https://doi.org/10.25923/jyw3-ys65

NOAA Technical Memorandum NMFS

MAY 2024

ASSESSMENT OF THE PACIFIC SARDINE RESOURCE (*SARDINOPS SAGAX*) IN 2024 FOR U.S. MANAGEMENT IN 2024-2025

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NOAA-TM-NMFS-SWFSC-698

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
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Recommended citation

Kuriyama, Peter T., Caitlin Allen Akselrud, Juan P. Zwolinski, and Kevin T. Hill. 2024. Assessment of the Pacific sardine resource (*Sardinops sagax*) in 2024 for U.S. management in 2024-2025. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-SWFSC-698.
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Assessment of the Pacific sardine resource (*Sardinops sagax*) in 2024 for U.S. management in 2024-2025

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April 2024

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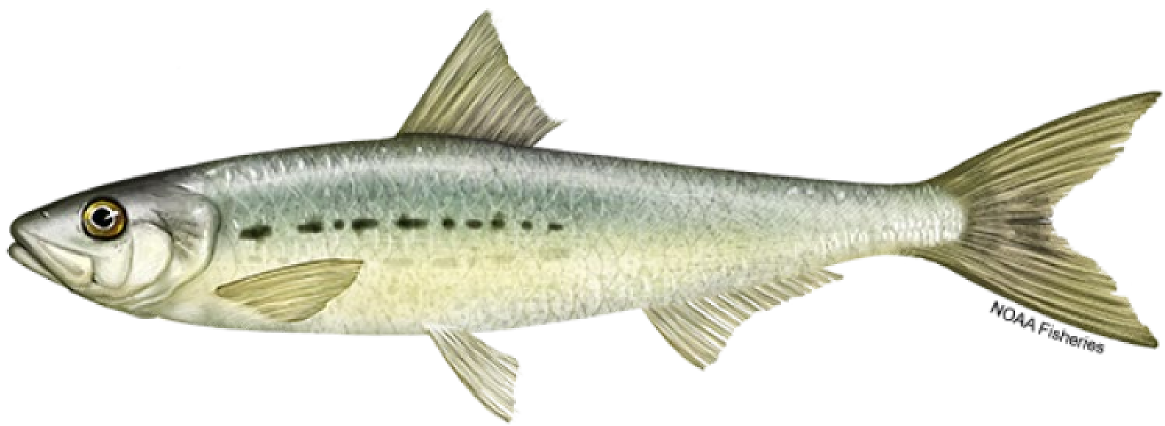

This report may be cited as: Kuriyama, P., Allen Akselrud, C., Zwolinski, J. and Hill, K., 2024. Assessment of the Pacific sardine resource (*Sardinops sagax*) in 2024 for U.S. management in 2024-2025. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-SWFSC.

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1 Executive Summary

This benchmark assessment was conducted to inform U.S. fishery management for the cycle that begins July 1, 2024 and ends June 30, 2025. This base model was reviewed by an independent review called the Stock Assessment Review (STAR) panel in February 2024.

Stock

This assessment focuses on the northern subpopulation of Pacific sardine (NSP) that ranges from northern Baja California, México to British Columbia, Canada and extends up to 300 nm offshore. The habitat model used to partition out northern subpopulation (NSP) sardine has been updated since the 2020 benchmark sardine assessment (Zwolinski and Demer 2023). Satellite oceanography data (Demer and Zwolinski 2014; Zwolinski and Demer 2019) were used in the updated habitat model to partition catch data from Ensenada (ENS) and southern California (SCA) ports to include landings and biological compositions attributed only to the northern subpopulation.

Catches

The assessment includes sardine landings (mt) from six major fishing regions: Ensenada (ENS), southern California (SCA), central California (CCA), Oregon (OR), Washington (WA), and British Columbia (BC). Landings for each port and for the NSP over the modeled years/seasons are given in Table 1.1. The updated habitat model has been applied to distinguish NSP in the catch data.

Table 1.1: 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	44,418	6,395	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	35,565	4,364	1,575
2007-1	2006-2	13,981	5,800	27,546	20,567	6,013	2,102	0	0
2007-2	2007-1	22,866	11,928	22,047	5,531	28,769	40,041	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	22,949	6,032	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	21,481	8,009	15,334
2010-1	2009-2	12,989	2,781	20,334	13,812	2,909	437	0	422
2010-2	2010-1	43,832	0	11,261	384	1,404	20,415	12,389	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	8,009	20,719
2012-1	2011-2	10,534	3,166	12,649	7,856	3,673	2,874	2,981	0
2012-2	2012-1	48,535	0	8,621	930	598	39,792	32,758	19,172
2013-1	2012-2	13,609	0	3,102	973	84	149	1,423	0
2013-2	2013-1	37,804	0	4,997	0	811	26,139	29,064	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	6,876	0
2015-1	2014-2	16,497	0	1,543	0	728	2,131	31	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	85	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	7	2	0
2019-1	2018-2	30,119	0	750	421	58	4	0	0
2019-2	2019-1	64,295	0	870	49	174	9	1	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	0	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

Data and Assessment

The integrated assessment model was developed using Stock Synthesis (SS version 3.30.22), and includes fishery and survey data collected from 2005 through 2023. The model is based on a July-June biological year (aka 'model year'), with two semester-based seasons each year (S1=Jul-Dec and S2=Jan-Jun). Catches and biological samples for the fisheries off ENS, SCA, and CCA were pooled into a single MexCal fleet, for which selectivity was modeled separately by season (S1 and S2). Catches and biological samples from OR, WA, and BC were modeled by season as a single Pacific Northwest (PNW) fleet. A single AT survey index of abundance from ongoing SWFSC surveys (2005-2023) was included in the model. Note that the data used for the AT survey biomass index for 2022 were collected from a combination of the NOAA R/V *Reuben Lasker* and F/V *Lisa Marie*.

The 2024 base model incorporates the following specifications:

- Updated habitat model for the landings data
- Updated AT survey data through 2023 applying the updated habitat model to the time series
- Steepness fixed at 0.6
- Natural mortality (*M*) modelled using the Lorenzen function
- The Hamel-Cope prior for *M*
- Empirical fisheries weight-at-age data derived from a model
- Time-varying selectivity for MexCal S1 and MexCal S2 modelled using the 2D-AR approach

Spawning Stock Biomass and Recruitment

The initial level of spawning stock biomass (SSB) was estimated to be 451,464 mt. The SSB has continually declined since 2005-2006, reaching low levels in recent years (2014-present). The SSB was projected to be 45,376 mt (SD= 12,953) on January 1, 2025 (Table 1.2).

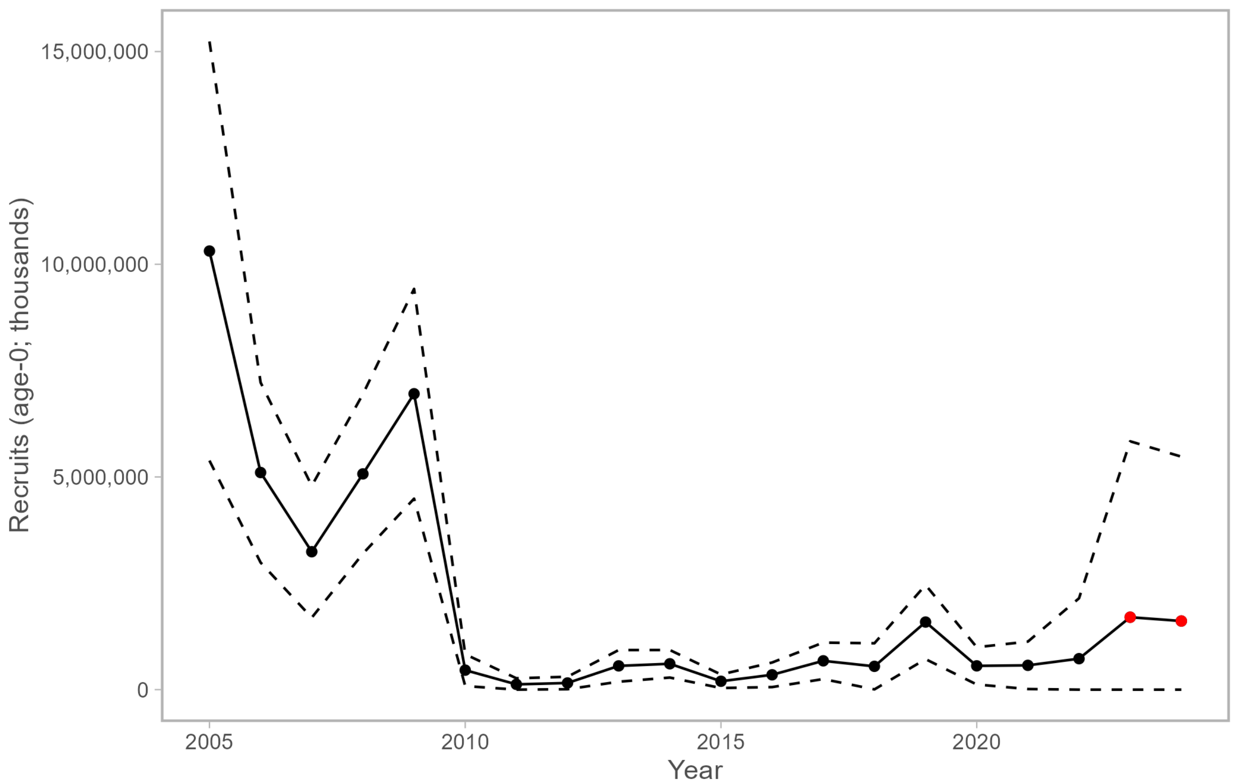

Figure 1.1: Estimated recruitment (age-0 fish, thousands) time series for the base model. Red points indicate recruitment values calculated from the stock-recruitment relationship.

Table 1.2: Spawning stock biomass (SSB) and recruitment (1000s) estimates with asymptotic standard errors for the base model. SSB estimates were calculated at the beginning of Season 2 (S2) of each model year (January). Recruits were age-0 fish (1000s) 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	128,741	21,679	2,107,020	416,624.0
--	INIT-1	0	0	0	0.0
--	INIT-2	451,464	110,222	0	0.0
2005-2	2005-1	0	0	26,832,100	6,483,930.0
2006-1	2005-2	606,649	95,849	0	0.0
2006-2	2006-1	0	0	10,310,600	2,513,570.0
2007-1	2006-2	764,708	103,257	0	0.0
2007-2	2007-1	0	0	5,104,020	1,079,660.0
2008-1	2007-2	691,358	83,227	0	0.0
2008-2	2008-1	0	0	3,242,180	790,659.0
2009-1	2008-2	544,826	54,933	0	0.0
2009-2	2009-1	0	0	5,071,680	956,872.0
2010-1	2009-2	383,947	33,777	0	0.0
2010-2	2010-1	0	0	6,955,380	1,258,020.0
2011-1	2010-2	280,779	22,629	0	0.0
2011-2	2011-1	0	0	458,216	190,657.0
2012-1	2011-2	219,141	16,214	0	0.0
2012-2	2012-1	0	0	124,023	73,009.3
2013-1	2012-2	114,090	10,465	0	0.0
2013-2	2013-1	0	0	156,313	74,869.2
2014-1	2013-2	54,150	6,873	0	0.0
2014-2	2014-1	0	0	558,439	189,929.0
2015-1	2014-2	27,975	4,818	0	0.0
2015-2	2015-1	0	0	607,810	165,156.0
2016-1	2015-2	25,067	3,888	0	0.0
2016-2	2016-1	0	0	196,999	81,227.6
2017-1	2016-2	25,863	3,719	0	0.0
2017-2	2017-1	0	0	348,990	147,353.0
2018-1	2017-2	24,359	3,484	0	0.0
2018-2	2018-1	0	0	677,292	218,823.0
2019-1	2018-2	23,831	3,265	0	0.0
2019-2	2019-1	0	0	547,956	276,593.0
2020-1	2019-2	25,793	3,402	0	0.0
2020-2	2020-1	0	0	1,588,620	444,842.0
2021-1	2020-2	30,734	4,199	0	0.0
2021-2	2021-1	0	0	559,253	223,672.0
2022-1	2021-2	40,320	6,072	0	0.0
2022-2	2022-1	0	0	571,405	284,496.0
2023-1	2022-2	43,627	7,138	0	0.0
2023-2	2023-1	0	0	727,951	724,397.0
2024-1	2023-2	42,773	8,131	0	0.0
2024-2	2024-1	0	0	-	-
2025-1	2024-2	45,376	12,953	0	0.0

Time series of estimated recruitment (age-0, thousands of fish) abundance is presented in Figure 1.1 and Table 1.2. The initial level of recruitment was estimated to be 26,832,100 age-0 thousands of fish. As indicated for SSB above, recruitment has largely declined since 2005-2006.

Stock Biomass for Pacific Fishery Management Council (PFMC) Management in 2024

Stock biomass, used for calculating annual harvest specifications, is defined as the sum of the biomass for sardine aged one and older (age 1+, mt) at the start of the management year. The time series of estimated stock biomass from the base model is presented in Figure 1.2. As discussed above for SSB and recruitment, a similar trend of declining stock biomass has been observed since 2005-06. The base model stock biomass is projected to be 58,614 mt on July 1, 2024.

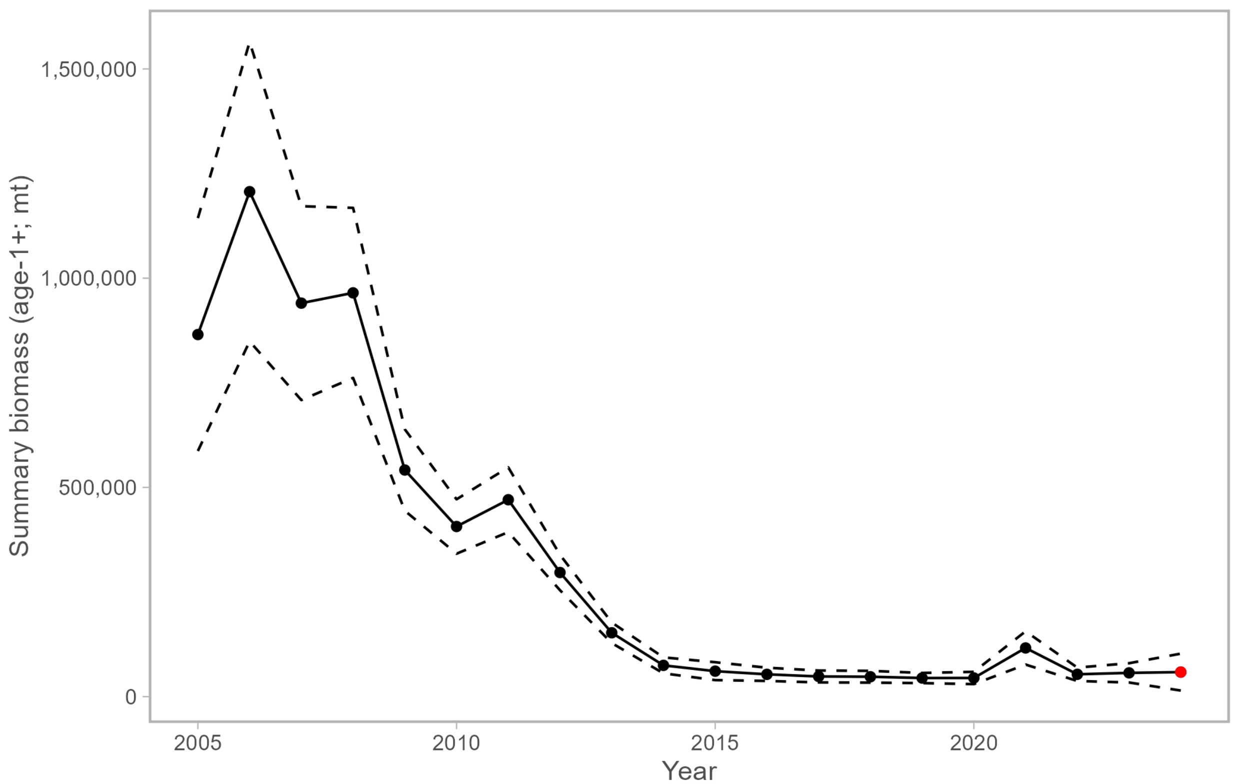

Figure 1.2: Summary (age-1+) biomass time series (95% CI dashed lines) for the base model. Red points indicate biomass based on recruitment calculated from the stock-recruitment relationship.

Exploitation Status

Exploitation rate is defined as the calendar year NSP catch divided by the total mid-year biomass (July-1, ages 0+). Based on the base model estimates, the U.S. exploitation rate has been below 5% since 2014, having peaked peaking at 38% in 2013. Exploitation rates for the NSP, calculated from the base model, are presented in Table 1.3 and Figure 1.3.

Table 1.3: Annual exploitation rate (calendar year landings / July total biomass) by country and calendar year.

Calendar Year	Mexico	USA	Canada	Total
2005	0.004	0.050	0.003	0.057
2006	0.002	0.055	0.001	0.058
2007	0.018	0.107	0.002	0.126
2008	0.006	0.076	0.010	0.092
2009	0.009	0.106	0.025	0.140
2010	0.006	0.105	0.045	0.156
2011	0.036	0.088	0.043	0.168
2012	0.011	0.307	0.064	0.382
2013	0.000	0.379	0.000	0.379
2014	0.000	0.278	0.000	0.278
2015	0.000	0.047	0.000	0.047
2016	0.000	0.006	0.000	0.006
2017	0.000	0.006	0.000	0.006
2018	0.000	0.004	0.000	0.004
2019	0.000	0.010	0.000	0.010
2020	0.000	0.007	0.000	0.007
2021	0.000	0.002	0.000	0.002
2022	0.000	0.006	0.000	0.006
2023	0.000	0.008	0.000	0.008

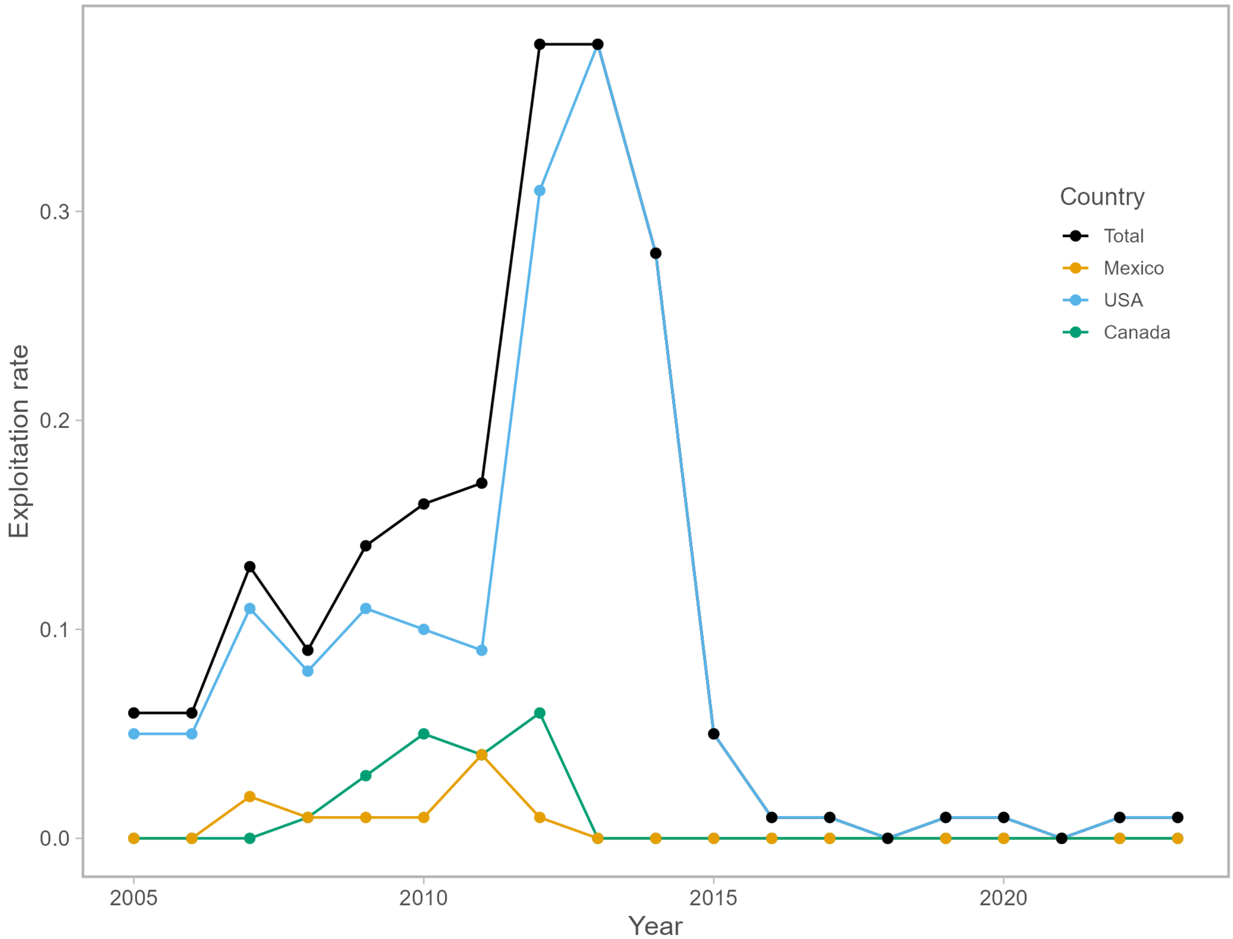

Figure 1.3: Annual exploitation rates (calendar year landings / July total biomass) for the base model.

Ecosystem Considerations

Pacific sardine represent an important forage base in the California Current Ecosystem (CCE). At times of high abundance, Pacific sardine can comprise a substantial portion of the 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), NMFS (2019a,b), and PFMC (2023) for comprehensive information regarding environmental processes generally hypothesized to influence small pelagic species that inhabit the CCE.

Harvest Control Rules

Evaluation of Scientific Uncertainty

Scientific uncertainty in the base model is based on asymptotic standard errors associated with summary biomass (age-1+) estimates derived in the model relative to the default sigma when calculating ABCs from OFLs. The base model summary biomass was forecasted to be 58,614 mt, with a SD of 22,511 in July 2024. The CV is 0.38, and the corresponding σ for calculating P-star buffer is 0.5, the default value for Tier 1 assessments.

Harvest Guideline

Annual catch limits for the U.S. sardine fishery are calculated using a set of harvest control rules (HCRs) that modulate the annual exploitation rate (E_{MSY}) based on prevailing environmental conditions. The control rules defined in the CPS-FMP are:

$$OFL = Biomass * E_{MSY} * Distribution,$$

$$ABC = Biomass * Buffer_{P-star} * E_{MSY} * Distribution$$

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

where OFL is the overfishing limit, ABC is the Acceptable Biological Catch, and HG is the harvest guideline for the directed fishery, Biomass is the projected biomass of sardine aged 1+, E_{MSY} is the environmentally-linked annual exploitation rate, Distribution is the presumed U.S. distribution of the sardine NSP, CUTOFF (150,000 mt) is the age 1+ biomass threshold below which HGs for directed fishing are set to zero, and $Buffer_{P-star}$ is the uncertainty buffer used to set ABCs based on a range of probabilities of overfishing (Wetzel and Hamel 2023). Values for the above HCRs are all presented in Table 1.4.

OFL and ABC

Calculated OFL, ABCs and HG for the 2024-25 fishing year are presented in Table 1.4. Stock biomass (ages 1+) in on July 1, 2024 is forecasted to be 58,614 mt. The overfishing limit associated with that biomass was 8,312 mt. Acceptable biological catches (ABCs) for a range of P-star values and assessment tiers for the base model are presented in Table 1.4. ABC buffers were based on uncertainty of the biomass of age 1+ sardine projected on July, 1 2024 (58,614 mt, SE = 22,511) and were calculated using methods described in Wetzel and Hamel (2023). Corresponding buffers and ABC values are presented in Table 1.4. Given the current stock biomass is below the 150,000 CUTOFF threshold, the HG for the directed fishery will be set to zero (see figure below).

Table 1.4: Pacific sardine harvest control rules for fishing year 2024-2025.

Harvest Control Rule Formulas

OFL = BIOMASS * E_{MSY} * DISTRIBUTION; where E_{MSY} is bounded 0.00 to 0.25
$ABC_{P\text{-}star}$ = BIOMASS * $BUFFER_{P\text{-}star}$ * E_{MSY} * DISTRIBUTION; where E_{MSY} is bounded 0.00 to 0.25
HG = (BIOMASS - CUTOFF) * FRACTION * DISTRIBUTION; where FRACTION is E_{MSY} bounded 0.05 to 0.20

Harvest Formula Parameters									
BIOMASS (ages 1+, mt)	**58,614**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
P-star	0.45	0.4	0.35	0.3	0.25	0.2	0.15	0.1	0.05
ABC $Buffer_{Tier1}$	0.9225	0.8499	0.7809	0.7142	0.6486	0.5826	0.5141	0.4392	0.3479
ABC $Buffer_{Tier 2}$	0.851	0.7223	0.6097	0.51	0.4206	0.3394	0.2643	0.1929	0.121
ABC $Buffer_{Tier 3}$	0.7778	0.6025	0.4627	0.3504	0.2595	0.1858	0.1258	0.0771	0.0373
CalCOFI SST (2021-23)	15.597	-	-	-	-	-	-	-	-
E_{MSY}	0.163	-	-	-	-	-	-	-	-
FRACTION	0.163	-	-	-	-	-	-	-	-
CUTOFF (mt)	150,000	-	-	-	-	-	-	-	-
DISTRIBUTION (U.S.)	0.87	-	-	-	-	-	-	-	-
Harvest Control Rule Values (MT)									
OFL =	**8,312**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
$ABC_{Tier 1}$ =	7,668	7,064	6,491	5,936	5,391	4,843	4,273	3,651	2,892
$ABC_{Tier 2}$ =	7,074	6,004	5,068	4,239	3,496	2,821	2,197	1,603	1,006
$ABC_{Tier 3}$ =	6,465	5,008	3,846	2,913	2,157	1,544	1,046	641	310
HG =	0	-	-	-	-	-	-	-	-

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 sardine 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 2022). U.S. harvest specifications and landings since 2000 are displayed in Table 1.5. Harvests in major fishing regions from ENS to BC are provided in Table 1.1.

Table 1.5: 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.

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

Unresolved Problems and Major Uncertainties

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 coordinated F/Vs using acoustics and purse seining. The habitat model used to separate NSP sardine has been updated, resulting in a more biologically plausible time series of catch values. Survey and assessment methods will continue to be revisited and adapted as warranted.

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 future assessments. The data sets that will be affected in particular include those related to the AT survey (biomass, survey age composition data (including ageing uncertainty), survey weights-at-age) and also fishery data such as fishery catch, fishery age-composition and fishery weight-at-age. While collection of data on Japanese sardine is incorporated in the AT survey methods, there is currently no data being collected on the fishery data itself for Japanese sardine.

2 Introduction

2.1 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), and Leet *et al.* (2001) as well as references cited below.

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. Sardines did not generally occur in significant quantities north of Baja California when abundance was low during the 1960-70s.

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 10.1), 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 NSP sardine out of 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 this assessment. The NSP is exploited by fisheries off Canada, the U.S., and northern Baja California (Figure 10.1), 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 (Janssen Jr 1938; Clark and Janssen 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. Several tons of sardine were collected 300 nm west of the Southern California Bight during a cooperative U.S.-U.S.S.R. research cruise for jack mackerel in 1991 (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 on the AT survey from 2014-2023, and found Japanese sardine only in 2022 and 2023, although one individual Japanese sardine was observed in 2014 (Longo and Craig in prep). Genetic samples collected during the 2022 AT survey were sampled prior to knowing Japanese sardine were present and thus were not systematically sampled in such a way as to be able to separate Japanese sardine out of the AT survey biomass estimate. The 2023 AT survey genetic samples were collected in a systematic way to be able to separate out Japanese sardine biomass, but not all samples were received or processed in time for incorporation into the biomass estimate or this benchmark stock assessment. Separating out Japanese sardine from Pacific sardine for the 2023 AT survey and beyond is an ongoing research priority of the SWFSC. See Appendix A for a model sensitivity accounting for the presence of Japanese sardine.

2.2 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 323 g. 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 on 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, spawning was observed in areas north of Cape Mendocino to central Oregon during April 2015 and 2016 (Dorval *et al.* 2013, 2016).

2.3 Ecosystem Considerations

Pacific sardine represent an important forage base in the California Current Ecosystem (CCE). Pacific sardine can comprise a substantial portion of biomass in the CCE at times of high abundance. 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.

2.4 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 southern California (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. 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 million mt 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). 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% during 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 (PFMC 2013).

2.5 Relevant History of the Fishery and Important Features of the Current Fishery

The fishery for Pacific sardine 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 supported the largest fishery in the western hemisphere during the 1930s and 1940s, with landings from 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. Sardines were taken incidentally with Pacific and jack mackerel in the SCA mackerel fishery during the early 1980s. 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.

2.6 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 2022). U.S. harvest specifications and landings since 2005 are displayed in Table 9.1. Harvests in major fishing regions from ENS to BC are provided in Table 9.2 and Figure 10.2.

3 Data

Data used in the Pacific sardine assessment are summarized in Figure 10.3. The data updated for this assessment are:

- Fishery catches, updated based on the revised habitat model through 2023
- Fishery age compositions from exempted fishing permits for 2021 and 2023
- Model-based fishery weight-at-age values for 2005-2023
- AT survey index of abundance, updated through 2023 using the revised habitat model (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)

3.1 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);

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 9.3.

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 9.2). 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, '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 modeled with semester-based selectivities ('MexCal S1' and 'MexCal S2'). The rationale for this fleet design is provided in Hill *et al.* (2011).

3.1.1 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 data to include only purported NSP catches 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. There has only been one month (Jan 2022) of NSP habitat off Ensenada since 2012 according to the updated habitat model (Zwolinski and Demer 2023). Including this catch amount would result in approximately 11,000 mt of NSP catch in semester 2 of model year 2021. Although the habitat model identifies potential sardine habitat in January 2022, ancillary information showing that the northern stock has been practically absent from its southernmost distribution in the recent past, particularly during 2022 and 2023, and provides support to excluding the Ensenada catches in semester 2 of model year 2021 from the assessment. The time series of Ensenada catches and Ensenada NSP catches used in the assessment are shown in Table 9.2.

United States landings of NSP sardine were obtained from the PacFIN database (2005-2023) and then verified with state agency sources. The NSP sardine habitat model was applied to data from Southern California, and catches were filtered to only include NSP. 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 9.2 and Figure 10.2. Landings aggregated by model year-semester and the three fleets are presented in Table 9.4 and Figure 10.4. The changes to catch values (some due to database updates and others due to the updated habitat model) are shown in Table 9.5.

3.1.2 Updated Habitat Model

To attribute landings from Ensenada and San Pedro to the NSP, the putative fishing regions (Figure 1 of Zwolinski and Demer 2023) were classified as NSP based on a fishing-area index that uses the output of the updated habitat model and a predetermined probability threshold above which monthly landings are considered to be from the NSP (Zwolinski and Demer 2023). The fishing-area index is a three-point running mean of 8-day-composite satellite images, from the 1st and 16th day of each month. If more than half of the fishing area includes a probability greater than the threshold (0.18), then all of the landings there that month are attributed to the NSP. When the proportion of the fishing area suitable for the NSP is less than 50%, all of the monthly landings are assumed to be from the SSP. Additional criteria such as continuity in length distributions, age-at-length, and presence of spawning activity can be supporting information (Zwolinski and Demer 2023).

3.1.3 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 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 U.S. Pacific coast. It is generally acknowledged that the small purse seine fishery for coastal pelagic fishes discards negligible volumes of sardine.

3.1.4 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 some missing weight-at-age 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. This assessment 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.

3.1.5 Age compositions

Age compositions for each fleet and season were the sums of catch-weighted age observations, with monthly landings within each port and season serving as the weighting unit. As indicated above, environmental criteria used to assign landings to NSP (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 10.5-10.7):

- Identify 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

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

- Calculate the number of fish (F) in the catch by m, a, y

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

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

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

- 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 10.5-10.7.

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 relatively 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.

3.1.6 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 at 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.

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 10.8). See Appendix 2 in Hill *et al.* (2011), as well as Dorval *et al.* (2013) for additional details regarding age-reading data sets, model development and assumptions.

3.2 Fishery-Independent Data: Acoustic-Trawl Survey

This assessment uses a time series of biomass estimates from the SWFSC's acoustic-trawl (AT) survey. Acoustic sampling of marine environments for determining the 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 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).

3.2.1 Index of abundance

Indices from the spring (when available) and summer AT surveys from calendar years 2005-2023 were used in this assessment. The acoustic-trawl biomass estimate was derived using nautical area scattering coefficients (NASC) from putative 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, uncrewed 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. Uncrewed 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 (*Lisa Marie* off the PNW and *Long Beach Carnage* off California) with acoustic echosounders and conducting a minimum of 3-5 purse seine sets if possible during daylight hours. A set is conducted at night in the case of abundant CPS or an unsuccessful daytime set.

R/V *Reuben Lasker* had logistical challenges during summer 2022 (Figure 10.9) 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. *Lisa Marie* and *Lasker* both 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 Pacific 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 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, CV=0.28), the *Lisa Marie* core survey biomass estimate (coasts of northern CA, OR, and WA; 42,946 mt, CV=0.32) and the nearshore biomass estimate (15,765 mt, CV=0.23). The three biomass values were summed together and input as the 2022 biomass estimate with a q=1.

The biomass from the surveys is classified as NSP based on its geographic distribution relative to that of the habitat, and ancillary information of spatial separation, and continuity of length distribution and age-at-length supports the NSP classification (Zwolinski and Demer 2023).

The full time series is shown in Figure 10.10 and Table 9.6. The spring calendar year 2021 (model year-semester 2020-2) AT survey biomass was not attributed to NSP based on the habitat model, and was not included in this assessment (Zwolinski *et al.* 2023).

3.2.2 Age compositions

Estimates of abundance-at-length (Table 9.7) were converted to abundance-at-age (Table 9.8) using summer survey-specific age-length keys (Figure 10.11). ALKs from 2021, 2022, and 2023 are shown in Figures 10.12 to 10.14. The ALKs from *Lisa Marie* and *Lasker* for 2022 were pooled (Figure 10.13). Note, generally ALKs are generated from data collected aboard NOAA ships (e.g. *Lasker*), but 2022 was an exception due to logistical issues. Age-length keys were constructed using ordinal generalized additive regression models from the R package mgcv (Wood 2017). More details are given in Appendix A of Kuriyama *et al.* (2020). A generalized additive model with an ordinal categorical distribution fits an ordered logistic regression model in which the linear predictor provides the expected value of a latent variable following sequentially ordered logistic distributions. Unlike previous iterations in which the conditional age-at-length was modeled as a multinomial response function ‘multinom’ from the R package ‘nnet’, and hence, disregarding the order of the age classes, the order logistical framework provides a more strict structure for the conditional age-at-length, which might, arguably, be beneficial with small sample sizes. The resulting survey age-composition data are shown in Figure 10.15.

3.2.3 Ageing error

There were four ageing error vectors for age data (see Appendix C). These were for the periods of 2005-2016, 2017-2018, 2021-2023, and an updated vector for 2016 (Figure 10.8).

3.3 Fishery-Independent Data: Aerial Survey

Relating the aerial survey estimates to the length compositions was difficult due to 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 4.5.5, Appendix D, and in Lynn *et al.* (2020).

Aerial survey data are available for springs and summers in calendar years 2022 and 2023 (Appendix D). 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 of the aerial estimates for summer 2022 and 2023 were not attributed to NSP. As a result, these aerial estimates were not used in adjusting catchability values as done for 2015-2019 and 2021.

3.4 Biological Parameters

3.4.1 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 10.1). The current approach involves analyzing satellite oceanographic data to partition monthly catches and biological compositions from ENS and SCA ports to include only data from the NSP (Demer and Zwolinski 2014) using the recently updated habitat model (see Zwolinski and Demer (2023)). This approach was first adopted in the 2014 full assessment (Hill *et al.* 2014; PFMC 2014) and has carried forward each year, including this assessment.

3.4.2 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 involve more estimable model parameters than the empirical weight-at-age approach. For these reasons, this base model was constructed to bypass growth estimation internally in Stock Synthesis, instead opting for use of empirical weight-at-age time series (as done for the 2020 benchmark assessment). The length-weight relationship used for fishery-independent data is shown in Figure 10.16. This was the same length-weight relationship that has been used for fishery-independent data in every assessment beginning with Hill *et al.* (2016). The current base model further updates this method by applying a state-space model conditional on year, age, and cohort for the fishery weight-at-age data (See Appendix B 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 some 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 approach used in this assessment used model output from the model with the best fit to each fleet-specific data set. More details on the approach are given in Appendix B. Fishery-dependent weight-at-age vectors are displayed by years in Figures 10.17 to 10.19.

Fishery-independent weight-at-age

AT survey weight-at-age time series (Figure 10.20) 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 start 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. Start 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, and used the time-invariant length-weight relationship shown in Figure 10.16. The current benchmark assessment maintains the 2020 benchmark structure.

3.4.3 Maturity

Maturity was modeled using a fixed vector of fecundity × maturity by age. The vector was derived from the 2016 assessment 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:

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

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.

Maturity-at-length was converted to maturity-at-age using a pooled age-length key from all spring survey samples. The resulting proportions at age were 0.03 for age 0, 0.34 for age 1, 0.73 for age 2, 0.93 for age 3, 0.98 for age 4, and 1 for ages 5 and above. Maturity-at-age and fecundity-at-age have not changed between the 2020 benchmark and the current base model.

3.4.4 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 start 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 maximum age) and SD of 0.31 (Hamel and Cope 2022). The single value of *M* was adjusted to have age-specific values, based on the Lorenzen *M* option in SS3 (after 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.

3.5 Available Data Sets Not Used in Assessment

Past sardine stock assessments have included a time series of estimates of spawning stock biomass (SSB) based on the daily egg production method (DEPM). 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 because it requires having relatively high sample sizes of mature adults. However, DEPM surveys have not sampled sufficient mature adults in the later years of the survey. This is not unexpected since these years were around the closure of the fishery when abundance had declined. Additionally, the SWFSC has focused on summer AT surveys, and there are not likely to be future spring surveys.

The SWFSC's Rockfish Recruitment and Ecosystem Assessment Survey has been previously evaluated as part of the sardine stock assessment (Hill *et al.* 2011) and found to have limitations as a fishery-independent data source for Pacific sardine. The survey (core area) design represents a limited spatial area in relation to this species' biology and movement. The survey was not designed to accurately sample coastal pelagic species in general, which exhibit highly variable depth distributions and overall availabilities to a survey/fishery due largely to prevailing oceanographic conditions (e.g., no sardines were observed in 2010-12). A formal methods review of the rockfish survey should be conducted before potentially including results (abundance and/or size-composition data) in the Pacific sardine assessment. Interpretation of CPS distributions from this survey indicate that Pacific sardine (and other CPS) are typically more abundant in the core area during oceanographic regimes of low productivity and/or low upwelling.

4 Assessment

4.1 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. 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 the 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) and 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.

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 with 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 yr^{-1}, 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 4.5.4 for a more complete explanation.

The 2020 benchmark assessment (Kuriyama *et al.* 2020) and 2022 update assessment (Kuriyama *et al.* 2022) utilized SS version 3.30.14. These assessments also relied solely on the AT survey data as an index of abundance and the modeling time frame began in 2005. Catchability values were fixed at 0.733 for 2015-2019. The 2022 update assessment had catchability values of 0.589 for model year-semester 2020-2 and 0.733 for 2020-1. In both assessments, catchability values were adjusted based on the ratios of AT survey and aerial survey biomass estimates. Additionally, steepness was fixed at 0.3 and used F values (yr^{-1}) as opposed to catch values in the forecasts. AT survey age compositions were derived using survey-specific age-length keys

4.2 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 the assessment due to the updated habitat model resulting in CCPSS data occurring in areas that are not NSP habitat. 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 used in the nearshore areas utilize a mesh size that can catch sardine effectively. In 2022, a portion of the AT survey area was surveyed by the Lisa Marie, which used the same fishing gear as that used in the nearshore surveys.

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.
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 (Yau 2023), resulting in an updated habitat model published by Zwolinski and Demer (2023). This updated habitat model was applied to the data for this 2024 benchmark 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 encountered 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 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 C.

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 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.

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 the 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 off Ensenada. Mexico does not 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 catches 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 synoptic 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

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. 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 were last collected during 2012, with the fishery closed since 2015. It is unlikely this would affect current biomass estimates or projections due to the fishery closure.

4.3 Changes between 2020 and the 2024 Base Model

- Updated habitat model applied to the AT survey biomass and catch data
- Updated AT survey data through 2023
- Steepness fixed at 0.6
- *M* modelled using the Lorenzen function
- The Hamel-Cope prior for *M*
- Empirical fisheries weight-at-age data derived from the model
- Time-varying selectivity for MexCal S1 and MexCal S2 fleets modeled using the 2D-AR approach

Table 9.9 summarizes the differences between the 2020 base assessment and current 2024 assessment.

4.4 Model Description

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

4.4.2 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 one fleet, although it 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, several 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 were collected from both *Lasker* and *Lisa Marie*. The STAT decided to model the components as one fleet with a catchability value equal to 1.

4.4.3 Fisheries

Fishery structure in the base model is the same as implemented in recent assessments. Three fisheries are included in the model: 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).

4.5 Model Parameters

4.5.1 Longevity and natural mortality

Assumptions regarding the biology of Pacific sardine in the 2024 base model were similar to those used in past assessments. There were 11 age bins, representing ages 0 to 10+, although the age-composition data were pooled into an age 8+ bin for model fitting. The prior for natural mortality (*M*) was calculated using the updated Hamel and Cope method (Hamel and Cope 2022) which assumed a maximum age of 8 (see Figure 10.21). Additionally, natural mortality was time-invariant and age-specific (1996; Lorenzen 2022).

4.5.2 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.

4.5.3 Stock-recruitment relationship

In this model, equilibrium recruitment (R_0) and initial equilibrium offset (SR_{regime}) were estimated, and steepness (h) was fixed at 0.6. Steepness is difficult to estimate from available data, and a likelihood profile suggests that values ranging from 0.25 to 0.6 are supported by the data.

Recommended practices for stock assessment are to estimate steepness with a prior (Punt 2023). The challenge with estimating steepness for Pacific sardine is that the population has undergone a "one-way trip" in which biomass was high at the beginning of the time series and is currently at comparatively low levels. A two-way trip in which biomass has a high, low, then high period may improve the ability to estimate steepness, as an increasing population may facilitate estimation of stock-recruit parameters. However, simulation studies show that a two-way trip does not improve estimation, even with properly specified assessment models (Lee *et al.* 2012). Additionally, previous studies of priors for values of steepness have focused on rockfish (Dorn 2002; Thorson *et al.* 2019), and there have not been any studies of steepness for coastal pelagic species. Thus, the STAT decided to fix steepness at 0.6, which is the highest value supported by the data (corresponding to the upper 95% confidence interval for *h* based on a likelihood profile. Steepness is estimated to be low (roughly 0.3), which is likely inconsistent with the life history of sardine. A 2021 stock assessment update for Canadian Pacific herring (*Clupea pallasii*), which has a similar life history to sardine, found steepness values ranging from 0.662-0.903 were supported by the data (DFO 2021). In summary, estimating steepness for sardine results in a value that seems implausible given sardine life history, and there are no studies that might inform a prior for the value of steepness. As a result, steepness is fixed at 0.6, which is the highest value that is consistent with being in the 95% confidence interval based on a likelihood profile and is similar to values estimated in recent assessments of Pacific herring.

Following recommendations from past assessment reviews, the estimate of recruitment variability (σ_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, σ_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 size of the 2024 year-class being freely estimated in the model.

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.

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).

4.5.4 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 variation in these migrations and to provide better model fits to age compositions from the fisheries and AT survey.

MexCal S1 and MexCal S2 fishery selectivities were estimated to be time-varying using 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 forced to be time-varying and 5-8+ were assumed to be time-invariant. Both fleets had time-varying estimation for the years 2006-2014. 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 selectivity curves but poorer fits to the age-composition data. Increasing the SE values resulted in improved fits to the age-composition data but higher values associated with parameter deviations in the total objective function calculations. The goal of this configuration was to capture the year-to-year variability in the fishery age composition data so an SE of 1 was retained.

The PNW fleet was modeled using a two-parameter logistic selectivity form as implemented in past assessments. 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 survey in any given year.

4.5.5 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) excluding 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 9.6). 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 2021 were calculated with the same assumption that q for the AT survey is $\frac{ATcore+ATnearshore}{ATcore+ATnearshore+aerial}$, resulting in a value of 0.733, respectively (Table 9.6).

The 2022 AT survey had logistical challenges, but the total spatial coverage of the components spanned the West Coast of the US. As a result, the STAT assumed a q of 1 for 2022. A value of 1 was also assumed for the 2023 AT survey. For both 2022 and 2023, aerial survey data was not included in the q calculation because those aerial surveys occurred in habitat that was mostly not NSP habitat.

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, Pacific mackerel, and northern anchovy.

4.5.6 Likelihood components and model parameters

A complete list of model parameters for the base model is presented in Table 9.11. 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 the 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.

4.5.7 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. Thus, while parameters associated with equilibrium conditions (such as R_0) are estimated, the model is assumed to begin at an exploited state. This required 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 by 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 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.

4.5.8 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.

4.5.9 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 the developers of SS 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 E. Results from a bridging analysis that adds each feature of the assessment model are shown in Figures 10.22 and 10.23 and in Table 9.12.

4.5.10 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 objective function and final gradient estimates for the base model were 225.539 and 3.69e-06, respectively.

4.6 Base Model Results

4.6.1 Likelihoods and derived quantities of interest

The base model total objective function value was 225.539 (Table 9.10). Likelihood values from the AT survey and PNW fishery age compositions made up the majority of the total objective function. The forecasted stock biomass for July 2024 was 58,614 (age 1+; mt).

4.6.2 Parameter estimates and errors

Parameter estimates and standard errors for the 2024 base model are presented in Table 9.11.

4.6.3 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 10.17 to 10.19).

4.6.4 Selectivity estimates and fits to fishery and survey age compositions

Time-varying age-based selectivities were estimated for the three fisheries (Figures 10.24) and AT survey (Figure 10.25). Time-varying selectivities resulted in good fits to fishery age compositions (Figures 10.26, 10.27, and 10.28), and residuals of the fits to age compositions had a maximum absolute scale of about two (Figures 10.29, 10.30, and 10.31).

Time-varying age-0 parameters resulted in adequate fits to AT survey age composition data in some years, and some poor fits in other years (Figures 10.32 and 10.33)

4.6.5 Fit to survey index of abundance

Model fits to the AT survey abundance index in arithmetic and log scale are presented in Figures 10.34 and 10.35 for the AT survey. The predicted fit to the survey index was generally good (near mean estimates and within error bounds).

4.6.6 Stock-recruitment relationship

Recruitment was modeled using a Beverton-Holt stock-recruitment relationship (Figure 10.36). The assumed level of underlying recruitment deviation error was fixed (σ_R=1.2), equilibrium recruitment was estimated ($log(R_0$)= 14.561), and steepness (h) was set to 0.6.

Recruitment deviations for the early (1999-2004), main (2005-2023), and forecast (2024-2025) periods in the model are presented in Figure 10.37. Asymptotic standard errors for the recruitment deviations are shown in Figure 10.38, and the recruitment bias adjustment plot for the three periods is shown in Figure 10.39.

4.6.7 Population number- and biomass-at-age estimates

Population numbers-at-age estimates for the base model are presented for semester 1 in Table 9.13 and semester 2 in Table 9.14.

Corresponding estimates of population biomass-at-age, total biomass (age-0+, mt) and stock biomass (age-1+ fish, mt) are shown for semester 1 in Table 9.15 and semester 2 in Table 9.16. Age 0-3 fish have comprised about a majority of the total population biomass from 2005-2023.

4.6.8 Spawning stock biomass

Time series of estimated spawning stock biomass (SSB; mt) and associated 95% confidence intervals are presented in Table 9.17. The initial level of SSB was estimated to be 451,464 mt. The SSB has continually declined since 2005-2006, reaching low levels in recent years (2014-present). The SSB was projected to be 45,375 mt in January 2025.

4.6.9 Recruitment

Time series of estimated recruitment abundance are presented in Tables 9.14 and 9.17 and Figure 10.40. The equilibrium level of recruitment R_0 was estimated to be 2,107,020 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.

4.6.10 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 9.18 and Figure 10.41. 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 decreasing to low levels since 2014. The base model stock biomass is projected to be 58,614 mt in July 1, 2024. Pacific sardine NSP biomass is near the 50,000 mt minimum stock size threshold as defined in the CPS-FMP.

Stock biomass had a large increase from 2020 to 2021 of 44,581 to 116,358 mt. The STAT explored this through the base model development process and at the STAR panel. One reason for this increase is an increase in age-0 and age-1 weight-at-age values in the survey data (which are also assumed to be representative of the population). Values from 2021 were about twice as large as those from the previous 2019 summer survey. Seemingly small changes in weight-at-age for young fish can lead to large changes in the biomass as these age-0 and age-1 fish make up a majority of the population by number. Additional explanations for the biomass bump are an increase in the survey biomass from 2020 to 2021 and the change in survey age selectivity (age-0 fully selected in 2020 and age-0 not selected in 2021).

4.6.11 Fishing mortality

Estimated fishing mortality (apical F) time series by fishery are presented in Figure 10.42. In recent years (2015-2023), fishing mortality estimates have been low. US landings have been low, and landings of NSP in Mexico have been zero with the updated habitat model (Table 9.19; Figure 10.43).

4.7 Modeling Diagnostics

4.7.1 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 20% for 50 replicates (although only 47 converged). A better minimum was not found, and the STAT concluded that the model results are those from a global minimum (Table 9.20). Rephasing of the parameter estimation order did not result in a better fit to the data. There were no difficulties in inverting the Hessian matrix to obtain estimates of variability, and the STAT concluded that the base model represents the best fit to the data given the modeling assumptions.

4.7.2 Historical analysis

Estimates of stock biomass (Figure 10.44; age 1+ fish, mt) and recruitment (Figure 10.46; 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 some years. It is important to note that previous (2014-16) assessments were structured very similarly (e.g., similar model dimensions, data, assumptions, and parameterizations). In contrast, 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.

4.7.3 Retrospective analysis

Results from a retrospective analysis in which the models are run with one year of data dropped at a time are in Figure 10.45. Pacific sardine and CPS more generally have high recruitment variability, so *a priori* one might expect a strong retrospective pattern. However, for this specific model there is not much retrospective pattern. This is likely due to the fixed catchability values used in the base model.

4.7.4 Likelihood profiles

Likelihood profiles were conducted for steepness, natural mortality (with steepness fixed at 0.6), catchability adjusted by percentages, and terminal year biomass. The terminal year biomass sensitivity included an additional survey fleet in the model that was very heavily weighted (lambda=500) to force the model to fit the terminal year biomass essentially perfectly.

Recruitment estimates support low values of steepness (Figure 10.47). There is relatively little information on steepness in the age compositions. One explanation for the low steepness value having the highest likelihood 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 during the time period. Increasing values of steepness had relatively small changes on 2023 and 2024 forecast stock biomasses (Table 9.21). Estimates of summary biomass across fixed values of steepness are all relatively similar (Figure 10.48).

Natural mortality estimates between 0.5 and 0.6 yr^{-1} (Figure 10.49) 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 10.49). The changes in select parameter estimates and stock biomass estimates at fixed values of natural mortality are shown in Table 9.22. Generally, increases in natural mortality values resulted in decreased estimates of initial F, survey catchability (q), and R_0 (Table 9.22). Stock biomass values in 2019 and 2020 increased with increasing natural mortality, due to the negative correlation with survey catchability (Table 9.22 and Figure 10.50).

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 10.51). Percentage increases in catchability values resulted in increased estimates of initial F and decreased estimates of natural mortality and R_0 (Table 9.23). Increased catchability values resulted in decreased forecast stock biomass estimates (Figure 10.52).

Terminal year biomass values between 40,000-80,000 mt were consistent with the other data sets (Figure 10.53), 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 9.24 and Figure 10.54.

4.7.5 Sensitivity to alternative data weighting

The base model was run with age compositions reweighted according to the Francis method (Francis 2011) to evaluate model sensitivity to data weighting. The variance adjustment values are

are shown in Table 9.25. Parameter estimates, biomass estimates, and likelihood values are shown in Table 9.25 and Figure 10.55.

5 Harvest Control Rules

5.1 Evaluation of Scientific Uncertainty

Scientific uncertainty in the base model is based on asymptotic standard errors associated with summary biomass (age-1+) estimates derived in the model. The base model summary biomass was forecasted to be 58,614 mt, with a SD of 22,511 in July 2024 (Table 9.18). The CV is 0.38, and the corresponding σ for calculating P-star buffer is 0.5, the default value for Tier 1 assessments. The default σ value of 0.5 was used.

5.2 Harvest Guideline

Annual catch limits for the U.S. sardine fishery are computed using a set of harvest control rules (HCRs) that modulate the annual exploitation rate (E_{MSY}) based on prevailing environmental conditions. The control rules defined in the CPS-FMP are:

$$OFL = Biomass * E_{MSY} * Distribution,$$

$$ABC = Biomass * Buffer_{P-star} * E_{MSY} * Distribution$$

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

where OFL is the overfishing limit, ABC is the Acceptable Biological Catch, and HG is the harvest guideline for the directed fishery, Biomass is the projected biomass of sardine aged 1+, E_{MSY} is the environmentally-linked annual exploitation rate, Distribution is the presumed U.S. distribution of the NSP sardine, CUTOFF (150,000 mt) is the age 1+ biomass threshold below which HGs for directed fishing are set to zero, and $Buffer_{P-star}$ is the uncertainty buffer used to set ABCs based on a range of probabilities of overfishing (Wetzel and Hamel 2023). Values for the above HCRs are all presented in Table 9.27 and further explained below.

5.3 CalCOFI SST and E_{MSY}

In 2014, the PFMC adopted the use of CalCOFI sea-surface temperature (SST) data for specifying environmentally-dependent E_{MSY} each year. The E_{MSY} is calculated as,

$$E_{MSY} = -18.46452 + 3.25209(T) - 0.19723(T^2) + 0.0041863(T^3)$$

where T is the three-year running average of CalCOFI SST (Table 9.26). E_{MSY} is bounded between 0 and 0.25 for OFLs and ABCs and between 0.05 and 0.20 for the HG.

The CalCOFI sea surface temperature (SST) used to calculate E_{MSY} for 2024-25 was derived from the mean temperature over the most recent three years of quarterly CalCOFI cruise data collection (2021-2023). The average SST is derived from: an average for every cruise and station (5-10 m depth), a total average for each cruise (representing a specific year and season), and all four seasons from each year are averaged into an annual mean temperature. The annual mean temperature is reported, as is the running mean for the three most recent years. Three cruises were missed or incomplete (fewer than 55 stations sampled) in Fall 2023, Winter 2022, and Spring 2021 (Figure 10.56). To fill these three missing cruises, a regression of mean temperatures from CalCOFI cruises against the Extended Reconstructed SST (ERSST) satellite data (National Centers for Environmental Information. 2024. Extended Reconstructed SST. Accessed March 6, 2024. https://www.ncei.noaa.gov/products/extended-reconstructed-sst) for the missing season was applied and used to predict the missing season using available ERSST data (Figure 10.56). The annual mean was derived from the available CalCOFI seasonal means and the replacement ERSST regression for each year. Based on these methods, the annual average SSTs were 15.48 °C for 2021, 15.69 °C for 2022, and 15.62 °C for 2023. Average temperature during 2021-2023 was 15.597 °C, resulting in E_{MSY}=0.163.

5.4 OFL, ABC, and HG values for the 2024-2025 Fishing Year

Calculated OFL, ABCs and HG for the 2024-25 fishing year are presented in Table 9.27. Stock biomass (ages 1+) on July, 1 2024 is forecasted to be 58,614 mt. The overfishing limit associated with that biomass is 8,312 mt. Acceptable biological catches (ABCs) for a range of P-star values and assessment tiers for the base model are presented in Table 9.27. ABC buffers were based on uncertainty of the biomass of age 1+ sardine projected for July 1, 2024 (58,614 mt, SE = 22,511) and were calculated using methods described in Wetzel and Hamel (2023). Corresponding buffers and ABC values are presented in Table 9.27. The HG for the directed fishery will be set to zero given the current stock biomass is below the 150,00 mt CUTOFF threshold.

6 Regional Management Considerations

Pacific sardine, as well as other species considered in the CPS FMP, are not managed formally on a regional basis within the U.S., due primarily to the extensive distribution and annual migration exhibited by these small pelagic stocks. A form of regional (spatial/temporal) management has been adopted for Pacific sardine, whereby seasonal allocations are stipulated in attempts to ensure regional fishing sectors have at least some access to the directed harvest each year (PFMC 2014).

7 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 coordinated F/Vs using acoustics and purse seining. The habitat model used to separate NSP sardine from SSP sardine has been updated, resulting in a more biologically plausible time series of catch values. Survey and assessment methods will continue to be revisited and adapted as warranted.

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 future assessments. The data sets that will be affected in particular include those related to the AT survey (biomass, survey age composition data (including ageing uncertainty), survey weights-at-age) and also fishery data such as fishery catch, fishery age-composition and fishery weight-at-age. While collection of data on Japanese sardine is incorporated in the AT survey methods, there is currently no data being collected on the fishery data itself for Japanese sardine.

8 Acknowledgements

The Pacific sardine stock assessment relies on data contributed by a number of groups and individuals.

Port samples and ageing data for the California fishery were provided by California Department of Fish and Wildlife Marine Region personnel in Monterey (Chelsea Protasio, Katie Grady, Dane McDermott, Christian Juico) San Pedro (Dianna Porzio, Leeanne Laughlin, Trung Nguyen, Sandy Diaz, Heather Lee), and Santa Barbara (Jarrett Seiler).

Fishery-dependent and -independent data for the Washington fishery were provided by Washington Department of Fish and Wildlife staff including Lisa Hillier, Zachary Calef, Erin Jaco, and Emily Seubert. Kristen Hinton from WDFW was involved with the CPS survey and planning for F/V *Lisa Marie*.

Fishery dependent and independent data for the Oregon fishery were provided by Oregon Department of Fish and Wildlife staff including Greg Krutzikowsky, Cyreis Schmidt, Jill Smith, Kelly Corbett, Keith Matteson, Wolfe Wagman and Alisson Whitman.

There are a number of collaborations between the California Wetfish Producers Association (CWPA) and SWFSC. Nearshore acoustic-purse seine surveys were conducted aboard F/V *Long Beach Carnage*. Thanks to Captains Tom Brinton and Richie Ashley, CWPA biologist Joel Van Noord, and crew William Hargrave and John Marcopolous.

Aerial surveys were a collaboration between CWPA and CDFW, piloted by Devin Reed and Andrew White. Aerial survey data and analysis were provided by Kirk Lynn (CDFW) and Emmanis Dorval (SWFSC).

Exempted fishing permit point sets and biological sampling were contributed by the crews of F/V *King Philip* (Anthony Russo), F/V *Trionfo* (Neil Guglielmo), F/V *Provider* (Jamie Ashley), F/V *Eileen* (Corbin Hanson and Nick Jurlin), and the F/V *Triton* (Peter Ciaramitaro).

Nearshore acoustic and purse seine surveys are conducted in collaboration with SWFSC. Thanks to the captains (Tom Brinton and Richie Ashley) and crew (William Hargrave and John Marcopolous) of F/V *Long Beach Carnage*. Thanks to Ocean Gold Seafood, Greg Shaughnessy, and Mike Okoniewski in the PNW as well.

Port samples for the Ensenada, Mexico fishery were collected by INAPESCA (Ensenada). Recent landings data from the Ensenada fishery were kindly provided by Concepción Enciso-Enciso (INAPESCA-Ensenada).

We thank Richard Methot for developing and continuously improving the Stock Synthesis code and Ian Taylor (NWFSC) for technical support with SS3.

Thanks to the members of the STAR panel (Cheryl Barnes, Andre Punt, Theresa Tsou) and the CIE reviewers (John Neilson and Gary Melvin).

Finally, thanks to numerous staff from the SWFSC for the ongoing collection and processing of mid-water trawl samples and acoustic data used in this assessment. Data were collected, analyzed, and provided by members of the Life History Group (Kelsey James, Brittany Schwartzkopf, Emmanis Dorval, Jon Walker, and Brad Erisman) and Advanced Survey Technologies Group (Kevin Stierhoff, Josiah Renfree, Steve Sessions, Scott Mau, David Murfin, Alice Beittel, and Dave Demer).

9 Tables

Table 9.1: 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.

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 9.2: 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	44,418	6,395	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	35,565	4,364	1,575
2007-1	2006-2	13,981	5,800	27,546	20,567	6,013	2,102	0	0
2007-2	2007-1	22,866	11,928	22,047	5,531	28,769	40,041	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	22,949	6,032	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	21,481	8,009	15,334
2010-1	2009-2	12,989	2,781	20,334	13,812	2,909	437	0	422
2010-2	2010-1	43,832	0	11,261	384	1,404	20,415	12,389	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	8,009	20,719
2012-1	2011-2	10,534	3,166	12,649	7,856	3,673	2,874	2,981	0
2012-2	2012-1	48,535	0	8,621	930	598	39,792	32,758	19,172
2013-1	2012-2	13,609	0	3,102	973	84	149	1,423	0
2013-2	2013-1	37,804	0	4,997	0	811	26,139	29,064	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	6,876	0
2015-1	2014-2	16,497	0	1,543	0	728	2,131	31	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	85	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	7	2	0
2019-1	2018-2	30,119	0	750	421	58	4	0	0
2019-2	2019-1	64,295	0	870	49	174	9	1	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	0	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 9.3: 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 the 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 9.4: Pacific sardine NSP landings (mt) by year-semester and fleet for the 2024 base model. Fishing mortality values estimated from 2023-1 and 2023-2 landings were used to forecast model year-semesters (2024-1, 2024-2).

Calendar Y-S	Model Y-S	MexCal S1	MexCal S2	PNW
2005-2	2005-1	13,803	0	54,044
2006-1	2005-2	0	15,386	102
2006-2	2006-1	20,726	0	41,504
2007-1	2006-2	0	32,381	2,102
2007-2	2007-1	46,228	0	46,225
2008-1	2007-2	0	23,701	0
2008-2	2008-1	30,249	0	39,406
2009-1	2008-2	0	26,069	0
2009-2	2009-1	14,045	0	44,824
2010-1	2009-2	0	19,502	859
2010-2	2010-1	1,787	0	54,605
2011-1	2010-2	0	15,679	0
2011-2	2011-1	24,689	0	39,751
2012-1	2011-2	0	14,694	5,855
2012-2	2012-1	1,528	0	91,722
2013-1	2012-2	0	1,057	1,572
2013-2	2013-1	811	0	55,203
2014-1	2013-2	0	4,894	908
2014-2	2014-1	1,831	0	14,664
2015-1	2014-2	0	728	2,162
2015-2	2015-1	6	0	66
2016-1	2015-2	0	1	1
2016-2	2016-1	284	0	88
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	9
2019-1	2018-2	0	479	4
2019-2	2019-1	224	0	10
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	12
2022-1	2021-2	0	193	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 9.5: Pacific sardine NSP catch values from the 2020 benchmark assessment and the current assessment. Differences greater than or equal to 1 are shown by model year-semester. The changes in catch values were due to the updated habitat model for the two MexCal fleets and updated Oregon and Washington values in the PacFIN database for the PNW fleet.

Fleet name	Model Y-S	2020 values	2024 values	Difference
MexCal_S1	2010-1	11,274	1,787	-9,487
	2011-1	24,871	24,689	-182
	2013-1	922	811	-111
	2020-1	542	429	-113
MexCal_S2	2005-2	30,364	15,386	-14,978
	2006-2	39,900	32,381	-7,519
	2007-2	42,910	23,701	-19,209
	2008-2	41,198	26,069	-15,129
	2009-2	31,146	19,502	-11,644
	2010-2	27,268	15,679	-11,589
	2011-2	23,190	14,694	-8,496
	2012-2	13,885	1,057	-12,828
	2013-2	5,625	4,894	-731
	2015-2	186	1	-185
	2016-2	7,081	145	-6,936
	2017-2	6,229	177	-6,052
	2018-2	11,819	479	-11,340
	2019-2	33,070	395	-32,675
	2020-2	48,312	224	-48,088
	2021-2	48,312	193	-48,119
PNW	2005-1	54,153	54,044	-109
	2006-1	41,221	41,504	283
	2006-2	0	2,102	2,102
	2007-1	48,237	46,225	-2,012
	2008-1	39,800	39,406	-394
	2009-1	44,841	44,824	-17
	2009-2	1,370	859	-511
	2010-1	54,086	54,605	519
	2011-1	39,750	39,751	1
	2011-2	5,806	5,855	49
	2012-1	91,426	91,722	296
	2012-2	1,571	1,572	1
	2013-1	57,218	55,203	-2,015
	2014-1	15,217	14,664	-553
	2014-2	2,194	2,162	-32
	2016-1	173	88	-85
	2018-1	8	9	1
	2018-2	3	4	1
	2019-1	8	10	2
	2021-1	11	12	1
	2021-2	3	0	-3

Table 9.6: 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), and aerial survey are shown. The AT biomass, CVs, and Q values used as input in the base model are shown in the final three columns.

Model Y-S	AT Core	AT CV	AT Nearshore	Near. CV	Method	Aerial	AT Input	CV	Qadj
2005-2	1,947,060	0.3	--	--	--	--	1,947,060	0.3	1
2006-1	--	--	--	--	--	--	--	--	--
2006-2	--	--	--	--	--	--	--	--	--
2007-1	--	--	--	--	--	--	--	--	--
2007-2	751,075	0.09	--	--	--	--	751,075	0.09	1
2008-1	801,000	0.3	--	--	--	--	801,000	0.3	1
2008-2	--	--	--	--	--	--	--	--	--
2009-1	--	--	--	--	--	--	--	--	--
2009-2	357,006	0.41	--	--	--	--	357,006	0.41	1
2010-1	--	--	--	--	--	--	--	--	--
2010-2	493,672	0.3	--	--	--	--	493,672	0.3	1
2011-1	--	--	--	--	--	--	--	--	--
2011-2	469,480	0.28	--	--	--	--	469,480	0.28	1
2012-1	340,831	0.33	--	--	--	--	340,831	0.33	1
2012-2	305,146	0.24	--	--	--	--	305,146	0.24	1
2013-1	306,191	0.293	--	--	--	--	306,191	0.29	1
2013-2	35,339	0.38	--	--	--	--	35,339	0.38	1
2014-1	26,279	0.697	--	--	--	--	26,279	0.7	1
2014-2	29,048	0.29	--	--	--	--	29,048	0.29	1
2015-1	16,375	0.94	452	0.32	Ext	--	16,375	0.94	0.733
2015-2	83,030	0.47	--	--	--	--	83,030	0.47	0.733
2016-1	72,867	0.497	1,403	0.42	Ext	--	72,867	0.5	0.733
2016-2	--	--	--	--	--	--	--	--	--
2017-1	14,103	0.3	146	0.57	Ext	--	14,103	0.3	0.733
2017-2	--	--	--	--	--	--	--	--	--
2018-1	25,148	0.67	308	0.86	USV/Ext	--	25,148	0.67	0.733
2018-2	--	--	--	--	--	--	--	--	--
2019-1	33,632	0.19	494	0.28	F/V	12,279	33,632	0.19	0.733
2019-2	--	--	--	--	--	--	--	--	--
2020-1	--	--	--	--	--	--	--	--	--
2020-2	--	--	--	--	--	18,409	--	--	--
2021-1	40,528	0.37	443	0.42	F/V	14,942	40,528	0.37	0.733
2021-2	--	--	--	--	--	--	--	--	--
2022-1	53,741	0.26	15,765	0.23	F/V	--	69,506	0.21	1
2022-2	--	--	--	--	--	--	--	--	--
2023-1*	49,643	0.79	27,610	--	F/V	--	77,252	0.47	1

Table 9.7: 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 9.8: 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

Table 9.9: 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 (0.6)
-	Tot. recruitment variability (σ_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; 0.733 for 2015-2019 and 2021; 1 for 2022-2023)
Selectivity (age-based)	-	Estimated	Estimated
Fishery selectivity	-	Dome-shaped and asymptotic	Dome-shaped and asymptotic
-	Age composition	Yes	Yes
-	Form	Age-specific, random walk (MexCal) / Logistic (PNW)	Age-specific, 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	-	Stage 1 only	Stage 1 only

Table 9.10: 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	225.539
-	Age_comp	119.516
-	Parm_devs	92.092
-	Recruitment	13.025
-	Survey	0.631
-	Parm_priors	0.234
-	Parm_softbounds	0.042
-	Catch	0.000
Fleet likelihoods	AT_Survey Age_like	63.315
-	MexCal_S1 Age_like	21.306
-	PNW Age_like	21.263
-	MexCal_S2 Age_like	13.632
-	AT_Survey Surv_like	0.631
Parameters	NatM_Lorenzen_averageFem_GP_1	0.546
-	SR_LN(R0)	14.561
-	SR_regime_BLK1repl_2004	2.544
-	InitF_seas_1_flt_1MexCal_S1	2.302
Summary biomass	2021	116,358
-	2022	53,391
-	2023	56,811
-	2024	58,614

Table 9.11: 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	0.5461	2	(0.2,0.94)	OK	0.0386	Log_Norm(-0.393,0.31)
SR_LN(R0)	14.5608	1	(3,25)	OK	0.1977	-
SR_regime_BLK1repl_2004	2.5443	4	(-15,15)	OK	0.2150	-
Early_InitAge_6	-0.3278	2	(-5,5)	act	0.7872	-
Early_InitAge_5	-0.3860	2	(-5,5)	act	0.6979	-
Early_InitAge_4	-0.1742	2	(-5,5)	act	0.5409	-
Early_InitAge_3	-0.2440	2	(-5,5)	act	0.5075	-
Early_InitAge_2	0.8985	2	(-5,5)	act	0.2008	-
Early_InitAge_1	0.4906	2	(-5,5)	act	0.1761	-
Main_RecrDev_2005	2.1131	1	(-5,5)	act	0.2144	-
Main_RecrDev_2006	1.4015	1	(-5,5)	act	0.2090	-
Main_RecrDev_2007	0.9511	1	(-5,5)	act	0.2316	-
Main_RecrDev_2008	1.4082	1	(-5,5)	act	0.1893	-
Main_RecrDev_2009	1.7428	1	(-5,5)	act	0.1834	-
Main_RecrDev_2010	-0.9543	1	(-5,5)	act	0.3973	-
Main_RecrDev_2011	-2.2379	1	(-5,5)	act	0.5522	-
Main_RecrDev_2012	-1.9141	1	(-5,5)	act	0.4571	-
Main_RecrDev_2013	-0.4553	1	(-5,5)	act	0.3110	-
Main_RecrDev_2014	-0.1070	1	(-5,5)	act	0.2586	-
Main_RecrDev_2015	-1.1796	1	(-5,5)	act	0.3996	-
Main_RecrDev_2016	-0.6235	1	(-5,5)	act	0.4082	-
Main_RecrDev_2017	0.0699	1	(-5,5)	act	0.3298	-
Main_RecrDev_2018	-0.1306	1	(-5,5)	act	0.4780	-
Main_RecrDev_2019	0.8935	1	(-5,5)	act	0.2668	-
Main_RecrDev_2020	-0.2343	1	(-5,5)	act	0.3777	-
Main_RecrDev_2021	-0.3854	1	(-5,5)	act	0.4652	-
Main_RecrDev_2022	-0.4628	1	(-5,5)	act	0.9344	-
Main_RecrDev_2023	0.1047	1	(-5,5)	act	1.1698	-
ForeRecr_2024	0.0000	5	(-5,5)	act	1.2000	-
InitF_seas_1_flt_1MexCal_S1	2.3021	1	(0,3)	OK	0.5165	-
AgeSel_P1_MexCal_S1(1)	1.0000	3	(-7,9)	OK	178.8820	-
AgeSel_P2_MexCal_S1(1)	2.6185	3	(-7,9)	OK	0.5737	-
AgeSel_P3_MexCal_S1(1)	1.0516	3	(-7,9)	OK	0.3129	-
AgeSel_P4_MexCal_S1(1)	-1.4559	3	(-7,9)	OK	0.5144	-
AgeSel_P5_MexCal_S1(1)	-0.2556	3	(-7,9)	OK	0.7024	-
AgeSel_P6_MexCal_S1(1)	-1.0827	3	(-7,9)	OK	2.0295	-
AgeSel_P7_MexCal_S1(1)	0.0763	3	(-7,9)	OK	2.7760	-
AgeSel_P8_MexCal_S1(1)	-1.7662	3	(-7,9)	OK	6.1584	-
AgeSel_P9_MexCal_S1(1)	-0.2998	3	(-7,9)	OK	7.4895	-
AgeSel_P2_MexCal_S2(2)	0.5987	3	(-7,9)	OK	0.2583	-
AgeSel_P3_MexCal_S2(2)	-0.6295	3	(-7,9)	OK	0.3343	-
AgeSel_P4_MexCal_S2(2)	-0.7398	3	(-7,9)	OK	0.5672	-
AgeSel_P5_MexCal_S2(2)	-0.1793	3	(-7,9)	OK	0.7487	-

Parameter	Value	Phase	Bounds	Status	SD	Prior (Exp.Val, SD)
AgeSel_P6_MexCal_S2(2)	0.4048	3	(-7,9)	OK	0.7432	-
AgeSel_P7_MexCal_S2(2)	-0.7860	3	(-7,9)	OK	1.0279	-
AgeSel_P8_MexCal_S2(2)	-0.0639	3	(-7,9)	OK	1.6949	-
AgeSel_P9_MexCal_S2(2)	-1.8570	3	(-7,9)	OK	4.5037	-
Age_inflection_PNW(3)	2.3978	4	(0,10)	OK	0.1629	-
Age_95%width_PNW(3)	0.6313	4	(-5,15)	OK	0.1605	-
AgeSel_P2_AT_Survey(4)	0.0004	4	(0,9)	LO	0.0159	-
Age_inflection_PNW(3)_BLK3repl_2006	3.1713	4	(0,10)	OK	0.1929	-
Age_inflection_PNW(3)_BLK3repl_2007	3.0809	4	(0,10)	OK	0.1262	-
Age_inflection_PNW(3)_BLK3repl_2008	3.5625	4	(0,10)	OK	0.1952	-
Age_inflection_PNW(3)_BLK3repl_2009	4.1474	4	(0,10)	OK	0.1177	-
Age_inflection_PNW(3)_BLK3repl_2010	3.9538	4	(0,10)	OK	0.2696	-
Age_inflection_PNW(3)_BLK3repl_2011	3.2117	4	(0,10)	OK	0.2076	-
Age_inflection_PNW(3)_BLK3repl_2012	2.2125	4	(0,10)	OK	0.0974	-
Age_inflection_PNW(3)_BLK3repl_2013	2.8439	4	(0,10)	OK	0.1737	-
Age_inflection_PNW(3)_BLK3repl_2014	3.5546	4	(0,10)	OK	0.3346	-
AgeSel_P2_AT_Survey(4)_BLK2repl_2007	2.2873	4	(0,9)	OK	6.1149	-
AgeSel_P2_AT_Survey(4)_BLK2repl_2008	2.3518	4	(0,9)	OK	1.7299	-
AgeSel_P2_AT_Survey(4)_BLK2repl_2009	6.4967	4	(0,9)	OK	48.2495	-
AgeSel_P2_AT_Survey(4)_BLK2repl_2010	0.0036	4	(0,9)	LO	0.1161	-
AgeSel_P2_AT_Survey(4)_BLK2repl_2011	0.0043	4	(0,9)	LO	0.1384	-
AgeSel_P2_AT_Survey(4)_BLK2repl_2012	7.4968	4	(0,9)	OK	31.7485	-
AgeSel_P2_AT_Survey(4)_BLK2repl_2013	8.1334	4	(0,9)	OK	20.5096	-
AgeSel_P2_AT_Survey(4)_BLK2repl_2014	8.6505	4	(0,9)	OK	9.5597	-
AgeSel_P2_AT_Survey(4)_BLK2repl_2015	0.0002	4	(0,9)	LO	0.0110	-
AgeSel_P2_AT_Survey(4)_BLK2repl_2016	2.6409	4	(0,9)	OK	1.7047	-
AgeSel_P2_AT_Survey(4)_BLK2repl_2017	0.4193	4	(0,9)	OK	0.6324	-
AgeSel_P2_AT_Survey(4)_BLK2repl_2018	1.1410	4	(0,9)	OK	0.6172	-
AgeSel_P2_AT_Survey(4)_BLK2repl_2019	8.4313	4	(0,9)	OK	14.4745	-
AgeSel_P2_AT_Survey(4)_BLK2repl_2021	8.2116	4	(0,9)	OK	18.5022	-
AgeSel_P2_AT_Survey(4)_BLK2repl_2022	5.5412	4	(0,9)	OK	4.2100	-
AgeSel_P2_AT_Survey(4)_BLK2repl_2023	2.2905	4	(0,9)	OK	1.4877	-
MexCal_S1_ARDEV_y2006_A0	-0.5358	3	(-10,10)	act	0.8419	-
MexCal_S1_ARDEV_y2006_A1	0.8834	3	(-10,10)	act	0.6314	-
MexCal_S1_ARDEV_y2006_A2	-0.1966	3	(-10,10)	act	0.6494	-
MexCal_S1_ARDEV_y2006_A3	-0.0754	3	(-10,10)	act	0.7918	-
MexCal_S1_ARDEV_y2007_A0	0.3179	3	(-10,10)	act	0.7716	-
MexCal_S1_ARDEV_y2007_A1	-0.0409	3	(-10,10)	act	0.5993	-
MexCal_S1_ARDEV_y2007_A2	0.2777	3	(-10,10)	act	0.5693	-
MexCal_S1_ARDEV_y2007_A3	0.2901	3	(-10,10)	act	0.7701	-
MexCal_S1_ARDEV_y2008_A0	0.2352	3	(-10,10)	act	1.0025	-
MexCal_S1_ARDEV_y2008_A1	0.4930	3	(-10,10)	act	0.7372	-
MexCal_S1_ARDEV_y2008_A2	0.7945	3	(-10,10)	act	0.6241	-
MexCal_S1_ARDEV_y2008_A3	-0.6068	3	(-10,10)	act	0.8219	-
MexCal_S1_ARDEV_y2009_A0	-0.3486	3	(-10,10)	act	0.8789	-
MexCal_S1_ARDEV_y2009_A1	-0.1284	3	(-10,10)	act	0.8282	-
MexCal_S1_ARDEV_y2009_A2	1.6608	3	(-10,10)	act	0.6674	-
MexCal_S1_ARDEV_y2009_A3	-0.1467	3	(-10,10)	act	0.9205	-

Parameter	Value	Phase	Bounds	Status	SD	Prior (Exp.Val, SD)
MexCal_S1_ARDEV_y2010_A0	-0.3629	3	(-10,10)	act	0.8687	-
MexCal_S1_ARDEV_y2010_A1	1.1486	3	(-10,10)	act	0.6759	-
MexCal_S1_ARDEV_y2010_A2	-0.0910	3	(-10,10)	act	0.7574	-
MexCal_S1_ARDEV_y2010_A3	-0.0634	3	(-10,10)	act	0.9202	-
MexCal_S1_ARDEV_y2011_A0	-0.1133	3	(-10,10)	act	0.9515	-
MexCal_S1_ARDEV_y2011_A1	-0.5288	3	(-10,10)	act	0.6400	-
MexCal_S1_ARDEV_y2011_A2	0.0309	3	(-10,10)	act	0.6345	-
MexCal_S1_ARDEV_y2011_A3	1.2293	3	(-10,10)	act	0.7550	-
MexCal_S1_ARDEV_y2012_A0	-0.0298	3	(-10,10)	act	0.9739	-
MexCal_S1_ARDEV_y2012_A1	0.3498	3	(-10,10)	act	0.7569	-
MexCal_S1_ARDEV_y2012_A2	-1.1274	3	(-10,10)	act	0.6541	-
MexCal_S1_ARDEV_y2012_A3	0.8882	3	(-10,10)	act	0.7215	-
MexCal_S1_ARDEV_y2013_A0	-0.0165	3	(-10,10)	act	0.9198	-
MexCal_S1_ARDEV_y2013_A1	-0.4455	3	(-10,10)	act	0.8420	-
MexCal_S1_ARDEV_y2013_A2	-0.7016	3	(-10,10)	act	0.7517	-
MexCal_S1_ARDEV_y2013_A3	-0.7622	3	(-10,10)	act	0.7637	-
MexCal_S1_ARDEV_y2014_A0	-0.6296	3	(-10,10)	act	0.8364	-
MexCal_S1_ARDEV_y2014_A1	-0.8685	3	(-10,10)	act	0.8048	-
MexCal_S1_ARDEV_y2014_A2	-0.8802	3	(-10,10)	act	0.8245	-
MexCal_S1_ARDEV_y2014_A3	-0.2240	3	(-10,10)	act	0.8810	-
MexCal_S2_ARDEV_y2006_A0	-0.3695	3	(-10,10)	act	0.5974	-
MexCal_S2_ARDEV_y2006_A1	0.3925	3	(-10,10)	act	0.5864	-
MexCal_S2_ARDEV_y2006_A2	0.3279	3	(-10,10)	act	0.6203	-
MexCal_S2_ARDEV_y2006_A3	-0.2296	3	(-10,10)	act	0.7937	-
MexCal_S2_ARDEV_y2006_A4	-0.0519	3	(-10,10)	act	0.9761	-
MexCal_S2_ARDEV_y2007_A0	0.8395	3	(-10,10)	act	0.5625	-
MexCal_S2_ARDEV_y2007_A1	0.2892	3	(-10,10)	act	0.5668	-
MexCal_S2_ARDEV_y2007_A2	-0.4597	3	(-10,10)	act	0.6390	-
MexCal_S2_ARDEV_y2007_A3	-0.2282	3	(-10,10)	act	0.8017	-
MexCal_S2_ARDEV_y2007_A4	-0.3705	3	(-10,10)	act	0.8716	-
MexCal_S2_ARDEV_y2008_A0	-0.1065	3	(-10,10)	act	0.6428	-
MexCal_S2_ARDEV_y2008_A1	1.2110	3	(-10,10)	act	0.5799	-
MexCal_S2_ARDEV_y2008_A2	0.4781	3	(-10,10)	act	0.7072	-
MexCal_S2_ARDEV_y2008_A3	-0.3643	3	(-10,10)	act	0.8143	-
MexCal_S2_ARDEV_y2008_A4	-0.4800	3	(-10,10)	act	0.8556	-
MexCal_S2_ARDEV_y2009_A0	1.0131	3	(-10,10)	act	0.5146	-
MexCal_S2_ARDEV_y2009_A1	1.5015	3	(-10,10)	act	0.5585	-
MexCal_S2_ARDEV_y2009_A2	0.5755	3	(-10,10)	act	0.7860	-
MexCal_S2_ARDEV_y2009_A3	-0.5964	3	(-10,10)	act	0.8257	-
MexCal_S2_ARDEV_y2009_A4	-0.8706	3	(-10,10)	act	0.8006	-
MexCal_S2_ARDEV_y2010_A0	-0.9528	3	(-10,10)	act	0.5236	-
MexCal_S2_ARDEV_y2010_A1	-0.9381	3	(-10,10)	act	0.5520	-
MexCal_S2_ARDEV_y2010_A2	-0.7910	3	(-10,10)	act	0.7341	-
MexCal_S2_ARDEV_y2010_A3	0.2350	3	(-10,10)	act	0.7963	-
MexCal_S2_ARDEV_y2010_A4	0.7804	3	(-10,10)	act	0.7585	-
MexCal_S2_ARDEV_y2011_A0	0.1740	3	(-10,10)	act	0.5988	-
MexCal_S2_ARDEV_y2011_A1	-1.5924	3	(-10,10)	act	0.4978	-
MexCal_S2_ARDEV_y2011_A2	-0.1741	3	(-10,10)	act	0.5378	-

Parameter	Value	Phase	Bounds	Status	SD	Prior (Exp.Val, SD)
MexCal_S2_ARDEV_y2011_A3	0.6222	3	(-10,10)	act	0.6889	-
MexCal_S2_ARDEV_y2011_A4	0.5180	3	(-10,10)	act	0.7869	-
MexCal_S2_ARDEV_y2012_A0	-0.3011	3	(-10,10)	act	0.8833	-
MexCal_S2_ARDEV_y2012_A1	-0.0766	3	(-10,10)	act	0.8010	-
MexCal_S2_ARDEV_y2012_A2	-0.0817	3	(-10,10)	act	0.7267	-
MexCal_S2_ARDEV_y2012_A3	0.6080	3	(-10,10)	act	0.8714	-
MexCal_S2_ARDEV_y2012_A4	0.0792	3	(-10,10)	act	0.9781	-
MexCal_S2_ARDEV_y2013_A0	-1.4102	3	(-10,10)	act	0.7482	-
MexCal_S2_ARDEV_y2013_A1	-0.7610	3	(-10,10)	act	0.7695	-
MexCal_S2_ARDEV_y2013_A2	0.2500	3	(-10,10)	act	0.7246	-
MexCal_S2_ARDEV_y2013_A3	0.3089	3	(-10,10)	act	0.6682	-
MexCal_S2_ARDEV_y2013_A4	0.9690	3	(-10,10)	act	0.7852	-
MexCal_S2_ARDEV_y2014_A0	-0.7256	3	(-10,10)	act	0.6945	-
MexCal_S2_ARDEV_y2014_A1	0.9973	3	(-10,10)	act	0.7336	-
MexCal_S2_ARDEV_y2014_A2	0.5117	3	(-10,10)	act	0.8823	-
MexCal_S2_ARDEV_y2014_A3	-0.2487	3	(-10,10)	act	0.9123	-
MexCal_S2_ARDEV_y2014_A4	-0.5191	3	(-10,10)	act	0.8448	-

Table 9.12: 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. The age-1+ biomass values are those associated with the terminal model year. Step G had time-varying block selectivity, and step H had no time-varying selectivity which resulted in a decrease in the number of parameters and an increase to the likelihood values.

Model description	# pars	Likelihood	Terminal year	Age 1+ biomass (mt)
A: Benchmark 2020	140	91.690	2019	35,186
B: 2020 w/ SS update	140	84.790	2019	38,827
C: catch 2020 habitat model	140	80.690	2019	41,092
D: catch and comps 2023	144	83.080	2023	79,720
E: index and comps 2023	144	93.760	2023	35,824
F: index fleet: Lisa Marie	144	100.970	2023	40,341
G: waa	144	101.940	2023	30,965
H: Lorenzen M	73	218.720	2023	36,792
I: Hamel prior M	73	218.970	2023	36,560
J: steepness	73	221.220	2023	38,962
K: SR sd prior and rec devs	73	221.350	2023	39,260
L: bias adj	73	221.470	2023	37,081
M: 2dAR selex	226	284.920	2023	36,721
N: Benchmark 2024	156	225.539	2023	58,614

Table 9.13: Pacific sardine numbers-at-age (thousands) by model year for semester 1.

Calendar Y-S	Model Y-S	Age0	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10+
--	VIRG	2,107,020	884,480	457,699	260,478	155,725	95,775	59,930	37,911	24,151	15,456	27,867
--	INIT	26,832,100	10,938,100	3,786,010	681,503	311,516	155,629	90,762	53,214	33,462	21,209	37,229
2005-2	2005-1	26,832,100	9,179,120	4,777,220	290,629	151,868	65,447	43,129	53,214	33,462	21,209	37,229
2006-2	2006-1	10,310,600	11,089,000	4,564,030	2,425,440	109,419	57,443	25,216	16,874	21,012	13,316	23,373
2007-2	2007-1	5,104,020	4,257,000	5,240,430	2,445,160	1,249,590	43,575	23,050	10,302	6,957	8,747	15,351
2008-2	2008-1	3,242,180	1,962,820	1,955,690	2,584,030	1,282,170	602,703	21,308	11,521	5,214	3,566	12,413
2009-2	2009-1	5,071,680	1,304,740	741,308	871,023	1,487,500	644,302	299,544	10,849	5,937	2,725	8,398
2010-2	2010-1	6,955,380	1,947,180	511,890	310,402	510,788	812,038	289,617	136,687	5,001	2,768	5,214
2011-2	2011-1	458,216	2,826,640	937,503	277,874	175,582	241,755	344,494	127,193	60,571	2,266	3,635
2012-2	2012-1	124,023	162,231	1,334,340	388,729	113,035	64,369	92,292	138,785	52,276	25,763	2,522
2013-2	2013-1	156,313	51,598	81,082	608,086	108,907	32,473	18,838	27,398	41,558	15,764	8,558
2014-2	2014-1	558,439	63,578	23,731	37,933	206,178	28,650	9,209	5,613	8,264	12,924	7,595
2015-2	2015-1	607,810	229,760	26,753	11,443	20,546	75,060	10,214	3,349	2,087	3,111	7,757
2016-2	2016-1	196,999	255,133	118,856	15,212	6,838	12,597	46,809	6,439	2,126	1,331	6,969
2017-2	2017-1	348,990	82,287	129,996	65,928	9,027	4,159	7,803	29,350	4,071	1,352	5,307
2018-2	2018-1	677,292	145,441	41,838	72,424	39,155	5,521	2,589	4,921	18,656	2,603	4,282
2019-2	2019-1	547,956	280,266	73,225	23,379	42,965	23,905	3,421	1,629	3,120	11,918	4,421
2020-2	2020-1	1,588,620	227,773	141,600	40,477	13,851	26,217	14,848	2,154	1,034	1,994	10,484
2021-2	2021-1	559,253	664,143	116,005	78,103	23,999	8,463	16,341	9,365	1,371	662	8,027
2022-2	2022-1	571,405	234,140	341,450	65,489	46,554	14,723	5,283	10,321	5,958	876	5,590
2023-2	2023-1	727,951	238,416	119,622	192,072	38,979	28,526	9,174	3,334	6,562	3,811	4,160
2024-2	2024-1	1,702,470	305,505	122,969	67,437	114,574	23,932	17,839	5,800	2,124	4,199	5,124

Table 9.14: Pacific sardine numbers-at-age (thousands) by model year for semester 2.

Calendar Y-S	Model Y-S	Age0	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10+
--	VIRG	1,334,030	631,744	345,310	202,003	122,663	76,154	47,934	30,437	19,438	12,460	22,504
--	INIT	16,497,500	5,225,670	903,456	404,092	199,320	115,332	67,282	42,172	26,673	16,934	29,777
2006-1	2005-2	16,972,900	6,470,320	3,262,130	143,089	74,091	32,360	21,447	26,614	16,778	10,652	18,731
2007-1	2006-2	6,524,780	7,701,160	3,345,050	1,649,780	57,923	30,568	13,494	9,081	11,337	7,196	12,654
2008-1	2007-2	3,221,320	2,949,530	3,502,970	1,685,700	779,459	27,654	14,708	6,631	4,491	5,655	9,942
2009-1	2008-2	2,047,500	1,339,610	1,237,180	1,957,120	833,939	390,491	13,878	7,565	3,433	2,351	8,201
2010-1	2009-2	3,208,320	918,335	434,908	668,053	1,048,400	378,072	175,783	6,407	3,516	1,616	4,989
2011-1	2010-2	4,402,820	1,373,260	382,143	239,167	332,227	459,457	164,406	77,934	2,858	1,585	2,991
2012-1	2011-2	288,827	1,939,250	577,446	168,823	97,257	137,276	196,569	73,636	35,173	1,318	2,118
2013-1	2012-2	78,470	114,049	819,099	145,729	42,719	24,631	35,520	53,695	20,277	10,009	982
2014-1	2013-2	98,824	36,376	58,657	293,138	42,475	12,833	7,486	10,964	16,674	6,335	3,445
2015-1	2014-2	352,296	43,675	16,029	27,178	106,296	14,691	4,742	2,944	4,348	6,811	4,010
2016-1	2015-2	384,820	164,061	20,167	8,870	16,134	59,485	8,142	2,680	1,674	2,500	6,244
2017-1	2016-2	124,659	180,874	87,774	11,734	5,336	9,941	37,153	5,136	1,700	1,066	5,592
2018-1	2017-2	220,877	58,474	96,652	50,954	7,091	3,304	6,234	23,558	3,276	1,089	4,285
2019-1	2018-2	428,770	103,719	31,423	56,103	30,796	4,385	2,069	3,947	15,003	2,097	3,455
2020-1	2019-2	346,755	198,782	54,147	18,045	33,698	18,970	2,731	1,307	2,509	9,599	3,567
2021-1	2020-2	1,005,100	161,106	103,883	31,187	10,855	20,810	11,854	1,729	832	1,607	8,464
2022-1	2021-2	354,035	473,450	87,030	60,458	18,874	6,723	13,058	7,514	1,102	533	6,478
2023-1	2022-2	361,725	166,893	256,088	50,701	36,618	11,698	4,222	8,282	4,794	706	4,512
2024-1	2023-2	460,783	169,729	89,400	148,623	30,650	22,668	7,333	2,677	5,281	3,072	3,359
2025-1	2024-2	1,077,710	217,688	92,142	52,215	90,137	19,021	14,262	4,656	1,709	3,385	4,138

Table 9.15: Pacific sardine biomass-at-age by model year for semester 1.

Calendar Y-S	Model Y-S	Age0	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10+	Total Age0+	Total Age1+
--	VIRG	26,338	39,359	33,595	33,289	22,471	16,052	10,656	7,279	4,837	3,001	5,560	202,437	176,099
--	INIT	335,401	486,744	277,893	87,096	44,952	26,084	16,138	10,217	6,702	4,119	7,427	1,302,772	967,371
2005-2	2005-1	335,401	408,471	350,648	37,142	21,915	10,969	7,668	10,217	6,702	4,119	7,427	1,200,680	865,279
2006-2	2006-1	128,882	624,311	342,302	198,159	14,367	8,651	4,423	3,110	4,041	2,667	4,663	1,335,575	1,206,693
2007-2	2007-1	63,800	191,991	369,450	236,936	124,460	5,874	3,617	1,899	1,324	1,699	3,075	1,004,124	940,323
2008-2	2008-1	49,605	173,317	203,587	321,453	173,093	84,740	2,996	1,620	987	679	2,411	1,014,487	964,882
2009-2	2009-1	63,396	58,192	65,976	102,955	186,979	81,440	40,978	1,678	1,130	529	1,675	604,928	541,532
2010-2	2010-1	86,942	93,465	36,242	33,772	68,854	111,087	40,604	19,997	952	538	1,040	493,493	406,551
2011-2	2011-1	6,003	203,518	103,219	32,761	21,491	33,096	48,884	17,667	8,722	431	706	476,499	470,496
2012-2	2012-1	1,625	18,243	154,784	47,114	14,457	9,733	15,330	22,594	9,274	4,604	480	298,237	296,612
2013-2	2013-1	2,048	5,802	12,146	92,551	16,859	5,904	3,679	4,567	7,173	2,541	1,379	154,649	152,601
2014-2	2014-1	5,417	11,171	4,238	6,934	38,060	5,538	1,885	1,128	1,660	2,597	1,526	80,154	74,737
2015-2	2015-1	2,431	29,157	4,165	2,262	4,230	15,590	2,091	674	437	651	1,623	63,312	60,880
2016-2	2016-1	9,141	17,859	16,093	2,414	1,327	2,468	9,465	1,455	465	297	1,459	62,442	53,302
2017-2	2017-1	3,734	8,961	16,366	9,487	1,460	791	1,672	6,941	963	320	1,255	51,951	48,217
2018-2	2018-1	13,207	7,985	7,481	13,970	7,655	1,129	569	1,114	5,567	777	1,278	60,732	47,524
2019-2	2019-1	24,055	16,424	5,448	3,446	8,228	4,917	630	357	804	3,072	1,140	68,521	44,465
2020-2	2020-1	69,740	13,348	10,535	5,966	2,652	5,393	2,732	472	267	514	2,703	114,322	44,581
2021-2	2021-1	30,032	64,621	19,837	14,863	5,745	2,190	4,087	2,511	341	165	1,998	146,390	116,358
2022-2	2022-1	13,771	11,286	19,804	5,953	7,118	2,872	1,133	2,339	1,384	204	1,299	67,162	53,391
2023-2	2023-1	6,115	15,783	9,953	16,902	3,789	4,484	1,718	726	1,560	906	989	62,926	56,811
2024-2	2024-1	14,301	20,224	10,231	5,934	11,137	3,762	3,341	1,262	505	999	1,219	72,915	58,614

Table 9.16: Pacific sardine biomass-at-age by model year for semester 2.

Calendar Y-S	Model Y-S	Age0	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10+	Total Age0+	Total Age1+
--	VIRG	77,908	42,769	26,105	18,160	13,039	9,755	7,746	6,081	3,794	2,129	3,846	211,334	133,426
--	INIT	963,457	353,778	68,301	36,328	21,188	14,774	10,873	8,426	5,207	2,894	5,089	1,490,314	526,857
2006-1	2005-2	991,214	438,041	246,617	12,864	7,876	4,145	3,466	5,318	3,275	1,820	3,201	1,717,837	726,623
2007-1	2006-2	381,047	521,368	252,886	148,315	6,157	3,916	2,181	1,814	2,213	1,230	2,163	1,323,289	942,242
2008-1	2007-2	226,136	237,732	322,273	190,147	99,693	3,786	2,134	1,023	897	1,104	1,462	1,086,387	860,251
2009-1	2008-2	143,734	107,973	113,820	220,763	106,661	53,458	2,014	1,167	525	470	1,601	752,185	608,451
2010-1	2009-2	128,012	81,181	52,058	92,258	153,801	57,618	27,756	1,052	574	257	997	595,565	467,553
2011-1	2010-2	268,132	88,438	26,139	32,898	40,797	68,229	26,880	13,599	495	264	497	566,368	298,236
2012-1	2011-2	22,875	197,028	66,637	23,027	15,114	22,911	34,498	13,453	6,394	234	376	402,547	379,672
2013-1	2012-2	8,953	14,131	105,991	20,198	6,361	3,904	6,017	9,826	3,672	1,726	169	180,948	171,995
2014-1	2013-2	15,377	5,795	9,497	48,778	7,251	2,236	1,331	1,994	3,023	1,132	616	97,028	81,651
2015-1	2014-2	32,200	6,796	2,763	3,908	19,442	2,872	955	606	892	1,380	812	72,627	40,427
2016-1	2015-2	13,815	17,314	3,138	1,529	2,993	12,165	1,740	588	366	538	1,344	55,531	41,716
2017-1	2016-2	4,475	7,669	9,883	1,570	990	2,033	7,940	1,128	372	230	1,204	37,493	33,018
2018-1	2017-2	7,929	2,479	6,166	6,818	1,315	676	1,332	5,173	717	235	923	33,764	25,834
2019-1	2018-2	15,393	4,398	2,005	7,507	5,713	897	442	867	3,284	452	744	41,700	26,307
2020-1	2019-2	12,448	8,428	3,455	2,414	6,251	3,879	584	287	549	2,067	768	41,130	28,682
2021-1	2020-2	36,083	6,831	6,628	4,173	2,014	4,256	2,533	380	182	346	1,822	65,247	29,164
2022-1	2021-2	12,710	20,074	5,552	8,089	3,501	1,375	2,790	1,650	241	115	1,395	57,493	44,783
2023-1	2022-2	12,986	7,076	16,338	6,784	6,793	2,392	902	1,819	1,049	152	971	57,263	44,277
2024-1	2023-2	16,542	7,196	5,704	19,886	5,686	4,636	1,567	588	1,156	661	723	64,345	47,803
2025-1	2024-2	38,690	9,230	5,879	6,986	16,720	3,890	3,048	1,022	374	729	891	87,459	48,769

Table 9.17: Spawning stock biomas (SSB) and recruitment (1000s of fish) estimates and asymptotic standard errors for the 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	128,741	21,679	2,107,020	416,624.0
--	INIT-1	0	0	0	0.0
--	INIT-2	451,464	110,222	0	0.0
2005-2	2005-1	0	0	26,832,100	6,483,930.0
2006-1	2005-2	606,649	95,849	0	0.0
2006-2	2006-1	0	0	10,310,600	2,513,570.0
2007-1	2006-2	764,708	103,257	0	0.0
2007-2	2007-1	0	0	5,104,020	1,079,660.0
2008-1	2007-2	691,358	83,227	0	0.0
2008-2	2008-1	0	0	3,242,180	790,659.0
2009-1	2008-2	544,826	54,933	0	0.0
2009-2	2009-1	0	0	5,071,680	956,872.0
2010-1	2009-2	383,947	33,777	0	0.0
2010-2	2010-1	0	0	6,955,380	1,258,020.0
2011-1	2010-2	280,779	22,629	0	0.0
2011-2	2011-1	0	0	458,216	190,657.0
2012-1	2011-2	219,141	16,214	0	0.0
2012-2	2012-1	0	0	124,023	73,009.3
2013-1	2012-2	114,090	10,465	0	0.0
2013-2	2013-1	0	0	156,313	74,869.2
2014-1	2013-2	54,150	6,873	0	0.0
2014-2	2014-1	0	0	558,439	189,929.0
2015-1	2014-2	27,975	4,818	0	0.0
2015-2	2015-1	0	0	607,810	165,156.0
2016-1	2015-2	25,067	3,888	0	0.0
2016-2	2016-1	0	0	196,999	81,227.6
2017-1	2016-2	25,863	3,719	0	0.0
2017-2	2017-1	0	0	348,990	147,353.0
2018-1	2017-2	24,359	3,484	0	0.0
2018-2	2018-1	0	0	677,292	218,823.0
2019-1	2018-2	23,831	3,265	0	0.0
2019-2	2019-1	0	0	547,956	276,593.0
2020-1	2019-2	25,793	3,402	0	0.0
2020-2	2020-1	0	0	1,588,620	444,842.0
2021-1	2020-2	30,734	4,199	0	0.0
2021-2	2021-1	0	0	559,253	223,672.0
2022-1	2021-2	40,320	6,072	0	0.0
2022-2	2022-1	0	0	571,405	284,496.0
2023-1	2022-2	43,627	7,138	0	0.0
2023-2	2023-1	0	0	727,951	724,397.0
2024-1	2023-2	42,773	8,131	0	0.0
2024-2	2024-1	0	0	0	0.0
2025-1	2024-2	45,376	12,953	0	0.0

Table 9.18: 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	865,278	141,965
2006-1	1,206,690	182,485
2007-1	940,323	118,169
2008-1	964,881	103,663
2009-1	541,532	49,667
2010-1	406,551	33,159
2011-1	470,496	39,461
2012-1	296,612	21,594
2013-1	152,601	12,540
2014-1	74,737	9,726
2015-1	60,880	10,909
2016-1	53,302	8,066
2017-1	48,217	7,238
2018-1	47,524	7,170
2019-1	44,465	6,205
2020-1	44,581	7,507
2021-1	116,358	20,266
2022-1	53,391	8,164
2023-1	56,811	11,749
2024-1	58,614	22,511

Table 9.19: Annual exploitation rate (calendar year landings / July total biomass) by country and calendar year.

Calendar Year	Mexico	USA	Canada	Total
2005	0.004	0.050	0.003	0.057
2006	0.002	0.055	0.001	0.058
2007	0.018	0.107	0.002	0.126
2008	0.006	0.076	0.010	0.092
2009	0.009	0.106	0.025	0.140
2010	0.006	0.105	0.045	0.156
2011	0.036	0.088	0.043	0.168
2012	0.011	0.307	0.064	0.382
2013	0.000	0.379	0.000	0.379
2014	0.000	0.278	0.000	0.278
2015	0.000	0.047	0.000	0.047
2016	0.000	0.006	0.000	0.006
2017	0.000	0.006	0.000	0.006
2018	0.000	0.004	0.000	0.004
2019	0.000	0.010	0.000	0.010
2020	0.000	0.007	0.000	0.007
2021	0.000	0.002	0.000	0.002
2022	0.000	0.006	0.000	0.006
2023	0.000	0.008	0.000	0.008

Table 9.20: Total objective function values and proportions from 50 runs with 10% jitter and 20% jitters (JitPerc). The total objective function in the base model was 225.539.

JitPerc	Likelihood	Count	Total	Proportion
0.10	225.539	39	50	0.78
0.10	225.937	6	50	0.12
0.10	710.437	3	50	0.06
0.10	1,001.460	1	50	0.02
0.10	1,416.430	1	50	0.02
0.20	225.539	35	50	0.70
0.20	226.407	2	50	0.04
0.20	230.568	1	50	0.02
0.20	255.967	1	50	0.02
0.20	710.437	6	50	0.12
0.20	710.536	1	50	0.02
0.20	711.741	1	50	0.02
0.20	758.118	2	50	0.04
0.20	861.355	1	50	0.02

Table 9.21: Parameter estimates, summary biomass (age 1+; mt) estimates, and total objective function values associated with fixed values of steepness. Steepness was fixed at 0.6 in the base model

-	-	0.25	0.3	0.4	0.5	Base=0.6	0.7	0.8	0.9	1
Parameters	NatM_Lorenzen_averageFem_GP_1	0.553	0.55	0.548	0.547	0.546	0.546	0.546	0.546	0.546
-	SR_LN(R0)	15.11	14.996	14.798	14.659	14.561	14.489	14.436	14.395	14.363
-	SR_regime_BLK1repl_2004	2.029	2.129	2.314	2.448	2.544	2.615	2.669	2.711	2.744
-	InitF_seas_1_flt_1MexCal_S1	2.271	2.279	2.29	2.298	2.302	2.305	2.308	2.309	2.31
Summary biomass	2020	42,369	42,842	43,563	44,127	44,581	44,944	45,235	45,469	45,659
-	2021	109,675	111,117	113,358	115,062	116,358	117,332	118,064	118,619	119,046
-	2022	49,413	50,417	51,824	52,757	53,391	53,825	54,127	54,341	54,496
-	2023	50,518	52,262	54,594	55,984	56,810	57,300	57,589	57,758	57,855
-	2024	45,192	48,986	54,238	57,162	58,614	59,235	59,418	59,381	59,237
-	Total objective function	223.846	223.836	224.3	224.931	225.539	226.076	226.537	226.93	227.266

Table 9.22: Parameter estimates, summary biomass (age 1+ mt) estimates, and total objective function values associated with fixed values of natural mortality and fixed steepness at a value of 0.6.

-	-	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Parameters	SR_LN(R0)	14.351	14.026	14.156	14.423	14.736	15.07	15.402	15.73	16.06
-	SR_BH_steep	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
-	SR_regime_BLK1repl_2004	0.988	1.774	2.152	2.421	2.663	2.88	3.096	3.309	3.523
-	InitF_seas_1_flt_1MexCal_S1	3	3	2.939	2.501	2.057	1.597	1.128	0.647	0.187
Summary biomass	2021	113,106	111,145	111,153	114,124	119,565	126,889	135,508	145,119	155,652
-	2022	76,152	66,953	59,708	54,981	51,904	49,949	48,679	47,842	47,290
-	2023	91,545	77,207	66,556	59,373	54,289	50,515	47,476	44,900	42,788
-	2024	101,063	82,374	69,308	61,255	56,334	53,522	51,877	50,998	51,227
-	Total objective function	291.848	256.756	234.755	226.251	227.241	240.274	264.435	298.484	341.815

Table 9.23: 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	0.67	0.644	0.619	0.594	0.57	0.546	0.524	0.498	0.474	0.451	0.43
-	SR_LN(R0)	15.403	15.183	14.994	14.83	14.686	14.561	14.451	14.346	14.253	14.174	14.106
-	SR_BH_steep	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
-	SR_regime_BLK1repl_2004	2.649	2.637	2.621	2.6	2.574	2.544	2.512	2.466	2.417	2.367	2.315
-	InitF_seas_1_flt_1MexCal_S1	1.92	1.985	2.057	2.136	2.219	2.302	2.385	2.482	2.578	2.671	2.76
-	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_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	-0.693	-0.511	-0.357	-0.223	-0.105	0	0.095	0.182	0.262	0.336	0.405
-	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	89,366	74,370	63,683	55,695	49,508	44,581	40,568	37,276	34,509	32,147	30,106
-	2021	246,882	202,982	171,803	148,542	130,586	116,358	104,833	95,182	87,114	80,288	74,446
-	2022	99,818	84,218	73,128	64,866	58,479	53,391	49,240	45,900	43,093	40,688	38,595
-	2023	101,201	86,202	75,574	67,697	61,631	56,810	52,883	49,802	47,222	45,008	43,075
-	2024	101,075	86,528	76,313	68,815	63,104	58,614	54,990	52,205	49,902	47,939	46,229
-	Total objective function	234.899	232.824	230.829	228.935	227.166	225.539	224.068	222.771	221.665	220.752	220.03

Table 9.24: Parameter estimates, summary biomass (age 1+ mt) estimates, and total objective function values associated with 2023 AT survey biomass values ranging from 10,000 to 150,000 mt. Steepness was fixed at 0.6 in these model runs.

-	-	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	0.582	0.566	0.557	0.551	0.544	0.541	0.539	0.537	0.537	0.537	0.537	0.537	0.537	0.537
-	SR_LN(R0)	14.25	14.372	14.467	14.528	14.582	14.616	14.651	14.688	14.707	14.736	14.749	14.767	14.789	14.803
-	SR_regime_BLK1	3.046	2.84	2.717	2.602	2.534	2.46	2.414	2.39	2.349	2.338	2.308	2.292	2.29	2.278
-	InitF_seas_1_flt_1	2.17	2.227	2.242	2.284	2.292	2.327	2.339	2.331	2.355	2.342	2.364	2.367	2.351	2.353
Summary biomass	2020	31,089	36,741	40,532	43,245	45,056	46,380	47,245	47,784	48,212	48,435	48,651	48,773	48,823	48,883
-	2021	58,350	78,976	95,868	109,236	119,270	126,807	132,358	136,452	139,391	141,662	143,293	144,599	145,699	146,536
-	2022	25,205	34,667	42,764	49,527	55,012	59,330	62,667	65,244	67,180	68,735	69,902	70,865	71,692	72,344
-	2023	20,003	30,002	40,002	50,001	60,000	69,998	79,997	89,996	99,995	109,994	119,993	129,992	139,991	149,990
-	2024	22,393	32,835	42,887	52,339	61,613	70,305	78,808	87,220	95,081	103,137	110,660	118,269	126,021	133,475
-	Total obj. fun.	-1256.47	-1266.8	-1270.35	-1272.13	-1271.90	-1271.85	-1271.09	-1269.78	-1269.18	-1267.78	-1267.15	-1266.14	-1264.77	-1263.81

Table 9.25: Variance adjustment, parameter estimates, summary biomass (age-1+; mt) and total objective function from the base model and a model with Francis reweighting of age compositions.

-	Base model	Francis
MexCal_S1	-	0.857
MexCal_S2	-	1.485
PNW	-	1.669
AT_Survey	-	0.473
NatM_Lorenzen_averageFem_GP_1	0.546	0.554
SR_LN(R0)	14.561	14.616
SR_BH_steep	0.600	0.600
SR_regime_BLK1repl_2004	2.544	2.477
2021 Age 1+ biomass	116,358	109,428
2022 Age 1+ biomass	53,391	55,125
2023 Age 1+ biomass	56,811	69,875
2024 Age 1+ biomass	58,614	70,387
Total Likelihood	225.539	206.889

Table 9.26: CalCOFI three-year (calendar) running average sea surface temperature (degrees C) and E_{MSY} values.

Years	CalCOFI SST	E_{MSY}
2012-14	15.656	0.172
2013-15	16.383	0.286
2014-16	16.856	0.364
2015-17	16.639	0.327
2016-18	16.112	0.243
2017-19	15.997	0.225
2018-20	16.093	0.240
2019-21	15.956	0.218
2020-22	15.860	0.203
2021-23	15.597	0.163

Table 9.27: Pacific sardine harvest control rules for fishing year 2024-2025.

Harvest Control Rule Formulas

OFL = BIOMASS * E_{MSY} * DISTRIBUTION; where E_{MSY} is bounded 0.00 to 0.25
$ABC_{P\text{-}star}$ = BIOMASS * $BUFFER_{P\text{-}star}$ * E_{MSY} * DISTRIBUTION; where E_{MSY} is bounded 0.00 to 0.25
HG = (BIOMASS - CUTOFF) * FRACTION * DISTRIBUTION; where FRACTION is E_{MSY} bounded 0.05 to 0.20

Harvest Formula Parameters									
BIOMASS (ages 1+, mt)	**58,614**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
P-star	0.45	0.4	0.35	0.3	0.25	0.2	0.15	0.1	0.05
ABC $Buffer_{Tier1}$	0.9225	0.8499	0.7809	0.7142	0.6486	0.5826	0.5141	0.4392	0.3479
ABC $Buffer_{Tier\ 2}$	0.851	0.7223	0.6097	0.51	0.4206	0.3394	0.2643	0.1929	0.121
ABC $Buffer_{Tier\ 3}$	0.7778	0.6025	0.4627	0.3504	0.2595	0.1858	0.1258	0.0771	0.0373
CalCOFI SST (2021-23)	15.597	-	-	-	-	-	-	-	-
E_{MSY}	0.163	-	-	-	-	-	-	-	-
FRACTION	0.163	-	-	-	-	-	-	-	-
CUTOFF (mt)	150,000	-	-	-	-	-	-	-	-
DISTRIBUTION (U.S.)	0.87	-	-	-	-	-	-	-	-
Harvest Control Rule Values (MT)									
OFL =	**8,312**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
$ABC_{Tier\ 1}$ =	7,668	7,064	6,491	5,936	5,391	4,843	4,273	3,651	2,892
$ABC_{Tier\ 2}$ =	7,074	6,004	5,068	4,239	3,496	2,821	2,197	1,603	1,006
$ABC_{Tier\ 3}$ =	6,465	5,008	3,846	2,913	2,157	1,544	1,046	641	310
HG =	0	-	-	-	-	-	-	-	-

10 Figures

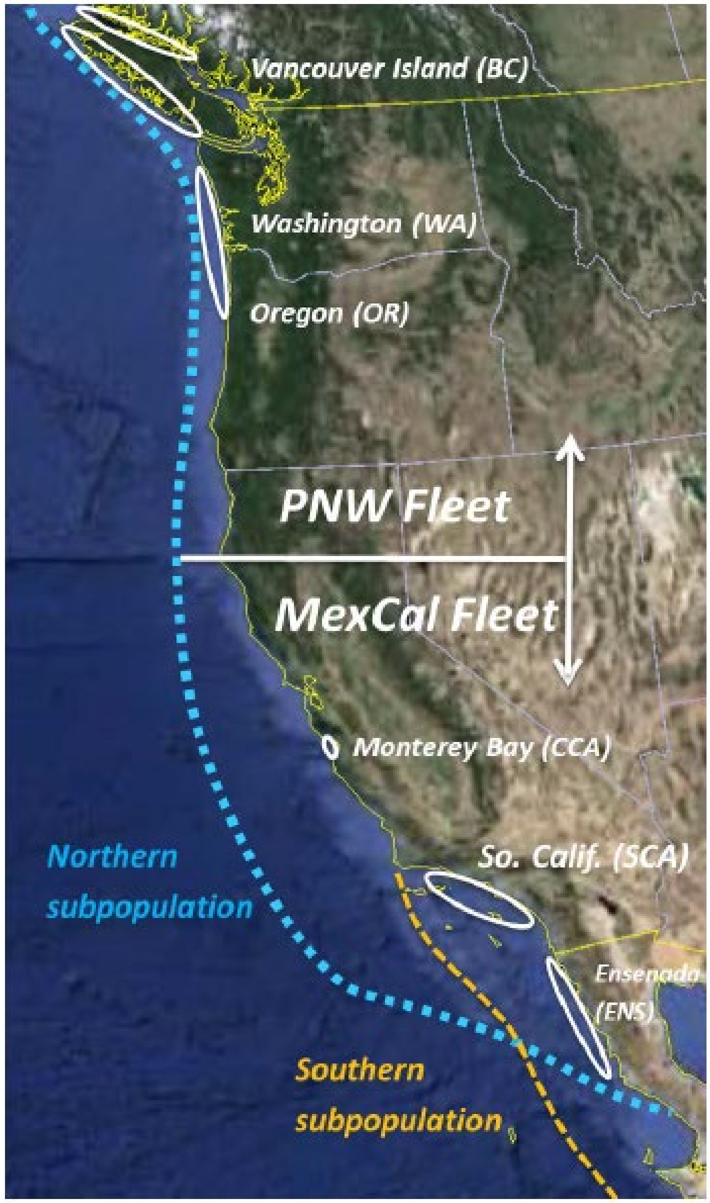

Figure 10.1: Distribution of the northern subpopulation (NSP) of Pacific sardine, primary commercial fishing areas, and modeled fishing fleets.

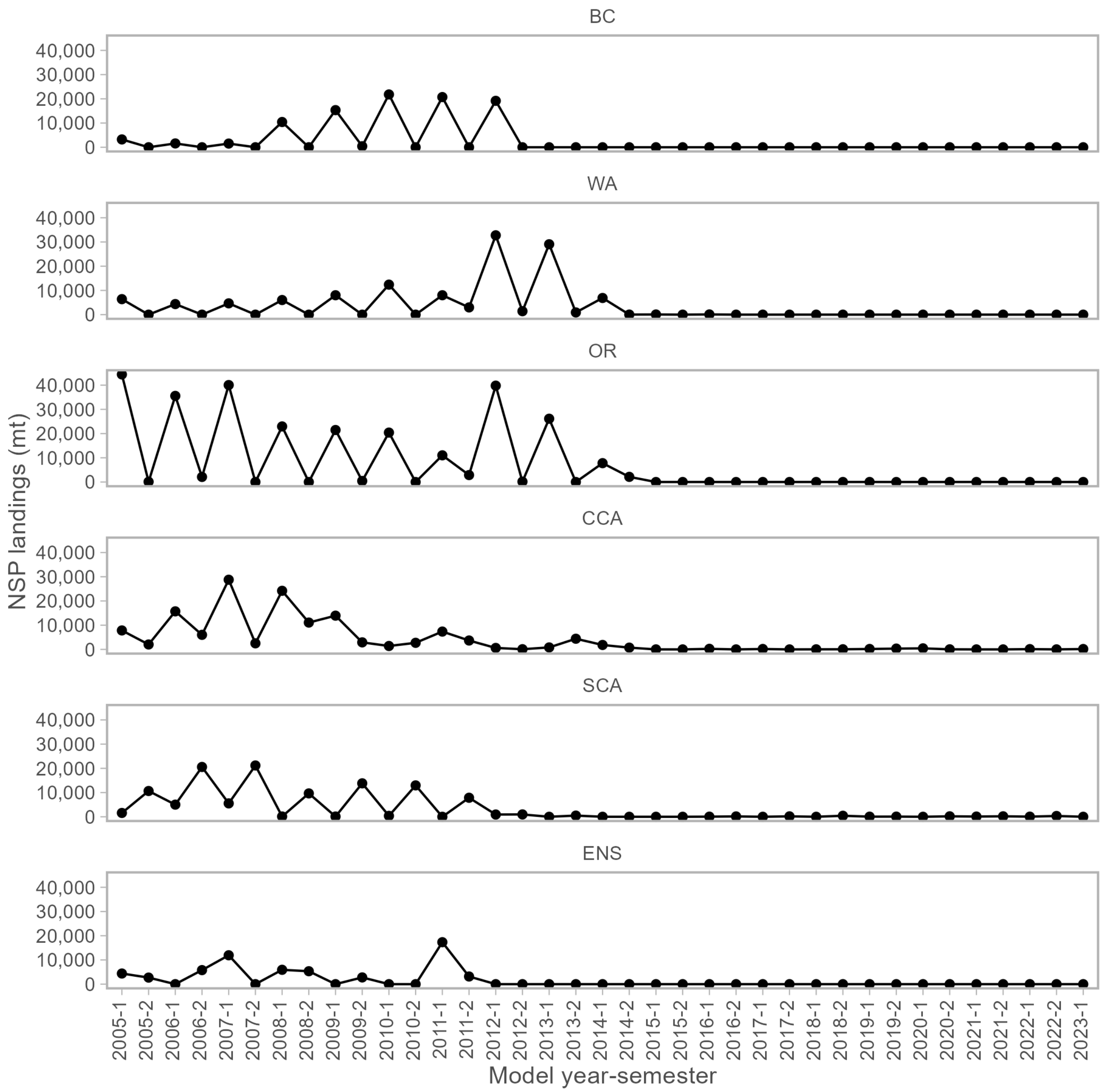

Figure 10.2: Pacific sardine northern subpopulation landings (mt) from British Columbia, Canada (BC), Washington (WA), Oregon (OR), central California (CCA), southern California (SCA) and Ensenada, Mexico (ENS).

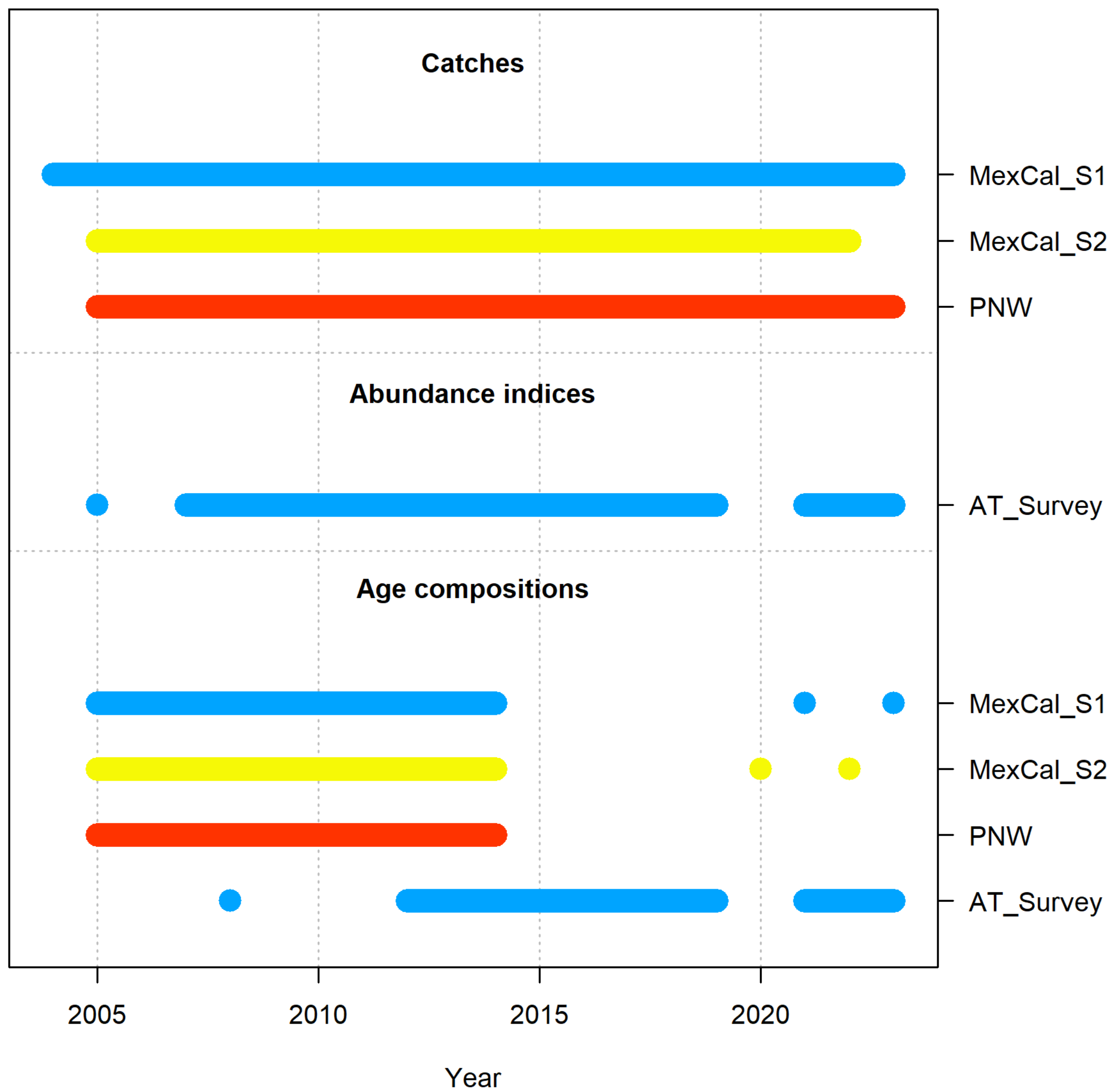

Figure 10.3: Summary of data sources used in the base model.

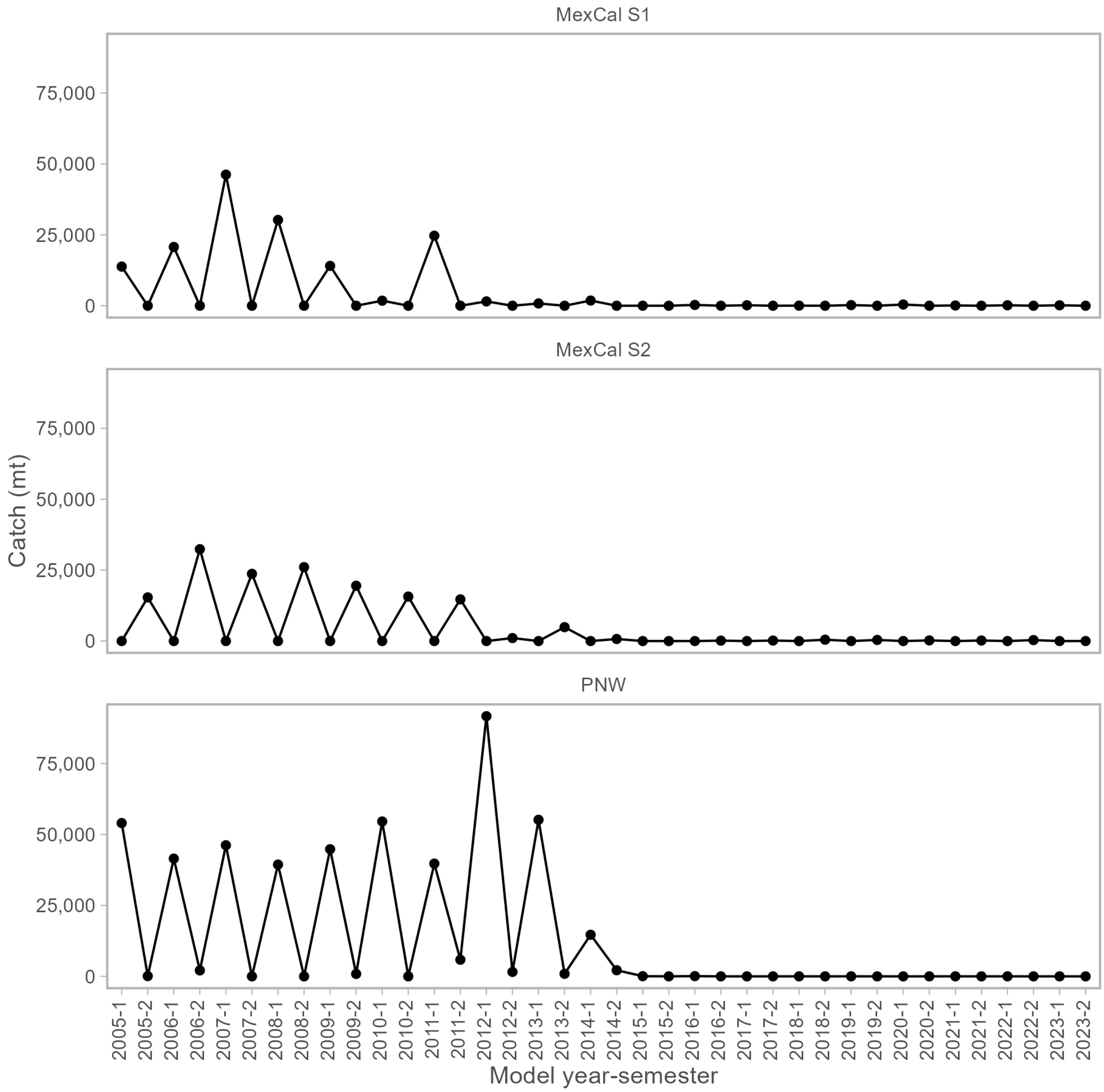

Figure 10.4: Pacific sardine landings (mt) by fleet, model year-semester as used in the base model.

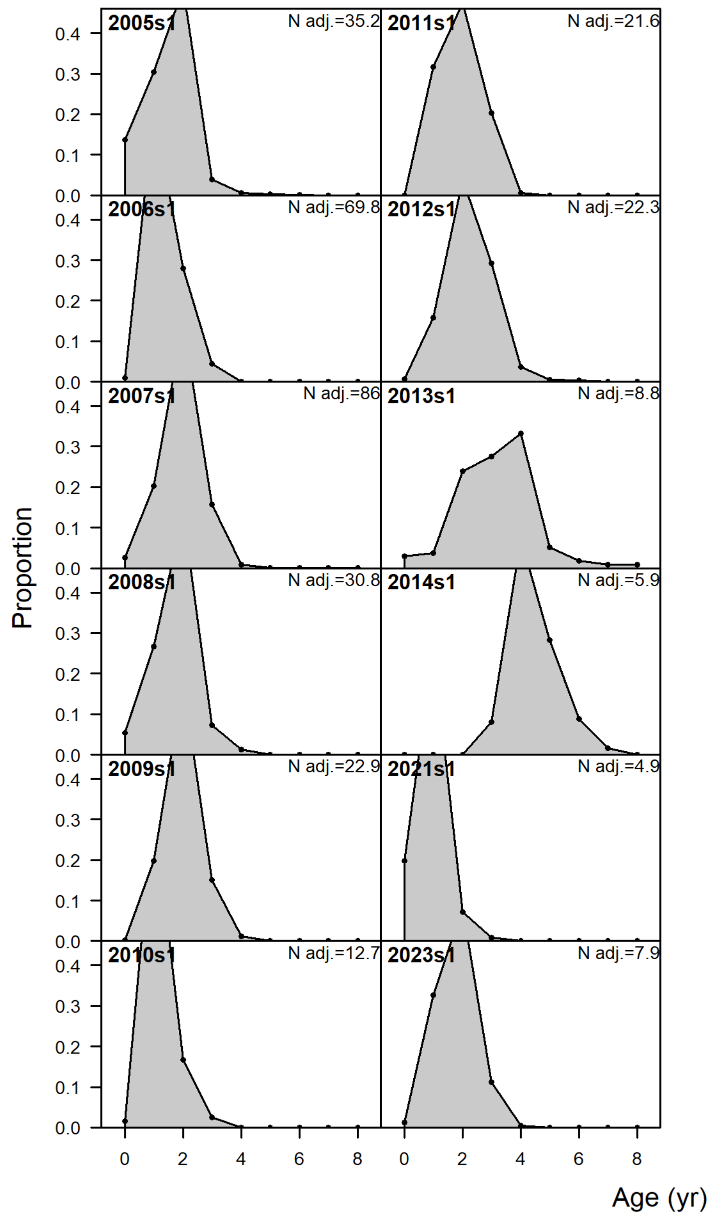

Figure 10.5: Age-composition time series for the MexCal fleet in semester 1 (S1). N represents input sample sizes.

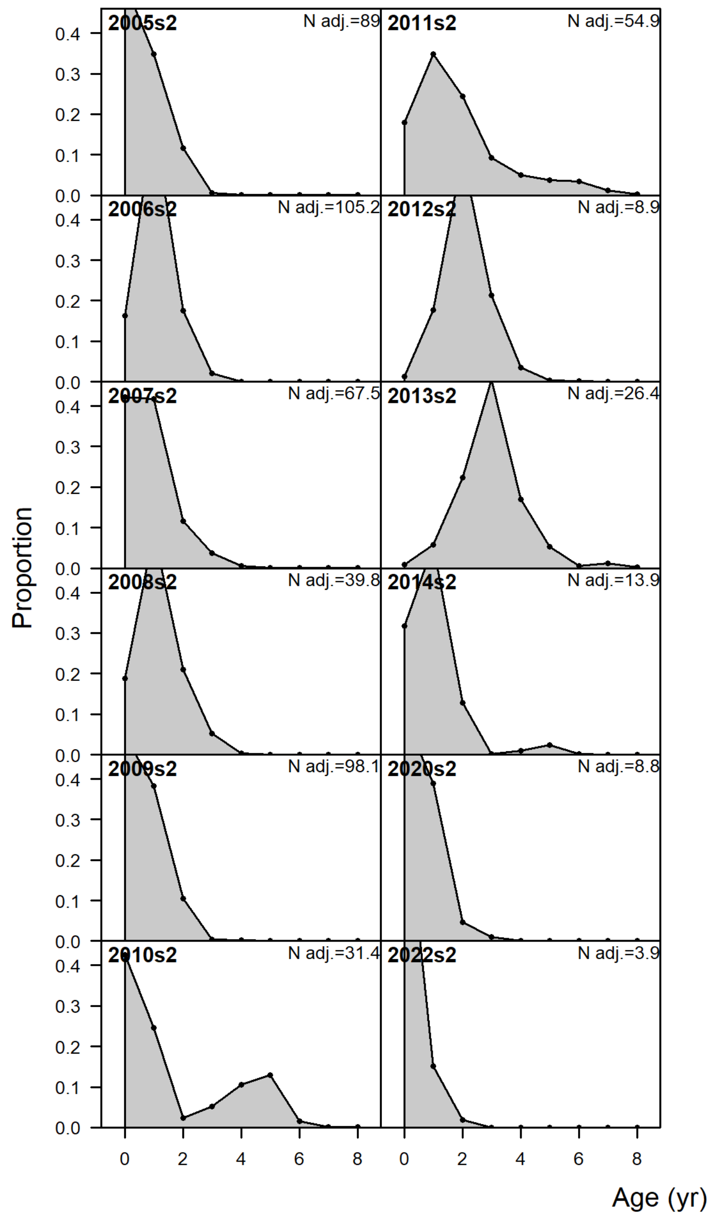

Figure 10.6: Age-composition time series for the MexCal fleet in semester 2 (S2). N represents input sample sizes.

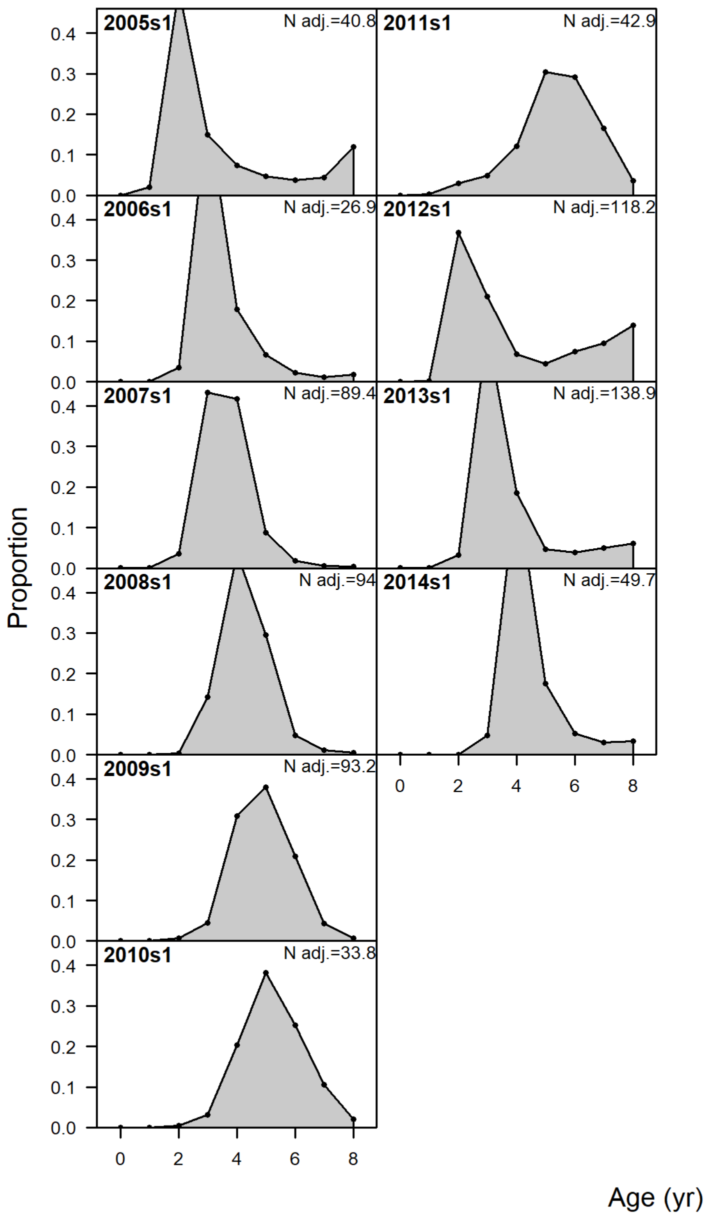

Figure 10.7: Age-composition time series for the PNW fleet. N represents input sample sizes.

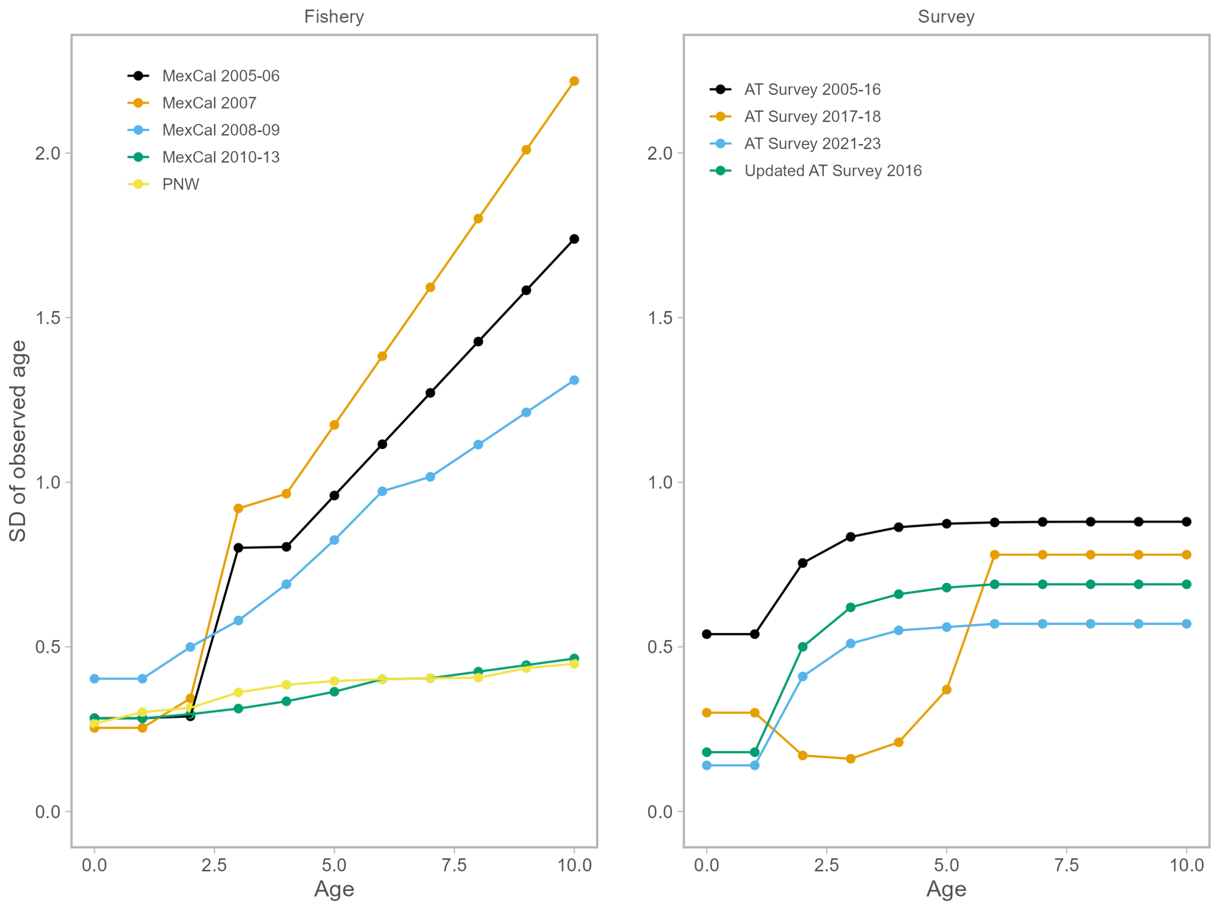

Figure 10.8: Laboratory- and year-specific ageing errors for the fishery and survey data in the base model.

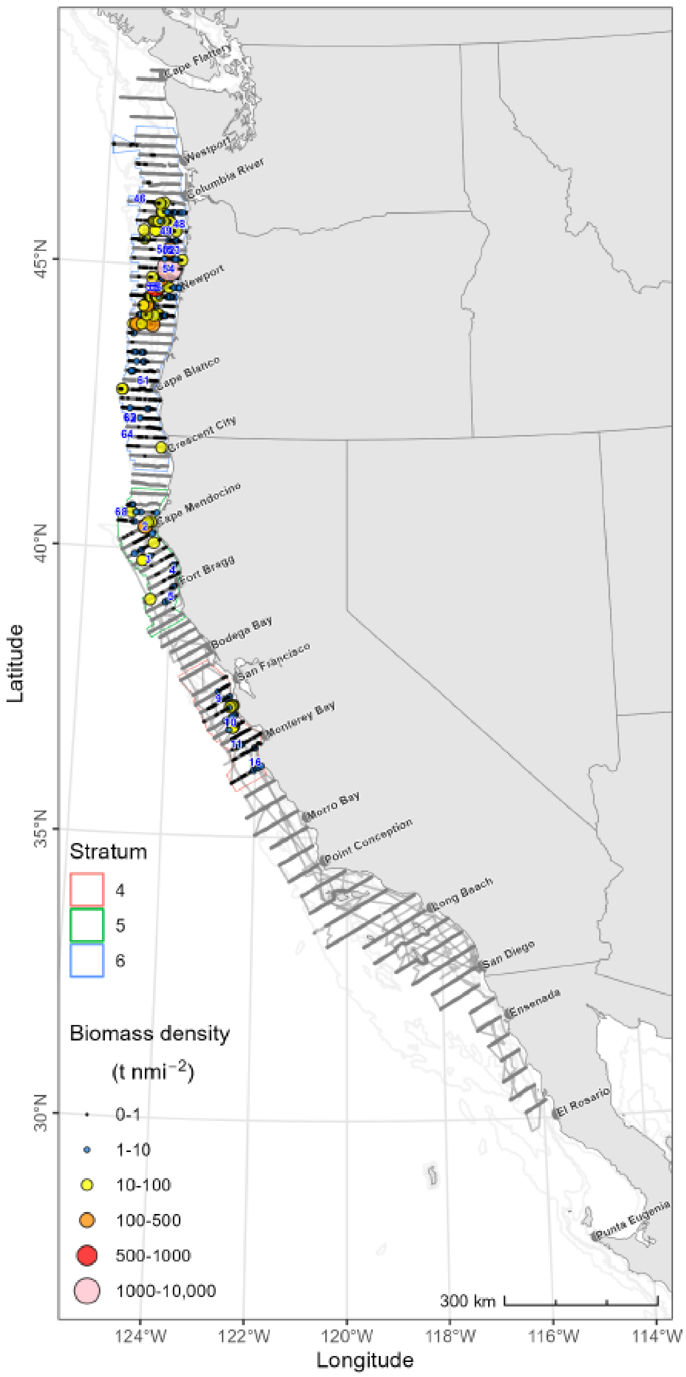

Figure 10.9: Biomass densities of NSP Pacific sardine by stratum for the summer 2022 AT survey region. Blue numbers represent locations of positive sardine trawl clusters. Gray lines represent the vessel track.

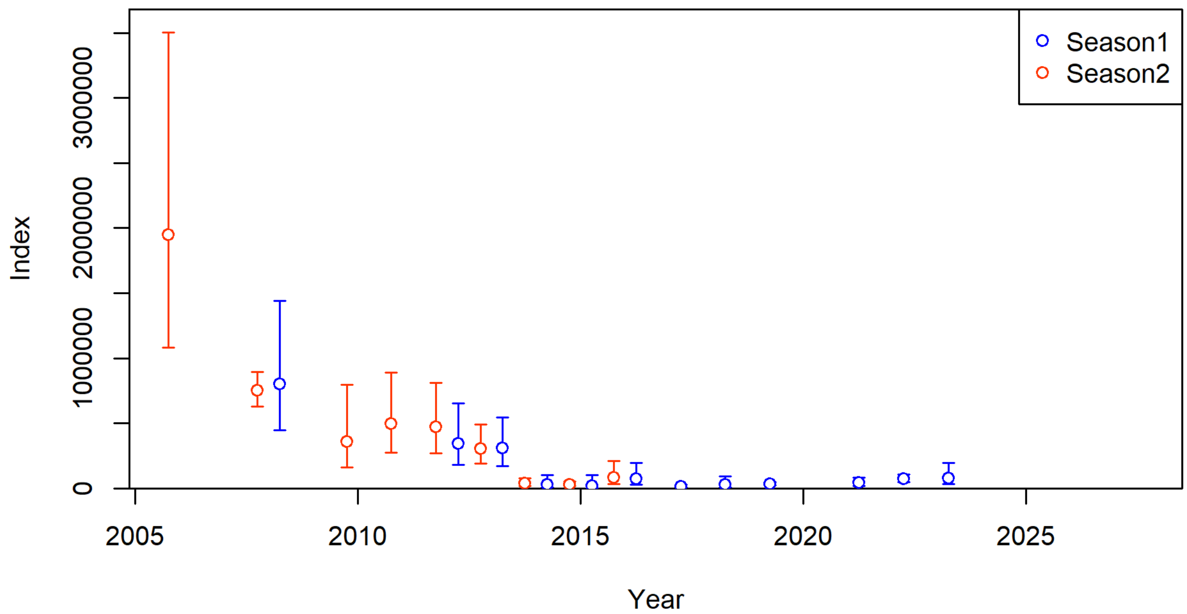

Figure 10.10: Time series of Pacific sardine biomass (age 0+, mt) from the summer (semester 1) and spring (semester 2) AT surveys, 2005-2023 (bars are 95% CI).

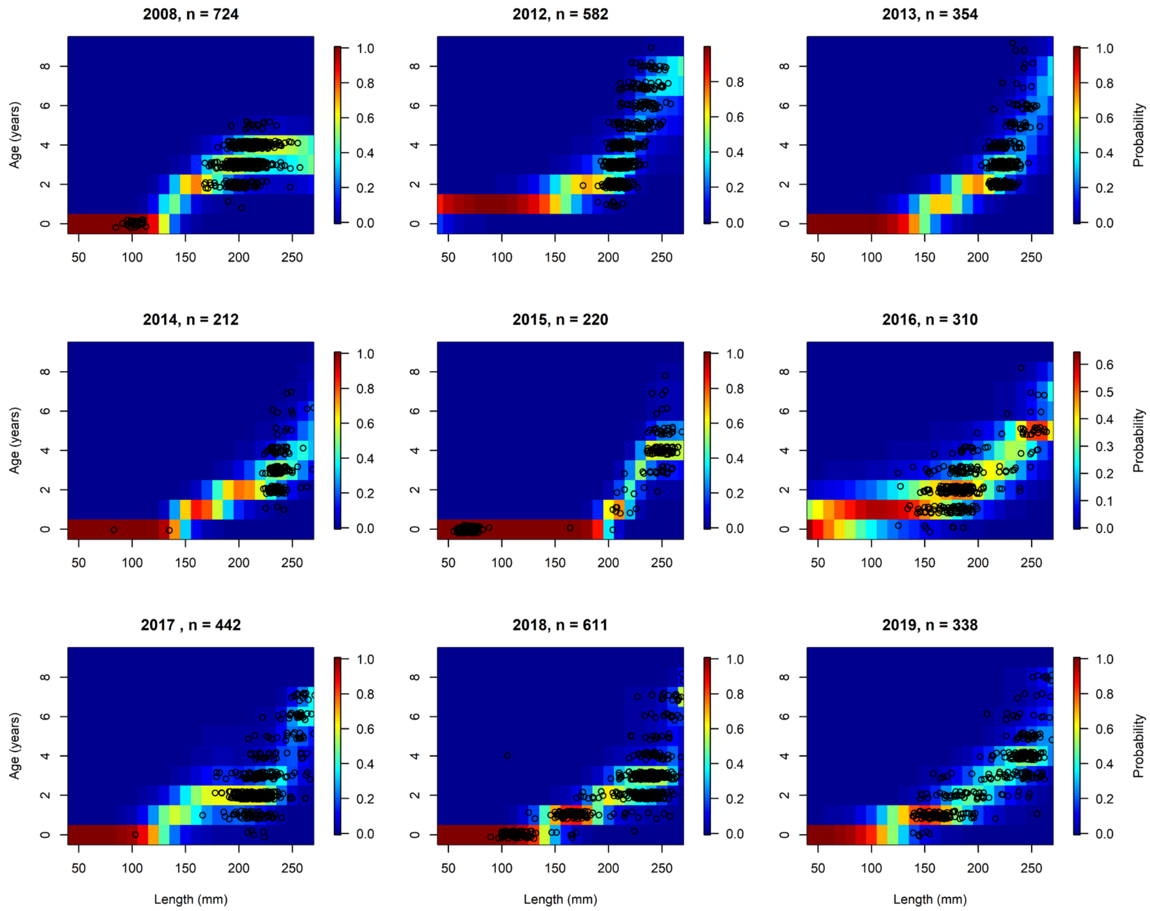

Figure 10.11: Annual age-length keys derived from summer AT survey samples collected from 2008-2019.

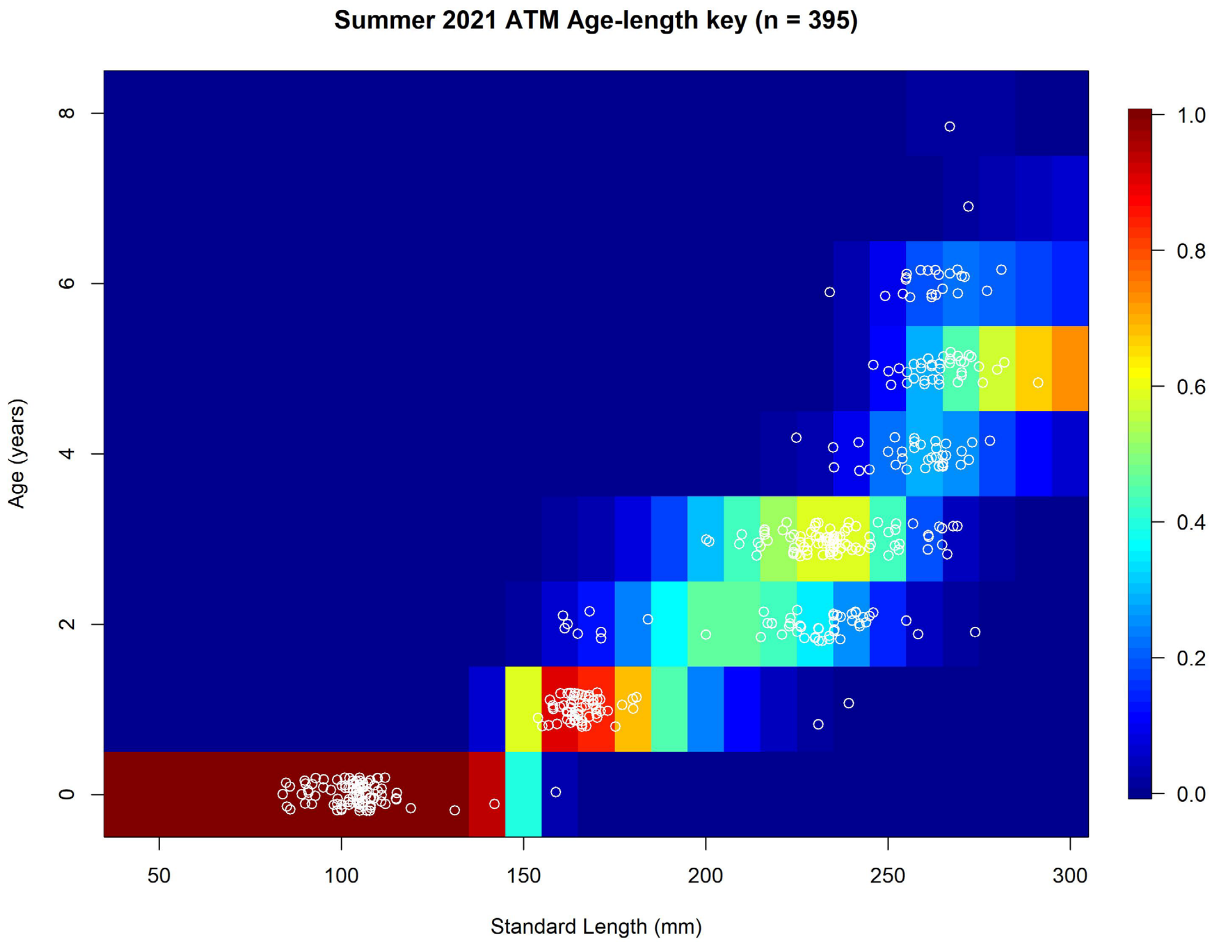

Figure 10.12: Age-length key derived from summer 2021 AT survey samples.

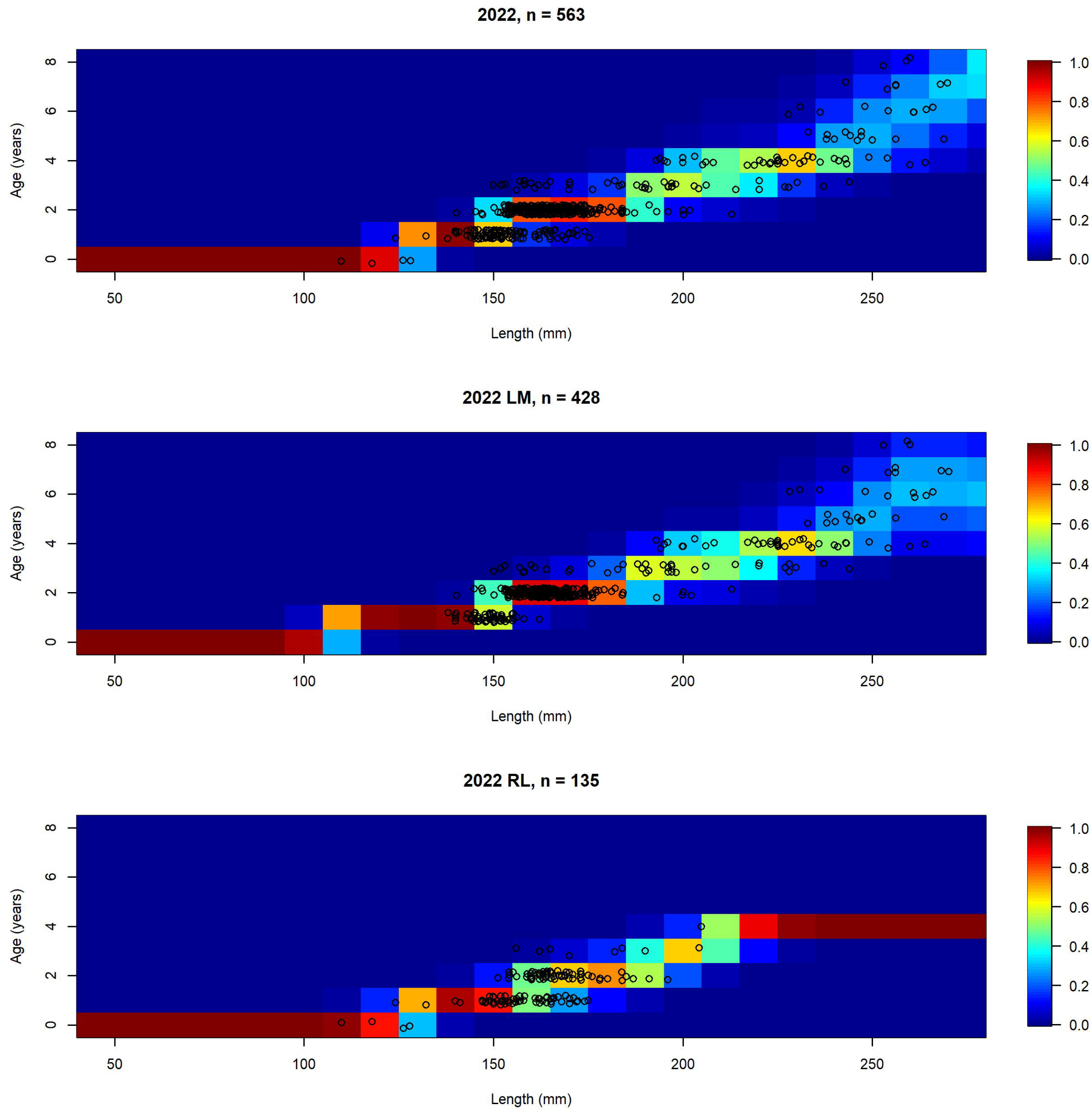

Figure 10.13: Age-length key derived from summer 2022 AT survey samples. The top panel is for the combined data, middle panel F/V *Lisa Marie*, and bottom panel R/V *Reuben Lasker*. The weight-at-age values were based on the combined age-length key (top panel).

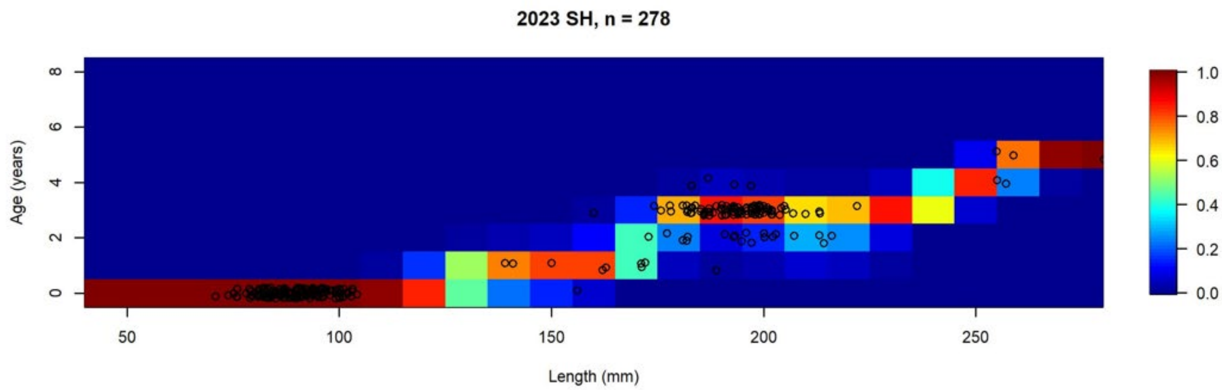

Figure 10.14: Age-length key derived from summer 2023 AT survey samples.

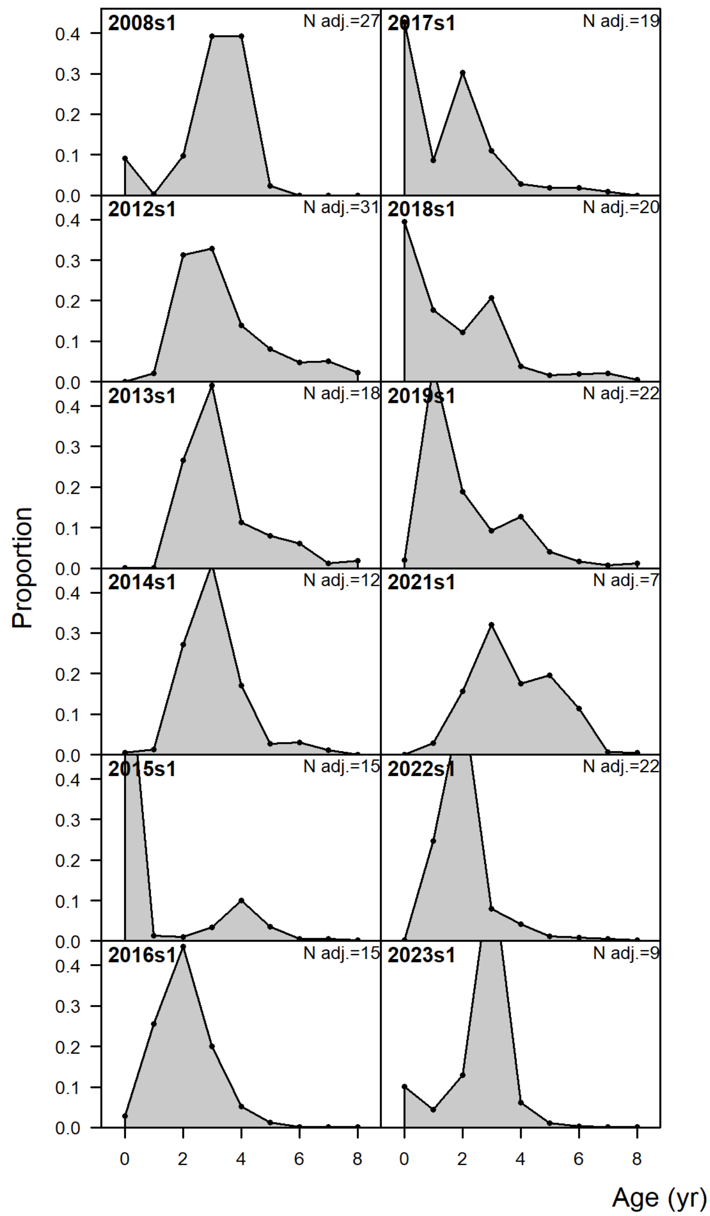

Figure 10.15: Age-composition time series for the AT Survey. N represents input sample sizes.

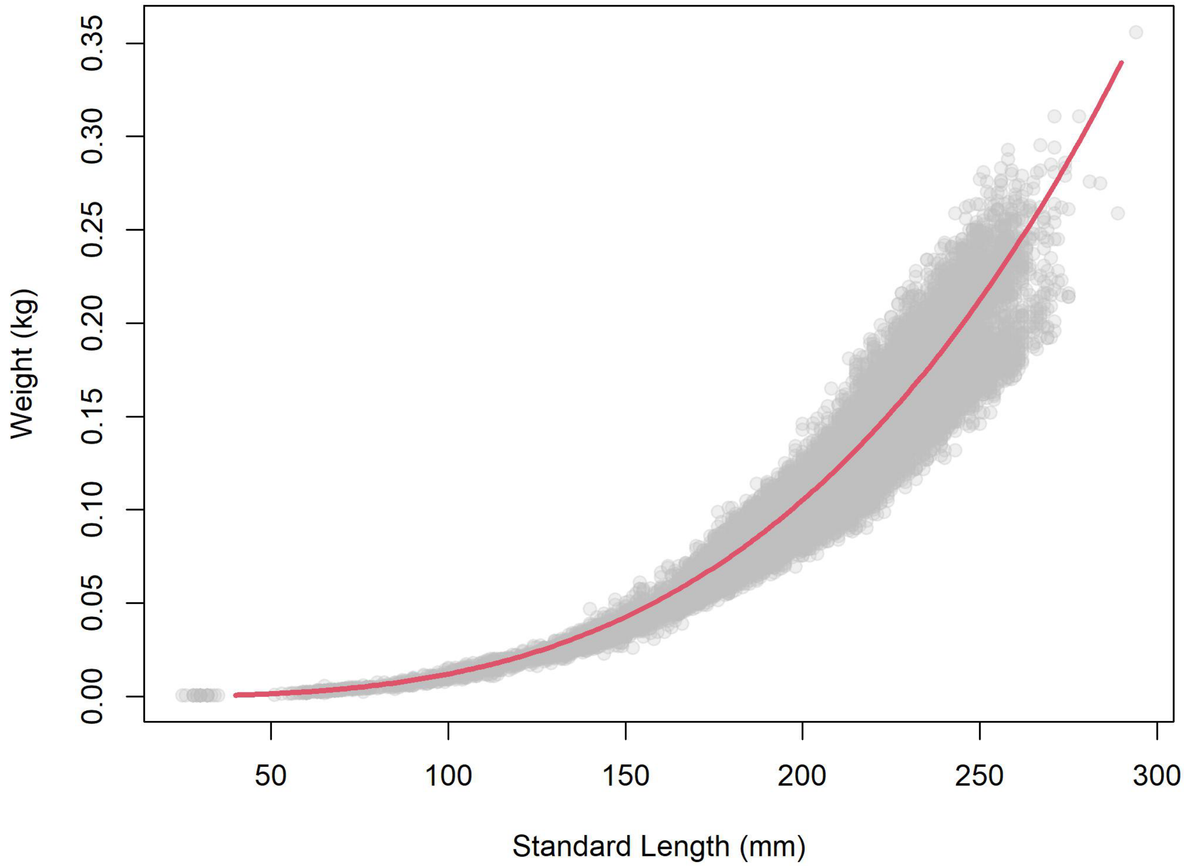

Figure 10.16: Implied length-weight relationship for Pacific Sardine used in biomass estimates and computation of weight-at-age: $weight(kg) = 4.446313e - 06 * \left(totallength(cm)\right)^{3.197}$, where $totallength(cm) = (3.574 + standardlength(mm) * 1.149)/10$. The points in grey are individual pairs of length and weights of pacific sardine collected during CPS surveys between 2003 and 2017.

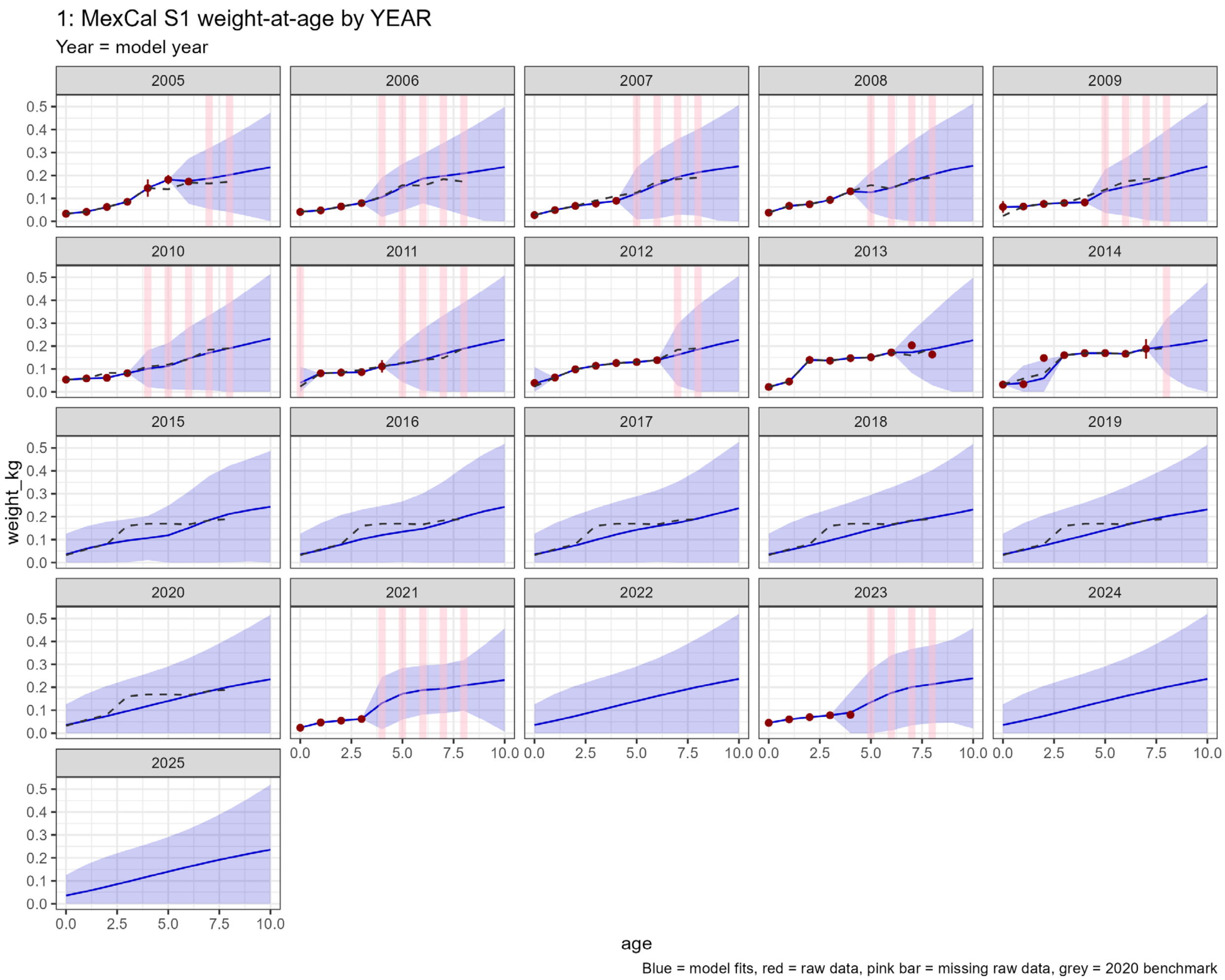

Figure 10.17: MexCal S1 model fits (blue line) from the conditional variance method applied to weight-at-age data. The data (red points), missing values (vertical pink bar), and values used in the 2020 benchmark (grey line) are shown. The values on the blue line were input to this assessment model.

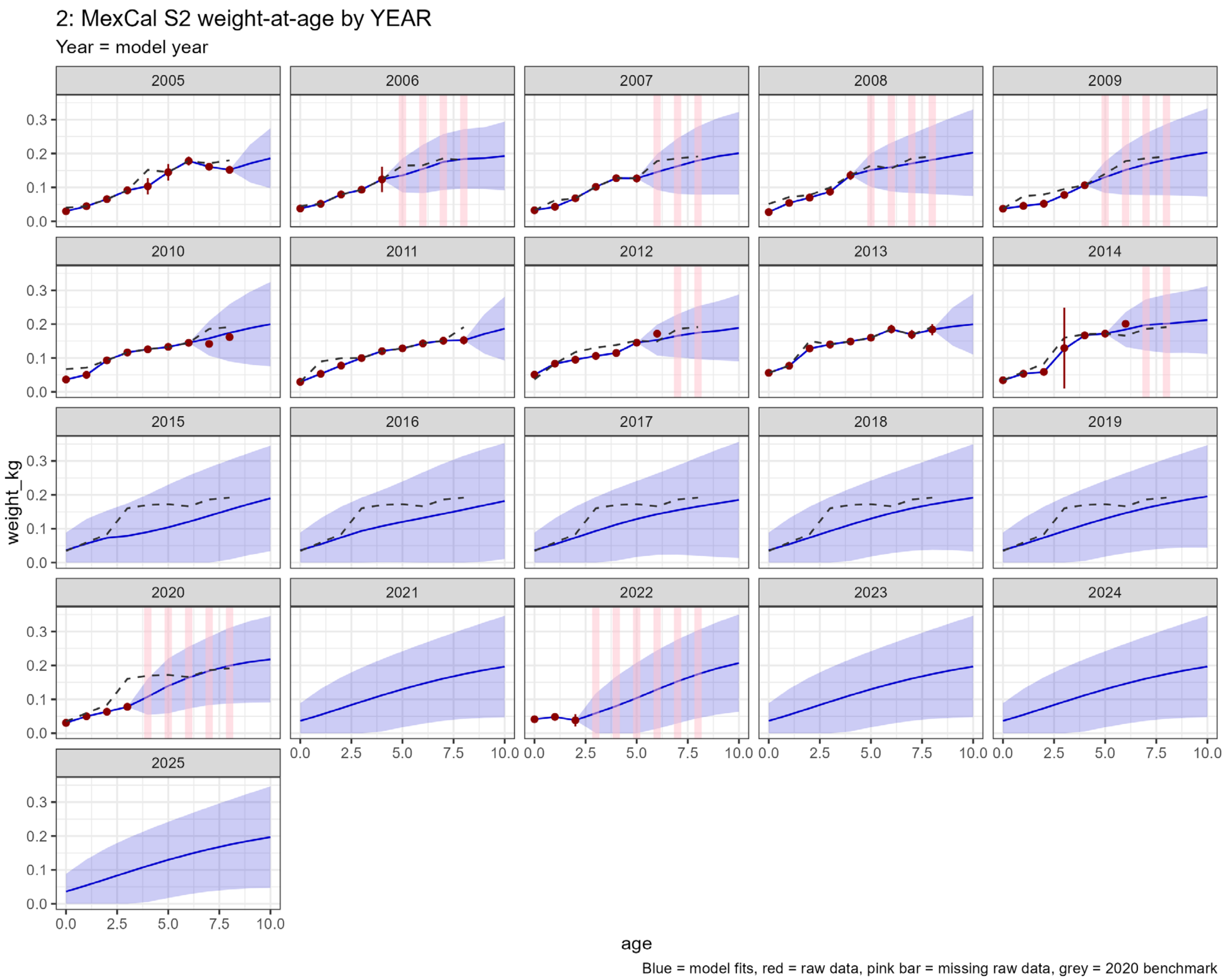

Figure 10.18: MexCal S2 model fits (blue line) from the conditional variance method applied to weight-at-age data. The data (red points), missing values (vertical pink bar), and values used in the 2020 benchmark (grey line) are shown. The values on the blue line were input to this assessment model.

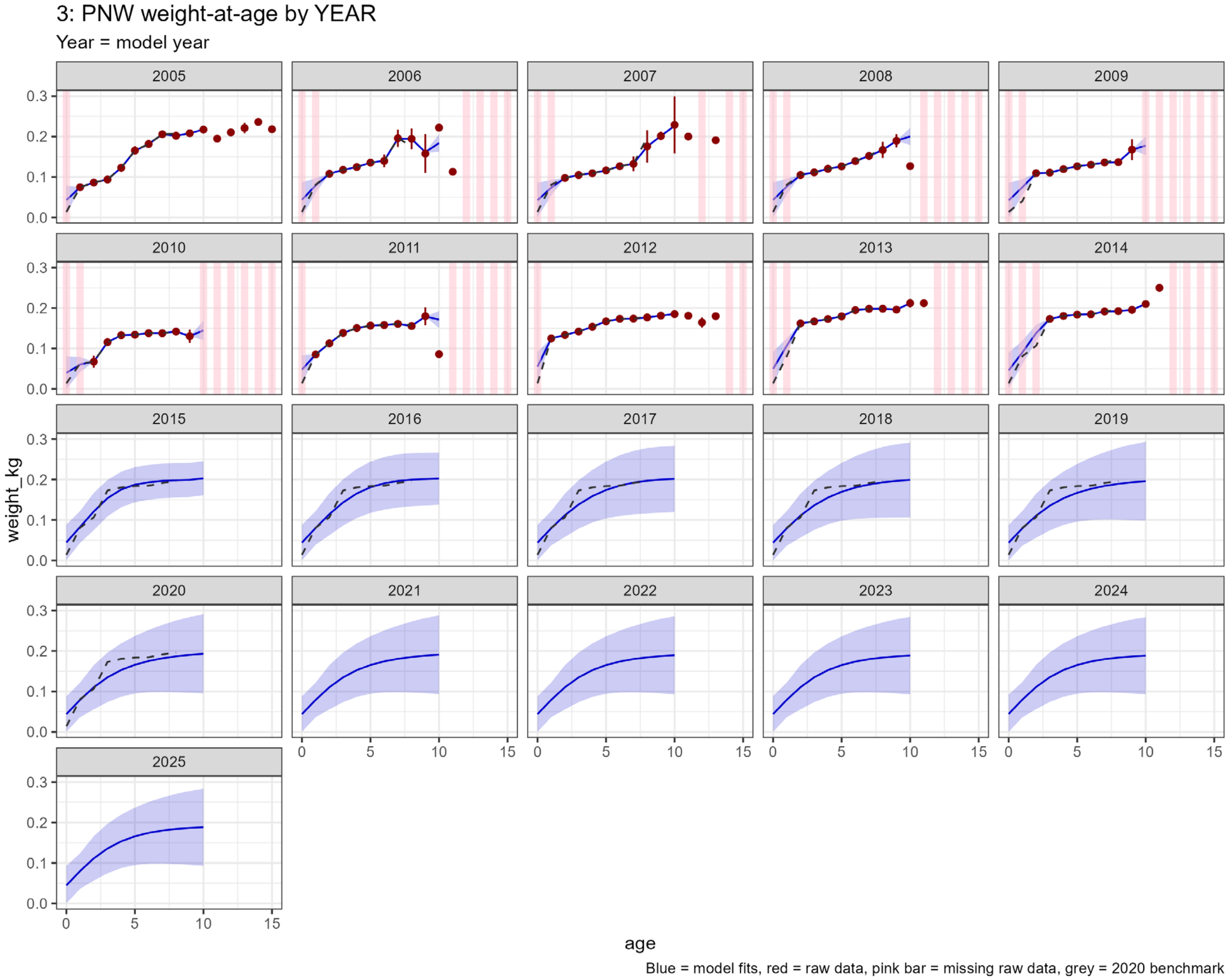

Figure 10.19: PNW model fits (blue line) from the conditional variance method applied to weight-at-age data. The data (red points), missing values (vertical pink bar), and values used in the 2020 benchmark (grey line) are shown. The values on the blue line were input to this assessment model.

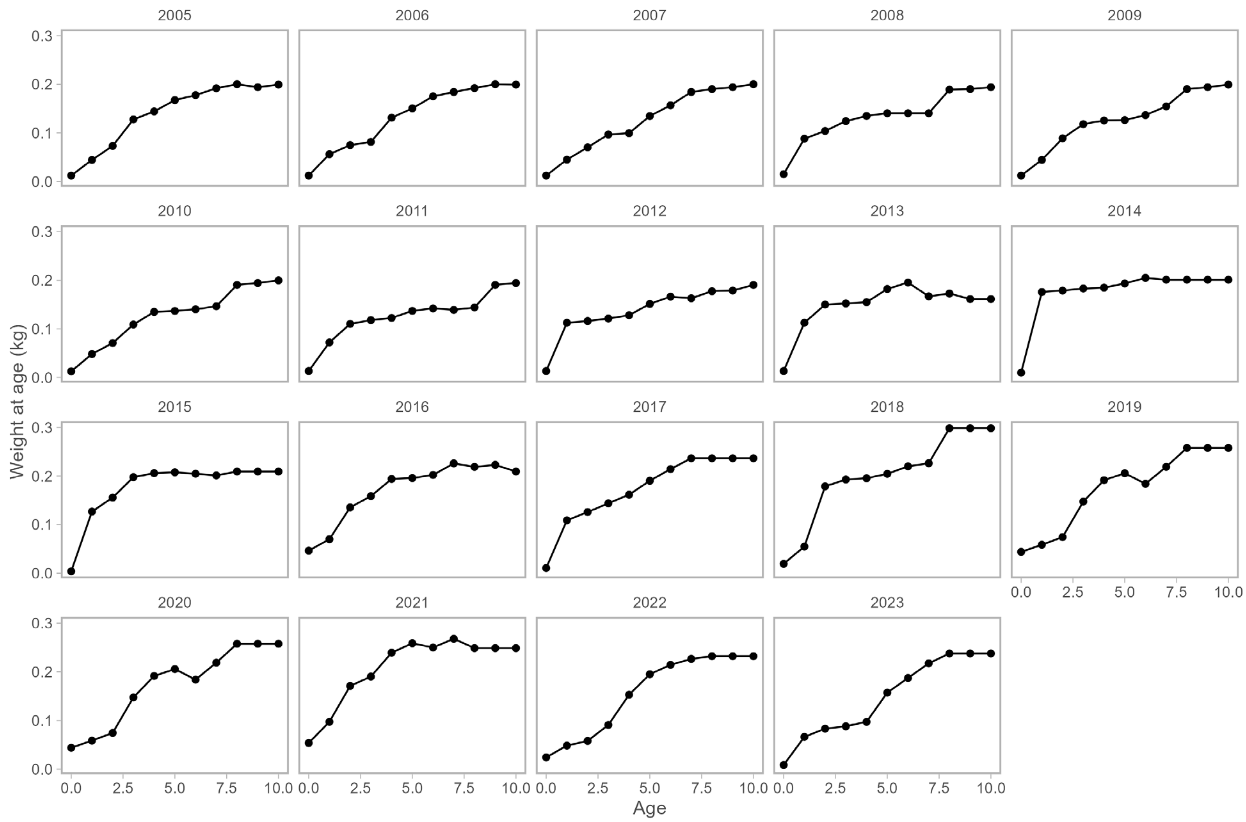

Figure 10.20: AT Survey weight-at-age summer values by year. These values were calculated using survey-specific age-length keys.

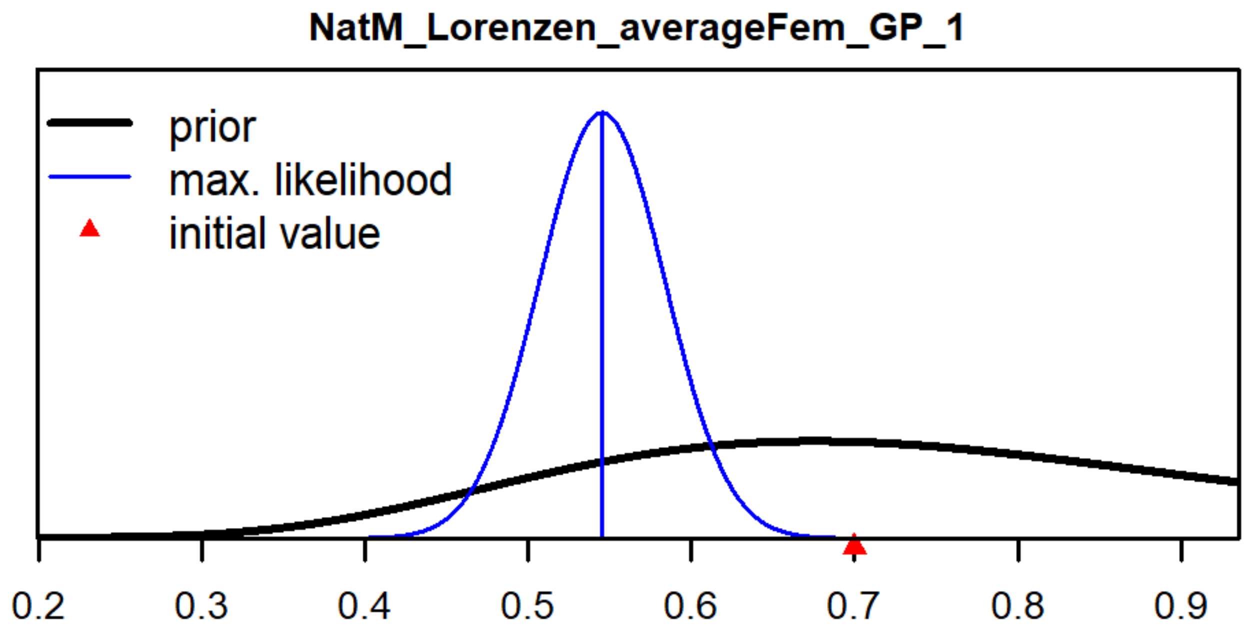

Figure 10.21: Natural mortality M prior and estimate. The prior was calculated assuming a maximum age of 8.

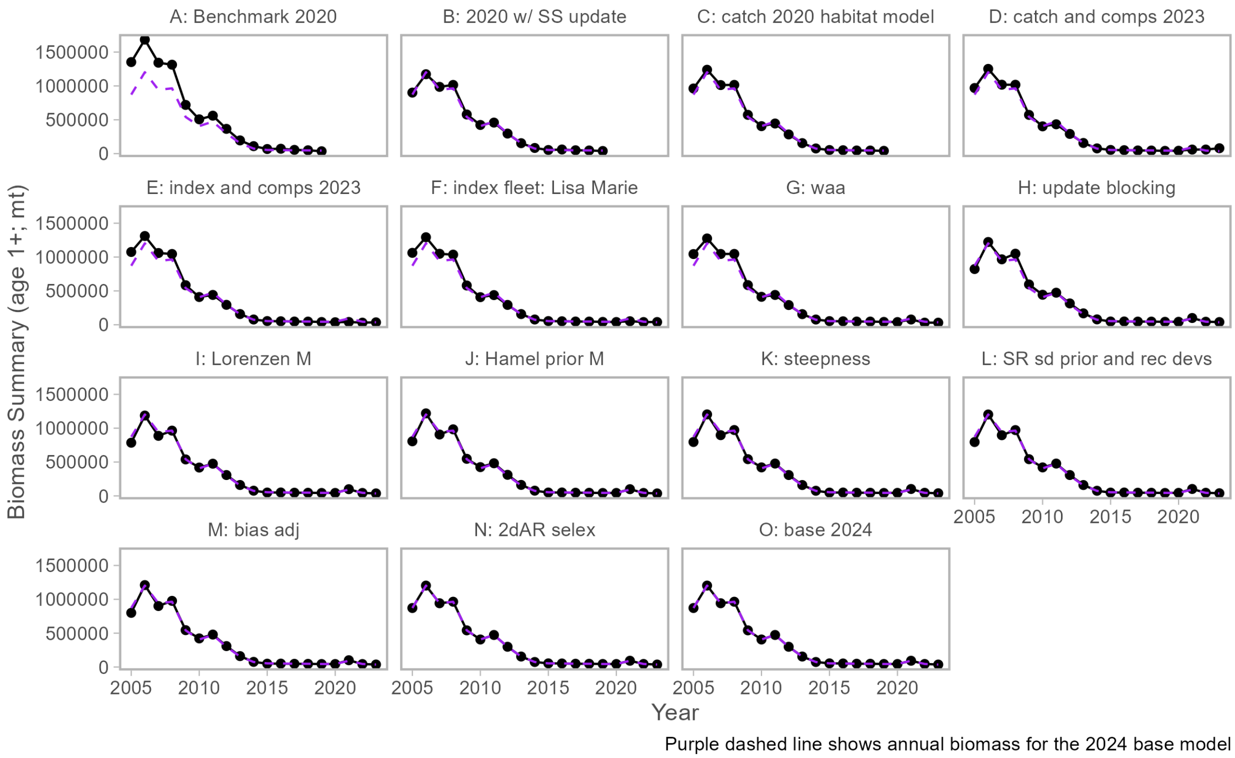

Figure 10.22: Summary biomass time series with each change to model configuration. Time series for the 2024 base model is included (dashed line).

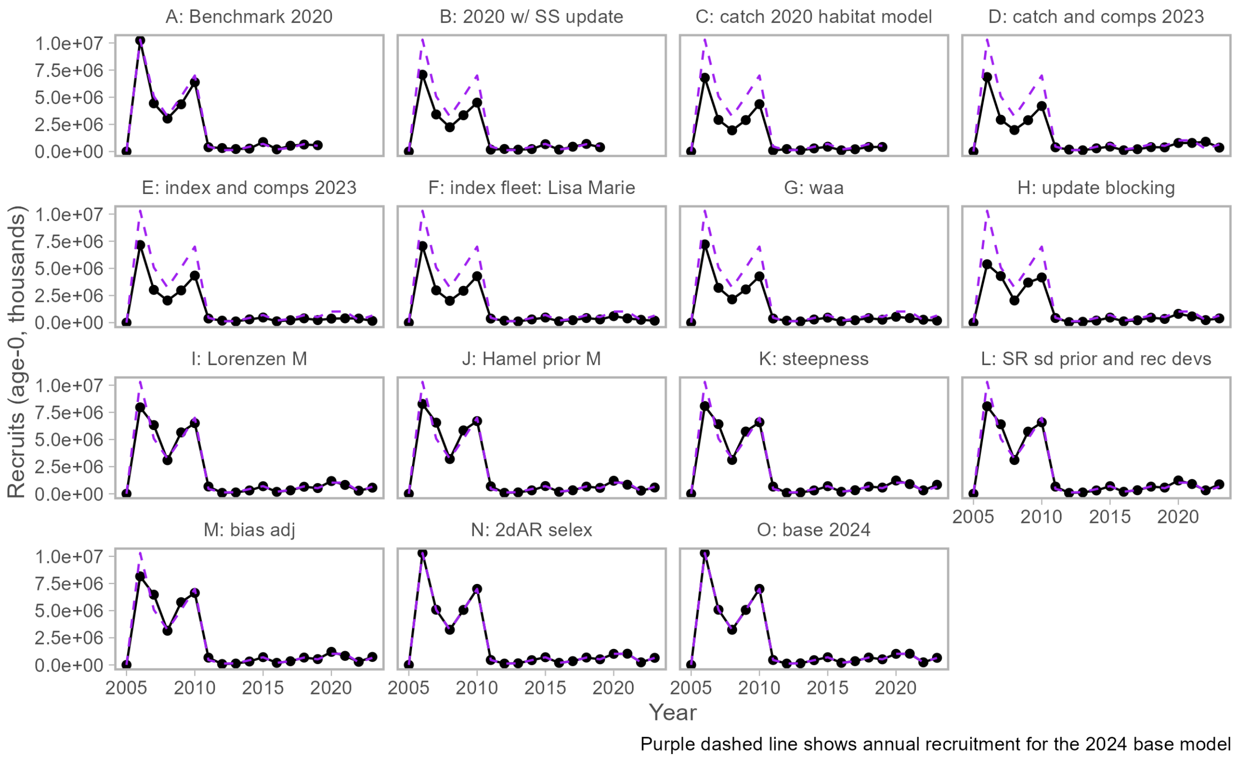

Figure 10.23: Recruitment time series with each change to model configuration. Time series for the 2024 base model is included (dashed line).

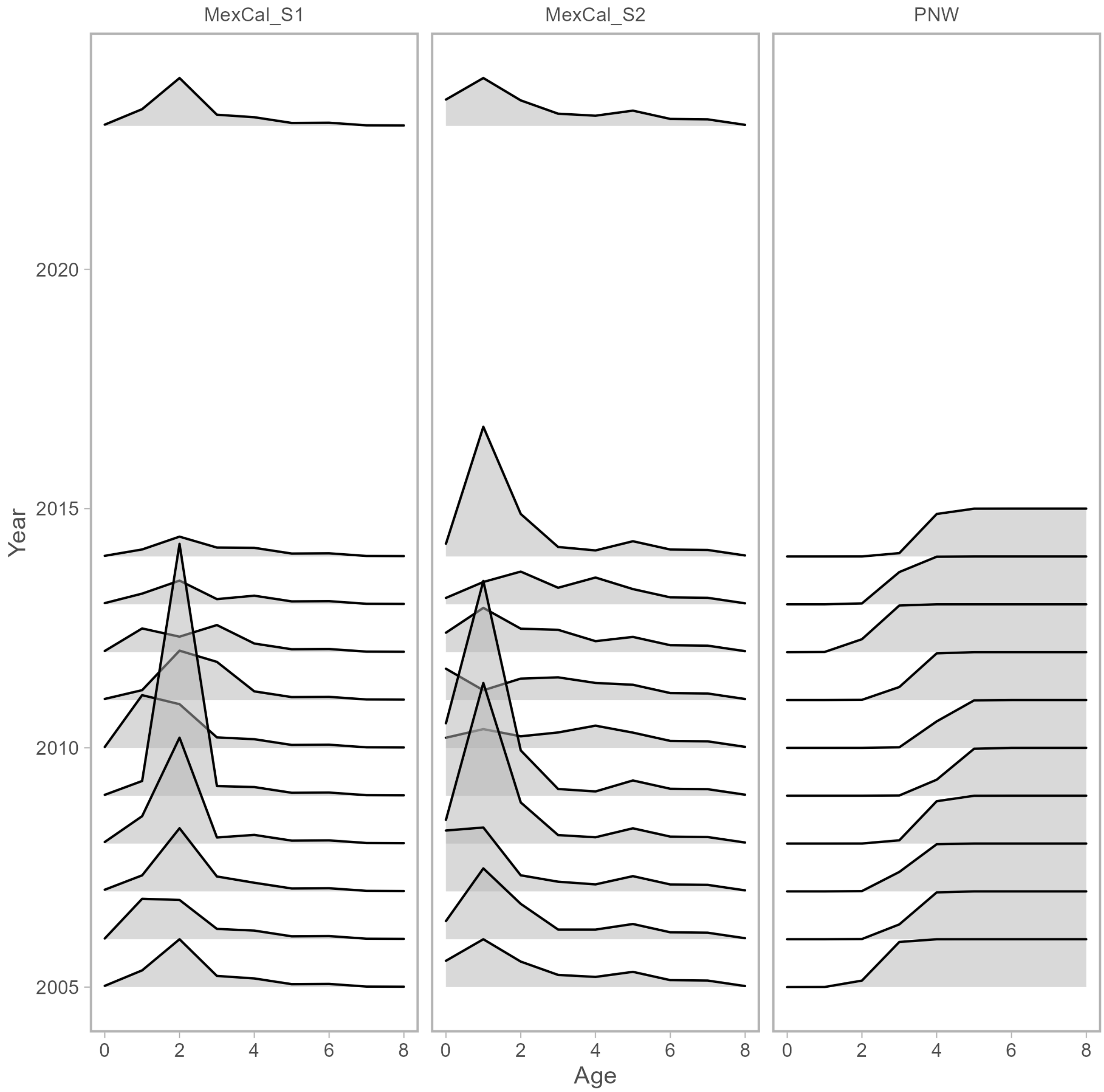

Figure 10.24: Time-varying age-based selectivity patterns for the three fishing fleets.

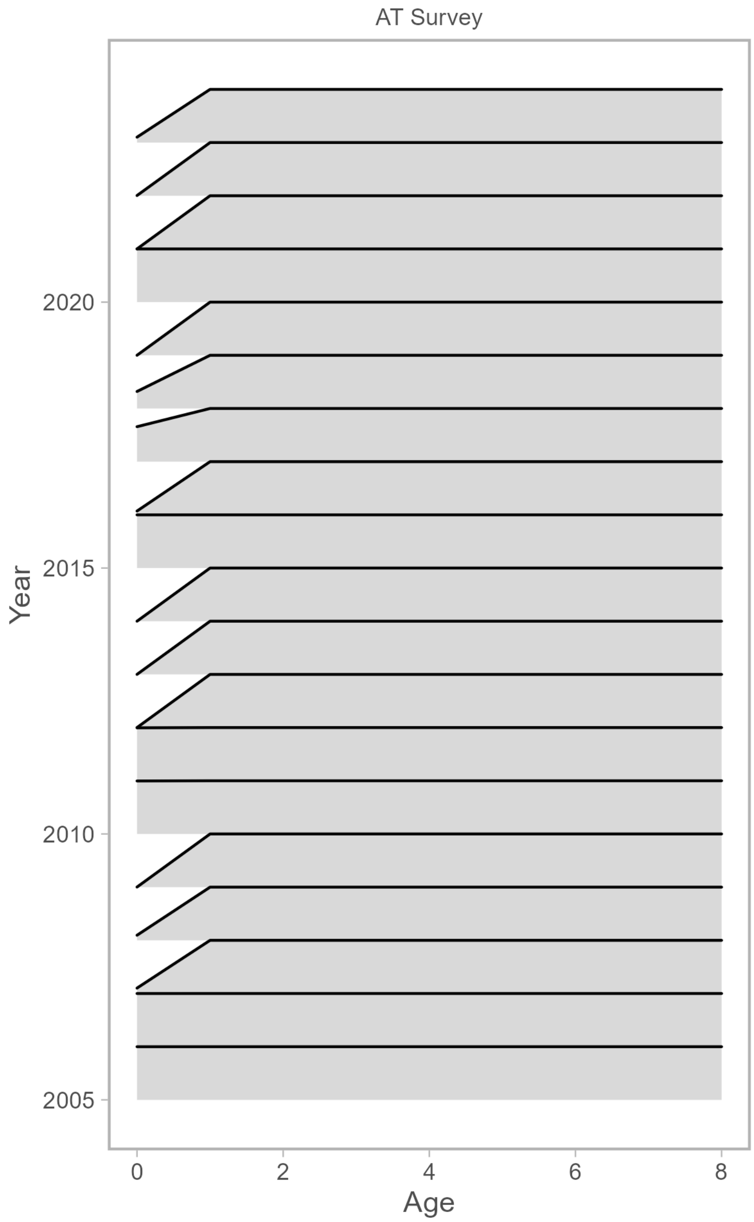

Figure 10.25: Time-varying age-based selectivity patterns for AT survey and *Lisa Marie*.

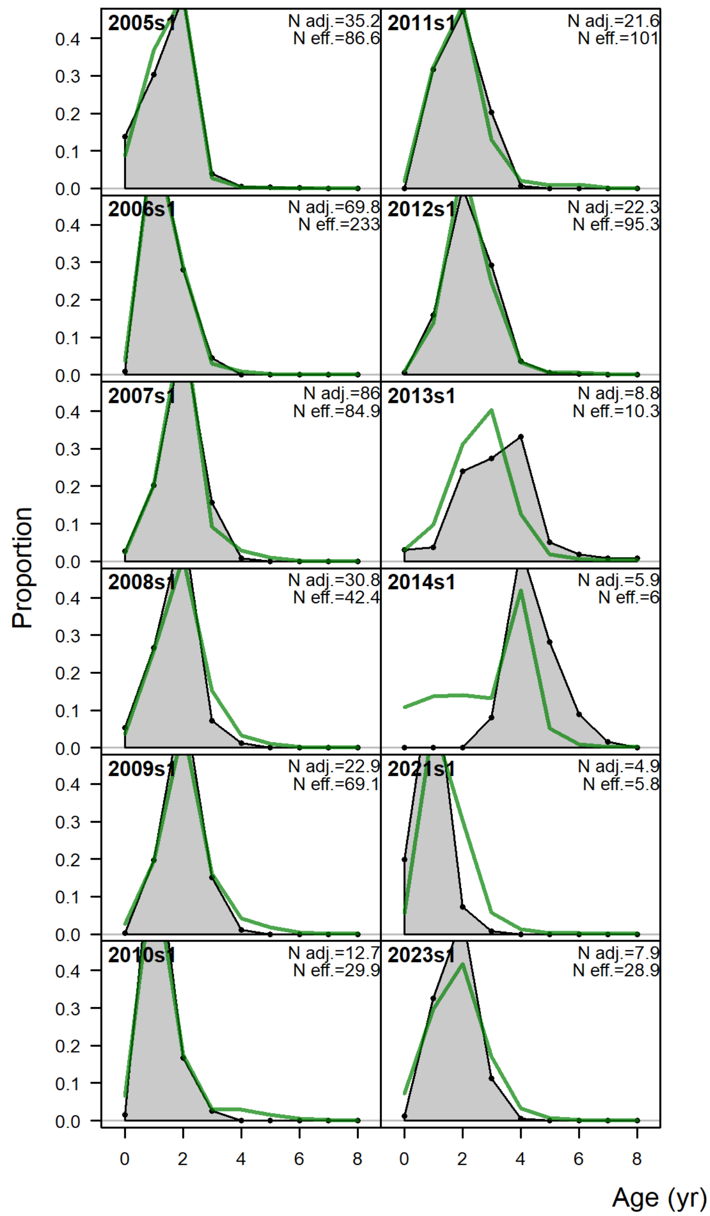

Figure 10.26: Fit to age-composition time series for the MexCal S1 fleet in the base model. Values in the top right are input sample sizes (N adj) and effective sample size given statistical fit in the model (N eff.).

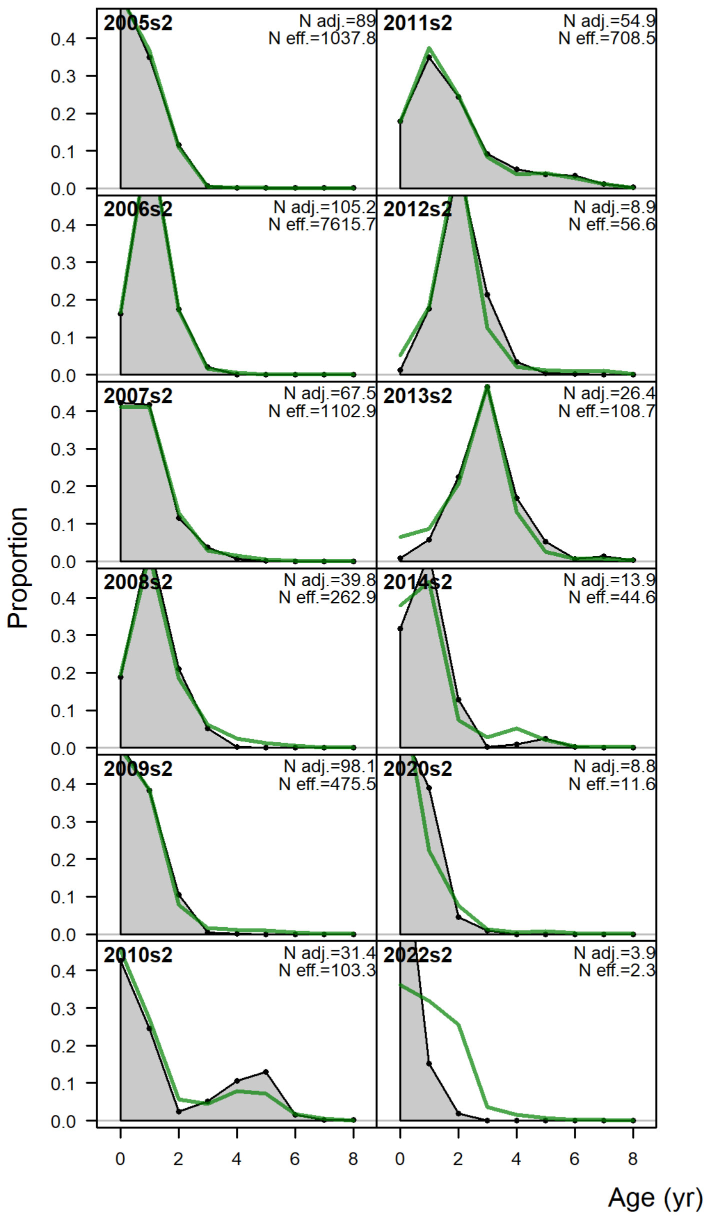

Figure 10.27: Fit to age-composition time series for the MexCal S2 fleet in the base model. Values in the top right are input sample sizes (N adj) and effective sample size given statistical fit in the model (N eff.).

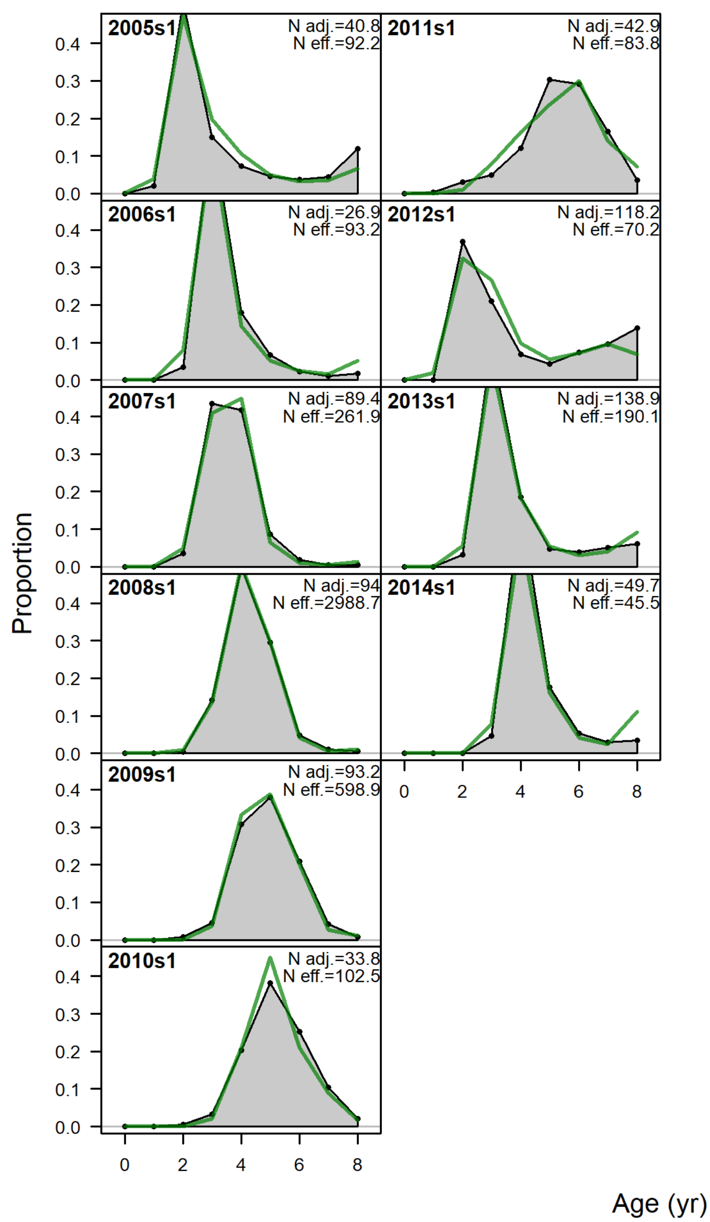

Figure 10.28: Fit to age-composition time series for the PNW fleet in the base model. Values in the top right are input sample sizes (N adj) and effective sample size given statistical fit in the model (N eff.).

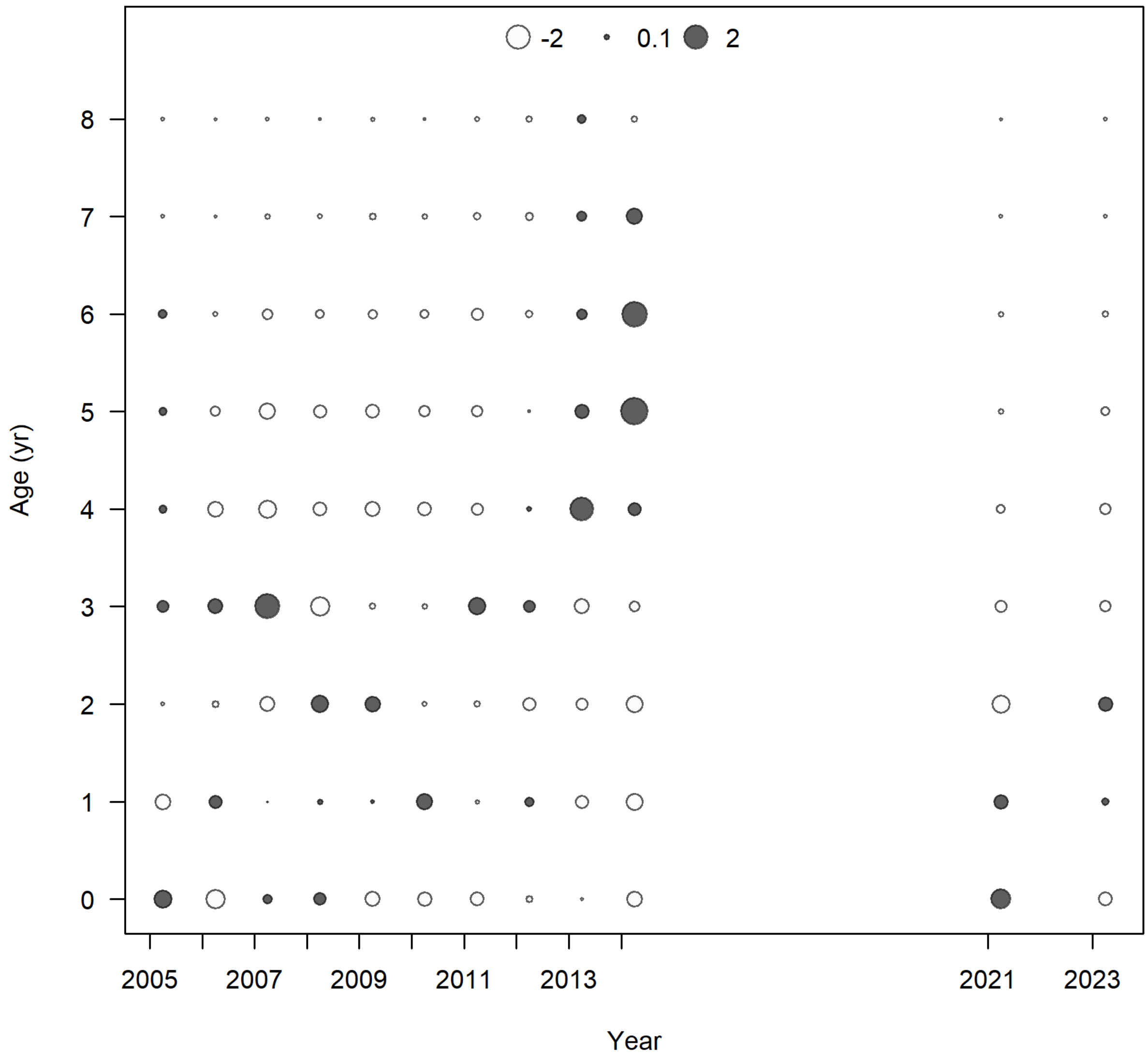

Figure 10.29: Residuals of the fit to the age-composition time series for the MexCal S1 fleet in the base model.

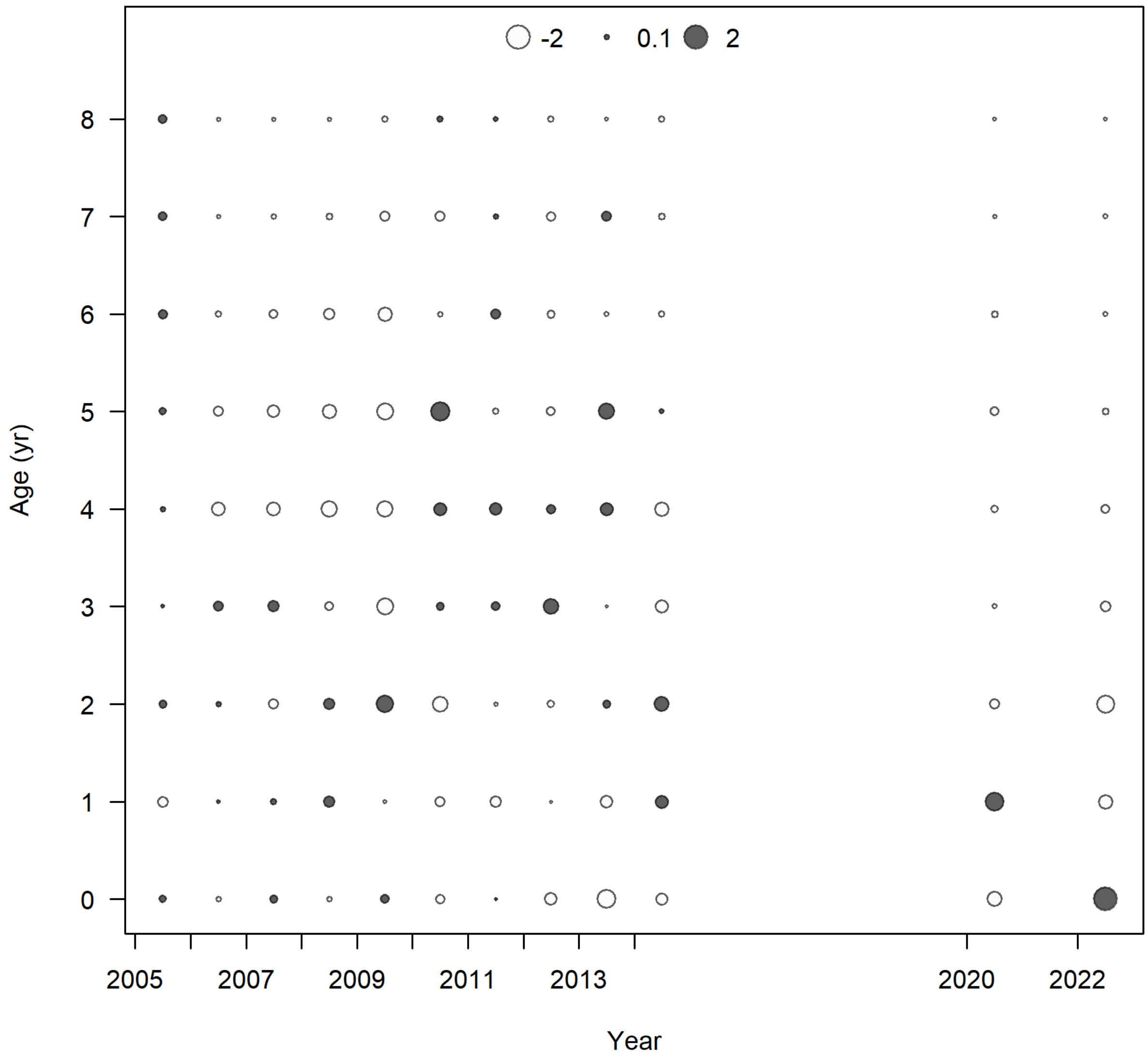

Figure 10.30: Residuals of the fit to the age-composition time series for the MexCal S2 fleet in the base model.

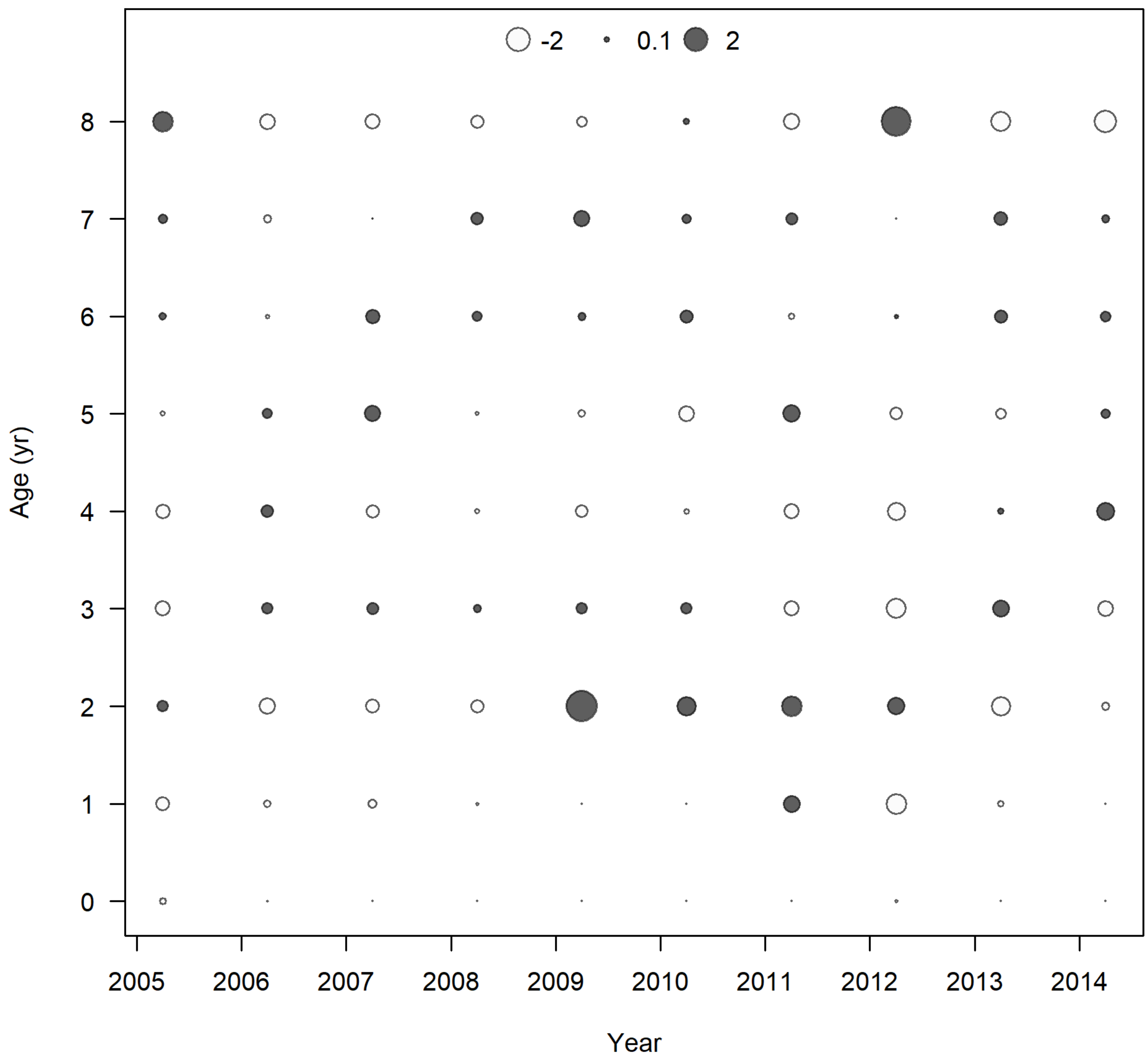

Figure 10.31: Residuals of the fit to the age-composition time series for the PNW fleet in the base model.

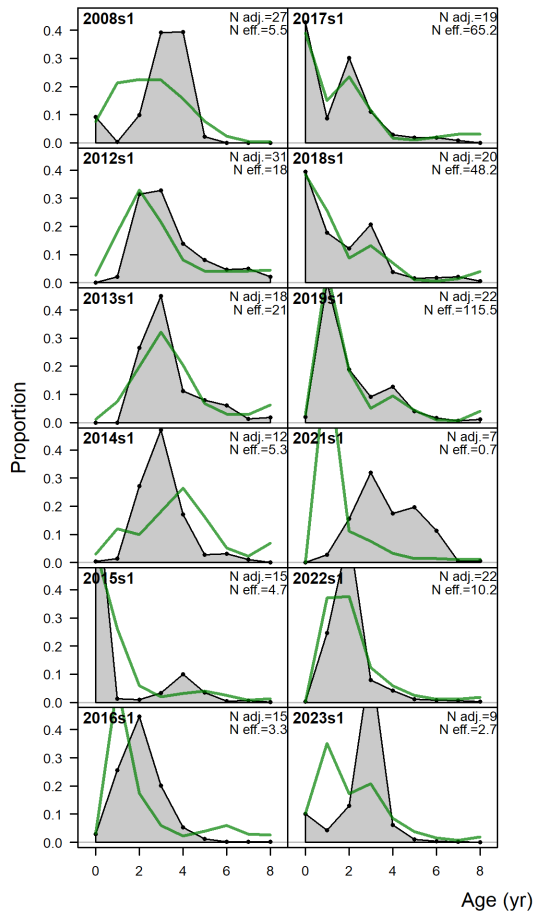

Figure 10.32: Fit to the age-composition time series for the AT survey in the base model. Values in the top right are input sample sizes (N adj) and effective sample size given statistical fit in the model (Neff).

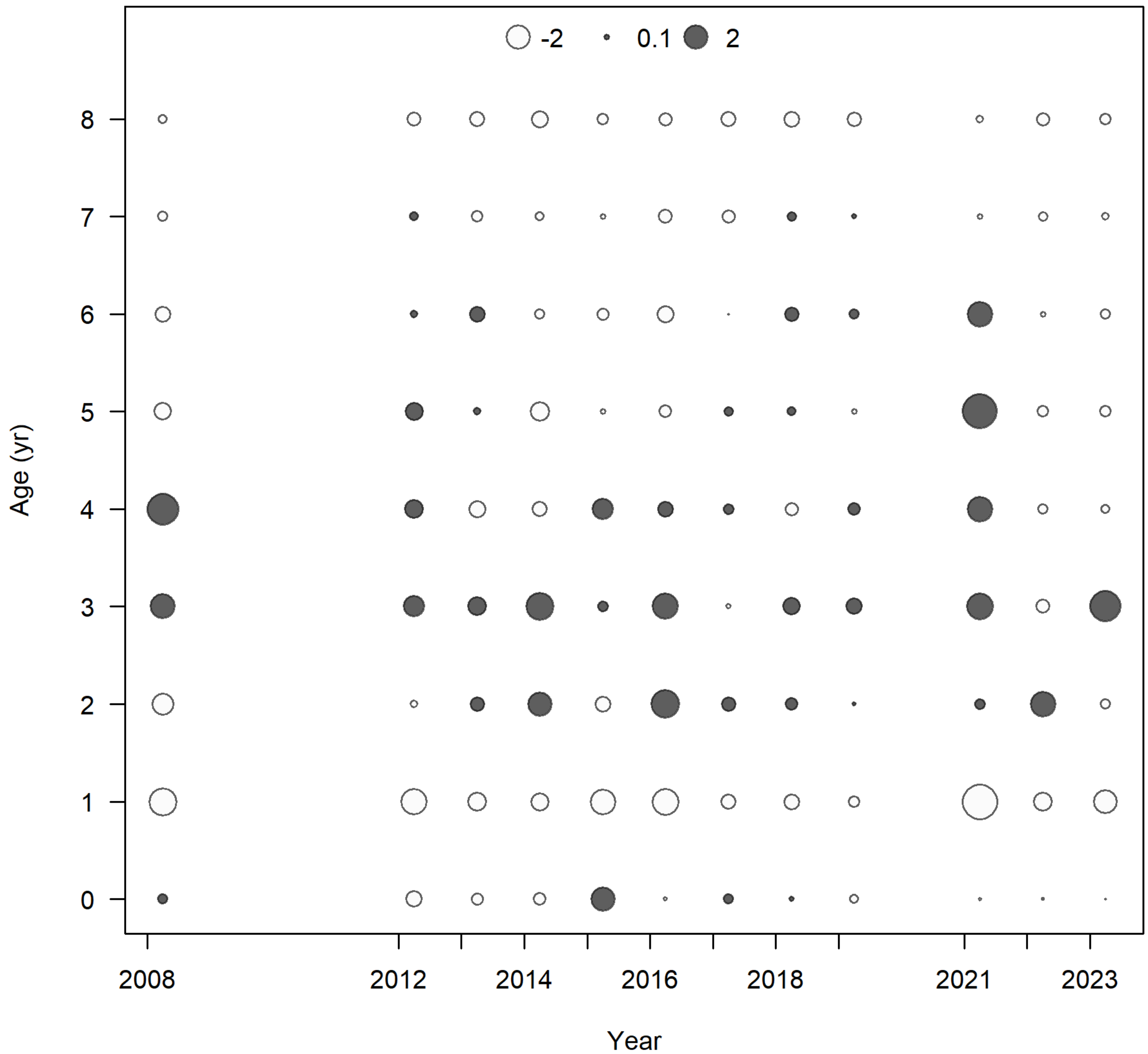

Figure 10.33: Residuals of the fit to the age-composition time series for the AT survey in the base model.

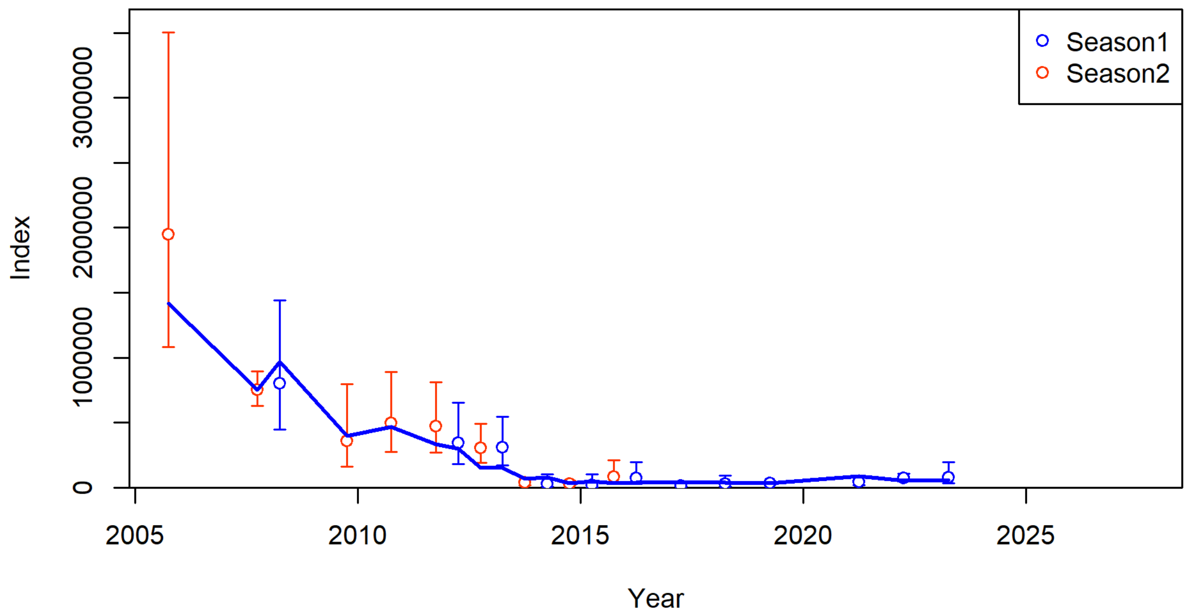

Figure 10.34: Fit to the index data for the AT survey. Lines indicate 95% uncertainty interval around index values.

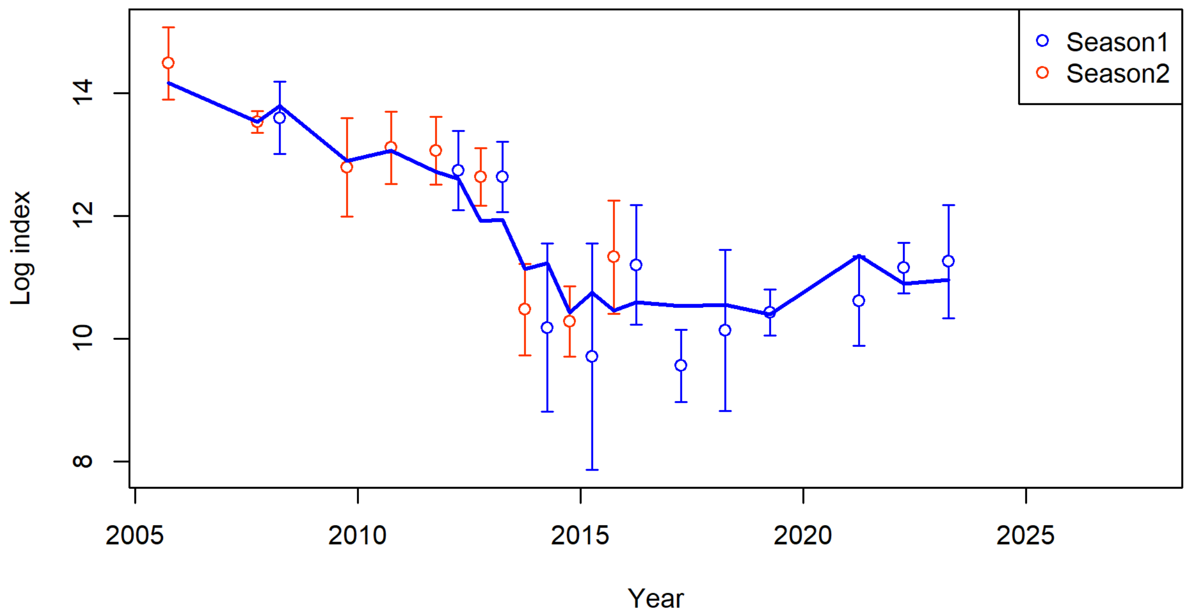

Figure 10.35: Fit to log-transformed index data for the AT survey. Lines indicate 95% uncertainty interval around index values.

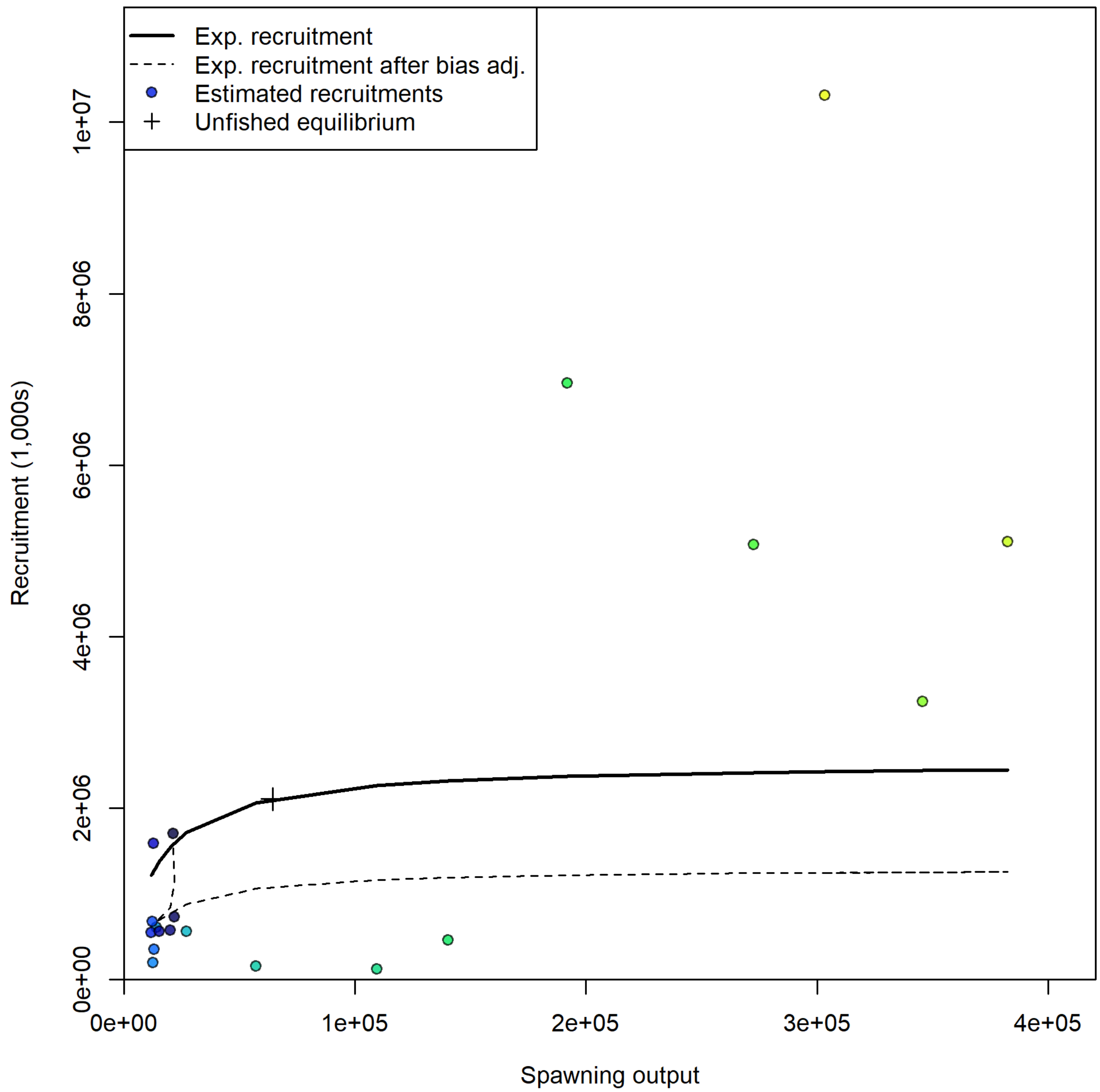

Figure 10.36: Estimated stock-recruitment (Beverton-Holt) relationship for the base model. Steepness is fixed ($h = 0.6$). Year labels represent the year of SSB producing the subsequent recruitment year class.

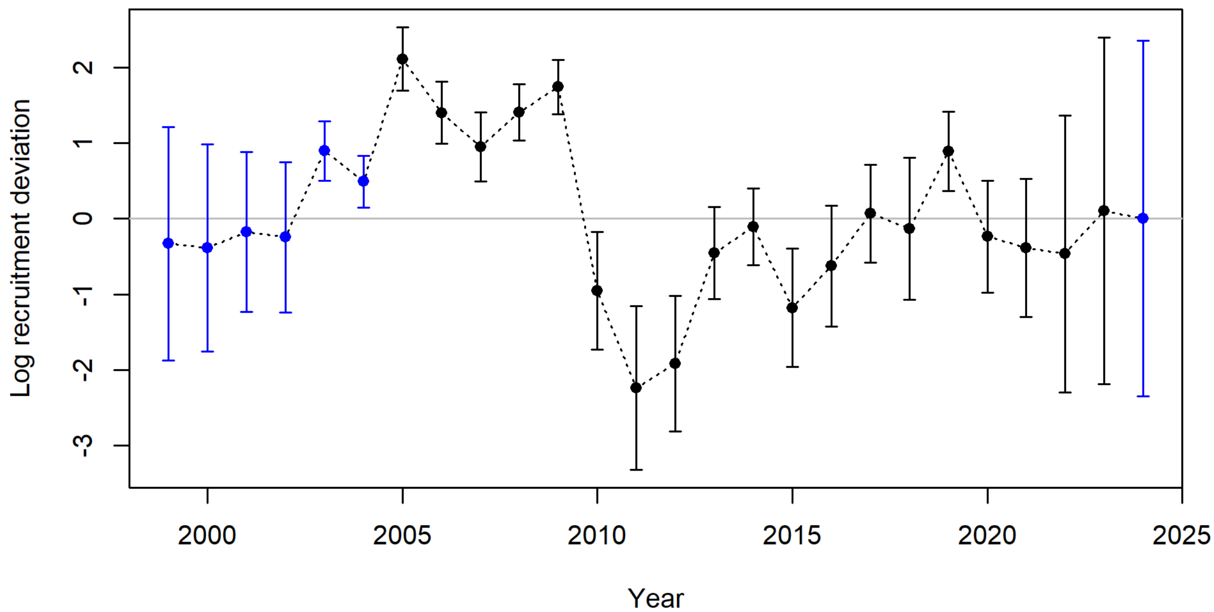

Figure 10.37: Recruitment deviations and standard errors (σ_R=1.2) for the base model.

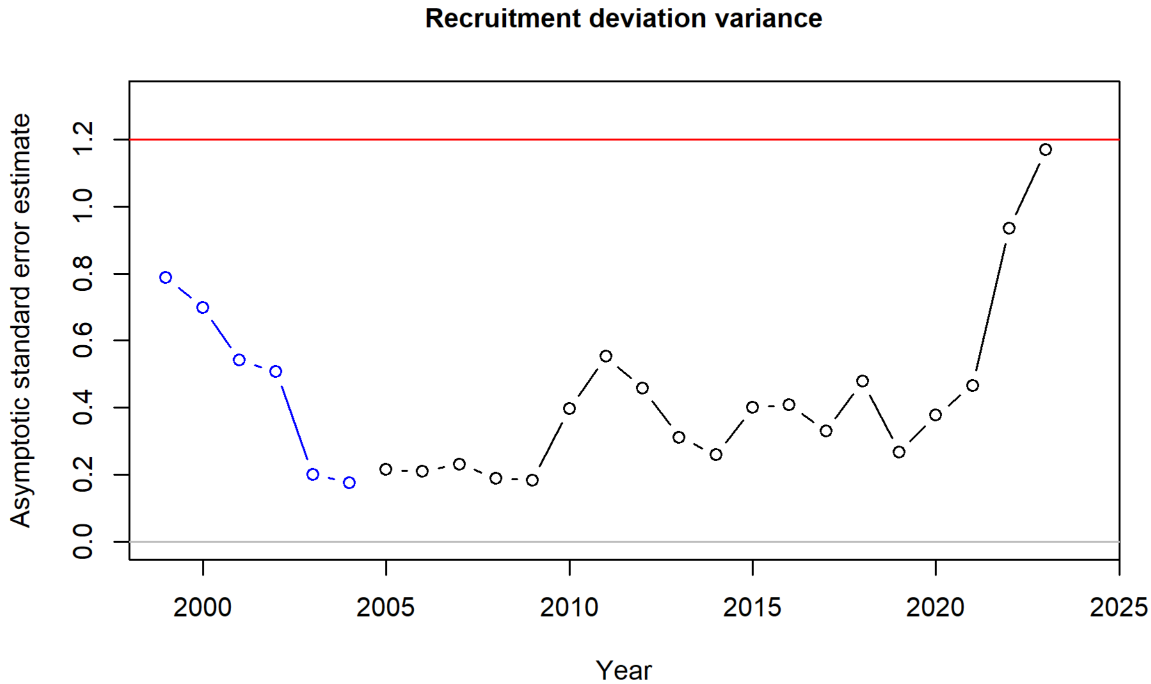

Figure 10.38: Asymptotic standard errors for estimated recruitment deviations for the base model.

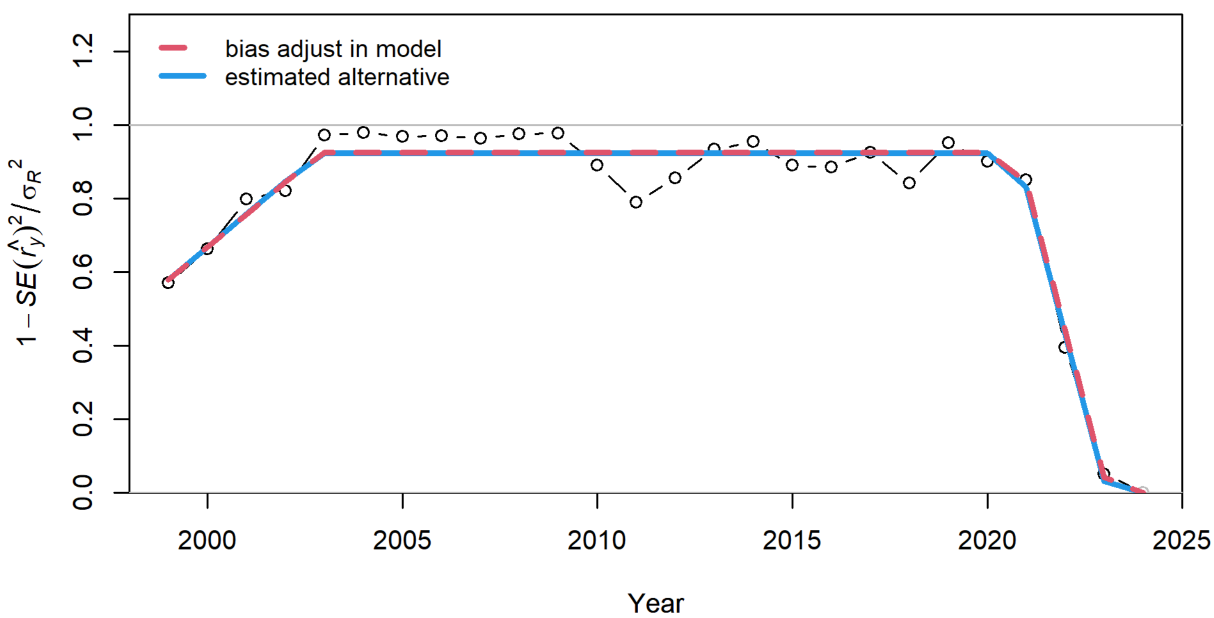

Figure 10.39: Recruitment bias adjustment plot for the early, main, and forecast periods in the base model.

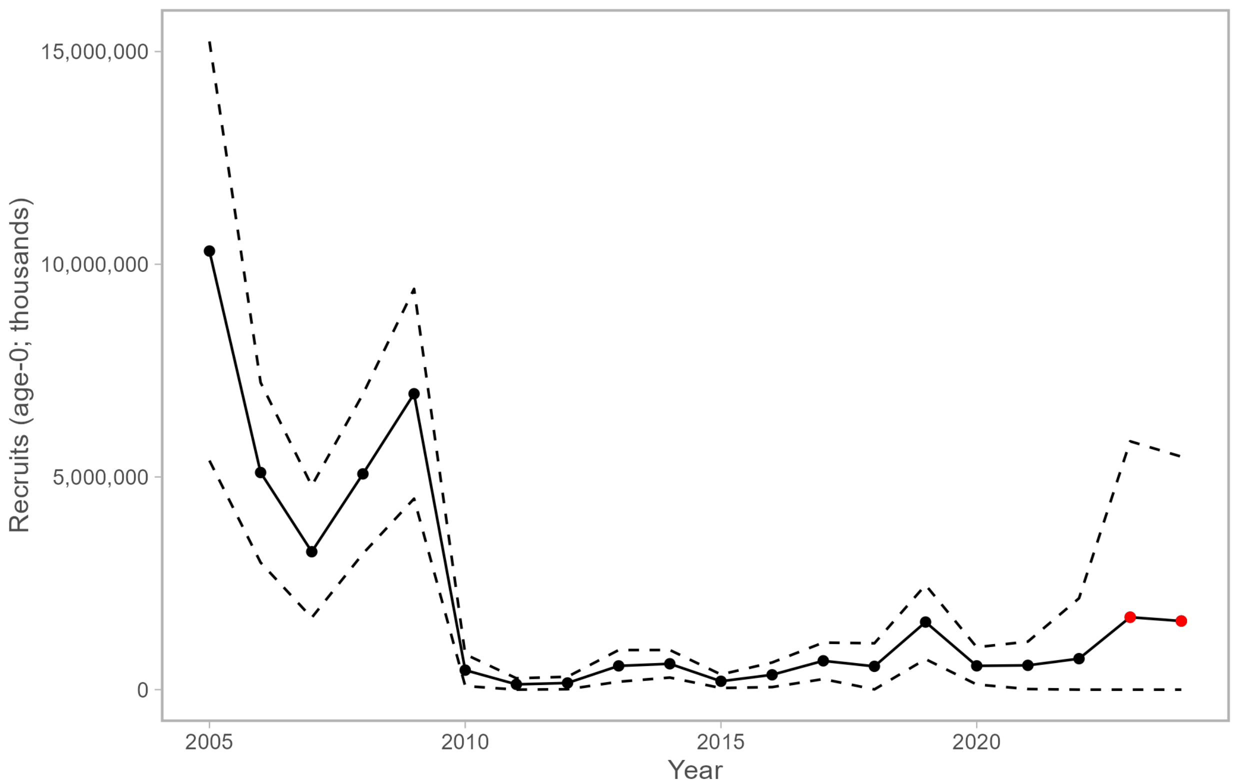

Figure 10.40: Estimated recruitment (age-0 fish, thousands) time series for the base model. Red points indicate values based on recruitment values from the stock-recruit relationship.

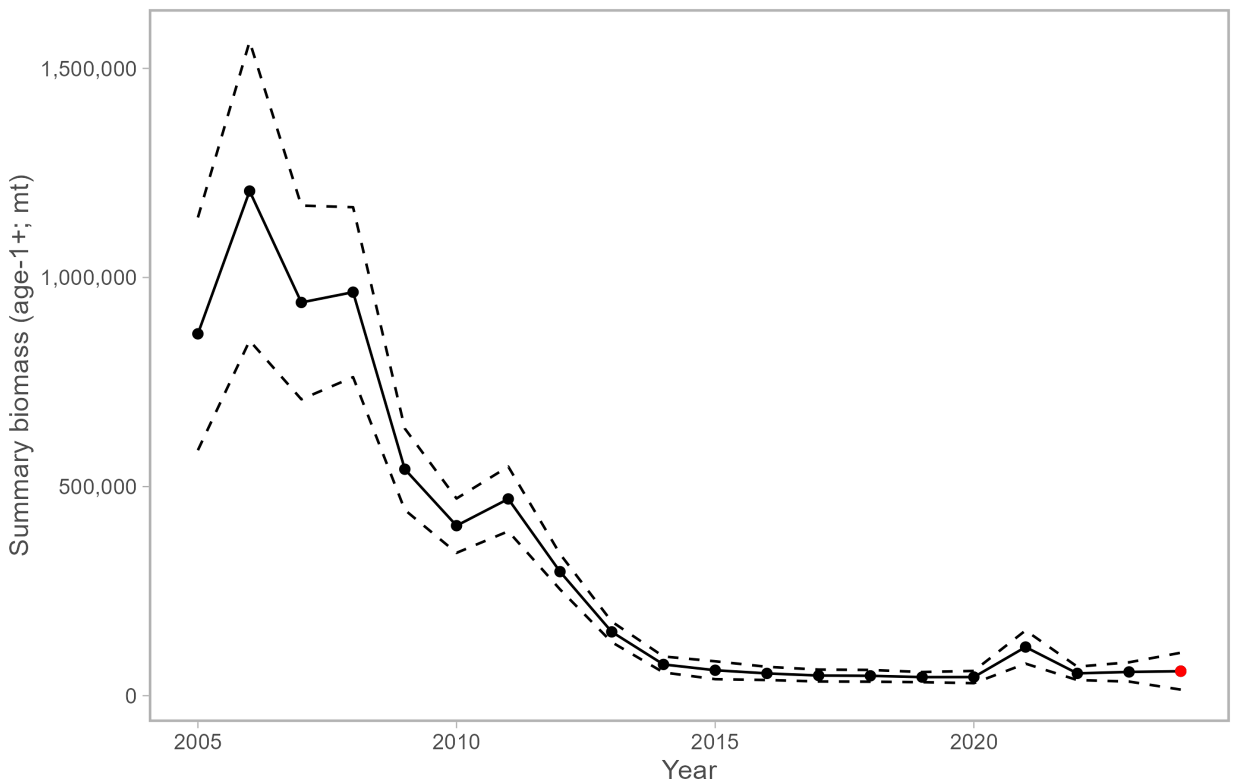

Figure 10.41: Summary (age-1+) biomass time series (95% CI dashed lines) for the base model. Red points indicate values based on recruitment values from the stock-recruit relationship.

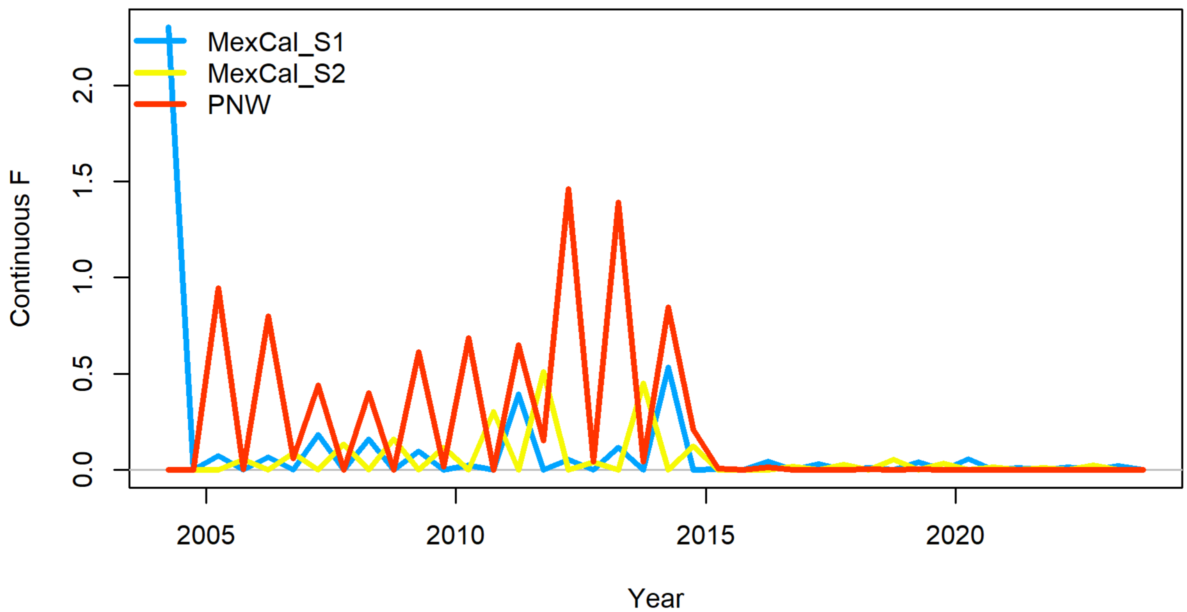

Figure 10.42: Instantaneous fishing mortality (apical F) time series for the base model.

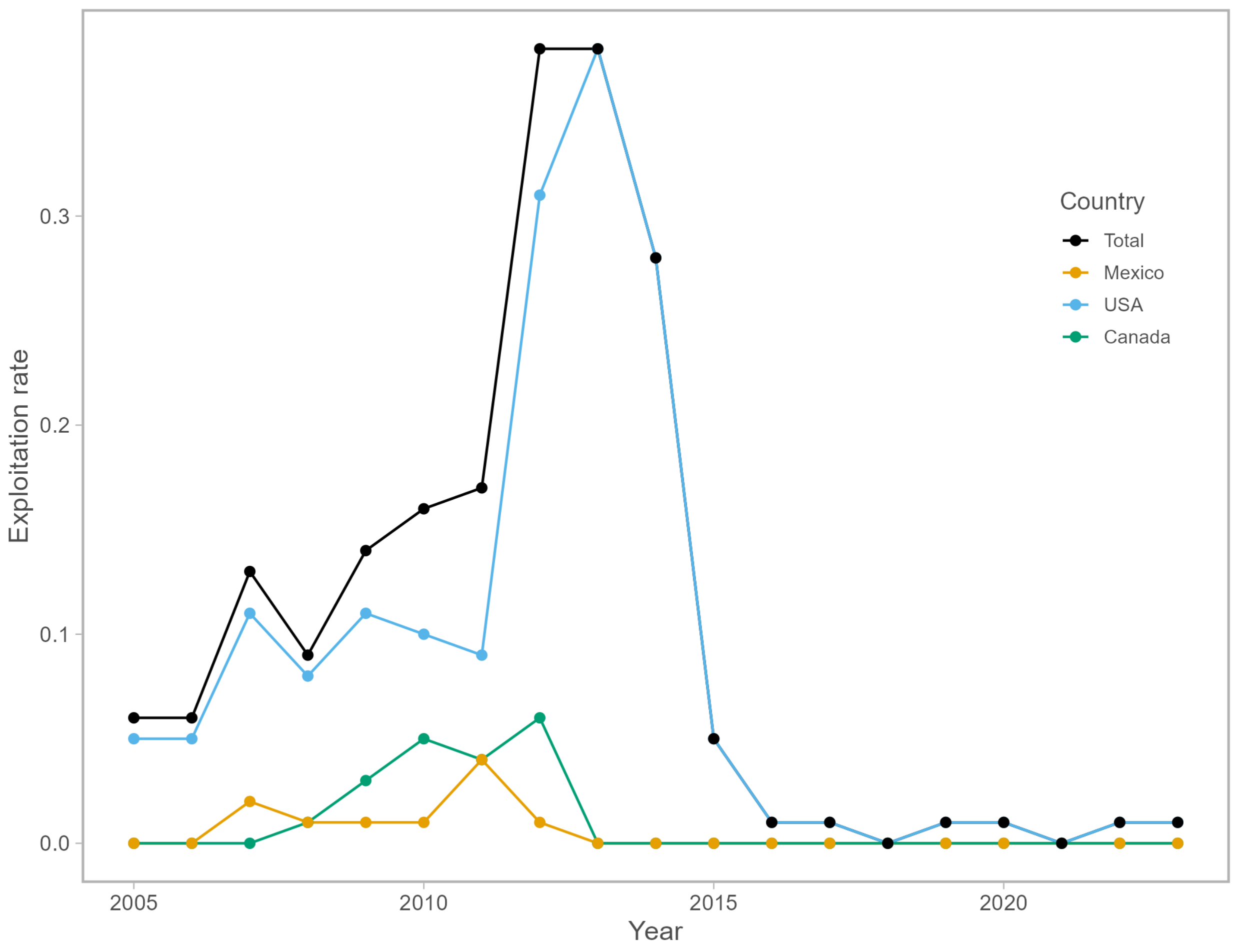

Figure 10.43: Annual exploitation rates (calendar year landings / July total biomass) for the base model.

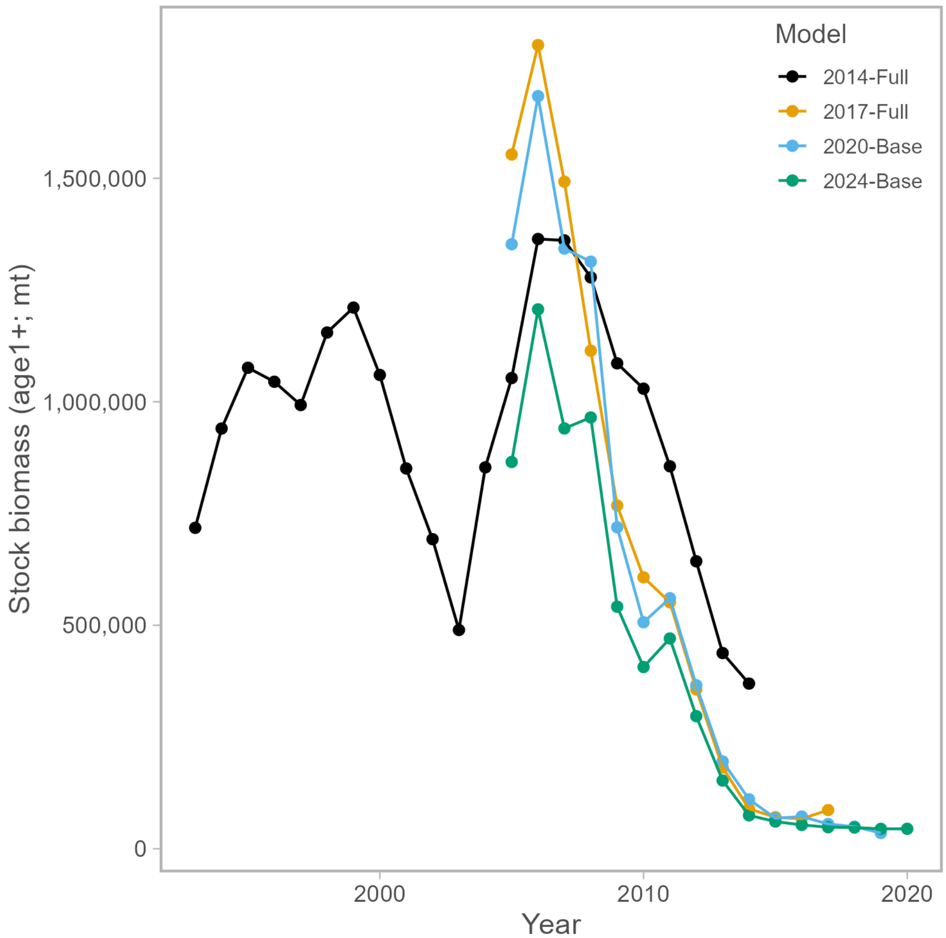

Figure 10.44: Estimated stock biomass (age 1+, mt) time series for the current base model and past assessment models used for management. It is not possible to compare uncertainties around these estimates as SS only added this option in 2022.

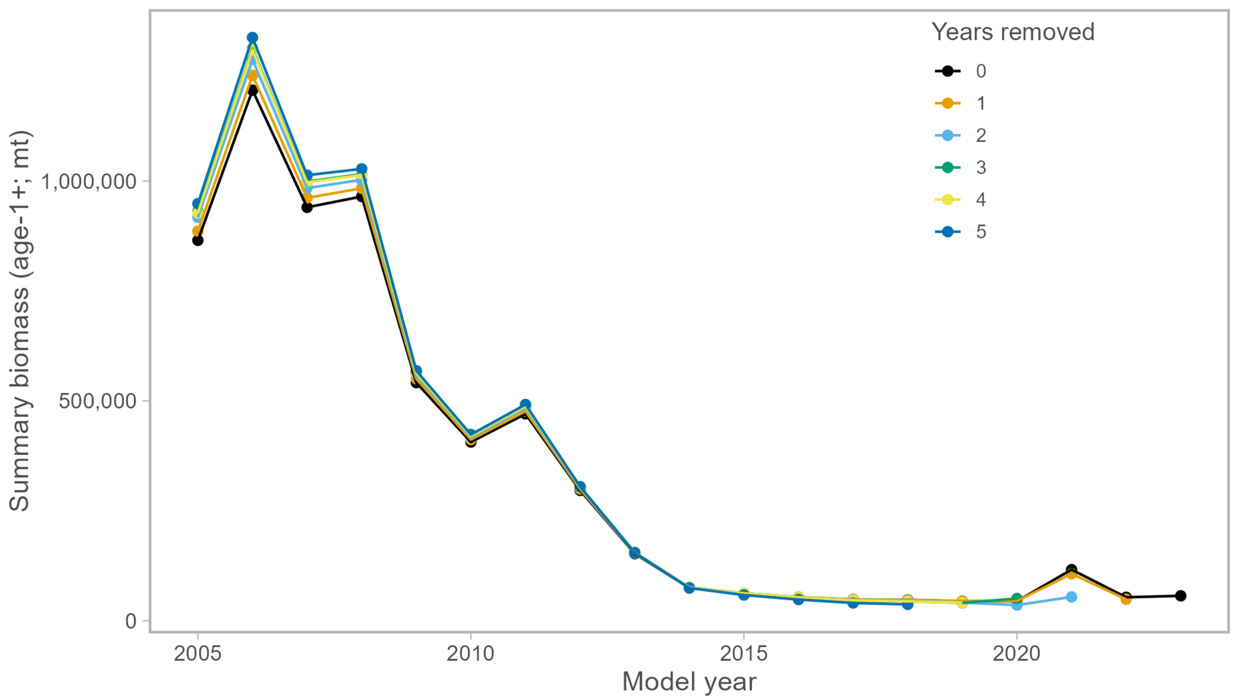

Figure 10.45: Retrospective analysis of summary biomass estimates. One year of data is removed for each model run.

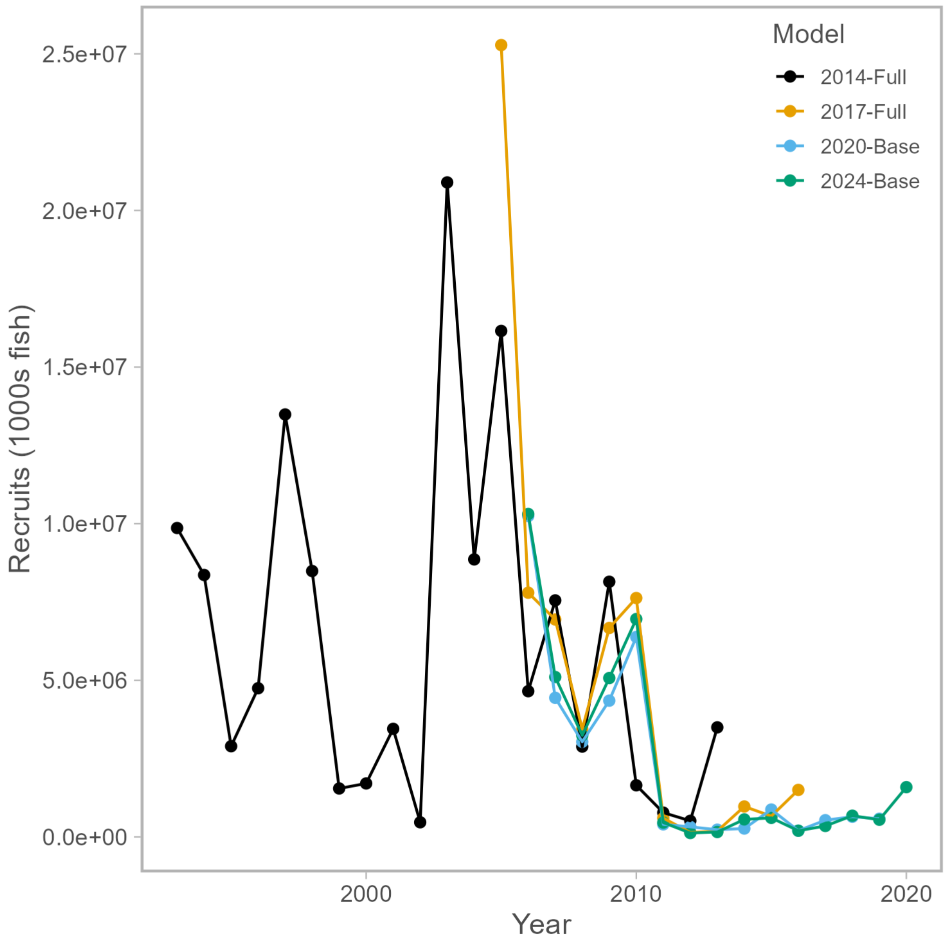

Figure 10.46: Estimated recruits (age-0) time series for this base model and past assessment models used for management.

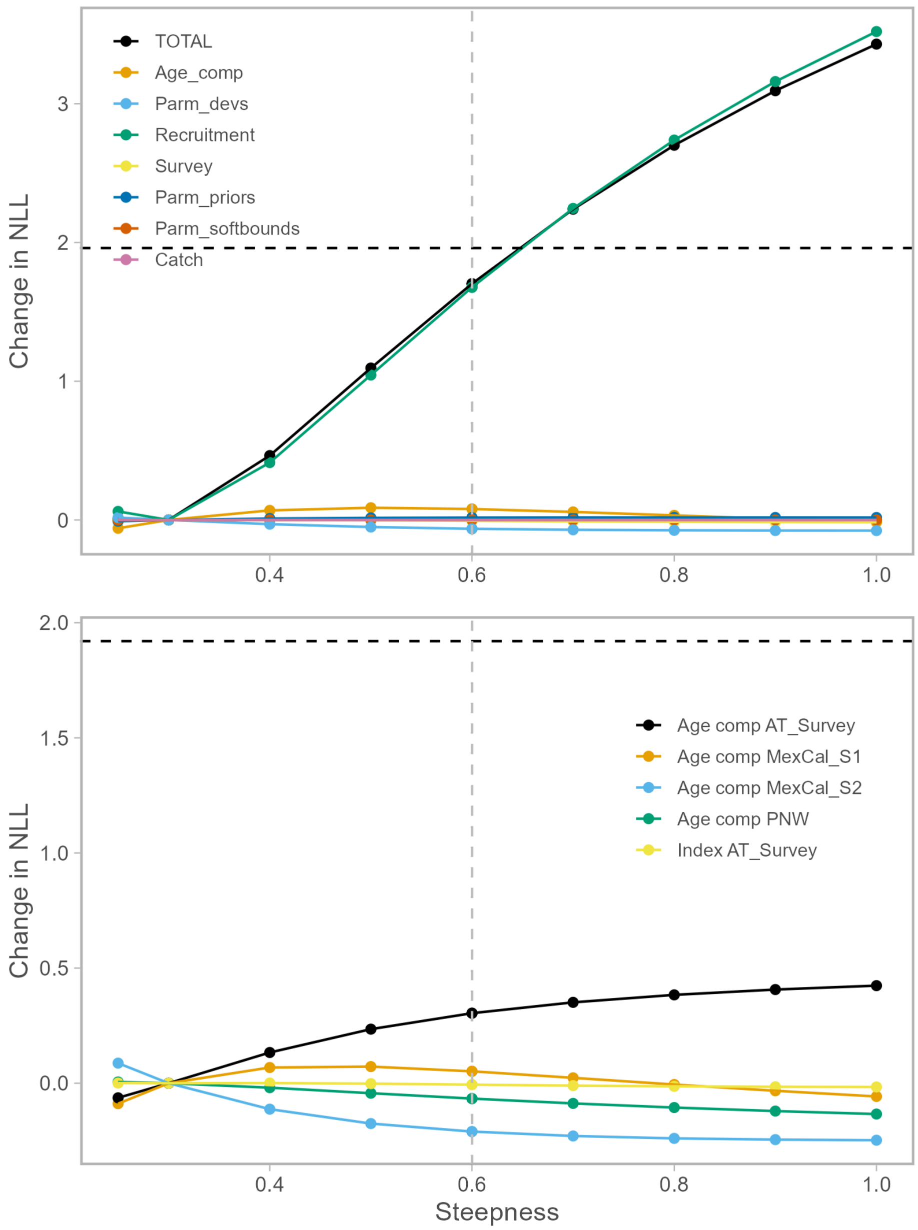

Figure 10.47: Likelihood profile across fixed values of steepness (h) for likelihood components (top plot) and fleet-specific likelihood components (bottom). Steepness was fixed at 0.6 in the 2024 base model (vertical dashed line). Values within 1.92 units of the MLE (dashed horizontal line) are within the 95% confidence interval.

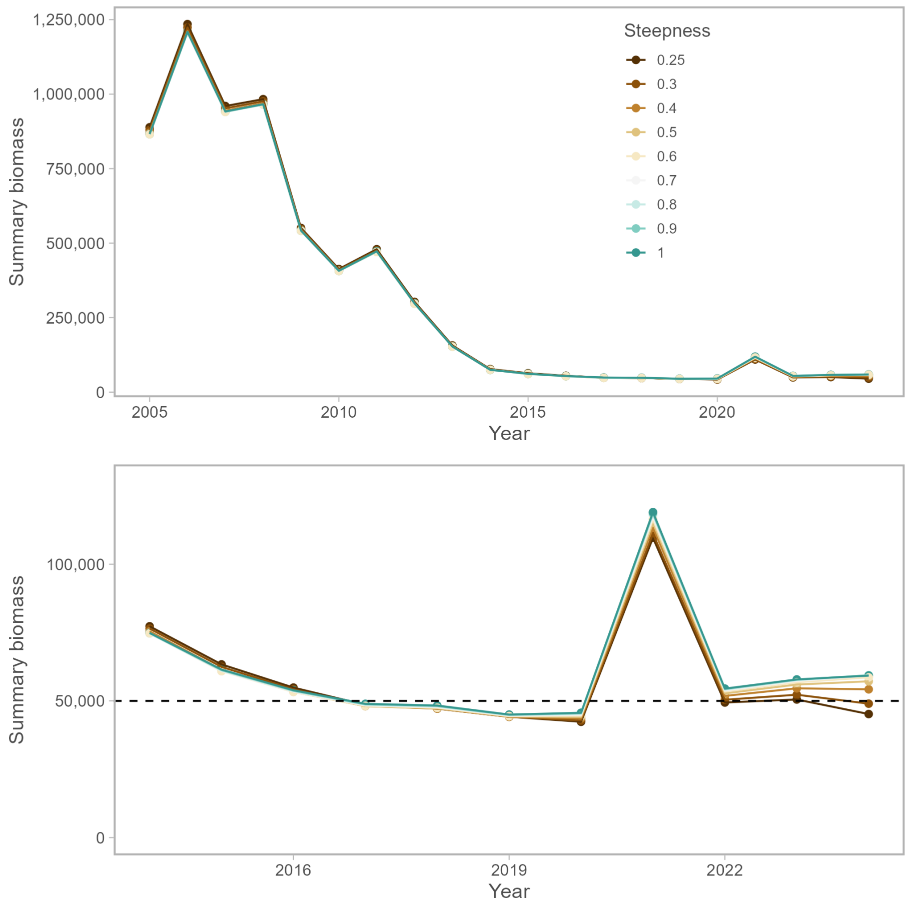

Figure 10.48: Summary biomass (age-1+; mt) estimates from models with fixed values of steepness (h) ranging from 0.25 to 1.

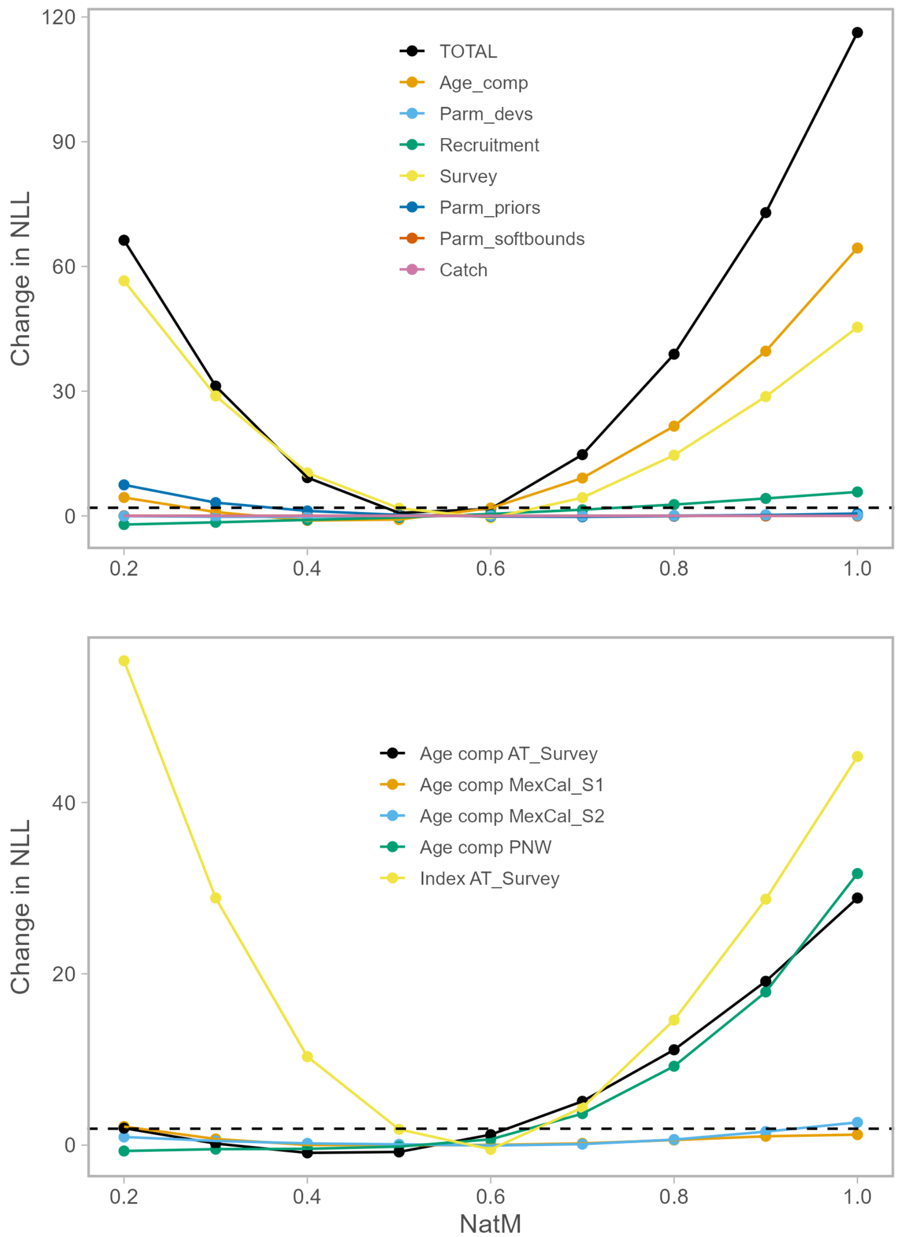

Figure 10.49: Likelihood profile across fixed values of natural mortality ranging from 0.2 to 1 yr^{-1} and fixed steepness (h) at 0.6 for likelihood components (top plot) and fleet-specific likelihood components (bottom). Values within 1.92 units of the MLE (dashed horizontal line) are within the 95% confidence interval.

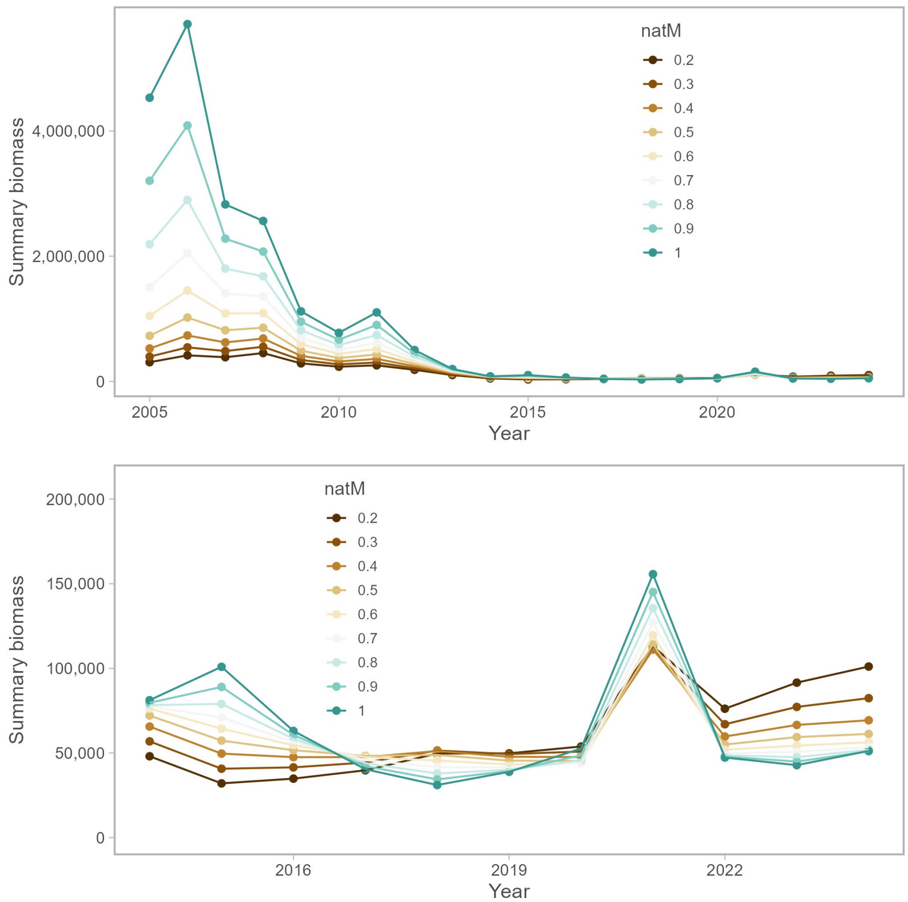

Figure 10.50: Summary biomass (age-1+; mt) estimates from models with fixed values of natural mortality (M) ranging from 0.2 to 1 yr^{-1} and fixed steepness (h) at 0.6.

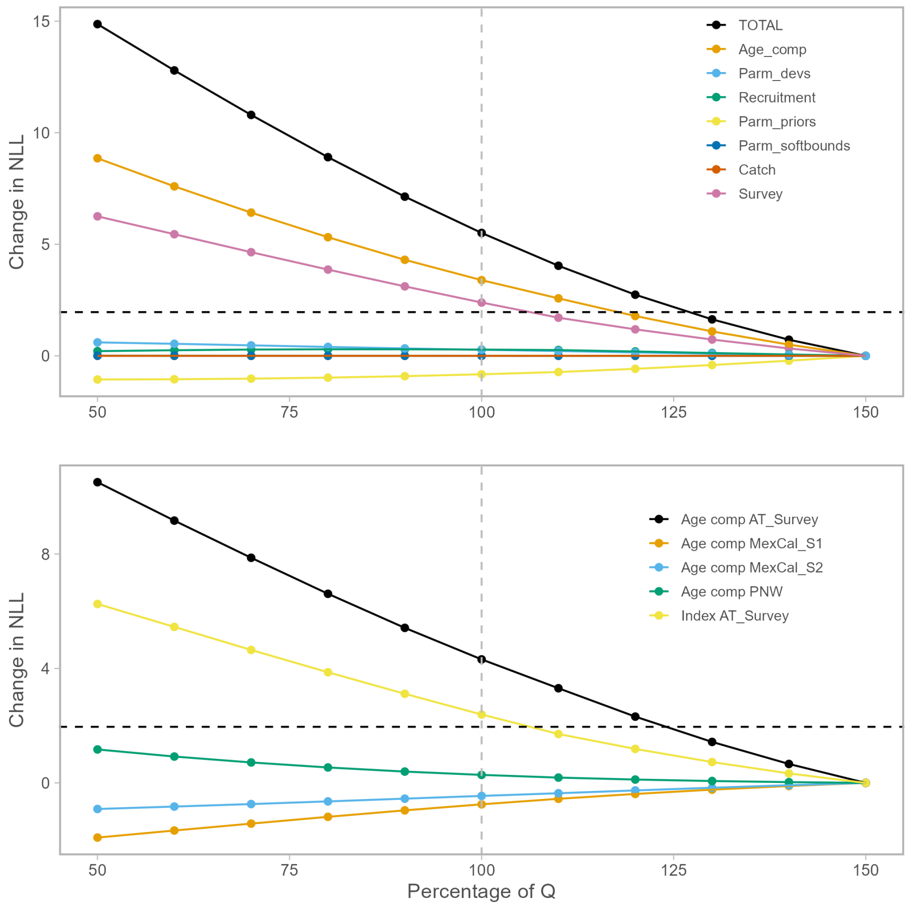

Figure 10.51: Likelihood profile across percentage adjustments to catchability values q ranging from 50% to 150%. Values within 1.92 units of the MLE (dashed horizontal line) are within the 95% confidence interval.

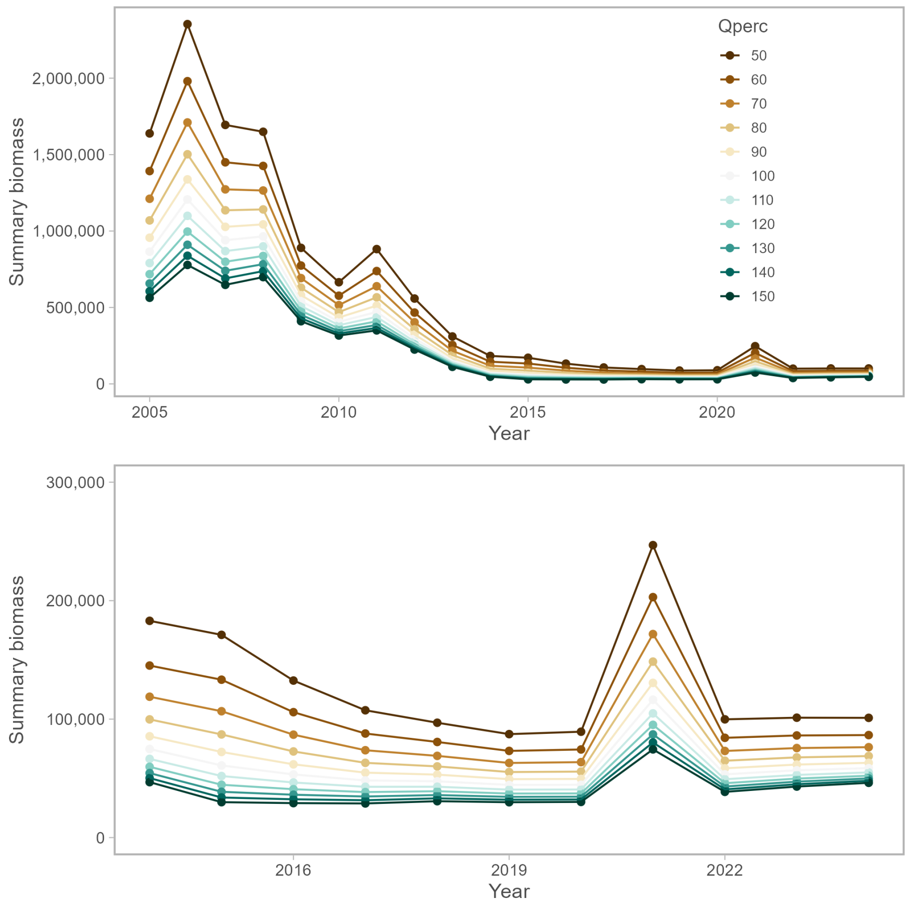

Figure 10.52: Summary biomass (age-1+; mt) estimates from models with catchability (q) values ranging from 50% to 150%

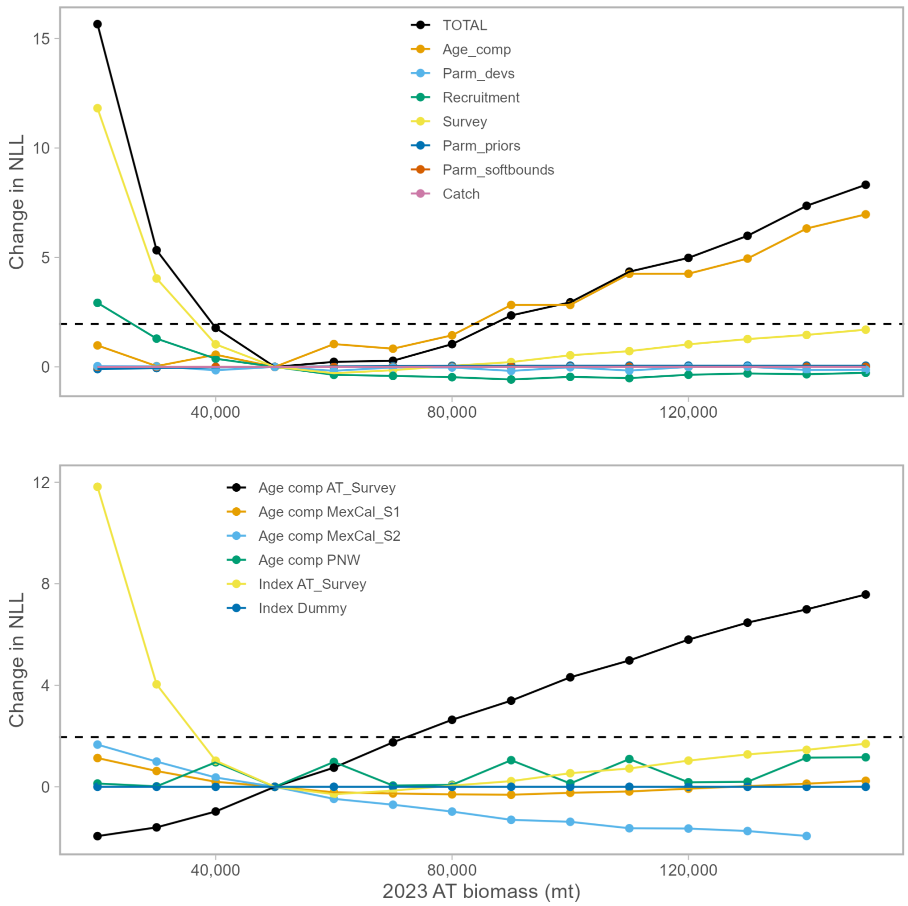

Figure 10.53: Likelihood profile across terminal year survey biomass values ranging from 20,000 to 150,000 mt. These biomass values were added as an additional survey in the model. Values within 1.92 units of the MLE (dashed horizontal line) are within the 95% confidence interval.

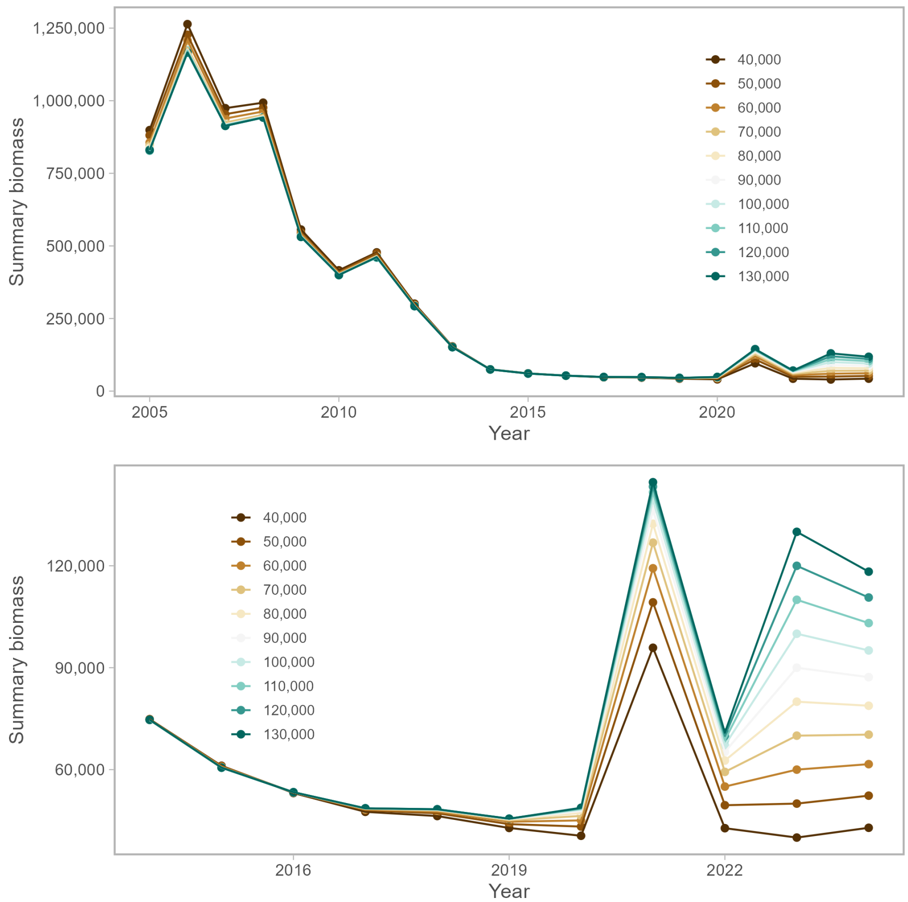

Figure 10.54: Summary biomass (age-1+; mt) estimates from models with terminal year biomass values ranging from 40,000 to 130,000 mt. Note that the range of biomass values does not include 20,000; 30,000; 140,000; nor 150,000 mt due to insufficient colors to plot in the R software.

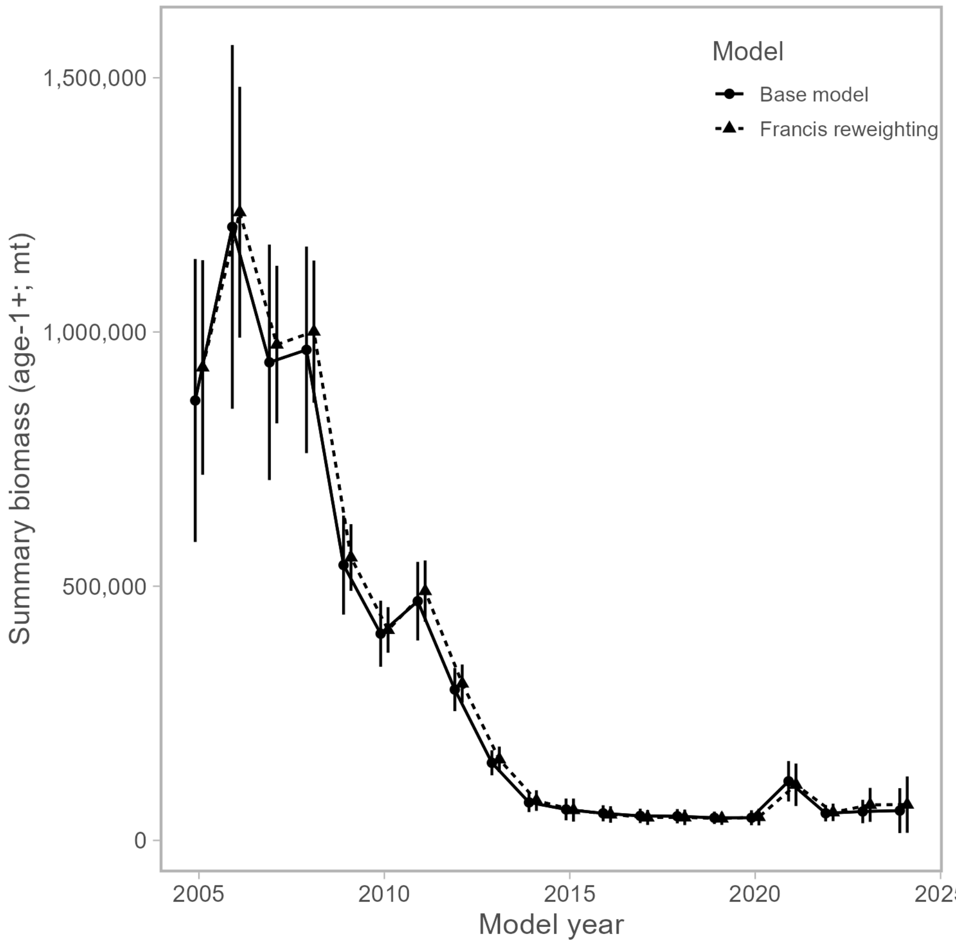

Figure 10.55: Age-1+ summary biomass (mt) values estimated from the base model (solid line) and the model with Francis reweighting (dashed line) for the age-composition data for the fishing fleets and the AT survey.

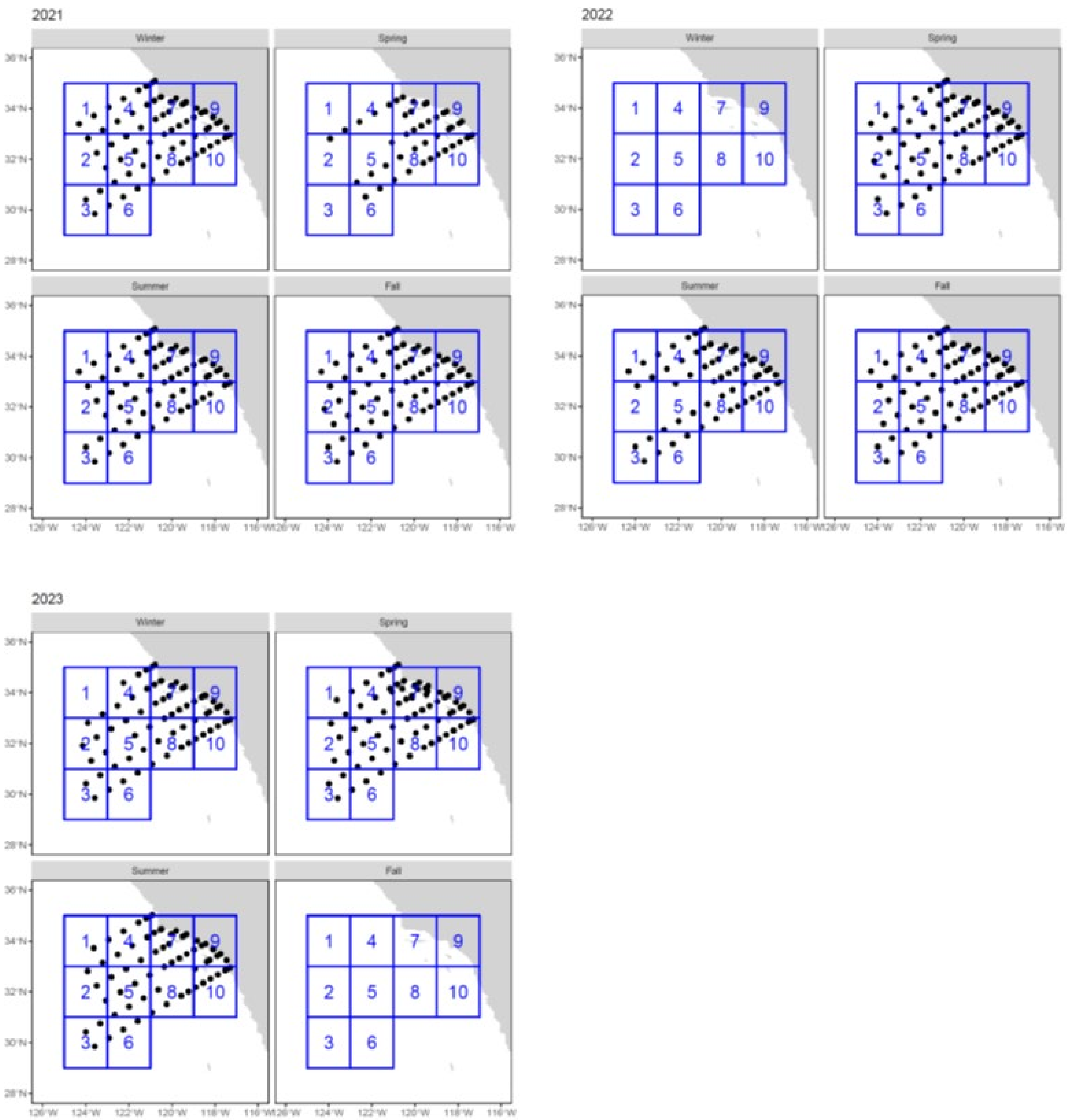

Figure 10.56: Quarterly CalCOFI survey sample coverage (black points) and ERSST grid (blue) for 2021-2023.

11 Appendix A: 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 currently not possible to calculate Pacific sardine and Japanese sardine biomass estimates separately using AT survey data. We present an illustrative and exploratory 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 reduces the 2023 biomass estimate of 77,252 mt by 30%. The resulting biomass estimate was 54,076 mt, and we assumed that Q for the survey remains at 1. The figure below shows the summary biomass (age-1+; mt) estimates from this run. This is just one coarse way to account for Japanese sardine and is not necessarily endorsed by the STAT.

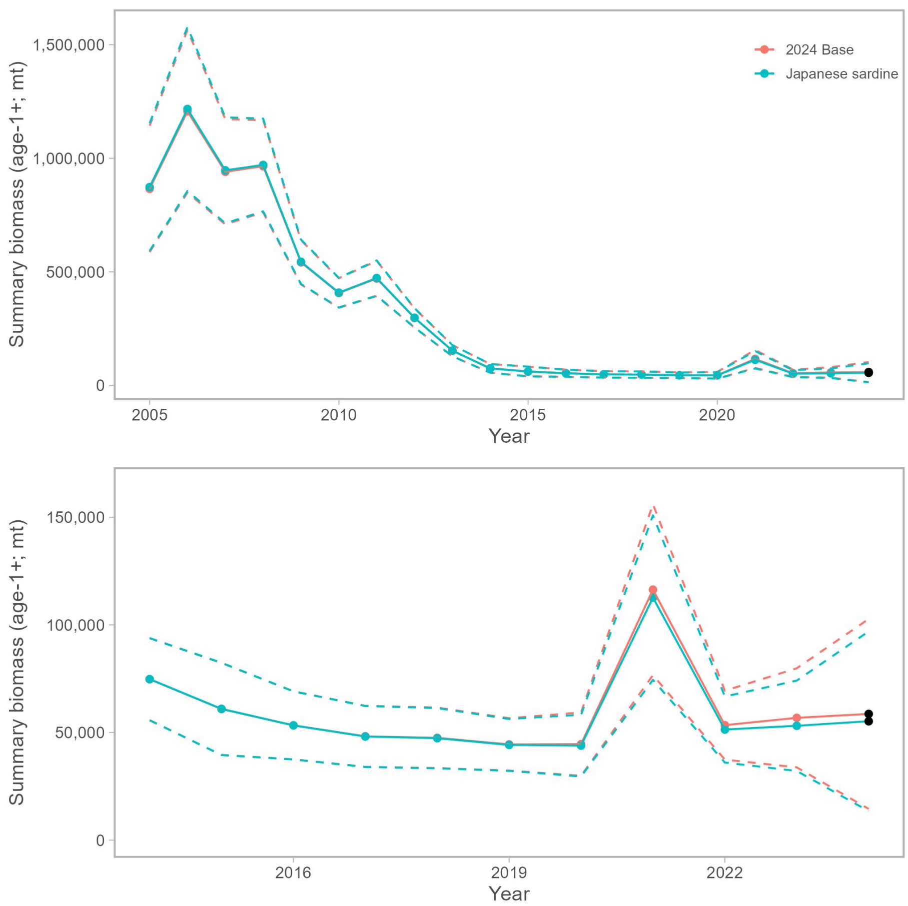

Figure 11.1: Summary biomass (age-1+; mt) estimates from the base model and a model run that accounts for Japanese sardine. The top panel shows the full time series, and the bottom panel shows the time series from 2014-2024.

12 Appendix B: Weight-at-age data update

The fishery empirical weights-at-age were updated in this 2024 benchmark to use conditional variance weight-at-age for the fishery data based on the methods described 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 Markov 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, the conditional weight-at-age variability parameterization was given the variability in the California Current conditions and natural fluctuations in the population weight-at-age through time. While the conditional variance approach 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 and cohort correlation parameters (Table 12.1); the MexCal season 2 (fleet 2) used year and age correlation parameters (Table 12.2); and the PNW (fleet 3) used year and cohort correlation parameters (Table 12.3). Note that due to the fishery closure in 2014, this model uses fishery data through 2014 and exempted fishing permit (EFP) data for the remaining years. We compared the resulting weight-at-age matrices to those used in the 2020 benchmark (Figure 12.1).

We identified several necessary adjustments when comparing the resulting weight-at-age matrices to those used in 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 weights for age-0 sardine. We anchored the model by filling the missing PNW age-0 weights with the overall mean age-0 weights for 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 this update, we re-ran the model and model selection (Figures 12.2 - 12.4). The model parameter configurations selected by fleet did not change (Tables 12.1 - 12.3). 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 and the STAR panel agreed, given that it is a more intentional implementation of weight-at-age compared with previous methods for deriving empirical weight-at-age which applied ad-hoc adjustments to individual years in the past.

12.1 Tables and figures

Table 12.1: MexCal S1 conditional weight-at-age model results.

Model	Parameter	Parameter estimate	St dev	AIC	dAIC	Pos-def Hessian
None	rho_a			9.37	-17.31	TRUE
None	rho_c			9.37	-17.31	TRUE
None	rho_y			9.37	-17.31	TRUE
None	log_sigma2	0.06	0.18	9.37	-17.31	TRUE
a	rho_a	0.26	0.13	7.71	-15.65	TRUE
a	rho_c			7.71	-15.65	TRUE
a	rho_y			7.71	-15.65	TRUE
a	log_sigma2	0.06	0.18	7.71	-15.65	TRUE
c	rho_a			84.04	-91.98	FALSE
c	rho_c	1.09	0.12	84.04	-91.98	FALSE
c	rho_y			84.04	-91.98	FALSE
c	log_sigma2	0.19	0.18	84.04	-91.98	FALSE
a_c	rho_a	0.10	0.12	-2.84	-5.10	TRUE
a_c	rho_c	0.57	0.14	-2.84	-5.10	TRUE
a_c	rho_y			-2.84	-5.10	TRUE
a_c	log_sigma2	0.04	0.18	-2.84	-5.10	TRUE
y	rho_a			-3.48	-4.46	TRUE
y	rho_c			-3.48	-4.46	TRUE
y	rho_y	0.54	0.13	-3.48	-4.46	TRUE
y	log_sigma2	0.05	0.18	-3.48	-4.46	TRUE
y_a	rho_a	0.26	0.12	-6.12	-1.81	TRUE
y_a	rho_c			-6.12	-1.81	TRUE
y_a	rho_y	0.51	0.12	-6.12	-1.81	TRUE
y_a	log_sigma2	0.04	0.18	-6.12	-1.81	TRUE
y_c	rho_a			-7.94	0.00	TRUE
y_c	rho_c	0.48	0.15	-7.94	0.00	TRUE
y_c	rho_y	0.31	0.13	-7.94	0.00	TRUE
y_c	log_sigma2	0.04	0.18	-7.94	0.00	TRUE
y_a_c	rho_a	0.14	0.13	-7.15	-0.78	TRUE
y_a_c	rho_c	0.40	0.18	-7.15	-0.78	TRUE
y_a_c	rho_y	0.34	0.14	-7.15	-0.78	TRUE
y_a_c	log_sigma2	0.04	0.18	-7.15	-0.78	TRUE

Table 12.2: MexCal S2 conditional weight-at-age model results.

Model	Parameter	Parameter estimate	St dev	AIC	dAIC	Pos-def Hessian
None	rho_a			-19.30	-33.56	TRUE
None	rho_c			-19.30	-33.56	TRUE
None	rho_y			-19.30	-33.56	TRUE
None	log_sigma2	0.04	0.16	-19.30	-33.56	TRUE
a	rho_a	0.23	0.13	-20.50	-32.35	TRUE
a	rho_c			-20.50	-32.35	TRUE
a	rho_y			-20.50	-32.35	TRUE
a	log_sigma2	0.04	0.16	-20.50	-32.35	TRUE
c	rho_a			-24.74	-28.12	TRUE
c	rho_c	0.38	0.14	-24.74	-28.12	TRUE
c	rho_y			-24.74	-28.12	TRUE
c	log_sigma2	0.04	0.16	-24.74	-28.12	TRUE
a_c	rho_a	0.06	0.15	-22.93	-29.93	TRUE
a_c	rho_c	0.35	0.16	-22.93	-29.93	TRUE
a_c	rho_y			-22.93	-29.93	TRUE
a_c	log_sigma2	0.04	0.16	-22.93	-29.93	TRUE
y	rho_a			-50.29	-2.57	TRUE
y	rho_c			-50.29	-2.57	TRUE
y	rho_y	0.69	0.11	-50.29	-2.57	TRUE
y	log_sigma2	0.03	0.17	-50.29	-2.57	TRUE
y_a	rho_a	0.14	0.11	-49.90	-2.95	TRUE
y_a	rho_c			-49.90	-2.95	TRUE
y_a	rho_y	0.67	0.11	-49.90	-2.95	TRUE
y_a	log_sigma2	0.03	0.17	-49.90	-2.95	TRUE
y_c	rho_a			-52.85	0.00	TRUE
y_c	rho_c	0.24	0.11	-52.85	0.00	TRUE
y_c	rho_y	0.64	0.10	-52.85	0.00	TRUE
y_c	log_sigma2	0.02	0.17	-52.85	0.00	TRUE
y_a_c	rho_a	0.01	0.13	-50.85	-2.00	TRUE
y_a_c	rho_c	0.24	0.14	-50.85	-2.00	TRUE
y_a_c	rho_y	0.64	0.10	-50.85	-2.00	TRUE
y_a_c	log_sigma2	0.02	0.17	-50.85	-2.00	TRUE

Table 12.3: PNW conditional weight-at-age model results.

Model	Parameter	Parameter estimate	St dev	AIC	dAIC	Pos-def Hessian
None	rho_a			-35.50	-86.23	TRUE
None	rho_c			-35.50	-86.23	TRUE
None	rho_y			-35.50	-86.23	TRUE
None	log_sigma2	0.03	0.15	-35.50	-86.23	TRUE
a	rho_a	0.67	0.11	-63.98	-57.75	TRUE
a	rho_c			-63.98	-57.75	TRUE
a	rho_y			-63.98	-57.75	TRUE
a	log_sigma2	0.02	0.15	-63.98	-57.75	TRUE
c	rho_a			-47.28	-74.46	FALSE
c	rho_c	0.88	0.08	-47.28	-74.46	FALSE
c	rho_y			-47.28	-74.46	FALSE
c	log_sigma2	0.02	0.16	-47.28	-74.46	FALSE
a_c	rho_a	0.19	0.14	-86.76	-34.97	TRUE
a_c	rho_c	0.66	0.12	-86.76	-34.97	TRUE
a_c	rho_y			-86.76	-34.97	TRUE
a_c	log_sigma2	0.02	0.15	-86.76	-34.97	TRUE
y	rho_a			-111.17	-10.56	TRUE
y	rho_c			-111.17	-10.56	TRUE
y	rho_y	0.83	0.07	-111.17	-10.56	TRUE
y	log_sigma2	0.01	0.16	-111.17	-10.56	TRUE
y_a	rho_a	0.28	0.08	-121.74	0.00	TRUE
y_a	rho_c			-121.74	0.00	TRUE
y_a	rho_y	0.70	0.07	-121.74	0.00	TRUE
y_a	log_sigma2	0.01	0.16	-121.74	0.00	TRUE
y_c	rho_a			-121.42	-0.32	TRUE
y_c	rho_c	0.33	0.10	-121.42	-0.32	TRUE
y_c	rho_y	0.63	0.09	-121.42	-0.32	TRUE
y_c	log_sigma2	0.01	0.16	-121.42	-0.32	TRUE
y_a_c	rho_a	0.16	0.12	-121.27	-0.47	TRUE
y_a_c	rho_c	0.18	0.15	-121.27	-0.47	TRUE
y_a_c	rho_y	0.64	0.09	-121.27	-0.47	TRUE
y_a_c	log_sigma2	0.01	0.16	-121.27	-0.47	TRUE

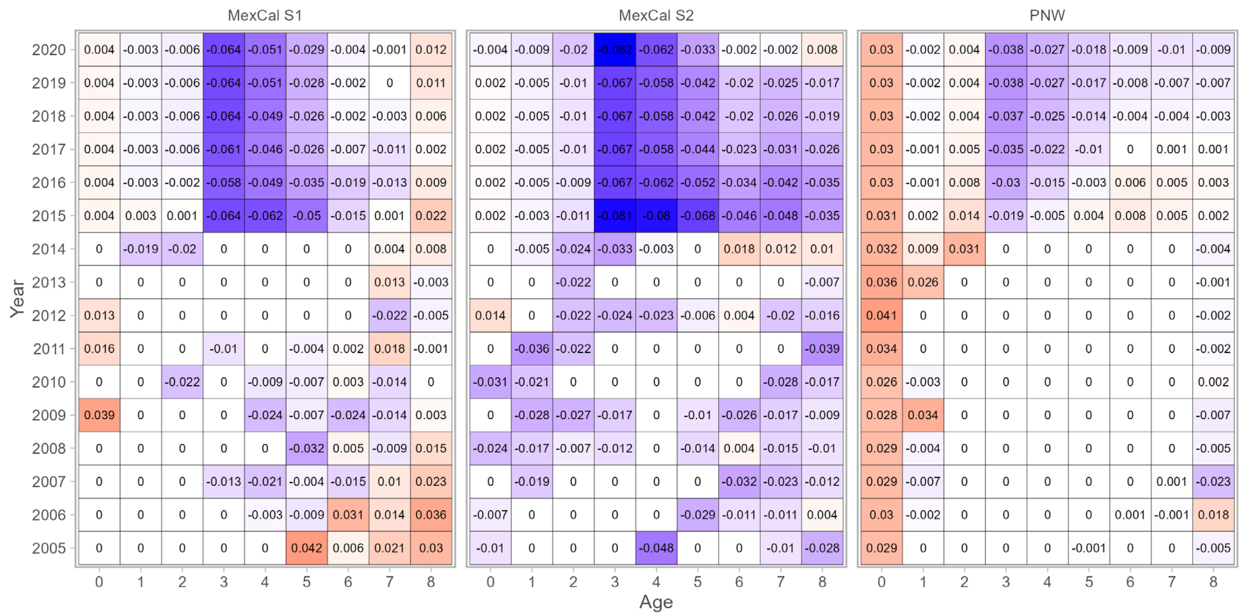

Figure 12.1: Comparison of the new weight-at-age values to those used in the 2020 benchmark assessment. The numbers represent the difference between the new and the old values. For example, 2009 weight-at-age for MexCal S1, age-0 was 0.039 kg larger than it was in the 2020 benchmark.

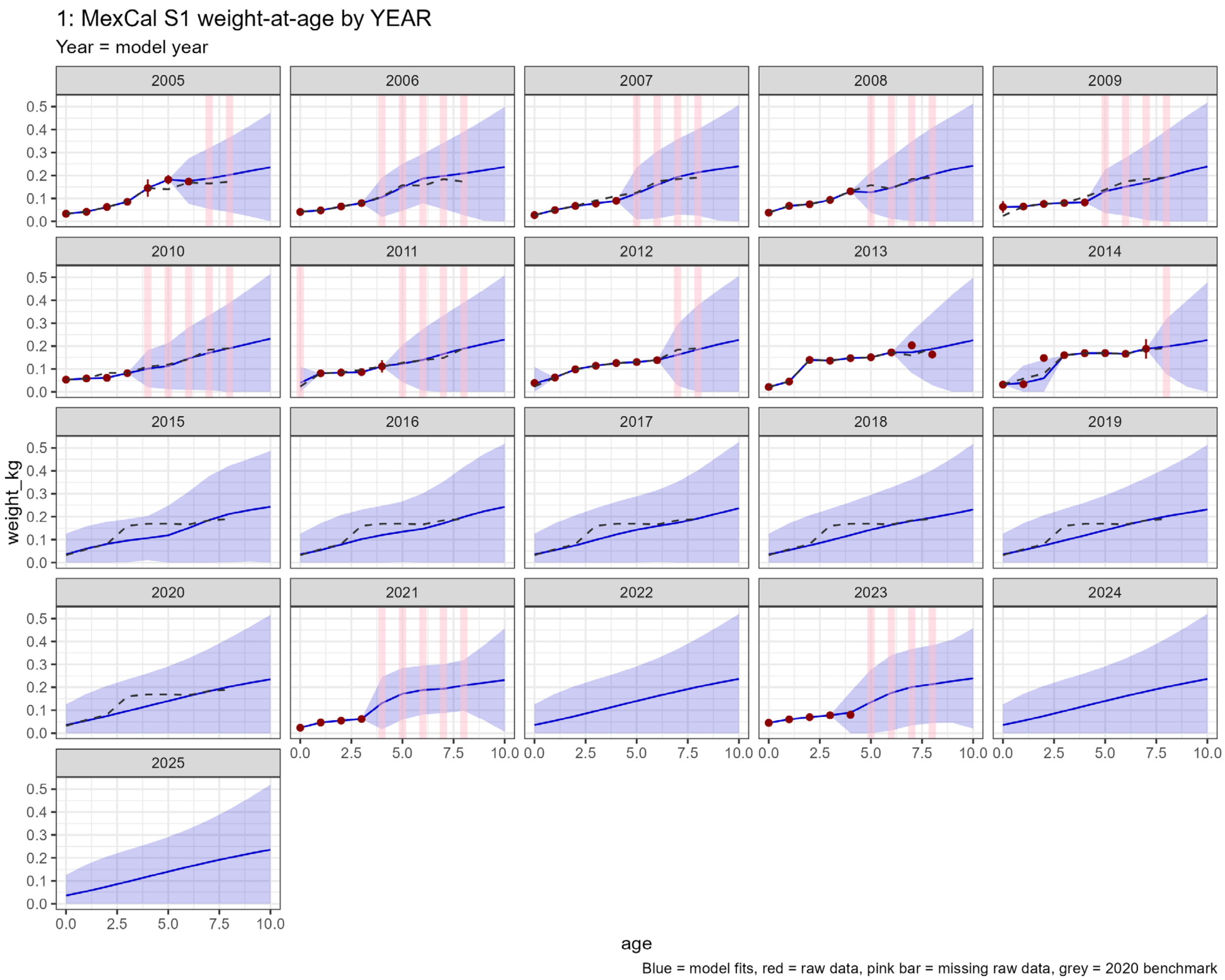

Figure 12.2: Comparison of the new weight-at-age values to those used in the 2020 benchmark assessment for MexCal S1. The vertical pink bars denote missing values and shading represents 95% confidence intervals.

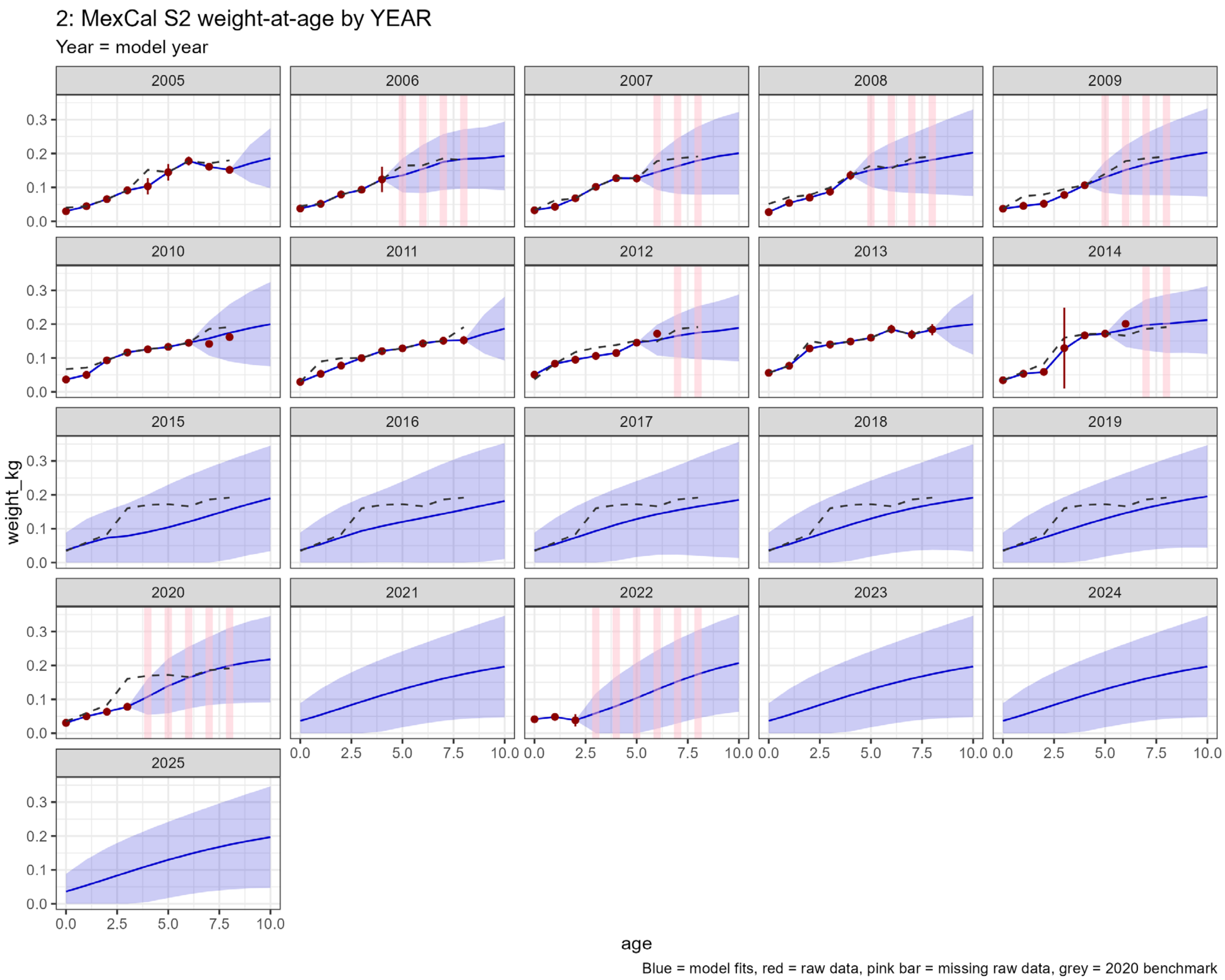

Figure 12.3: Comparison of the new weight-at-age values to the 2020 benchmark weight-at-age values used for MexCal S2. The vertical pink bars denote missing values and shading represents 95% confidence intervals.

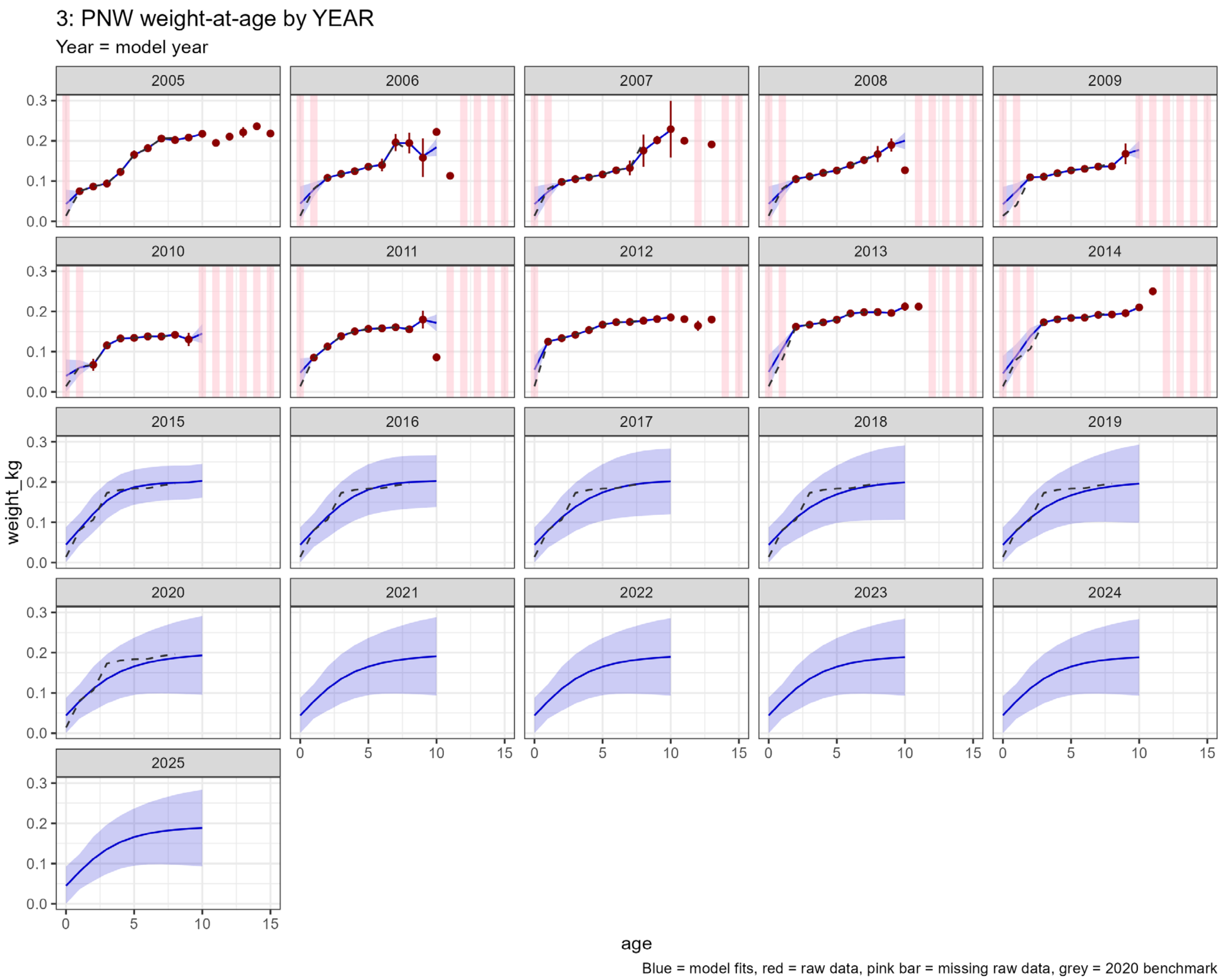

Figure 12.4: Comparison of the new weight-at-age values to the 2020 benchmark weight-at-age values used for the PNW fleet. The vertical pink bars denote missing values and shading represents 95% confidence intervals.

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

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Summary
We provide a summary report on the biological data (length, weight, and age) collected by surface trawl for the NSP 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 during 2021 and 2022.

Background
Stock assessments of Pacific sardine (*Sardinops sagax*) since 2004 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, 2011). The abundance of Pacific sardine 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. The Pacific Fishery Management Council prohibited directed fishing on Pacific sardine in 2015 due to low stock biomass. By 2019, the National Marine Fisheries Service declared the NSP (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).

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 since 2015. 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 duering 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 during 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 the sampled fish (maximum of 50 per haul). Hauls containing samples of Pacific sardine assigned to the NSP (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 13.1). 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*).

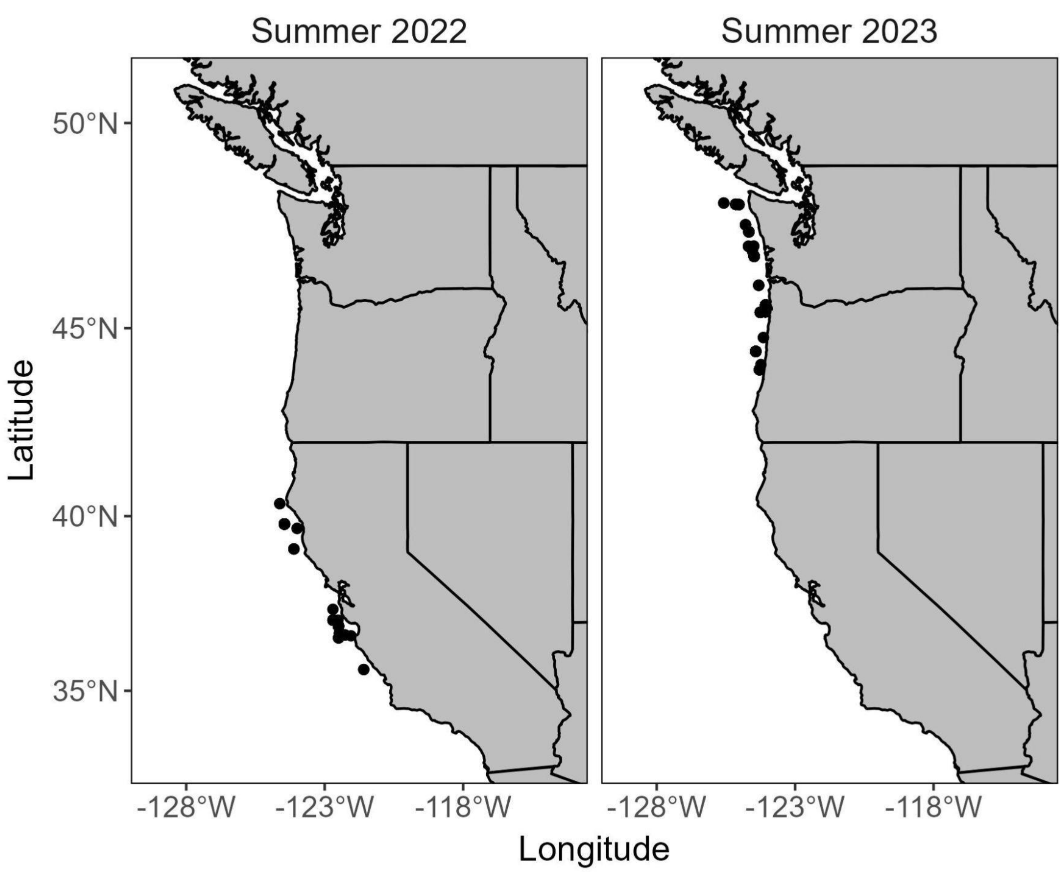

Figure 13.1: Spatial distribution of NSP Pacific sardine (*Sardinops sagax*) caught during the SWFSC AT surveys using surface trawl gear in 2022 and 2023. These maps do not represent the full extent of biosampling aboard NOAA vessels in each year.

Age-readings
NSP Pacific sardine collected during 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, 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 using the 2022 AT survey samples, increasing the sample size of double read otoliths to 130. We computed a new ageing error vector for 2021 and 2022 using this updated dataset. 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, 2022). We defined various model scenarios, including those involving models that assumed equal or unequal *SD*s among readers. As in previous assessments (e.g. Dorval *et al.* 2013), , Model C 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 NSP sampled in 2022. Sampled fish ranged in length from 110 mm to 205 mm SL (Figure 13.2A) and in weight from 15 to 103.5 g (Figure 13.2C). A total of 136 of those 171 fish were aged, and they ranged from 0 to 4 years old (Figure 13.2E). 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 NSP sampled during 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 13.2B), weighed 4 to 291.5 g (Figure 13.2D), and ranged in age from 0 to 5 years old (Figure 13.2F). Fish of age 0 and 3 dominated trawl samples in 2023, representing 38% and 25%, respectively (Figure 13.2F).

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 13.2B, 13.2D, and 13.2F). 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, *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 NSP Pacific sardine were collected from July to September, which is the typical timing of the AT survey.

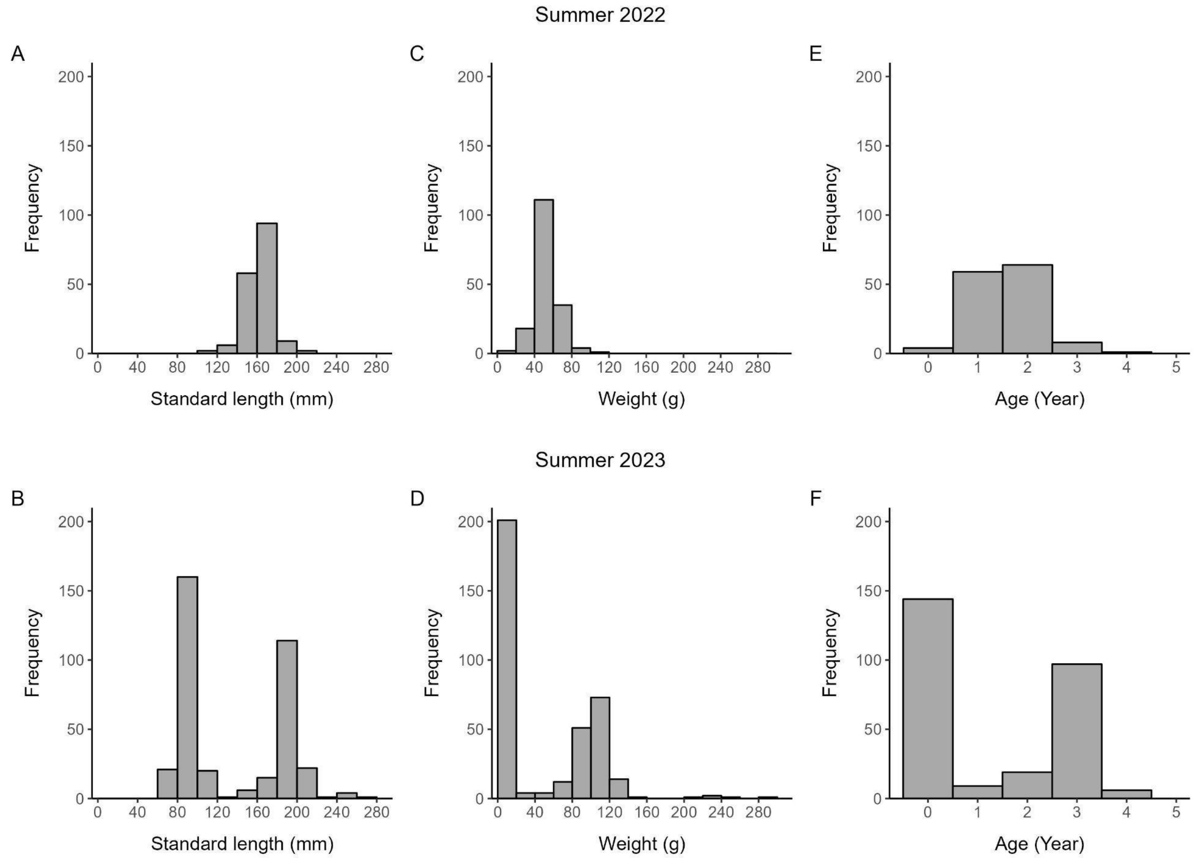

Figure 13.2: Distribution of lengths (A, B), weights (C, D), and ages (E, F) of NSP Pacific sardine (*Sardinops sagax)* collected during the 2022 and 2023 AT surveys.

Age-Reading Errors

A total of 130 otoliths were used to estimate age-reading error matrices for NSP Pacific sardine collected during 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 13.3). 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 13.1). As no double readings were conducted for Pacific sardine from the NSP collected during 2023, we recommend that the 2021-2022 *SD*-at-age vector be applied to the 2023 age data.

Table 13.1: Coefficient of variation (*CV*) and standard deviation (*SD*) at age estimated for NSP Pacific Sardine (*Sardinops sagax*) collected from the SWFSC AT survey during 2021 and 2022.

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

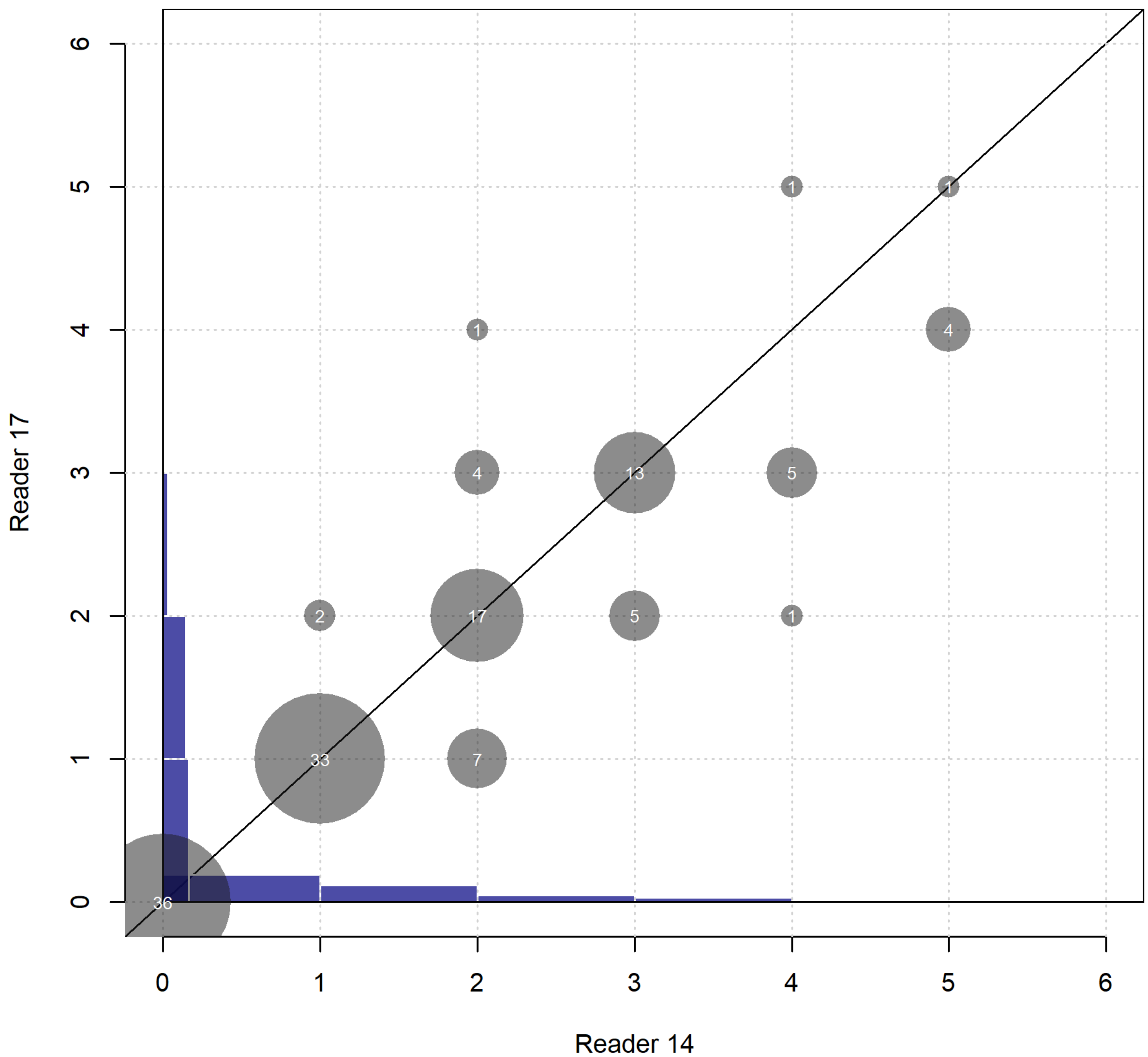

Figure 13.3: Age bias plots from the Agemat model for readers 14 and 17 for NSP Pacific sardine (*Sardinops sagax*) collected from SWFSC AT surveys in 2021 and 2022.

References

Dorval, E., Porzio, D., Schwartzkopf, B. D, James, K. C. Vasquez, L., and Erisman, B. 2022. Sampling methodology for estimating life history parameters of coastal pelagic species along the U.S. Pacific Coast. U.S. Dep. Commer., NOAA Tech. Memo., NMFS-SWFSC-660. 46 p.

Dorval, E., McDaniel, J. D., Porzio, D.L., Felix-Uraga, R., Hodes, V., and Rosenfield, S. 2013. Computing and selecting ageing errors to include in stock assessment models of Pacific sardine (*Sardinops sagax*). California Cooperative Oceanic Fisheries Investigative Reports 54:1–13.

Fitch, J. E. 1951. Age composition of the southern California catch of Pacific Mackerel 1939–40 through 1950–51. California Department of Fish and Game 83:1–73.

Hill, K. T., Crone, P. R., Demer, D. A., Zwolinski, J., Dorval, E., and Macewicz, B. J. 2014. Assessment of the Pacific sardine resource in 2014 for U.S.A. management in 2014-15. U.S. Dep. Commer., NOAA Tech. Memo., NOAA-SWFSC-531.

Hill, K. T., Crone, P. R., Lo, N. C. H., Macewicz, B. J., Dorval, E., McDaniel, J. D., and Gu, Y. 2011. Assessment of the Pacific sardine resource in 2011 for U.S. management in 2012. U.S. Dep. Commer., NOAA Tech. Memo., NOAA-SWFSC-487.

Hill, K. T., Dorval, E., Lo, N. C. H., Macewicz, B. J., Show, C., and Felix-Uraga, R. 2007. Assessment of the Pacific sardine resource in 2007 for U.S. Management in 2008. NOAA-SWFSC-413.

Kuriyama, P. T., Hill, K. T., and Zwolinski, J. P., 2022. Update assessment of the Pacific sardine resource in 2022 for U.S. management in 2022-2023. NOAA-SWFSC-662.

Kuriyama, P. T., Zwolinski, J. P., Hill, K. T., and Crone, P. R., 2020. Assessment of the Pacific sardine resource in 2020 for U.S. management in 2020-2021. NOAA-SWFSC-628

Punt, A. E., Smith, D. C., Krusisc Golub, K., and Robertson, S. 2008. Quantifying age-reading error for use in fisheries stock assessments, with application to species in Australia's southern and eastern scalefish and shark Fishery. Canadian Journal Fisheries and Aquatic Sciences 65:1991–2005.

PFMC (Pacific Fishery Management Council). 1998. Amendment 8 (to the northern anchovy fishery management plan) incorporating a name change to: the coastal pelagic species fishery management plan. Pacific Fishery Management Council, Portland, OR.

PFMC (Pacific fishery Management Council). 2021. Pacific sardine rebuilding plan, including rebuilding plan specification, final environmental assessment, and Magnuson-Stevens Fishery Conservation and Management Act analysis. Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 101, Portland, Oregon 97220-1384.

Renfree, J. S., Beittel, A., Bowlin, N. M., Erisman, B. E., James, K. C., Mau, S. A., Murfin, D.W., Sessions, T. S., Stierhoff, K. L., Vasquez, L., Watson, W., Zwolinski, J. P., and Demer, D. A. 2023. Report on the Summer 2022 California Current Ecosystem Survey (CCES) (2207RL), 27 June to 30 September 2022, conducted aboard NOAA ship Reuben Lasker, fishing vessels Lisa Marie and Long Beach Carnage, and uncrewed surface vehicles. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-SWFSC-678. https://doi.org/10.25923/66p9-hc28.

Renfree, J. S., Beittel, A., Bowlin, N. M., Erisman, B. E., Mau, S. A., Murfin, D. W., Schwartzkopf, B. D., Sessions, T. S., Stierhoff, K. L., Vasquez, L. Watson, W., Zwolinski, J. P., and Demer, D. A. *in prep*. Report on the Summer 2023 California Current Ecosystem Survey (CCES) (2307RL), 17 July to 3 November 2023, conducted aboard NOAA ships Reuben Lasker and Bell M. Shimada, fishing vessels Lisa Marie and Long Beach Carnage, and three uncrewed surface vehicles.

Thorson, J. T., Stewart, J. J., and Punt, A. E. 2012. nwfscAgeingError: a user interface in R for the Punt et al. (2008) method for calculating ageing error and imprecision. Available from: http://github.com/nwfsc-assess/nwfscAgeingError.

Yaremko, M. L. 1996. Age determination in Pacific sardine, *Sardinops sagax*. U.S. Dep. Commer., NOAA Tech. Memo., NMFS SWFSC-223.

Zwolinski, J. P., and Demer D. A. 2023. An updated model of potential habitat for northern stock Pacific Sardine (*Sardinops sagax*) and its use for attributing survey observations and fishery landings. Fisheries Oceanography, doi:10.1111/fog.12664.

14 Appendix D: Pacific sardine nearshore aerial biomass estimates in 2022 and 2023 for the 2024 stock assessment

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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 press). Survey regions are Northern California (NCA) between Point Arena and Port San Luis and Southern California (SCA) between Point Conception and San Diego (Figure 14.1). 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 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 (Figure 14.1). For southern California, some expansion strata were surveyed and the observed biomass was included in regional biomass estimates. Final survey region areas for each season are bounded by flown strata at either end. The survey region for the 2022 and 2023 SCA seasons was bounded by two strata, S1 and S6. There were only two flown strata for each season for 2022 and 2023 NCA seasons.

Scheduling of survey flights was designed to coincide in space and time as closely as possible with offshore acoustic-trawl (AT) surveys by the 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.

<u>Aerial Survey: 2022</u>
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 14.1). Biomass observed in each of these strata are shown in Table 14.1. Total nearshore biomass observed in SCA for this season was estimated to be 1,326 metric tons (mt)(Table 14.2).

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 14.1. The following SCA strata were then flown from August 28 to September 2: S3, S4, S4E, S1, S1E, S2, S5, and S6 (Table 14.1). Total nearshore biomass observed for SCA this season was estimated to be 24,401 mt (Table 14.2).

<u>Aerial Survey: 2023</u>
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 14.1). Nearshore biomass observed in SCA was estimated to be 11,083 mt (Table 14.2).

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 14.1). Nearshore biomass observed in SCA was estimated to be 10,085 mt (Table 14.2).

The survey then shifted to NCA, where only the 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 14.1.

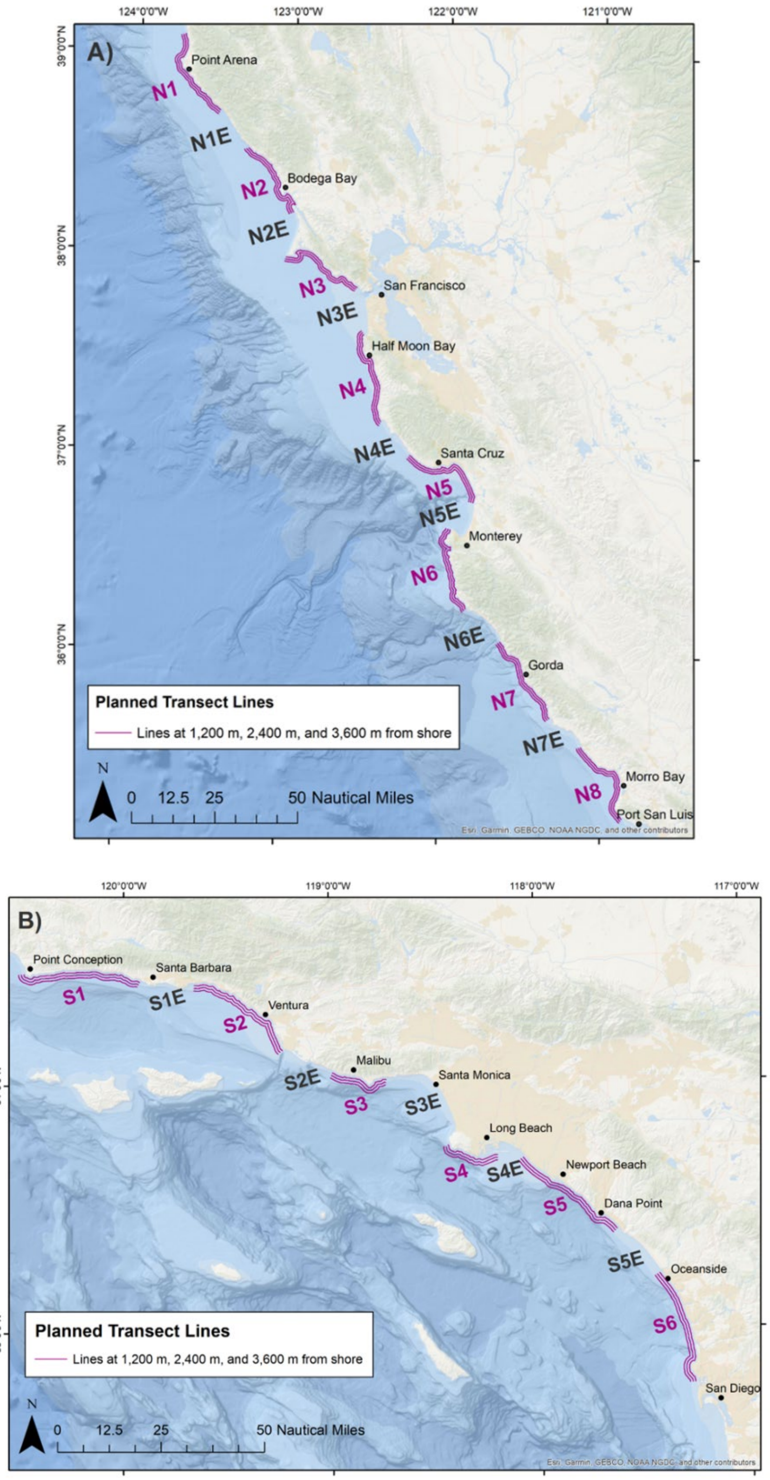

Figure 14.1: Spatial distribution of strata (Panels A and B) off northern California (NCA) and southern California (SCA) for surveys between 2020 and 2023. Planned survey strata are in pink; strata for expansion of biomass are in black and labeled with an "E". Note strata S3 and S4 are smaller to circumvent airspace restrictions near the Los Angeles Airport.

Table 14.1: Mean biomass (metric tons) of Pacific sardine observed during 2022-2023 CCPSS survey flight dates by 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
01/13/23	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

Table 14.2: Seasonal SCA biomass estimates in metric tons, 2022-2023.

Dates	Region	Year	Season	Area_ Region (km²)	Density_ Region (mt/km²)	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

References

Dorval, E., Lynn, K., Porzio, D., Nguyen, T., and Grady, K. *In press*. Computing bias and variance for Pacific Sardine (*Sardinops sagax*) biomass estimated from aerial surveys in California nearshore waters.

Lynn, K., Dorval, E., Porzio, D., and Nguyen, T. 2022. A collaborative aerial survey of coastal pelagic species in nearshore California Waters. Fisheries, 47, 501-508. https://doi.org/10.1002/fsh.10840

Lynn, K., Dorval, E., Porzio, D., Nguyen, T., Myers, D., and Grady, K. 2023. Estimation of nearshore aerial survey biomass for the 2021 stock assessment of the central subpopulation of northern anchovy (*Engraulis mordax*). NOAA-SWFSC-677.

15 Appendix E: Bridging Analysis

The first step of the bridging analysis was to run the 2020 benchmark sardine assessment, which was conducted using ss3.30.14, with ss3.30.22 (the most recent version of SS3 as of December 2023). There were relatively large differences in parameter estimates (e.g. natural mortality, unfished recruitment), biomass estimates, and likelihood values. The difference in summary biomass values is shown in Figure 15.1 below.

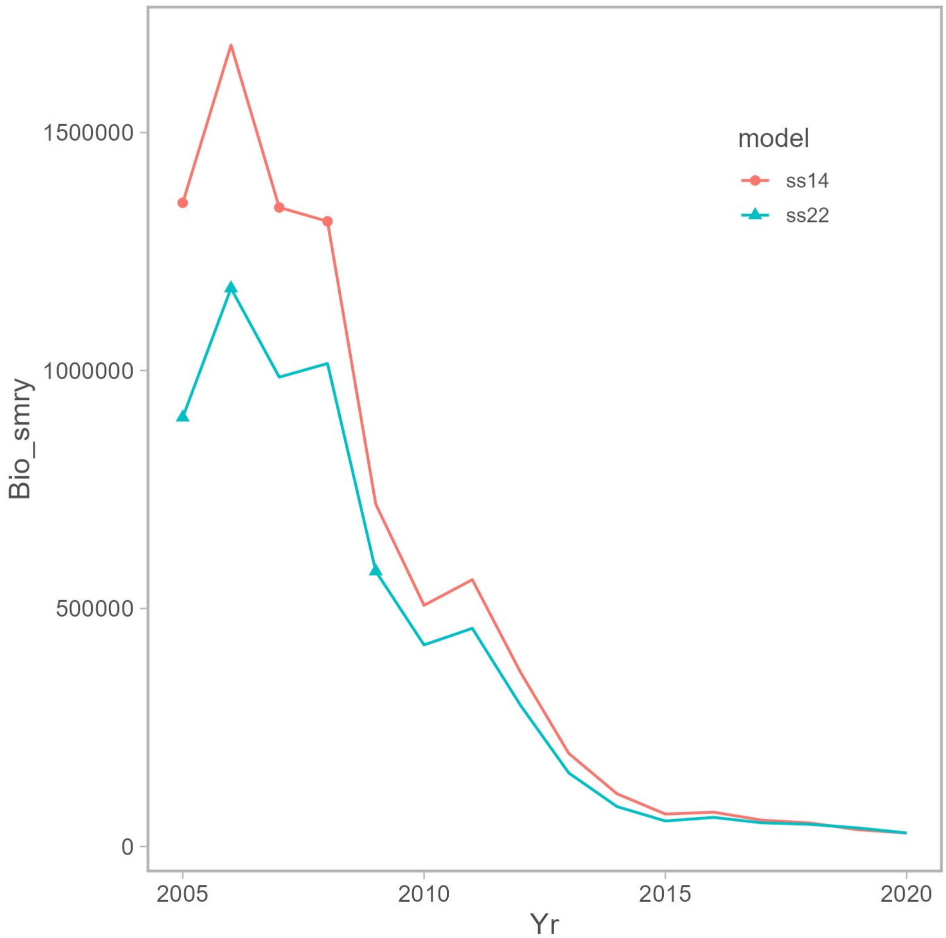

Figure 15.1: Summary biomass (age-1+; mt) from models run with ss3.30.14 (red line; ss14) and ss3.30.22 (blue line; ss22).

The next step was to check the calculations between ss3.30.14 and ss3.30.22. A model implemented using 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 15.2) and the expectation was that these values would be identical.

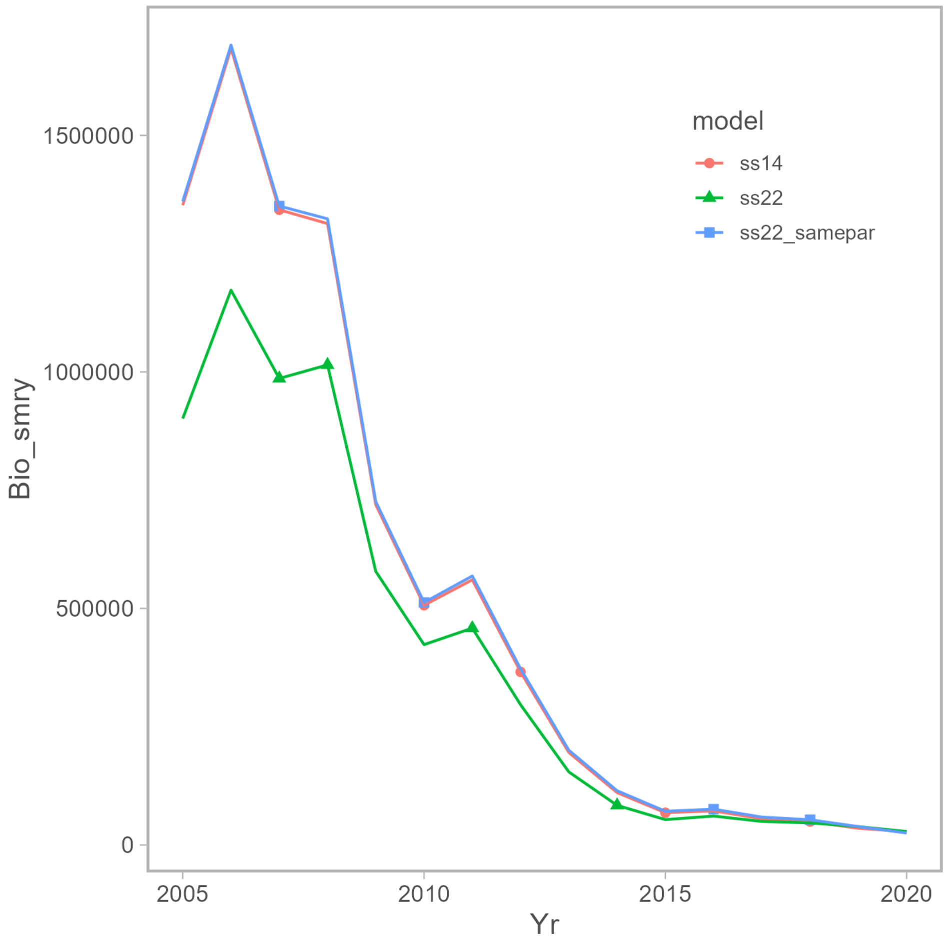

Figure 15.2: Summary biomass (age-1+; mt) from models run with ss3.30.14 (red line; ss14), ss3.30.22 (green line; ss22), and ss3.30.22 from the ss14 par file (blue line; ss22_samepar).

It seemed that something changed with the 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 15.3 below), and ss3.30.22 had the aforementioned difference.

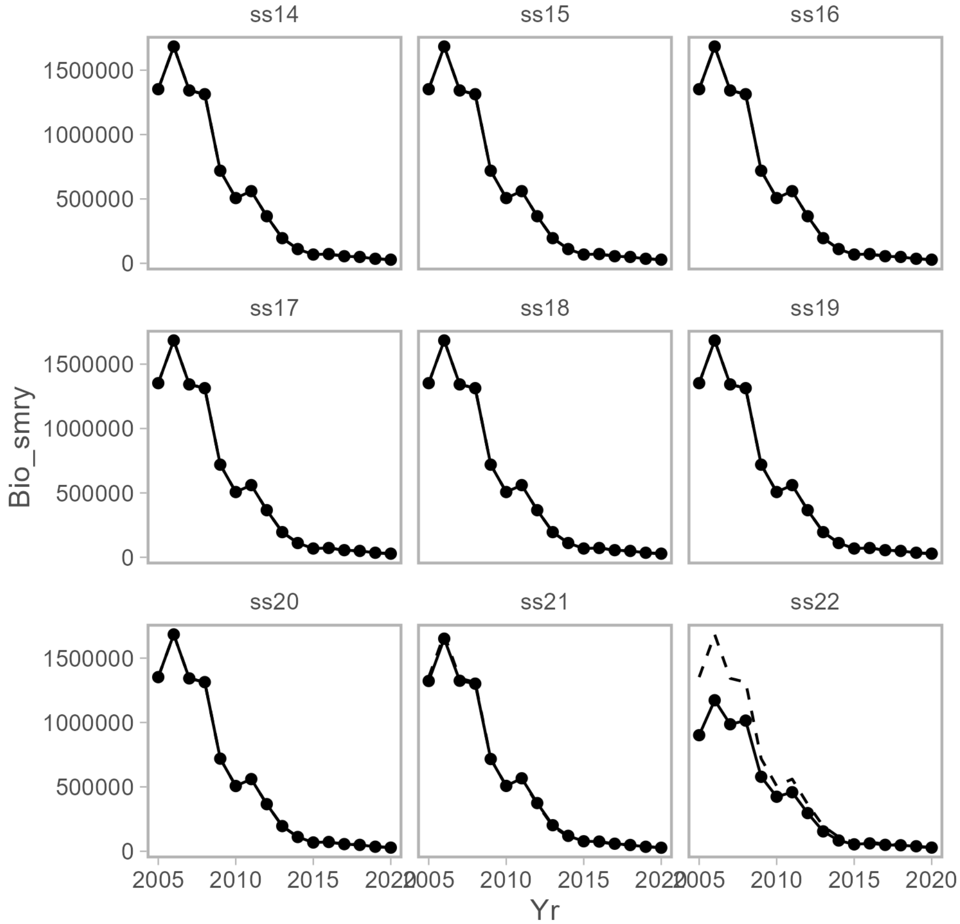

Figure 15.3: Summary biomass (age-1+; mt) from models run with ss3.30.14 (ss14) to SS3.30.22 (ss22).

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. The ALK tolerance was set to 0.0001 for the 2020 benchmark assessment. This feature is deprecated in ss3.30.22 and nonzero ALK values are overwritten to 0.

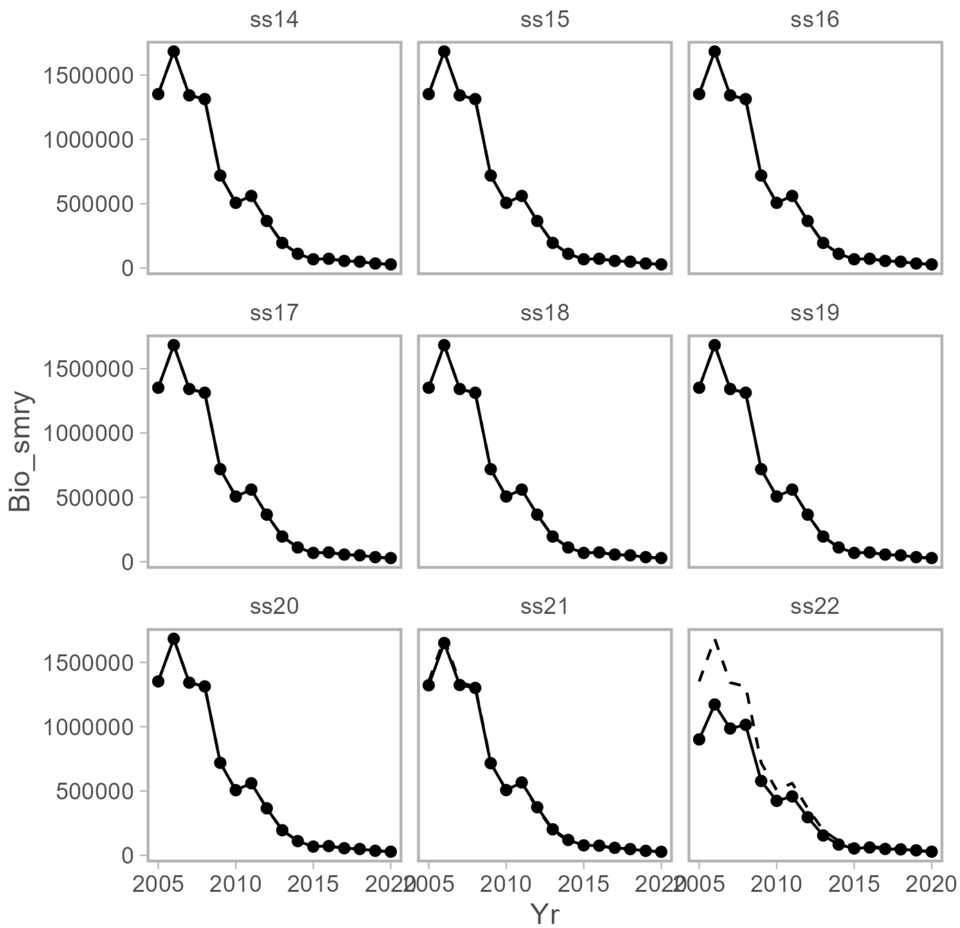

Figure 15.4: Summary biomass (age-1+; mt) from models run with ss3.30.14 ALK=0.0001 (ss14), ss3.30.14 and ALK = 0 (ss14_ALK0), and ss3.30.22 with ALK = 0 (SS22_ALK0_par14).

The model results are identical from ss3.30.14 and ss3.30.22 if the ALK tolerance is set to 0 in both but the likelihood values are different (Figure 15.4 and Table 15.1).

Table 15.1: 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, an annual model was developed by removing any data associated with semester 2 (e.g., catch from the MexCal S2 fleet, survey observations, etc). Estimated biomass and likelihood values were identical between ss3.30.14 and ss3.30.22 with ALK tolerance set to 0. Estimated biomass values were higher with ALK tolerance set to 0.0001 (Figure 15.5).

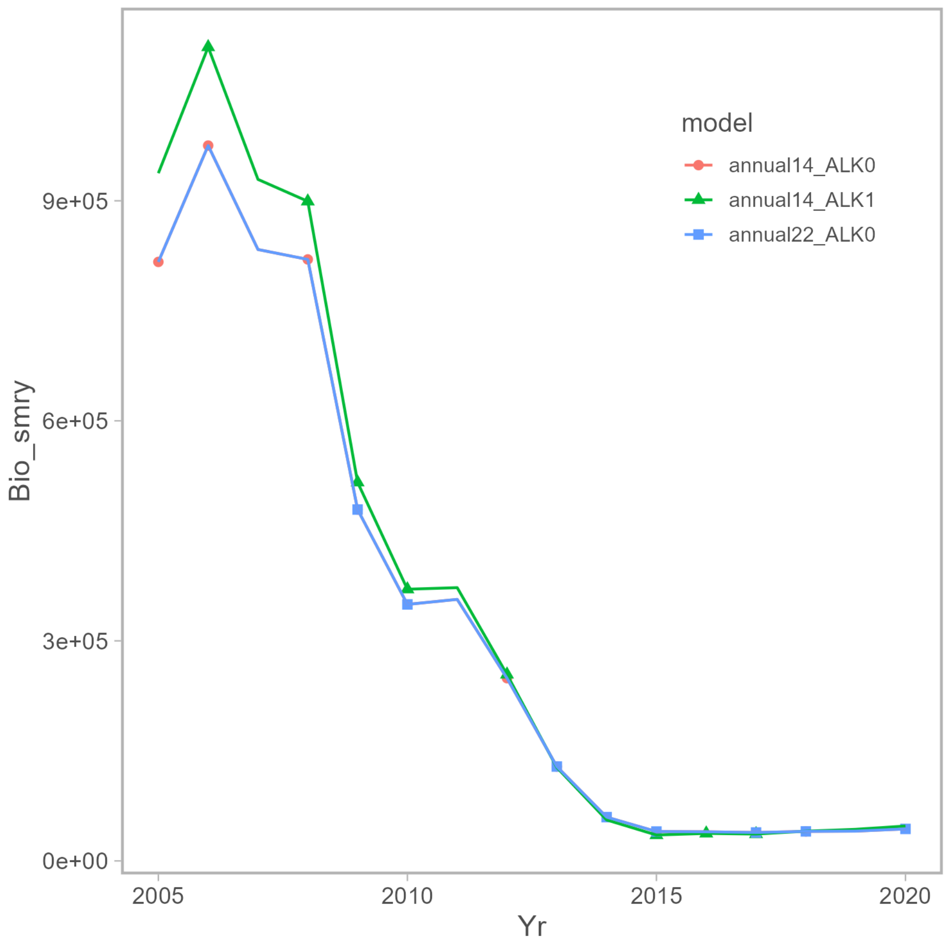

Figure 15.5: Summary biomass (age-1+; mt) from models run with ss3.30.14 ALK=0.0001 (ss14), ss3.30.14 and ALK = 0 (ss14_ALK0), and ss3.30.22 with ALK = 0 (SS22_ALK0_par14).

16 References

Ahlstrom, E.H. (1960) Synopsis on the biology of the Pacific sardine (Sardinops caerulea). *Proc. World Sci. Meet. Biol. Sardines and Related Species* 2, 415–451.

Barnes, J.T., Jacobson, L.D., MaCall, A.D. and Wolf, P. (1992) Recent population trends and abundance estimates for the Pacific sardine (Sardinops sagax). *CalCOFI Reports* 33, 60–75.

Baumgartner, T.R., Soutar, A. and Ferreira-Bartrina, V. (1992) Reconstruction of the history of Pacific sardine and northern anchovy populations over the past two millenia from sediments of the Santa Barbara Basin, California. *CalCOFI Reports* 33, 24–40.

Butler, J.L. (1987) Comparisons of the larval and juvenile growth and larval mortality rates of Pacific sardine and northern anchovy and implications for species interactions.

Butler, J.L., Smith, P.E. and Lo, N.C. (1993) The effect of natural variability of life-history parameters on anchovy and sardine population growth. *CalCOFI Reports* 34, 104–111.

Cheng, M.L., Thorson, J.T., Ianelli, J.N. and Cunningham, C.J. (2023) Unlocking the triad of age, year, and cohort effects for stock assessment: Demonstration of a computationally efficient and reproducible framework using weight-at-age. *Fisheries Research* 266, 106755.

Clark, F.N. and Janssen Jr, J.F. (1945) Movements and abundance of the sardine as measured by tag returns. *California Division Fish Game Fisheries Bulletin* 61, 7–42.

Clark, F.N. and Marr, J.C. (1955) Population dynamics of the Pacific sardine. *CalCOFI Reports* 5, 11–48.

CONAPESCA (2022) ANUARIO ESTADÍSTICO DE ACUACULTURA y PESCA DE LA COMISIÓN NACIONAL DE ACUACULTURA y PESCA 2022.

Conser, R.J., Hill, K.T., Crone, P.R., Lo, N.C.H. and Bergen, D. (2003) Stock assessment of Pacific sardine with management recommendations for 2004. *Pacific Fishery Management Council*.

Conser, R.J., Hill, K.T., Crone, P.R., Lo, N.C.H. and Felix-Uraga, R. (2004) Assessment of the Pacific sardine stock for U.S. management in 2005. *Pacific Fishery Management Council*.

Cushing, D.H. (1971) The Dependence of Recruitment on Parent Stock in Different Groups of Fishes. *ICES Journal of Marine Science* 33, 340–362.

Demer, D.A. and Zwolinski, J.P. (2014) Corroboration and refinement of a method for differentiating landings from two stocks of Pacific sardine (Sardinops sagax) in the California Current. *ICES Journal of Marine Science* 71, 328–335.

Demer, D.A., Zwolinski, J.P., Byers, K.A., Cutter, G.R., Renfree, J.S., Sessions, T.S. and Macewicz, B.J. (2012) Prediction and confirmation of seasonal migration of Pacific sardine (Sardinops sagax) in the California Current Ecosystem. *Fisheries Bulletin* 110, 52–70.

Deriso, R.B., Barnes, J.T., Jacobson, L.D. and Arenas, P.R. (1996) Catch-at-age analysis for Pacific sardine (Sardinops sagax), 1983-1995. *CalCOFI Reports* 37, 175–187.

Deriso, R.B., II, T.J.Q. and Neal, P.R. (1985) Catch-Age Analysis with Auxiliary Information. *Canadian Journal of Fisheries and Aquatic Sciences* 42, 815–824.

DFO (2021) Stock status update with application of management procedures for pacific herring (clupea pallasii) in british columbia: Status in 2021 and forecast for 2022. *Fisheries and Oceans Canada*.

Dorn, M.W. (2002) Advice on west coast rockfish harvest rates from bayesian meta-analysis of stock- recruit relationships. *North American Journal of Fisheries Management* 22, 280–300.

Dorval, E., Macewicz, B.J., Griffith, D.A. and Gu, Y. (2016) Spawning biomass of Pacific sardine (Sardinops sagax) estimated from the daily egg production method off California in 2015. *NOAA Technical Memorandum* NOAA-TM-NMFS-SWFSC-560, 47.

Dorval, E., McDaniel, J.D., Porzio, D.L., Hodes, V., Felix-Uraga, R. and Rosenfield, S. (2013) Computing and selecting ageing errors to include in stock assessment models of Pacific sardine (Sardinops sagax). *CalCOFI Reports* 54, 192–204.

Eschmeyer, W.N., Herald, E.S. and Hamman, H. (1983) A field guide to Pacific Coast fishes of North America.

Felix-Uraga, R., Gomez-Munoz, V.M., Quinonez-Velazquez, C., Melo-Barrera, F.N. and Garcia-Franco, W. (2004) On the existence of Pacific sardine groups off the west coast of Baja California and Southern California. *CalCOFI Reports* 45, 146–151.

Felix-Uraga, R., Gomez-Munoz, V.M., Quinonez-Velazquez, C., Melo-Barrera, F.N., Hill, K.T. and Garcia-Franco, W. (2005) Pacific sardine (Sardinops sagax) stock discrimination off the west coast of Baja California and Southern California using otolith morphometry. *CalCOFI Reports* 46, 113–121.

Francis, R.C. (2011) Data weighting in statistical fisheries stock assessment models. *Canadian Journal of Fisheries and Aquatic Sciences* 68, 1124–1138.

Garcia-Morales, R., Shirasago-German, B., Felix-Uraga, R. and Perez-Lezama, E.L. (2012) Conceptual models of Pacific sardine distribution in the California Current system. *Current Development in Oceanography* 5, 23–47.

Hamel, O.S. and Cope, J.M. (2022) Development and considerations for application of a longevity-based prior for the natural mortality rate. *Fisheries Research* 256, 106477.

Hart, J.L. (1973) Pacific fishes of Canada. 740 pp.

Hedgecock, D., Hutchinson, E.S., Li, G., Sly, F.L. and Nelson, K. (1989) Genetic and Morphometric Variation in the Pacific Sardine, Sardinops sagax caerulea: Comparisons and Contrasts with Historical Data and with Variability in the Northern Anchovy, Engraulis Mordax. *Fishery Bulletin* 87, 653–571.

Hill, K.T. (1999) Determining age composition of coastal pelagic species in northern California, Oregon, and Washington coastal waters. 47 pp.

Hill, K.T., Crone, P.R., Demer, D.A., Zwolinski, J.P., Dorval, E. and Macewicz, B.J. (2014) Assessment of the Pacific sardine resource in 2014 for U.S.A. management in 2014-15. US Department of Commerce.

Hill, K.T., Crone, P.R., Dorval, E. and Macewicz, B.J. (2015) Assessment of the Pacific sardine resource in 2015 for U.S.A. management in 2015-16.

Hill, K.T., Crone, P.R., Dorval, E. and Macewicz, B.J. (2016) Assessment of the Pacific sardine resource in 2016 for U.S.A. management in 2016-17.

Hill, K.T., Crone, P.R., Lo, N.C.H., Demer, D.A., Zwolinski, J.P. and Macewicz, B.J. (2012) Assessment of the Pacific sardine resource in 2012 for U.S. management in 2013.

Hill, K.T., Crone, P.R., Lo, N.C.H., Macewicz, B.J., Dorval, E., McDaniel, J.D. and Gu, Y. (2011) Assessment of the Pacific sardine resource in 2011 for U.S. management in 2012.

Hill, K.T., Crone, P.R. and Zwolinski, J.P. (2017) Assessment of the Pacific sardine resource in 2017 for U.S. management in 2017-18.

Hill, K.T., Crone, P.R. and Zwolinski, J.P. (2018) Assessment of the Pacific sardine resource in 2018 for U.S. management in 2018-19.

Hill, K.T., Crone, P.R. and Zwolinski, J.P. (2019) Assessment of the Pacific sardine resource in 2019 for U.S. management in 2019-20. *NOAA Technical Memorandum* NOAA-TM-NMFS-SWFSC-615.

Hill, K.T., Dorval, E., Lo, N.C.H., Macewicz, B.J., Show, C. and Felix-Uraga, R. (2007) Assessment of the Pacific sardine resource in 2007 for U.S. management in 2008.

Hill, K.T., Dorval, E., Lo, N.C.H., Macewicz, B.J., Show, C. and Felix-Uraga, R. (2008) Assessment of the Pacific sardine resource in 2008 for U.S. management in 2009.

Hill, K.T., Jacboson, L.C., Lo, N.C.H., Yaremko, M. and Cege, M. (1999) Stock assessment of Pacific sardine for 1998 with management recommendations for 1999. *California Department of Fish and Game, Marine Region.*

Hill, K.T., Lo, N.C.H., Crone, P.R., Macewicz, B.J. and Felix-Uraga, R. (2009) Assessment of the Pacific sardine resource in 2009 for USA management in 2010.

Hill, K.T., Lo, N.C.H., Crone, P.R., Macewicz, B.J. and Felix-Uraga, R. (2010) Assessment of the Pacific sardine resource in 2010 for U.S. management in 2011.

Hill, K.T., Lo, N.C.H., Macewicz, B.J. and Felix-Uraga, R. (2006a) Assessment of the Pacific sardine (Sardinops sagax caerulea) population for U.S. Management in 2006. *NOAA Technical Memorandum* NOAA-TM-NMFS-SWFSC-386.

Hill, K.T., Lo, N.C.H., Macewicz, B.J. and Felix-Uraga, R. (2006b) Assessment of the Pacific sardine (Sardinops sagax caerulea) population for U.S. Management in 2007. *NOAA Technical Memorandum* NOAA-TM-NMFS-SWFSC-396.

ICES (2015) Manual for international pelagic surveys (IPS). *Series of ICES Survey Protocols SISP 9–IPS*, 92.

Jacobson, L.D. and MacCall, A.D. (1995) Stock-recruitment models for Pacific sardine (Sardinops sagax). *Canadian Journal of Fisheries and Aquatic Sciences* 52, 566 577.

Janssen Jr, J.F. (1938) Second report of sardine tagging in California. *California Fish and Game Fish Bulletin* 24, 376–389.

Koenigstein, S., Jacox, M.G., Pozo Buil, M., et al. (2022) Population projections of pacific sardine driven by ocean warming and changing food availability in the california current. *ICES Journal of Marine Science* 79, 2510–2523.

Kuriyama, P.T., Zwolinski, J.P., Hill, K.T. and Crone, P.R. (2020) Assessment of the pacific sardine resource in 2020 for US management in 2020-2021.

Kuriyama, P.T., Zwolinski, J.P., Hill, K.T. and Crone, P.R. (2022) Update assessment of the pacific sardine resource in 2022 for US management in 2022-2023. *PFMC*.

Lee, H.-H., Maunder, M.N., Piner, K.R. and Methot, R.D. (2012) Can steepness of the stock–recruitment relationship be estimated in fishery stock assessment models? *Fisheries Research* 125, 254–261.

Leet, W.S., Dewees, C.M., Klingbeil, R. and Larson, E.J. (2001) California's living marine resources: A status report.

Lo, N.C.H., Macewicz, B.J. and Griffith, D.A. (2005) Spawning biomass of Pacific sardine (Sardinops sagax) from 1994-2004 off California. *CalCOFI Reports* 46, 93–112.

Lo, N.C.H., Ruiz, Y.A.G., Cervantes, M.J., Moser, H.G. and Lynn, R.J. (1996) Egg production and spawning biomass of Pacific sardine (Sardinops sagax) in 1994, determined by the daily egg production method. *CalCOFI Reports* 37, 160–174.

Lo, N.C., Macewicz, B.J. and Griffith, D.A. (2011) Migration of Pacific Sardine (Sardinops Sagax) Off the West Coast of United States in 2003–2005. *Bulletin of Marine Science* 87, 395–412.

Longo, G.C. and Craig, M.T. (in prep) Evaluation of the temporal and geographic occurrence of Japanese sardine (Sardinops melanostictus) in the California Current Large Marine Ecosystem 2013-2023.

Lorenzen, K. (2022) Size-and age-dependent natural mortality in fish populations: Biology, models, implications, and a generalized length-inverse mortality paradigm. *Fisheries Research* 255, 106454.

Lorenzen, K. (1996) The relationship between body weight and natural mortality in juvenile and adult fish: A comparison of natural ecosystems and aquaculture. *Journal of fish biology* 49, 627–642.

Lynn, K., Porzio, D. and Nguyen, T. (2020) California Coastal Pelagic Species Survey Results from Summer 2017 and 2019 for Pacific sardine (Sardinops sagax). *California Department of Fish and Wildlife*, 15 pp.

MacCall, A.D. (1979) Population estimates for the waning years of the Pacific sardine fishery. *CalCOFI Reports*.

Macewicz, B.J. and Abramenkoff, D.N. (1993) Collection of Jack Mackerel, Trachurus symmetricus, off Southern California during 1991 Cooperative U.S.-U.S.S.R Cruise. *Southwest Fisheries Science Center, National Marine Fisheries Service, Admin. Rep.* LJ-93-07, 13.

Macewicz, B.J., Gonzalez, J.J.C., Cotero-Altamirano, C.E. and Hunter, J.R. (1996) Adult reproductive parameters of Pacific Sardine (Sardinops sagax) during 1994. *CalCOFI Reports* 37, 140–151.

McClatchie, S., Hendy, I.L., Thompson, A.R. and Watson, W. (2017) Collapse and recovery of forage fish populations prior to commercial exploitation. *Geophysical Research Letters* 371, 285 9.

McDaniel, J., Piner, K., Lee, H.-H. and Hill, K. (2016) Evidence that the Migration of the Northern Subpopulation of Pacific Sardine (Sardinops sagax) off the West Coast of the United States Is Age-Based. *PLOS ONE* 11, e0166780.

Methot, R.D. (2005) Technical description of the Stock Synthesis II Assessment Program. Version 1.17- March 2005. *NOAA Fisheries, Seattle WA*.

Methot, R.D. (2009) User manual for Stock Synthesis. Model version 3.03a. *NOAA Fisheries, Seattle WA*, 143.

Methot, R.D. (2011) User manual for Stock Synthesis. Model version 3.24s. *NOAA Fisheries, Seattle WA*.
Methot, R.D. and Taylor, I.G. (2011) Adjusting for bias due to variability of estimated recruitments in fishery assessment models. *Canadian Journal of Fisheries and Aquatic Sciences* 68, 1744–1760.
Methot, R.D. and Wetzel, C.R. (2013) Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. *Fisheries Research* 142, 86–99.
Murphy, G.I. (1966) Population biology of the Pacific sardine (Sardinops caerulea). *Proceedings of the California Academy of Sciences* 34, 1–84.
NMFS (2019a) California Current integrated ecosystem assessment (CCIEA) California Current ecosystem status report.
NMFS (2019b) Supplementary Materials for the California Current integrated ecosystem assessment (CCIEA) California Current ecosystem status report.
PFMC (2023) 2022-2023 CALIFORNIA CURRENT ECOSYSTEM STATUS REPORT.
PFMC (1998) Amendment 8 (to the northern anchovy fishery management plan) incorporating a name change to: the coastal pelagic species fishery management plan.
PFMC (2018) Methodology review panel report: acoustic trawl methodology review for use in coastal pelagic species stock assessments. *Pacific Fishery Management Council, Portland, OR*.
PFMC (2014) Pacific sardine STAR panel meeting report.
PFMC (2013) Report of the Pacific Sardine Harvest Parameters Workshop.
PFMC (2017) *Status of the Pacific coast coastal pelagic species fishery and recommended acceptable biological catches: Stock assessment and fishery evaluation 2017*.
PFMC (2022) *Status of the Pacific coast coastal pelagic species fishery and recommended acceptable biological catches: Stock assessment and fishery evaluation 2021*.
Phillips, J.B. (1948) Growth of the sardine, Sardinops caerulea, 1941-42 through 1946-47. *California Division of Fish and Game Bureau of Marine Fishes Fish Bulletin* 71, 33.
Punt, A.E. (2023) Those who fail to learn from history are condemned to repeat it: A perspective on current stock assessment good practices and the consequences of not following them. *Fisheries Research* 261, 106642.
Simmonds, E.J. and MacLennan, D.N. (2005) *Fisheries acoustics: Theory and practice.* Wiley-Blackwell.
Smith, J.A., Muhling, B., Sweeney, J., Tommasi, D., Pozo Buil, M., Fiechter, J. and Jacox, M.G. (2021) The potential impact of a shifting pacific sardine distribution on US west coast landings. *Fisheries Oceanography* 30, 437–454.
Smith, P.E. (2005) A history of proposals for subpopulation structure in the Pacific sardine (Sardinops sagax) population off western North America. *CalCOFI Reports* 46, 75–82.
Soutar, A. and Isaacs, J.D. (1974) Abundance of pelagic fish during the 19th and 205h centuries as recorded in anaerobic sediment off the Californias. *Fishery Bulletin* 72, 257–273.
Soutar, A. and Isaacs, J.D. (1969) History of fish populations inferred from fish scales in anaerobic sediments off California. *CalCOFI Reports* 13.
Stierhoff, K.L., Zwolinski, J.P. and Demer, D.A. (2020) Distribution, biomass, and demography of coastal pelagic fishes in the California Current Ecosystem during summer 2019 based on acoustic-trawl sampling. *U.S. Dep. Commer., NOAA Tech. Memo.* NMFS-SWFSC-626, 80 pp.
Stierhoff, K.L., Zwolinski, J.P., Renfree, J.S. and Demer, D.A. (2023) Distribution, biomass, and demography of coastal pelagic fishes in the Calironia current ecosystem during summer 2022 based on acoustic-trawl sampling. *NOAA Technical Memorandum* NOAA-TM-NMFS-SWFSC-683.
Thorson, J.T., Dorn, M.W. and Hamel, O.S. (2019) Steepness for west coast rockfishes: Results from a twelve-year experiment in iterative regional meta-analysis. *Fisheries Research* 217, 11–20.
Vrooman, A.M. (1964) Seriologicaly differentiated subpopulations of the Pacific sardine, Sardinops caerulea. 21, 691–701.
Walford, L.A. and Mosher, K.H. (1943) Studies on the Pacific pilchard or sardine (Sardinops caerulea). 33.
Wetzel, C.R. and Hamel, O.S. (2023) Applying a probability harvest control rule to account for increased uncertainty in setting precautionary harvest limits from past stock assessments. *Fisheries Research* 262, 106659.

Wood, S. (2017) *Generalized Additive Models: An Introduction with R, 2nd edition*. Chapman; Hall/CRC.
Xu, H., Thorson, J.T., Methot, R.D. and Taylor, I.G. (2019) A new semi-parametric method for autocorrelated age-and time-varying selectivity in age-structured assessment models. *Canadian Journal of Fisheries and Aquatic Sciences* 76, 268–285.
Yaremko, M.L. (1996) Age determination in Pacific sardine, Sardinops sagax. *NOAA Technical Memorandum* NMFS-SWFSC-223, 33.
Yau, A. (2023) Report from the pacific sardine stock structure workshop, november 2022.
Zwolinski, J.P. and Demer, D.A. (2023) An updated model of potential habitat for northern stock pacific sardine (sardinops sagax) and its use for attributing survey observations and fishery landings. *Fisheries Oceanography* 33(3), e12664.
Zwolinski, J.P. and Demer, D.A. (2013) Measurements of natural mortality for Pacific sardine (Sardinops sagax). *ICES Journal of Marine Science* 70, 1408–1415.
Zwolinski, J.P. and Demer, D.A. (2019) Re-evaluation of the environmental dependence of pacific sardine recruitment. *Fisheries Research* 216, 120–125.
Zwolinski, J.P., Emmett, R.L. and Demer, D.A. (2011) Predicting habitat to optimize sampling of Pacific sardine (Sardinops sagax). *ICES Journal of Marine Science* 68, 867–879.
Zwolinski, J.P., Renfree, J.S., Stierhoff, K.L. and Demer, D.A. (2023) Distribution, biomass, and demographics of coastal pelagic fishes in the California Current ecosystem during spring 2021 based on acoustic-trawl sampling. *NOAA Technical Memorandum NMFS* NOAA-TM-NMFS-SWFSC-675, 53.
Zwolinski, J.P., Stierhoff, K.L. and Demer, D.A. (2019) Distribution, biomass, and demography of coastal pelagic fishes during summer 2017, estimated from acoustic-trawl sampling. *NOAA Technical Memorandum* NOAA-TM-NMFS-SWFSC-610.