 | 1,093,260.0 |
| 2008-1 | 2007-2 | 695,188 | 84,817 | 0 | 0.0 |
| 2008-2 | 2008-1 | 0 | 0 | 3,258,840 | 801,641.0 |
| 2009-1 | 2008-2 | 547,226 | 55,916 | 0 | 0.0 |
| 2009-2 | 2009-1 | 0 | 0 | 5,104,120 | 973,739.0 |
| 2010-1 | 2009-2 | 385,648 | 34,340 | 0 | 0.0 |
| 2010-2 | 2010-1 | 0 | 0 | 7,054,870 | 1,289,240.0 |
| 2011-1 | 2010-2 | 282,515 | 23,002 | 0 | 0.0 |
| 2011-2 | 2011-1 | 0 | 0 | 454,991 | 190,250.0 |
| 2012-1 | 2011-2 | 221,180 | 16,438 | 0 | 0.0 |
| 2012-2 | 2012-1 | 0 | 0 | 121,228 | 71,678.2 |
| 2013-1 | 2012-2 | 116,115 | 10,511 | 0 | 0.0 |
| 2013-2 | 2013-1 | 0 | 0 | 148,780 | 71,978.7 |
| 2014-1 | 2013-2 | 54,324 | 6,845 | 0 | 0.0 |
| 2014-2 | 2014-1 | 0 | 0 | 440,649 | 176,274.0 |
| 2015-1 | 2014-2 | 27,310 | 4,767 | 0 | 0.0 |
| 2015-2 | 2015-1 | 0 | 0 | 709,515 | 192,516.0 |
| 2016-1 | 2015-2 | 23,816 | 3,780 | 0 | 0.0 |
| 2016-2 | 2016-1 | 0 | 0 | 195,692 | 80,773.3 |
| 2017-1 | 2016-2 | 25,182 | 3,621 | 0 | 0.0 |
| 2017-2 | 2017-1 | 0 | 0 | 349,790 | 147,192.0 |
| 2018-1 | 2017-2 | 24,223 | 3,462 | 0 | 0.0 |
| 2018-2 | 2018-1 | 0 | 0 | 682,832 | 222,904.0 |
| 2019-1 | 2018-2 | 23,874 | 3,279 | 0 | 0.0 |
| 2019-2 | 2019-1 | 0 | 0 | 554,469 | 319,863.0 |
| 2020-1 | 2019-2 | 25,953 | 3,481 | 0 | 0.0 |
| 2020-2 | 2020-1 | 0 | 0 | 1,296,340 | 398,097.0 |
| 2021-1 | 2020-2 | 30,131 | 4,359 | 0 | 0.0 |
| 2021-2 | 2021-1 | 0 | 0 | 1,021,860 | 385,799.0 |
| 2022-1 | 2021-2 | 38,804 | 5,477 | 0 | 0.0 |
| 2022-2 | 2022-1 | 0 | 0 | 501,355 | 287,209.0 |
| 2023-1 | 2022-2 | 38,566 | 6,443 | 0 | 0.0 |
| 2023-2 | 2023-1 | 0 | 0 | 734,804 | 737,359.0 |
| 2024-1 | 2023-2 | 38,872 | 8,026 | 0 | 0.0 |
| 2024-2 | 2024-1 | 0 | 0 | 0 | 0.0 |
| 2025-1 | 2024-2 | 42,393 | 13,080 | 0 | 0.0 |

Table 7.16: Summary biomass (age-1+; mt) estimates and standard deviations (SD) from the base model arranged by model year-semester.

| Model Y-S | SummBio | SD |
|---|---:|---:|
| 2005-1 | 876,121 | 146,317 |
| 2006-1 | 1,211,570 | 185,670 |
| 2007-1 | 947,384 | 120,486 |
| 2008-1 | 968,981 | 105,511 |
| 2009-1 | 543,673 | 50,511 |
| 2010-1 | 407,931 | 33,723 |
| 2011-1 | 474,907 | 40,223 |
| 2012-1 | 299,800 | 21,798 |
| 2013-1 | 154,899 | 12,507 |
| 2014-1 | 74,321 | 9,557 |
| 2015-1 | 54,034 | 10,367 |
| 2016-1 | 52,454 | 7,927 |
| 2017-1 | 48,531 | 7,300 |
| 2018-1 | 47,991 | 7,246 |
| 2019-1 | 44,786 | 6,356 |
| 2020-1 | 45,078 | 8,426 |
| 2021-1 | 104,944 | 18,291 |
| 2022-1 | 48,826 | 8,780 |
| 2023-1 | 52,357 | 12,218 |
| 2024-1 | 55,494 | 22,998 |

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Table 7.17: Annual exploitation rate (calendar year landings / July total biomass) by country and calendar year.

| Calendar Year | MEX | USA | CAN | Total |
|---|---|---|---|---|
| 2005 | 0.00 | 0.05 | 0.00 | 0.06 |
| 2006 | 0.00 | 0.05 | 0.00 | 0.06 |
| 2007 | 0.02 | 0.11 | 0.00 | 0.13 |
| 2008 | 0.01 | 0.08 | 0.01 | 0.09 |
| 2009 | 0.01 | 0.11 | 0.03 | 0.14 |
| 2010 | 0.01 | 0.10 | 0.04 | 0.16 |
| 2011 | 0.04 | 0.09 | 0.04 | 0.17 |
| 2012 | 0.01 | 0.30 | 0.06 | 0.38 |
| 2013 | 0.00 | 0.39 | 0.00 | 0.39 |
| 2014 | 0.00 | 0.29 | 0.00 | 0.29 |
| 2015 | 0.00 | 0.05 | 0.00 | 0.05 |
| 2016 | 0.00 | 0.01 | 0.00 | 0.01 |
| 2017 | 0.00 | 0.01 | 0.00 | 0.01 |
| 2018 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2019 | 0.00 | 0.01 | 0.00 | 0.01 |
| 2020 | 0.00 | 0.01 | 0.00 | 0.01 |
| 2021 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2022 | 0.22 | 0.01 | 0.00 | 0.22 |
| 2023 | 0.00 | 0.01 | 0.00 | 0.01 |

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Table 7.18: Total likelihood values and proportions from 50 runs with 10% jitter. The total likelihood in the base model was 285.235.

| Likelihood | Count | Proportion |
|---:|---:|---:|
| 285.235 | 42 | 0.84 |
| 285.689 | 1 | 0.02 |
| 286.160 | 1 | 0.02 |
| 302.108 | 1 | 0.02 |
| 307.997 | 1 | 0.02 |
| 785.324 | 1 | 0.02 |
| 851.724 | 1 | 0.02 |
| 851.842 | 1 | 0.02 |
| 1,078.750 | 1 | 0.02 |

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Table 7.19: Parameter estimates, summary biomass (age 1+; mt) estimates, and total likelihood values associated with fixed values of steepness (h). Steepness was fixed at 0.65 in the base model

| | | 0.25 | 0.3 | 0.4 | 0.5 | 0.6 | Base=0.65 | 0.7 | 0.8 | 0.9 | 1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Parameters | NatM_Lorenzen_averageFem_GP_1 | 0.553 | 0.552 | 0.549 | 0.547 | 0.547 | 0.546 | 0.546 | 0.546 | 0.546 | 0.546 |
| | SR_LN(R0) | 15.147 | 15.024 | 14.819 | 14.675 | 14.572 | 14.532 | 14.498 | 14.441 | 14.399 | 14.365 |
| | SR_regime_BLK1repl_2004 | 1.987 | 2.1 | 2.29 | 2.428 | 2.528 | 2.567 | 2.602 | 2.658 | 2.701 | 2.736 |
| | InitF_seas_1_flt_1MexCal_S1 | 2.243 | 2.252 | 2.267 | 2.276 | 2.283 | 2.285 | 2.287 | 2.29 | 2.293 | 2.295 |
| Summary biomass | 2020 | 42,735 | 43,209 | 43,914 | 44,456 | 44,892 | 45,078 | 45,244 | 45,526 | 45,753 | 45,937 |
| | 2021 | 99,908 | 100,892 | 102,428 | 103,627 | 104,562 | 104,944 | 105,277 | 105,822 | 106,237 | 106,558 |
| | 2022 | 44,729 | 45,746 | 47,157 | 48,052 | 48,623 | 48,826 | 48,989 | 49,224 | 49,377 | 49,478 |
| | 2023 | 45,639 | 47,404 | 49,821 | 51,256 | 52,088 | 52,357 | 52,557 | 52,814 | 52,947 | 53,008 |
| | 2024 | 40,753 | 44,521 | 50,003 | 53,258 | 54,995 | 55,493 | 55,825 | 56,152 | 56,212 | 56,135 |
| | Total likelihood | 283.494 | 283.421 | 283.797 | 284.38 | 284.964 | 285.235 | 285.489 | 285.946 | 286.338 | 286.675 |

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Table 7.20: Parameter estimates, summary biomass (age 1+ mt) estimates, and total likelihood values associated with fixed values of natural mortality (M) and estimated steepness (h). This model configuration differs from that of the base model.

| | | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1 |
|---|---|---|---|---|---|---|---|---|---|---|
| Parameters | SR_LN(R0) | 14.88 | 14.928 | 14.946 | 15.009 | 15.14 | 15.34 | 15.502 | 15.451 | 12.207 |
| | SR_BH_steep | 0.546 | 0.419 | 0.345 | 0.303 | 0.275 | 0.256 | 0.239 | 0.221 | 0.2 |
| | SR_regime_BLK1repl_2004 | 0.456 | 0.866 | 1.354 | 1.823 | 2.245 | 2.592 | 2.972 | 3.564 | 7.351 |
| | InitF_seas_1_flt_1MexCal_S1 | 3 | 3 | 2.922 | 2.478 | 2.028 | 1.572 | 1.106 | 0.638 | 0.17 |
| Summary biomass | 2020 | 55,151 | 51,438 | 47,476 | 44,308 | 42,177 | 42,718 | 46,792 | 58,387 | 86,659 |
| | 2021 | 108,172 | 103,292 | 100,872 | 100,432 | 101,229 | 110,758 | 122,705 | 137,192 | 153,321 |
| | 2022 | 63,338 | 55,178 | 49,561 | 46,513 | 44,905 | 45,553 | 46,467 | 47,462 | 48,359 |
| | 2023 | 80,829 | 66,062 | 56,044 | 49,604 | 44,988 | 42,648 | 40,485 | 38,370 | 36,204 |
| | 2024 | 87,931 | 67,827 | 54,894 | 46,832 | 41,242 | 38,374 | 35,908 | 33,601 | 31,270 |
| | Total likelihood | 349.747 | 314.806 | 292.869 | 284.284 | 284.917 | 297.24 | 320.981 | 354.926 | 397.781 |

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Table 7.21: Parameter estimates, summary biomass (age 1+ mt) estimates, and total likelihood values associated with 2023 AT survey biomass values ranging from 10,000 to 150,000 mt.

| | | 20,000 | 30,000 | 40,000 | 50,000 | 60,000 | 70,000 | 80,000 | 90,000 | 100,000 | 110,000 | 120,000 | 130,000 | 140,000 | 150,000 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Parameters | NatM_Lorenzen_averageFem_GP_1 | 0.564 | 0.557 | 0.553 | 0.549 | 0.546 | 0.545 | 0.545 | 0.546 | 0.548 | 0.55 | 0.551 | 0.553 | 0.554 | 0.554 |
| | SR_LN(R0) | 14.25 | 14.349 | 14.427 | 14.486 | 14.54 | 14.588 | 14.633 | 14.675 | 14.712 | 14.743 | 14.768 | 14.788 | 14.803 | 14.816 |
| | SR_regime_BLK1repl_2004 | 2.946 | 2.808 | 2.708 | 2.624 | 2.559 | 2.505 | 2.462 | 2.426 | 2.398 | 2.377 | 2.362 | 2.351 | 2.342 | 2.333 |
| | InitF_seas_1_flt_1MexCal_S1 | 2.264 | 2.27 | 2.272 | 2.281 | 2.286 | 2.288 | 2.288 | 2.287 | 2.283 | 2.278 | 2.274 | 2.27 | 2.267 | 2.266 |
| Summary biomass | 2020 | 38,543 | 41,321 | 43,155 | 44,374 | 45,175 | 45,693 | 46,017 | 46,197 | 46,265 | 46,255 | 46,210 | 46,159 | 46,114 | 46,078 |
| | 2021 | 76,731 | 88,263 | 96,300 | 101,719 | 105,398 | 107,856 | 109,440 | 110,360 | 110,748 | 110,769 | 110,623 | 110,437 | 110,261 | 110,106 |
| | 2022 | 26,345 | 34,023 | 40,236 | 45,289 | 49,370 | 52,601 | 55,068 | 56,815 | 57,867 | 58,365 | 58,562 | 58,641 | 58,685 | 58,722 |
| | 2023 | 23,283 | 31,667 | 39,353 | 46,577 | 53,315 | 59,464 | 64,782 | 68,842 | 71,199 | 71,987 | 71,949 | 71,650 | 71,327 | 71,049 |
| | 2024 | 19,690 | 28,226 | 37,040 | 46,572 | 57,127 | 69,213 | 83,655 | 101,761 | 124,901 | 152,739 | 183,091 | 214,247 | 245,531 | 276,775 |
| | Total likelihood | 283.895 | 277.498 | 274.96 | 274.022 | 273.845 | 274.053 | 274.458 | 274.955 | 275.481 | 275.995 | 276.481 | 276.932 | 277.352 | 277.744 |

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Table 7.22: Parameter estimates and summary biomass (age 1+ mt) associated with percentage changes in catchability (Q) ranging from 50% to 150%.

| | | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 | 130 | 140 | 150 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Parameters | NatM_Lorenzen_averageFem_GP_1 | 0.674 | 0.647 | 0.622 | 0.596 | 0.571 | 0.546 | 0.523 | 0.497 | 0.473 | 0.449 | 0.427 |
| | SR_LN(R0) | 15.381 | 15.16 | 14.971 | 14.805 | 14.66 | 14.532 | 14.418 | 14.309 | 14.214 | 14.131 | 14.059 |
| | SR_BH_steep | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 |
| | SR_regime_BLK1repl_2004 | 2.685 | 2.669 | 2.65 | 2.626 | 2.598 | 2.567 | 2.533 | 2.488 | 2.44 | 2.392 | 2.343 |
| | InitF_seas_1_flt_1MexCal_S1 | 1.886 | 1.954 | 2.03 | 2.113 | 2.199 | 2.285 | 2.373 | 2.473 | 2.572 | 2.667 | 2.758 |
| | LnQ_base_AT_Survey(4) | -0.693 | -0.511 | -0.357 | -0.223 | -0.105 | 0 | 0.095 | 0.182 | 0.262 | 0.336 | 0.405 |
| | LnQ_base_Lisa_Marie(5) | -1.177 | -0.995 | -0.841 | -0.707 | -0.59 | -0.484 | -0.389 | -0.302 | -0.222 | -0.148 | -0.079 |
| | LnQ_base_AT_Survey(4)_BLK4repl_2015 | -1.004 | -0.822 | -0.668 | -0.534 | -0.416 | -0.311 | -0.216 | -0.129 | -0.049 | 0.025 | 0.094 |
| | LnQ_base_AT_Survey(4)_BLK4repl_2020 | -1.223 | -1.041 | -0.887 | -0.753 | -0.635 | -0.53 | -0.435 | -0.348 | -0.268 | -0.194 | -0.125 |
| | LnQ_base_AT_Survey(4)_BLK4repl_2021 | -1.004 | -0.822 | -0.668 | -0.534 | -0.416 | -0.311 | -0.216 | -0.129 | -0.049 | 0.025 | 0.094 |
| | LnQ_base_AT_Survey(4)_BLK4repl_2022 | -1.651 | -1.469 | -1.314 | -1.181 | -1.063 | -0.958 | -0.862 | -0.775 | -0.695 | -0.621 | -0.552 |
| | LnQ_base_AT_Survey(4)_BLK4repl_2023 | -0.693 | -0.511 | -0.357 | -0.223 | -0.105 | 0 | 0.095 | 0.182 | 0.262 | 0.336 | 0.405 |
| Summary biomass | 2020 | 88,127 | 73,748 | 63,477 | 55,791 | 49,831 | 45,078 | 41,208 | 38,041 | 35,371 | 33,086 | 31,105 |
| | 2021 | 209,432 | 174,671 | 149,780 | 131,088 | 116,555 | 104,944 | 95,458 | 87,560 | 80,900 | 75,214 | 70,303 |
| | 2022 | 93,774 | 78,759 | 68,040 | 60,018 | 53,794 | 48,826 | 44,778 | 41,463 | 38,672 | 36,285 | 34,218 |
| | 2023 | 92,400 | 78,964 | 69,399 | 62,278 | 56,763 | 52,357 | 48,773 | 45,924 | 43,515 | 41,438 | 39,619 |
| | 2024 | 95,498 | 81,861 | 72,253 | 65,177 | 59,764 | 55,493 | 52,059 | 49,371 | 47,128 | 45,210 | 43,538 |
| | Total likelihood | 293.629 | 291.781 | 289.993 | 288.289 | 286.697 | 285.235 | 283.919 | 282.769 | 281.8 | 281.011 | 280.403 |

Table 7.23: 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.

| | basemod | francis |
|---|---|---|
| MexCal_S1 | - | 0.963 |
| MexCal_S2 | - | 1.889 |
| PNW | - | 1.682 |
| AT_Survey | - | 0.543 |
| NatM_Lorenzen_averageFem_GP_1 | 0.546 | 0.551 |
| SR_LN(R0) | 14.532 | 14.540 |
| SR_BH_steep | 0.650 | 0.650 |
| SR_regime_BLK1repl_2004 | 2.567 | 2.546 |
| 2020 Age 1+ biomass | 44,686 | 44,686 |
| 2021 Age 1+ biomass | 104,124 | 104,124 |
| 2022 Age 1+ biomass | 48,370 | 48,370 |
| 2023 Age 1+ biomass | 51,731 | 51,731 |
| 2024 Age 1+ biomass | 54,274 | 54,274 |
| Total Likelihood | 285.235 | 279.179 |

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# 8 Figures

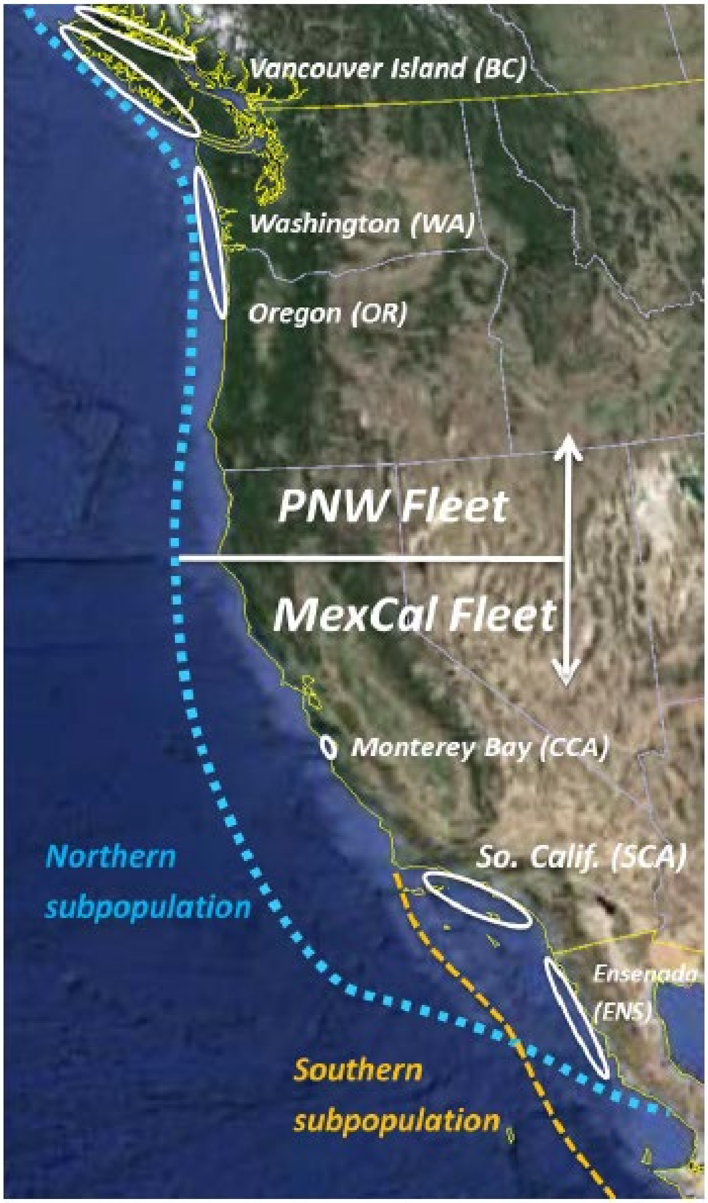

Figure 8.1: Distribution of the northern subpopulation (NSP) of Pacific sardine, primary commercial fishing areas, and modeled fishing fleets.

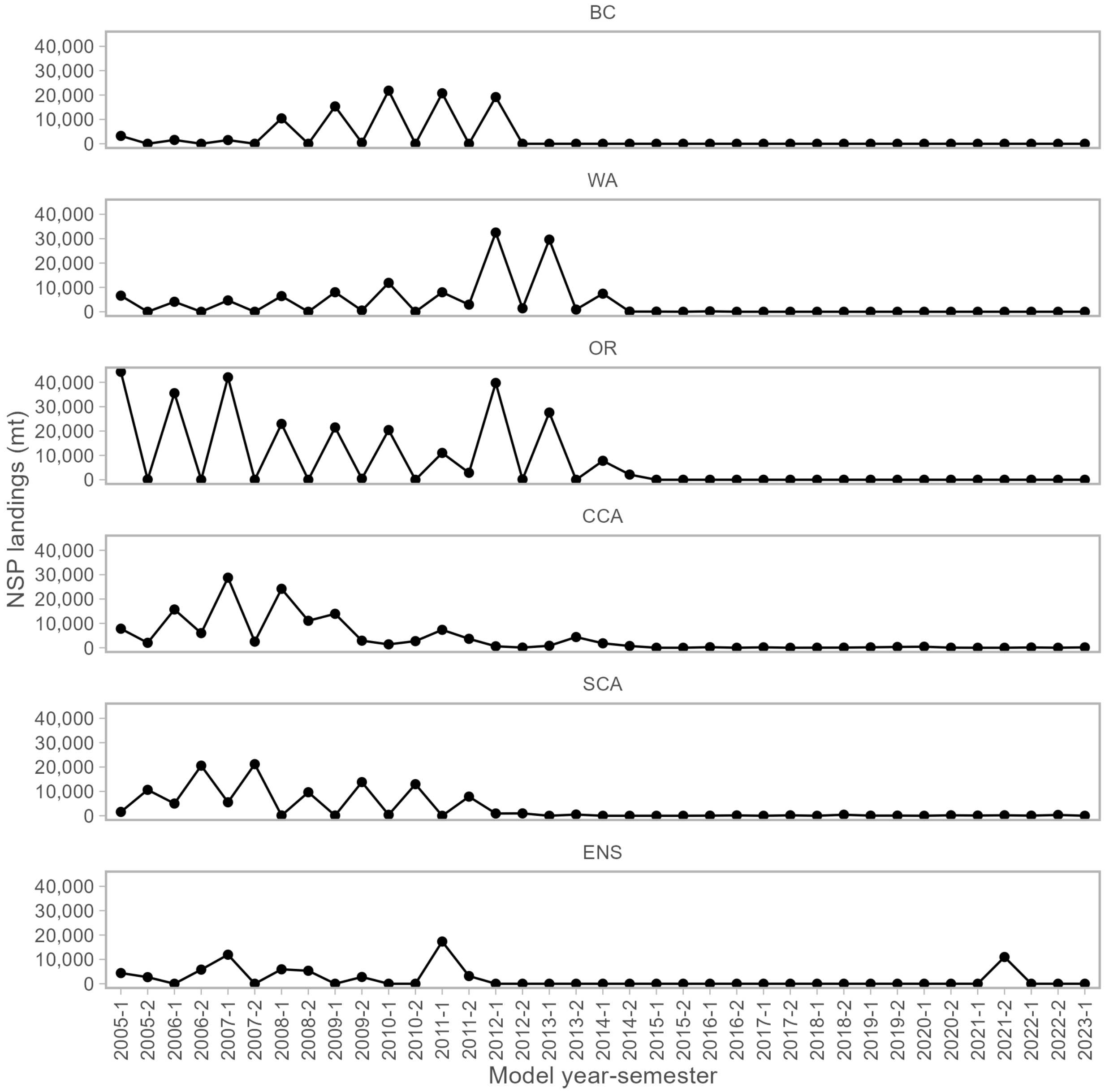

Figure 8.2: Pacific sardine northern subpopulation landings (mt) from British Columbia, Canada (BC), Washington (WA), Oregon (OR), central California (CCA), southern California (SCA) and Ensenada, Mexico (ENS).

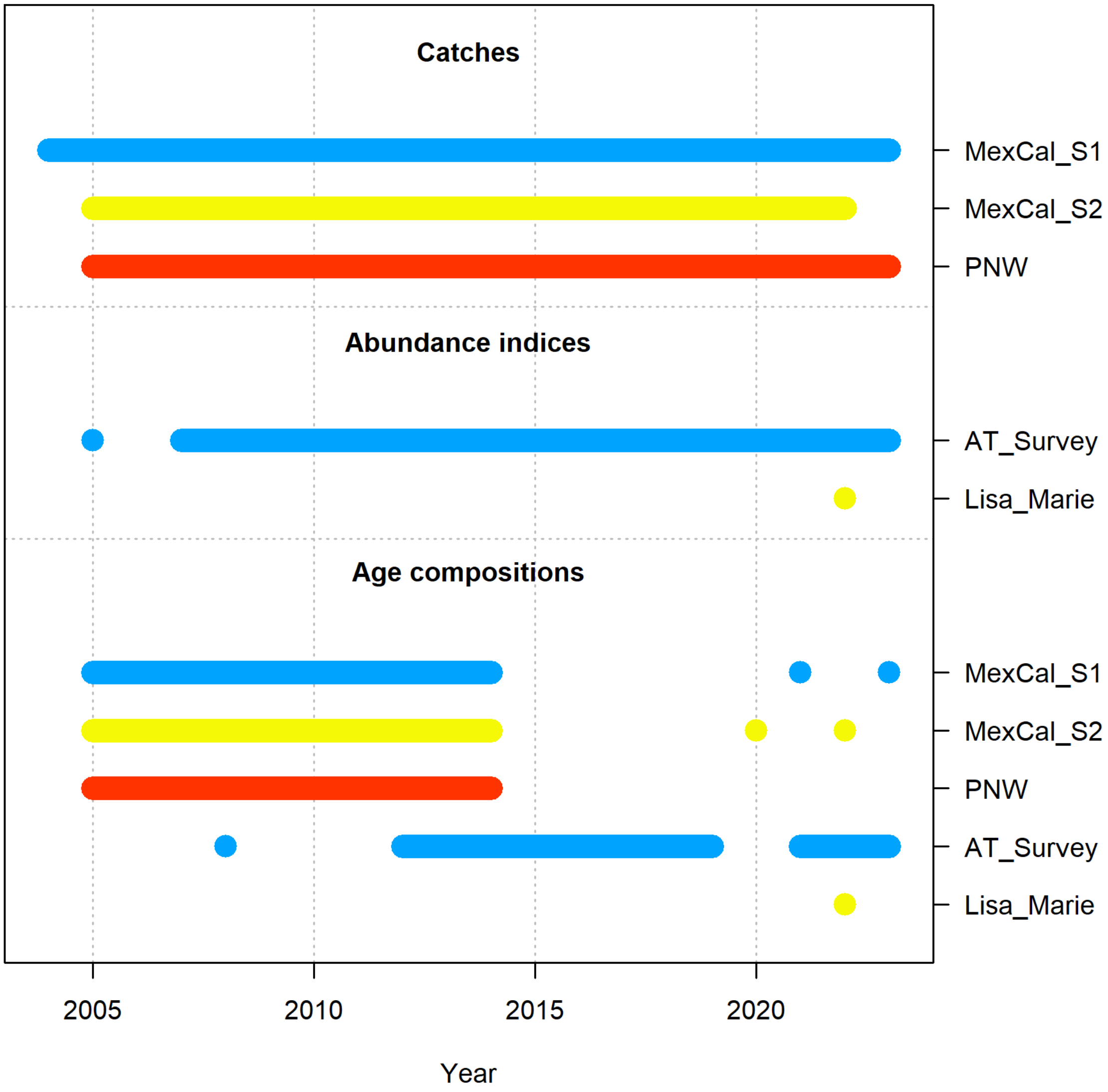

Figure 8.3: Summary of data sources used in the base model.

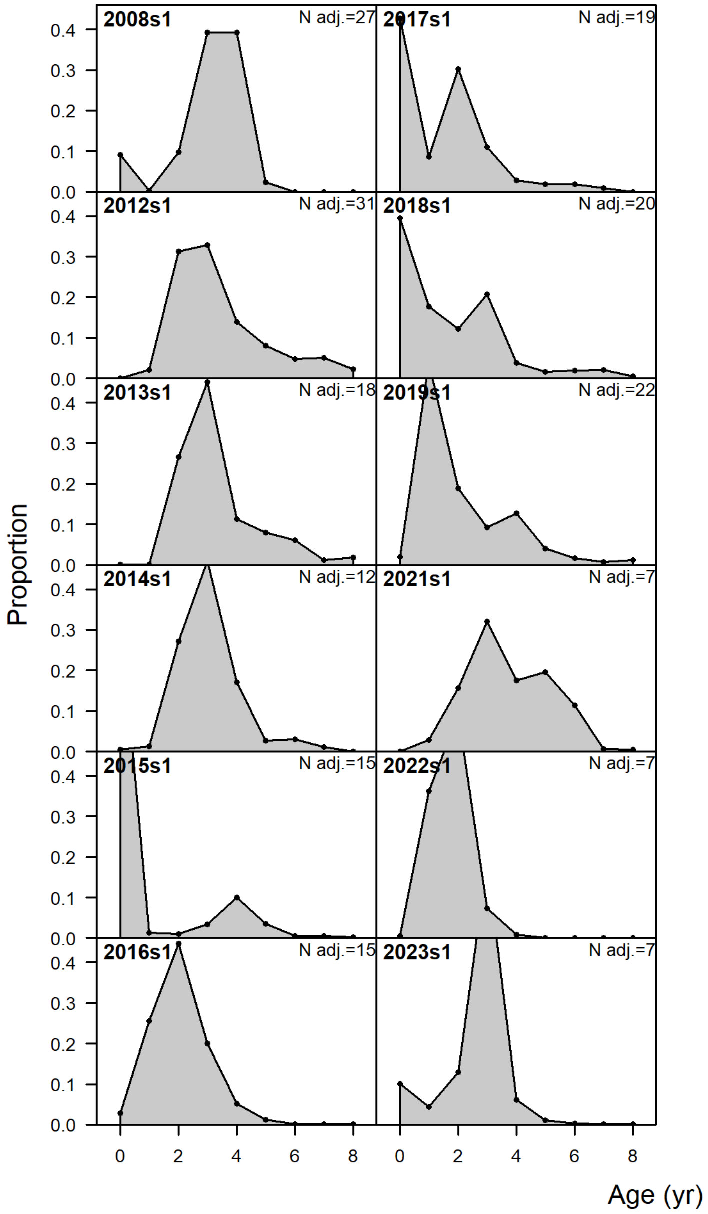

Figure 8.4: Age-composition time series for the AT Survey. N represents input sample sizes.

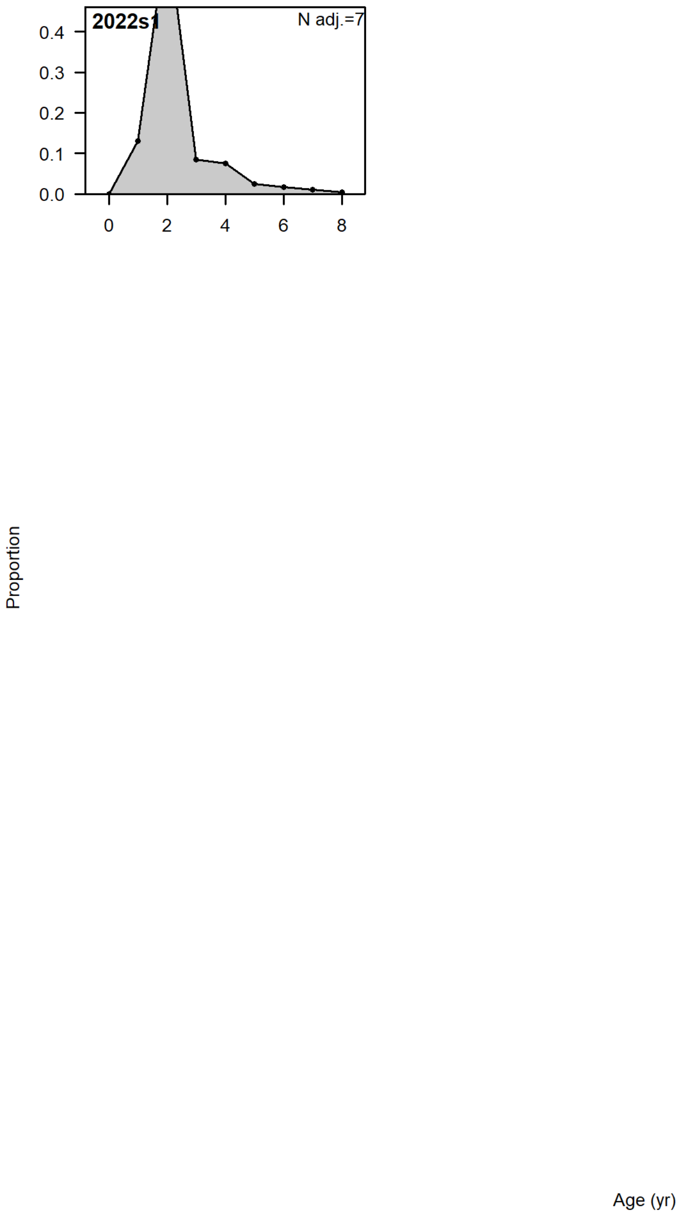

Figure 8.5: Age-composition time series for the Lisa Marie. N represents input sample sizes.

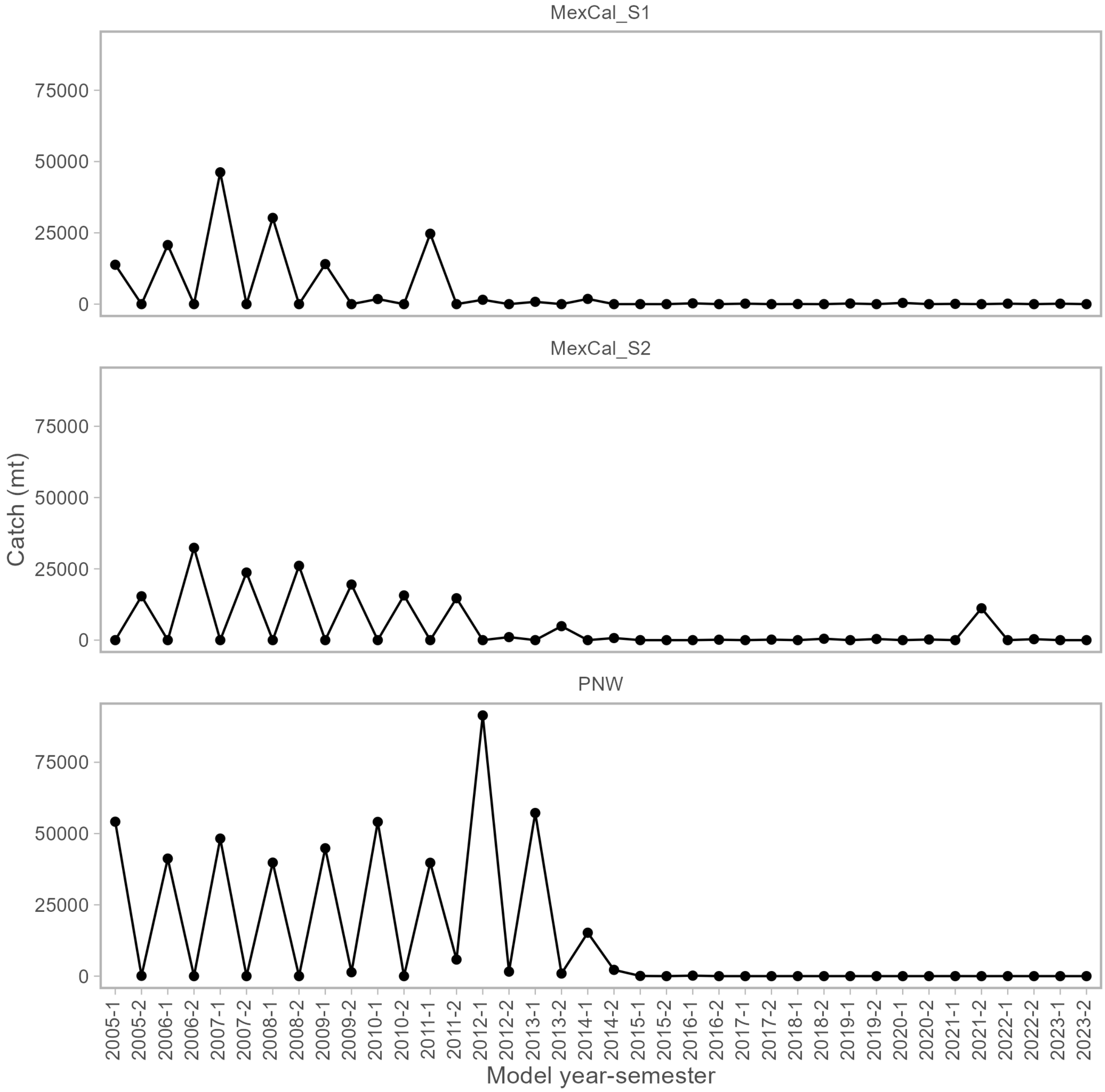

Figure 8.6: Pacific sardine landings (mt) by fleet, model year-semester as used in the base model.

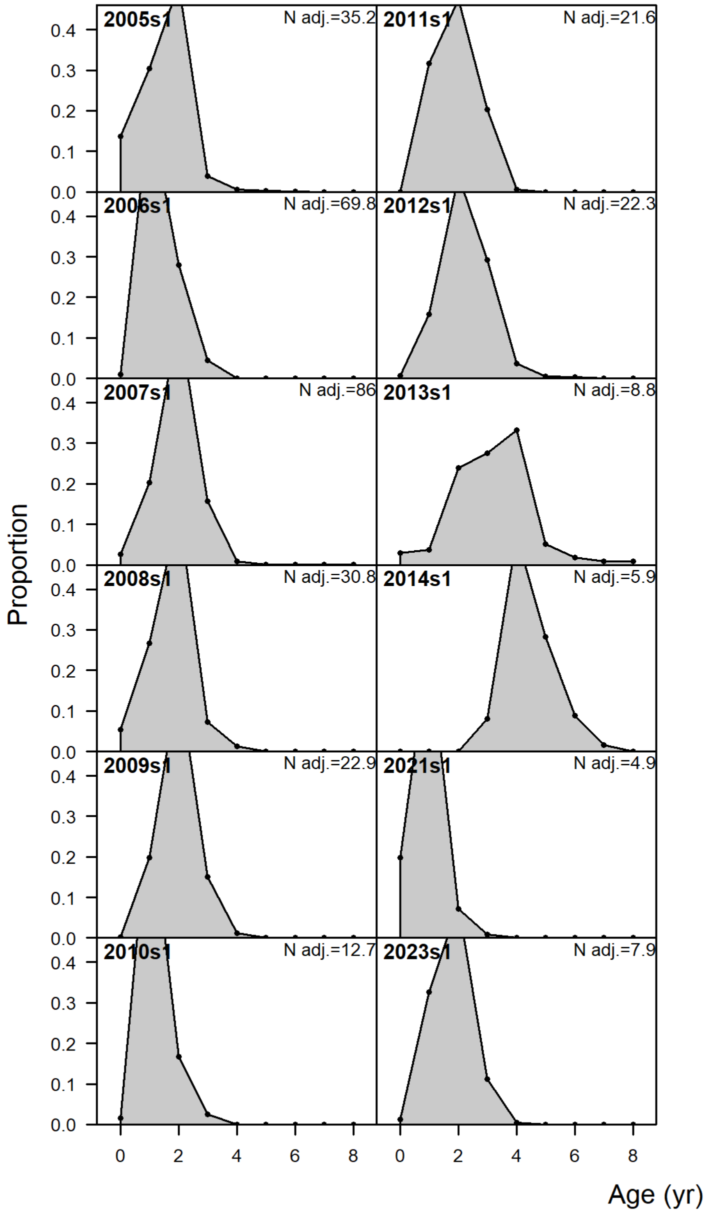

Figure 8.7: Age-composition time series for the MexCal fleet in semester 1 (S1). N represents input sample sizes.

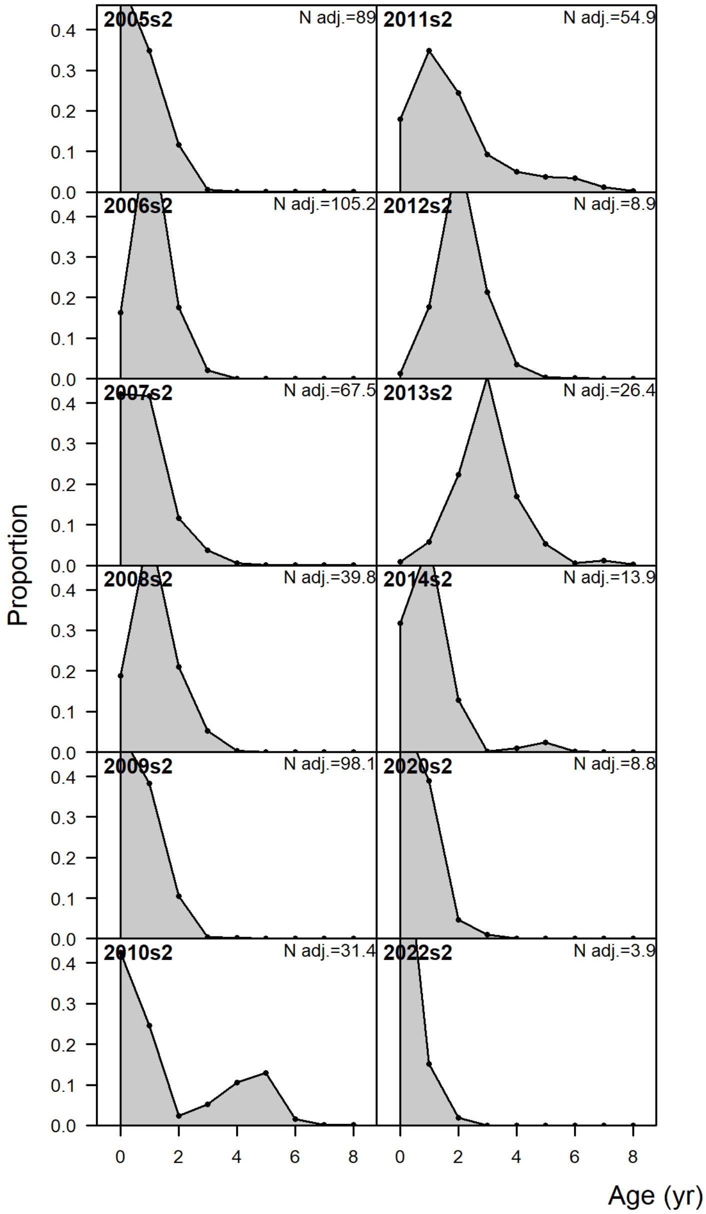

Figure 8.8: Age-composition time series for the MexCal fleet in semester 2 (S2). N represents input sample sizes.

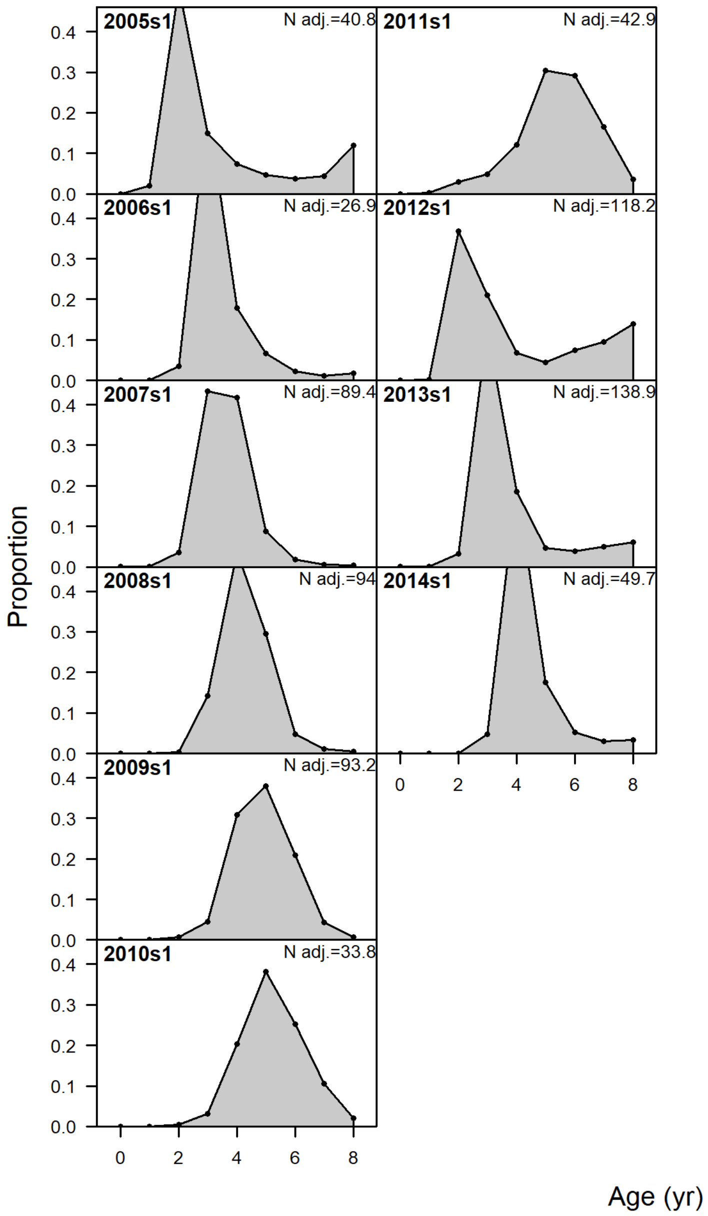

Figure 8.9: Age-composition time series for the PNW fleet. N represents input sample sizes.

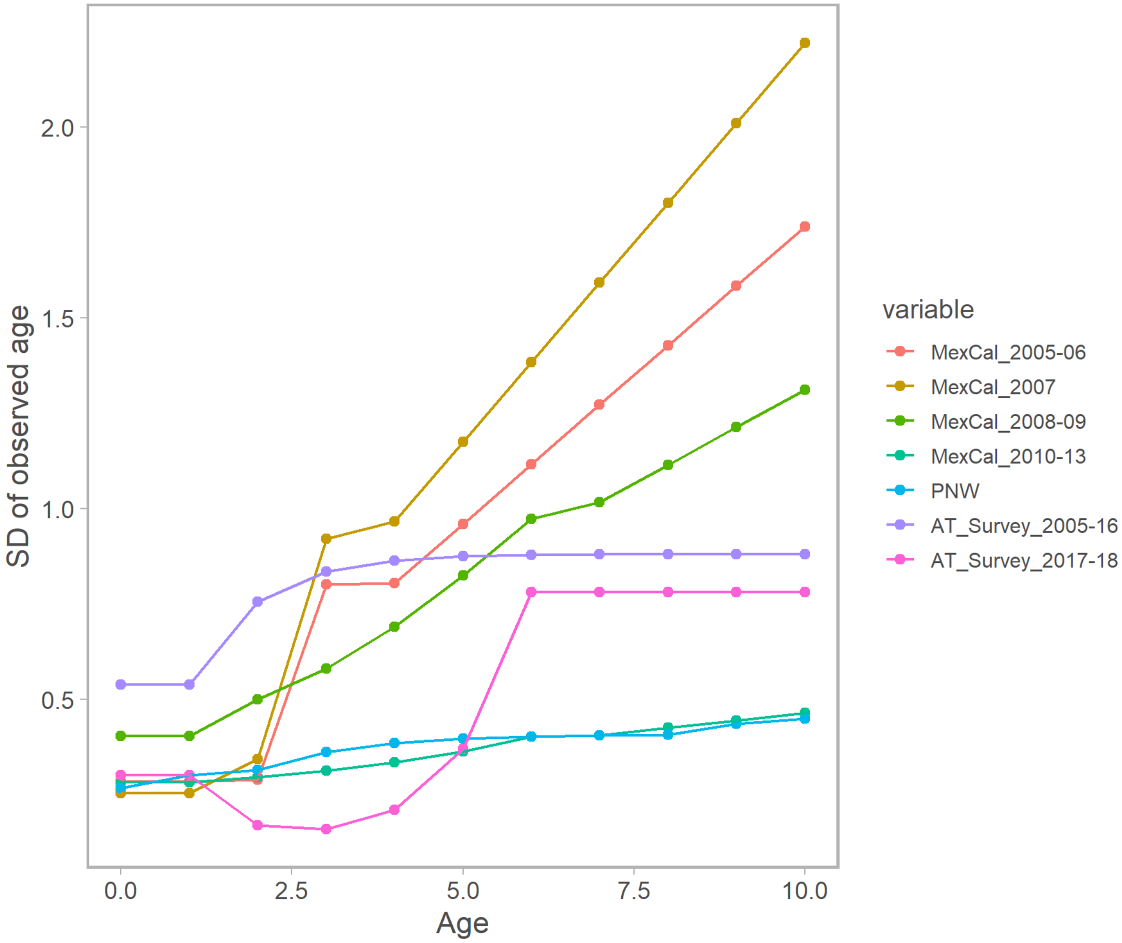

Figure 8.10: Laboratory- and year-specific ageing errors in the base model.

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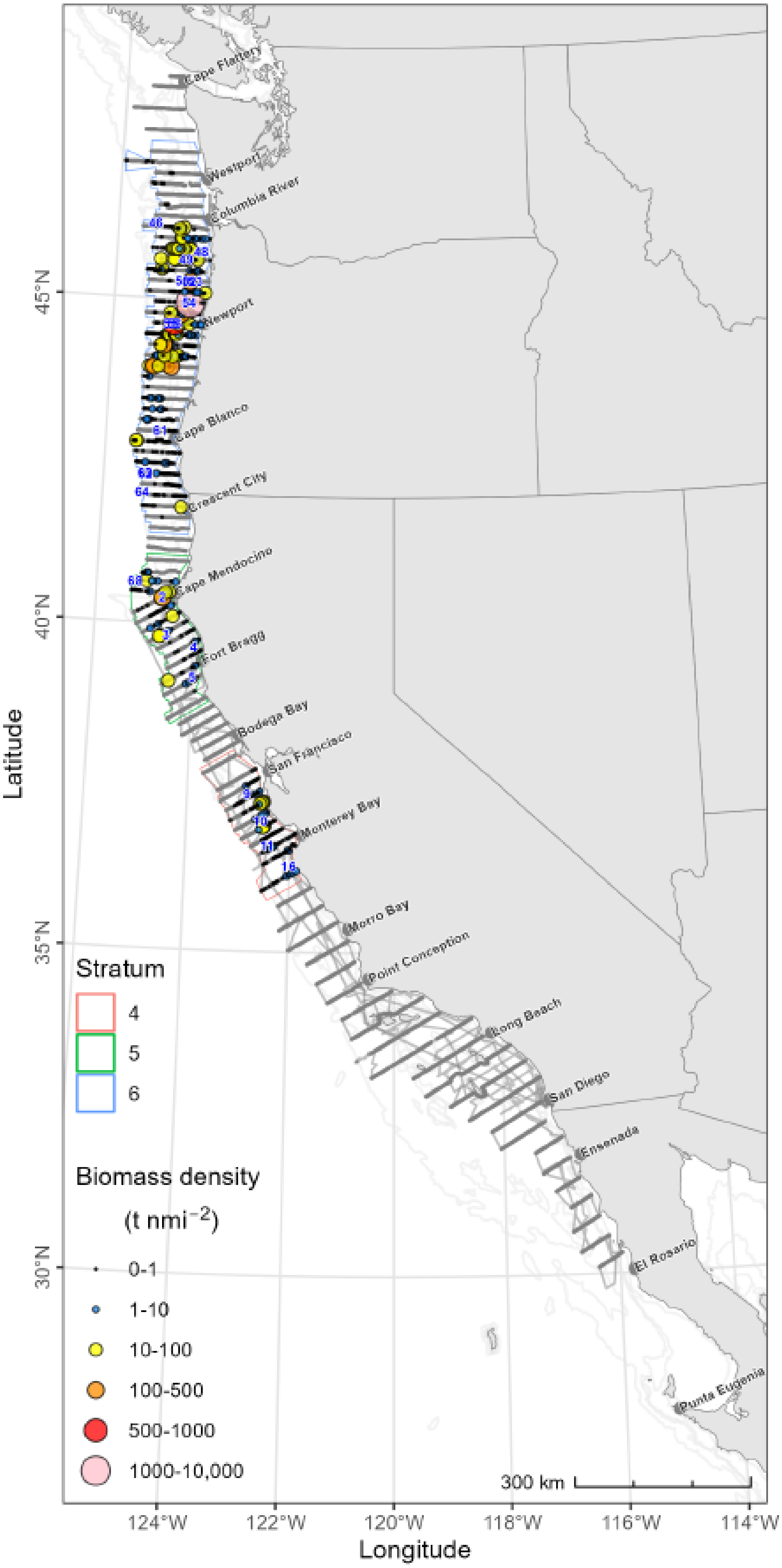
Cape Flattery
Westport
Columbia River
Newport
Cape Blanco
Crescent City
Cape Mendocino
Fort Bragg
Bodega Bay
San Francisco
Monterey Bay
Morro Bay
Point Conception
Long Beach
San Diego
Ensenada
El Rosario
Punta Eugenia
46
48
49
50
53
54
58
61
63
64
68
2
3
4
5
9
10
11
16
45°N
40°N
35°N
30°N
Latitude
124°W
122°W
120°W
118°W
116°W
114°W
Longitude
Stratum
4
5
6
Biomass density
(t nmi$^{-2}$)
0-1
1-10
10-100
100-500
500-1000
1000-10,000
300 km

Figure 8.11: Biomass densities of Pacific sardine, northern stock, per stratum throughout the summer 2022 AT survey region. Blue numbers represent locations of positive sardine trawl clusters. Gray lines represent the vessel track.

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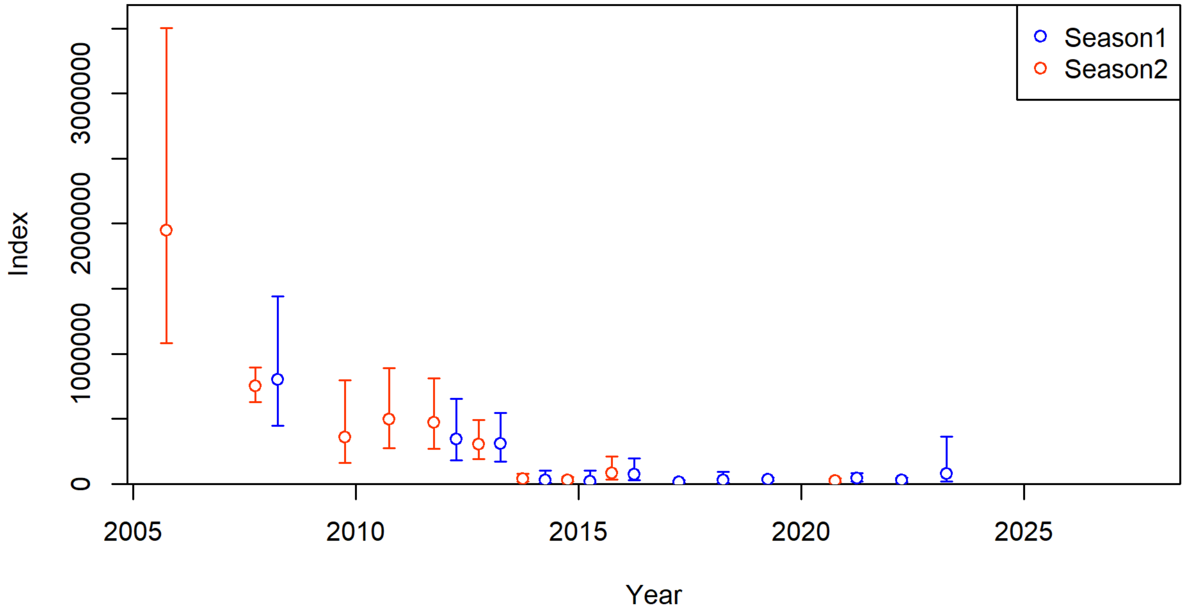

Figure 8.12: Time series of Pacific sardine biomass (age 0+, mt) from summer (semester 1) and spring (semester 2) AT surveys, 2006-2019 (bars are 95% CI).

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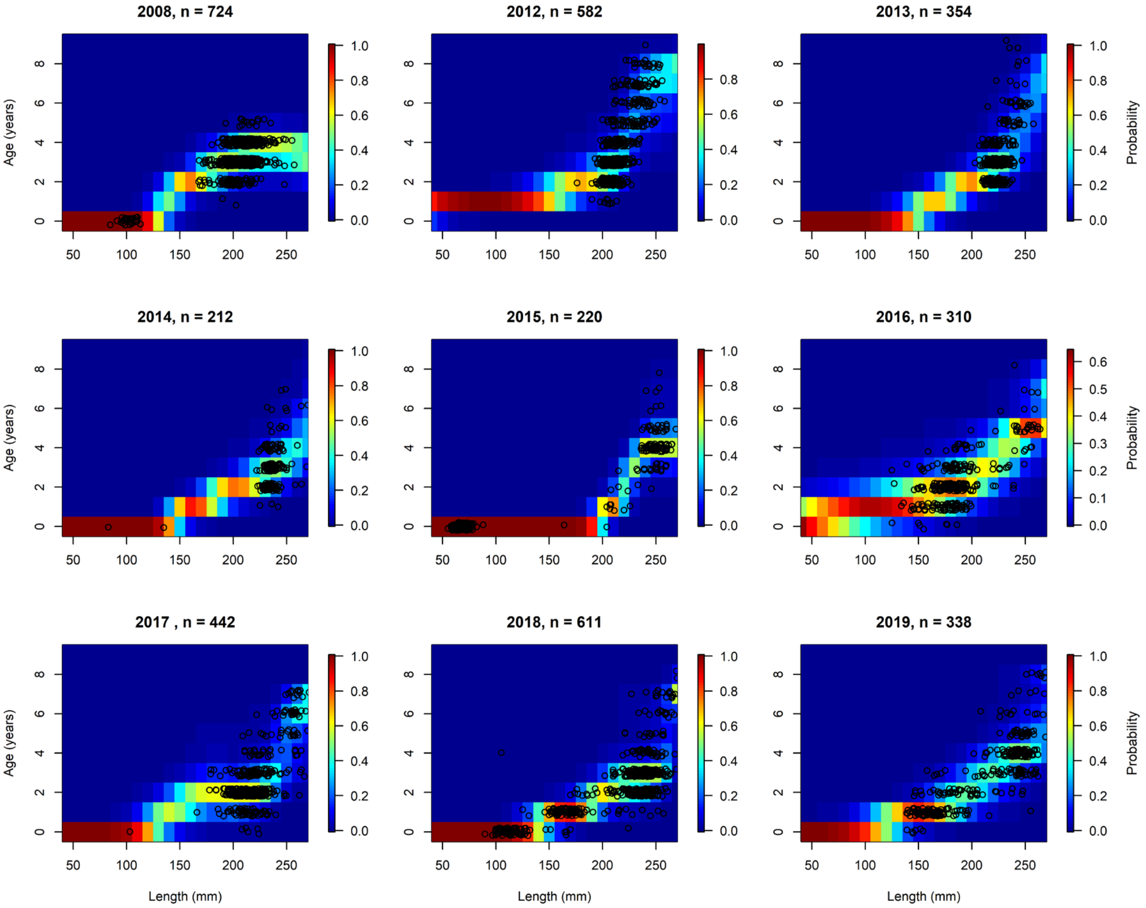


Figure 8.13: Annual age-length keys derived from summer AT survey samples collected from 2008-2019.

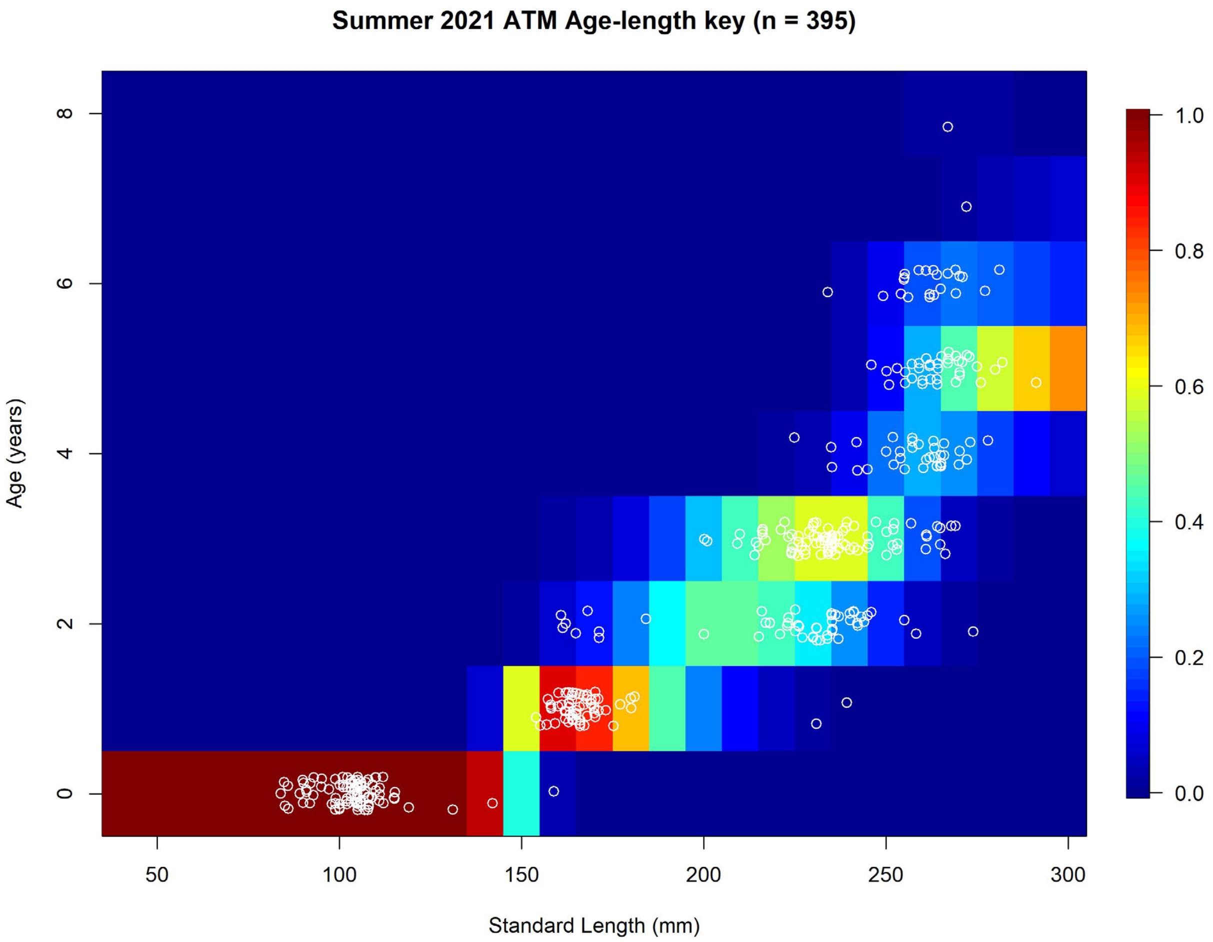
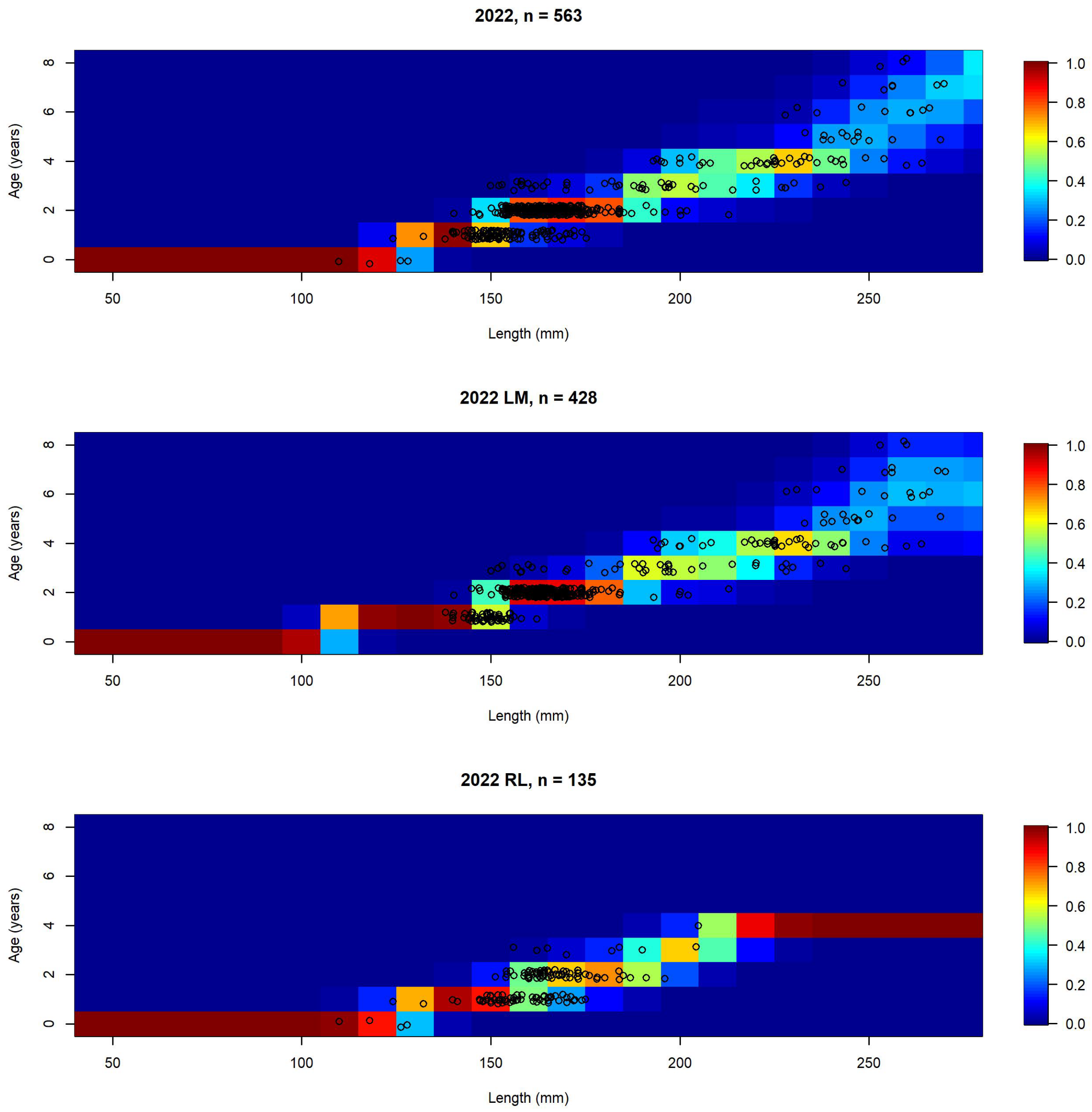


Figure 8.14: Age-length key derived from summer 2021 AT survey samples.


2022, n = 563

2022 LM, n = 428

2022 RL, n = 135

Figure 8.15: Age-length key derived from summer 2022 AT survey samples. Top panel is from the combined data, middle panel F/V Lisa Marie, and bottom panel R/V Reuben Lasker.

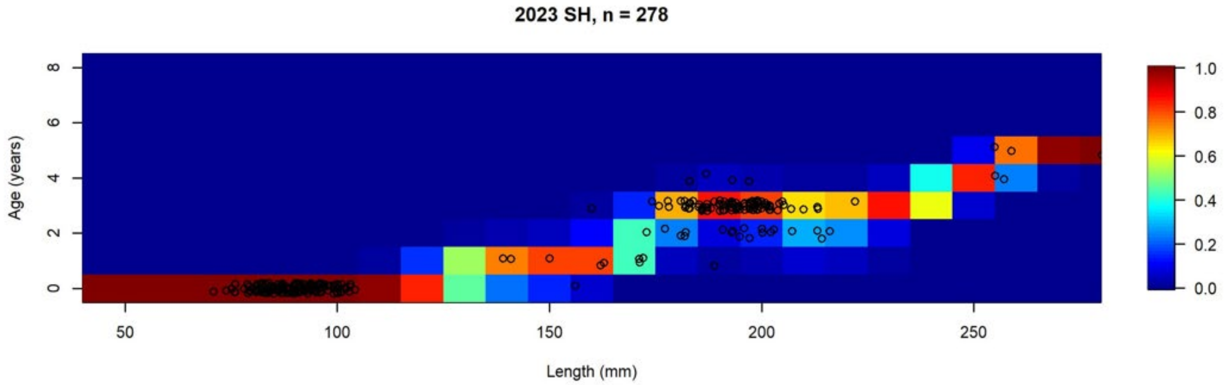


Figure 8.16: Age-length key derived from summer 2023 AT survey samples.

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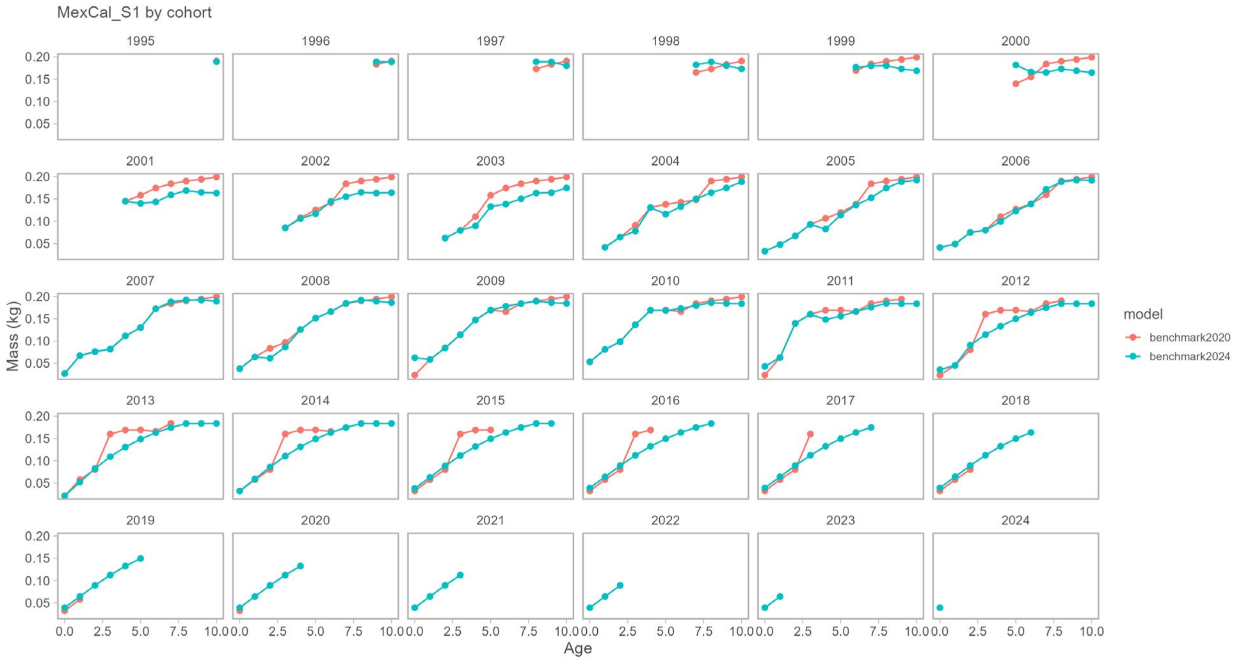

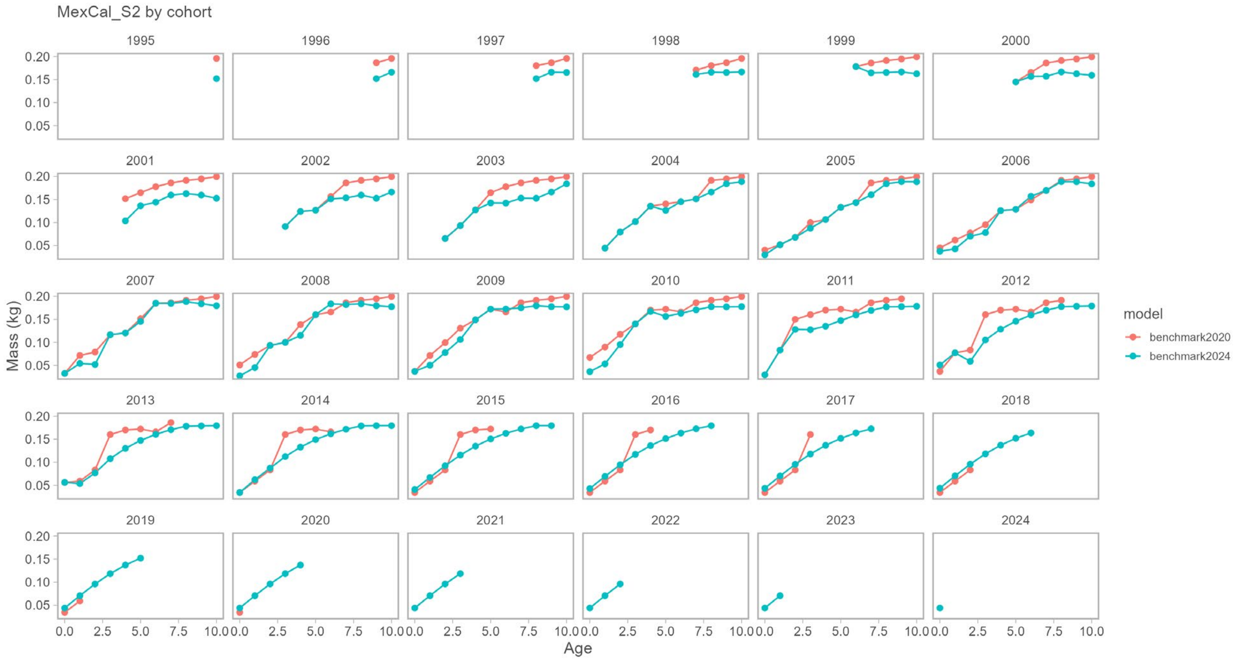

Figure 8.18: MexCal_S2 weight-at-age values plotted by cohort from the 2020 benchmark assessment (red) and current benchmark assessment (blue).

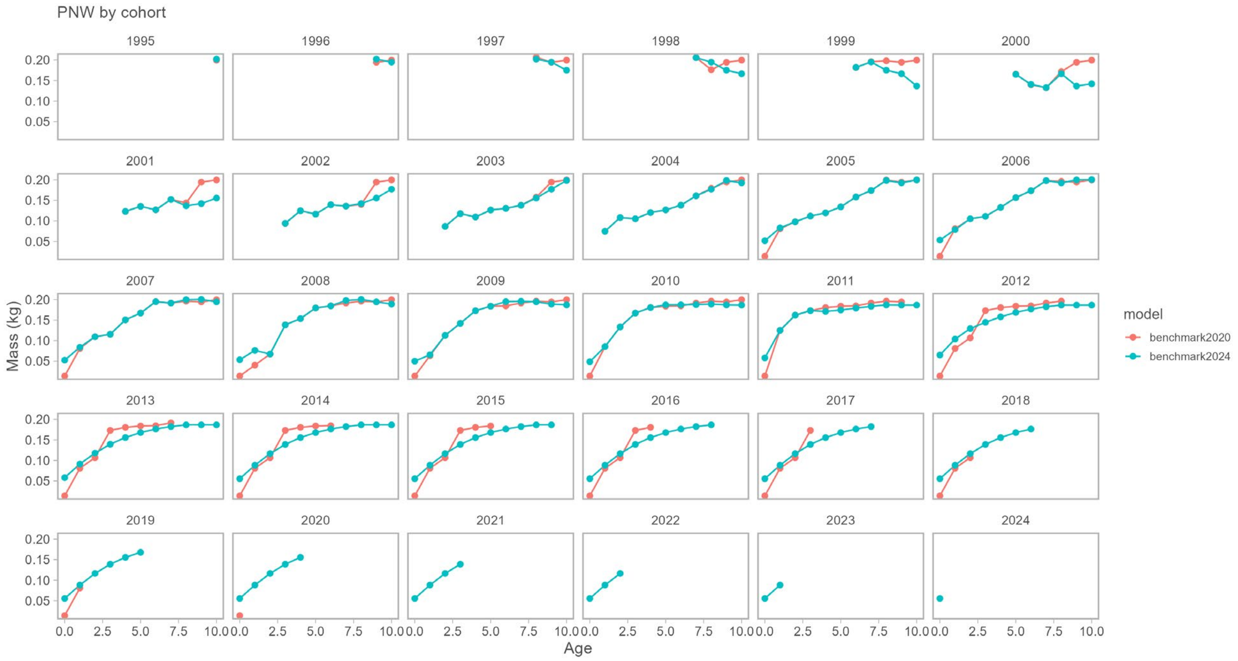

Figure 8.19: PNW weight-at-age values plotted by cohort from the 2020 benchmark assessment (red) and current benchmark assessment (blue).

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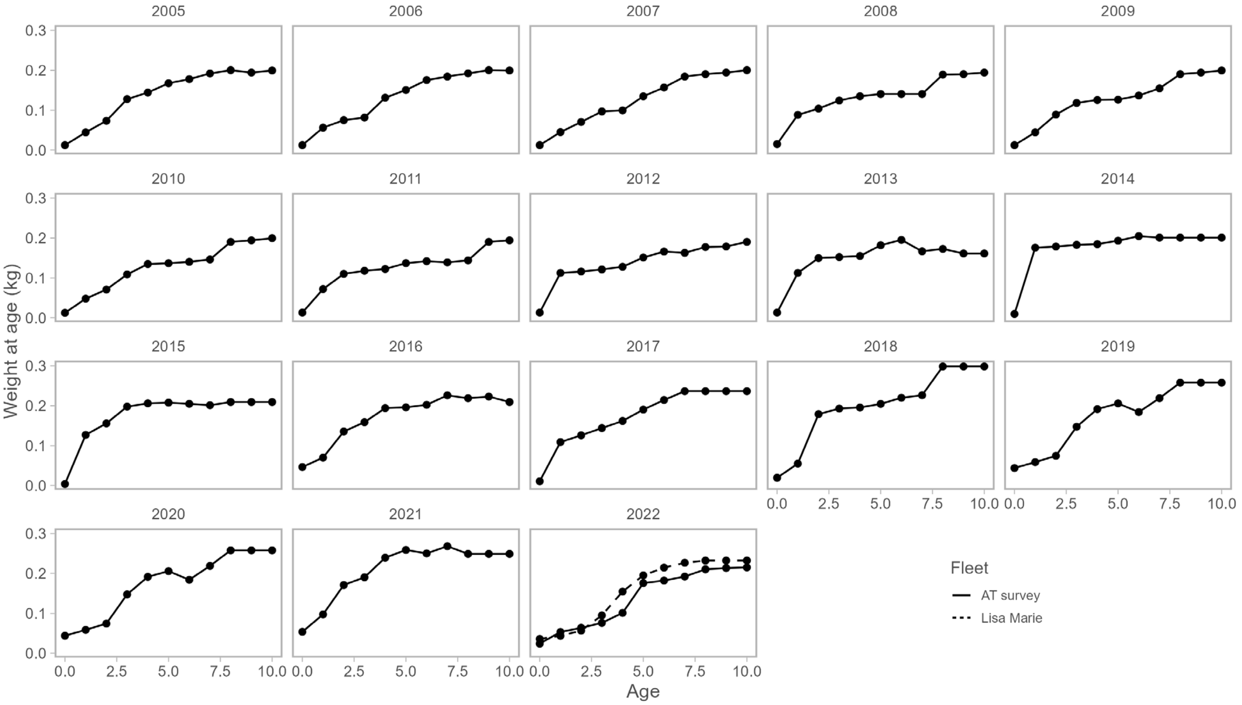

Figure 8.20: AT Survey weight-at-age values plotted by year (not cohort) for summer. Values from the AT Survey (solid line) and Lisa Marie in 2022 (dashed line) are shown.

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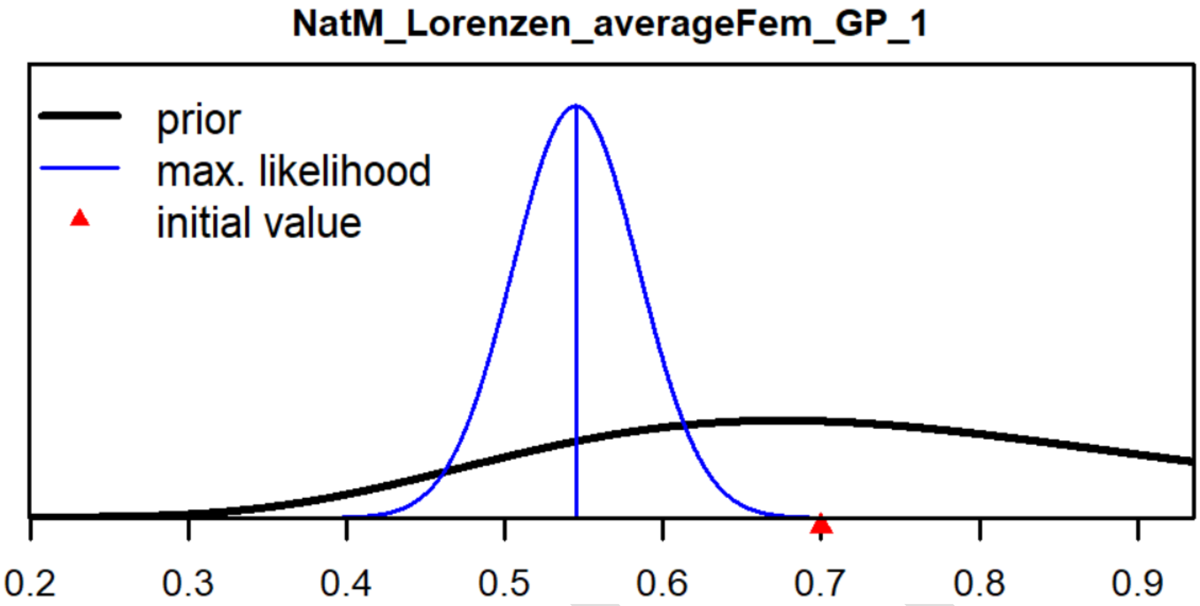

Figure 8.21: Natural mortality (M) prior and estimate. The prior was estimated based on a maximum age of 8.

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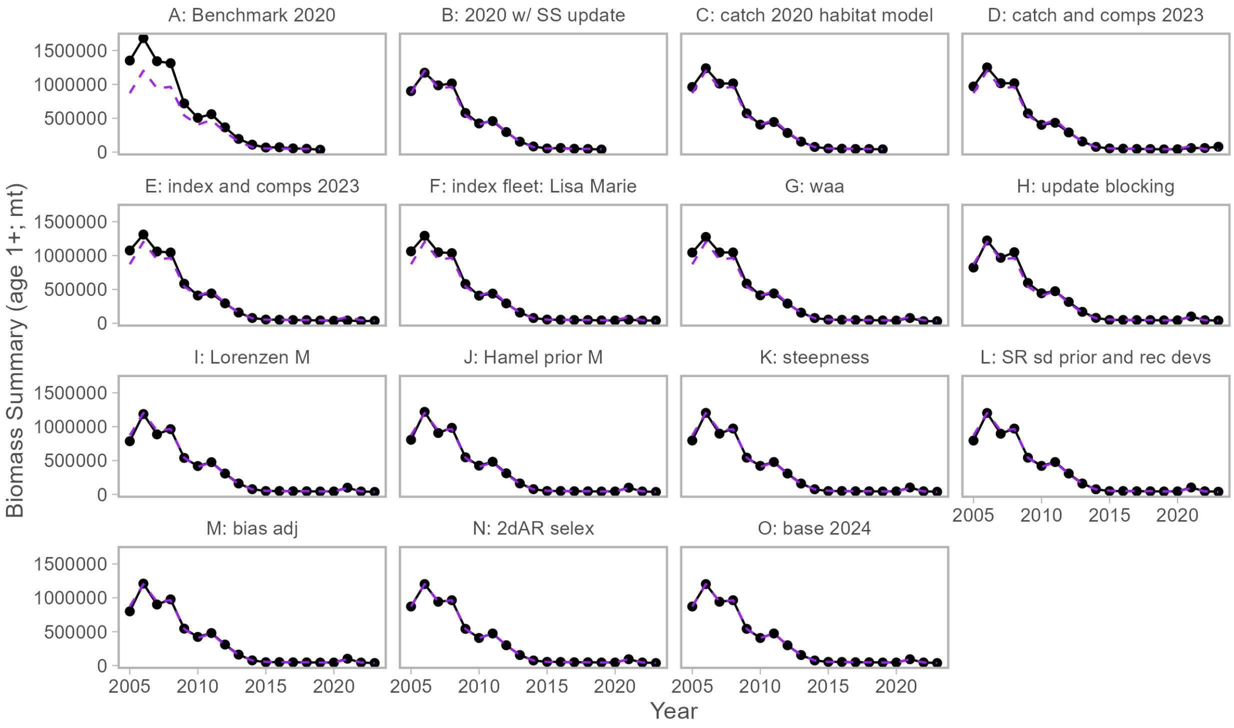

Purple dashed line shows annual biomass for the 2024 base model

Figure 8.22: Summary biomass time series with each change to model configuration. Time series for the 2024 base model is included (dashed line).

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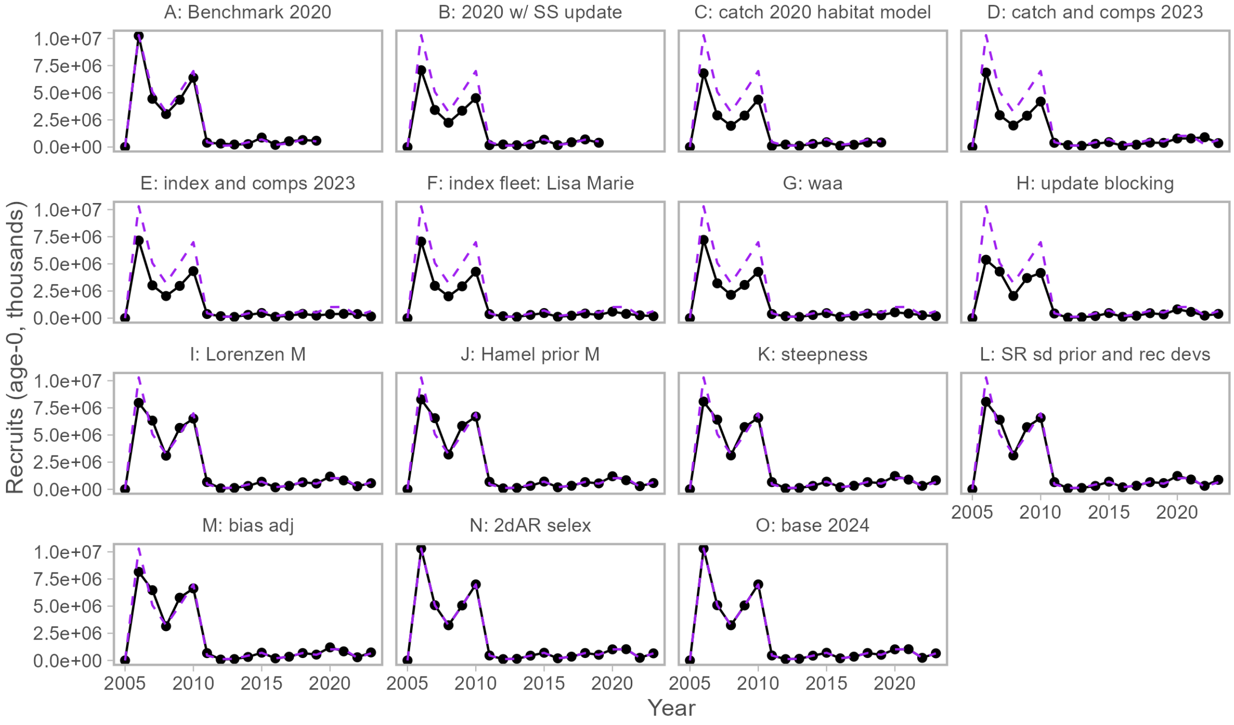

Purple dashed line shows annual recruitment for the 2024 base model

Figure 8.23: Recruitment time series with each change to model configuration. Time series for the 2024 base model is included (dashed line).

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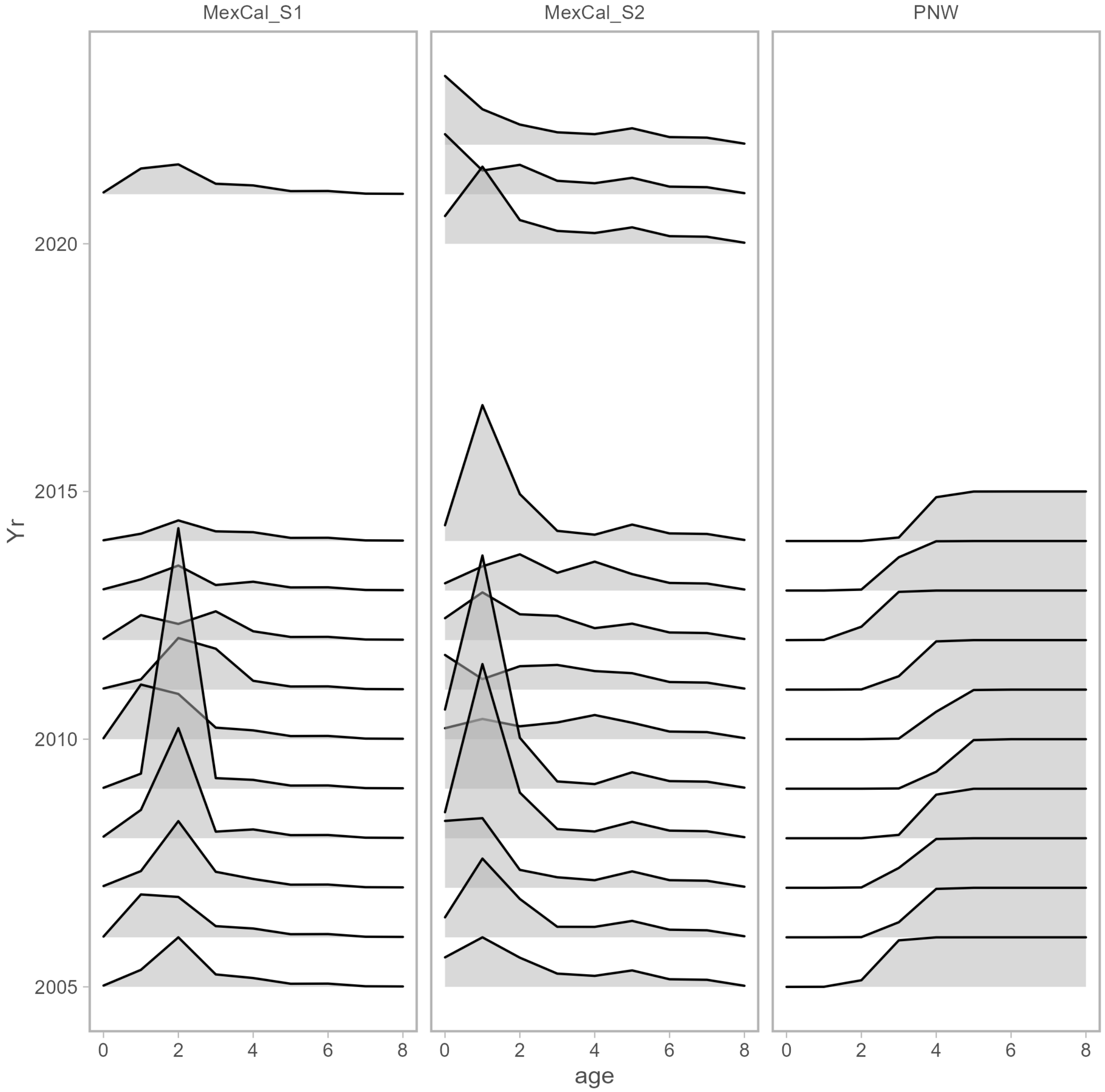

Figure 8.24: Time-varying age-based selectivity patterns for the three fishing fleets.

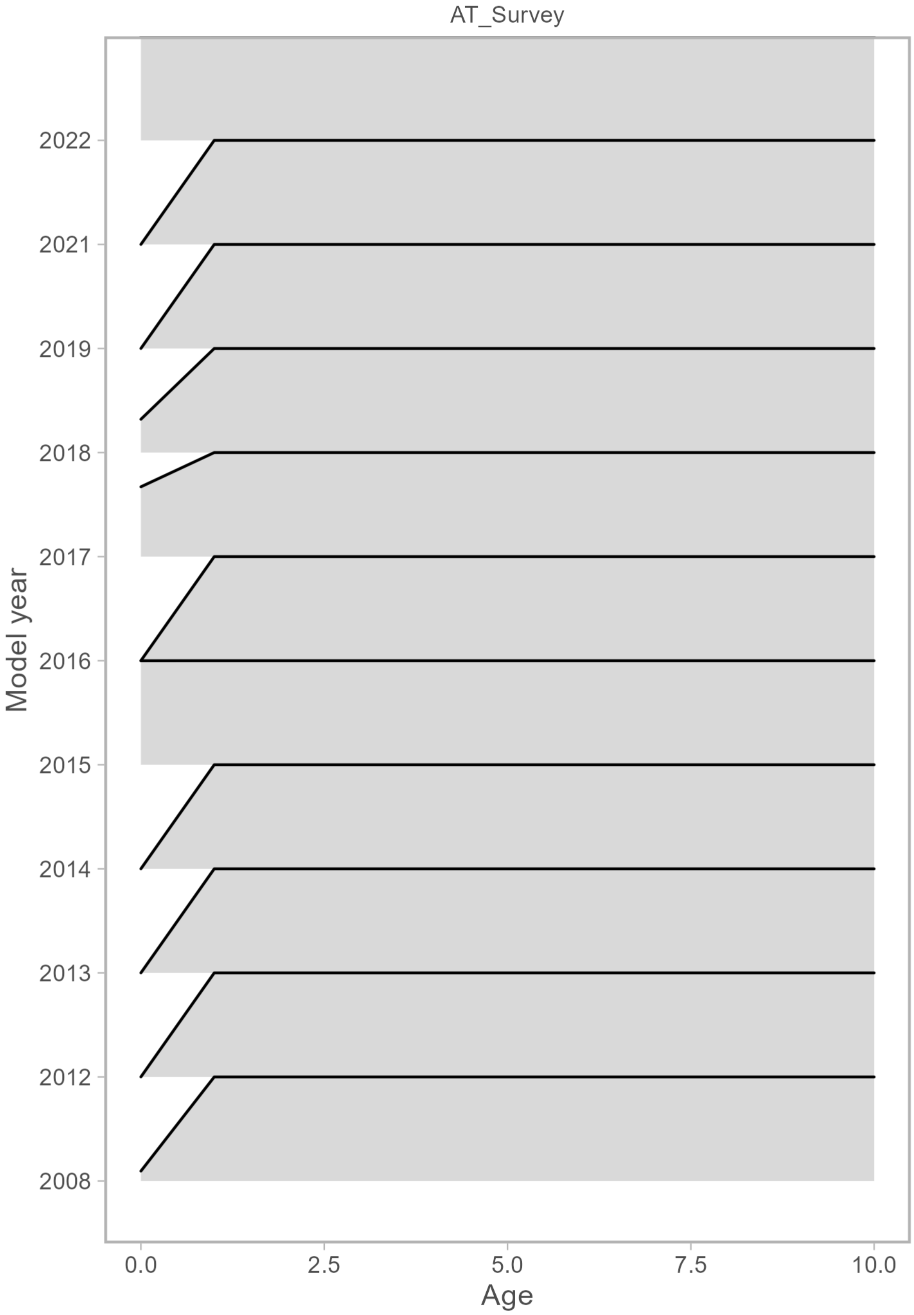

Figure 8.25: Time-varying age-based selectivity patterns for AT survey and Lisa Marie.

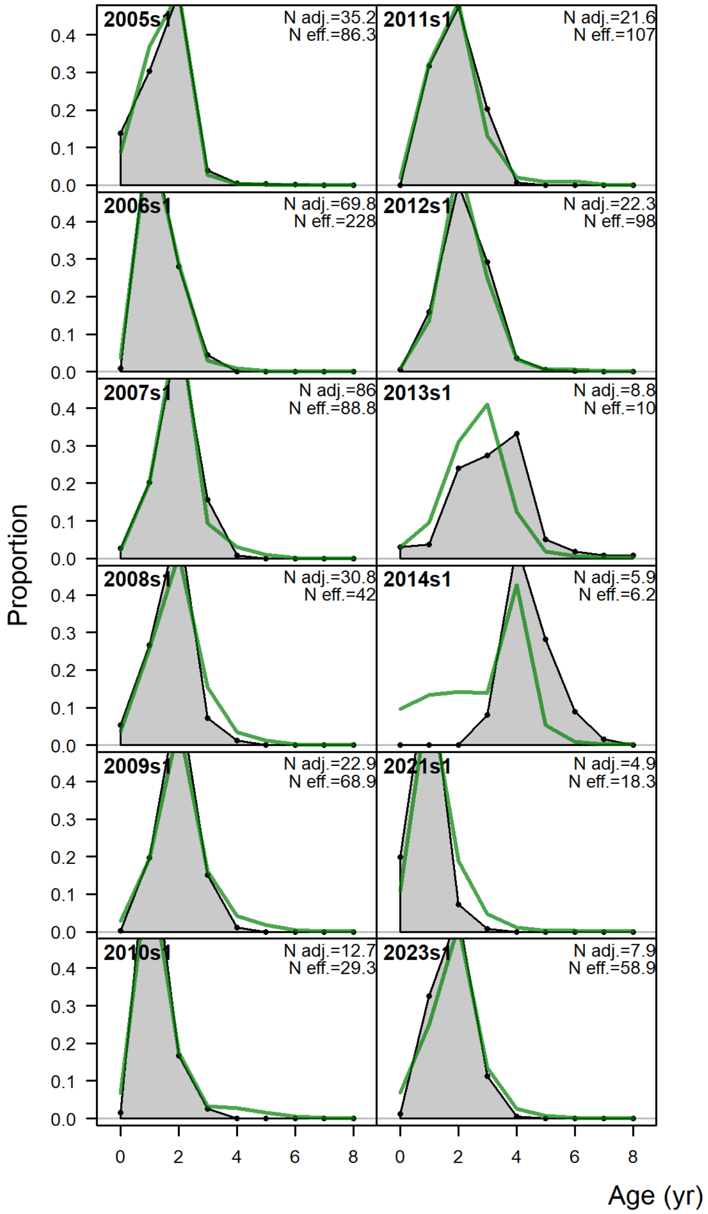

Figure 8.26: Fit to age-composition time series for the MexCal S1 fleet in the base model. Values in the top right are input sample sizes (N adj) and effective sample size given statistical fit in the model (N eff.).

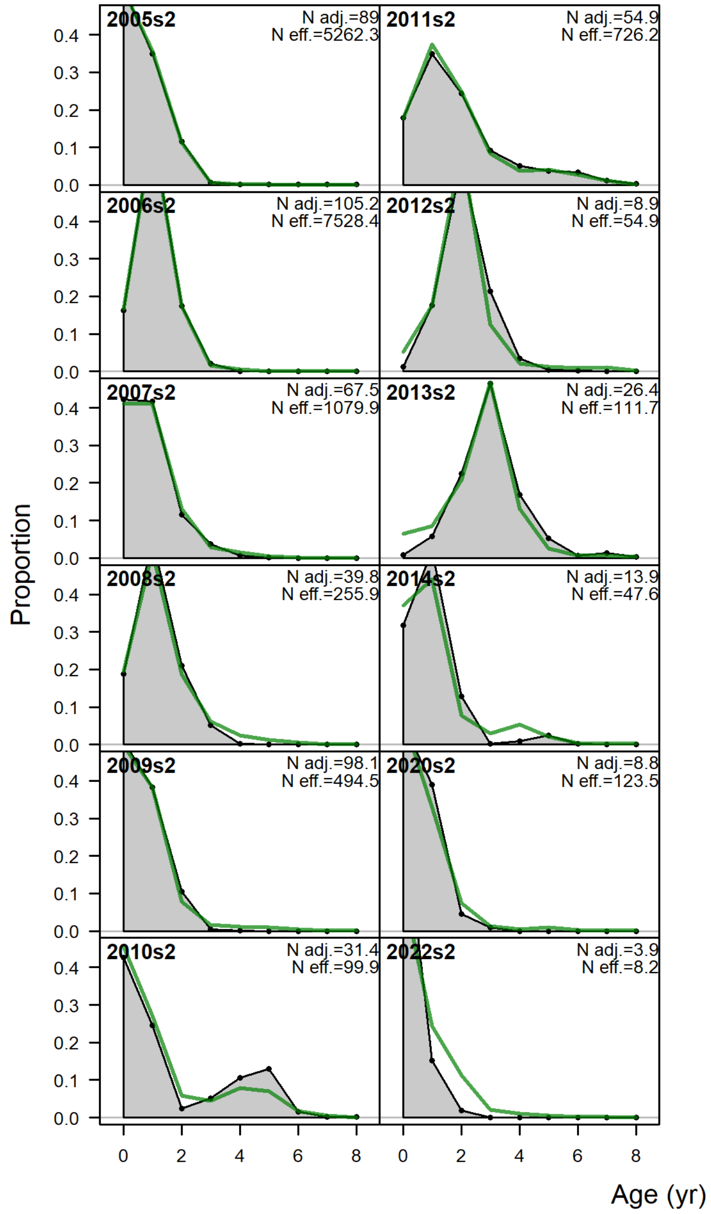

Figure 8.27: Fit to age-composition time series for the MexCal S2 fleet in the base model. Values in the top right are input sample sizes (N adj) and effective sample size given statistical fit in the model (N eff.).

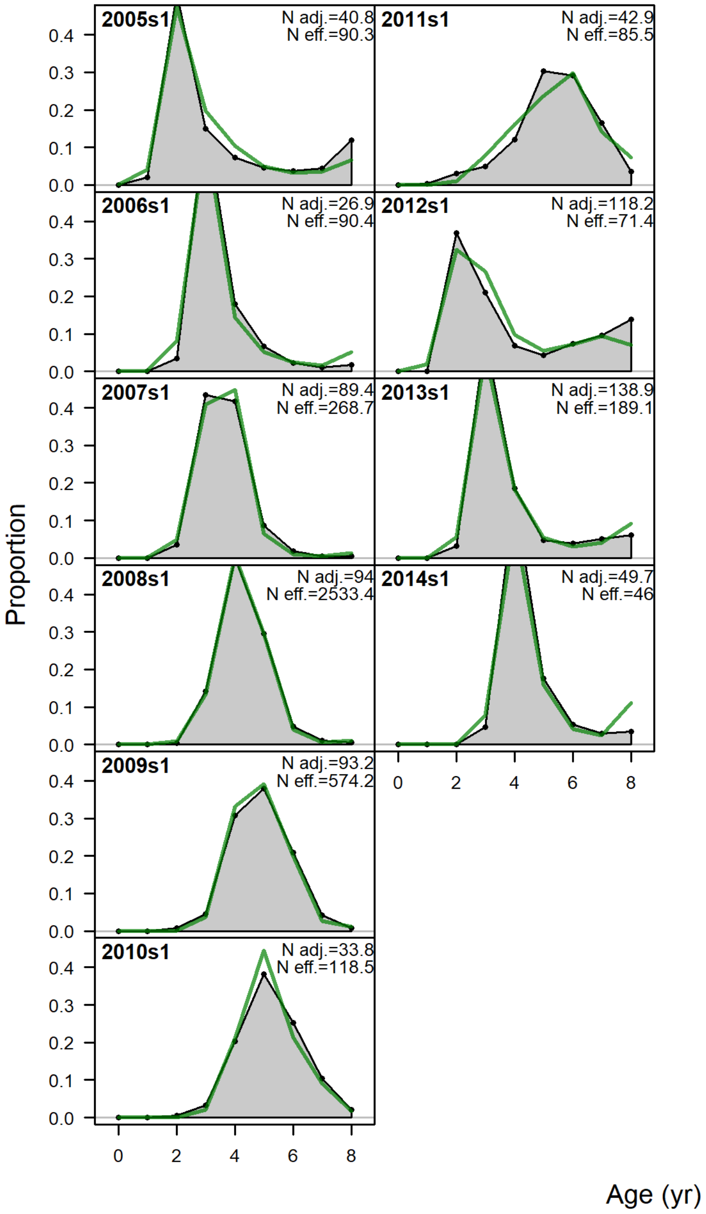

Figure 8.28: Fit to age-composition time series for the PNW fleet in the base model. Values in the top right are input sample sizes (N adj) and effective sample size given statistical fit in the model (N eff.).

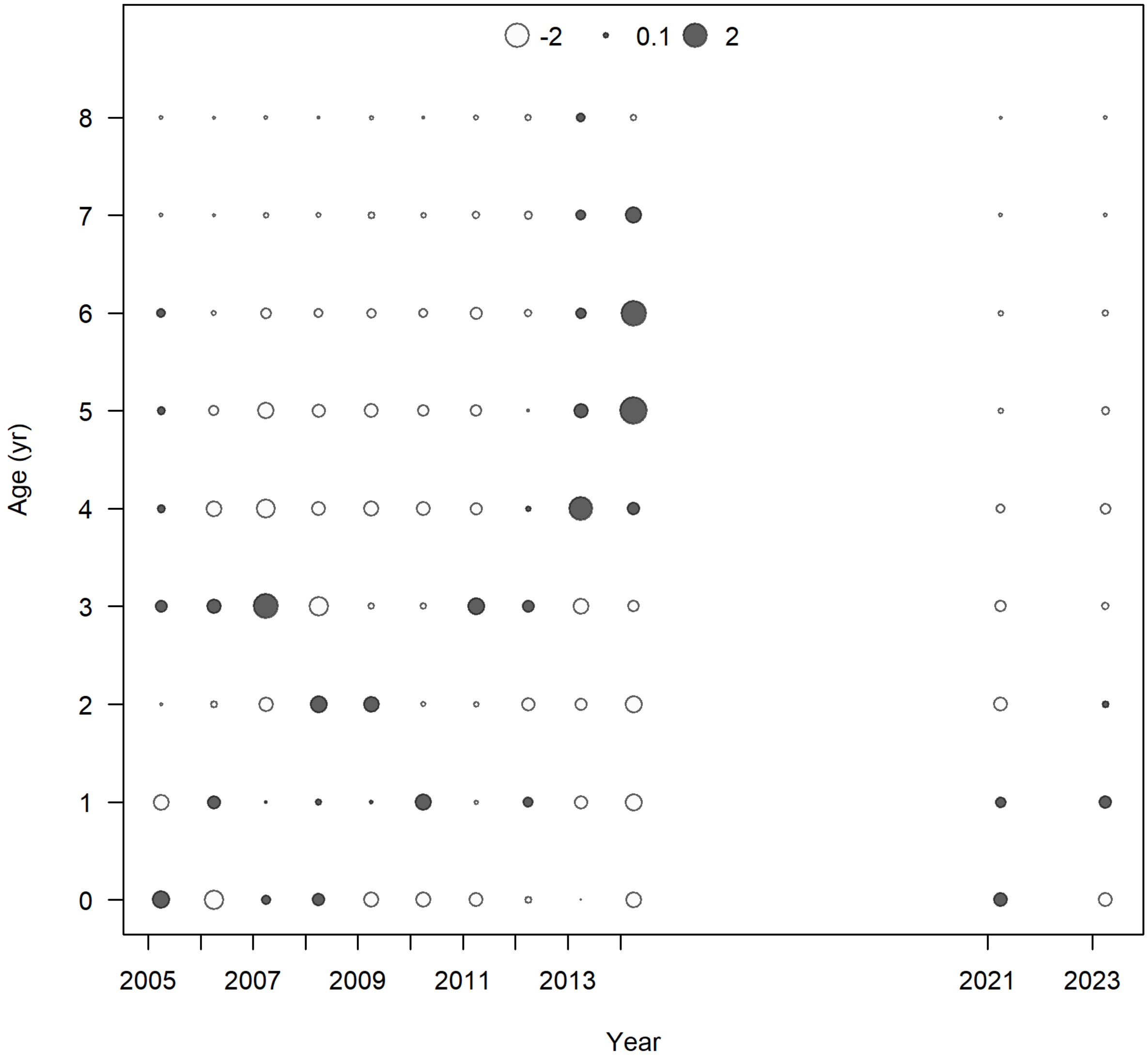

Figure 8.29: Residuals of fit to age-composition time series for the MexCal S1 fleet in the base model.

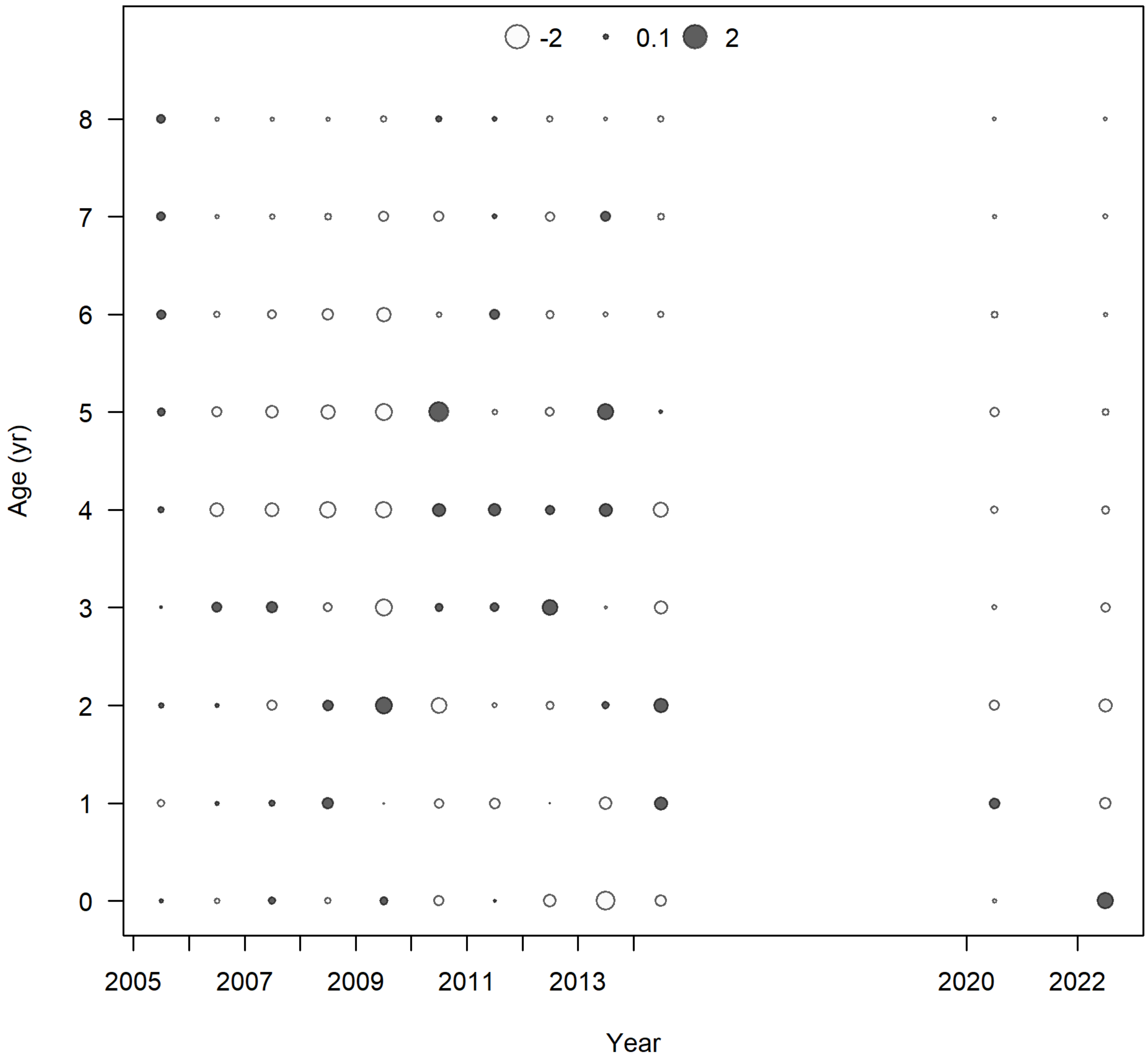

Figure 8.30: Residuals of fit to age-composition time series for the MexCal S2 fleet in the base model.

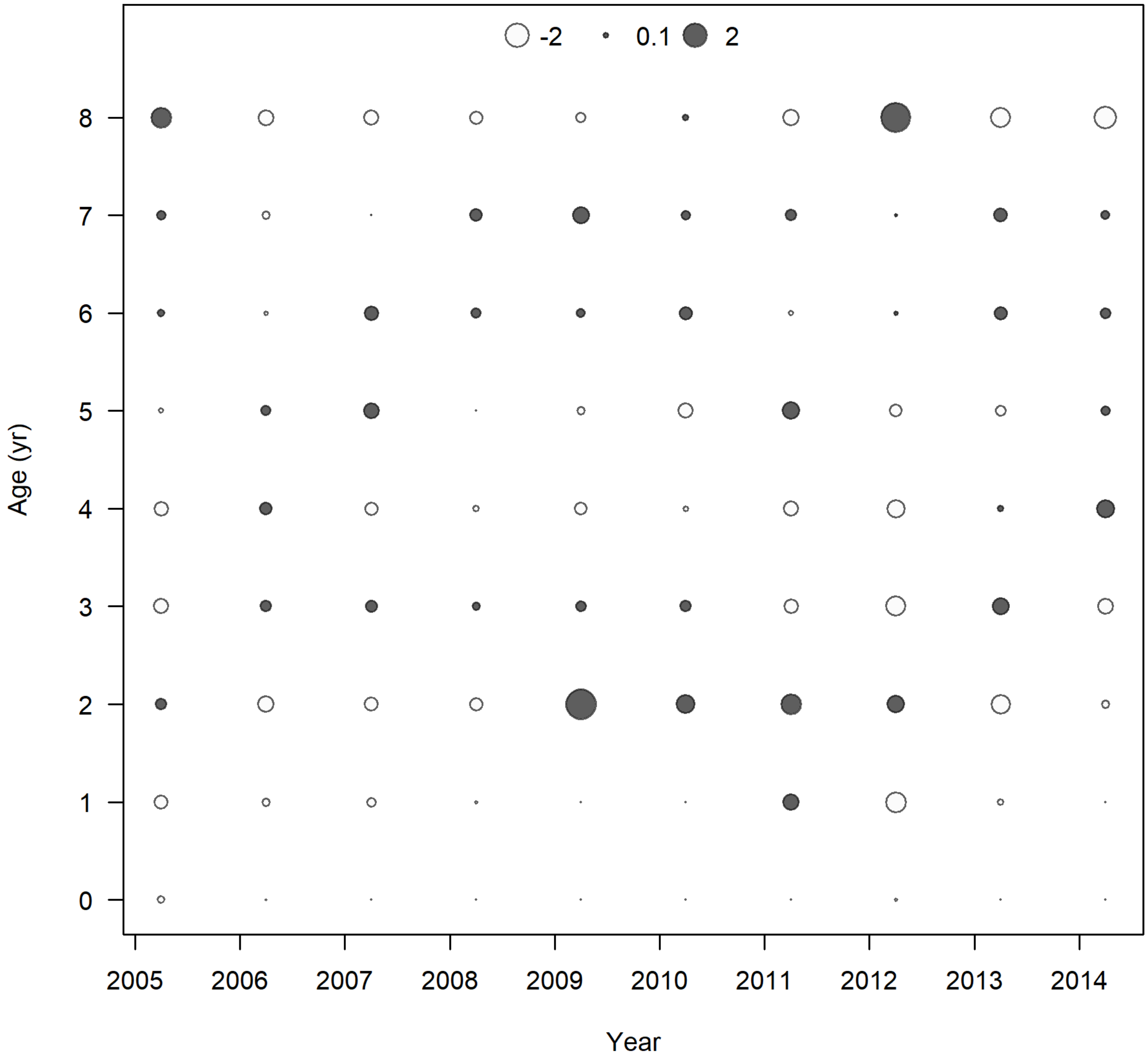

Figure 8.31: Residuals of fit to age-composition time series for the PNW fleet in the base model.

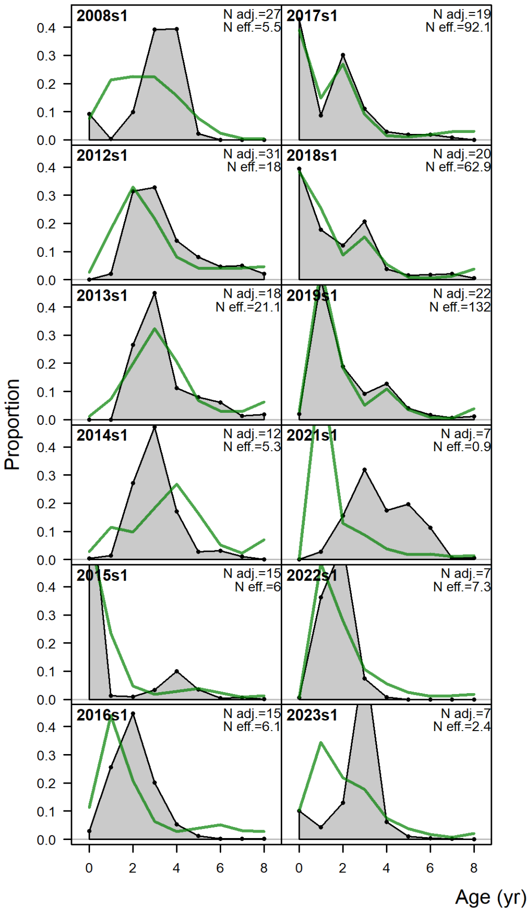

Figure 8.32: Fit to age-composition time series for the AT survey in the base model. Values in the top right are input sample sizes (N adj) and effective sample size given statistical fit in the model (Neff).

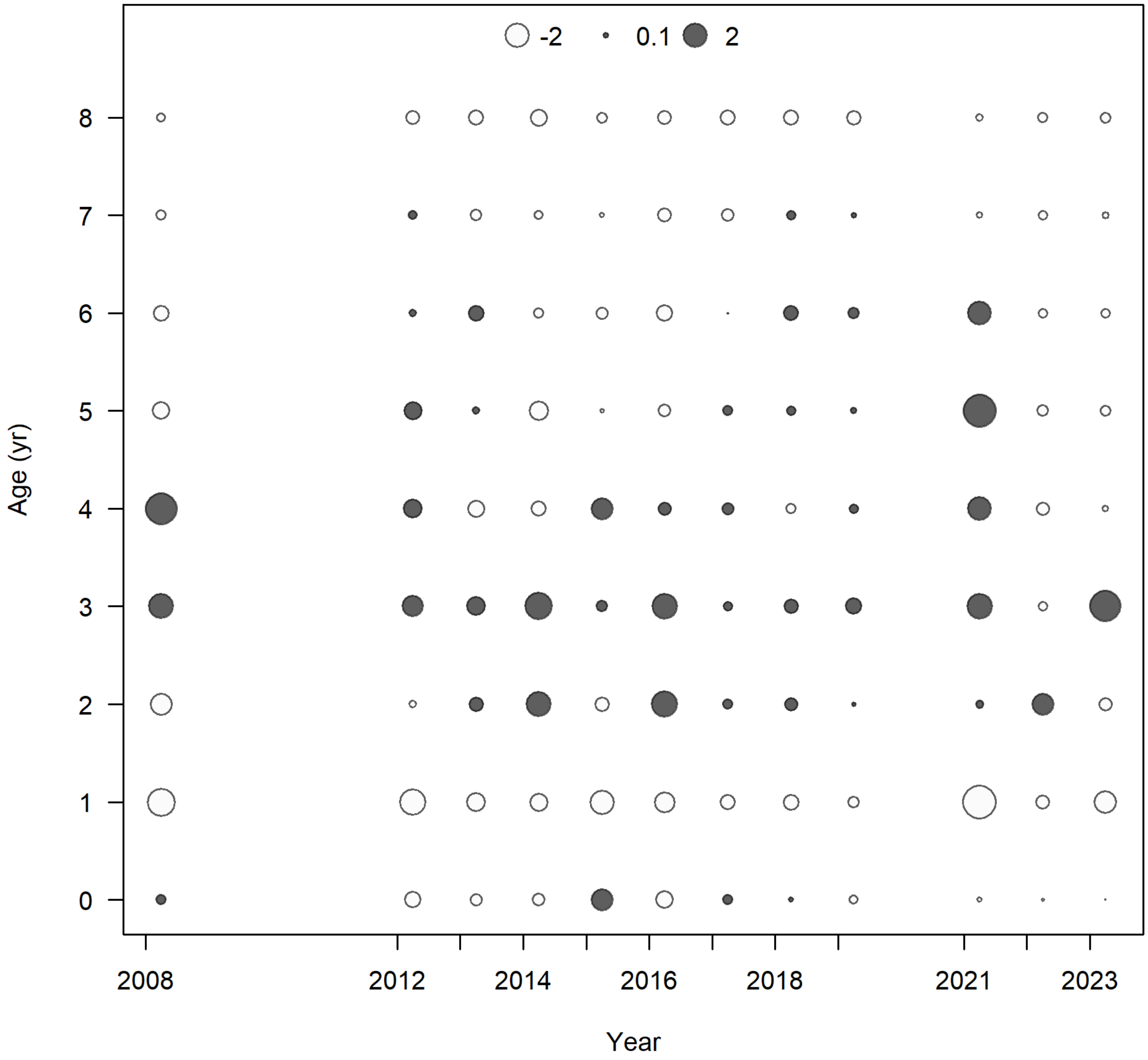

Figure 8.33: Residuals of fit to age-composition time series for the AT survey in the base model.

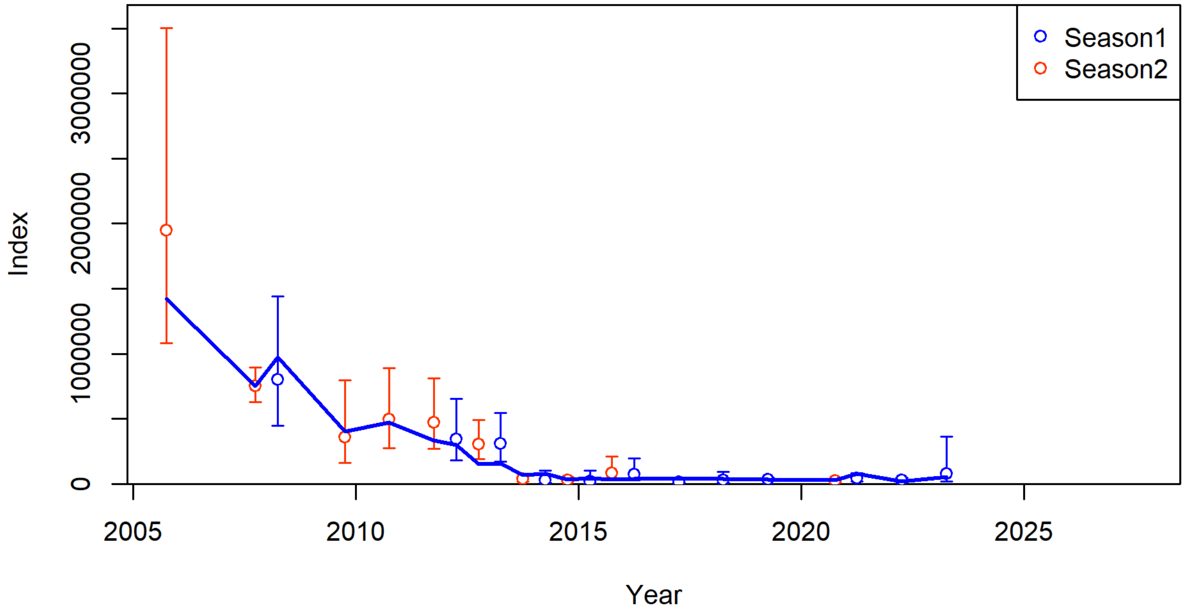

Figure 8.34: Fit to index data for AT survey. Lines indicate 95% uncertainty interval around index values.

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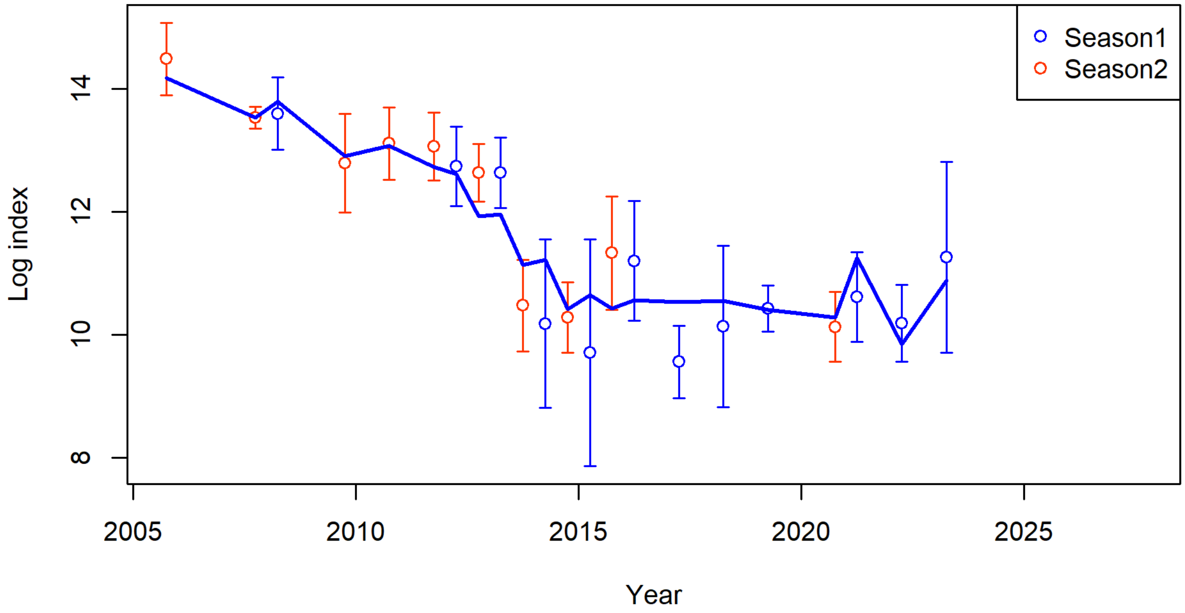

Figure 8.35: Fit to log-transformed index data for AT survey. Lines indicate 95% uncertainty interval around index values.

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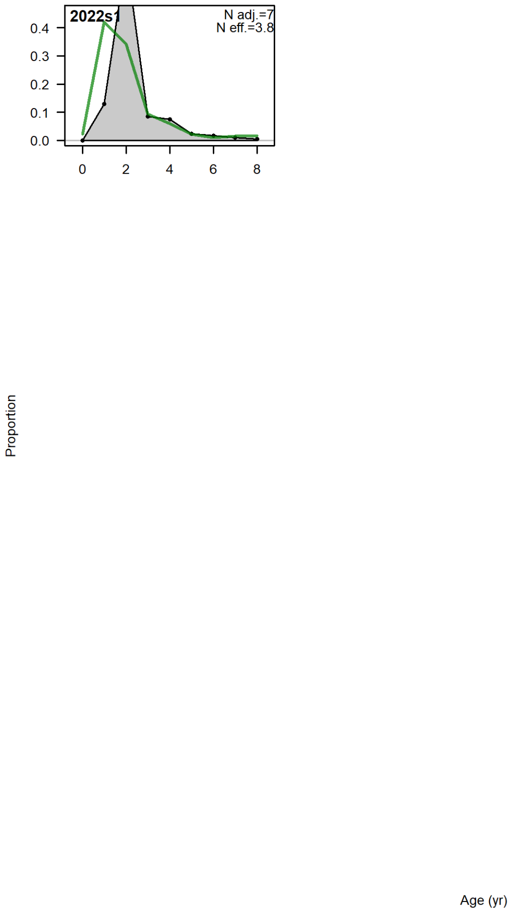

Figure 8.36: Fit to age-composition time series for the Lisa Marie survey in the base model. Values in the top right are input sample sizes (N adj) and effective sample size given statistical fit in the model (Neff).

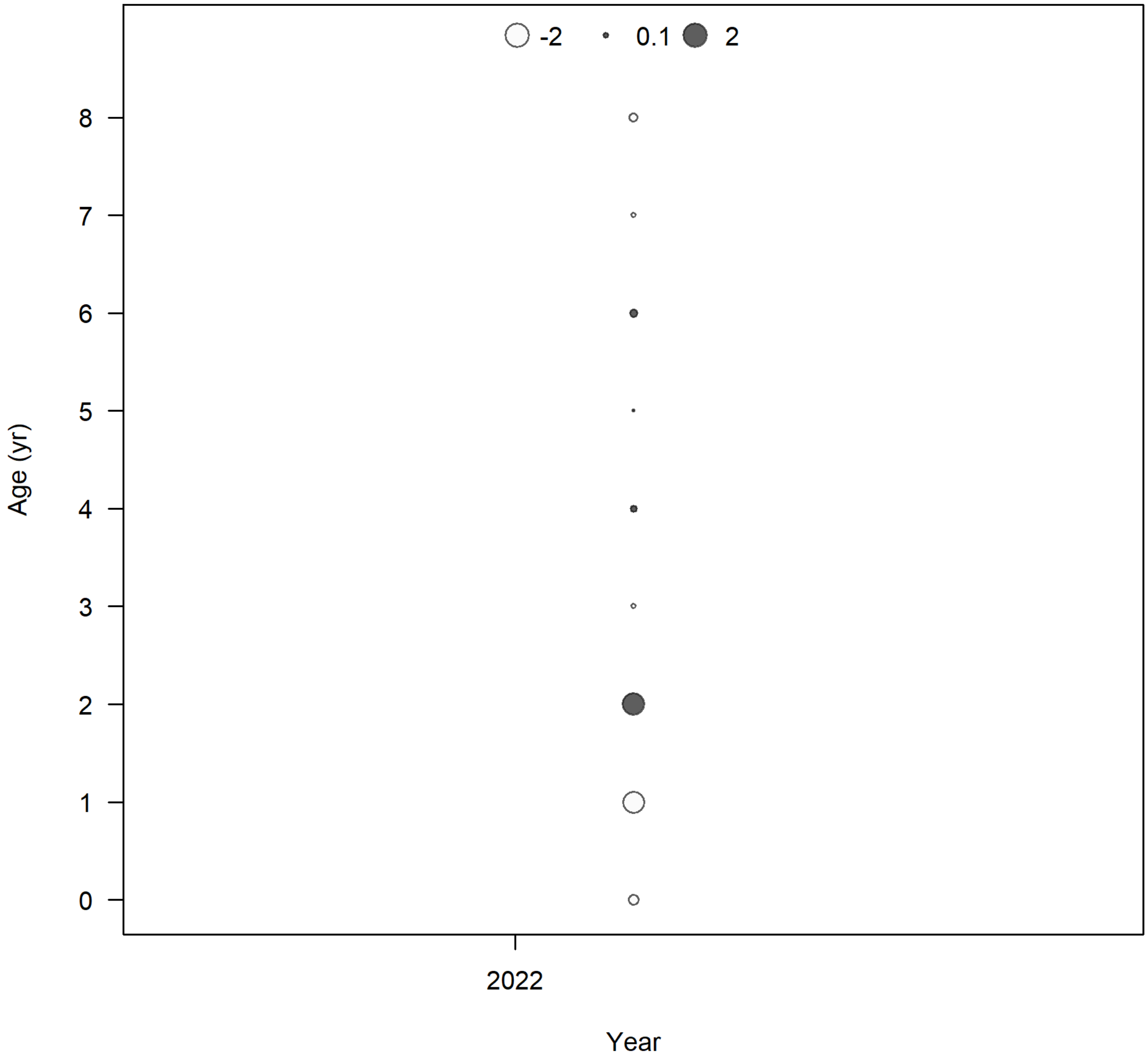

Figure 8.37: Residuals of fit to age-composition time series for the Lisa Marie survey in the base model.

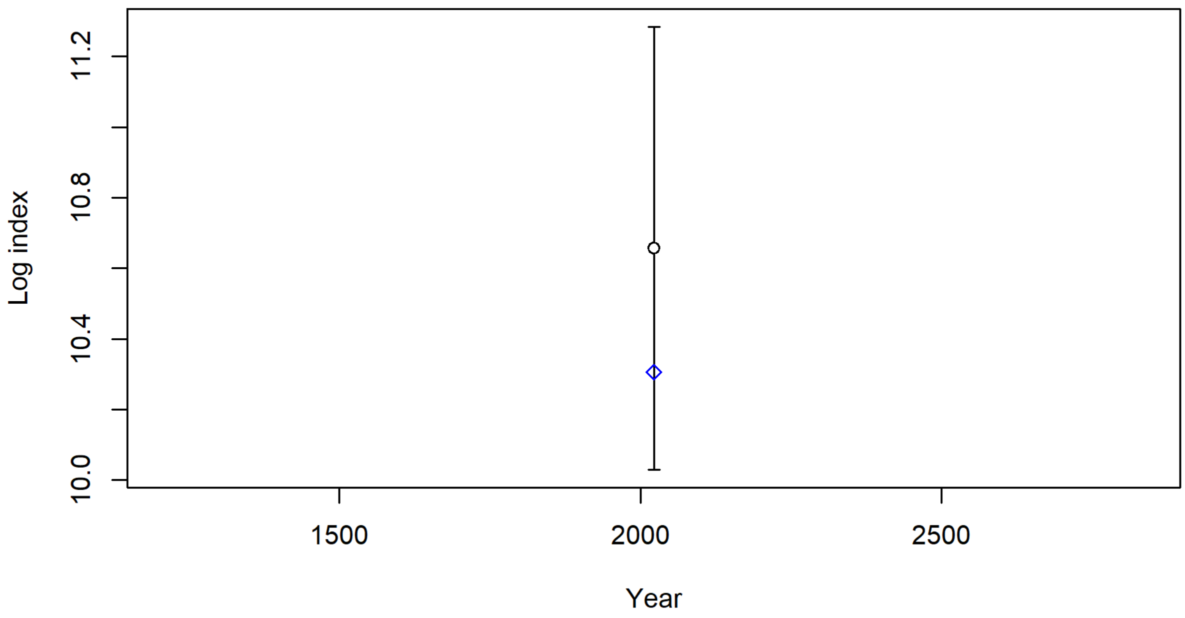

Figure 8.38: Fit to log-transformed index data for Lisa Marie survey. Lines indicate 95% uncertainty interval around index values.

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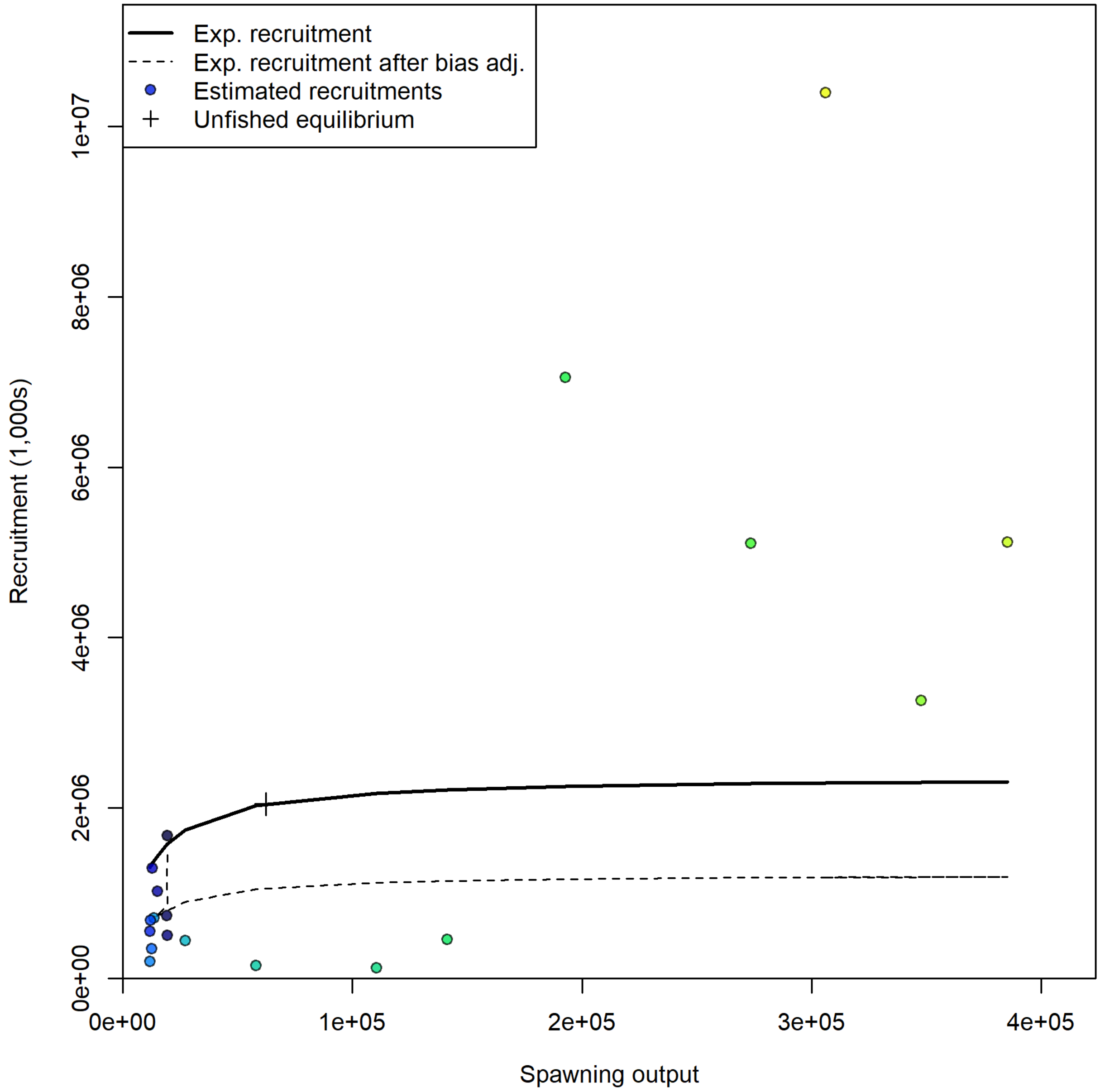

Figure 8.39: Estimated stock-recruitment (Beverton-Holt) relationship for the base model. Steepness is fixed (h = 0.3). Year labels represent year of SSB producing the subsequent recruitment year class.

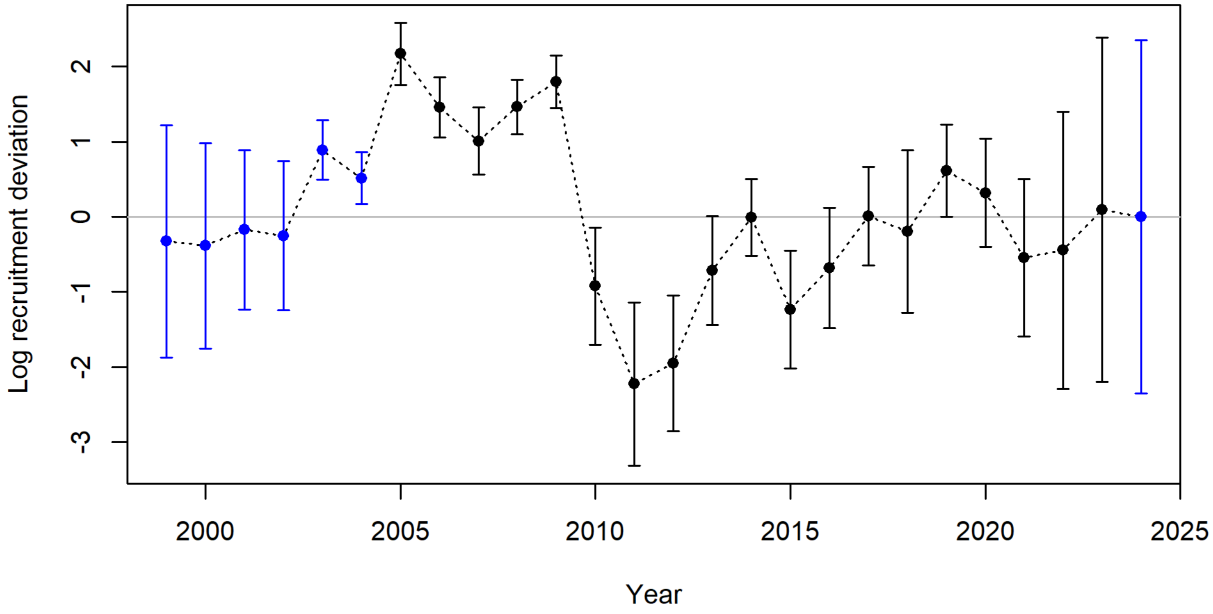

Figure 8.40: Recruitment deviations and standard errors ($\sigma_R$=1.2) for the base model.

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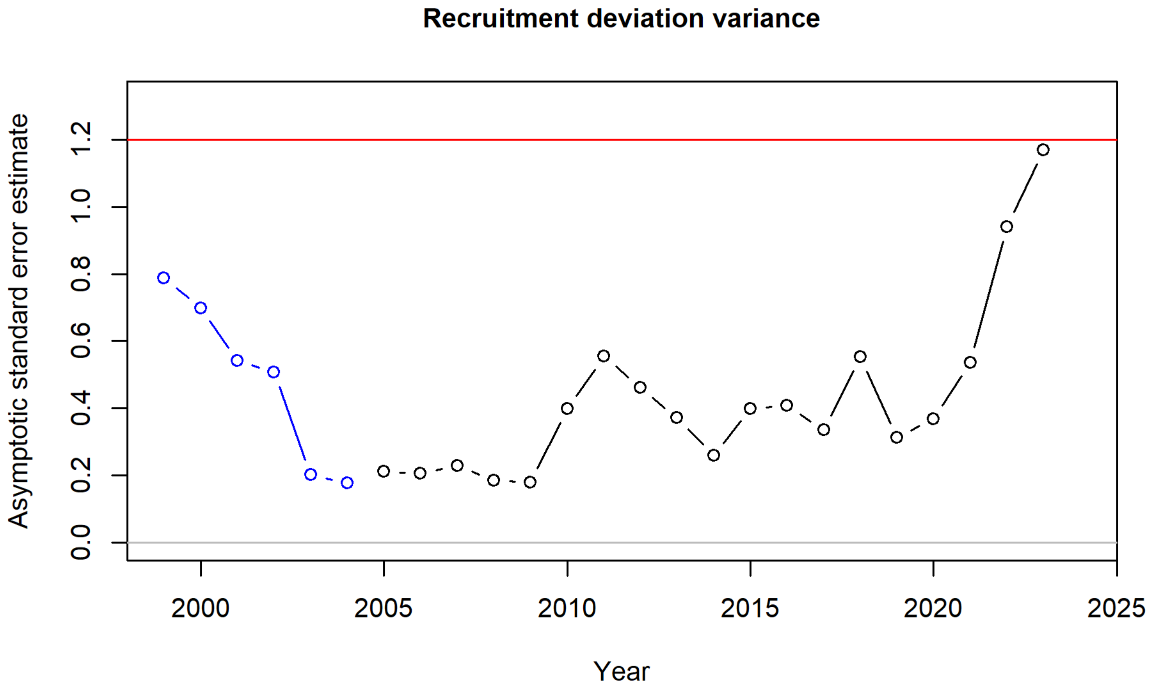

Figure 8.41: Asymptotic standard errors for estimated recruitment deviations for the base model.

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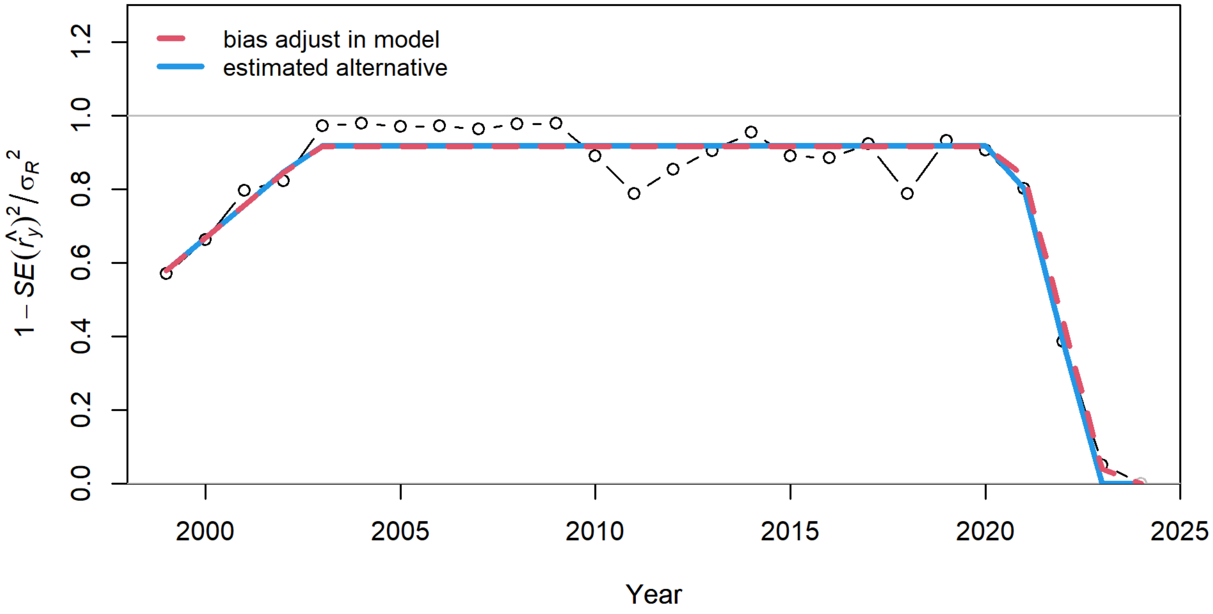

Figure 8.42: Recruitment bias adjustment plot for early, main, and forecast periods in the base model.

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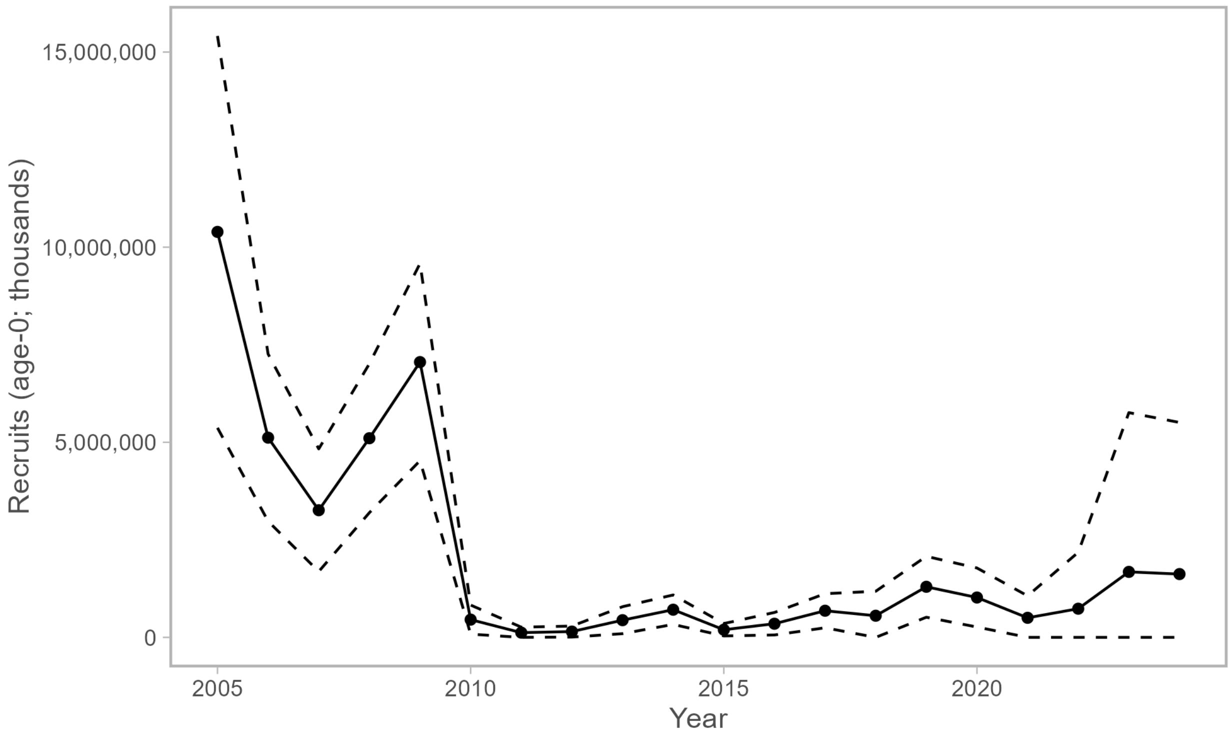

Figure 8.43: Estimated recruitment (age-0 fish, thousands) time series for the base model.

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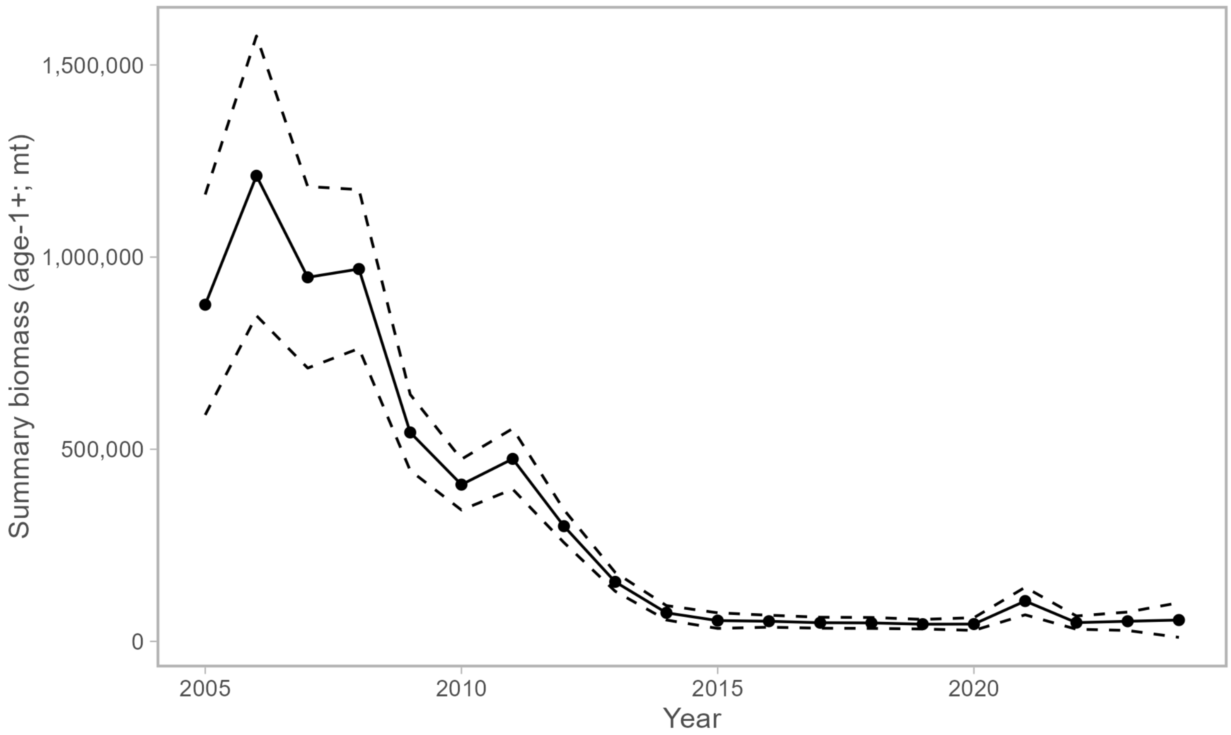

Figure 8.44: Summary (age-1+) biomass time series (95% CI dashed lines) for the base model.

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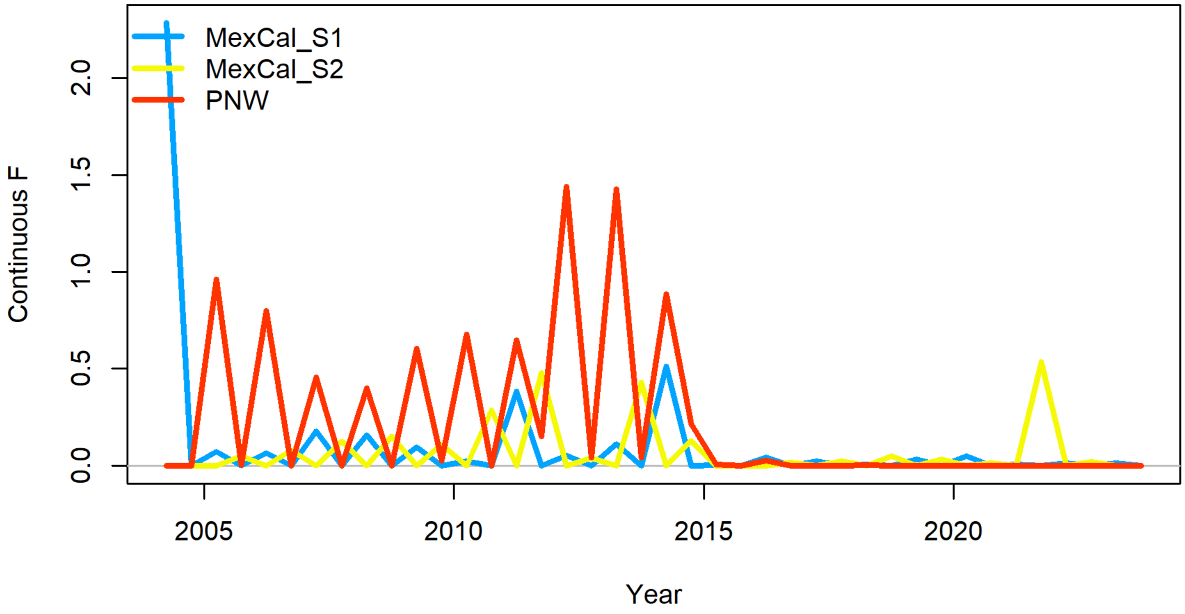

Figure 8.45: Instantaneous fishing mortality (apical F) time series for the base model.

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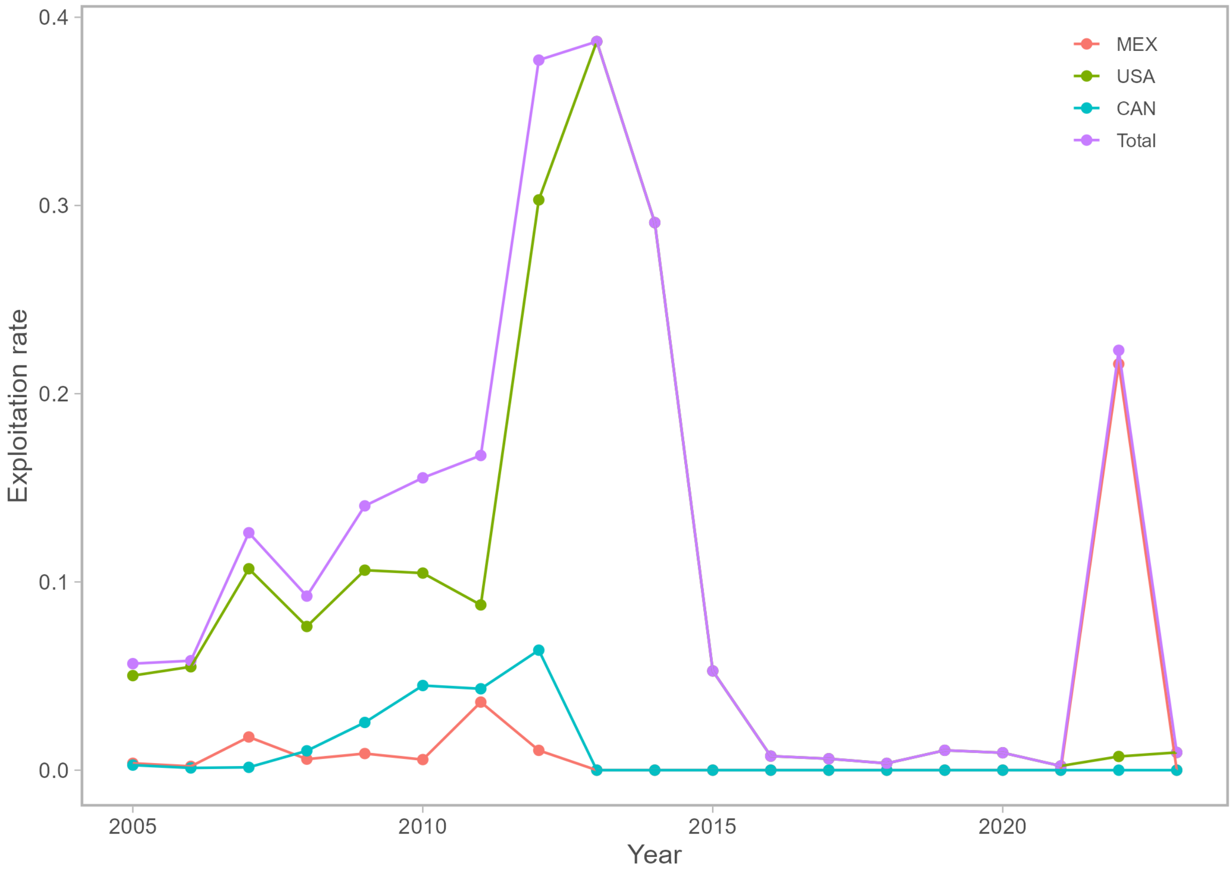

Figure 8.46: Annual exploitation rates (calendar year landings / July total biomass) for the base model.

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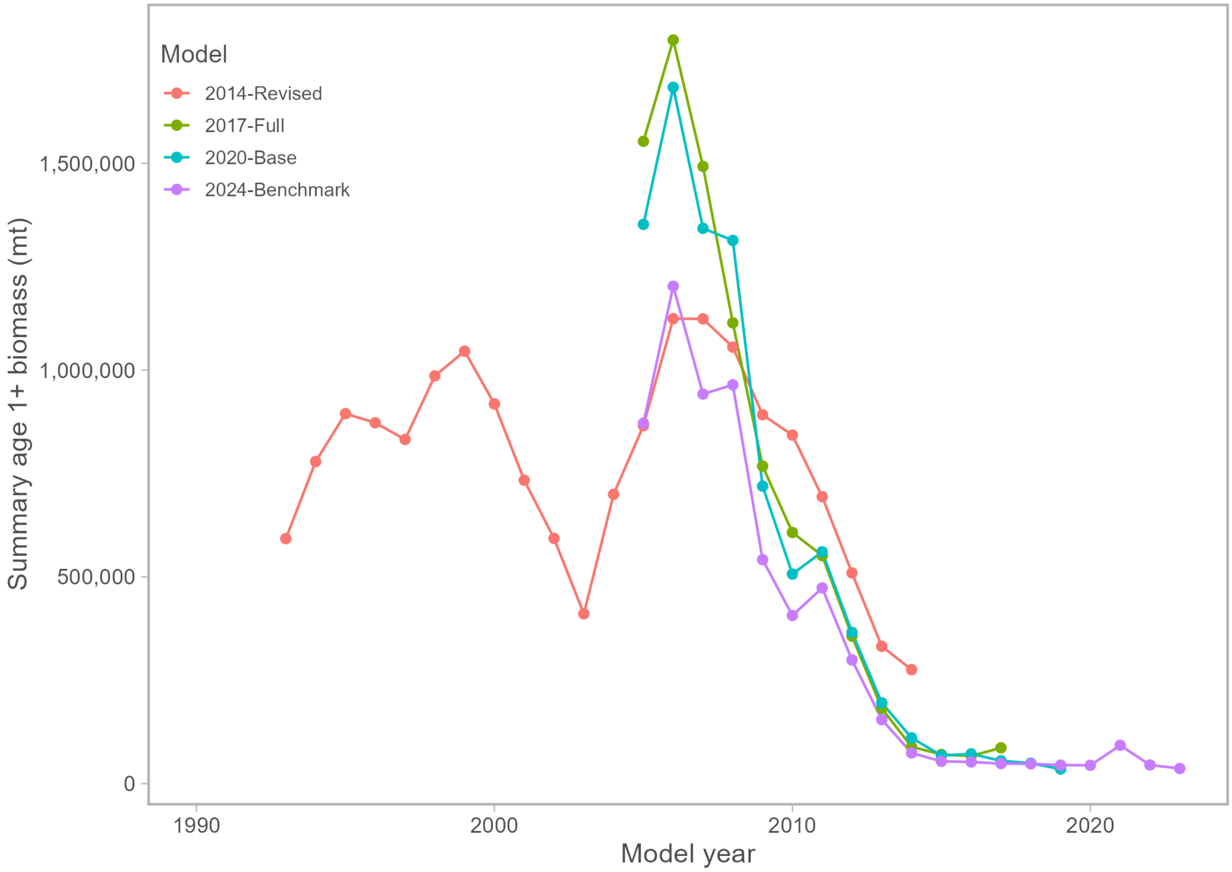

Figure 8.47: Estimated stock biomass (age 1+, mt) time series for 2020 base model and past assessment models used for management. It is not possible to compare uncertainties around these estimates as SS3 only added this option in 2022.

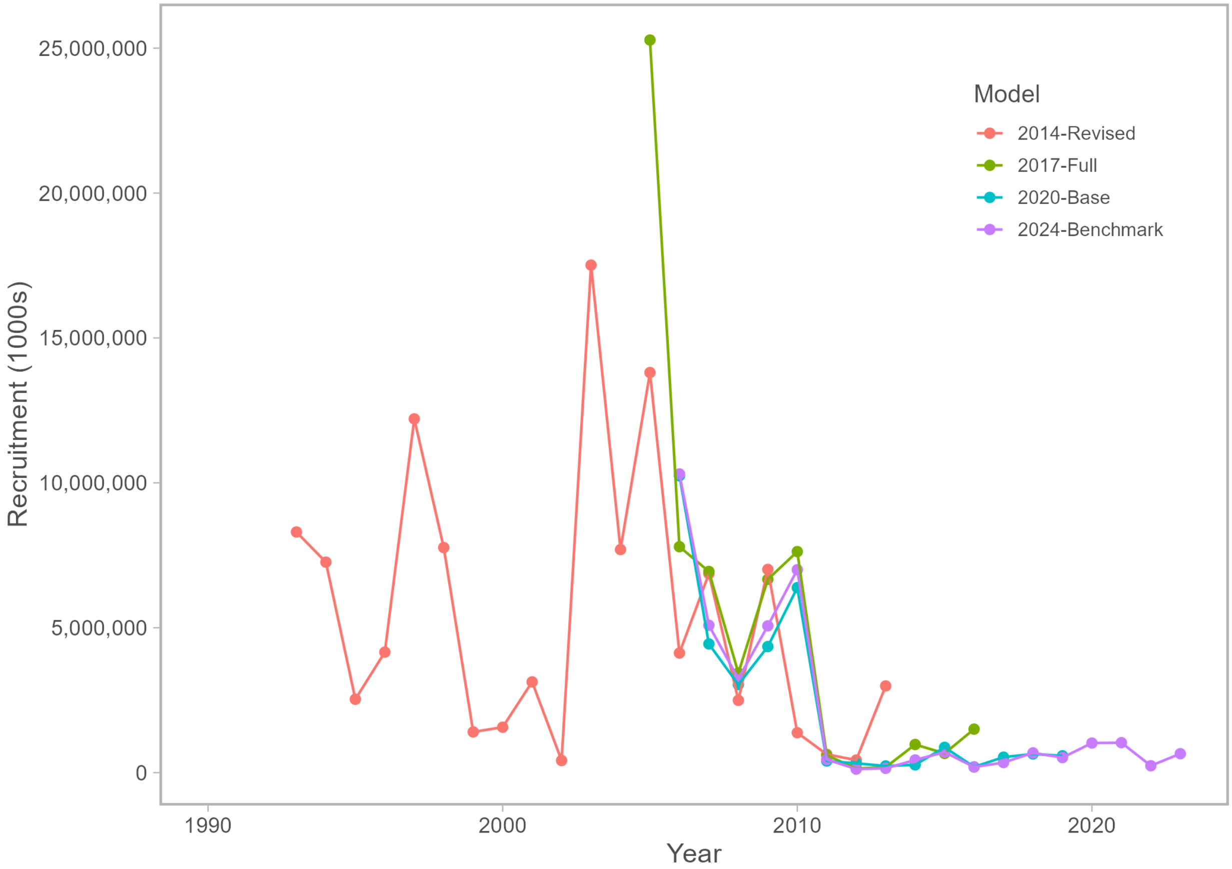

Figure 8.48: Estimated recruits (age-0) time series for 2020 base model and past assessment models used for management.

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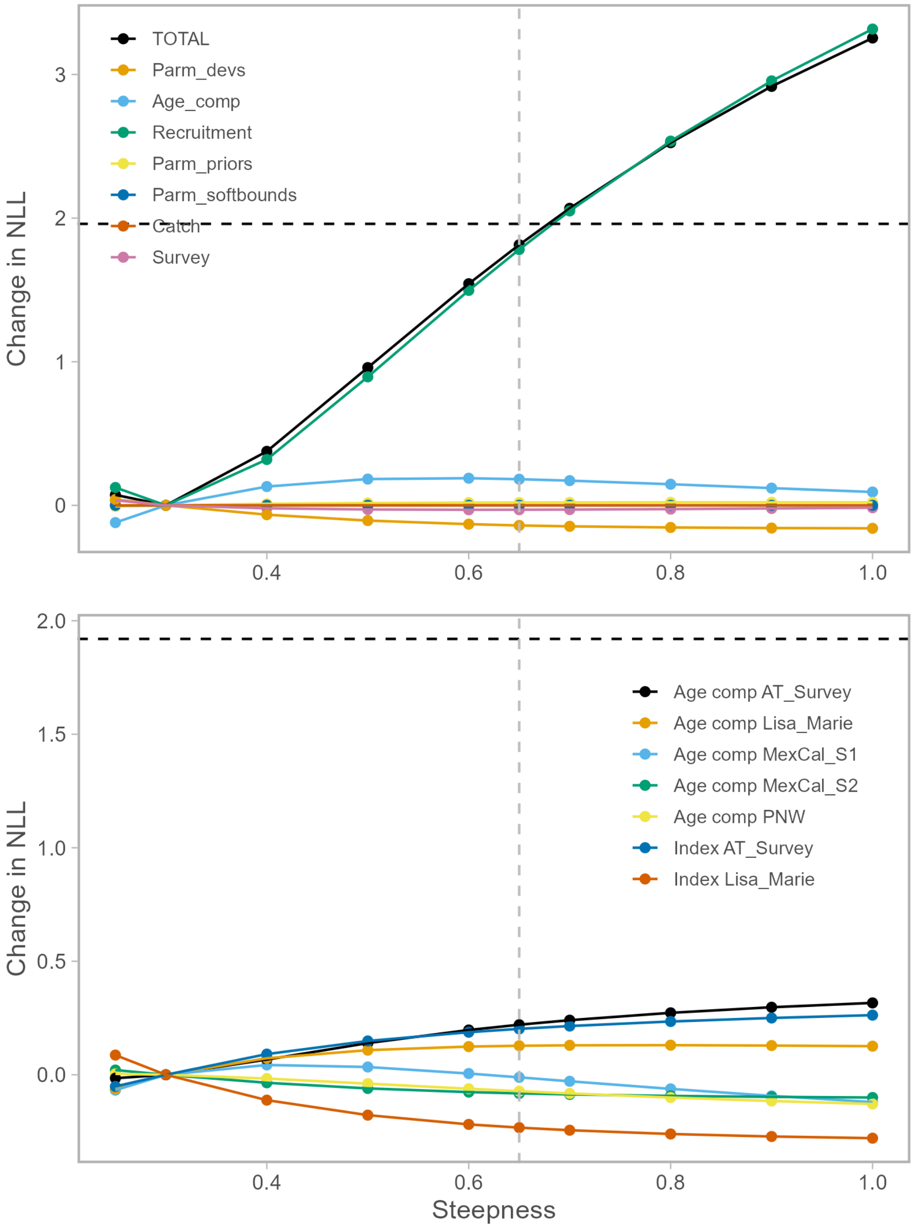

Figure 8.49: Likelihood profile across fixed values of steepness (h) for likelihood components (top plot) and fleet-specific likelihood components (bottom). Steepness was fixed at 0.65 in the 2024 base model (vertical dashed line). Values within 1.92 units of the MLE (dashed horizontal line) are within the 95% confidence interval.

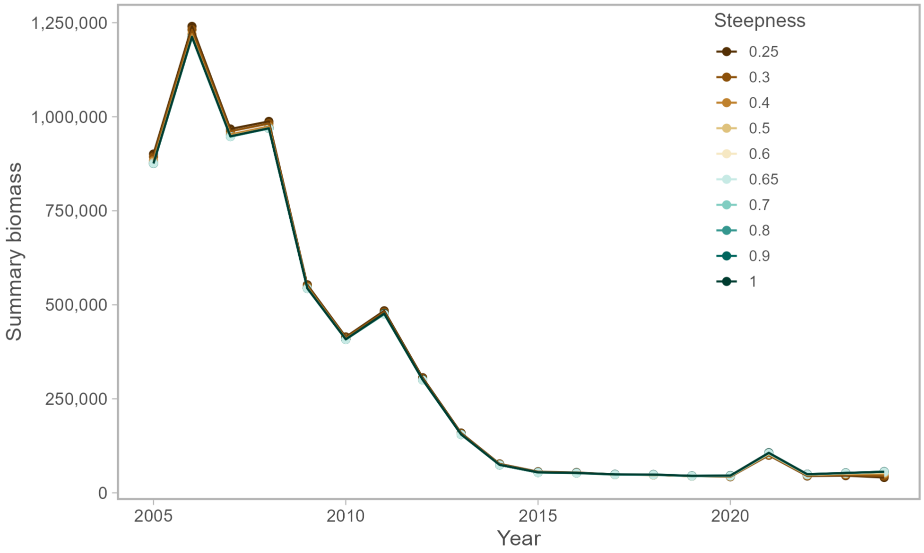

Figure 8.50: Summary biomass (age-1+; mt) estimates from models with fixed values of steepness (h) ranging from 0.25 to 1.

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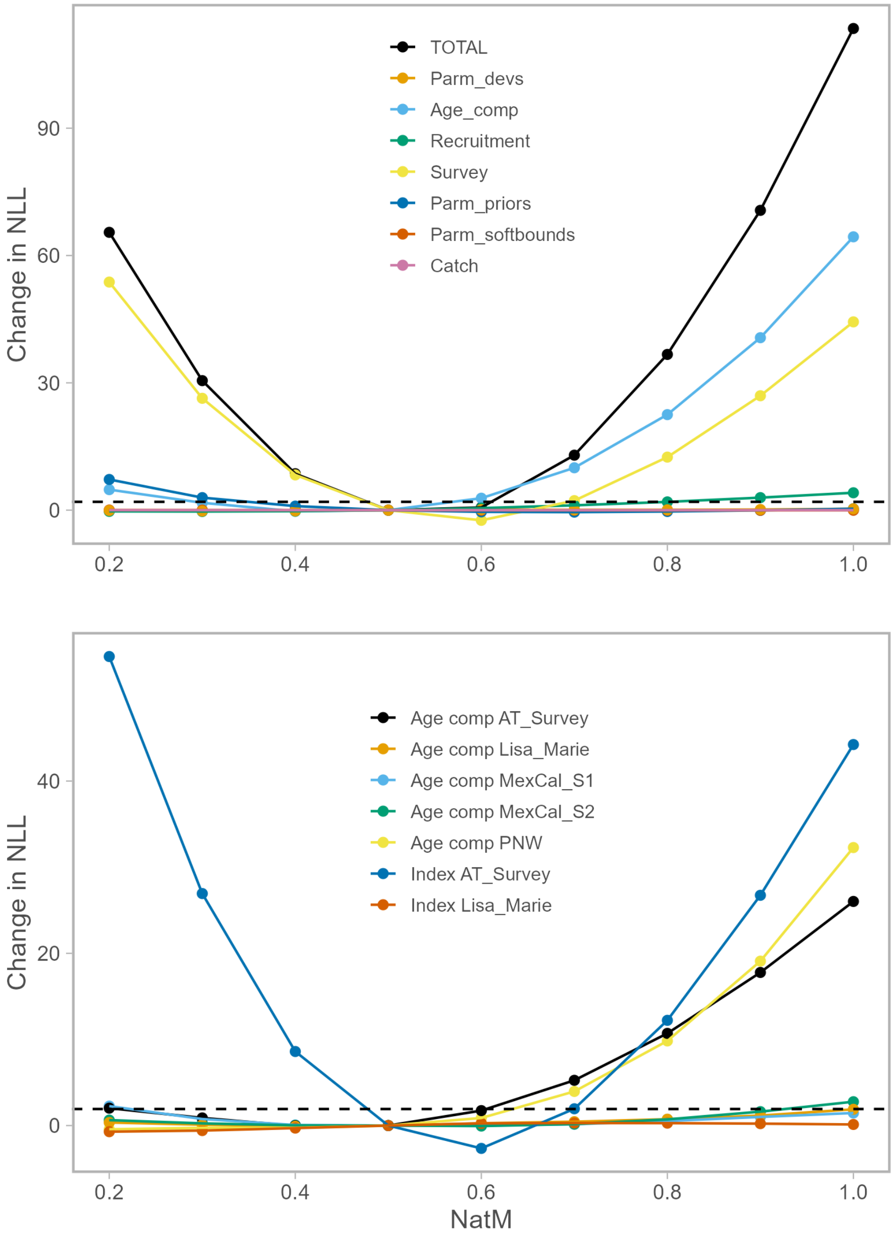

Figure 8.51: Likelihood profile across fixed values of natural mortality (M) ranging from 0.2 to 1 and estimated steepness for likelihood components (top plot) and fleet-specific likelihood components (bottom). This model configuration differs from that of the base model (fixed steepness and estimated natural mortality). Values within 1.92 units of the MLE (dashed horizontal line) are within the 95% confidence interval.

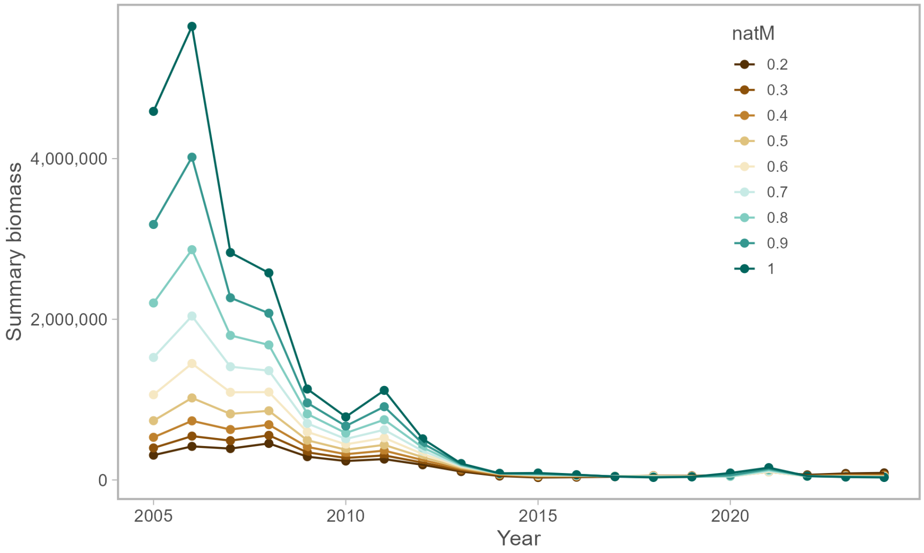

Figure 8.52: Summary biomass (age-1+; mt) estimates from models with fixed values of natural mortality (M) ranging from 0.2 to 1 and estimated steepness (h).

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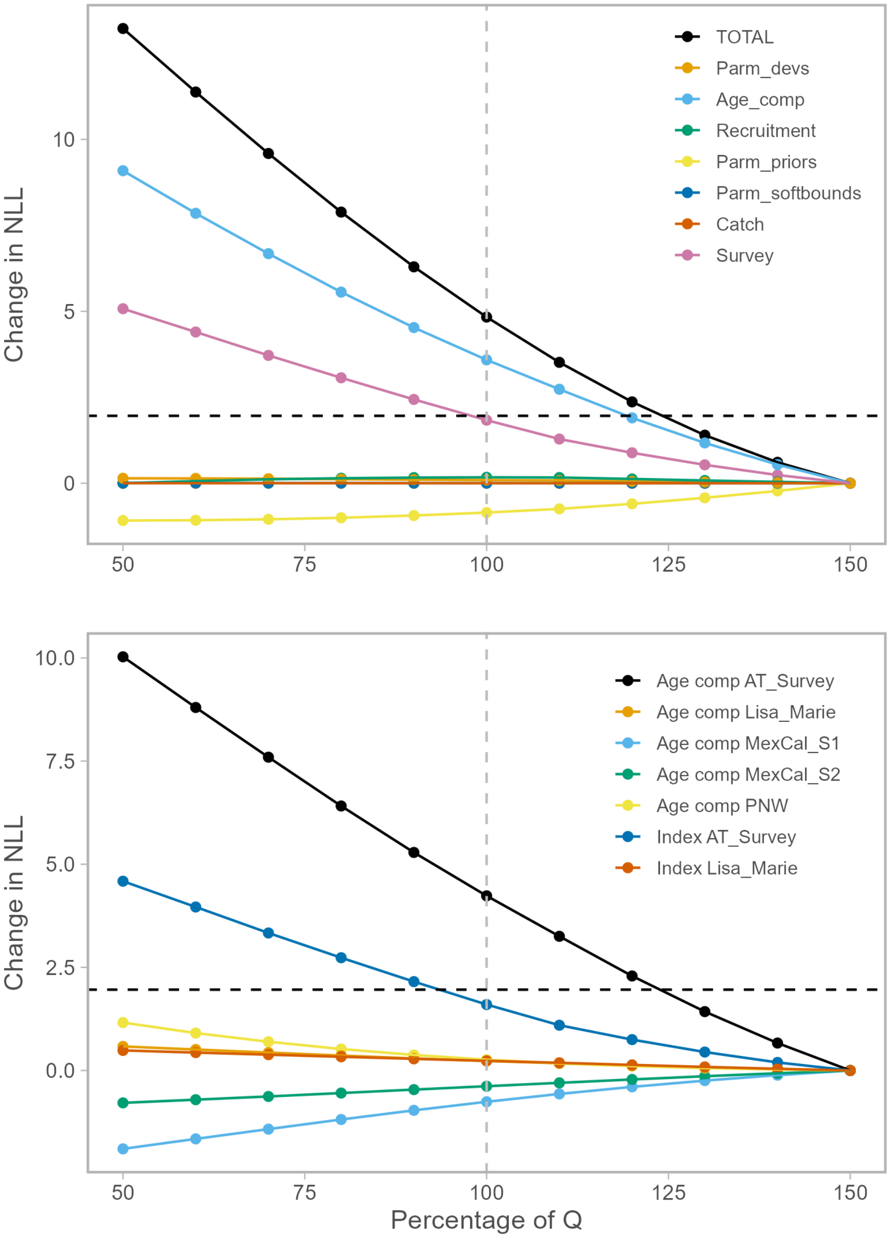

Figure 8.53: Likelihood profile across percentage adjustments to catchability (Q) values ranging from 50% to 150%. Values within 1.92 units of the MLE (dashed horizontal line) are within the 95% confidence interval.

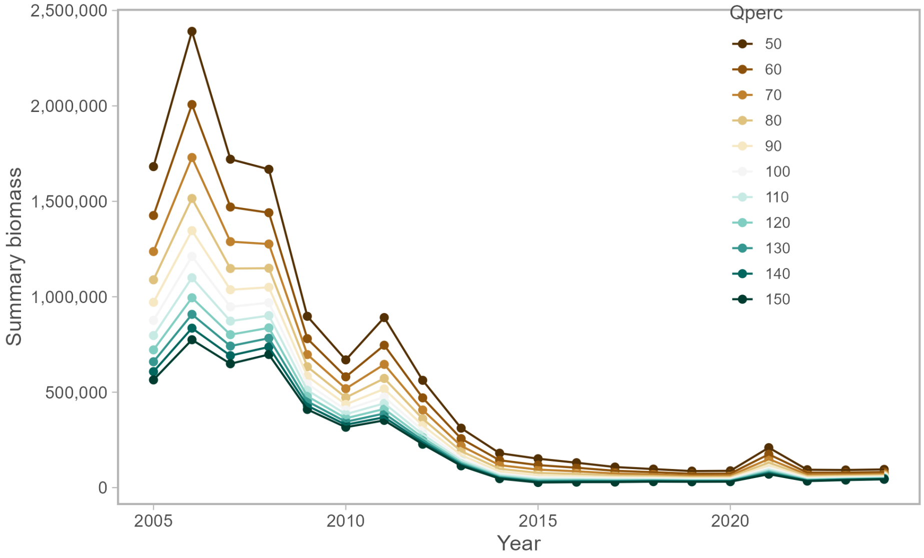

Figure 8.54: Summary biomass (age-1+; mt) estimates from models with catchability (Q) values ranging from 50% to 150%

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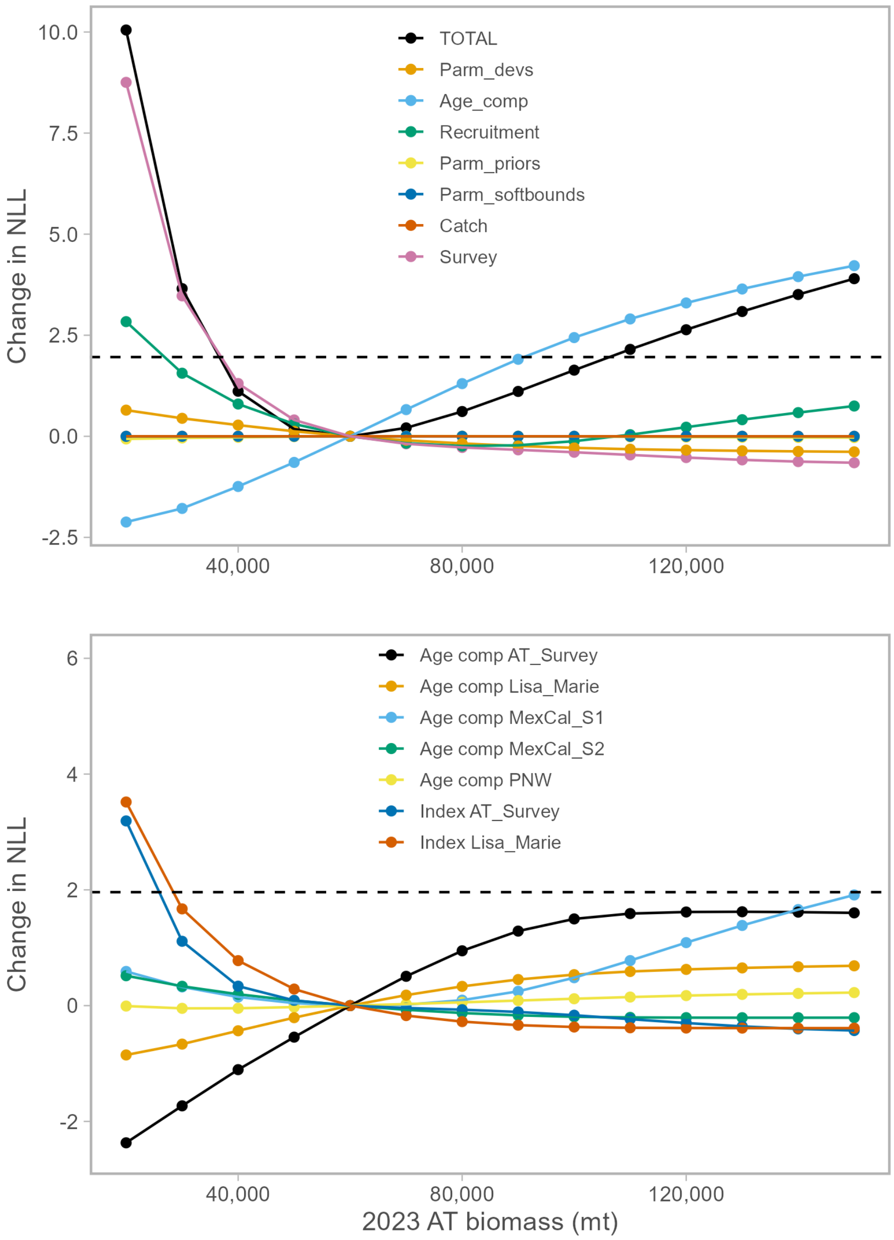

Figure 8.55: Likelihood profile across 2023 survey biomass values ranging from 20,000 to 150,000 mt. These biomass values were added as an additional survey in the model. Values within 1.92 units of the MLE (dashed horizontal line) are within the 95% confidence interval.

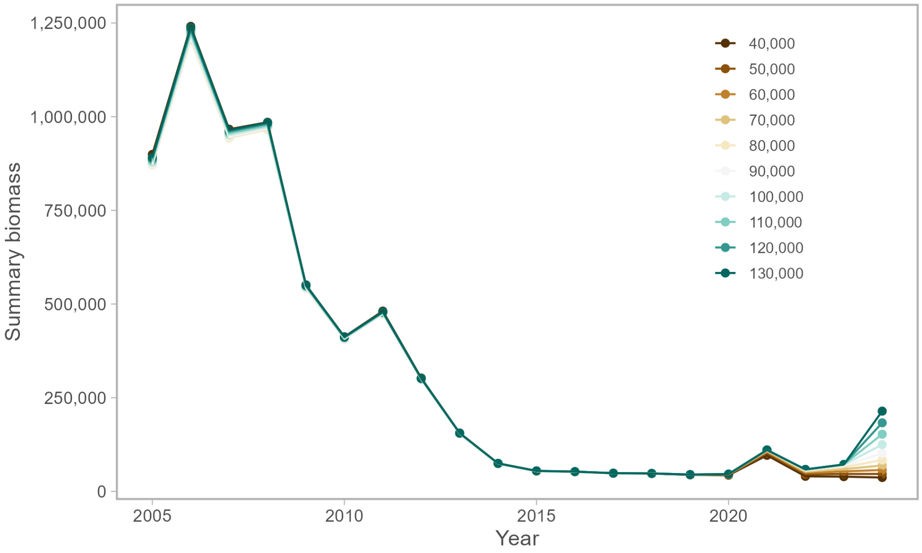

Figure 8.56: Summary biomass (age-1+; mt) estimates from models with 2023 survey biomass values ranging from 40,000 to 130,000. Note that the range of biomass values does not include 20,000; 30,000; 140,000; nor 150,000 mt due to insufficient colors to plot in the R software.

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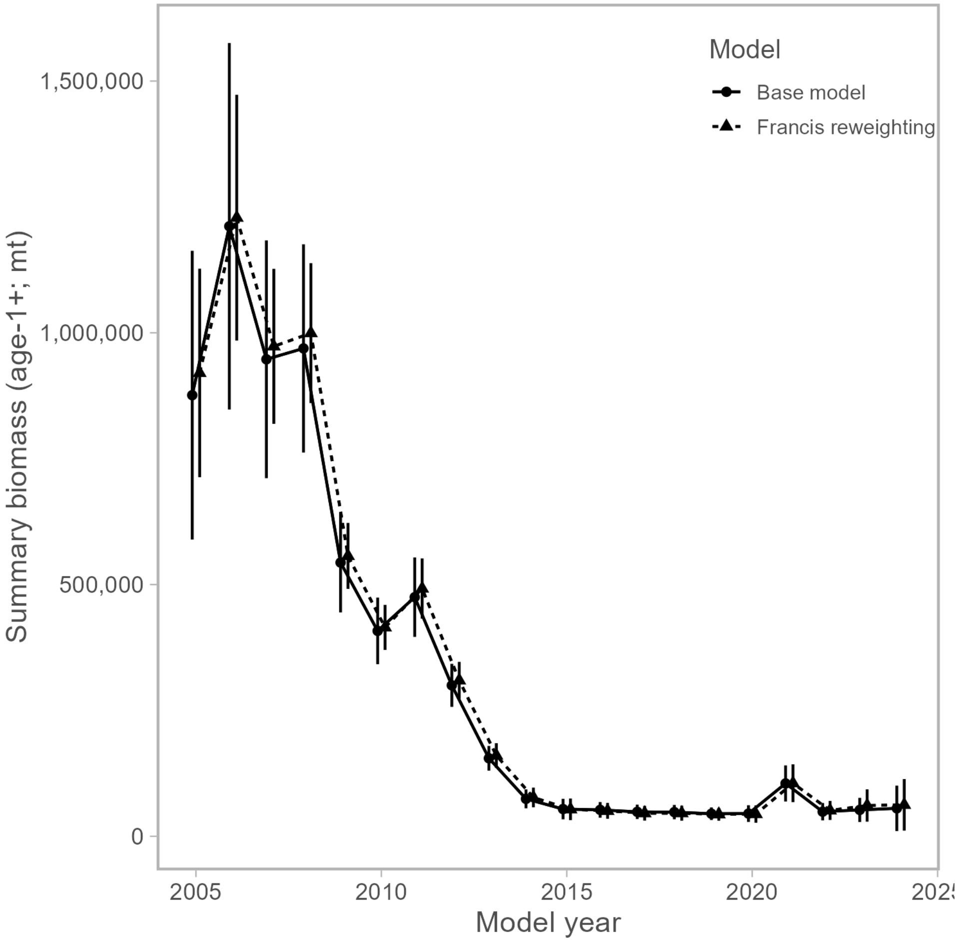

Figure 8.57: Age-1+ summary biomass (mt) values estimated from the base model (solid line)and the model with Francis reweighting (dashed line) for the age composition from the fishing and AT survey fleets.

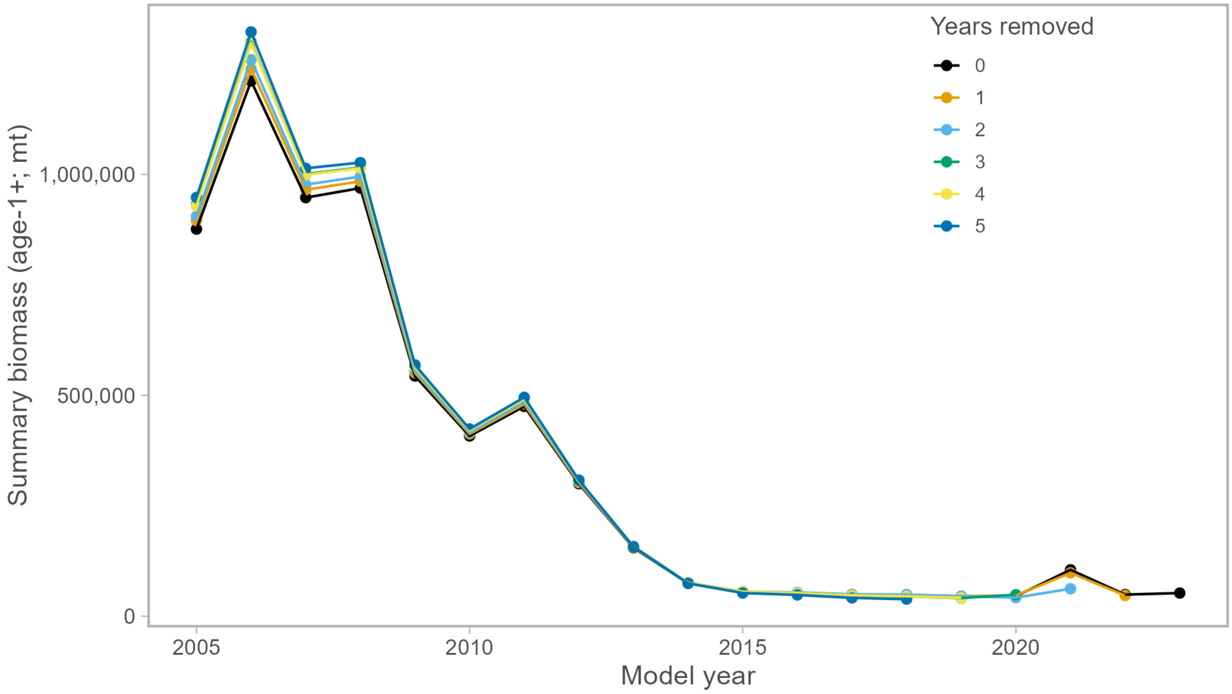

Figure 8.58: Retrospective analysis of summary biomass estimates. One year of data is removed for each model run.

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# 9 Appendix A: Bridging Analysis

The first step of the bridging analysis was to run the 2020 benchmark sardine assessment, which was run with ss3.30.14, with ss3.30.22 (the most recent version of SS3 as of December 2023). There were relatively large differences parameter estimates (e.g. natural mortality, unfished recruitment), biomass estimates, and likelihood values. The difference in summary biomass values is shown in Figure 9.1 below.

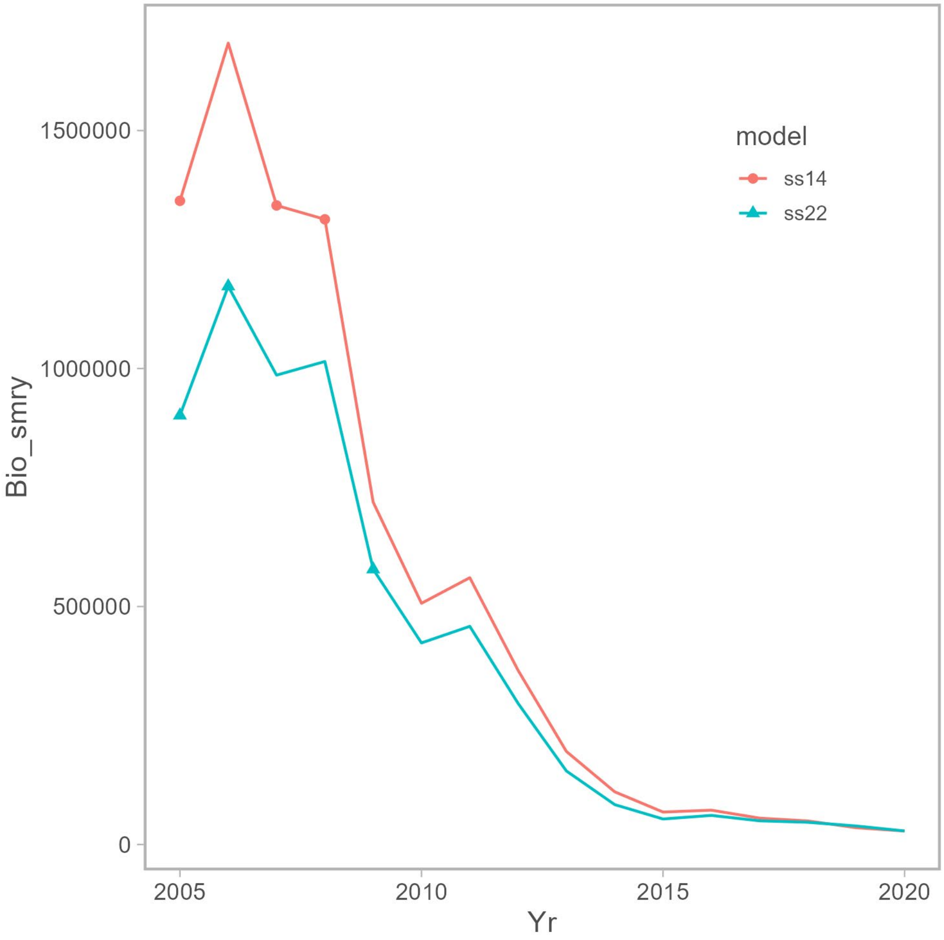

Figure 9.1: Summary biomass (age-1+; mt) from models run with ss3.30.14 (red line; ss14) and ss3.30.22 (blue line; ss22).

The next step was to check the calculations between ss3.30.14 and ss3.30.22. A model with ss3.30.22 was run with no estimation (-maxI 0 in the SS command line call) from the par file from the 2020 benchmark assessment (ss3.30.14). One technical note is that the Fcast_impl_error line in the par file had to be deleted to be compatible with ss3.30.22. This run had slight differences in the calculated values (Figure 9.2) and the expectation was that these values would be identical.

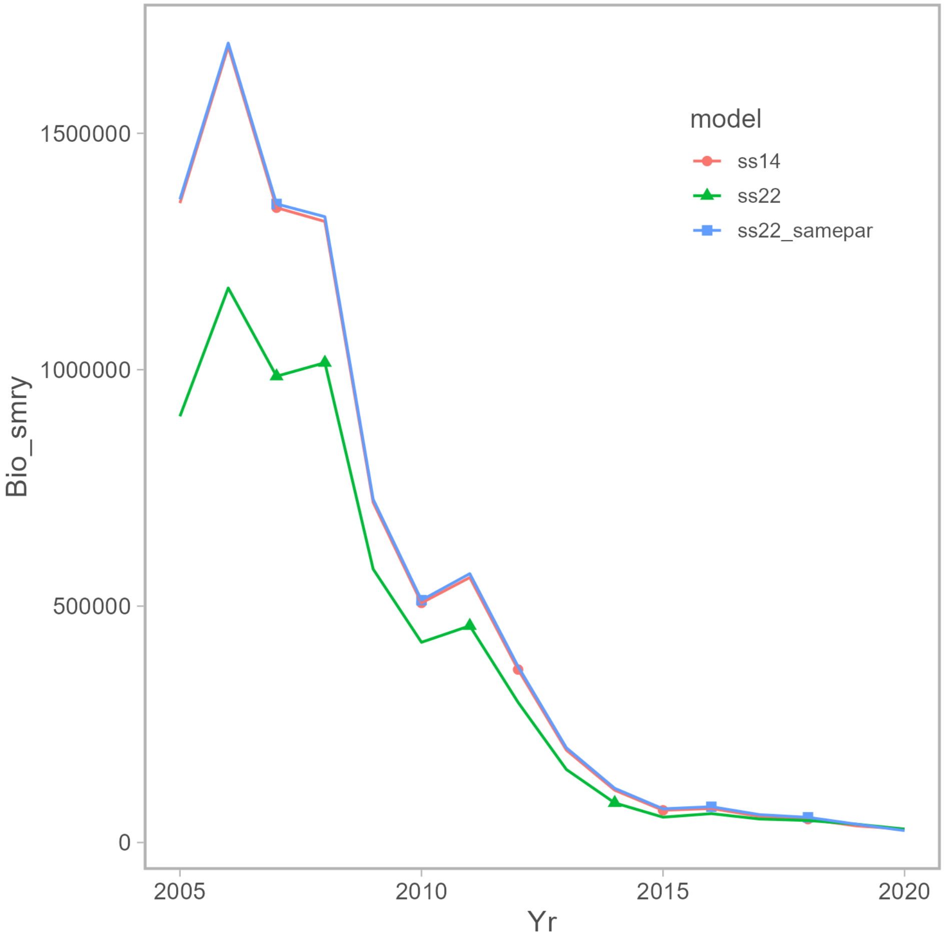

Figure 9.2: Summary biomass (age-1+; mt) from models run with ss3.30.14 (red line; ss14), ss3.30.22 (green line; ss22), and ss3.30.22 from the ss14 par file (blue line; ss22_samepar).

It seemed that something changed in updated versions of SS3. The 2020 sardine benchmark assessment was then run with each version of SS3 between ss3.30.14 and ss3.30.22. The estimates from ss3.30.14 to ss3.30.20 were identical. The version ss3.30.21 had some slight changes (difficult to see in the Figure 9.3 below), and ss3.30.22 had the aforementioned difference.

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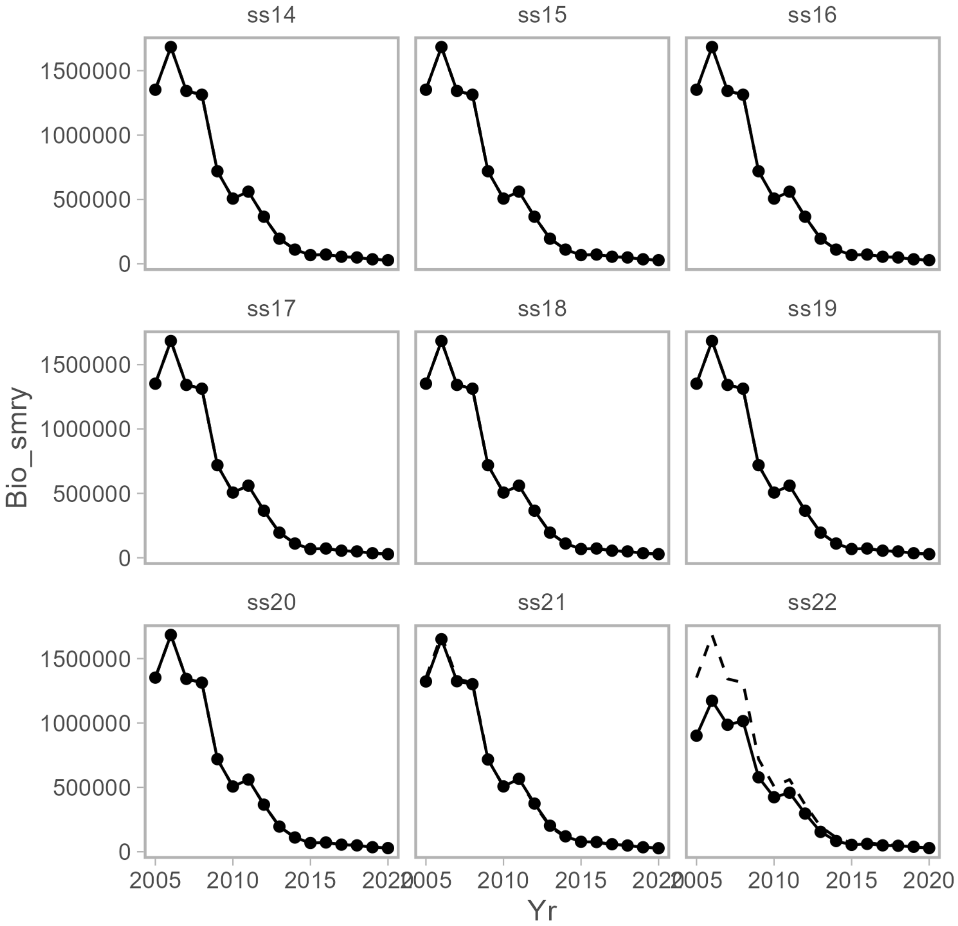

Figure 9.3: Summary biomass (age-1+; mt) from models run with ss3.30.14 (ss14) to SS3.30.22 (ss22).

Ian Taylor (NOAA NWFSC) identified the age length key (ALK) tolerance setting as one change that affected model estimates between ss3.30.14 and ss3.30.22. For the 2020 benchmark assessment, the ALK tolerance was set to 0.0001. This feature is deprecated in ss3.30.22 and nonzero ALK values are overwritten to 0.

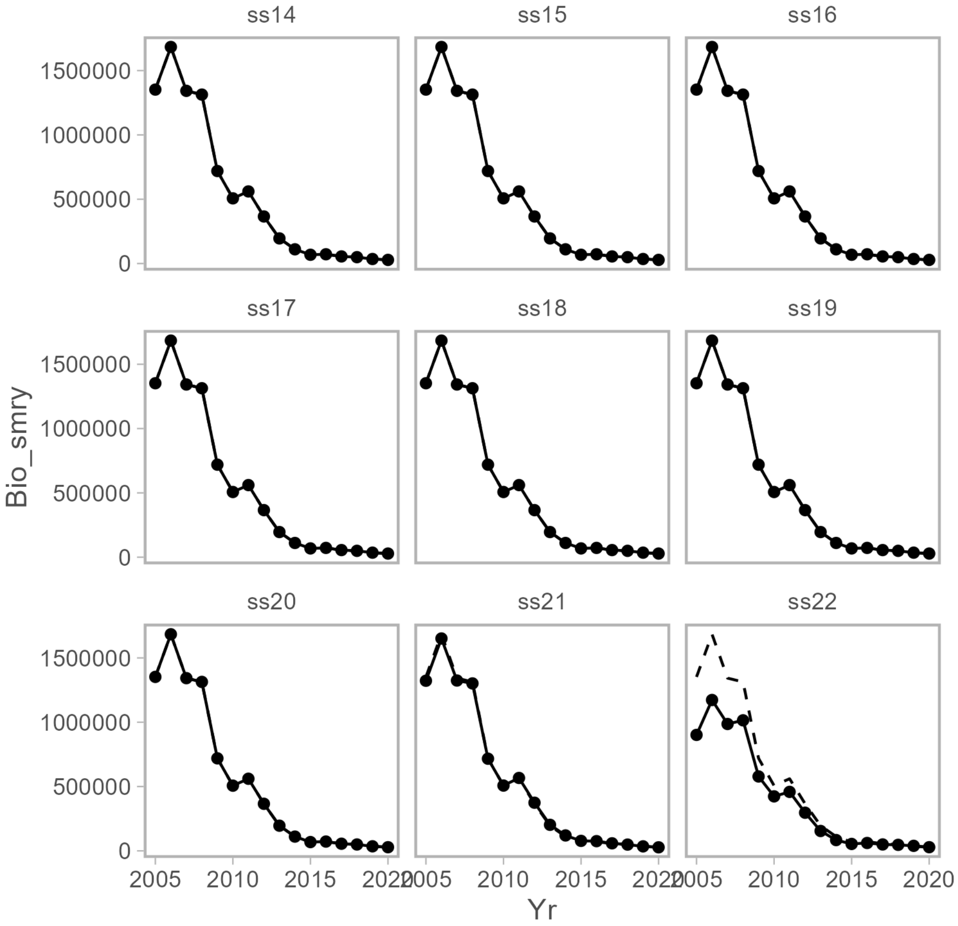

Figure 9.4: Summary biomass (age-1+; mt) from models run with ss3.30.14 ALK=0.0001 (ss14), ss3.30.14 and ALK = 0 (ss14_ALK0), and ss3.30.22 with ALK = 0 (SS22_ALK0_par14).

If ALK tolerance = 0 in both ss3.30.14 and ss3.30.22, the model results are identical biomass estimates but different likelihood values (Figure 9.4 and Table 9.1).

Table 9.1: Table of likelihood values and summary (age-1+; mt) biomass values from the different versions of SS3

| Likelihood.values | ss14 | ss14_ALK0 | SS22_ALK0_par14 |
|---|---|---|---|
| Age_comp | 78.6415 | 73.761 | 73.761 |
| Catch | 0 | 0 | 0 |
| Parm_priors | 0.0123 | 0.0078 | |
| Parm_softbounds | 0.0767 | 0.0608 | 0.0608 |
| Recruitment | 8.6901 | 8.2683 | 8.2683 |
| Survey | 4.2645 | 5.7042 | 11.8958 |
| TOTAL | 91.6851 | 87.8022 | 93.9859 |
| 2005 summary bio | 1,352,340 | 1,322,340 | 1,322,340 |
| 2019 summary bio | 35,186 | 34,786 | 34,786 |
| 2020 summary bio | 28,276 | 27,412 | 27,412 |

Ian added the numbers at age * survey selectivity * weight at age for 2005 (as an example year) from the 3.30.14 and 3.30.22 models and got the same value of 1,850,251 mt. However, the “Vuln_bio” values in the index output for ss3.30.14 was 979,269 mt and for ss3.30.22 model was 1,950,250 (which matches the external calculation). A bug in SS3 was corrected for ss3.30.22 in which seasonal weight at age values were not referenced correctly.

To double check this, I developed an annual model by removing any data associated with semester 2 (e.g. catch from MexCal_S2 fleet, survey observations, etc). With ALK = 0, estimated biomass and likelihood values were identical between ss3.30.14 and ss3.30.22. With ALK = 0.0001 (Figure 9.5) estimated biomass values were higher.

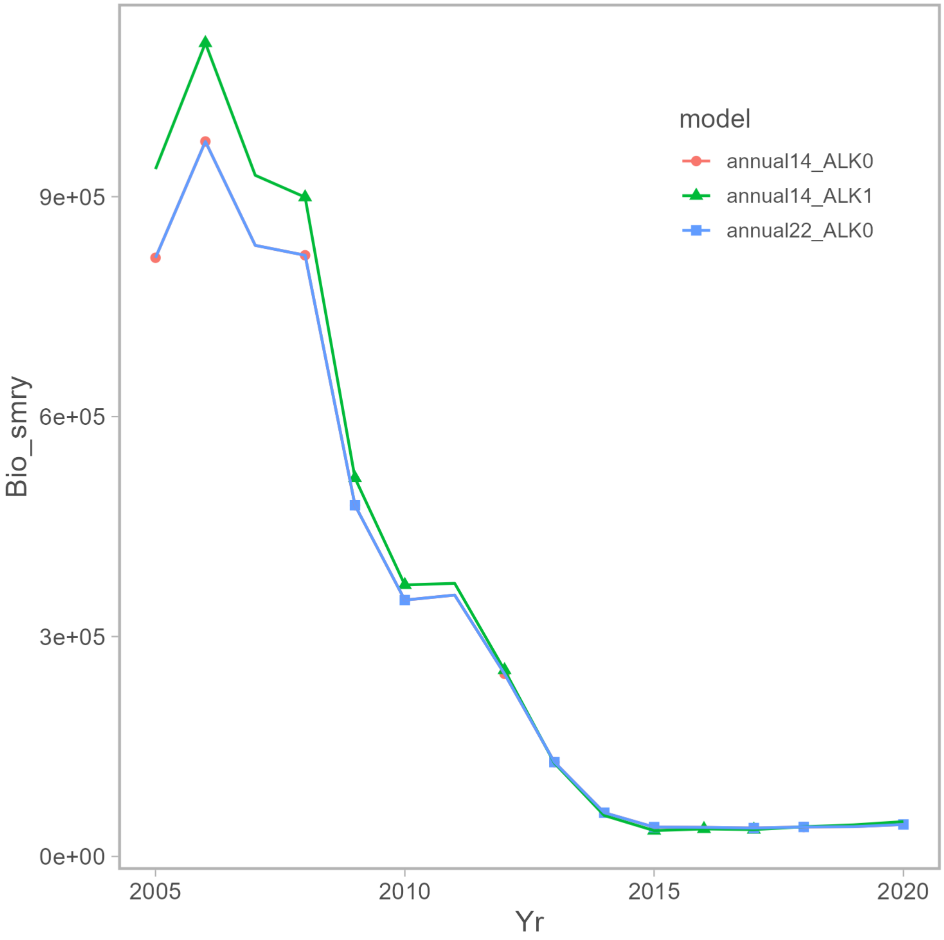

Figure 9.5: Summary biomass (age-1+; mt) from models run with ss3.30.14 ALK=0.0001 (ss14), ss3.30.14 and ALK = 0 (ss14_ALK0), and ss3.30.22 with ALK = 0 (SS22_ALK0_par14).

# 10 Appendix B: weight-at-age update

The empirical weight-at-age was updated in this 2024 benchmark to use conditional variance weight-at-age for fishery data based on the methods designed in Cheng et al. (2023) for the Bering Sea pollock (*Gadus chalcogrammus*) assessment. The methods by Cheng et al. (2023) allow for the simultaneous estimation of autocorrelation for time, age, and cohort in a Gaussian Markhov Random Field (GMRF) implemented in a state-space model with weight-at-age as the random effect. We used the conditional variance method, which estimates the probability of a weight-at-age variance given previous year, age, and cohort values. The marginal variance method, which would assume the same variance for years, ages, or cohorts, resulted in convergence issues and was not explored further for this assessment (additional details on the challenges of implementing the marginal method are addressed in the manuscript and Appendix C of Cheng *et al.* (2023)). In addition, given the variability in the California Current conditions and natural fluctuations in the population weight-at-age through time, the conditional weight-at-age variability parameterization was deemed appropriate. While the conditional variance can be applied to all three factors (year, age, and cohort), it is also possible to apply a factorial design in which combinations of each of the three are explored.

We followed Cheng's method of implementing a factorial design for the correlation parameters: none, year, age, and cohort. We ran the models separately for each individual fleet: MexCal season 1, MexCal season 2, and PNW. We applied AIC model selection to choose a correlation structure for each fleet independently. Based on the AIC values, the MexCal season 1 (fleet 1) used year, age, and cohort correlation parameters (Table 10.1); the MexCal season 2 (fleet 2) used year and age correlation parameters (Table 10.2); the PNW (fleet 3) used year and cohort correlation parameters (Table 10.3). Note that due to the fishery closure in 2014, this model uses fishery data through 2014 (Figure 10.1). We compared the resulting weight-at-age matrices to the 2020 benchmark weights-at-age.

We identified several necessary adjustments when comparing the resulting weight-at-age matrices to the 2020 benchmark and examining 2024 model diagnostics. First, the PNW fleet includes no age-0 sardine. While the GMRF model will run with missing data, it produced unrealistically large individuals for age-0 sardine. We anchored the model by filling the missing PNW age-0 weights with the overall mean age-0 weights from the MexCal season 1 fleet (0.0415 kg), and set the standard deviation to a large number (1.111) such that it would not be heavily weighted in the overall calculation. At the time of this report, the methods to share information between fleets is still under development (Matt Cheng, *pers. comm.*). Following these two updates, we re-ran the model and model selection (Figures 10.2 - 10.4). The model parameter configurations selected by fleet did not change (Tables 10.1 - 10.3). The STAT chose to move forward with these data and model configurations.

The STAT chose to move forward with the conditional variance in weight-at-age in the current base model, given that it is a more intentional implementation of weight-at-at compared with previous empirical weight-at-age methods that applied ad-hoc adjustments to individual years in the past. The conditional variance weight-at-age approach also acts as a smoother on the data.

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Table 10.1: MexCal S1 conditional weight-at-age model results.

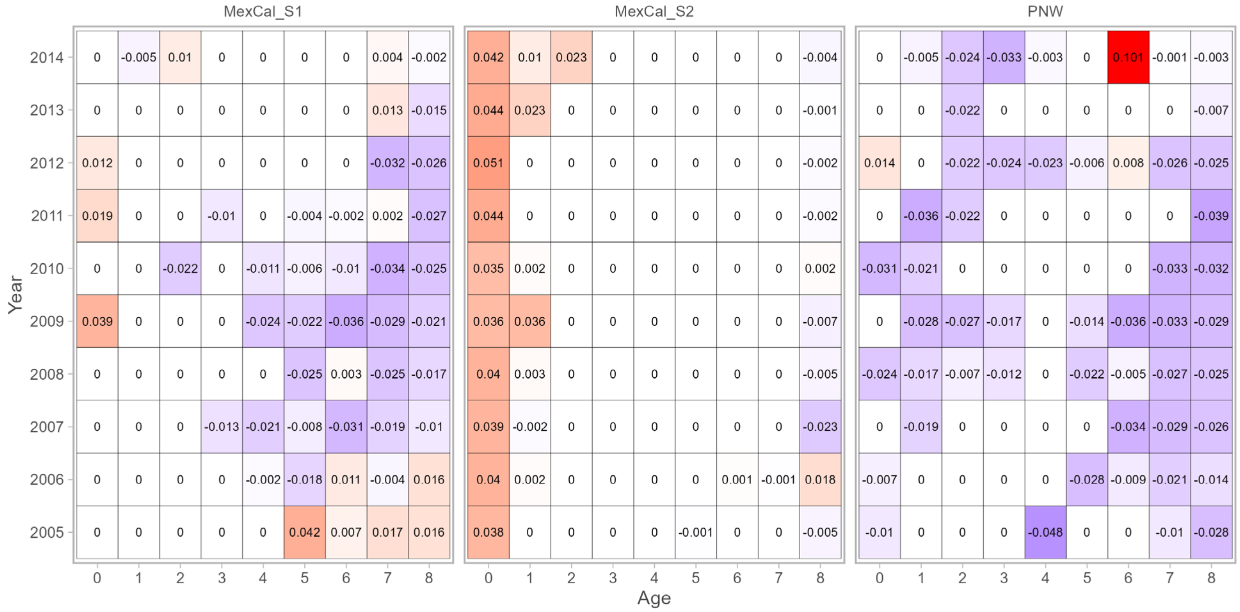
| Model | Parameter | Parameter estimate | St dev | AIC | dAIC | Pos-def Hessian |
|---|---|---|---|---|---|---|
| None | rho_a | | | 36.23 | -54.73 | TRUE |
| None | rho_c | | | 36.23 | -54.73 | TRUE |
| None | rho_y | | | 36.23 | -54.73 | TRUE |
| None | log_sigma2 | 0.07 | 0.12 | 36.23 | -54.73 | TRUE |
| a | rho_a | 0.37 | 0.09 | 23.16 | -41.66 | TRUE |
| a | rho_c | | | 23.16 | -41.66 | TRUE |
| a | rho_y | | | 23.16 | -41.66 | TRUE |
| a | log_sigma2 | 0.06 | 0.12 | 23.16 | -41.66 | TRUE |
| c | rho_a | | | 167.97 | -186.47 | FALSE |
| c | rho_c | 1.10 | 0.06 | 167.97 | -186.47 | FALSE |
| c | rho_y | | | 167.97 | -186.47 | FALSE |
| c | log_sigma2 | 0.16 | 0.12 | 167.97 | -186.47 | FALSE |
| a_c | rho_a | 0.23 | 0.09 | 13.89 | -32.39 | TRUE |
| a_c | rho_c | 0.33 | 0.10 | 13.89 | -32.39 | TRUE |
| a_c | rho_y | | | 13.89 | -32.39 | TRUE |
| a_c | log_sigma2 | 0.06 | 0.12 | 13.89 | -32.39 | TRUE |
| y | rho_a | | | -8.07 | -10.44 | TRUE |
| y | rho_c | | | -8.07 | -10.44 | TRUE |
| y | rho_y | 0.60 | 0.08 | -8.07 | -10.44 | TRUE |
| y | log_sigma2 | 0.05 | 0.12 | -8.07 | -10.44 | TRUE |
| y_a | rho_a | 0.24 | 0.07 | -16.68 | -1.82 | TRUE |
| y_a | rho_c | | | -16.68 | -1.82 | TRUE |
| y_a | rho_y | 0.54 | 0.08 | -16.68 | -1.82 | TRUE |
| y_a | log_sigma2 | 0.05 | 0.12 | -16.68 | -1.82 | TRUE |
| y_c | rho_a | | | -17.75 | -0.75 | TRUE |
| y_c | rho_c | 0.28 | 0.08 | -17.75 | -0.75 | TRUE |
| y_c | rho_y | 0.51 | 0.08 | -17.75 | -0.75 | TRUE |
| y_c | log_sigma2 | 0.05 | 0.12 | -17.75 | -0.75 | TRUE |
| y_a_c | rho_a | 0.15 | 0.09 | -18.50 | 0.00 | TRUE |
| y_a_c | rho_c | 0.19 | 0.10 | -18.50 | 0.00 | TRUE |
| y_a_c | rho_y | 0.49 | 0.08 | -18.50 | 0.00 | TRUE |
| y_a_c | log_sigma2 | 0.04 | 0.12 | -18.50 | 0.00 | TRUE |

Table 10.2: MexCal S2 conditional weight-at-age model results.

| Model | Parameter | Parameter estimate | St dev | AIC | dAIC | Pos-def Hessian |
|---|---|---|---|---|---|---|
| None | rho_a | | | 92.18 | -199.33 | TRUE |
| None | rho_c | | | 92.18 | -199.33 | TRUE |
| None | rho_y | | | 92.18 | -199.33 | TRUE |
| None | log_sigma2 | 0.09 | 0.10 | 92.18 | -199.33 | TRUE |
| a | rho_a | 0.66 | 0.05 | -19.07 | -88.08 | TRUE |
| a | rho_c | | | -19.07 | -88.08 | TRUE |
| a | rho_y | | | -19.07 | -88.08 | TRUE |
| a | log_sigma2 | 0.05 | 0.10 | -19.07 | -88.08 | TRUE |
| c | rho_a | | | -1.84 | -105.31 | TRUE |
| c | rho_c | 0.66 | 0.06 | -1.84 | -105.31 | TRUE |
| c | rho_y | | | -1.84 | -105.31 | TRUE |
| c | log_sigma2 | 0.05 | 0.10 | -1.84 | -105.31 | TRUE |
| a_c | rho_a | 0.47 | 0.07 | -32.66 | -74.49 | TRUE |
| a_c | rho_c | 0.29 | 0.08 | -32.66 | -74.49 | TRUE |
| a_c | rho_y | | | -32.66 | -74.49 | TRUE |
| a_c | log_sigma2 | 0.05 | 0.10 | -32.66 | -74.49 | TRUE |
| y | rho_a | | | -33.56 | -73.59 | FALSE |
| y | rho_c | | | -33.56 | -73.59 | FALSE |
| y | rho_y | 0.87 | 0.05 | -33.56 | -73.59 | FALSE |
| y | log_sigma2 | 0.05 | 0.10 | -33.56 | -73.59 | FALSE |
| y_a | rho_a | 0.30 | 0.05 | -107.15 | 0.00 | TRUE |
| y_a | rho_c | | | -107.15 | 0.00 | TRUE |
| y_a | rho_y | 0.62 | 0.06 | -107.15 | 0.00 | TRUE |
| y_a | log_sigma2 | 0.03 | 0.10 | -107.15 | 0.00 | TRUE |
| y_c | rho_a | | | -91.78 | -15.37 | TRUE |
| y_c | rho_c | 0.22 | 0.06 | -91.78 | -15.37 | TRUE |
| y_c | rho_y | 0.69 | 0.06 | -91.78 | -15.37 | TRUE |
| y_c | log_sigma2 | 0.04 | 0.10 | -91.78 | -15.37 | TRUE |
| y_a_c | rho_a | 0.29 | 0.07 | -105.15 | -2.00 | TRUE |
| y_a_c | rho_c | 0.00 | 0.08 | -105.15 | -2.00 | TRUE |
| y_a_c | rho_y | 0.62 | 0.07 | -105.15 | -2.00 | TRUE |
| y_a_c | log_sigma2 | 0.03 | 0.10 | -105.15 | -2.00 | TRUE |

Table 10.3: PNW conditional weight-at-age model results.

| Model | Parameter | Parameter estimate | St dev | AIC | dAIC | Pos-def Hessian |
|---|---|---:|---:|---:|---:|---:|
| None | rho_a | | | -42.89 | -114.80 | TRUE |
| None | rho_c | | | -42.89 | -114.80 | TRUE |
| None | rho_y | | | -42.89 | -114.80 | TRUE |
| None | log_sigma2 | 0.03 | 0.13 | -42.89 | -114.80 | TRUE |
| a | rho_a | 0.55 | 0.08 | -76.66 | -81.04 | TRUE |
| a | rho_c | | | -76.66 | -81.04 | TRUE |
| a | rho_y | | | -76.66 | -81.04 | TRUE |
| a | log_sigma2 | 0.03 | 0.13 | -76.66 | -81.04 | TRUE |
| c | rho_a | | | -98.09 | -59.61 | TRUE |
| c | rho_c | 0.68 | 0.07 | -98.09 | -59.61 | TRUE |
| c | rho_y | | | -98.09 | -59.61 | TRUE |
| c | log_sigma2 | 0.02 | 0.13 | -98.09 | -59.61 | TRUE |
| a_c | rho_a | 0.14 | 0.11 | -97.69 | -60.00 | TRUE |
| a_c | rho_c | 0.58 | 0.11 | -97.69 | -60.00 | TRUE |
| a_c | rho_y | | | -97.69 | -60.00 | TRUE |
| a_c | log_sigma2 | 0.02 | 0.13 | -97.69 | -60.00 | TRUE |
| y | rho_a | | | -138.36 | -19.34 | TRUE |
| y | rho_c | | | -138.36 | -19.34 | TRUE |
| y | rho_y | 0.80 | 0.06 | -138.36 | -19.34 | TRUE |
| y | log_sigma2 | 0.01 | 0.14 | -138.36 | -19.34 | TRUE |
| y_a | rho_a | 0.22 | 0.06 | -148.47 | -9.23 | TRUE |
| y_a | rho_c | | | -148.47 | -9.23 | TRUE |
| y_a | rho_y | 0.71 | 0.06 | -148.47 | -9.23 | TRUE |
| y_a | log_sigma2 | 0.01 | 0.14 | -148.47 | -9.23 | TRUE |
| y_c | rho_a | | | -157.70 | 0.00 | TRUE |
| y_c | rho_c | 0.31 | 0.07 | -157.70 | 0.00 | TRUE |
| y_c | rho_y | 0.66 | 0.07 | -157.70 | 0.00 | TRUE |
| y_c | log_sigma2 | 0.01 | 0.14 | -157.70 | 0.00 | TRUE |
| y_a_c | rho_a | -0.03 | 0.10 | -155.79 | -1.91 | TRUE |
| y_a_c | rho_c | 0.34 | 0.11 | -155.79 | -1.91 | TRUE |
| y_a_c | rho_y | 0.66 | 0.07 | -155.79 | -1.91 | TRUE |
| y_a_c | log_sigma2 | 0.01 | 0.14 | -155.79 | -1.91 | TRUE |



MexCal_S1

| Year | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| 2014 | 0 | -0.005 | 0.01 | 0 | 0 | 0 | 0 | 0.004 | -0.002 |
| 2013 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.013 | -0.015 |
| 2012 | 0.012 | 0 | 0 | 0 | 0 | 0 | 0 | -0.032 | -0.026 |
| 2011 | 0.019 | 0 | 0 | -0.01 | 0 | -0.004 | -0.002 | 0.002 | -0.027 |
| 2010 | 0 | 0 | -0.022 | 0 | -0.011 | -0.006 | -0.01 | -0.034 | -0.025 |
| 2009 | 0.039 | 0 | 0 | 0 | -0.024 | -0.022 | -0.036 | -0.029 | -0.021 |
| 2008 | 0 | 0 | 0 | 0 | 0 | -0.025 | 0.003 | -0.025 | -0.017 |
| 2007 | 0 | 0 | 0 | -0.013 | -0.021 | -0.008 | -0.031 | -0.019 | -0.01 |
| 2006 | 0 | 0 | 0 | 0 | -0.002 | -0.018 | 0.011 | -0.004 | 0.016 |
| 2005 | 0 | 0 | 0 | 0 | 0 | 0.042 | 0.007 | 0.017 | 0.016 |

MexCal_S2

| Year | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| 2014 | 0.042 | 0.01 | 0.023 | 0 | 0 | 0 | 0 | 0 | -0.004 |
| 2013 | 0.044 | 0.023 | 0 | 0 | 0 | 0 | 0 | 0 | -0.001 |
| 2012 | 0.051 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -0.002 |
| 2011 | 0.044 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -0.002 |
| 2010 | 0.035 | 0.002 | 0 | 0 | 0 | 0 | 0 | 0 | 0.002 |
| 2009 | 0.036 | 0.036 | 0 | 0 | 0 | 0 | 0 | 0 | -0.007 |
| 2008 | 0.04 | 0.003 | 0 | 0 | 0 | 0 | 0 | 0 | -0.005 |
| 2007 | 0.039 | -0.002 | 0 | 0 | 0 | 0 | 0 | 0 | -0.023 |
| 2006 | 0.04 | 0.002 | 0 | 0 | 0 | 0 | 0.001 | -0.001 | 0.018 |
| 2005 | 0.038 | 0 | 0 | 0 | 0 | -0.001 | 0 | 0 | -0.005 |

PNW

| Year | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| 2014 | 0 | -0.005 | -0.024 | -0.033 | -0.003 | 0 | 0.101 | -0.001 | -0.003 |
| 2013 | 0 | 0 | -0.022 | 0 | 0 | 0 | 0 | 0 | -0.007 |
| 2012 | 0.014 | 0 | -0.022 | -0.024 | -0.023 | -0.006 | 0.008 | -0.026 | -0.025 |
| 2011 | 0 | -0.036 | -0.022 | 0 | 0 | 0 | 0 | 0 | -0.039 |
| 2010 | -0.031 | -0.021 | 0 | 0 | 0 | 0 | 0 | -0.033 | -0.032 |
| 2009 | 0 | -0.028 | -0.027 | -0.017 | 0 | -0.014 | -0.036 | -0.033 | -0.029 |
| 2008 | -0.024 | -0.017 | -0.007 | -0.012 | 0 | -0.022 | -0.005 | -0.027 | -0.025 |
| 2007 | 0 | -0.019 | 0 | 0 | 0 | 0 | -0.034 | -0.029 | -0.026 |
| 2006 | -0.007 | 0 | 0 | 0 | 0 | -0.028 | -0.009 | -0.021 | -0.014 |
| 2005 | -0.01 | 0 | 0 | 0 | -0.048 | 0 | 0 | -0.01 | -0.028 |

Figure 10.1: Comparison of the new weight at age values to the 2020 benchmark weight at age values used. The numbers represent the difference between the new and the old values. For example, MexCal_S1, age 0, 2009 weight at age was 0.039 kg larger than it was in the 2020 benchmark.

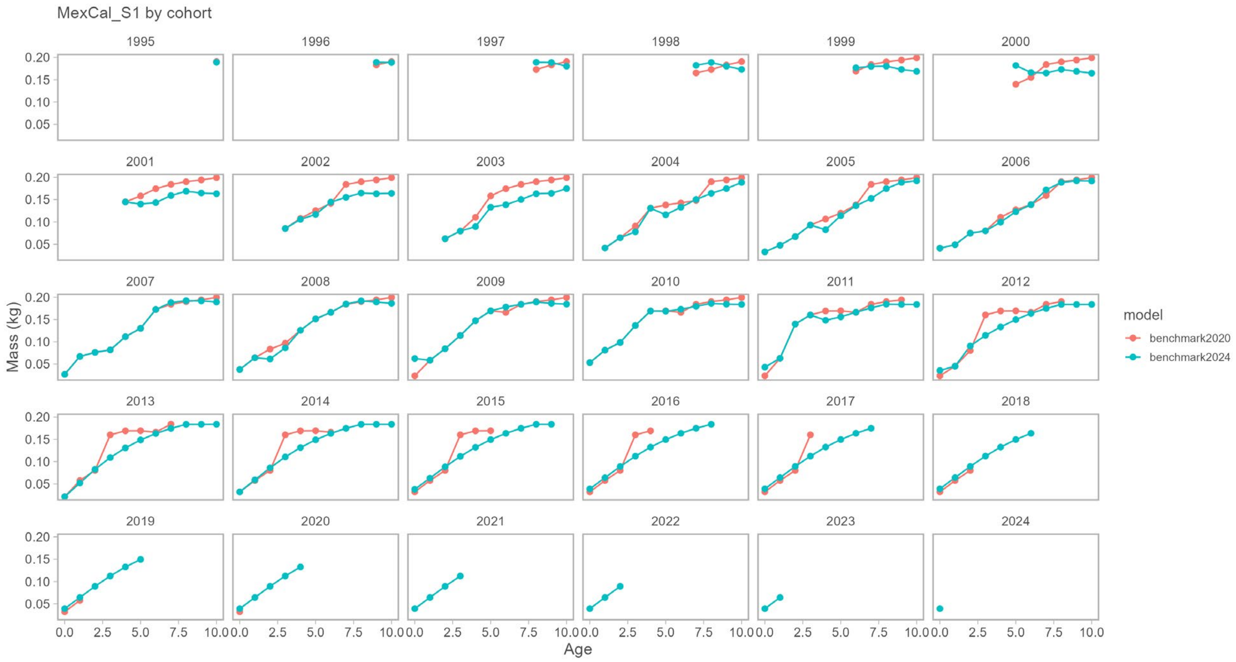


Figure 10.2: Comparison of the new weight at age values to the 2020 benchmark weight at age values used for the MexCal fleet, semester 1.

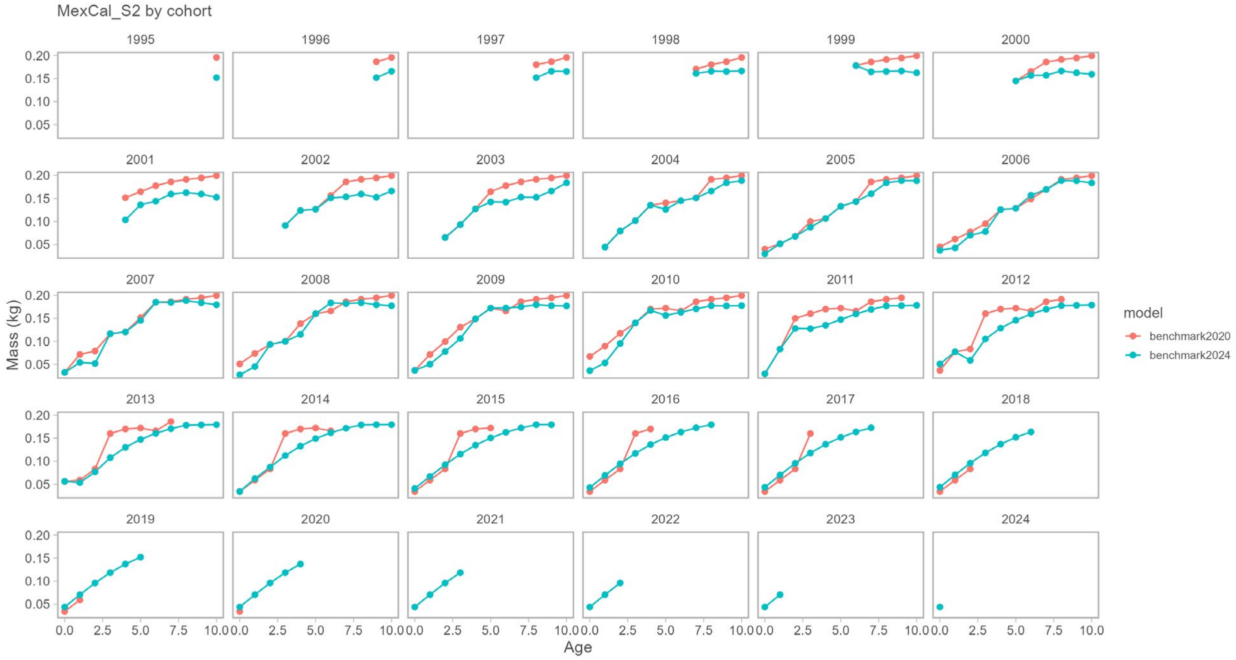


Figure 10.3: Comparison of the new weight at age values to the 2020 benchmark weight at age values used for the MexCal fleet, semester 2.

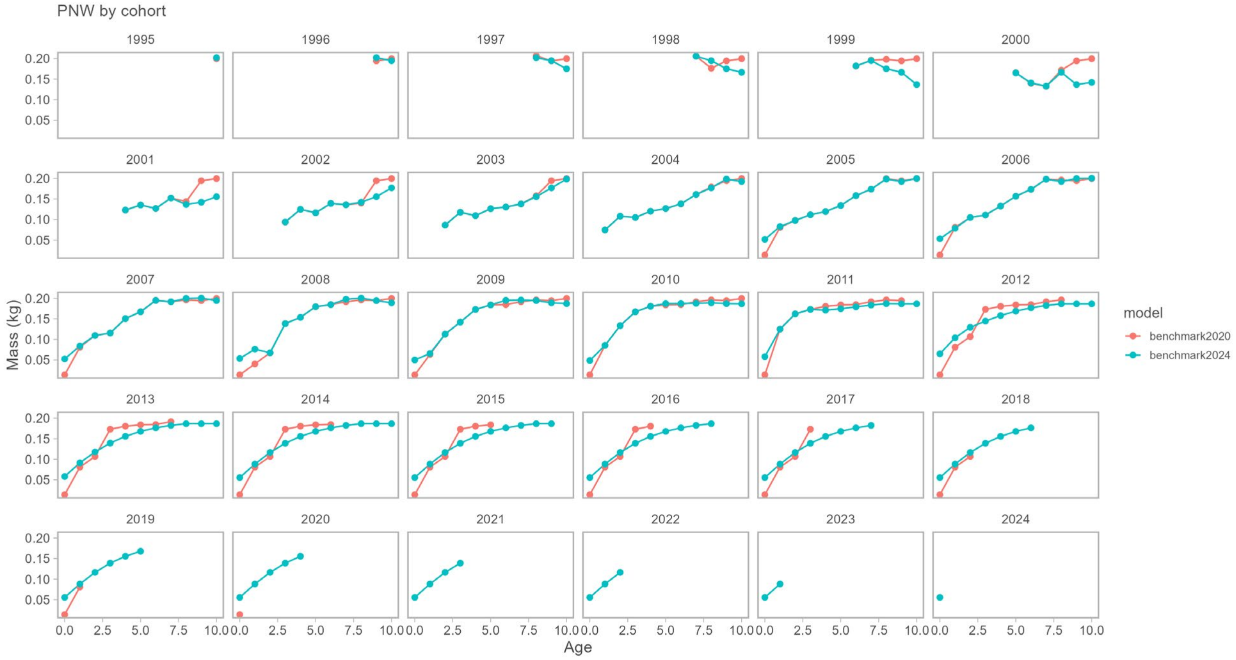


Figure 10.4: Comparison of the new weight at age values to the 2020 benchmark weight at age values used for the PNW fleet.

# 11 Appendix C: Base model sensitivity to Japanese sardine (*Sardinops melanostictus*)

Genetic sampling indicates the presence of Japanese sardine (*Sardinops melanostictus*) in the AT survey area (Longo and Craig in prep). Not all samples collected from the 2023 AT survey have been analyzed yet, so it is currrently not possible to calculate Pacific sardine and Japanese sardine biomass estimates separately using AT survey data. We present a model sensitivity run that accounts for Japanese sardine using the data available to date.

Preliminary estimates indicate that in 2023, 30% of the sardine biologically sampled (i.e. in trawl gear) were Japanese sardine (note this value is *not* finalized and may be different from the proportion of biomass that is Japanese sardine). The model run shown here adjusts the $Q$ for the 2023 AT survey from 1 (in the base model) to 0.7. The figure below shows the summary biomass (age-1+; mt) estimates from this run. This is just one coarse method of accounting for Japanese sardine and is not necessarily endorsed by the STAT.

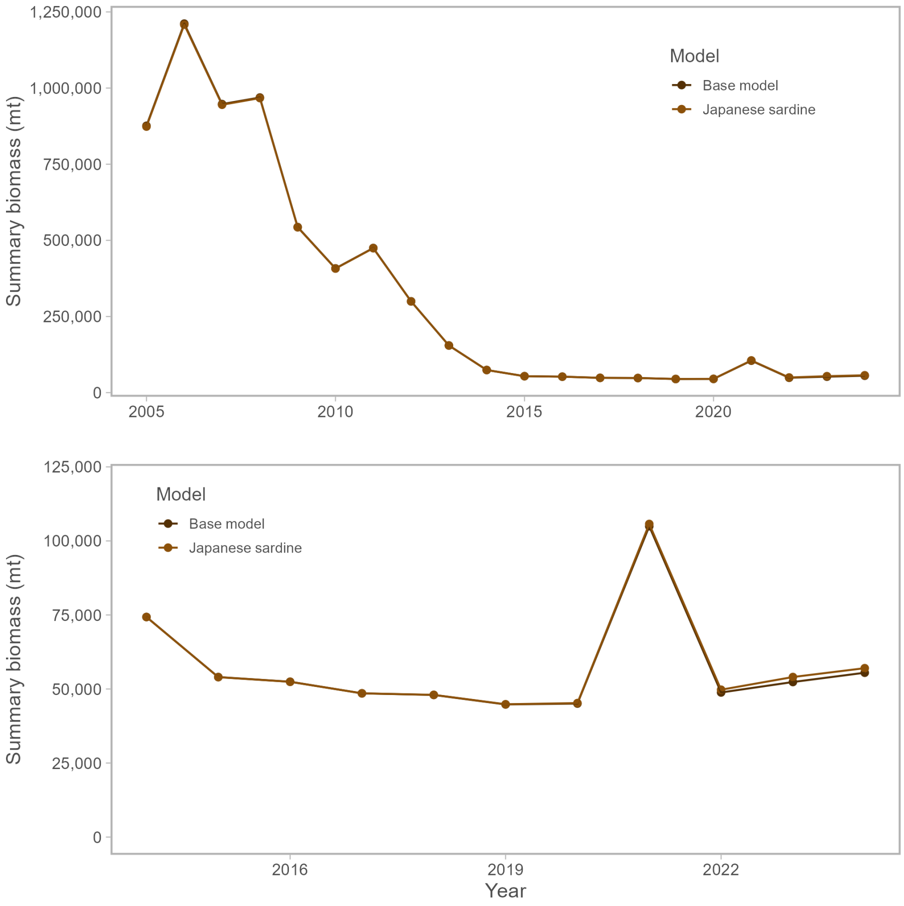


Figure 11.1: Summary biomass (age-1+; mt) estimates from the base model and a model run that accounts for Japanese sardine. The top panel shows the full time series, and the bottom panel shows the time series from 2014-2024.

# 12 Appendix D: Biological data collected from the 2022 and 2023 SWFSC AT surveys and ageing error estimates for Pacific sardine (*Sardinops sagax*)

Kelsey C. James[1], Emmanis Dorval[1,2], Jonathan Walker[1,3], Brittany D. Schwartzkopf[1], and Brad E. Erisman[1]

[1]NOAA Fisheries, SWFSC Fisheries Resources Division, 8901 La Jolla Shores Drive, La Jolla, CA 92037, USA

[2]Lynker Corporation under contract with Southwest Fisheries Science Center, 338 East Market Street, Suite 100, Leesburg, VA 20176, USA

[3]University of California Santa Cruz, The Cooperative Institute for Marine, Earth, and Atmospheric Systems (CIMEAS) under partnership with NOAA Fisheries, 1156 High Street, Santa Cruz, CA 95064, USA

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## Summary

Here we provide a summary report on the biological data (length, weight, and age) collected by surface trawl for the northern stock of Pacific sardine (*Sardinops sagax*) generated from the 2022 and 2023 Southwest Fisheries Science Center acoustic-trawl (AT) surveys for consideration in the 2024 stock assessment. We also computed a new ageing error vector for the stock assessment from age data produced from AT surveys in 2021 and 2022.

## Background

Since 2004, stock assessments of Pacific sardine (*Sardinops sagax*) have included biological data (length, weight, and age) collected from fishery-dependent surveys conducted by the California Department of Fish and Wildlife, the Washington Department of Fish and Wildlife, and the Centro Interdisciplinario de Ciencias Marinas, Mexico, and from fishery-independent surveys conducted by the Southwest Fisheries Science Center (SWFSC), and the Pacific Biological Station (PBS) of the Department of Fisheries and Oceans, Canada (Hill et al. 2007; Hill et al. 2011). Pacific sardine abundance off British Columbia declined in 2013, and subsequently the PBS stopped targeting this species in their trawl surveys and stopped providing biological data to the stock assessment. In 2015, due to low stock biomass, the Pacific Fishery Management Council prohibited directed fishing on Pacific sardine. By 2019, the National Marine Fisheries Service declared the northern stock (the stock included in the Coastal Pelagic Species Fishery Management Plan (PFMC 1998)) to be overfished and subsequently closed the directed U.S. fishery with the exception of the live bait fishery (PFMC 2021).

Since 2015, fishery-independent data collected from the SWFSC acoustic-trawl (AT) survey have been primarily used to update the time series of biological data in the Pacific sardine stock assessment. The last update assessment (Kuriyama et al. 2022) included age data from the AT survey from surface trawl gear up to 2021 and from fishery-dependent Exempted Fishery Permits in 2021. In this report, we present a summary of the new length, weight, and age data generated from the 2022 and 2023 AT surveys aboard the NOAA Ships *Reuben Lasker* and *Bell M. Shimada* using trawl gear. We also computed a new ageing error vector to be applied to the 2022 and 2023 age data using age data produced from AT surveys in 2021 and 2022.

## Sample collections

Length and weight data were recorded, and otoliths were collected from Pacific sardine during AT surveys using surface trawl gear in 2022 and 2023 following methods described in Dorval et al. (2022). In each year, Pacific sardine were randomly subsampled (n = 75 maximum) from the catch of each haul and measured for standard length (SL; mm) and weight (g). If fewer than 75 Pacific sardine were caught in a haul, all fish were measured and weighed. Sagittal otoliths were then extracted from sampled fish (maximum of 50 per haul). Hauls containing samples of Pacific sardine assigned to the northern stock (Zwolinski and Demer 2023) were collected from 26 July to 22 September in 2022, from south of Cape Mendocino, CA (40.379°N, 124.674°W) to north of Point Conception, CA (35.600°N, 121.550°W). It should be noted that the 2022 survey sampled from north to south and the NOAA vessel did not sample north of Cape Mendocino due to logistical constraints (Renfree et al. 2023). Following the same approach, samples were collected from 13 October to 1 November in 2023, from north of Cape Blanco, OR (43.932°N, 124.256°W) to Cape Flattery, WA (48.107°N, 125.577°W) (Figure 1). It should be noted that the 2023 survey aboard the NOAA vessel sampled from south to north and did not sample between Cape Mendocino and Cape Blanco again due to logistical constraints (Renfree et al. *in prep*).

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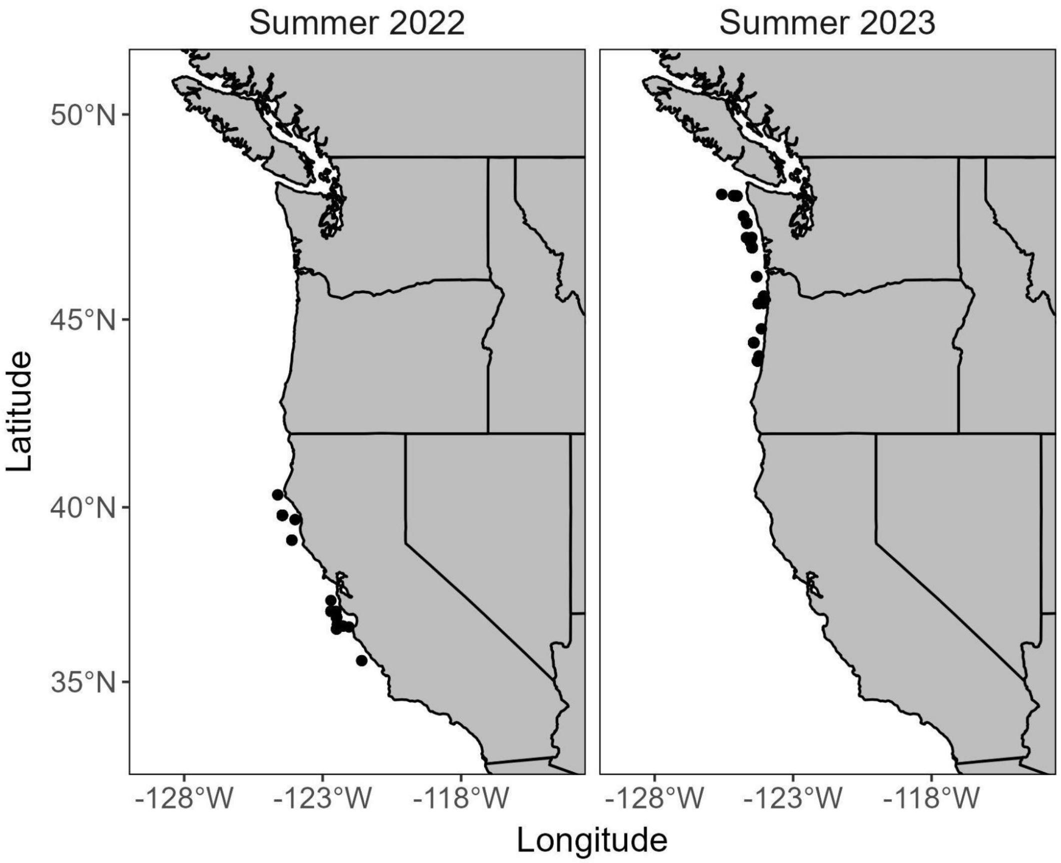

**Fig. 1**. Spatial distribution of northern stock Pacific sardine (*Sardinops sagax*) caught during the SWFSC AT surveys using surface trawl gear in 2022 and 2023. These maps do not represent the full extent of biosampling aboard NOAA vessels in each year.

**Age-readings**

Northern stock Pacific sardine collected from the 2022 and 2023 AT surveys were aged using whole otolith surface ageing, following the method described by Yaremko (1996) and in the same manner as for past stock assessments. Briefly, otoliths were immersed in distilled water, and the translucent and opaque increments were identified from the primordium to the margin of otoliths. The number of annuli were then counted on the distal side of otoliths using a stereomicroscope at a magnification of 25X. An annulus is defined as the interface between an inner translucent growth increment and the successive outer opaque growth increment (Fitch 1951; Yaremko 1996). A final age was assigned to each individual fish based on the number of annuli, a July 1 birthdate, the capture date, and the interpretation of the most distal growth increment (Yaremko 1996).

Two experienced age readers from SWFSC, identified as readers 14 and 17, aged fish from otoliths collected from the 2022 AT survey. The 2022 otolith samples were stratified by haul and by length bin (20 mm SL) and randomly allocated to each reader. This ensures each reader is assigned otoliths that span the spatial and temporal extent and size range of the collected fish. Due to staffing constraints, all samples collected during the 2023 survey were aged only by reader 17. Age data from both readers have been included and used in past stock assessments of Pacific sardine, including the 2020 benchmark assessment and the 2022 update assessment (Kuriyama et al. 2020; Kuriyama et al. 2022).

Although the 2021 AT survey age data were used in the 2022 update stock assessment for Pacific sardine, the ageing error vector was based on a limited sample size of double readings (n = 84) conducted by readers 14 and 17. Additional double readings were conducted on the 2022 AT survey samples, increasing the sample size of double read otoliths to 130. Using this updated dataset, we computed a new ageing error vector for 2021 and 2022. 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 readers 14 and 17, and based on the following assumptions: (1) ageing bias depends on reader and the true age of a fish; (2) the age-reading error standard deviation (*SD*-at-age) depends on reader and the true age; and (3) age-reading error is normally distributed around the expected age (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 2021 and 2022 AT surveys, following similar methods used in the past for Pacific sardine (Hill et al. 2011; Dorval et al. 2013; Kuriyama et al. 2020; Kuriyama et al. 2022). We defined various model scenarios, including those 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 both readers were unbiased and had equal *SDs*. The functional form of random ageing error precisions was assumed to follow a curvilinear *SD* and a curvilinear *CV* based on a three parameter, Hollings-form relationship of *SD* or *CV* with true age (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

### *Biological data*

Length and weight data were collected from 171 Pacific sardine from the northern stock sampled in 2022. Sampled fish ranged in length from 110 mm to 205 mm SL (Figure 2A) and in weight from 15 g to 103.5 g (Figure 2C). A total of 136 of those 171 fish were aged, and they ranged from 0 to 4 years old (Figure 2E). However, 89% of the aged Pacific sardine were 1 or 2 years old.

Length and weight data were collected from 365 Pacific sardine from the northern stock sampled in 2023, and 278 of those sampled fish were aged. Compared to 2022, the fish sampled in 2023 showed a broader range in their length, weight, and age distributions; they measured from 71 mm to 280 mm SL (Figure 2B), weighed 4 g to 291.5 g (Figure 2D), and ranged in age from 0 to 5 years old (Figure 2F). Fish of age 0 and 3 dominated trawl samples in 2023, representing 38% and 25%, respectively (Figure 2F).

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While the distributions of length, weight, and age were unimodal in 2022, the distribution of these variables in 2023 showed two or three modes (Figures 2B, 2D, and 2F). We suspect the different patterns between years were related to the numerous logistical issues encountered during the survey in each year, which prevented the continuous implementation of acoustic and trawl sampling in space and time (Renfree et al. 2023; Renfree et al. *in prep*). Contrary to previous years and due to the loss of survey days during the summer, the 2023 AT survey was extended into October and November, and no samples of Pacific sardine from the northern stock were collected in July through September, which is the typical timing of the AT survey.

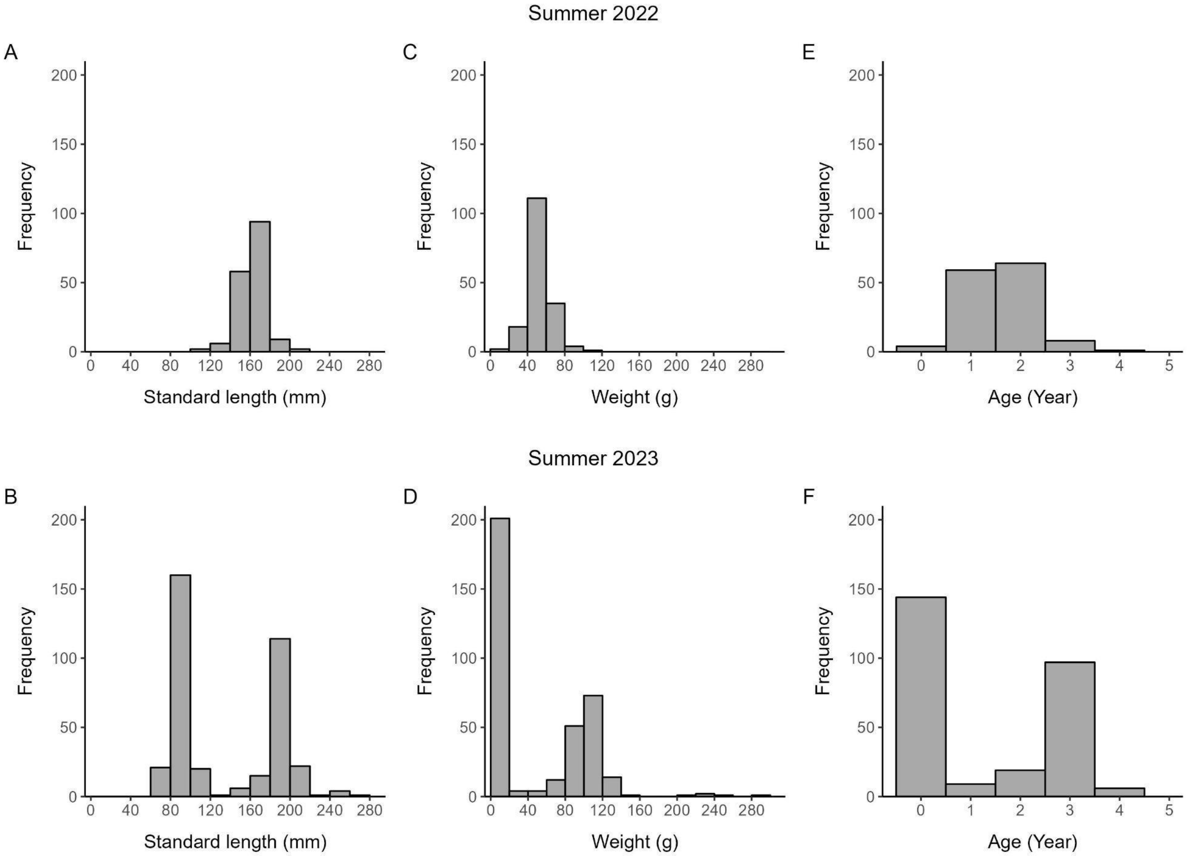

**Fig. 2:** Distribution of lengths (A, B), weights (C, D), and ages (E, F) of northern stock Pacific sardine (*Sardinops sagax)* collected during the 2022 and 2023 AT surveys.

*Age-Reading Errors*

A total of 130 otoliths were used to estimate age-reading errors for northern stock Pacific sardine collected from the 2021 and 2022 AT surveys. Ageing agreement between readers 14 and 17 was 100% at age 0, 94% at age 1, 57% at age 2, and 72% at age 3 (Figure 3). There was no agreement between the two readers at age 4, and they only agreed on one fish at age 5. As expected, *SDs*-at-age estimated from Model C increased with age, varying from 0.14 to 0.57 (Table 1). As no double readings were conducted on Pacific sardine from the northern stock collected in 2023, we recommend that the 2021-2022 *SD*-at-age vector be applied to the 2023 age data.

**Table 1.** Coefficient of variation (*CV*) and standard deviation (*SD*) at age estimated for northern stock Pacific Sardine (*Sardinops sagax*) collected from the SWFSC AT survey in 2021 and 2022.

| | | | | | **Model C** | | |
|---|---|---|---|---|---|---|---|
| **Survey** | **Collection Year** | **Number of Dataset** | **Sample size** | **Number of readers** | **Age** | ***CV*** | ***SD*** |
| | | | | | | | |
| Trawl | 2021-2022 | 1 | 130 | 2 | 0 | 0.14 | 0.14 |
| | | | | | 1 | 0.14 | 0.14 |
| | | | | | 2 | 0.21 | 0.41 |
| | | | | | 3 | 0.17 | 0.51 |
| | | | | | 4 | 0.14 | 0.55 |
| | | | | | 5 | 0.11 | 0.56 |
| | | | | | 6 | 0.09 | 0.57 |
| | | | | | 7 | 0.08 | 0.57 |
| | | | | | 8 | 0.07 | 0.57 |

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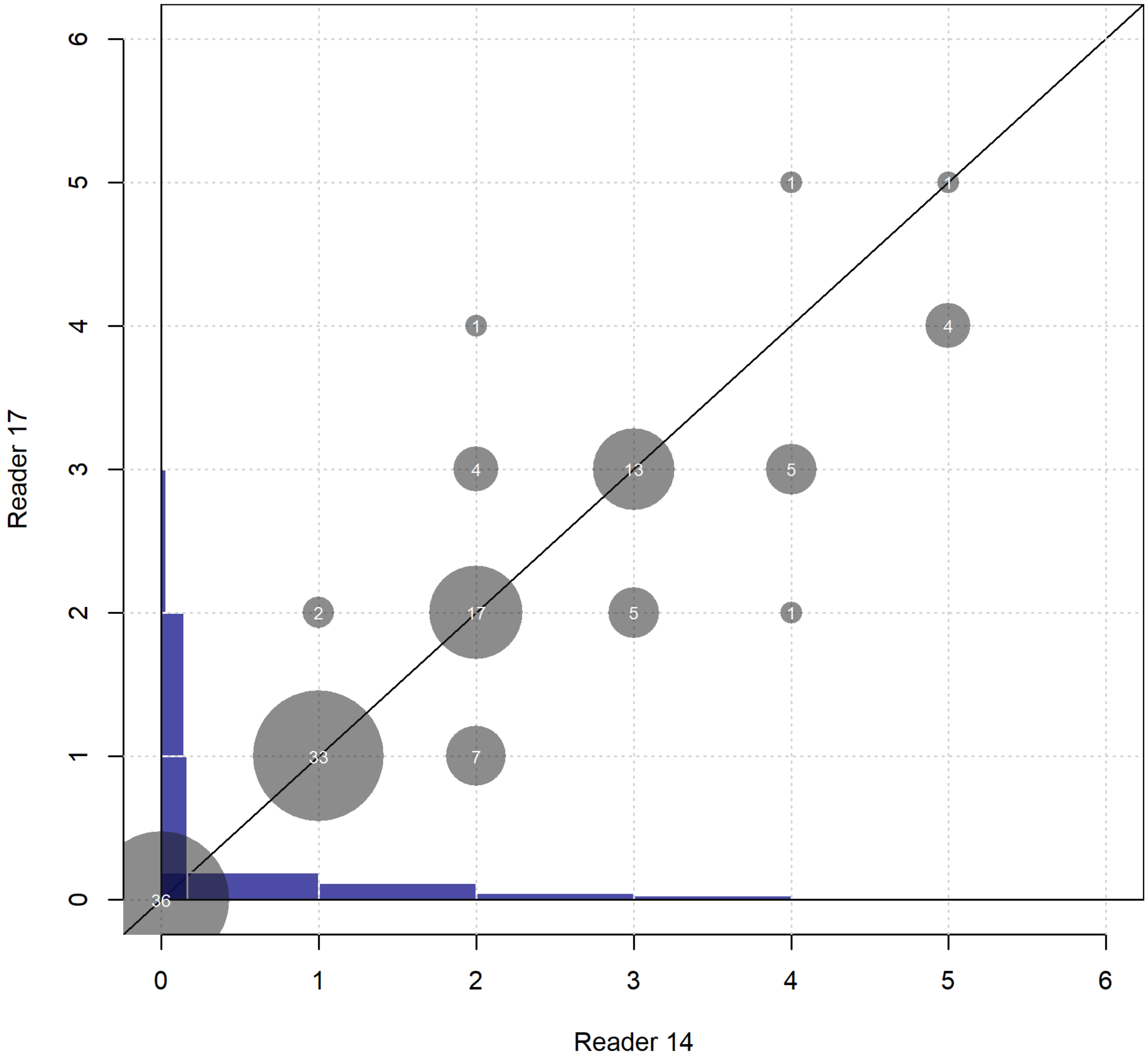

**Fig. 3.** Age bias plots from the Agemat model for readers 14 and 17 for northern stock Pacific sardine (*Sardinops sagax*) collected from SWFSC AT surveys in 2021 and 2022.

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# 13 Appendix E: Pacific sardine nearshore aerial biomass estimates in 2022 and 2023 for the 2024 stock assessment

Kirk Lynn[1], Emmanis Dorval[2], Dianna Porzio[1], Trung Nguyen[1], Katie Grady[1]

[1]California Department of Fish and Wildlife

[2]Lynker under contract with Southwest Fisheries Science Center

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## Background

The California Coastal Pelagic Species Survey (CCPSS) is an aerial survey of California nearshore waters that has been conducted since 2012 (Lynn et al. 2022, 2023). Since 2020, the survey has flown replicated transects within predesignated strata covering waters out to 3,600 m (Dorval et al. 2023, In review). Survey regions are in Northern California (NCA) between Point Arena and Port San Luis and Southern California (SCA) between Point Conception and San Diego (Fig.1). For a given survey season and region, the ability to survey strata is determined by availability of survey personnel and aircraft, airspace restrictions, and weather conditions. We summarize below the data collected and biomass estimates from 2022 and 2023 survey flights for Pacific sardine by season and region.

## Survey Methods and Data

Biomass estimates for each season and region are calculated from observed fish in flown strata and using average density from surveyed strata to expand into intervening unflown strata (Fig 1). For SCA, some expansion strata were surveyed and the observed biomass included in regional biomass estimates. Final survey region areas for each season are bounded by flown strata at either end. For the 2022 and 2023 SCA seasons the survey region was bounded by two strata, S1 and S6. For 2022 and 2023 NCA seasons, there were only two flown strata for each season.

Scheduling of survey flights was designed to coincide in space and time as closely as possible with offshore acoustic-trawl (AT) surveys by NOAA Ship *Reuben Lasker*. Aerial survey flight dates were planned ahead of time based on the AT survey schedule. However, weather conditions (particularly in NCA) and changes in AT survey plans affected coordination with CCPSS flights. For some strata, this resulted in significant discrepancies between ship and aerial survey coverage of the same latitudinal water areas. For each of the 2022 and 2023 summer seasons, only two NCA strata were surveyed due to unfavorable weather conditions in the limited time available for survey flights. These strata were separated by several unflown strata, and expansion was not performed because of the distance between surveyed strata. Thus, only observed biomass is provided, representing a minimum estimate for the region.

Aerial Survey: 2022

The spring 2022 CCPSS season in SCA progressed from south to north and flew the following strata (in order) from March 13 to 22: S6, S5E, S5, S4E, S3, S2E, S1E, and S1 (Table 1). Biomass observed in each of these strata are shown in Table 1. Total nearshore biomass observed in SCA for this season was estimated to be 1,326 metric tons (mt)(Table 2).

In summer 2022, strata were flown from north to south. Only two NCA strata were flown due to bad weather, N5 (July 31) and N2 (August 20). Nearshore biomass estimated in these two strata (N5 – 846 mt, N2 – 882 mt) are presented in Table 1. The following SCA strata were then flown from August 28 to September 2: S3, S4, S4E, S1, S1E, S2, S5, and S6 (Table 1). Total nearshore biomass observed for SCA this season was estimated to be 24,401 mt (Table 2).

Aerial Survey: 2023

In spring 2023, the SCA survey again moved north to south from April 2 to 8, flying the following strata: S1, S1E, S2, S3, S2E, S4, S5, S4E, and S6 (Table 1). Nearshore biomass observed in SCA was estimated to be 11,083 mt (Table 2).

Later that summer the CCPSS again flew SCA strata from July 10 to 14, but from south to north: S6, S5, S4E, S4, S3, S2, S1E, and S1 (Table 1). Nearshore biomass observed in SCA was estimated to be 10,085 mt (Table 2).

The survey then shifted to NCA, where only N8 and N3 strata were surveyed due to bad weather, on July 28 and 31, respectively. Nearshore biomass estimated in these two strata (N8 – 0 mt, N3 – 812 mt) are presented in Table 1.

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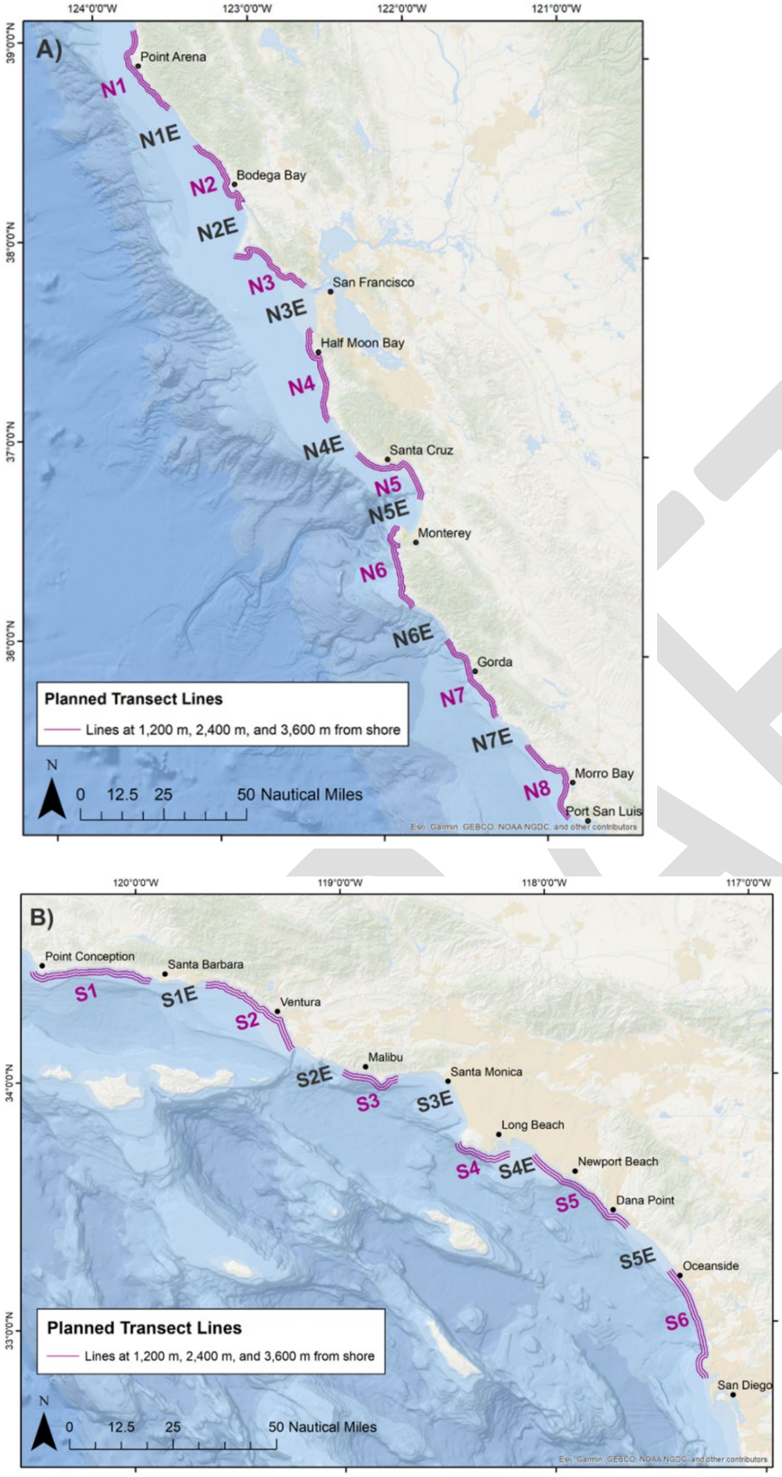

Figure 1. Spatial distribution of strata (Panels A and B) off northern California (NCA) and southern California (SCA) for surveys between 2020 and 2023. Planned survey strata are in pink; strata for expansion of biomass are in black and labeled with an “E”. Note strata S3 and S4 are smaller to circumvent airspace restrictions near the Los Angeles Airport.

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Table 1. Mean biomass (metric tons) of Pacific sardine observed during 2022-2023 CCPSS survey flight dates per stratum. Two replicated flights were conducted on each transect within a given stratum.

| **Date** | **Region** | **Season** | **Stratum** | **Mean Observed Biomass (mt)** |
|---|---|---|---|---|
| 03/13/22 | SCA | Spring | S6 | 155 |
| 03/13/22 | SCA | Spring | S5E | 177 |
| 03/14/22 | SCA | Spring | S5 | 343 |
| 03/14/22 | SCA | Spring | S4E | 29 |
| 03/15/22 | SCA | Spring | S3 | 0 |
| 03/15/22 | SCA | Spring | S2E | 105 |
| 03/22/22 | SCA | Spring | S1E | 201 |
| 03/22/22 | SCA | Spring | S1 | 113 |
| 07/31/22 | NCA | Summer | N5 | 846 |
| 08/20/22 | NCA | Summer | N2 | 882 |
| 08/28/22 | SCA | Summer | S3 | 1,863 |
| 08/28/22 | SCA | Summer | S4 | 139 |
| 08/28/22 | SCA | Summer | S4E | 1,258 |
| 08/31/22 | SCA | Summer | S1 | 4,643 |
| 08/31/22 | SCA | Summer | S1E | 2,003 |
| 09/01/22 | SCA | Summer | S2 | 948 |
| 09/02/22 | SCA | Summer | S5 | 3,108 |
| 09/02/22 | SCA | Summer | S6 | 1,263 |
| 04/02/23 | SCA | Spring | S1 | 275 |
| 04/02/23 | SCA | Spring | S1E | 873 |
| 04/04/23 | SCA | Spring | S2 | 188 |
| 04/04/23 | SCA | Spring | S3 | 109 |
| 04/04/23 | SCA | Spring | S2E | 397 |
| 04/07/23 | SCA | Spring | S4 | 230 |
| 04/07/23 | SCA | Spring | S5 | 928 |
| 04/07/23 | SCA | Spring | S4E | 201 |
| 04/08/23 | SCA | Spring | S6 | 5,851 |
| 07/10/23 | SCA | Summer | S6 | 772 |
| 07/12/23 | SCA | Summer | S5 | 2,742 |
| 07/12/23 | SCA | Summer | S4E | 477 |
| 07/12/23 | SCA | Summer | S4 | 217 |
| 07/13/23 | SCA | Summer | S3 | 185 |
| 07/13/23 | SCA | Summer | S2 | 2,631 |
| 07/14/23 | SCA | Summer | S1E | 307 |
| 07/14/23 | SCA | Summer | S1 | 341 |
| 07/28/23 | NCA | Summer | N8 | 0 |
| 07/31/23 | NCA | Summer | N3 | 812 |

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Table 2. Seasonal SCA  biomass estimates in metric tons, 2022-2023.

| Dates | Region | Year | Season | Area_Region ($km^2$) | Density_Region ($mt/km^2$) | Biomass_Region (mt) | SD_Biomass | CV_Biomass |
|---|---|---|---|---|---|---|---|---|
| 3/13-3/22 | SCA | 2022 | Spring | 1,514.68 | 0.88 | 1,326 | 16 | 0.012 |
| 8/28-9/2 | SCA | 2022 | Summer | 1,514.68 | 16.11 | 24,401 | 881 | 0.036 |
| 4/2-4/8 | SCA | 2023 | Spring | 1,514.68 | 7.32 | 11,083 | 1,436 | 0.130 |
| 7/10-7/14 | SCA | 2023 | Summer | 1,514.68 | 6.66 | 10,085 | 338 | 0.033 |

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