Assessment of the Northern anchovy (*Engraulis mordax*) central subpopulation in 2021 for U.S. management.

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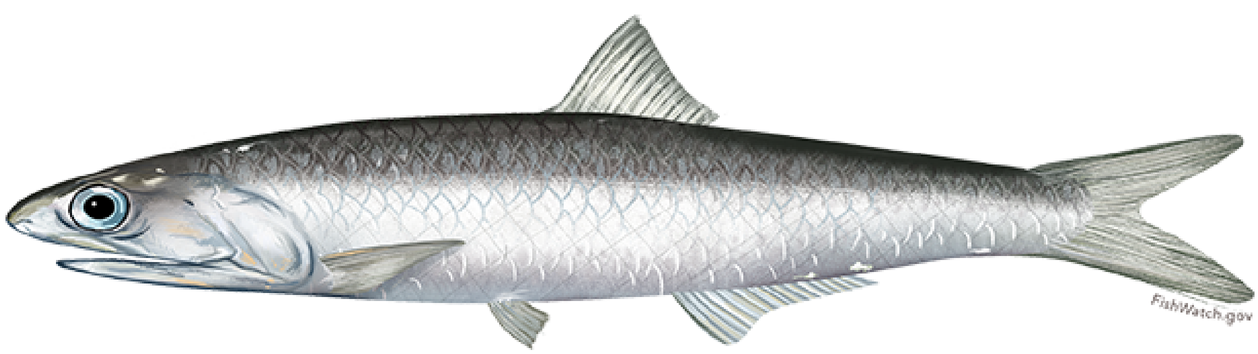

June 2022

This report may be cited as:

ex. Kuriyama, P.T., Zwolinski J.P., Teo, S.L.H, and Hill, K.T. 2021. Assessment of the Northern anchovy (*Engrualis mordax*) central subpopulation in 2021 for U.S. management. Pacific Fishery Management Council, Portland, OR. Available from https://www.pcouncil.org/stock-assessments-and-fishery-evaluation-safe-documents/

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Executive Summary

The following northern anchovy (*Engraulis mordax* Girard) stock assessment was reviewed at the STAR Panel in December 2021.

Stock

This assessment focuses on the central subpopulation of northern anchovy (CSNA), a small, short-lived coastal pelagic fish, which ranges from roughly northern California, USA to central Baja California, Mexico. There is a northern subpopulation, which ranges from waters off British Columbia, Canada to Cape Mendocino, CA, USA, and a southern subpopulation, which is found in waters off central Baja California to the Gulf of California, Mexico. The subpopulations have been found to have distinct meristic and serological characteristics (McHugh 1951, Vrooman et al. 1981). CSNA are typically found in waters ranging from 11° to 29° C (Lo 1985), and the three subpopulations do not seem to be genetically distinct (Lecomte et al. 2004). This assessment is focused on fishery and survey information available for CSNA.

Catches

The assessment includes CSNA landings from three major fishing regions: central California, USA (CCA), southern California, USA (SCA), and Ensenada, Mexico (ENS). Landings from each region over the model year-semester combinations are shown beginning in 2015 below in Table ES-1.

Table ES-1: CSNA landings (mt) for the three major fishing regions: central California, USA (CCA), southern California, USA (SCA), and Ensenada, Mexico (ENS). The values are reported for each calendar year-semester (Y-S) and model Y-S.

Calendar Y-S	Model Y-S	CCA	SCA	ENS
2015-2	2015-1	9,325	645	25,751
2016-1	2015-2	384	4,633	1,389
2016-2	2016-1	3,446	170	3,619
2017-1	2016-2	119	236	6,845
2017-2	2017-1	5,098	138	8,881
2018-1	2017-2	6,112	34	18,152
2018-2	2018-1	11,277	91	24,020
2019-1	2018-2	3,680	21	17,090
2019-2	2019-1	6,323	146	18,048
2020-1	2019-2	3,612	14	19,803
2020-2	2020-1	1,895	114	20,934
2021-1	2020-2	1,601	78	19,803
2021-2	2021-1	206	59	7,782

Data and Assessment

The integrated assessment model was developed using Stock Synthesis 3 (SS3; version 3.30.17), and includes fishery and survey data collected from mid-2015 through 2021. The model is based on a June-May biological year (aka 'model year'), with two semester-based seasons per year (S1=Jun-Dec and S2=Jan-May). 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 in each semester (S1 and S2). A single AT survey index of abundance from ongoing SWFSC surveys (2015-2021) was included in the model.

The base model incoporates the following specifications:

- Sexes were combined; ages 0-3+;
- One fishery (MexCal), with seasonal selectivity patterns (S1 and S2);
- MexCal fleets had age-based selectivity (time-varying and 2dAR option in SS3);
- AT survey age-based selectivity is assumed to be uniform (fully-selected) above age-1 and estimated annually for age-0.
- Length-based selectivity fixed at 1 for all lengths and for the AT survey and two semester-based fishing fleets;
- AT survey age compositions with effective sample sizes set to 1 per cluster (externally);
- Fishery age compositions with effective sample sizes calculated by dividing the number of fish sampled by 25 (externally) and lambda weighting=1 (internally);
- Beverton-Holt stock-recruitment relationship with steepness set to 0.6;
- Initial equilibrium ("SR regime" parameter) estimated with the 'lambda' for this parameter set to zero (no penalty contributing to total likelihood estimate);
- Natural mortality (M) estimated;
- Recruitment deviations estimated from 2015-2021;
- Virgin recruitment estimated, and total recruitment variability (σ_R) fixed at 1;
- Initial fishing mortality (F) estimated for the MexCal S1 fleet and assumed to be 0 yr^{-1} for the other fleets;
- AT survey biomass 2015-2021, partitioned into two (spring and summer) surveys, with catchability (Q) set to 0.579 for spring (0.580 for spring 2020 based on aerial survey estimate) and 0.930 for summer;

Spawning Stock Biomass and Recruitment

Time series of estimated spawning stock biomass (SSB, shown as million mt) from the base model and associated 95% confidence intervals are displayed in Figure ES-1 and Table ES-2. The initial level of SSB was estimated to be 92,598 mt. The SSB has continually increased since 2015, and the SSB was projected to be 3,548,420 mt in January 2022 from the base model.

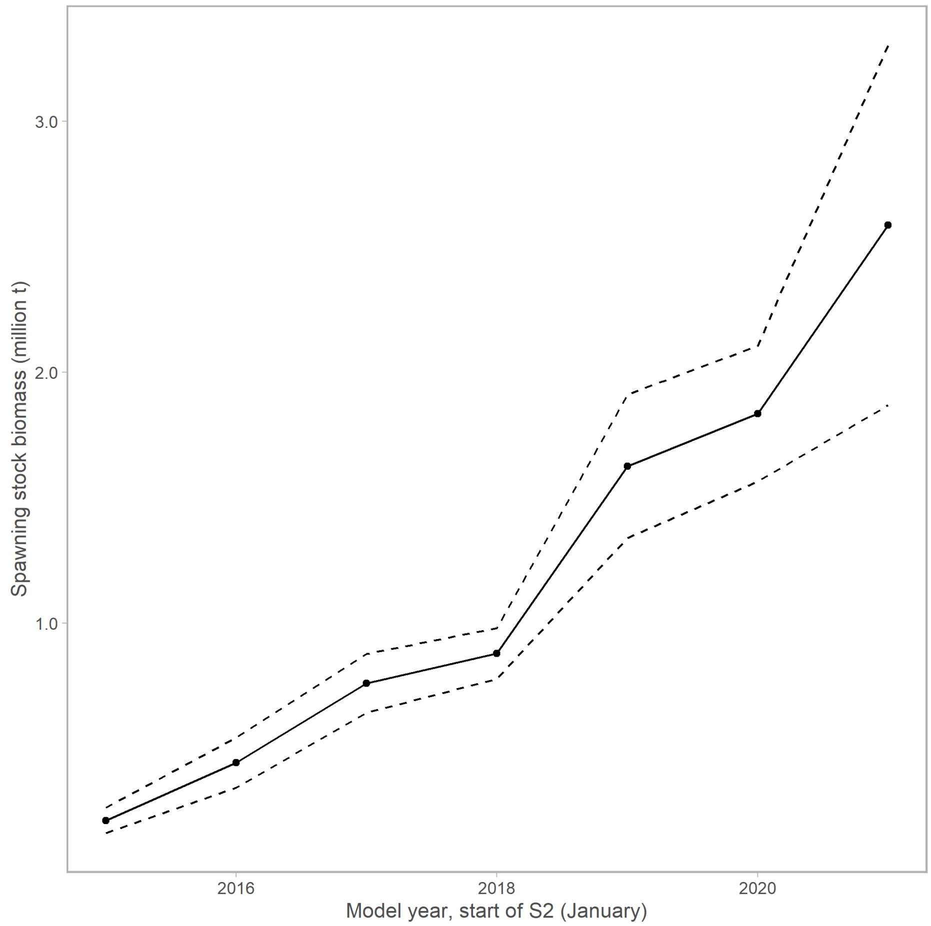

Figure ES-1: Time series of estimated spawning stock biomass (95% CI dashed lines).

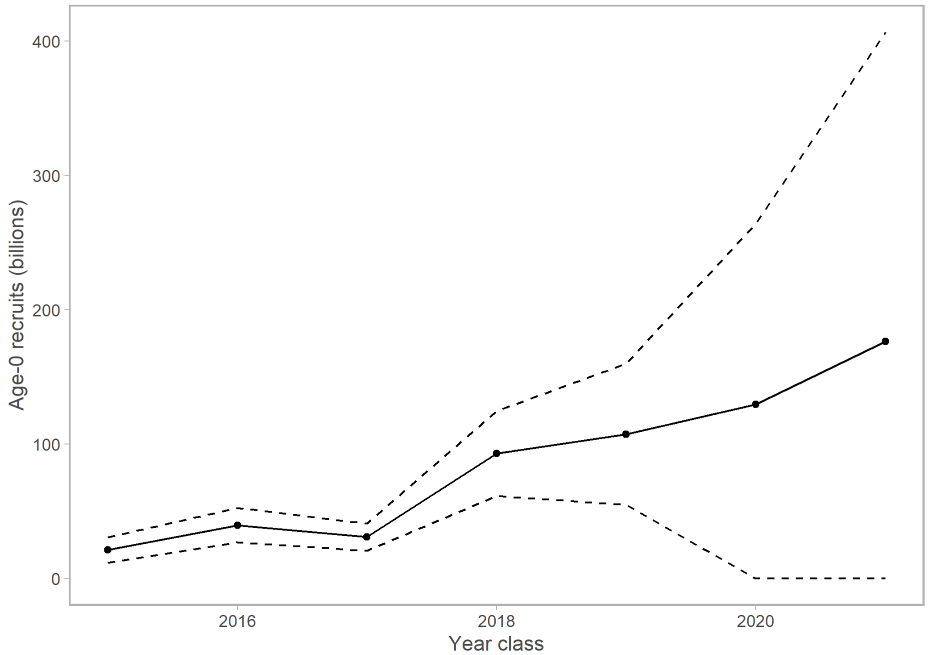

Figure ES-2: Time series of estimated recruitment (age-0, billions of fish).

Time series of estimated recruitment (age-0, billions of fish) abundance is presented in Figure ES-2 and Table ES-2 for the base model. The initial level of recruitment was estimated to be 25,745,900 age-0 thousands of fish. As indicated for SSB above, recruitment has increased throughout the base model time period.

Table ES-2: Estimates of spawning stock biomas (SSB) and recruitment (1000s of fish) with 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 (June).

Calendar Y-S	Model Y-S	SSB	SSB sd	Recruits	Recruits sd
–	VIRG-1	0	0	0	0
–	VIRG-2	10,685,800	12,514,700	269,708,000	247,391,000
–	INIT-1	0	0	0	0
–	INIT-2	92,598	52,012	0	0
2015-2	2015-1	0	0	25,745,900	7,001,730
2016-1	2015-2	213,162	50,714	0	0
2016-2	2016-1	0	0	21,009,800	9,480,240
2017-1	2016-2	443,476	99,593	0	0
2017-2	2017-1	0	0	39,546,800	12,836,000
2018-1	2017-2	759,613	117,717	0	0
2018-2	2018-1	0	0	30,643,300	10,092,800
2019-1	2018-2	879,476	101,516	0	0
2019-2	2019-1	0	0	92,894,400	31,484,800
2020-1	2019-2	1,625,280	285,553	0	0
2020-2	2020-1	0	0	107,169,000	52,421,600
2021-1	2020-2	1,835,140	270,099	0	0
2021-2	2021-1	0	0	129,427,000	134,584,000
2022-1	2021-2	2,586,700	718,182	0	0
2022-2	2022-1	0	0	176,376,000	230,134,000
2023-1	2022-2	3,548,420	2,003,880	0	0

Stock Biomass for PFMC Management

Stock biomass, used for calculating annual harvest specifications, is defined as the sum of the biomass for CSNA ages one and older (age-1+, mt) at the start of the management year. Time series of estimated stock biomass from the base model are presented in Figure ES-3 and Table ES-3. As discussed above for both SSB and recruitment, a similar trend of increasing stock biomass has been observed since 2015. The base model stock biomass was estimated to be 2,090,640 mt in 2021 and is projected to be 2,879,010 mt in June 2022.

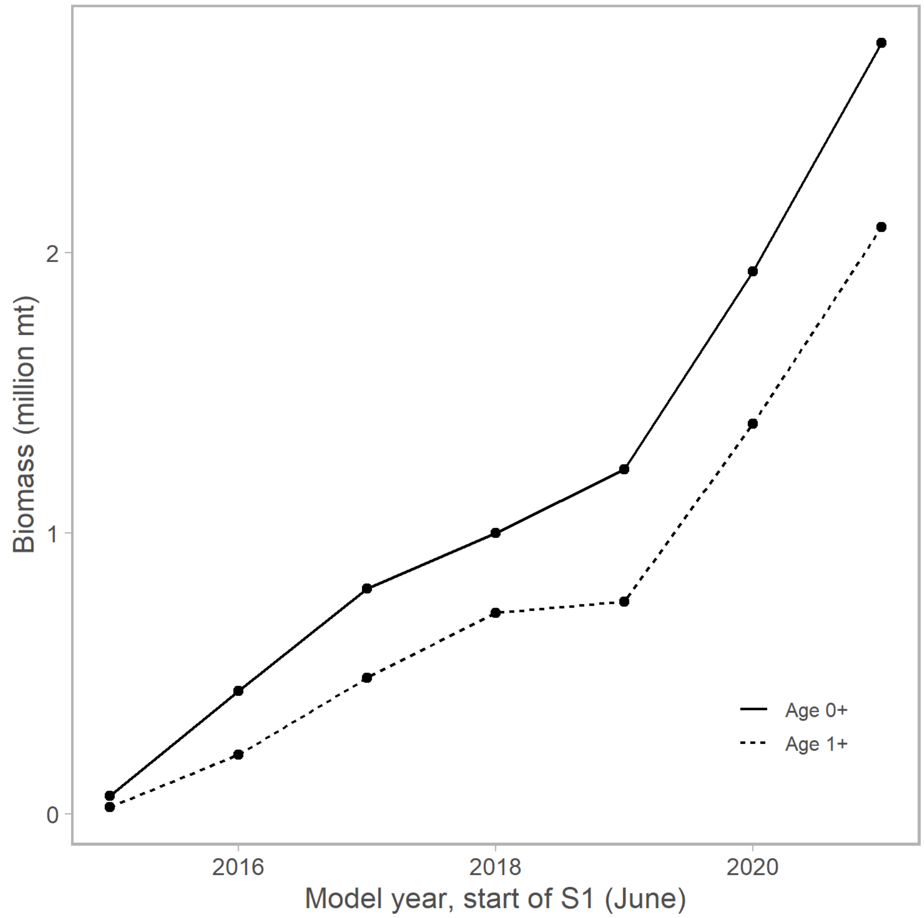

Figure ES-3: Estimated total biomass (age-0+ fish; mt) and stock biomass (age-1+ fish; mt) time series for the base model.

Table ES-3: Total (age-0+) and summary (age-1+) biomass values (mt) estimated for June 1 of each year.

Year	Age-0+	Age-1+
2015	64,830	24,810
2016	437,939	211,662
2017	803,290	484,605
2018	1,001,840	716,804
2019	1,227,790	757,029
2020	1,933,090	1,389,990
2021	2,746,530	2,090,640

Exploitation Status

Exploitation rate is defined as the calendar year CSNA catch divided by the total mid-year biomass (June-1, ages-0+). Based on the base model estimates, the U.S. exploitation rate has averaged about 3% since 2015, peaking at 15% in 2015. The total exploitation rates were 1% in 2021, largely driven by catches from Mexico. Exploitation rates for CSNA, calculated from the base model, are presented in Figure ES-4 and Table ES-4.

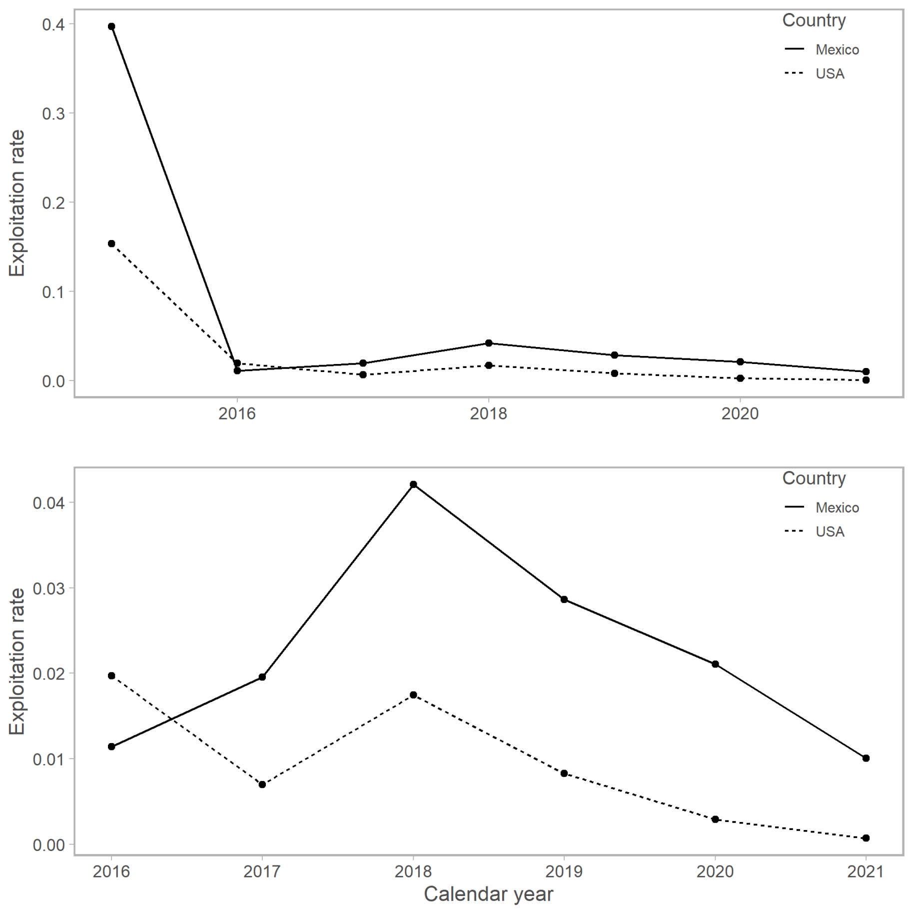

Figure ES-4: Annual exploitation rates (calendar year landings / June total biomass) for the base model.

Table ES-4: Annual exploitation rate (calendar year landings / June total biomass) by country and calendar year.

Calendar Year	Mexico	USA	Total
2015	0.40	0.15	0.55
2016	0.01	0.02	0.03
2017	0.02	0.01	0.03
2018	0.04	0.02	0.06
2019	0.03	0.01	0.04
2020	0.02	0.00	0.02
2021	0.01	0.00	0.01

Ecosystem Considerations

Juvenile anchovies, generally distributed inshore, are vulnerable to a variety of predators, including birds and some recreationally and commercially important species of fish (Szoboszlai et al. 2015, Koehn et al. 2016). As adults offshore, anchovies are fed upon by numerous marine fishes (some of which have recreational and commercial value), marine mammals, and birds such as the California brown pelican (Koehn et al. 2017).

Ecosystem linkages to CSNA productivity are poorly understood. Until recently, it has generally been assumed that anchovy increase productivity under cooler ocean conditions and sardine under warmer ocean conditions (Chavez et al. 2003), but the current CSNA boom began amid two marine heat waves seems to contradict this assumption (Thompson et al. 2019). Sardine and anchovy under warm and cold ocean regimes were thought to fluctuate asynchronously (Chavez et al. 2003), although analysis of sardine and anchovy time series across the world did not find evidence of widespread asynchrony (Siple et al. 2020). Environmental drivers may be density-dependent as no physical or biological variable correlated to CSNA biomass for time series dating from 1951 to 2015 have been found (Sydeman et al. 2020).

Harvest Control Rules

The CPS FMP includes a default harvest control for stocks without a stock-specific harvest control rule (HCR). The default HCR, which is currently used for CSNA, includes an OFL based on a species-specific MSY proxy. The default ABC control rule consists of a 75 percent reduction from OFL to ABC. The ACL is determined by the PFMC and may be equal or lower than the ABC.

E_{MSY} was estimated in the base model, which assumed a fixed steepness value of 0.6, to be 0.493 (see Appendix E). Note that E_{MSY} was calculated to be catch/summary age-1+ biomass and not the fully selected fishing mortality corresponding to MSY. In this case, E_{MSY} can exceed 1 because selectivity for age-0 fish is non-zero.

The STAT preferred the short-term model based on the period of greatest data availability for the AT survey from 2015 to 2021, and the fact that the longer-term model was less stable. A ten-year time series of biomass estimates is required under the anchovy management framework adopted in COP 9, schedule 3 for determination of the average biomass component of the OFL. The biomass estimates resulting from the shorter-term revised base model provide fewer years for estimating the average biomass. Surveys for short-term biomass are better informed given data availability in the recent past, and more years of data can be added to update the OFL and ABC with a longer-term average biomass from a longer time series. The management quantities can be informed with the current short-term assessment model but could be revisited when additional data are available from 2015 to 2025, and assessment considerations are addressed. Final recommendations will come from the SSC.

Management Performance

The CSNA fishery has been managed by the Pacific Fishery Management Council since 1978. Regulations currently described in the fishery management plan (FMP) designate the northern anchovy fishery as 'monitored', not 'actively managed', due to relatively low fishery demand (PFMC 1990). The FMP is currently being revised to remove the 'active' and 'monitored' management categories, and more regular assessments of the CSNA are anticipated. The default MSY control rule in the FMP gives an ABC for the entire stock equal to 25 percent of the MSY catch. An estimated 82 percent of the stock is assumed to be resident in U.S. waters. ABC in U.S. waters is 25,000 mt. NMFS issued a new rule in response to a 2020 court decision (Oceana, Inc. v. Ross et al.), implementing an OFL of 119,153 mt, an ABC of 29,788 mt, and an ACL of 25,000 mt. The fishery has not caught this default amount since the onset of federal management. Harvests in major fishing regions from Ensenada to Central California (CCA) are provided in Table ES-1 and Figure ES-5. The U.S. HG/ACL values and catches since the onset of federal management are presented in Table ES-5.

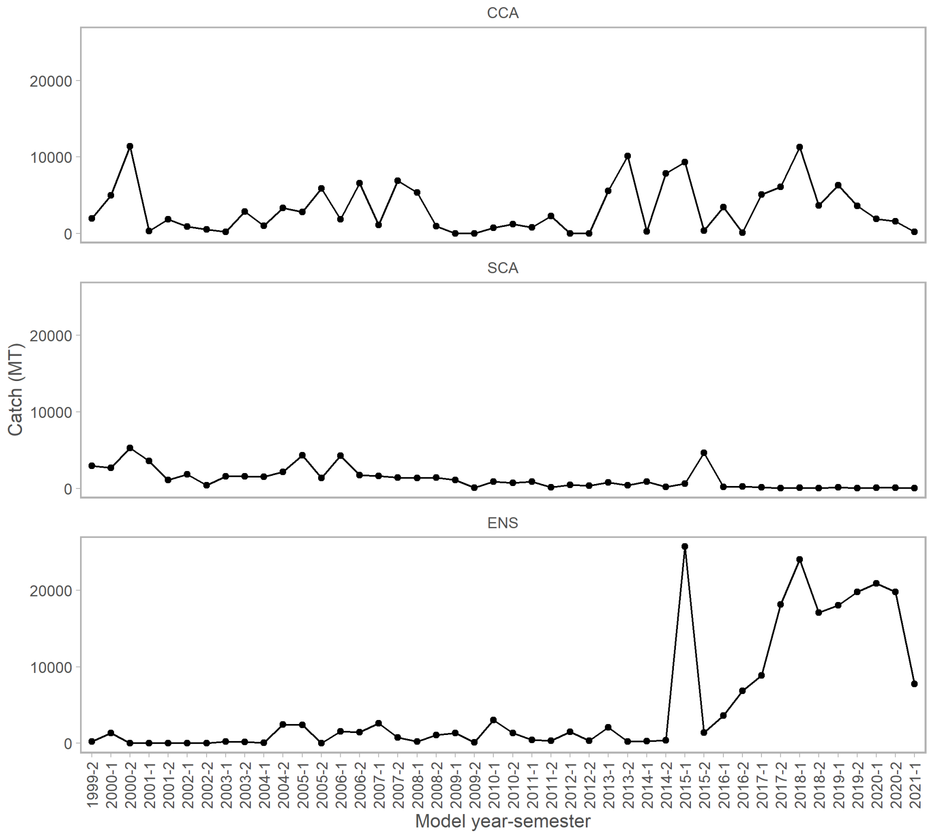

Figure ES-5: CSNA landings (mt) by major fishing region (Central California, Southern California, and Ensenada, Mexico).

Table ES-5: US CSNA landings (mt) by model year (beginning June 1). CSNA has been considered a monitored species with an OFL of 100,000 mt and ABC and ACL equal to 25,000 mt in most years. The 2021 ABC was 29,788 mt.

Model year	OFL	ABC/ACL	US Landings	Percentage ACL
1999	100,000	25,000	4,915	20
2000	100,000	25,000	24,363	97
2001	100,000	25,000	6,884	28
2002	100,000	25,000	3,617	14
2003	100,000	25,000	6,174	25
2004	100,000	25,000	8,096	32
2005	100,000	25,000	14,383	58
2006	100,000	25,000	14,437	58
2007	100,000	25,000	11,049	44
2008	100,000	25,000	9,120	36
2009	100,000	25,000	1,184	5
2010	100,000	25,000	3,604	14
2011	100,000	25,000	4,073	16
2012	100,000	25,000	787	3
2013	100,000	25,000	16,843	67
2014	100,000	25,000	9,191	37
2015	100,000	25,000	14,987	60
2016	100,000	25,000	3,971	16
2017	100,000	25,000	11,382	46
2018	100,000	25,000	15,069	60
2019	94,290	23,573	10,095	43
2020	94,290	23,573	3,688	16
2021	119,153	25,000	265	1

Research and Data Needs

Nearshore biomass, particularly the area inshore of the past AT survey footprint, will likely be an uncertainty when the anchovy population declines to low levels. There have been methodological improvements to the AT nearshore survey and aerial survey, and such refinements should continue.

The distribution of anchovy across the US-Mexico border will be a research need, particularly when the population drops to low levels. The summer 2021 AT survey was able to survey in Mexican waters, and hopefully such efforts will continue.

Ageing consistency remains a research need, that the SWFSC and CDFW are committed to working on in the future.

Habitat separation may be one research need, although northern and central subpopulation anchovy seem to be well separated given recent survey cruise reports (e.g. Stierhoff et al. 2019). This will continue to be revisited in the future.

1 Introduction

1.1 Distribution, Migration, Stock Structure, Management Units

Northern anchovy (*Engraulis mordax* Girard) are distributed from northern British Columbia, Canada to the Gulf of California, Baja California Sur, Mexico. Past studies support a hypothesis for three subpopulations along the west coast of North America based on meristic and serological evidence (McHugh 1951, Vrooman et al. 1981): 1) a northern subpopulation ranging from the Queen Charlotte Islands, British Columbia, to Cape Mendocino, California; 2) a central subpopulation ranging from approximately Point Reyes, California, to Punta Baja, Baja California; and 3) a southern subpopulation, ranging from Sebastian Vizcaino Bay to the Gulf of California Figure 1. The central subpopulation of northern anchovy is typically found in waters ranging from 11° to 29° C (Lo 1985). The subpopulations do not seem to be genetically distinct (Lecomte et al. 2004). The following assessment is focused on fishery and survey information available for the central subpopulation of northern anchovy (CSNA).

1.2 Life History Features Affecting Management

Northern anchovy life history information is available in Baxter (1967), Frey (1971), PFMC (1983), PFMC (1990), and references cited below. Northern anchovies are small, short-lived fish typically found in schools near the surface. They rarely exceed four years of age and 18 cm total length, although individuals as old as seven years and 23 cm have been recorded. Natural mortality is thought to be relatively high (e.g. M 0.8 yr^{-1} in Jacobson et al. 1994), which means that about 55% of the total stock would die each year of natural causes in the absence of fishing. There is a great deal of regional variation in age compositions (number of fish in each age group) and size at age, with older fish and larger fish found at relatively offshore and northerly locations, probably due to northern and offshore migration of large fish, regional differences in growth rate, and water temperature (Parrish et al. 1985).

Northern anchovy are all sexually mature at age two. The fraction of one year old fish that is sexually mature each year is theorized to depend on water temperature and has been observed to range from 47 to 100 percent (Methot 1989). Northern anchovy can spawn during every month of the year, but spawning increases during late winter and early spring and peaks during February to April. Spawning has been observed over a wide temperature range (12° to 22° C), but the preferred temperature is 14 °C and eggs are most abundant at temperatures of 12 °C to 16 °C. Individual females spawn batches of eggs throughout the spawning season at intervals as short as 7 to 10 days. Each large female spawns an estimated 20 to 30 thousand eggs annually. Spawned eggs are found near the surface, and require two to four days to hatch, depending on water temperature.

Information about long-term (ca 300 to 1970) changes in CSNA abundance is available from scales counted in sediment cores taken from the Southern California Bight (Soutar and Isaacs 1974, Baumgartner et al. 1992). These data indicate significant anchovy populations existed throughout the time period and that biomass levels during the late 1960s were modest relative to those during most of the previous two centuries. Sediment scale data indicate that CSNA tend to fluctuate less widely over time compared to Pacific sardine (Baumgartner et al. 1992).

Estimates of CSNA biomass (ages 1+) and recruitment were last provided by Jacobson et al. (1994, 1995). Biomass averaged 326,000 mt from 1963 through 1972, increased rapidly to over 1.54 million mt in 1974 and then declined to 326,000 mt in 1978. Since 1978, biomass levels have tended to decline slowly, falling to an average of 262,000 mt from 1986 through 1994. Anchovy biomass during 1995 was estimated to be 388,000 mt (Jacobson et al. 1995). Recruitment of CSNA is more variable than for most clupeoid fish (Beddington and Cooke 1983, Myers et al. 1990).

Northern anchovy have high fecundity and were recently estimated to have daily specific fecundity of 29 eggs per gram of population weight per day (Dorval et al. 2018). In high density spawning areas, this value was 41 eggs per gram of population weight per day and 4 in low density areas (Dorval et al. 2018).

Anchovy distributions tend to vary based on life stage. Anchovy are filter feeders consuming various planktonic species. Young of year are typically found in nearshore waters, juveniles are both further offshore and nearshore, and adults are mostly offshore (Parrish et al. 1985). Geostrophic flow and depth at which maximum chlorophyll a occurs are two important predictors in habitat models of anchovy spawning habitat (Weber and McClatchie 2010).

1.3 Ecosystem Considerations

Juvenile anchovies, generally distributed inshore, are vulnerable to a variety of predators, including birds and some recreationally and commercially important species of fish (Szoboszlai et al. 2015, Koehn et al. 2016). As adults offshore, anchovies are fed upon by numerous marine fishes (some of which have recreational and commercial value), marine mammals, and birds such as the California brown pelican (Koehn et al. 2017). Northern anchovy eat plankton either by filter feeding or biting, depending on size of the food. Adult anchovy are known to filter anchovy eggs and it is possible that this type of cannibalism is an important factor in regulating population size.

Ecosystem linkages to CSNA productivity are poorly understood. Until recently, it has generally been assumed that anchovy increase productivity under cooler ocean conditions and sardine under warmer ocean conditions (Chavez et al. 2003), but the current CSNA boom that began amid two marine heat waves seems to contradict this assumption (Thompson et al. 2019). Sardine and anchovy under warm and cold ocean regimes were thought to fluctuate asynchronously (Chavez et al. 2003), although analysis of sardine and anchovy time series across the world did not find evidence of widespread asynchrony (Siple et al. 2020). Environmental drivers may be density-dependent as no physical or biological variable correlated to CSNA biomass for time series dating from 1951 to 2015 have been found (Sydeman et al. 2020).

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

1.4.1 California's commercial fishery

Official records of California landings of northern anchovy date from 1916. Anchovy landings were small until the scarcity of Pacific sardines caused processors to begin canning anchovies in quantity during 1947, when landings increased to 8,586 mt from 780 mt in 1946. A portion of the catch was reduced for fish meal and oil (Frey 1971). Anchovy landings declined with the temporary resurgence of sardine landings around 1951. Following the collapse of the sardine fishery in 1952, anchovy landings increased to nearly 39,000 mt in 1953, but subsequently declined due to low consumer demand for canned anchovy and to a temporary increase in sardine landings. During the early years (1916 through 1964), anchovy were harvested almost exclusively by California commercial roundhaul fishermen. Beginning in 1965, the California Fish and Game Commission managed anchovy using a reduction quota. Increases in abundance and in prices for fish meal and oil raised reduction landings to record highs by the mid-1970s. In 1965, only 155 mt of anchovy were landed for reduction, which increased to an average of over 58,000 mt per year between 1965 and 1982. After 1982, reduction landings decreased dramatically to an average of only 837 mt per year from 1983 to 1991. During the period 1995 to 1999, only four tons were reported as reduction landings. Decreased prices of fishmeal and the low prices offered to fishermen have deterred any significant reduction fishing in recent years.

California's commercial anchovy fishery today differs from the historical one. There is virtually no reduction capacity in California, which is one reason why landings have averaged less than 10,000 mt a year since the mid-1980s. The commercial fishery is currently focused in the Monterey area, with three large processors and 12 to 15 vessels that utilize anchovy when market squid are unavailable. Southern California's commercial CPS fishery has limited markets for anchovy due to their typically small size in that region. Anchovy currently landed by Monterey's directed commercial fishery are used as dead frozen bait, fresh fish for human consumption, exported for canning and human consumption, as animal food, and anchovy paste. The anchovy fishery operates in a very limited area, close to the ports of Monterey and Moss Landing, with short travel distances required for maintaining the product quality. From 2000-2019, California's commercial landings of anchovy have averaged 4,419 mt annually.

1.4.2 California's live bait fishery

California's live-bait fleet is distributed mostly along the southern California coast to serve the sport fishing markets in Los Angeles, Orange, and San Diego counties. Anchovy harvested by the live bait fishery are not landed but kept alive for sale to anglers as bait. Transactions between buyers and sellers of live bait take at bait wells tied up at docks. Live bait dealers generally supply bait to commercial passenger fishing vessels (CPFVs) on a contract basis and receive a percentage of the fees paid by passengers. Bait is also sold by the "scoop" to anglers in private vessels.

Modest amounts of anchovy were harvested for live bait before World War II. Live bait harvests fell to zero during the war years. Historically, the anchovy live bait catch ranged from 3,600 to 7,300 mt per year and averaged approximately 4,100 mt annually between 1974 and 1991. Anchovies comprised approximately 85 percent of the live bait catch prior to 1991. Pacific sardines became available to the live bait fishery again in 1992, so live bait catches shifted from anchovy to primarily sardine. California's live bait anchovy catch ranged from 91 to 1,519 mt between 2000 and 2019, averaging 700 mt per year, comprising about one quarter of all live bait catch.

1.4.3 Mexico's commercial fishery

The CPS fishery based in Ensenada, Baja California, did not begin harvesting anchovy until 1962. Anchovy have historically been used primarily for reduction in Mexico. Mexico's harvesting and processing capacity increased significantly in the late 1970s when several large seiners were added to the fishing fleet and a large reduction plant was constructed by 'Pesquera Zapata' in Ensenada. Mexican anchovy landings averaged approximately 77,600 mt from 1962 to 1989, with a peak of over 260,000 mt in 1981. Northern anchovy catch decreased sharply in 1990, and despite landing 17,800 mt in 1995, average annual Mexican landings from 1990 to 1999 were only 3,300 mt per year. Landings remained at low levels from 2000-2009, averaging 1,600 mt year. Over the past decade (2010-2020), anchovy landings have increased by an order of magnitude to an average of ˜15,900 mt per year, with a peak of 42,200 mt in 2018 (CONAPESCA 2020). Although fisheries in Mexico and the U.S. both harvest CSNA, there is no bilateral management agreement with Mexico. The Mexican fishery is managed independently and is not restricted by a quota at present.

1.5 Recent Management Performance

The U.S. northern anchovy central subpopulation fishery has been managed by the Pacific Fishery Management Council since 1978. Regulations currently described in the fishery management plan (FMP) designate the northern anchovy fishery as 'monitored', not 'actively managed', due to relatively low fishery demand (PFMC 1990). The FMP is currently being revised to remove the 'active' and 'monitored' management categories, and more regular assessments of the CSNA are anticipated. The default MSY control rule in the FMP gives an ABC for the entire stock equal to 25 percent of the MSY catch. An estimated 82 percent of the stock is assumed to be resident in U.S. waters. The ABC in U.S. waters is 25,000 mt. NMFS issued a new rule in response to a 2020 court decision (Oceana, Inc. v. Ross et al.), implementing an OFL of 119,153 mt, an ABC of 29,788 mt, and an ACL of 25,000 mt. The fishery has not caught this default amount since the onset of federal management. Harvests in major fishing regions from Ensenada to Central California (CCA) are provided in Table 1 and Figure 2. The U.S. HG/ACL values and catches since the onset of federal management are presented in Table 2.

2 Data

The available data between 2015 and 2021 are shown in Figure 3. Note, that there were alternative indices of abundance considered, but only the AT_summer and AT_spring indices were included in the base model.

2.1 Fishery-Dependent Data

Available fishery data include commercial landings and biological samples from three regional fisheries: Ensenada (ENS), Southern California (SCA), and Central California (CCA) (Table 1). Standard biological samples include individual weight (kg), standard length (cm), sex, maturity, and otoliths for age determination. A complete list of available port sample data by fishing region, model year, and season is provided in Table 3.

All fishery catches and compositions were compiled based on the anchovy's biological year ('model year') to match the June 1st birth-date assumption used in age assignments (Schwartzkopf et al. 2021). For example, model year 2005 spans June 1, 2005 to May 31, 2006. Semester 1 spans June to December (7 months) and semester 2 spans January to May (5 months). Major fishery regions were pooled to represent two "MexCal" fleets, each with semester-based selectivities (Table 4), and the fishery age compositions were modeled with time-varying selectivity (see Section 3.2.7).

2.1.1 Landings

Final Ensenada monthly landings from 2000-2018 were taken from CONAPESCA's web archive of Mexican fishery yearbook statistics (CONAPESCA 2020). Monthly landings for 2018 to 2021 were provided by INAPESCA (Concepción Enciso-Enciso, pers. comm.).

California (SCA and CCA) monthly commercial landings were obtained from the PacFIN database (2000-2021). Values for the aggregated semester-based fleets are presented in Table 4 and in Figure 4. For forecasting beyond the model time frame for model year 2021-1 and 2021-2, landings were assumed to be the same as those from 2020-1 and 2020-2, respectively.

2.1.2 Age compositions

Age compositions for each fishing fleet and semester were the sums of catch-weighted age observations, with monthly landings (number of fish) within each port and season serving as the weighting unit. The following steps were used to develop the weighted age composition time series:

1. Determine the number of individuals measured for each year, semester, month, and age, as well as the number of samples taken (samples = fishing trips = unique combination of day-month-year-sample id).
2. Calculate total and average monthly catch weights, as well as average monthly weight-at-age estimates (in mt to match fishery catch units).
3. Average monthly weight-at-age estimates and multiplied by the number of specimens measured. Age-group proportions were these values divided by total monthly catch weight.
4. Multiply age-group proportions by the total monthly catch to produce the total weight (mt) of each age group in the fishery catch per month.
5. Calculate number of fish per age group by month by taking result of step 4 and dividing by the average monthly weight of each age group calculated in step 2.
6. Aggregate monthly calculations of numbers of fish to fishing semesters to produce the numbers of fish-at-age per fishing semester and subsequently summed across ages to produce the total number of fish landed per fishing semester.
7. Divide the result in step 6 by the total number of fish per year produced in the final weighted age composition time series (in proportion) for each fishing year.

Total numbers for ages observed in each fleet-semester stratum were divided by the typical number of fish collected per sampled load (25 fish per sample) to set the sample sizes for compositions included in the assessment model. Age compositions were input as proportions and presented in Figures 5-7.

Northern anchovy are routinely aged by fishery biologists at CDFW and the SWFSC based on the number of annuli, defined to be the interface between an inner translucent growth increment and outer opaque growth increment (Fitch 1951, Collins 1969, Yaremko 1996).

Note, the birth date is assumed to be June 1st. Ageing error vectors were calculated based on the methodology described in Punt et al. (2008). Further details on the ageing methodology, increment analysis, and edge analysis are available in Schwartzkopf et al. (2021). The ageing error vectors are shown in Figure 8.

2.1.3 Empirical weight-at-age

Fishery mean weight-at-age estimates were calculated based on semester-specific fleets. There were no composition data for MexCal_S2 for model year 2016. In this case, the age-0 weight-at-age (reference cohort year 2016 on the right side of Figure 9) was calculated based on the average (mean over all years) of other age-0 fish from the MexCal_S2 fleet. The age-4+ value (reference cohort year 2012) was calculated based on the average age-4+ values for the MexCal_S2 fleet (Figure 9). Missing weight-at-age values were linearly interpolated based on cohorts when calculated for ages 1-3. There was no other smoothing or filling of other weight-at-age values.

2.2 Fishery-Independent Data: Acoustic-Trawl Survey

This assessment uses a single time series of biomass based on the SWFSC's AT survey. This survey and estimation methods were vetted through formal methodology review processes in February 2011 and January 2018 (PFMC 2011, 2018, Simmonds 2011). Preliminary results from the Summer 2021 survey are shown in Figures 10 and 11. Time series of the indices of abundance input to the assessment are shown in Figures 12 and 13.

2.2.1 Index of abundance

The SWFSC acoustic-trawl survey is conducted in summer and sometimes in spring. Data from summer cruises in 2015-2021 and spring cruises in 2017 and 2021 are the primary fishery-independent data source used in this assessment (Stierhoff et al. 2019, 2021a, 2021b, Zwolinski et al. 2019, Stierhoff et al. 2020a, 2020b). Abundance by length and abundance by age are shown in Tables 5 and 6. The survey in 2015 was the first considered to have a suitable estimate of CSNA biomass. This was due to relatively sparse anchovy samples in trawls from surveys before 2015 (at the time, Pacific sardine were dominant and anchovy were less abundant).

The summer 2015 survey totaled 2,614 nmi from Cape Scott, BC to San Diego, CA with 62 daytime east-west transects, 158 nighttime surface trawls and 57 trawl clusters (Stierhoff et al. 2021a). CSNA biomass was estimated to be 10,528 mt (CI95%=3,210 to 19,787; CV=42%)

The summer 2016 survey totaled 4,590 nmi from Cape Scott, BC to San Diego, CA with 100 daytime east-west transects, 118 nighttime surface trawls and 50 trawl clusters (Stierhoff et al. 2021b). CSNA biomass was estimated to be 150,907 mt (CI95%=32,843 to 317,457; CV=51%).

The spring 2017 survey (model year-semester 2016-2) estimated CSNA biomass to be 173,973 mt with a CV of 0.33. The survey document is not available, but the values were calculated with the same methods as other cruises (Stierhoff pers. comm.).

The summer 2017 survey totaled 3,506 nmi from Cape Scott, BC to Morro Bay, CA with 103 daytime east-west transects, 84 nighttime surface trawls and 36 trawl clusters (Zwolinski et al. 2019). CSNA biomass was estimated to be 153,460 mt (CI95%=2,628 to 264,009; CV=45%).

The summer 2018 survey totaled 5,202 nmi from Cape Scott, BC to Morro Bay, CA with 136 daytime east-west transects, 170 nighttime surface trawls and 65 trawl clusters (Stierhoff et al. 2019). CSNA biomass was estimated to be 723,826 mt (CI95%=533,548 to 1,015,782; CV=17%).

The summer 2019 survey totaled 5,941 nmi from Cape Scott, BC to San Diego, CA with 118 daytime east-west transects, 163 nighttime surface trawls and 61 trawl clusters (Stierhoff et al. 2020b). CSNA biomass was estimated to be 769,154 mt (CI95%=559,915 to 984,059; CV=14%). Nearshore biomass with coupled fishing vessel acoustic and trawl sampling had an estimated biomass value of 41,480 mt (CI95%=27,402 to 82,206; CV=34%).

The spring 2021 (model year-semester 2020-2) survey estimated CSNA biomass to be 1,358,587 mt with CV of 0.17. These values are preliminary as the spring 2021 cruise summary document has yet to be finalized (Stierhoff pers. comm.).

The summer 2021 (model year-semester 2020-1) survey estimated CSNA biomass to be 2,357,000 mt with CV of 0.15. These values are preliminary and were incorporated with approval from SWFSC leadership and review by the STAR panel. At this time (June 2022), the core and nearshore survey estimates and associated survey report have not been finalized (Stierhoff pers. comm.).

2.2.2 Age compositions

Estimates of abundance-at-length were converted to abundance-at-age using survey-specific age-length keys for the summer surveys (Figure 14). Age-length keys were constructed using ordinal generalized additive regression models from the R package mgcv (Wood 2017). A generalized additive model with an ordinal categorical distribution fits an ordered logistic regression model in which the linear predictor provides the expected value of a latent variable following sequentially ordered logistic distributions. Unlike previous iterations in which the conditional age-at-length was modeled as a multinomial response function 'multinom' from the R package 'nnet', and hence, disregarding the order of the age classes, the order logistical framework provides a more strict structure for the conditional age-at-length, which might, arguably, be beneficial with small sample sizes. The survey age compositions were weighted (i.e input sample sizes in Stock Synthesis) by the number of positive clusters in each cruise. This is in contrast to the calculation for the fishery age compositions, which considered a sample to be the number of total aged fish / 25. More details on processing of the survey age compositions are included in Appendix A.

2.2.3 Ageing error

Ageing error vectors were calculated based on the methodology described in Punt et al. (2008). Further details on the ageing methodology, increment analysis, and edge analysis are available in Schwartzkopf et al. (2021). The ageing error vectors are shown in Figure 8. There were three ageing error vectors calculated for calendar years 2015-2016, 2017-2018, and 2019-2021 (Table 7).

2.2.4 Empirical weight-at-age

AT survey weight-at-age time series (Figure 9) 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. There were no missing weight-at-age values for the AT Survey, and no interpolations or averages (e.g. for MexCal_S2) were necessary.

2.3 Nearshore sampling

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

With model extrapolation, the easternmost portions of transects are extrapolated to the 5-m isobath in the unsampled nearshore areas. Thus, the length and species compositions associated with the end of the transects are extrapolated to the 5-m isobath. Generally, for CSNA there have been a small number (on the scale of 1-5) biomass densities observed at the end of all transects and extrapolated nearshore.

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

Fishing vessel acoustic-trawl methods involve equipping vessels with acoustic echosounders and conducting a maximum of one purse seine set during daylight hours. In the case of abundant coastal pelagic species or an unsuccessful daytime set, a set is conducted at night. Weights and lengths are recorded and otoliths collected for up to 50 randomly selected specimens of Pacific sardine and Northern anchovy. This survey protocol and the subsequent biomass calculation most closely matches the methods used in the core grid of the AT survey.

The California Department of Fish and Wildlife has conducted an aerial survey off the coast of central and southern California. The challenge with standardizing these data is that the spatial coverage of the surveys has varied year to year. Additionally, there has been a temporal and spatial mismatch between the aerial surveys and associated biological sampling. The AT survey can in some cases have acoustic observations and biological sampling separated by a day or two, whereas the aerial observations and associated biological samples have occurred weeks to months apart. There are age compositions associated with the aerial observations (Lynn et al. 2021), but there are technical challenges in incorporating these data to the assessment model.

The nearshore AT survey abundance values came from model extrapolation for model years 2015-1, 2016-1, and 2017-1. No 2016-2 AT nearshore value was available. 2018-1 nearshore AT values came from USVs and model extrapolation, and the 2019-1 value was from F/V acoustic-trawl surveys. The 2019-1 AT nearshore value was estimated to be 41,480 mt (Table 8), about 5% of the core survey area abundance estimate of 754,396 mt (Stierhoff et al. 2020b). The 2020-2 AT nearshore value was 13,047 mt and the AT core value was 1,358,587 mt. The 2020-2 value and 2021-1 AT core values are preliminary, and the 2021-1 AT neashore value is not yet available.

The AT core observation in model year-semester 2016-2 was adjusted based on the aerial observation. The adjustment was a multiplier on the spring catchability Q, calculated based on the AT core / (AT core + aerial value). This resulted in a lnQ value of -0.547 compared to -0.545 for the later spring observation. This approach was used in the 2020 Pacific sardine benchmark assessment (Kuriyama et al. 2020) which incorporated aerial survey data as an adjustment on the catchability (Q) associated with the AT survey. For sardine, the 2019 summer AT biomass observation was 33,138 mt, and the AT nearshore estimate was 494 mt. The aerial survey from summer 2019 had an estimated biomass of 12,279 mt. Because sardine biomass was so low, nearshore uncertainty was likely a greater issue than it would be with relatively high sardine biomass.

Biomass observations from the AT nearshore and aerial survey methods are in general agreement (Figure 15), and anchovy biomass in the AT survey has increased from 2015-2021 (Figure 12 and 13). Note that the surveys are not covering the same areas. The differences in mean biomass estimates between the AT methods is relatively small, particularly considering the AT survey estimates from 2018, 2019 and spring 2021 (Figure 16).

Nearshore sampling, particularly with consistent spatial coverage, sampling protocols, and closely-timed biological sampling (and ageing) is an important data source, and nearshore data collection efforts should continue. Uncertainty regarding nearshore and offshore anchovy distribution is likely to a more problematic when population biomass is low as it was for Pacific sardine. Currently, anchovy biomass seems to be high and distribution seems to be concentrated within the AT survey area.

2.4 Biological Parameters

2.4.1 Stock structure

Fishery and survey observations from central California, southern California, and Ensenada, Mexico were assumed to be from the central subpopulation. There is currently no habitat modeling nor analysis of size-at-age to distinguish central from northern and southern subpopulation anchovy. The distributions of northern and central subpopulations do not seem to overlap; northern spans Westport, WA to Coos Bay, OR, and central spans Fort Bragg, CA to San Diego, CA (Stierhoff et al. 2020b). Preliminary analysis of the summer 2021 acoustic-trawl cruise found that the presumed central subpopulation anchovy distribution ended in northern Baja California, Mexico, and nearly all central subpopulation anchovy were observed in US waters (forthcoming 2021 cruise report).

2.4.2 Growth

Size-at-age from fishery samples and survey samples provided no indication of sexual dimorphism related to growth (Figure 17), so combined sexes were included in the present assessment with a sex ratio of 50:50.

The assessment model used empirical weight-at-age values to account for anchovy growth. This approach is similar to that used in assessments of Pacific sardine (e.g. Kuriyama et al. 2020). Growth estimation for anchovy may be difficult due to growth variation in time and space and potential confounding of length-based selectivity and growth estimates. Growth estimation internal to SS3 was evaluated in the development of the base model but ultimately not included due to the greater number of parameters.

2.4.3 Maturity

Maturity was modeled with a fixed vector of fecundity multiplied by maturity at age. To estimate maturity at age, the equation:

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

was fit to age and maturity for female anchovy collected in the spring 2017 and 2021 acoustic-trawl surveys. Reproductive state was established through histological examination (n=701, Schwartzkopf et al. 2021).

Parameters for the logistic maturity function were slope = -1.62 and $age_{inflection} = -0.6$. Note that these values are not used in SS3 model as growth was not internally estimated. Based on the model estimates, 73% of age-0, 93% of age-1, 99% of age-2 and 100% of age-3+ fish are mature. These values were input as fixed as part of the weight-at-age file in Stock Synthesis. Fecundity was assumed to be fixed at 1 g egg per gram body weight.

2.4.4 Natural mortality

Natural mortality (M) is likely high for northern anchovy, similar to other small pelagic species which rarely become more than seven years old (Hoenig 1983). MacCall (1973) estimated instantaneous natural mortality to be 1.06 yr^{-1}, resulting in 65% mortality in the population each year. Methot (1989) assumed M to be 0.6 yr^{-1}, but estimates of biomass were not greatly affected by changing the value of M. Jacobson (1994) assumed M to be 0.8 yr^{-1}. In nature, M may be age- (or size-) specific and dependent on the population size. Estimates of M from catch curves are likely confounded by spatiotemporal variability in sampling and anchovy availability to fishing gear.

2.5 Available Data Sets Not Used in Assessment

The STAT considered assessment models that spanned 2000 to 2020 and contained alternative fishery-independent indices of relative abundance. The current base model spans 2015 to 2021 (calendar years) to align with the time series of available AT survey observations. Catch records for both fishing fleets are available back to 2000, but fishery age compositions only date back to calendar year 2013. Anchovy have relatively short life spans (maximum modeled age of 3 in the base model), there may not be many benefits to an extended model. A longer model may better estimate scaling parameters such as R_0 and M. Additionally, there may be better estimates of reference points (e.g. MSY values) as the model incorporates data from low and high periods of abundance.

John Field, Tanya Rogers, Rebecca Miller, and Keith Sakuma (SWFSC) provided indices of abundance from the Rockfish Recruitment and Ecosystem Assessment Survey (RREAS). The survey dates back to 1983 off central California, but beginning in 2004 coverage expanded into the Southern California Bight (see Appendix B). Length-composition data (assumed to be age 0) are available but were not evaluated in alternative models. The alternative model considered by the STAT used the anchovy young-of-year index as a recruitment index (survey units of 33 in Stock Synthesis), and fixed steepness, estimated M, and estimated R_0 (σ_R fixed at 1). For this alternative model, weight-at-age values for the RREAS index were from the AT survey.

Data from the California Cooperative Oceanographic Fishery Investigations (CalCOFI) survey began in 1951, although only data from 2000 to 2020 were considered in alternative model configurations. CalCOFI collects larval and egg data, and both indices were standardized with a delta-GLM. Egg data were also standardized with a vector autoregressive spatio-temporal (VAST) model (Thorson 2019). The standardized data sets showed similar trends from 2000 to 2020. More details on the data and modeling are available in Appendix C.

Alex Curtis (SWFSC) provided sea lion scat data collected on the Channel Islands in the Southern California Bight (see Appendix D). The STAT standardized the data with a delta-GLM but ultimately the data were not evaluated in alternative models. There were concerns regarding the ability of a delta-GLM to capture the sea lion sampling process and sea lion preferences for anchovy over other prey species.

The STAT focused on the RREAS young-of-year data in alternative model configurations. These data seemed to have potential as a recruitment index and be the most straightforward to incorporate into the assessment. CalCOFI eggs were also considered, as eggs would be an assumed proxy for spawning stock biomass. CalCOFI larvae were not evaluated thoroughly, as they would also be correlated to spawning stock biomass. However, there is likely stage-specific mortality as eggs transition to larvae, juveniles, and adults. It was not possible to explore these mortality rates further in development of this assessment. Results of alternative models are discussed at the end of the results section.

Aerial survey data were also considered as described in the Nearshore biomass section above.

3 Assessment

3.1 History of Modeling Approaches

The earliest attempts at estimating CSNA abundance used survey-based collections of eggs, larvae, and adults to back-calculate spawning stock biomass (SSB) based on the daily egg production method (DEPM) (Lasker 1985). Estimates of long-term biomass were first made available when the Stock Synthesis model was developed and implemented for this purpose (Methot 1989). The Stock Synthesis model was one of the earliest examples of fully integrated catch-at-age analyses incorporating auxiliary data on abundance (e.g., Fournier and Archibald 1982, Deriso et al. 1985). The PFMC based anchovy management on Stock Synthesis estimates until 1992, after which fishery composition data became greatly limited as the fishery declined. In addition to the loss of fishery composition data, areas of retrospective bias were identified in Stock Synthesis models, caused by using an over-parameterized model with limited data. This prompted the development of a simpler and more parsimonious model, SMPAR (Jacobson et al. 1994, 1995). SMPAR is a hybrid between simple surplus production and more complicated age-structured approaches, modeling catch and a variety of fishery-independent abundance indices but ignoring age-composition data from the fishery. SMPAR modeled the age 1+ population and age-0 recruits over time (Jacobson et al. 1994, 1995). SMPAR estimates were used for CSNA management until 1997, after which the CSNA was moved to 'monitored' status (i.e., no regular assessments) due to low catch levels and prioritization of Pacific Sardine and Pacific Mackerel management by the PFMC (PFMC 1998). More recent attempts to update the population status of CSNA have been based on ichthyoplankton density collected during CalCOFI surveys, using the assumption that egg and larval abundance is proportional to SSB in any given year (Fissel et al. 2011, MacCall et al. 2016, Thayer et al. 2017). The following benchmark assessment is the first fully integrated catch-at-age model for CSNA to be formally reviewed through the PFMC's STAR Panel process.

3.2 Model Description

3.2.1 Time period and time step

The modeled timeframe begins in 2015 and extends through 2021, to match the time periods of available data from the AT survey (Figure 3). Time steps are based on two semester blocks for each fishing year. Semester 1 spans June-December (7 months) and semester 2 spans January to May (5 months). The decision to begin semester 1 in June is informed by the assumed birthdate of June 1 for anchovy, which has earlier recruitment than Pacific sardine (Schwartzkopf et al. 2021).

The goal of this assessment is to estimate terminal year stock biomass, and for a short-lived species like CSNA, a model with a longer time frame would likely not enhance achievement of this goal. Extending the timeframe of the model may facilitate estimation of scaling parameters but does not appear to result in significantly different biomass estimates in recent years.

A ten-year time series of biomass estimates is required under the anchovy management framework adopted in COP 9, schedule 3 for determination of the average biomass component of the OFL. The biomass estimates resulting from the shorter-term revised base model provide fewer years for estimating the average biomass. Surveys for short-term biomass are better informed given data availability in the recent past, and more years of data can be added to update the OFL and ABC with a longer-term average biomass from a longer time series. The management quantities can be informed with the current short-term assessment model but could be revisited when additional data are available from 2015 to 2025, and assessment considerations are addressed. Final recommendations will come from the SSC.

3.2.2 Surveys

The AT survey is the only fishery-independent data source included in the assessment. The index of abundance, associated age-compositions, and weight-at-age values are included in this base model.

3.2.3 Fisheries

Two fisheries are included in the model, including two Mexico-California fleets separated into semesters (MexCal_S1 and MexCal_S2). Data are aggregated from three major fishing areas representing the range of CSNA distribution. The regions are northern Baja California (Ensenada, Mexico), southern California (Los Angeles to Santa Barbara), and central California (Monterey Bay). Age-based selectivity for the MexCal fleets was modeled separately for semesters 1 and 2.

3.2.4 Longevity and natural mortality

There are 4 modeled age bins representing ages 0 to 3+. Anchovy age 4 and older are infrequently observed in the fishery and survey samples (Table 3), and as a result the plus group begins at age 3. Natural mortality is likely to be high, as it is in other coastal pelagic species. Methot (1989) fixed M at 0.6 yr^{-1}, although it had been estimated to be 0.9 yr^{-1} by MacCall (1973). Jacobson (1994) assumed M to be 0.8 yr^{-1}, and this value has been used in subsequent PFMC analyses (e.g. Punt 2019 analysis of frequency of control rules and management guidelines).

The current base model estimates M and fixes steepness (h), and typically in assessments these values are negatively correlated. In development models, M was fixed at 0.8 yr^{-1} with steepness estimated. These models estimated $\log(R_0)$ at its upper limit (near 29) and steepness to be about 0.5. The resulting estimated biomass levels were unreasonably high at the end of the modeling period. As a result, the current base model fixes steepness at 0.6 and estimates M. The steepness value of 0.6 was the MLE in the model, although the likelihood profile for steepness indicated values ranging from 0.4 to 1.0 were reasonably supported by the data.

3.2.5 Growth

Empirical weight-at-age estimates by fleet/year/semester were used in the base model. Input of weight-at-age simplifies the assessment run time as an age-length growth curve (or curves) does not need to be estimated. Weight-at-age values, with relatively high numbers of sampled fish, tracks time-varying growth patterns. In development models, growth estimates had a L_{min} value of about 8 cm, L_{max} of 12 cm and high von Bertalanffy k of 1 yr^{-1}.

3.2.6 Stock-recruitment relationship

Equilibrium recruitment (R_0) and initial equilibrium offset (SR_{regime}) were estimated in the base model, and steepness (h) was fixed at 0.6. There was not much information in the data to estimate steepness, and the parameter was pre-specified as a result.

The value of average recruitment variability (σ_R) assumed in the stock-recruitment relationship was set to 1. This value was decided based on comparing likelihood values for models with different fixed values of steepness and σ_R. 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 2010-2014 (four 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 2015-2020 (S2 of each model year).

3.2.7 Selectivity

The base model estimated age-based selectivity from the fishery and AT survey age-compositions. Time-varying selectivity was implemented for both the fishery and the survey compositions. Time-varying selectivity was estimated to better capture seasonal and interannual variability in anchovy availability to gear (a proxy for movement) and to provide better fits to the age-composition data. Additionally, the Coastal Pelagic Species Advisory Subpanel (made up of primarily industry representatives) note that anchovy below a given size are not marketable.

Selectivities for the MexCal fisheries were modeled with a semiparametric form that allows for age- and time-varying selectivity (Xu et al. 2019). The other selectivity option considered was the non-parametric function with estimated age-specific values using a random walk [Option 17; Methot et al. (2021)]. Selectivity patterns from 2015-2020 were estimated because age-compositions showed year-to-year variability across some years. The semiparametric form offered more stability than the random walk option.

Following recommendations from the recent Pacific sardine benchmark review, the AT survey selectivity was modeled with time-varying age-0 selectivity and time-invariant full selectivity for ages 1+ fish. The AT survey is based on approved technical methods and an expansive sampling operation in the field using a habitat index for efficiently encountering all adult fish in the stock (Demer and Zwolinski 2014). Finally, in addition to potential biases associated with the trawling and ageing processes, the age-1+ selectivity assumption recognizes the vulnerability of adult anchovy with fully-developed swim bladders to echosounder energy in the acoustic sampling process. That is, there are three selectivity components to consider with the acoustic-trawl method: 1) fish availability with regard to the actual area surveyed each year; 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 anchovy 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 within the core survey area in any given year.

3.2.8 Catchability

Catchability (Q) was fixed at 0.930 (-0.073 in log space) for summer and 0.580 (-0.545 in log) for spring. The summer Q was calculated based on the summer 2021 AT survey, which extended off the coast of Baja California for the first time in many years. The summer Q of 0.930 was the ratio of anchovy biomass in US to the total of US and Mexican waters. The spring Q was calculated based on the biomass estimates of the spring 2021 and summer 2021 surveys, assuming no change in biomass between the surveys. Throughout the model development, Q was not estimable from the data (see likelihood profile section below).

Uncertainty in the proportion of total biomass nearshore is likely magnified when anchovy biomass is low. But in recent years, anchovy biomass has been high, and nearshore estimates (both from the AT survey and aerial methods) represent a small proportion of the total biomass. There are several technical challenges to incorporating estimates of both forms of nearshore estimates. The early nearshore estimates from the AT survey are from unmanned surface vehicles, with no associated biological sampling, and the summer 2019 and summer 2021 (which are not processed at the time of this report) nearshore estimates had coupled acoustic and biological sampling on fishing vessels. Nearshore estimates are prioritized based on the following order: 1) fishing vessel acoustic-trawl, 2) model extrapolation, and 3) aerial estimates. For this model, aerial estimates were used to adjust Q in spring 2016-2, in which neither fishing vessel acoustic-trawl nor model extrapolation values were available. The Q associated with this observation was adjusted to 0.579 from 0.580.

3.2.9 Likelihood components and model parameters

A complete list of model parameters for the base model is presented in Table 9. The total objective function was based on the likelihood components from fits to the AT survey abundance index and fits to age-compositions from the three fleets and AT survey, and catch time series (Table 10). Fits to equilibrium stock-recruitment relationship, and soft-bound penalties for specific parameters were not included in the total likelihood calculation.

3.2.10 Initial population and fishing conditions

Given the central subpopulation of northern anchovy 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 starting population dynamics calculations in the assessment model. One approach is to extend the modeled time period backwards in time to the start of the small pelagic fisheries off the U.S. west coast and in effect, ensure no fishing occurred prior to the start year in the model. In an integrated model, this method can be implemented by: 1) extending the catch time series back in time and confirming that harvest continues to decline generally as the onset of the fishery is approached; or 2) estimating additional parameters regarding initial population and fishing conditions in the model. Given assumptions regarding initial equilibrium for northern anchovy (a short-lived species with relatively high intrinsic rates of increase) are necessarily difficult to support regardless of when the modeled time period begins, as well as the extreme length of an extended catch time series (early 1900s) that would be needed in this case, the second approach was adopted in this assessment.

The initial population was defined by estimating 'early' recruitment deviations in 2011-2014, i.e., five years prior to the start year in the model. Initial fishing mortality (F) was estimated for the MexCal S1 fishery. In effect, the initial equilibrium age-composition in the model is adjusted via application of early recruitment deviations prior to the start year of the model, whereby the model applies the initial F level to an equilibrium age-composition to get a preliminary numbers-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 and Wetzel 2013, Methot et al. 2021). Ultimately, this parsimonious approach reflects a non-equilibrium analysis or rather, allows for a relaxed equilibrium assumption of the virgin (unfished) age structure at the start of the model as implied by the assumed natural mortality rate (M). Finally, an equilibrium 'offset' from the stock-recruitment relationship (R_1) was estimated (with no contribution to the likelihood) and along with the early recruitment deviation estimates, allowed the most flexibility for matching the population age structure to the initial age-composition data at the start of the modeled time period.

3.2.11 Assessment program with last revision date and bridging analysis

This section is not applicable to this assessment, as this is the first assessment of northern anchovy as part of the PFMC process.

3.2.12 Convergence criteria and status

The iterative process for determining numerical solutions in the models was continued until the difference between successive likelihood estimates was <0.00001. The total likelihood and final gradient estimates for the base model were 54.444 and 4.403e-06, respectively.

3.3 Base Model Results

3.3.1 Likelihoods and derived quantities of interest

The base model total likelihod was 54.444. Likelihood values from the age-compositions constituted the majority of the total likelihood. The forecasted summary (age 1+) biomass for June 2022 was 2,879,010 mt.

3.3.2 Parameter estimates and errors

Parameter estimates and standard errors for the base model are presented in Table 9

3.3.3 Growth

Growth parameters were not estimated in the base model. Rather, empirical weight-at-age estimates by year were used to convert estimated numbers into weight of fish for calculating biomass quantities relevant to management (Figure 9).

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

Time-varying age-based selectivities were estimated for MexCal S1, MexCal S2 and for the age-0 animals in the AT survey (Figure 18). The population age distributions (by numbers of fish) are greater than 50% age-0 fish in each year (Figure 19). Fits to the age comps for fleet MexCal_S1 were relatively good, as the flexible 2dAR selectivity was able to capture year-to-year variability in the age-compositions (Figures 20 and 21). The MexCal_S2 fleet generally caught age-0 and age-1 fish, and the flexible selectivity fit well, with the exception of 2020 which had the fewest fishery samples (Figures 22 and 23). The fishery selectivity curves likely explain the high estimated F value in 2015 (Figure 24), despite the low exploitation rates (Figure 25).

The fits to the age-compositions for the AT survey were worse than those from the fisheries, although the estimated modes generally matched the modes in the data (Figures 26 and 27). Note, that the survey selectivity only had time-varying age-0 selectivity.

3.3.5 Fit to survey index of abundance

Model fits to the summer and spring AT survey index of abundance in arithmetic space are presented in Figures 28 and 29 and in log space in Figures 30 and 31. The predicted index values were generally good (near mean estimates and within error bounds) for all values in the time series.

3.3.6 Stock-recruitment relationship

Recruitment was modeled using a Beverton-Hold stock-recruitment relationship (Figure 32). The assumed level of underlying recruitment deviation error was fixed (σ_R=1), equilibrium recruitment was estimated ($log(R_0)$=19.413) and steepness (h) was fixed at 0.6. Recruitment deviations for the early (2011-2014), main (2015-2021), and forecast (2022) periods in the model are presented in Figure 33. Asymptotic standard errors for recruitment deviations are shown in Figure 34, and the recruitment bias adjustment plot for the three periods are shown in Figure 35.

3.3.7 Population numbers- and biomass-at-age estimates

Population numbers-at-age estimates for the base model are presented in Table 11. Corresponding estimates of population biomass-at-age, total biomass (age-0+, mt) and stock biomass (age-1+ fish, mt) are shown in Table 12. On average, age 0 fish comprise 75% of the total population biomass from 2015-2021.

3.3.8 Spawning stock biomass

Time series of estimated spawning stock biomass (SSB; mt) and associated 95% confidence intervals are presented in Table 13 and Figure 36. The initial level of SSB was estimated to be 92,598 mt. The SSB has increased continuously from 2015-2021. The SSB was projected to be 1,835,140 mt in June 2022.

3.3.9 Summary (age-1+) biomass

Time series of estimated summary (age-1+) biomass are shown in Figure 37 and Table 14. The summary biomass in 2021 was estimated to be 2,090,640 mt, and the forecast biomass for June 2022 was 2,879,010 mt.

3.3.10 Recruitment

Time series of estimated recruitment abundance are presented in Tables 11 and 13 and Figure 38. The equilibrium level of recruitment R_0 was estimated to be 269,748,337 thousand age-0 fish.

3.3.11 Fishing mortality

Estimated fishing mortality (apical F) time series by fishery are presented in Figure 24. In early years of the modeling period, fishing mortality estimates are high due to catches of anchovy in Ensenada and a low estimated population size. Exploitation rate has been less than 5% since 2016 (Table 15 and Figure 25). Calendar year 2015 had an exploitation rate of 73% because the population was at low levels and US landings were about 16,000 mt and Mexico landings were about 26,000 mt.

3.4 Modeling Diagnostics

3.4.1 Convergence

Convergence was evaluated by starting model parameters from values jittered from the maximum likelihood estimates. Starting parameters were jittered by 5% and 10%, with 50 replicates for each percentage. A lower likelihood value was not found. There were no difficulties in inverting the Hessian to obtain estimates of variability, and the STAT feels that the base model represents the best fit to the data given the modeling assumptions.

3.4.2 Retrospective analysis

A retrospective analysis was not conducted due to the short timeframe of the assessment model. Typically, retrospective analyses sequentially remove up to five years of data. In this assessment only five years of AT survey data were available.

3.4.3 Historical analysis

A historical analysis was not conducted as the most recent PFMC-approved assessment was conducted in 1995 (Jacobson et al. 1995), which was before the beginning of the base model time period.

3.4.4 Likelihood profiles

There was not much information in the age compositions nor AT index of abundance to estimate steepness (Table 16 and Figure 39). Steepness was fixed at 0.6 in the base model. The steepness profiles are essentially flat between values of 0.5 and 1.0 for both the spring and summer indices of abundance (Figure 39).

None of the data sets contained information on summer catchability (Figure 40 and Table 17) no spring catchability (Figure 41 and Table 18). For summer catchability there were weak data conflicts between the age compositions and two indices of abundance. The summer Q with the lowest likelihood was about 0, which is close to the assumed value of 0.930 (although this solution was not significantly different than other values of Q). The spring Q with the lowest total likelihood at 0.1 but these values were not significantly different than those from other values of spring Q (Figure 41).

The AT survey age compositions seemed to contain the most information to estimate M although there was some conflict between these two data sets (Figure 42). With fixed h=0.6, a M=0.4 yr^{-1} had the best fit to the data (Table 19).

3.4.5 Sensitivity to alternative data weighting

The base model was run with age compositions reweighted according to the Francis method (Francis 2011) to evaluate model sensitivity to data weighting. The variance adjustment values were 4.980 for MexCal S1, 1.958 for MexCal S2, and 27.538 for for AT spring and 0.708 for AT summer (Table 20). Parameter estimates, biomass estimates, and likelihood values are shown in Table 20 and Figure 43. The model year-semester 2021-1 biomass estimates ranged from 2,090,640 mt in the base model and 2,035,610 mt with Francis reweighting (Figure 43).

The base model was also run with downweighted age compositions (lambda = 0.5 rather than 1 in the base model) to evaluate model sensitivity to data weighting. Parameter estimates, biomass estimates, and likelihood values are shown in Table 21 and Figure 44. The model year-semester 2020-1 biomass estimates ranged from 2,050,430 mt to 2,108,380 mt (Figure 44).

3.4.6 Evaluation of models with longer timeframe

The longer model considered and compared to the base model incorporated the RREAS young of year data as an index of recruitment, with a time period from 2000-2020 (model years). Main period recruitment deviations estimation started in 2000 (although the RREAS data began in 2005). The longer model estimated one InitF for MexCal S1, and assumed a fixed steepness of 0.6, as in the base model.

The biomass trajectories were similar in recent years (Figure 45), although the biomass estimates prior to relatively constant. It did not seem that many of the scaling parameters were estimable with the addition of the RREAS data as it was the only index of abundance. As a result, the model did not seem able to estimate the observation and process error from only one data set. Note, that no additional age compositions were available from the RREAS.

4 Harvest Control Rules

The CPS FMP includes a default harvest control for stocks without a stock-specific harvest control rule (HCR). The default HCR, which is currently used for CSNA, includes an OFL based on species-specific MSY proxy. The default ABC control rule consists of a 75 percent reduction from OFL to ABC. The ACL is determined by the PFMC and may be be equal or lower than the ABC.

The STAT preferred the short-term model based on the period of greatest data availability for the AT survey from 2015 to 2021, and the fact that the longer-term model was less stable. A ten-year time series of biomass estimates is required under the anchovy management framework adopted in COP 9, schedule 3 for determination of the average biomass component of the OFL. The biomass estimates resulting from the shorter-term revised base model provide fewer years for estimating the average biomass. Surveys for short-term biomass are better informed given data availability in the recent past, and more years of data can be added to update the OFL and ABC with a longer-term average biomass from a longer time series. The management quantities can be informed with the current short-term assessment model but could be revisited when additional data are available from 2015 to 2025, and assessment considerations are addressed. Final recommendations will come from the SSC.

5 Research and Data Needs

Nearshore biomass, particularly the area inshore of the past AT survey footprint, will likely be an uncertainty when the anchovy population declines to low levels. There have been methodological improvements to the AT nearshore survey and aerial survey, and such refinements should continue.

The distribution of anchovy across the US-Mexico border will be a research need, particularly when the population drops to low levels. The summer 2021 AT survey was able to survey in Mexican waters, and hopefully such efforts will be able to continue.

Ageing consistency remains a research need that the SWFSC and CDFW are committed to working on in the future.

Habitat separation may be one research need, although northern and central subpopulation anchovy seem to be well separated given recent survey cruise reports.

6 Acknowledgements

This anchovy assessment depends, in large part, on the diligence of many colleagues and the timely receipt of their data products. Port samples for the Ensenada, México fishery were collected by INAPESCA (Ensenada). Recent landings data from the Ensenada fishery were kindly provided by Concepción Enciso-Enciso (INAPESCA-Ensenada).

Port samples and ageing data for the California fishery were provided by CDFW Marine Region personnel in Monterey (Chelsea Protasio, Katie Grady, Evan Brunsvold, Aileen San, Dane McDermott, Katherine Hardisty), Los Alamitos (Dianna Porzio, Leeanne Laughlin, Trung Nguyen, Montana McLeod, Lindsay Hornsby, Kelly Kloos, Trevor Stocking, and Diego Aceituno), and Santa Barbara (David Gottesman and Kristen Ondrejko).

Numerous staff from the Advanced Survey Technologies, Life History, and CalCOFI groups at the SWFSC assisted in the ongoing collection and processing of ichthyoplankton samples, mid-water trawl samples, and acoustic data used in this assessment.

Thanks to Richard Methot for technical support and the Stock Synthesis team for updating and maintaining the software. Additional thanks to the STAR Panel.

7 Tables

Table 1: Northern anchovy landings (mt) for the three major fishing regions: central California, USA (CCA), southern California, USA (SCA), and Ensenada, Mexico (ENS). The values are reported for each calendar year-semester (Y-S) and model Y-S.

Calendar Y-S	Model Y-S	CCA	SCA	ENS
2000-1	1999-2	1,939	2,976	235
2000-2	2000-1	4,999	2,674	1,337
2001-1	2000-2	11,398	5,292	47
2001-2	2001-1	324	3,610	29
2002-1	2001-2	1,833	1,117	0
2002-2	2002-1	874	1,838	0
2003-1	2002-2	515	390	0
2003-2	2003-1	191	1,558	244
2004-1	2003-2	2,871	1,554	160
2004-2	2004-1	1,020	1,540	60
2005-1	2004-2	3,362	2,174	2,476
2005-2	2005-1	2,830	4,335	2,396
2006-1	2005-2	5,877	1,341	0
2006-2	2006-1	1,828	4,266	1,567
2007-1	2006-2	6,595	1,748	1,452
2007-2	2007-1	1,121	1,634	2,606
2008-1	2007-2	6,865	1,429	753
2008-2	2008-1	5,367	1,346	238
2009-1	2008-2	978	1,429	1,076
2009-2	2009-1	9	1,085	1,367
2010-1	2009-2	0	90	119
2010-2	2010-1	765	874	3,020
2011-1	2010-2	1,225	740	1,330
2011-2	2011-1	818	864	431
2012-1	2011-2	2,272	119	321
2012-2	2012-1	6	440	1,488
2013-1	2012-2	0	341	320
2013-2	2013-1	5,551	786	2,107
2014-1	2013-2	10,121	385	242
2014-2	2014-1	256	891	296
2015-1	2014-2	7,861	183	392
2015-2	2015-1	9,325	645	25,751
2016-1	2015-2	384	4,633	1,389
2016-2	2016-1	3,446	170	3,619
2017-1	2016-2	119	236	6,845
2017-2	2017-1	5,098	138	8,881
2018-1	2017-2	6,112	34	18,152
2018-2	2018-1	11,277	91	24,020
2019-1	2018-2	3,680	21	17,090
2019-2	2019-1	6,323	146	18,048
2020-1	2019-2	3,612	14	19,803
2020-2	2020-1	1,895	114	20,934
2021-1	2020-2	1,601	78	19,803
2021-2	2021-1	206	59	7,782

Table 2: US CSNA landings (mt) by model year (beginning June 1). CSNA has been considered a monitored species with an OFL of 100,000 mt and ABC and ACL equal to 25,000 mt in most years. The 2021 ABC was 29,788 mt.

Model year	OFL	ABC/ACL	US Landings	Percentage ACL
1999	100,000	25,000	4,915	20
2000	100,000	25,000	24,363	97
2001	100,000	25,000	6,884	28
2002	100,000	25,000	3,617	14
2003	100,000	25,000	6,174	25
2004	100,000	25,000	8,096	32
2005	100,000	25,000	14,383	58
2006	100,000	25,000	14,437	58
2007	100,000	25,000	11,049	44
2008	100,000	25,000	9,120	36
2009	100,000	25,000	1,184	5
2010	100,000	25,000	3,604	14
2011	100,000	25,000	4,073	16
2012	100,000	25,000	787	3
2013	100,000	25,000	16,843	67
2014	100,000	25,000	9,191	37
2015	100,000	25,000	14,987	60
2016	100,000	25,000	3,971	16
2017	100,000	25,000	11,382	46
2018	100,000	25,000	15,069	60
2019	94,290	23,573	10,095	43
2020	94,290	23,573	3,688	16
2021	119,153	25,000	265	1

Table 3: Northern anchovy samples available for the fishing regions central California (CCA), southern California (SCA), and the AT survey. The numbers of fish age 5+, numbers of total fish (with length, weights, and age measurements), and the number of fishery samples (one sample corresponds to 25 fish).

Region	Calendar Y-S	Model Y-S	N age 5+	N fish	N samples
CCA	2014-1	2013-2	1	1066	42.64
	2014-2	2014-1	0	75	3.00
	2015-1	2014-2	2	982	39.28
	2015-2	2015-1	3	868	34.72
	2016-2	2016-1	0	345	13.80
	2017-2	2017-1	2	393	15.72
	2018-1	2017-2	2	583	23.32
	2018-2	2018-1	8	1291	51.64
	2019-1	2018-2	3	646	25.84
	2019-2	2019-1	10	961	38.44
	2020-1	2019-2	2	574	22.96
	2020-2	2020-1	3	374	14.96
	2021-1	2020-2	0	50	2.00
SCA	2014-1	2013-2	0	24	0.96
	2014-2	2014-1	0	22	0.88
	2016-1	2015-2	0	593	23.72
Survey	2015-2	2015-1	1	490	19.60
	2016-2	2016-1	11	732	29.28
	2017-2	2017-1	1	129	5.16
	2018-2	2018-1	14	666	26.64
	2019-2	2019-1	52	1072	42.88
	2017-1	2016-2	0	548	21.92
	2021-1	2020-2	18	879	35.16

Table 4: Northern anchovy landings (mt) for the MexCal Semester 1 and MexCal Semester 2 fleet input to the stock assessment. The base model begins in Model Y-S 2015-1 (Calendar Y-S 2015-2) although landings from before this period are shown.

Calendar Y-S	Model Y-S	MexCal_S1	MexCal_S2
2000-1	1999-2	0	5,150
2000-2	2000-1	9,010	0
2001-1	2000-2	0	16,737
2001-2	2001-1	3,963	0
2002-1	2001-2	0	2,950
2002-2	2002-1	2,712	0
2003-1	2002-2	0	905
2003-2	2003-1	1,993	0
2004-1	2003-2	0	4,585
2004-2	2004-1	2,620	0
2005-1	2004-2	0	8,012
2005-2	2005-1	9,561	0
2006-1	2005-2	0	7,218
2006-2	2006-1	7,661	0
2007-1	2006-2	0	9,795
2007-2	2007-1	5,361	0
2008-1	2007-2	0	9,047
2008-2	2008-1	6,951	0
2009-1	2008-2	0	3,483
2009-2	2009-1	2,461	0
2010-1	2009-2	0	209
2010-2	2010-1	4,659	0
2011-1	2010-2	0	3,295
2011-2	2011-1	2,113	0
2012-1	2011-2	0	2,712
2012-2	2012-1	1,934	0
2013-1	2012-2	0	661
2013-2	2013-1	8,444	0
2014-1	2013-2	0	10,748
2014-2	2014-1	1,443	0
2015-1	2014-2	0	8,436
2015-2	2015-1	35,721	0
2016-1	2015-2	0	6,406
2016-2	2016-1	7,235	0
2017-1	2016-2	0	7,200
2017-2	2017-1	14,117	0
2018-1	2017-2	0	24,298
2018-2	2018-1	35,388	0
2019-1	2018-2	0	20,791
2019-2	2019-1	24,517	0
2020-1	2019-2	0	23,429
2020-2	2020-1	22,943	0
2021-1	2020-2	0	21,482
2021-2	2021-1	8,047	0

Table 5: Abundance by standard length (cm) for AT summer surveys 2015-2019 (column names indicate model year-semester).

SL (cm)	2015-1	2016-1	2017-1	2018-1	2019-1
2	250,619,407	0	0	0	0
3	1,292,317,502	0	0	0	0
4	1,475,141,089	201,057	1,491,102	0	0
5	657,205,955	1,809,517	5,258,743	0	0
6	1,873,943,383	10,171,636	14,313,025	0	1,327,146,647
7	321,597,788	10,213,614	5,807,935	41,096,412	17,037,319,882
8	269,580,402	119,689,413	329,109,882	965,545,771	23,764,446,374
9	213,665,089	830,060,821	1,818,405,723	7,001,913,071	14,505,847,274
10	69,196,363	3,087,640,798	872,893,159	10,175,229,266	5,558,883,914
11	21,648,640	6,446,239,518	234,063,154	7,951,612,854	7,235,447,927
12	3,988,222	1,170,748,671	2,631,008,139	10,226,207,789	7,346,805,051
13	44,299	151,476,699	2,905,452,584	7,288,001,624	5,349,671,276
14	0	2,535,570	106,004,589	2,956,678,550	2,587,963,418
15	0	136,428	105,824,824	22,580,864	272,519,042
16	0	0	0	0	9,350,727
17	0	0	0	0	0
18	0	0	0	0	0
19	0	0	0	0	0
20	0	0	0	0	0

Table 6: Abundance by age for AT summer surveys 2015-2019 (column names indicate model year-semester).

Age	2015-1	2016-1	2017-1	2018-1	2019-1
0.00	6,382,846,725	3,747,020,227	2,691,781,345	15,592,332,064	55,363,648,561
1.00	35,971,945	5,244,311,678	3,864,460,391	17,133,921,069	13,356,511,132
2.00	23,218,653	1,832,204,375	361,449,845	7,489,967,728	11,265,252,029
3.00	5,212,058	703,471,103	1,717,587,093	4,749,526,624	2,289,677,487
4.00	869,555	190,315,556	394,352,262	1,126,676,589	1,905,120,589
5.00	829,173	72,456,282	976	470,723,406	653,680,483
6.00	30	41,144,521	947	65,718,720	161,511,252

Table 7: Coefficient of variation (CV) and standard deviation (SD) at age estimated for CSNA from the AT survey (2015-2021) and fishery samples (2015-2021). Note, the assessment assumed a maximum age of 3. The AT Survey 2019-2021 values account for ageing bias with input expected ages.

	Years	N	N readers	Age	Expected Age	CV	SD
AT_Survey	2015-2016	397	3	0		0.56	0.56
				1		0.56	0.56
				2		0.70	1.41
				3		0.57	1.72
AT_Survey	2017-2018	424	2	0		0.43	0.43
				1		0.43	0.43
				2		0.54	1.07
				3		0.44	1.31
AT_Survey	2019-2021	424	2	0	0.53	0.32	0.32
				1	1.15	0.32	0.32
				2	1.79	0.33	0.66
				3	2.45	0.30	0.90
MexCal	2014-2016	763	3	0		0.45	0.45
				1		0.45	0.45
				2		0.24	0.48
				3		0.22	0.66
MexCal	2017-2018	552	3	0		0.38	0.38
				1		0.38	0.38
				2		0.19	0.38
				3		0.13	0.38
MexCal	2019-2021	617	3	0		0.39	0.39
				1		0.39	0.39
				2		0.19	0.39
				3		0.13	0.39

Table 8: Fishery-independent indices of Northern anchovy abundance and associated uncertainties (CVs). Nearshore methods shown are model extrapolation (Ext.), unmanned surface vehicle (USV), and fishing vessel acoustic-trawl survey (F/V). For the 2016-2 Model Y-S value (*) there was no spring AT nearshore value and the Q for the spring survey value was adjusted based on the aerial estimate of 294 mt. The 2021-1 Model Y-S AT value (**) is preliminary.

Calendar Y-S	Model Y-S	AT Core	CV	AT Nearshore	Method	AT Total	Aerial	Qadj
2015-2	2015-1	10,528	0.42	7,180	Ext.	17,708	-	-
2016-1	2015-2	-	-	-	-	-	-	-
2016-2	2016-1	150,907	0.51	274	Ext.	151,181	-	-
2017-1	2016-2	173,973	0.33	-	-	173,973*	294	0.579
2017-2	2017-1	153,460	0.45	45,446	Ext.	198,906	-	-
2018-1	2017-2	-	-	-	-	-	-	-
2018-2	2018-1	723,826	0.17	4,110	USV/Ext.	727,936	-	-
2019-1	2018-2	-	-	-	-	-	-	-
2019-2	2019-1	769,154	0.14	41,480	F/V	810,634	-	-
2020-1	2019-2	-	-	-	-	-	-	-
2020-2	2020-1	-	-	-	-	-	-	-
2021-1	2020-2	1,358,587	0.17	13,047	F/V	1,371,634	-	-
2021-2	2021-1	2,357,000	0.15	-	F/V	2,357,000**	-	-

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

Parameter	Value	Phase	Bounds	Status	SD
NatM_uniform_Fem_GP_1	0.4142	2	(0.2, 1.5)	OK	0.1349
SR_LN(R0)	19.4128	1	(3, 30)	OK	0.9173
SR_regime_BLK1repl_2014	-2.3491	4	(-15, 15)	OK	1.0764
Early_InitAge_3	0.0006	2	(-5, 5)	act	1.0003
Early_InitAge_2	0.3452	2	(-5, 5)	act	0.9669
Early_InitAge_1	-1.1216	2	(-5, 5)	act	0.6233
Main_RecrDev_2015	0.0905	1	(-5, 5)	act	0.4154
Main_RecrDev_2016	0.0839	1	(-5, 5)	act	0.3536
Main_RecrDev_2017	-0.5938	1	(-5, 5)	act	0.3666
Main_RecrDev_2018	0.4093	1	(-5, 5)	act	0.4130
Main_RecrDev_2019	0.0432	1	(-5, 5)	act	0.6297
Main_RecrDev_2020	-0.0284	1	(-5, 5)	act	0.8728
Main_RecrDev_2021	-0.0048	1	(-5, 5)	act	0.9163
ForeRecr_2022	0.0000	5	(-5, 5)	act	1.0000
InitF_seas_1_flt_1MexCal_S1	15.4642	1	(0, 25)	OK	11.4690
AgeSel_P2_MexCal_S1(1)	0.8003	2	(-5, 9)	OK	0.5366
AgeSel_P3_MexCal_S1(1)	1.4426	2	(-5, 9)	OK	0.6465
AgeSel_P4_MexCal_S1(1)	-0.4487	2	(-5, 9)	OK	0.8684
AgeSel_P2_MexCal_S2(2)	1.6659	2	(-5, 9)	OK	0.6482
AgeSel_P3_MexCal_S2(2)	-0.3347	2	(-5, 9)	OK	0.9354
AgeSel_P4_MexCal_S2(2)	-0.4375	2	(-5, 9)	OK	1.3110
AgeSel_P2_AT_summer(3)	0.0004	4	(0, 9)	LO	0.0152
AgeSel_P2_AT_spring(7)	1.9297	4	(0, 9)	OK	1.2783
AgeSel_P2_AT_summer(3)_BLK3repl_2016	0.3314	4	(0, 9)	OK	1.2088
AgeSel_P2_AT_summer(3)_BLK3repl_2017	1.0551	4	(0, 9)	OK	1.6033
AgeSel_P2_AT_summer(3)_BLK3repl_2018	0.0003	4	(0, 9)	LO	0.0120
AgeSel_P2_AT_summer(3)_BLK3repl_2019	0.0005	4	(0, 9)	LO	0.0195
AgeSel_P2_AT_spring(7)_BLK6repl_2020	0.4445	4	(0, 9)	OK	0.5243
MexCal_S1_ARDEV_y2016_A0	0.7283	3	(-10, 10)	act	0.7872
MexCal_S1_ARDEV_y2016_A1	-0.2748	3	(-10, 10)	act	0.7959
MexCal_S1_ARDEV_y2016_A2	-0.3064	3	(-10, 10)	act	0.8613
MexCal_S1_ARDEV_y2016_A3	-0.1472	3	(-10, 10)	act	0.9424
MexCal_S1_ARDEV_y2017_A0	-0.3397	3	(-10, 10)	act	0.8544
MexCal_S1_ARDEV_y2017_A1	0.1204	3	(-10, 10)	act	0.8055
MexCal_S1_ARDEV_y2017_A2	-0.0322	3	(-10, 10)	act	0.8133
MexCal_S1_ARDEV_y2017_A3	0.2515	3	(-10, 10)	act	1.0296
MexCal_S1_ARDEV_y2018_A0	-0.4885	3	(-10, 10)	act	0.8376
MexCal_S1_ARDEV_y2018_A1	0.6529	3	(-10, 10)	act	0.7174
MexCal_S1_ARDEV_y2018_A2	-0.0095	3	(-10, 10)	act	0.7533
MexCal_S1_ARDEV_y2018_A3	-0.1549	3	(-10, 10)	act	0.7906
MexCal_S1_ARDEV_y2019_A0	-0.8400	3	(-10, 10)	act	0.8012
MexCal_S1_ARDEV_y2019_A1	0.5409	3	(-10, 10)	act	0.7325
MexCal_S1_ARDEV_y2019_A2	0.0231	3	(-10, 10)	act	0.7319
MexCal_S1_ARDEV_y2019_A3	0.2760	3	(-10, 10)	act	0.7874
MexCal_S1_ARDEV_y2020_A0	-0.4530	3	(-10, 10)	act	0.8676
MexCal_S1_ARDEV_y2020_A1	0.0503	3	(-10, 10)	act	0.7680
MexCal_S1_ARDEV_y2020_A2	0.6287	3	(-10, 10)	act	0.7726
MexCal_S1_ARDEV_y2020_A3	-0.2259	3	(-10, 10)	act	0.8218
MexCal_S2_ARDEV_y2016_A0	0.0045	3	(-10, 10)	act	1.0014
MexCal_S2_ARDEV_y2016_A1	0.0154	3	(-10, 10)	act	0.9956
MexCal_S2_ARDEV_y2016_A2	-0.0169	3	(-10, 10)	act	0.9923
MexCal_S2_ARDEV_y2016_A3	-0.0030	3	(-10, 10)	act	0.9986
MexCal_S2_ARDEV_y2017_A0	0.6645	3	(-10, 10)	act	0.7468
MexCal_S2_ARDEV_y2017_A1	-0.3090	3	(-10, 10)	act	0.7925
MexCal_S2_ARDEV_y2017_A2	-0.5884	3	(-10, 10)	act	0.8533
MexCal_S2_ARDEV_y2017_A3	0.2330	3	(-10, 10)	act	1.0285

MexCal_S2_ARDEV_y2018_A0	0.5165	3	(-10, 10)	act	0.7368
MexCal_S2_ARDEV_y2018_A1	-0.3469	3	(-10, 10)	act	0.7711
MexCal_S2_ARDEV_y2018_A2	-0.0070	3	(-10, 10)	act	0.8449
MexCal_S2_ARDEV_y2018_A3	-0.1626	3	(-10, 10)	act	0.8857
MexCal_S2_ARDEV_y2019_A0	-0.5130	3	(-10, 10)	act	0.7556
MexCal_S2_ARDEV_y2019_A1	0.3474	3	(-10, 10)	act	0.7705
MexCal_S2_ARDEV_y2019_A2	0.1354	3	(-10, 10)	act	0.8283
MexCal_S2_ARDEV_y2019_A3	0.0302	3	(-10, 10)	act	0.8872
MexCal_S2_ARDEV_y2020_A0	0.5876	3	(-10, 10)	act	0.9036
MexCal_S2_ARDEV_y2020_A1	-0.3825	3	(-10, 10)	act	0.9066
MexCal_S2_ARDEV_y2020_A2	-0.1073	3	(-10, 10)	act	0.9530
MexCal_S2_ARDEV_y2020_A3	-0.0978	3	(-10, 10)	act	0.9549

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

	Description	Value
Likelihood	TOTAL	54.444
	Catch	0
	Equil_catch	0
	Survey	-7.079
	Length_comp	0
	Age_comp	20.977
	Recruitment	0.958
	InitEQ_Regime	0
	Forecast_Recruitment	0
	Parm_priors	0
	Parm_softbounds	0.031
	Parm_devs	39.558
	Crash_Pen	0
Parameter	NatM_uniform_Fem_GP_1	0.414
	SR_LN(R0)	19.413
	SR_BH_steep	0.6
	SR_sigmaR	1
	SR_regime_BLK1repl_2014	-2.349
	InitF_seas_1_flt_1MexCal_S1	15.464
	LnQ_base_AT_summer(3)	-0.073
	LnQ_base_AT_spring(7)	-0.547
	LnQ_base_AT_spring(7)_BLK6repl_2020	-0.545
Biomass (mt)	2020 Age1+	1,389,990
	2021 Age1+	2,090,640

Table 11: Northern anchovy numbers-at-age (thousands of fish) estimated in base model year-semesters.

Calendar Y-S	Model Y-S	Age 0	Age 1	Age 2	Age 3+
–	VIRG	269,708,000	178,246,000	117,800,000	229,575,000
–	VIRG	211,820,000	139,989,000	92,516,500	180,301,000
–	INIT	25,745,900	6,530,900	512,024	41
–	INIT	7,761,050	608,468	49	0
2015-2	2015-1	25,745,900	1,557,900	702,912	41
2016-1	2015-2	18,158,800	963,070	200,483	17
2016-2	2016-1	21,009,800	14,900,000	709,199	153,358
2017-1	2016-2	16,237,200	11,549,400	527,789	115,685
2017-2	2017-1	39,546,800	13,566,000	9,353,580	528,176
2018-1	2017-2	30,945,800	10,518,200	7,010,630	398,698
2018-2	2018-1	30,643,300	25,183,800	8,278,470	6,007,900
2019-1	2018-2	23,917,600	18,942,500	5,916,920	4,479,230
2019-2	2019-1	92,894,400	19,725,700	15,240,400	8,435,840
2020-1	2019-2	72,811,300	15,221,300	11,449,100	6,387,540
2020-2	2020-1	107,169,000	60,988,400	12,090,300	14,589,500
2021-1	2020-2	84,008,900	47,567,000	9,010,690	11,296,300
2021-2	2021-1	129,427,000	70,081,000	39,335,300	16,863,300
2022-1	2021-2	101,579,000	54,956,500	30,696,200	13,190,100

Table 12: Northern anchovy biomass-at-age for base model year-semesters.

Calendar Y-S	Model Y-S	0	1	2	3+	Total Age0+	Total Age1+
–	VIRG	419,244	1,843,010	1,458,280	3,310,160	7,030,694	6,611,450
–	VIRG	3,102,910	2,484,480	1,927,320	4,228,850	11,743,560	8,640,650
–	INIT	40,020	67,528	6,338	1	113,887	73,867
–	INIT	113,690	10,799	1	0	124,490	10,800
2015-2	2015-1	40,020	16,108	8,702	1	64,831	24,810
2016-1	2015-2	266,004	17,092	4,176	0	287,273	21,269
2016-2	2016-1	226,277	198,652	10,560	2,450	437,939	211,662
2017-1	2016-2	303,643	225,777	10,688	2,383	542,490	238,847
2017-2	2017-1	318,685	270,299	202,644	11,662	803,290	484,605
2018-1	2017-2	578,701	205,619	141,962	8,212	934,494	355,793
2018-2	2018-1	285,032	400,617	171,436	144,751	1,001,836	716,804
2019-1	2018-2	447,271	370,305	119,815	92,261	1,029,652	582,381
2019-2	2019-1	470,756	261,392	294,151	201,486	1,227,785	757,029
2020-1	2019-2	1,361,610	297,560	231,839	131,568	2,022,577	660,967
2020-2	2020-1	543,097	808,175	233,352	348,465	1,933,089	1,389,992
2021-1	2020-2	890,242	758,531	192,964	293,309	2,135,046	1,244,804
2021-2	2021-1	655,890	928,664	759,198	402,773	2,746,525	2,090,635
2022-1	2021-2	1,076,430	876,369	657,360	342,483	2,952,642	1,876,212

Table 13: 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 (June).

Calendar Y-S	Model Y-S	SSB	SSB sd	Recruits	Recruits sd
–	VIRG-1	0	0	0	0
–	VIRG-2	10,685,800	12,514,700	269,708,000	247,391,000
–	INIT-1	0	0	0	0
–	INIT-2	92,598	52,012	0	0
2015-2	2015-1	0	0	25,745,900	7,001,730
2016-1	2015-2	213,162	50,714	0	0
2016-2	2016-1	0	0	21,009,800	9,480,240
2017-1	2016-2	443,476	99,593	0	0
2017-2	2017-1	0	0	39,546,800	12,836,000
2018-1	2017-2	759,613	117,717	0	0
2018-2	2018-1	0	0	30,643,300	10,092,800
2019-1	2018-2	879,476	101,516	0	0
2019-2	2019-1	0	0	92,894,400	31,484,800
2020-1	2019-2	1,625,280	285,553	0	0
2020-2	2020-1	0	0	107,169,000	52,421,600
2021-1	2020-2	1,835,140	270,099	0	0
2021-2	2021-1	0	0	129,427,000	134,584,000
2022-1	2021-2	2,586,700	718,182	0	0
2022-2	2022-1	0	0	176,376,000	230,134,000
2023-1	2022-2	3,548,420	2,003,880	0	0

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

Year	Age-0+	Age-1+
2015	64,830	24,810
2016	437,939	211,662
2017	803,290	484,605
2018	1,001,840	716,804
2019	1,227,790	757,029
2020	1,933,090	1,389,990
2021	2,746,530	2,090,640

Table 15: Annual exploitation rate (calendar year landings / June total biomass) by country and calendar year for the base model.

Calendar Year	Mexico	USA	Total
2015	0.40	0.15	0.55
2016	0.01	0.02	0.03
2017	0.02	0.01	0.03
2018	0.04	0.02	0.06
2019	0.03	0.01	0.04
2020	0.02	0.00	0.02
2021	0.01	0.00	0.01

Table 16: Parameter estimates and summary biomass (age 1+; mt) associated with values of steepness.

	Steepness							
Label	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
InitF_seas_1_flt_1MexCal_S1	19.646	17.87	15.878	15.464	15.265	15.194	15.25	15.415
LnQ_base_AT_spring(7)	-0.547	-0.547	-0.547	-0.547	-0.547	-0.547	-0.547	-0.547
LnQ_base_AT_spring(7)_BLK6repl_2020	-0.545	-0.545	-0.545	-0.545	-0.545	-0.545	-0.545	-0.545
LnQ_base_AT_summer(3)	-0.073	-0.073	-0.073	-0.073	-0.073	-0.073	-0.073	-0.073
NatM_uniform_Fem_GP_1	0.65	0.556	0.442	0.414	0.402	0.4	0.405	0.417
SR_LN(R0)	29.999	29.998	29.963	19.413	18.795	18.471	18.267	18.136
SR_regime_BLK1repl_2014	-12.422	-12.638	-12.836	-2.349	-1.763	-1.448	-1.236	-1.078
2020 Age1+ biomass	1,260,740	1,308,100	1,353,810	1,389,990	1,410,930	1,420,330	1,420,350	1,413,070
2021 Age1+ biomass	2,104,340	2,079,150	2,049,410	2,090,640	2,115,270	2,127,880	2,132,660	2,132,780
Total NLL	59.135	55.702	54.549	54.444	54.494	54.637	54.841	55.08

Table 17: Parameter estimates and summary biomass (age 1+; mt) associated with fixed values of log catchability (Q) for summer surveys.

	Catchability										
Label	-0.5	-0.4	-0.3	-0.2	-0.1	0	0.1	0.2	0.3	0.4	0.5
InitF_seas_1_flt_1MexCal_S1	25	25	25	22.148	20.166	18.379	16.77	15.324	20.909	14.198	13.796
LnQ_base_AT_spring(7)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
LnQ_base_AT_spring(7)_BLK6repl_2020	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
NatM_uniform_Fem_GP_1	0.889	0.855	0.812	0.76	0.714	0.67	0.626	0.582	0.56	0.499	0.459
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_LN(R0)	19.823	19.72	19.603	19.475	19.368	19.268	19.178	19.1	19.031	18.997	18.986
SR_regime_BLK1repl_2014	-2.287	-2.316	-2.296	-2.243	-2.238	-2.238	-2.248	-2.267	-2.293	-2.353	-2.432
2020 Age1+ biomass	1,134,750	1,078,760	1,025,480	974,259	924,806	877,203	831,292	786,908	743,332	701,981	661,047
2021 Age1+ biomass	2,674,180	2,469,640	2,268,480	2,076,290	1,903,750	1,744,290	1,597,300	1,462,100	1,340,500	1,224,080	1,119,690
Total NLL	54.417	54.2	53.923	53.663	53.552	53.512	53.545	53.651	53.934	54.096	54.441

Table 18: Parameter estimates and summary biomass (age 1+; mt) associated with fixed values of log catchability (Q) for spring surveys.

	Catchability										
Label	-0.5	-0.4	-0.3	-0.2	-0.1	0	0.1	0.2	0.3	0.4	0.5
InitF_seas_1_flt_1MexCal_S1	15.478	15.524	15.587	15.665	15.759	15.867	15.988	16.121	16.867	18.195	19.658
LnQ_base_AT_summer(3)	-0.073	-0.073	-0.073	-0.073	-0.073	-0.073	-0.073	-0.073	-0.073	-0.073	-0.073
NatM_uniform_Fem_GP_1	0.422	0.442	0.464	0.488	0.514	0.542	0.571	0.602	0.635	0.668	0.702
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_LN(R0)	19.407	19.393	19.378	19.364	19.351	19.341	19.334	19.33	19.33	19.333	19.339
SR_regime_BLK1repl_2014	-2.346	-2.335	-2.321	-2.306	-2.29	-2.276	-2.263	-2.253	-2.245	-2.24	-2.237
2020 Age1+ biomass	1,371,670	1,329,220	1,284,650	1,238,490	1,191,280	1,143,540	1,095,770	1,048,380	1,001,710	956,041	911,585
2021 Age1+ biomass	2,081,200	2,059,830	2,037,960	2,015,810	1,993,530	1,971,250	1,948,990	1,926,720	1,904,360	1,881,770	1,858,780
Total NLL	54.216	53.779	53.428	53.161	52.977	52.876	52.855	52.912	53.045	53.253	53.534

Table 19: Parameter estimates and summary biomass (age-1+; mt) associated with fixed values of natural mortality and steepness (0.6).

	Natural Mortality						
Label	0.3	0.4	0.5	0.6	0.7	0.8	0.9
InitF_seas_1_flt_1MexCal_S1	4.711	5.469	16.627	17.99	19.38	23.147	25
LnQ_base_AT_spring(7)	-0.547	-0.547	-0.547	-0.547	-0.547	-0.547	-0.547
LnQ_base_AT_spring(7)_BLK6repl_2020	-0.545	-0.545	-0.545	-0.545	-0.545	-0.545	-0.545
LnQ_base_AT_summer(3)	-0.073	-0.073	-0.073	-0.073	-0.073	-0.073	-0.073
SR_BH_steep	0.6	0.6	0.6	0.6	0.6	0.6	0.6
SR_LN(R0)	20.622	19.514	19.249	19.2	19.216	19.273	19.372
SR_regime_BLK1repl_2014	-3.766	-2.518	-2.065	-1.876	-1.754	-1.677	-1.722
2020 Age1+ biomass	1,424,810	1,381,660	1,342,610	1,280,570	1,219,700	1,225,010	1,251,260
2021 Age1+ biomass	2,129,470	2,085,390	2,051,320	2,005,500	1,960,330	1,929,790	1,909,800
Total NLL	54.815	54.455	54.634	55.282	56.325	57.686	59.685

Table 20: Variance adjustment, parameter estimates, summary biomass (age 1+; mt), and total NLL from the base model and a model with Francis reweighting of age compositions.

		Base	Francis
Variance adjustment	MexCal_S1	–	4.980
	MexCal_S2	–	1.958
	AT_spring	–	27.538
	AT_summer	–	0.708
Parameter	InitF_seas_1_flt_1MexCal_S1	15.464	3.311
	LnQ_base_AT_spring(7)	-0.547	-0.547
	LnQ_base_AT_spring(7)_BLK6repl_2020	-0.545	-0.545
	LnQ_base_AT_summer(3)	-0.073	-0.073
	NatM_uniform_Fem_GP_1	0.414	0.237
	SR_BH_steep	0.600	0.600
	SR_LN(R0)	19.413	29.998
Biomass	2020 Age1+ biomass	1,389,990	1,327,360
	2021 Age1+ biomass	2,090,640	2,035,610
Likelihood	TOTAL	54.444	71.162

Table 21: Parameter estimates and summary biomass (age 1+; mt) associated with downweighting age compositions in the likelihood calculation. Lambda values were 1 in the base model, and 0.5 in each of the fleet sensitivities shown here.

Label	Base	MexCal S1	MexCal S2	AT Summer	AT Spring
Agecomp lambda	1	0.5	0.5	0.5	0.5
InitF_seas_1_flt_1MexCal_S1	15.464	14.528	18.394	13.189	16.898
LnQ_base_AT_spring(7)	-0.547	-0.547	-0.547	-0.547	-0.547
LnQ_base_AT_spring(7)_BLK6repl_2020	-0.545	-0.545	-0.545	-0.545	-0.545
LnQ_base_AT_summer(3)	-0.073	-0.073	-0.073	-0.073	-0.073
NatM_uniform_Fem_GP_1	0.414	0.412	0.411	0.339	0.484
SR_BH_steep	0.6	0.6	0.6	0.6	0.6
SR_LN(R0)	19.413	19.399	19.412	19.964	19.292
2020 Age1+ biomass	1,389,990	1,393,850	1,418,780	1,306,490	1,323,370
2021 Age1+ biomass	2,090,640	2,108,380	2,070,770	2,068,390	2,050,430
Total NLL	54.444	51.522	53.316	47.995	53.300

8 Figures

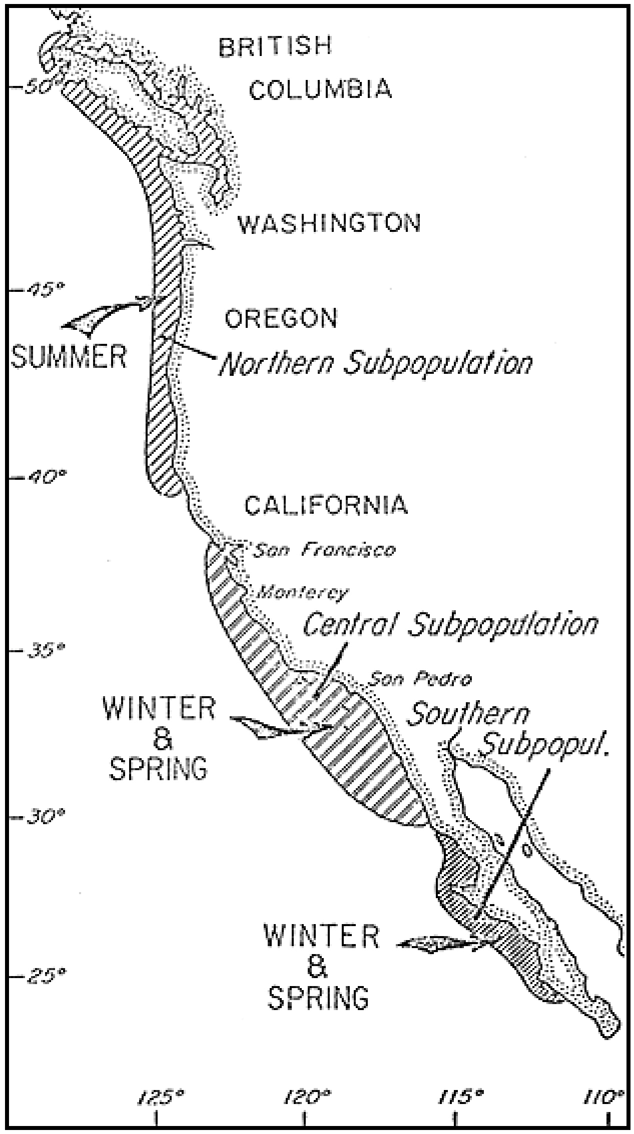

Figure 1: Map showing distribution of the three purported northern anchovy subpopulations.

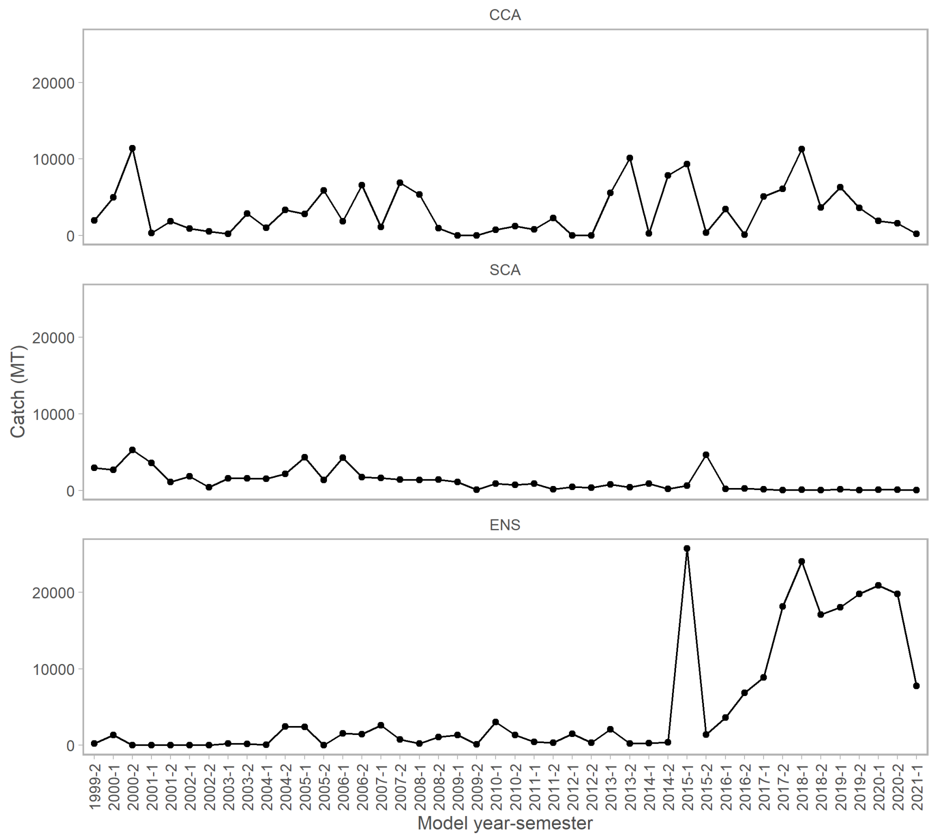

Figure 2: CSNA landings (mt) by major fishing region (Central California, Southern California, and Ensenada, Mexico).

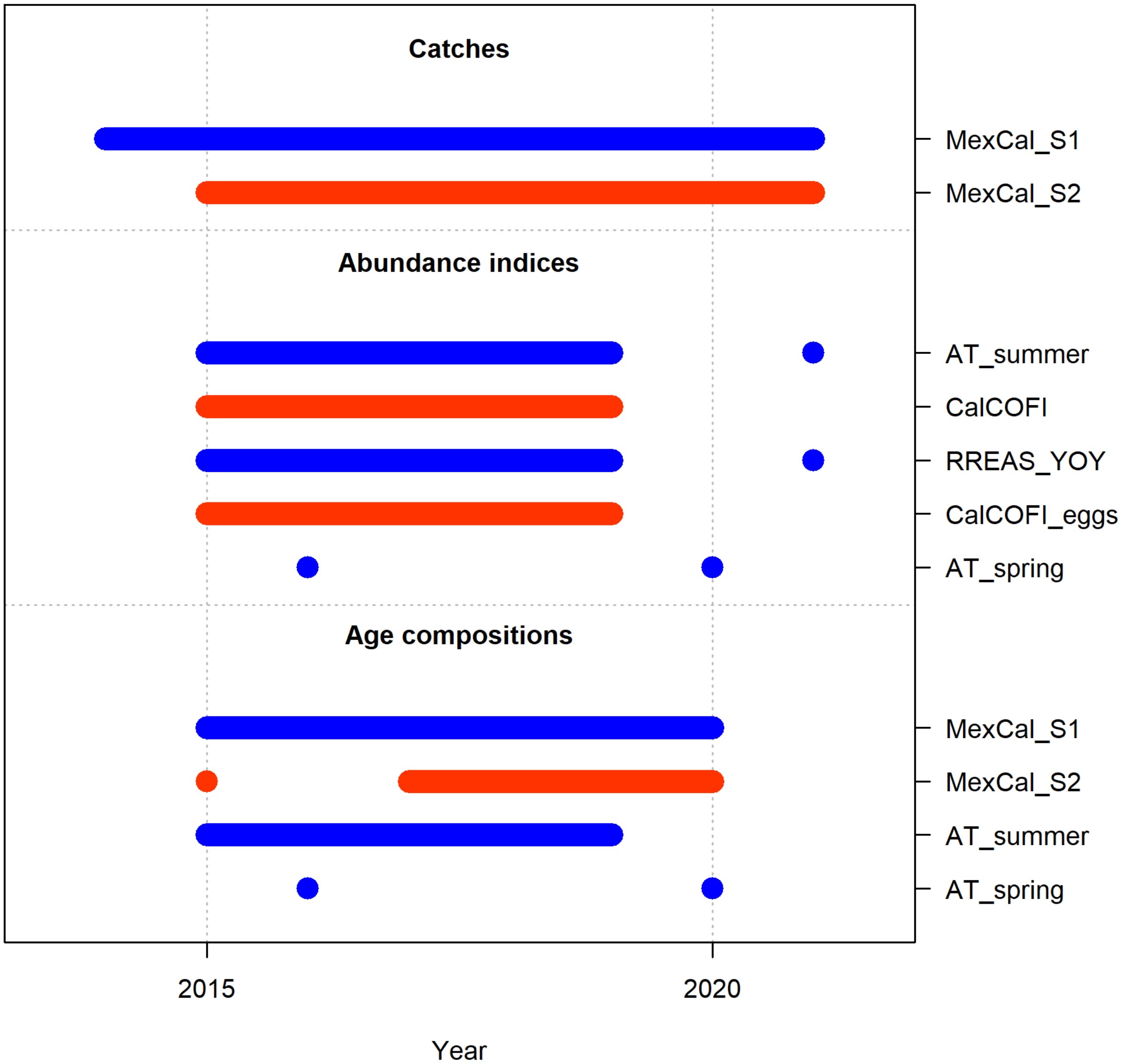

Figure 3: Summary of data sources used in the base model. Note for the abundance indices, only the AT_summer and AT_spring value were used.

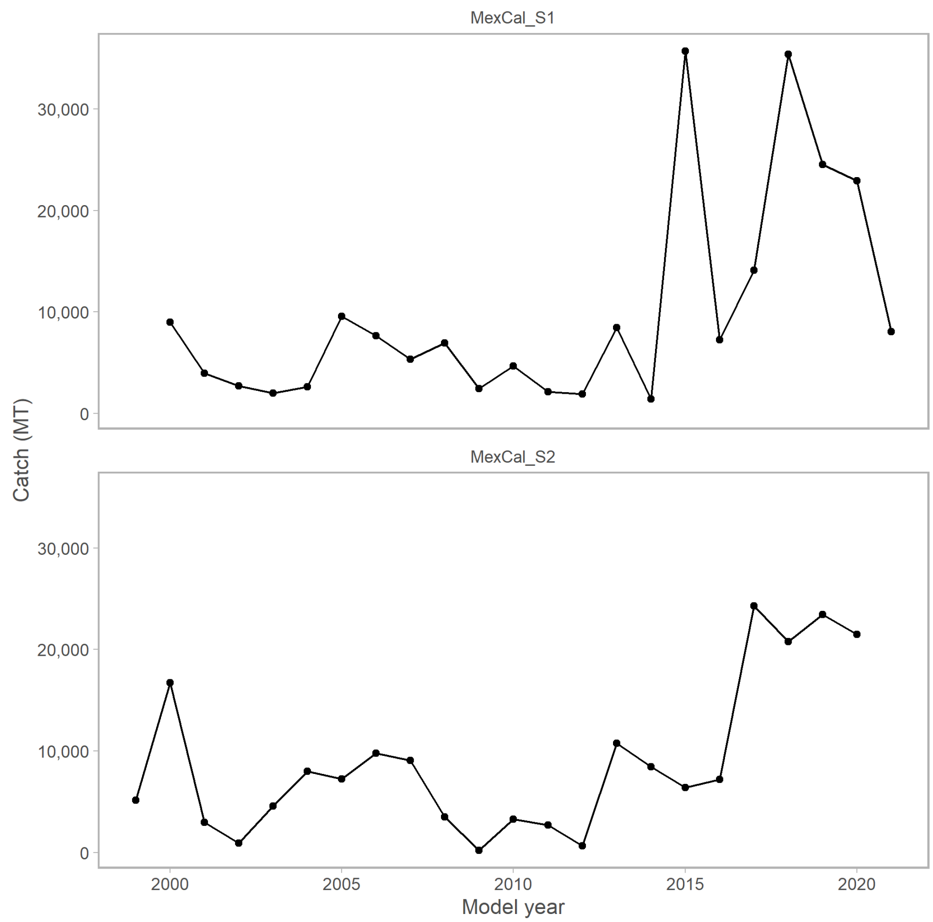

Figure 4: CSNA landings (mt) by fleet (MexCal_S1 and MexCal_S2) used as input in the stock assessment model .

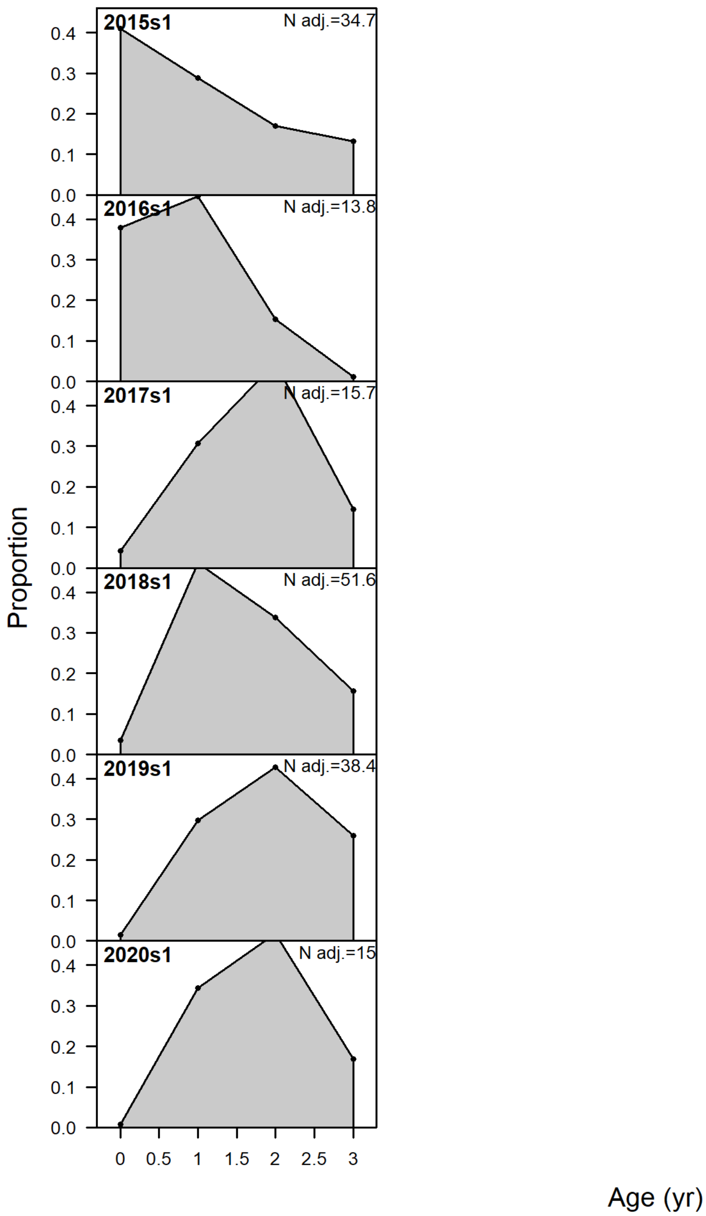

Figure 5: Age-composition data for the fishing fleet MexCal_S1. The input sample sizes (number of fish/25) are shown in the top right of each panel.

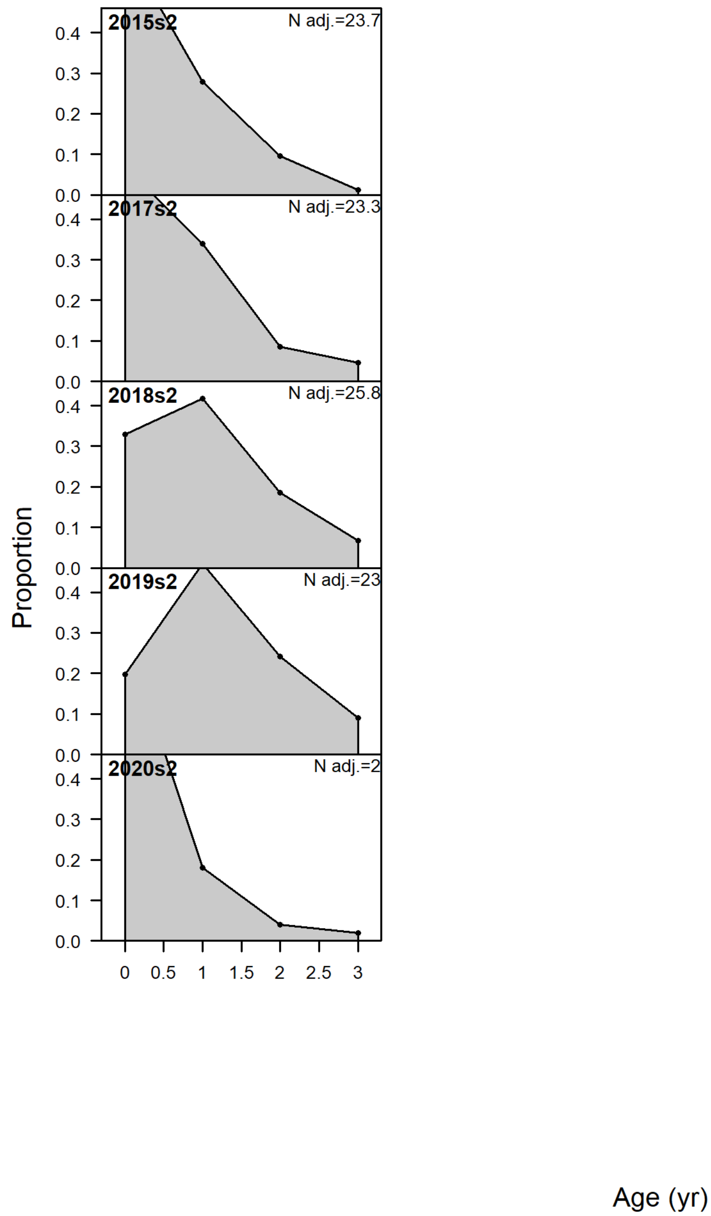

Figure 6: Age-composition data for the fishing fleet MexCal_S2. The input sample sizes (number of fish/25) are shown in the top right of each panel.

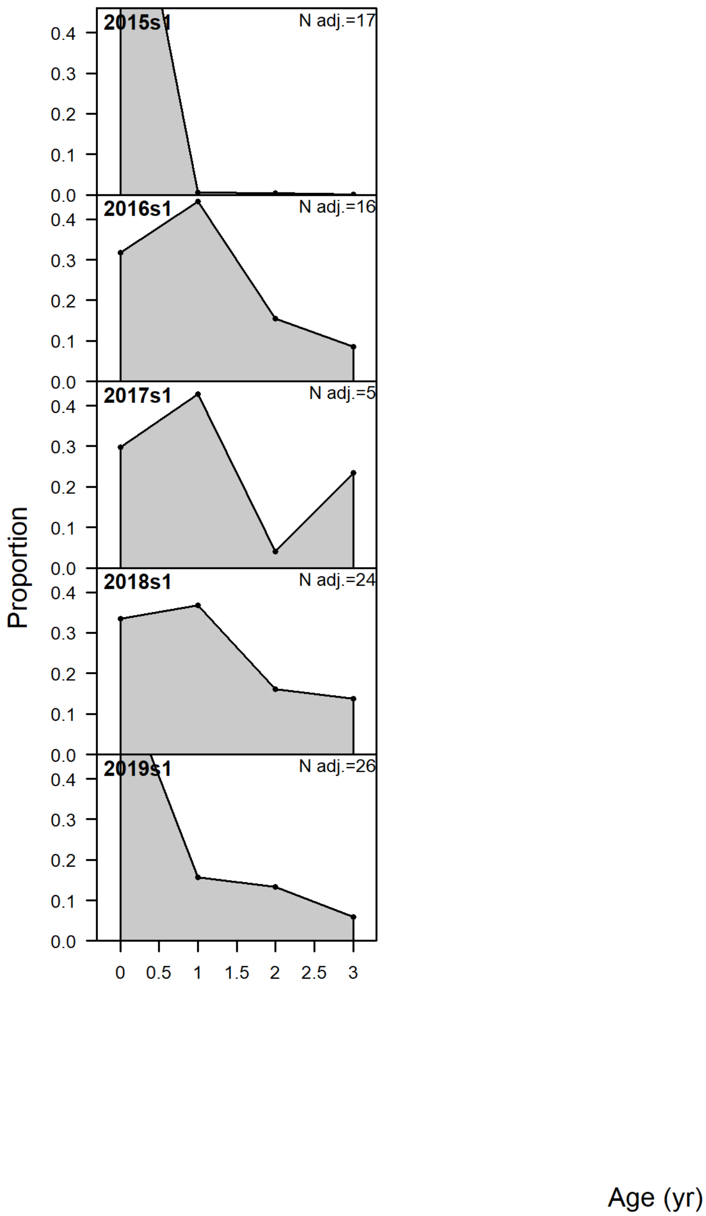

Figure 7: Age-composition data for the AT survey. The input sample sizes (number of positive clusters) are shown in the top right of each panel.

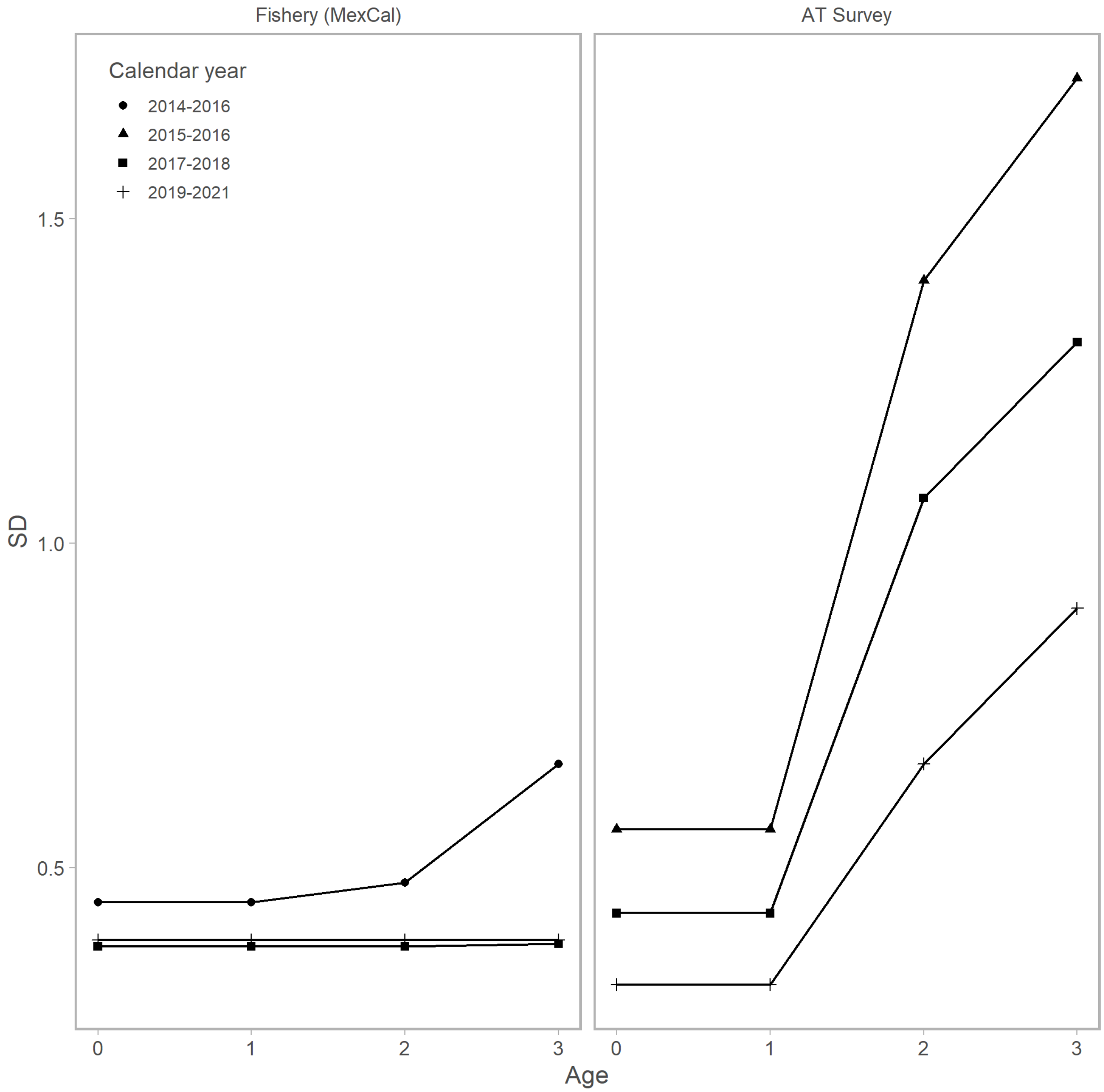

Figure 8: Ageing errors estimated for the MexCal fleets (aged by CDFW) and the AT Survey fleet (aged by CDFW and SWFSC).

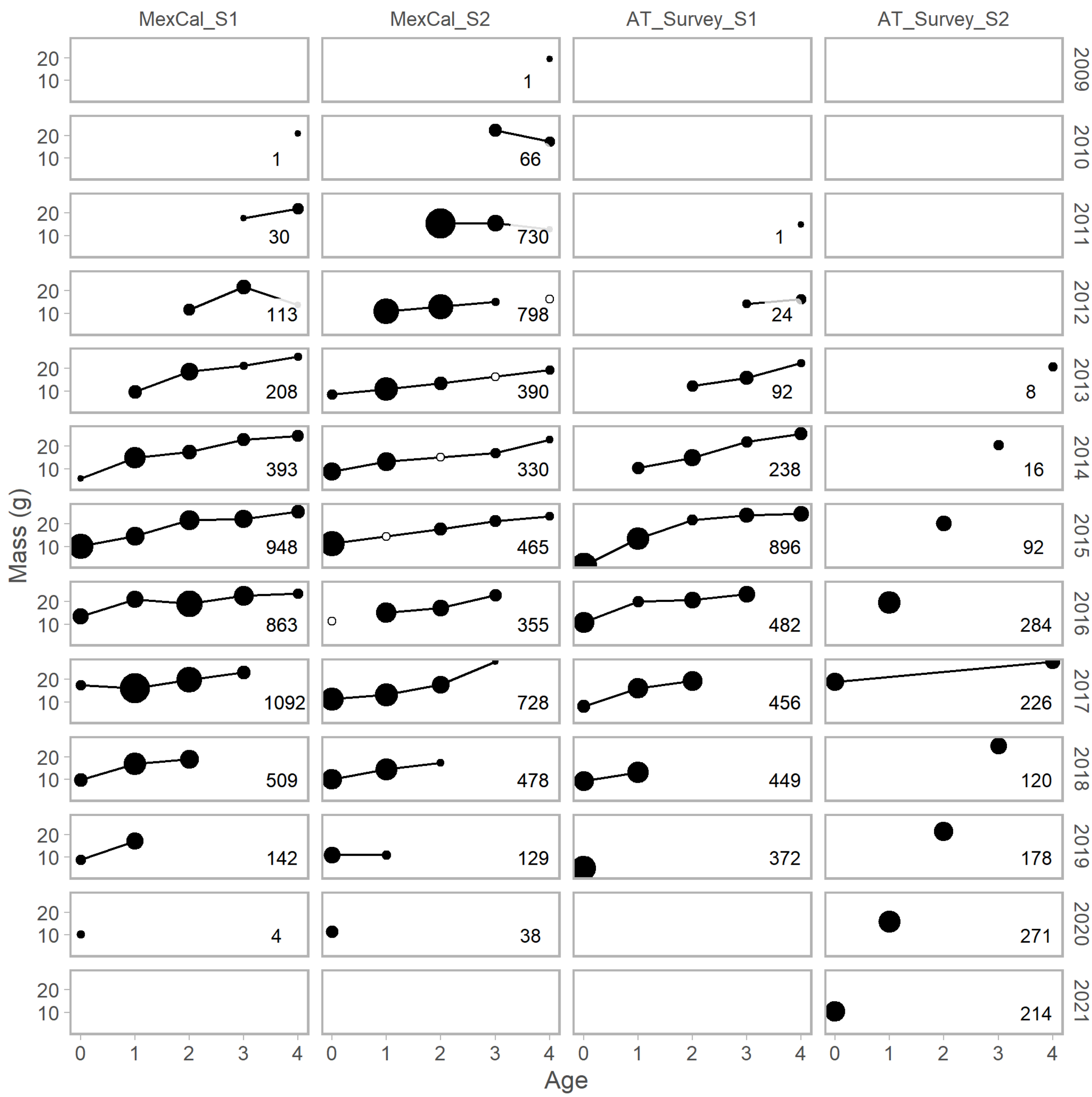

Figure 9: Weight-at-age values for anchovy arranged by fleet (columns) and cohort model year (rows). Numbers of fish are shown in the bottom right of each panel. The AT_Survey values are plotted as separate columns, but are part of the same fleet in the model. In the MexCal_S2 column, open points show the values interpolated for each cohort.

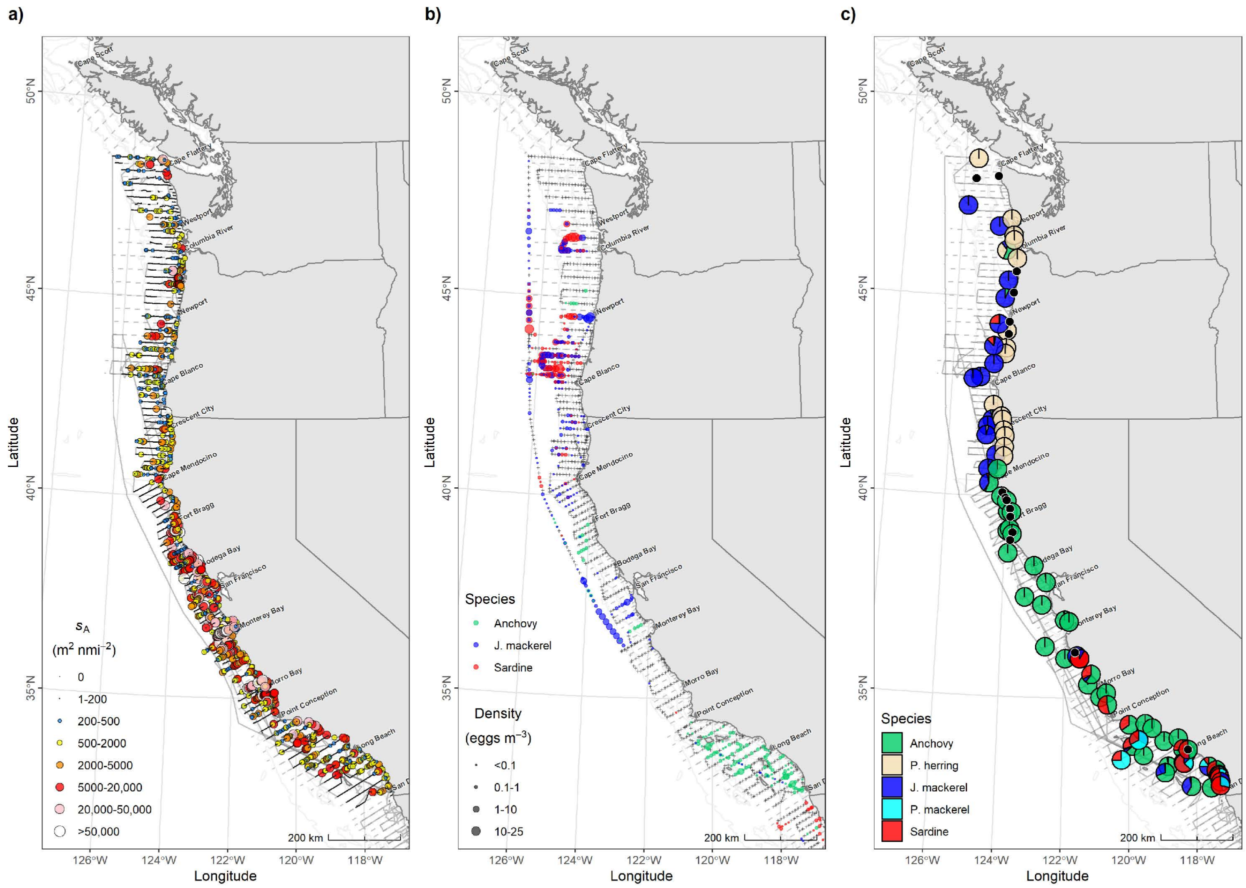

Figure 10: Preliminary results from the 2021 AT summer survey (Stierhoff et al., pers. comm.). A map of the: a) distribution of 38-kHz integrated backscattering coefficients (s_a, m^2nmi^-2; averaged over 2000m distance intervals) ascribed to CPS; b) CUFES egg density (eggs m^-3) for anchovy and sardine; and c) proportions of CPS species in trawls (black points indicate trawls with no CPS).

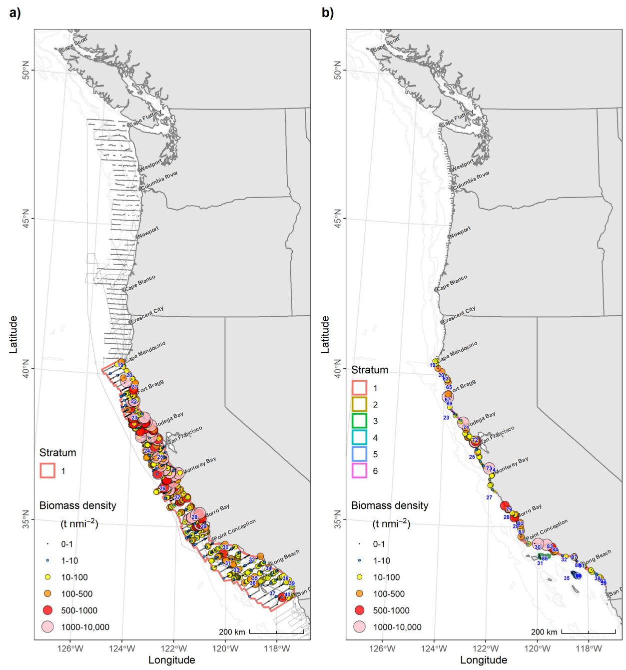

Figure 11: Preliminary biomass densities of northern anchovy, central stock, per stratum throughout the summer 2021 AT survey region from the Lasker and Long Beach Carnage. Blue numbers represent locations of positive sardine trawl clusters. Gray lines represent the vessel track.

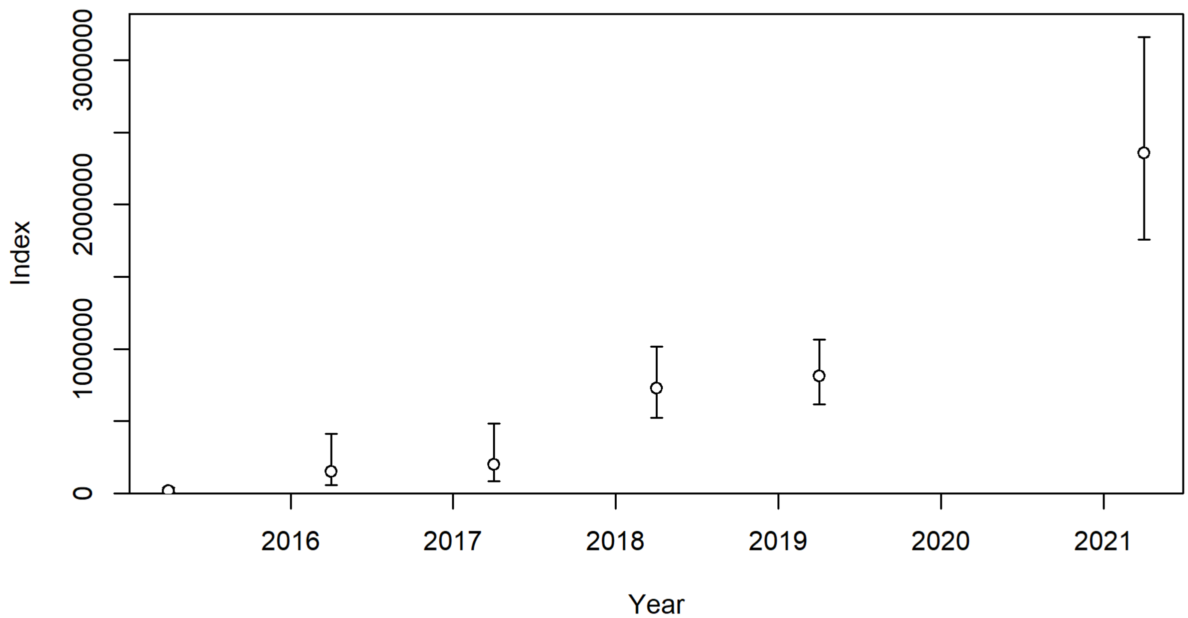

Figure 12: Observations of CSNA biomass (age-0+, mt) from summer AT surveys from 2015-2021 (with 95% CI assuming lognormal error). Note that years shown are model years.

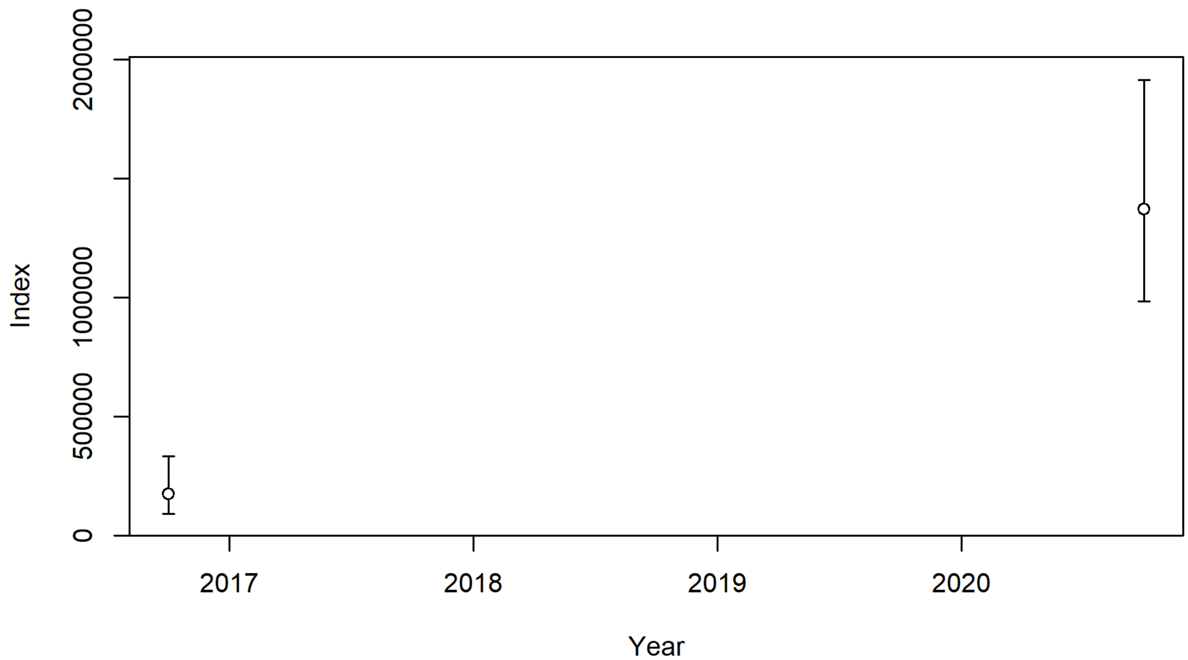

Figure 13: Observations of CSNA biomass (age-0+, mt) from spring AT surveys in model years 2016 and 2020 (with 95% CI assuming lognormal error).

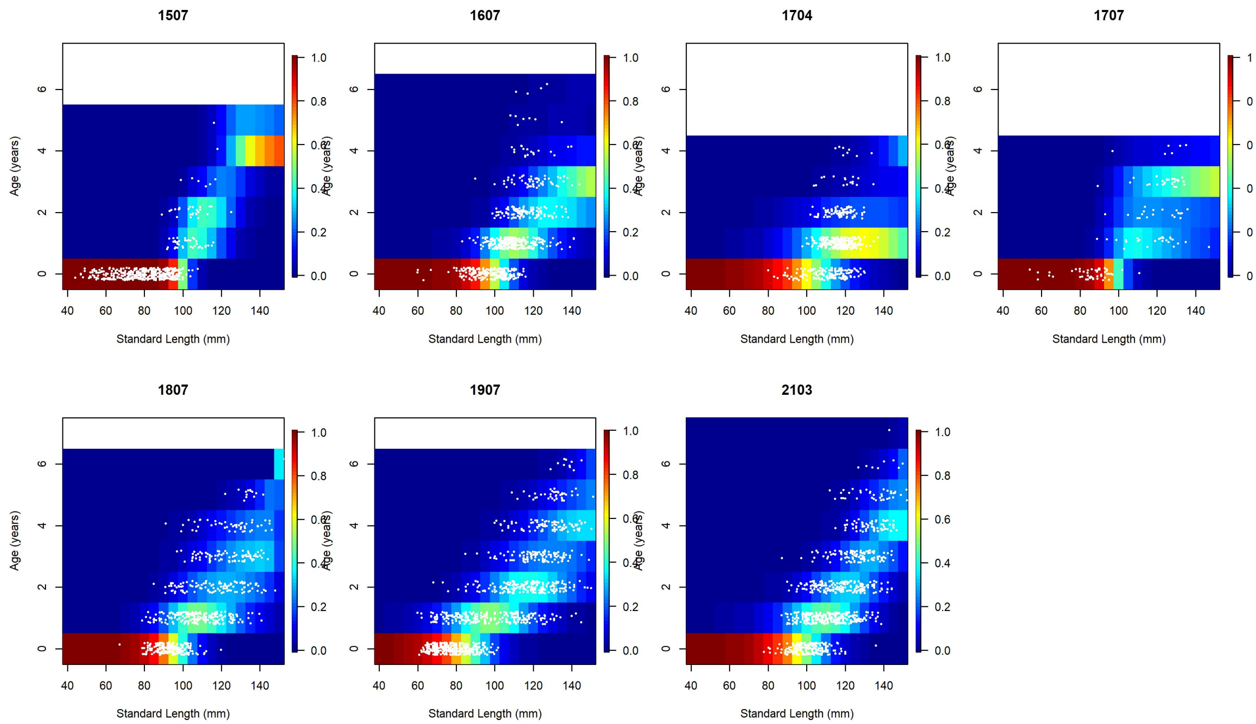

Figure 14: Cruise-specific age-length keys derived from acoustic-trawl survey trawl samples from summer 2015 to spring 2021.

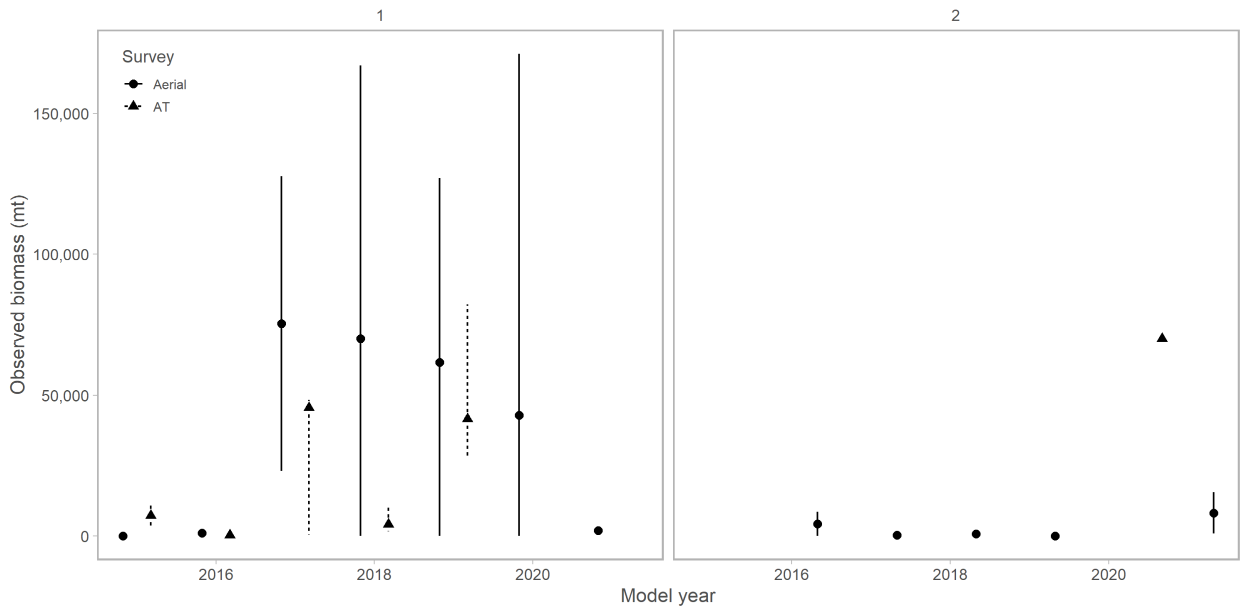

Figure 15: Nearshore biomass estimates from CDFW aerial surveys (circles) and AT methods (triangles) arranged by semester (1-June to December; 2-January to May). Aerial methods from 2015 to 2019 had one replicate for the inner and one replicate for the outer band. From 2020 on, the aerial survey conducted two replicates per band. AT nearshore values were calculated from model extrapolation for 2015-2018, and later surveys observed nearshore biomass with AT methods on fishing vessels. Note, that the 2020-2 (model year-semester) value is preliminary and has no calculated CV yet.

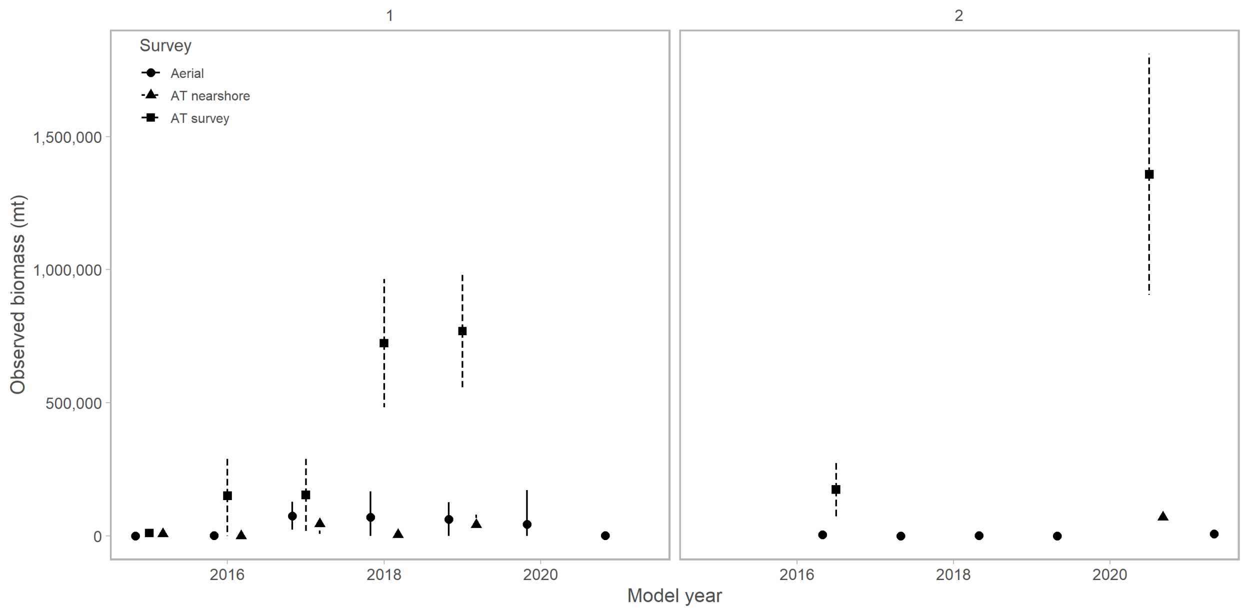

Figure 16: Nearshore biomass estimates from CDFW aerial surveys (circles) and AT methods (nearshore - triangles and core survey - squares) arranged by semester (1-June to December; 2-January to May). This plot contains the AT survey values from the core survey area resulting in a different scale on the y-axis. Aerial methods from 2015 to 2019 had one replicate for the inner and one replicate for the outer band. From 2020 on, the aerial survey conducted two replicates per band. AT nearshore values were calculated from model extrapolation for 2015-2018, and later surveys observed nearshore biomass with AT methods on fishing vessels. Note, that the 2020-2 (model year-semester) value is preliminary and has no calculated CV yet.

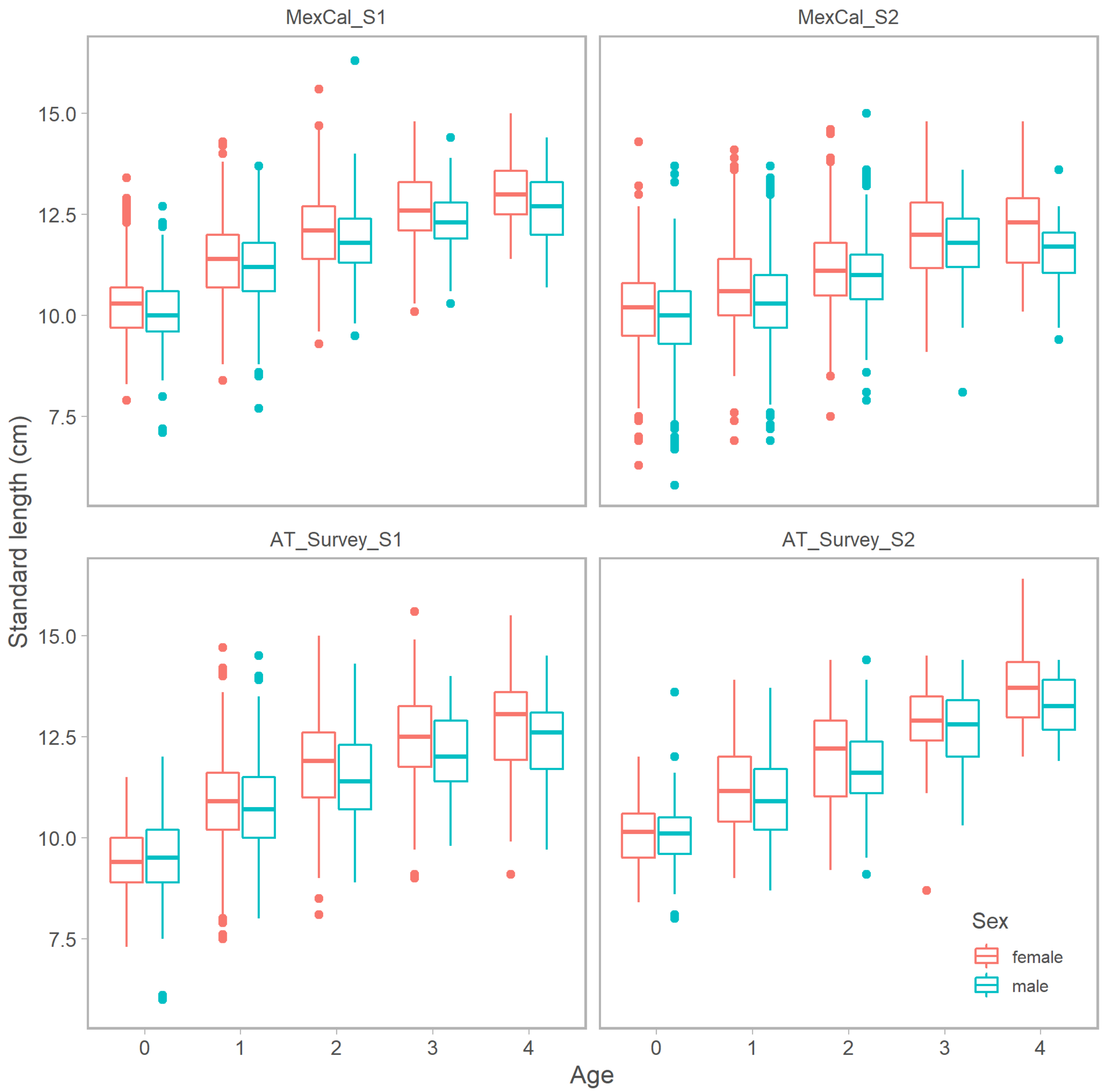

Figure 17: Length-at-age by sex, grouped by fleet, showing lack of sexually dimorphic growth. Boxes indicate the median and 25-75 percentiles of the data.

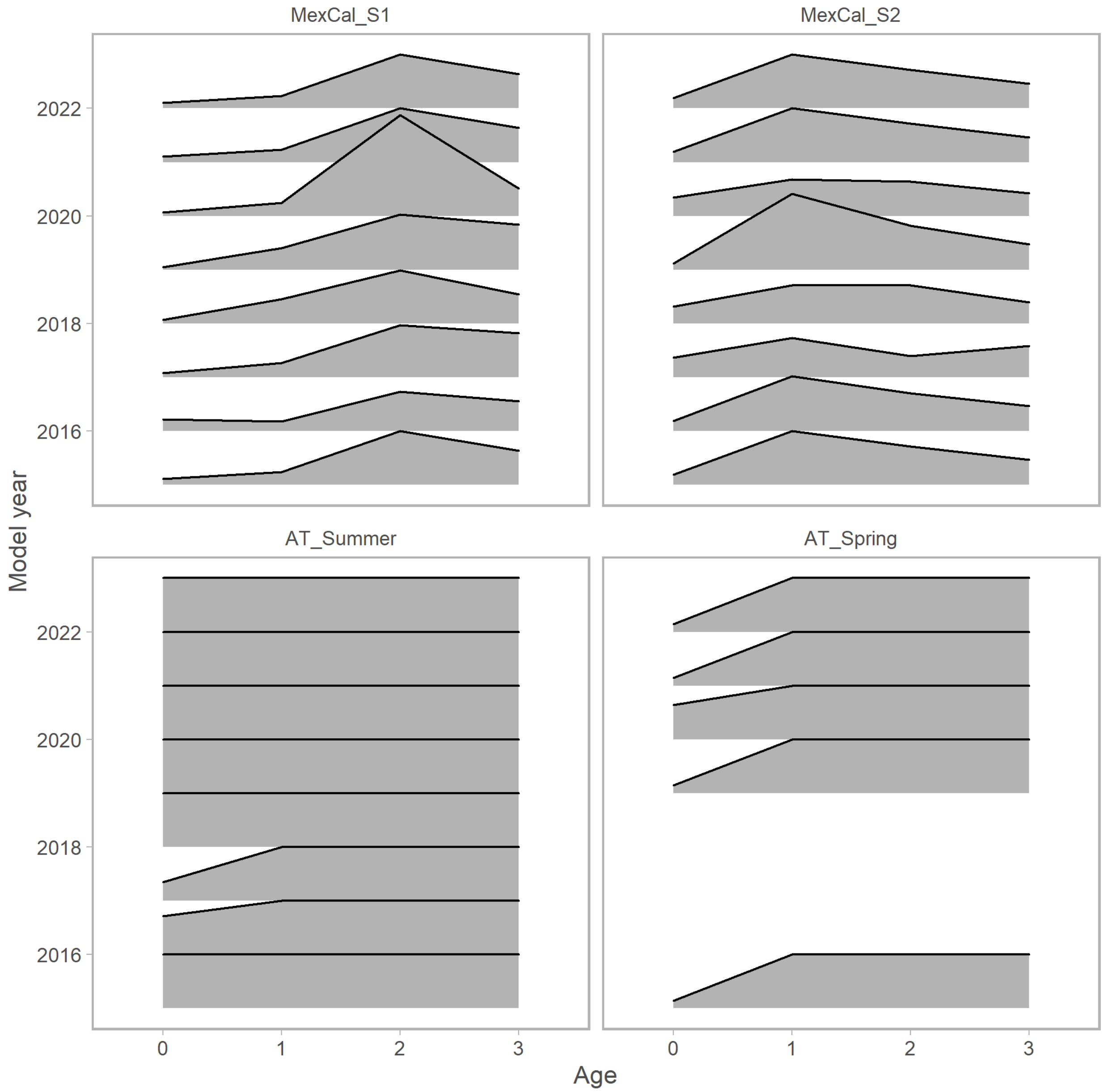

Figure 18: Time-varying age-based selectivity patterns for the MexCal_S1 and MexCal_S2 fishing fleets and the AT survey.

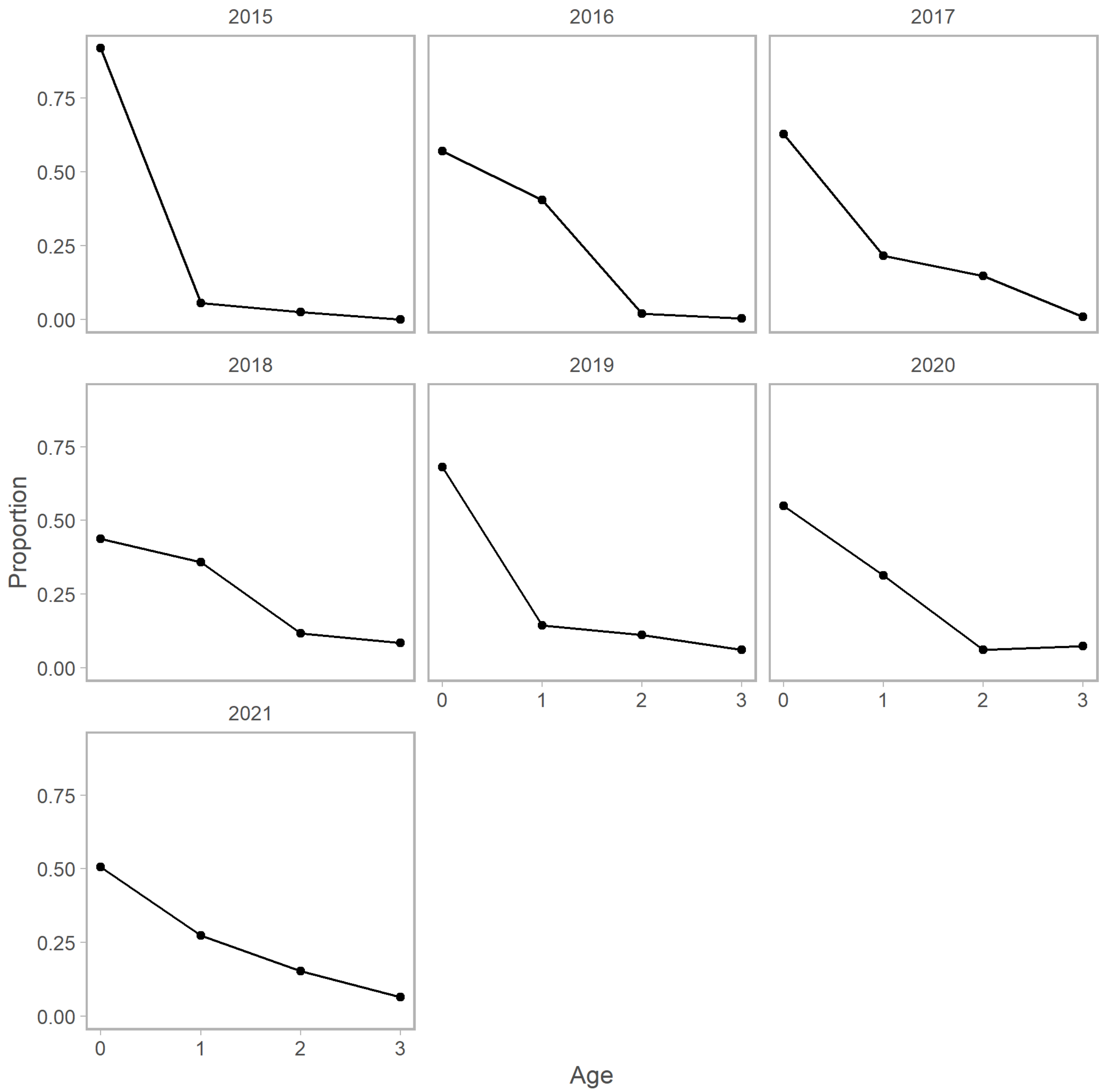

Figure 19: Population numbers at age from the base model. More than 50% of the population is age-0 fish in each year.

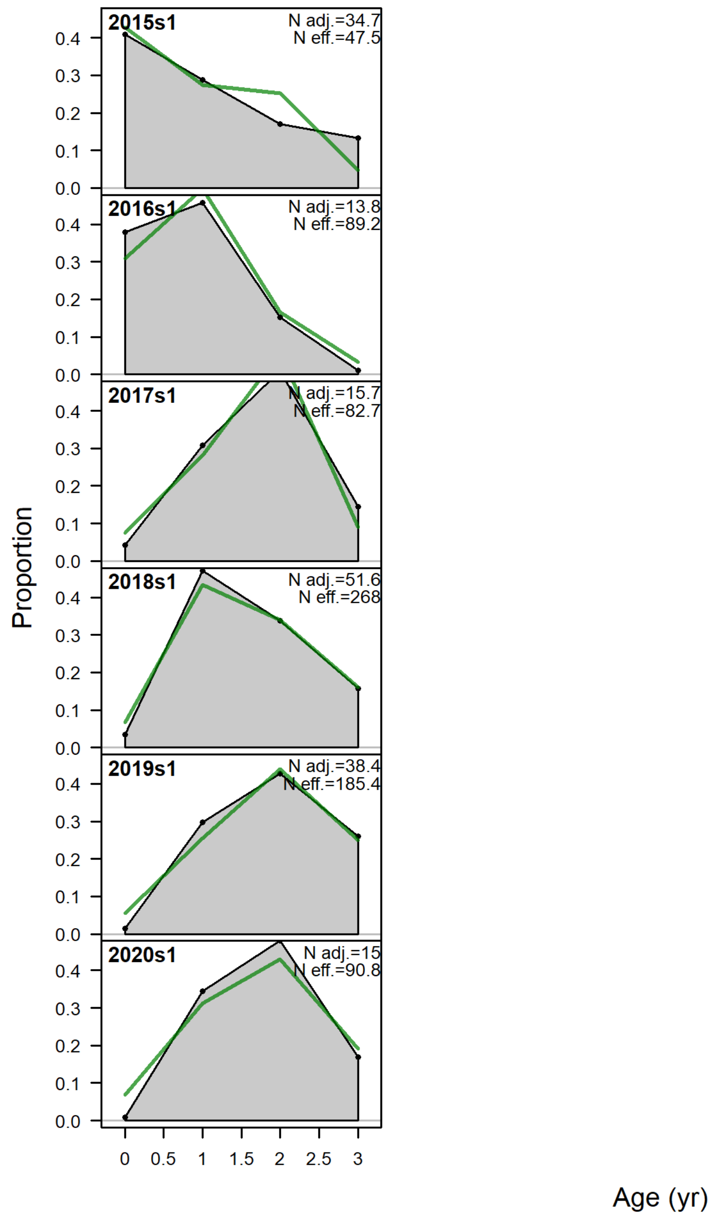

Figure 20: Fit to the age-composition time series for the MexCal_S1 fleet in the base model. Values in the top right are input sample sizes (N adj) and effective sample size given the statistical fit in the model (N eff).

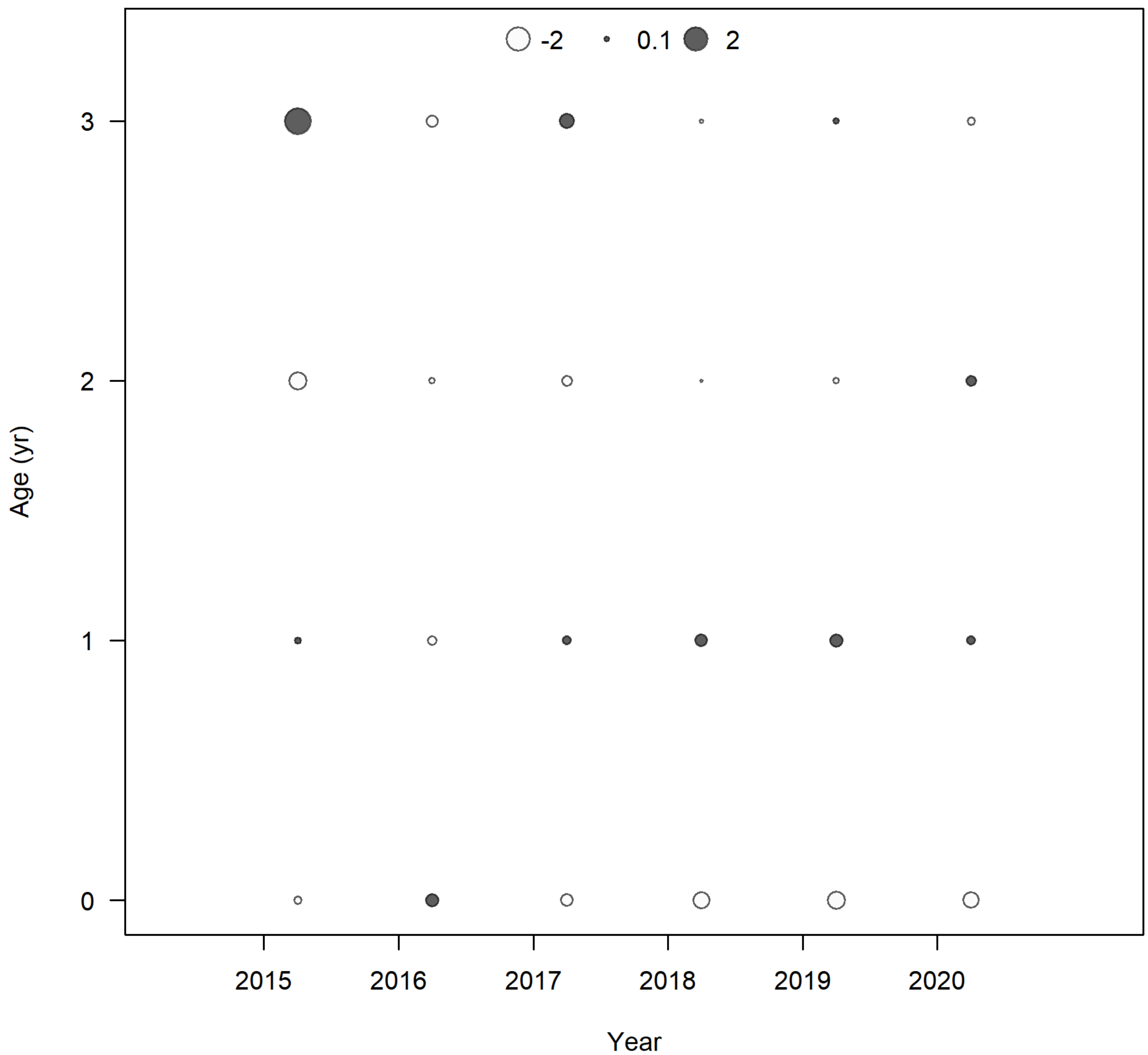

Figure 21: Residuals of fit to the age-composition time series for the MexCal_S1 fleet in the base model.

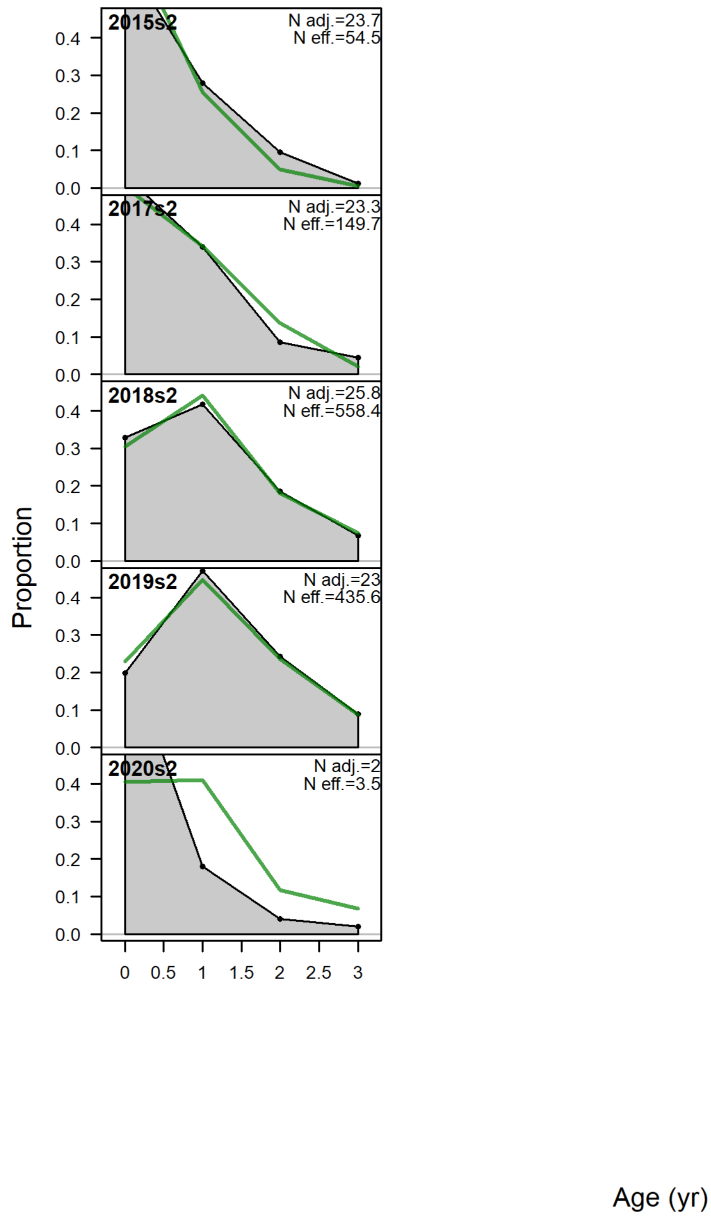

Figure 22: Fit to the age-composition time series for the MexCal_S2 fleet in the base model. Values in the top right are input sample sizes (N adj) and effective sample size given the statistical fit in the model (N eff).

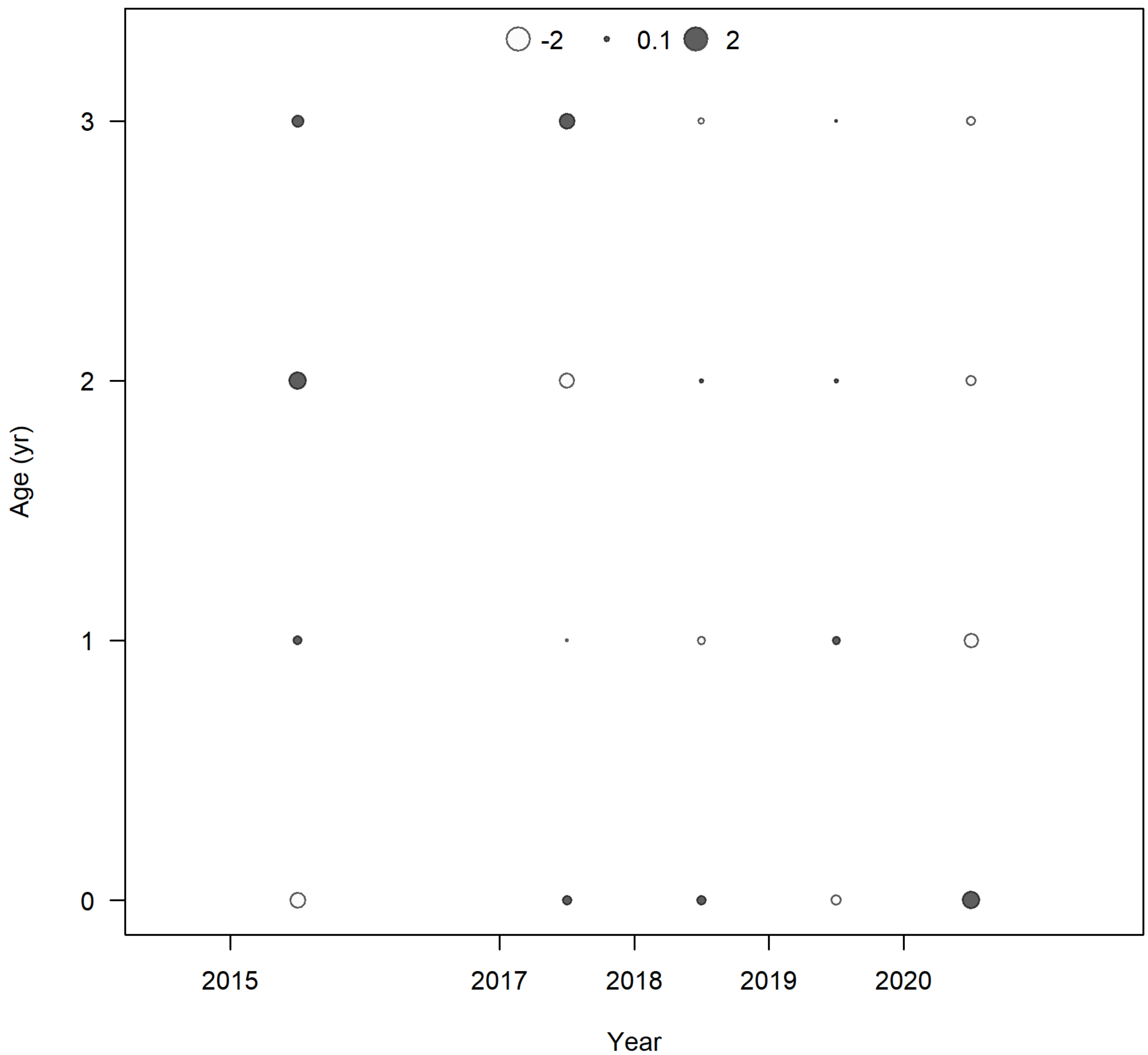

Figure 23: Residuals of fit to the age-composition time series for the MexCal_S2 fleet in the base model.

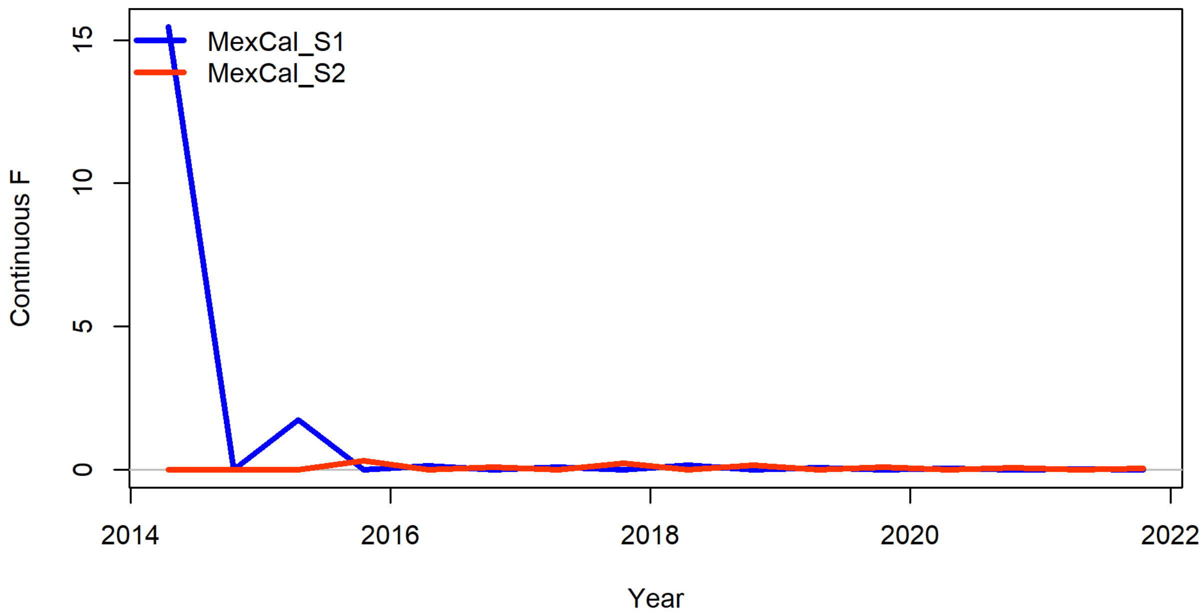

Figure 24: Continuous fishing mortality (F) estimates.

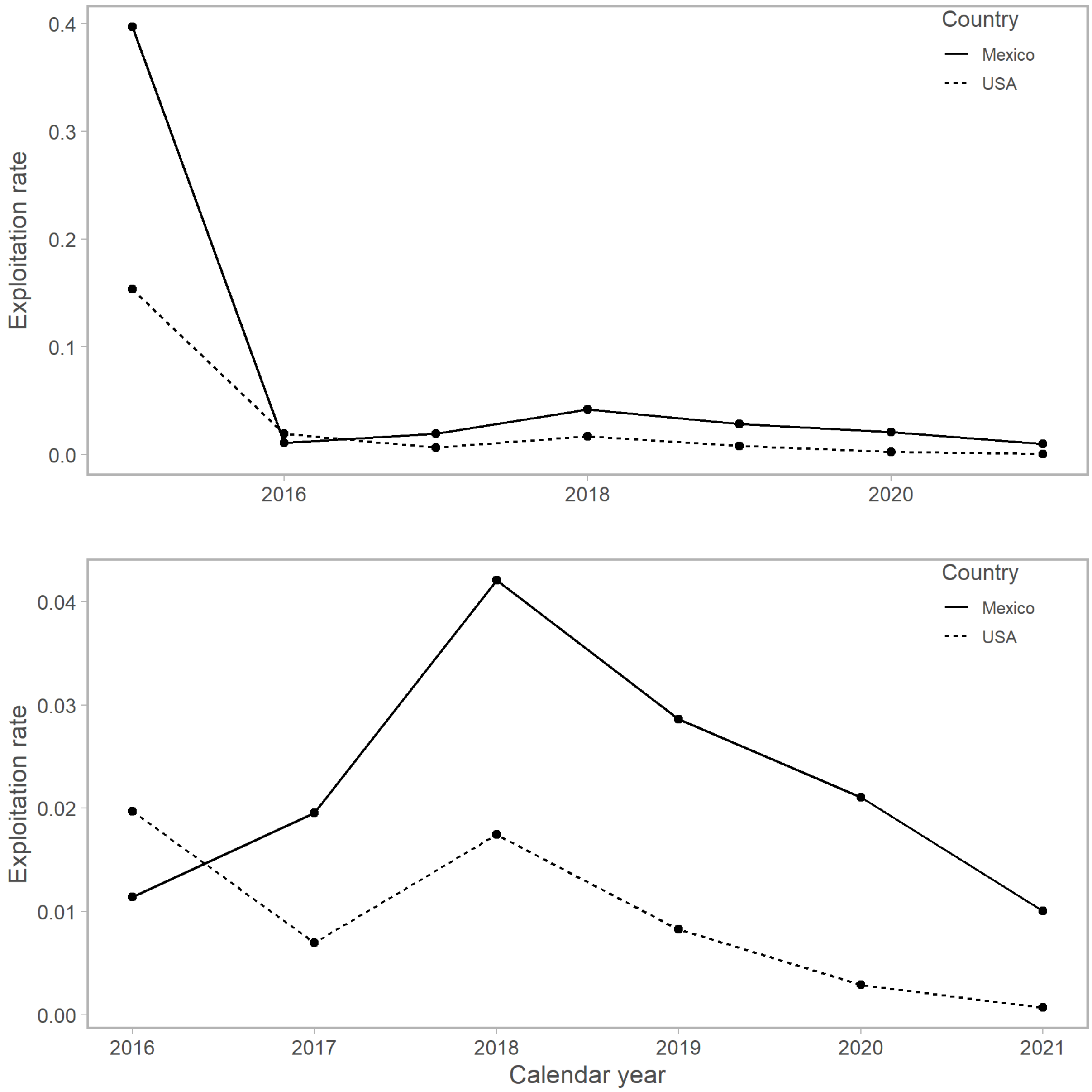

Figure 25: Annual exploitation rates (calendar year landings / June total biomass), including the 2015 estimate (top panel) and excluding it (bottom panel).

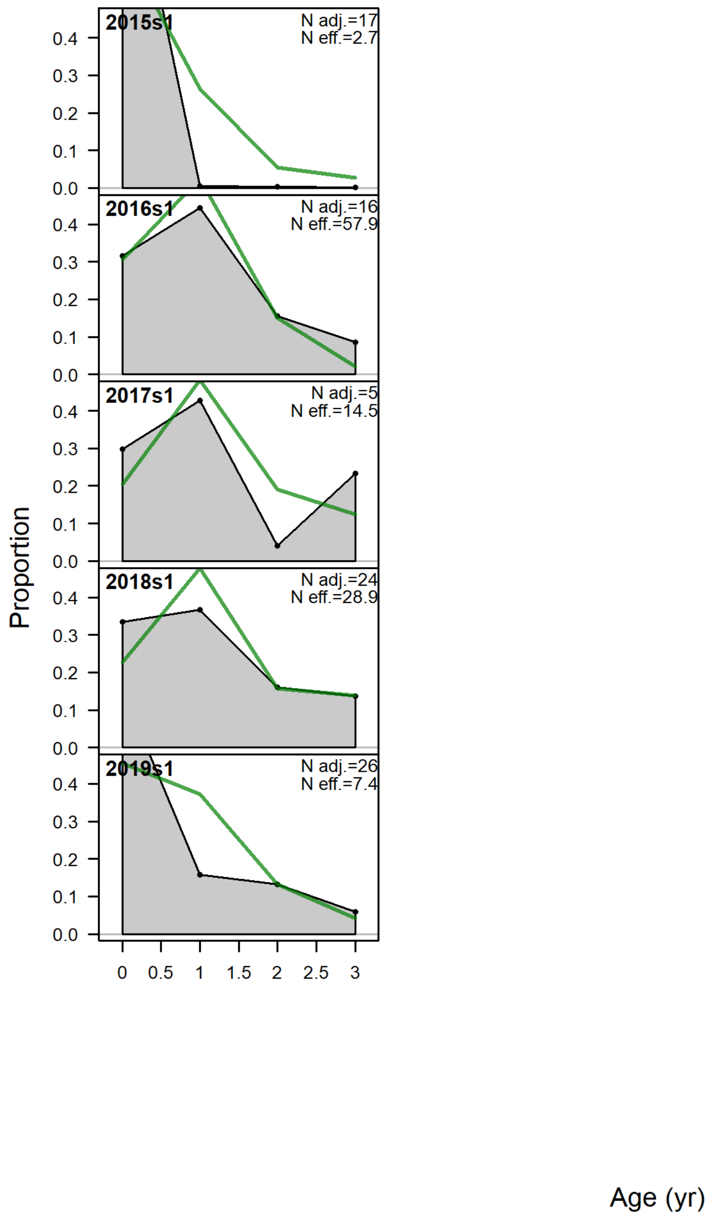

Figure 26: Fit to the age-composition time series for the AT survey in the base model. Values in the top right are input sample sizes (N adj) and effective sample size given the statistical fit in the model (N eff).

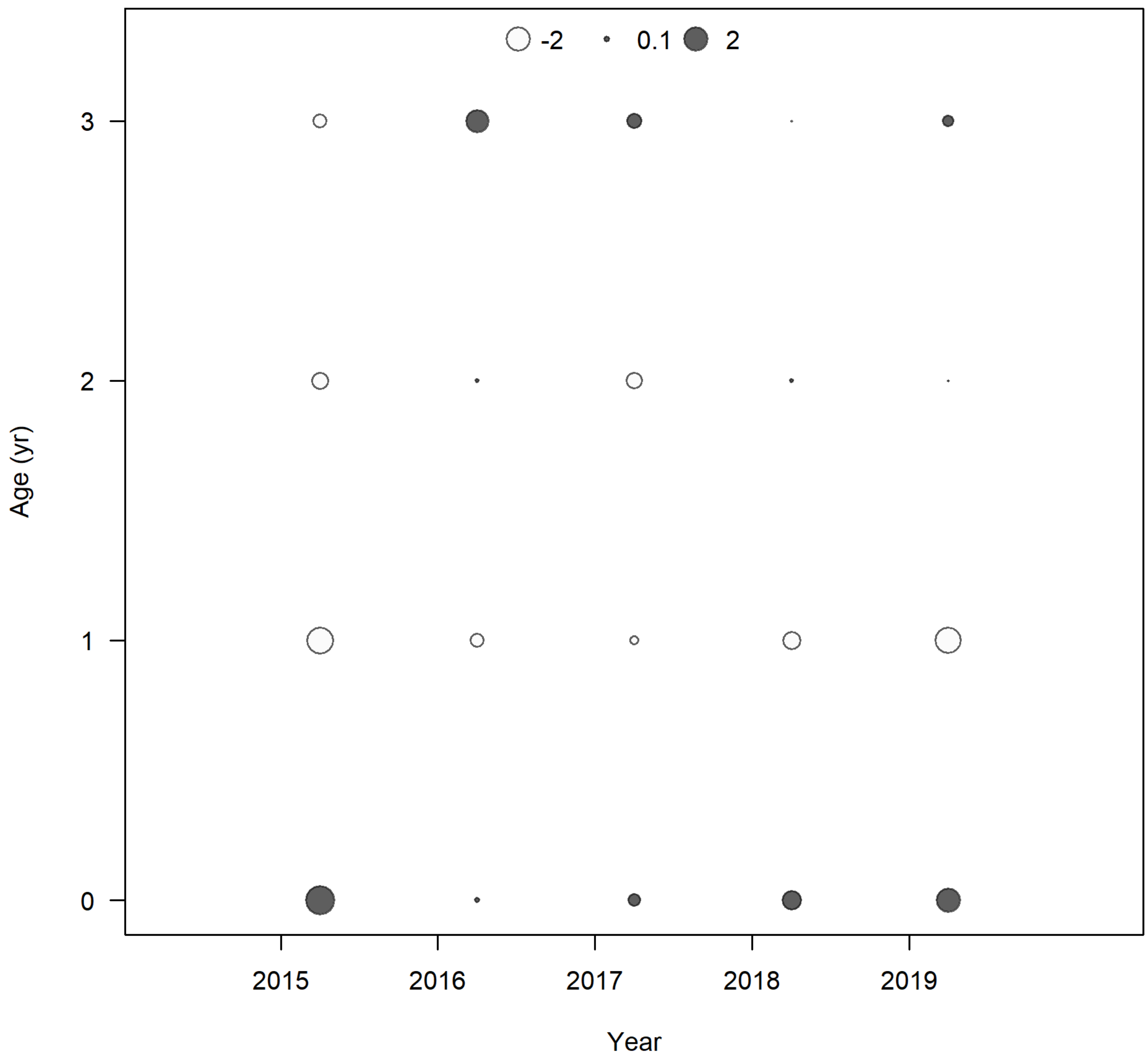

Figure 27: Residuals of fit to the age-composition time series for the AT survey fleet in the base model.

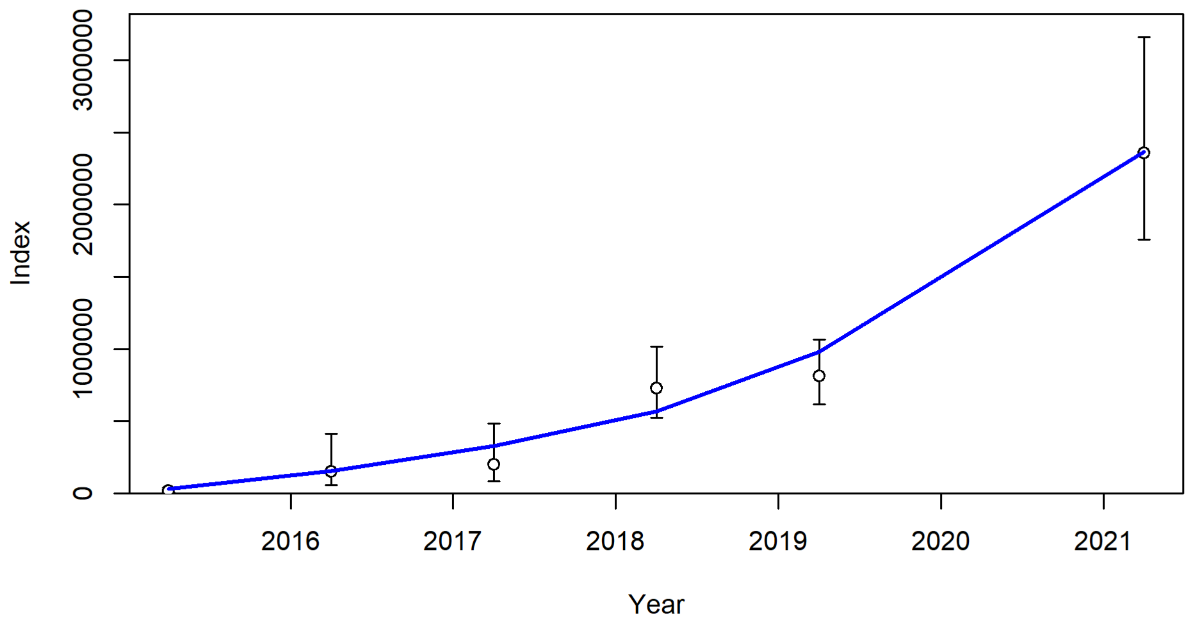

Figure 28: Fit to the index data for the AT summer survey in normal space. Vertical lines indicate 95% uncertainty intervals around index values based on the model assumption of lognormal error.

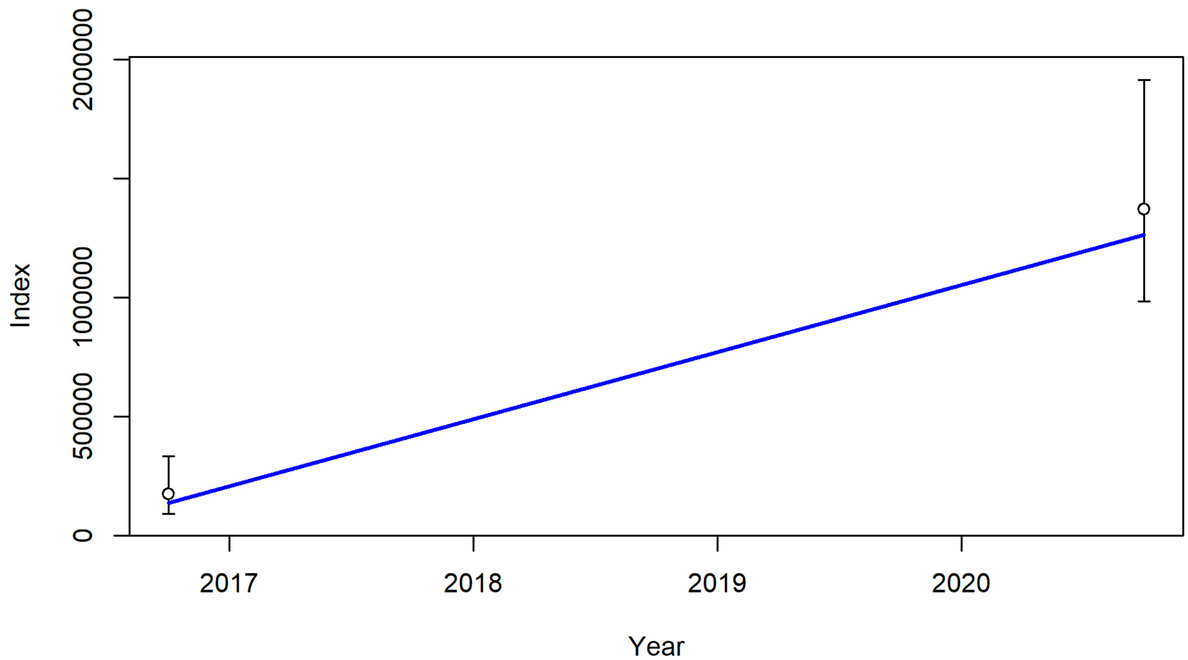

Figure 29: Fit to the index data for the AT spring survey in normal space. Vertical lines indicate 95% uncertainty intervals around index values based on the model assumption of lognormal error.

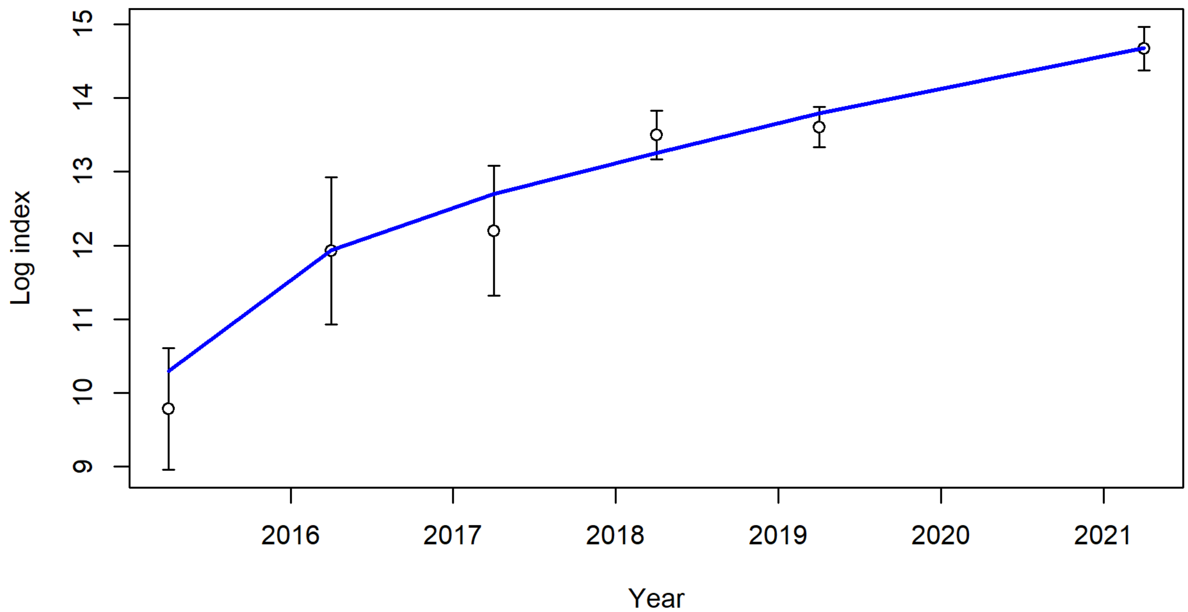

Figure 30: Fit to the index data for the AT summer survey in log space. Vertical lines indicate 95% uncertainty intervals around index values based on the model assumption of lognormal error.

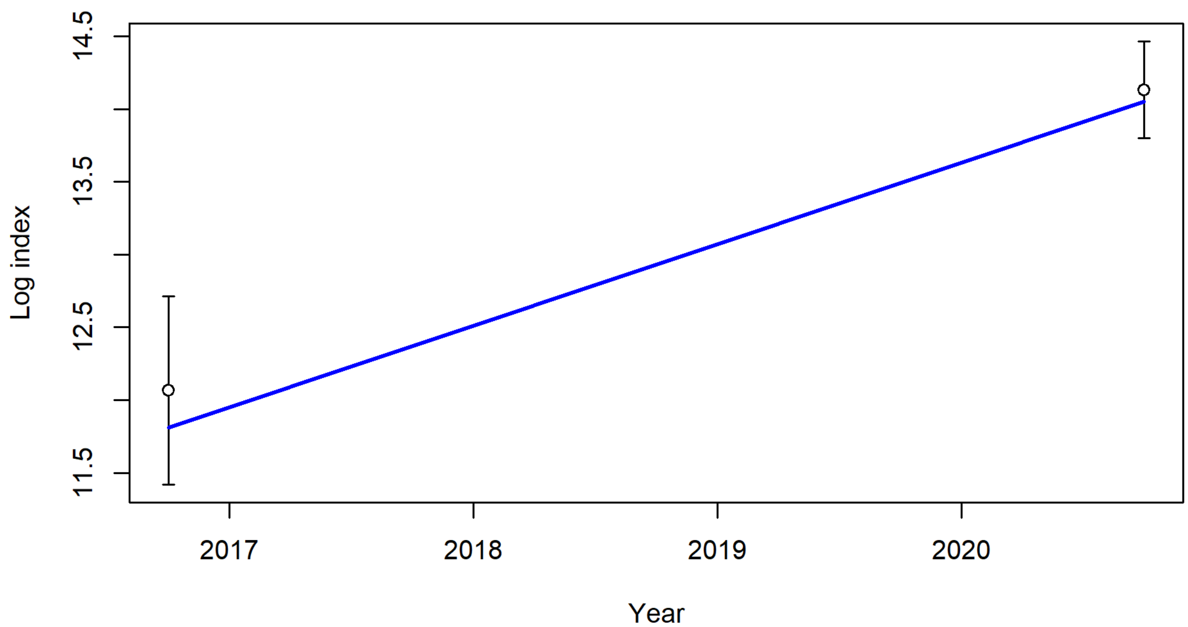

Figure 31: Fit to the index data for the AT spring survey in log space. Vertical lines indicate 95% uncertainty intervals around index values based on model assumption of lognormal error.

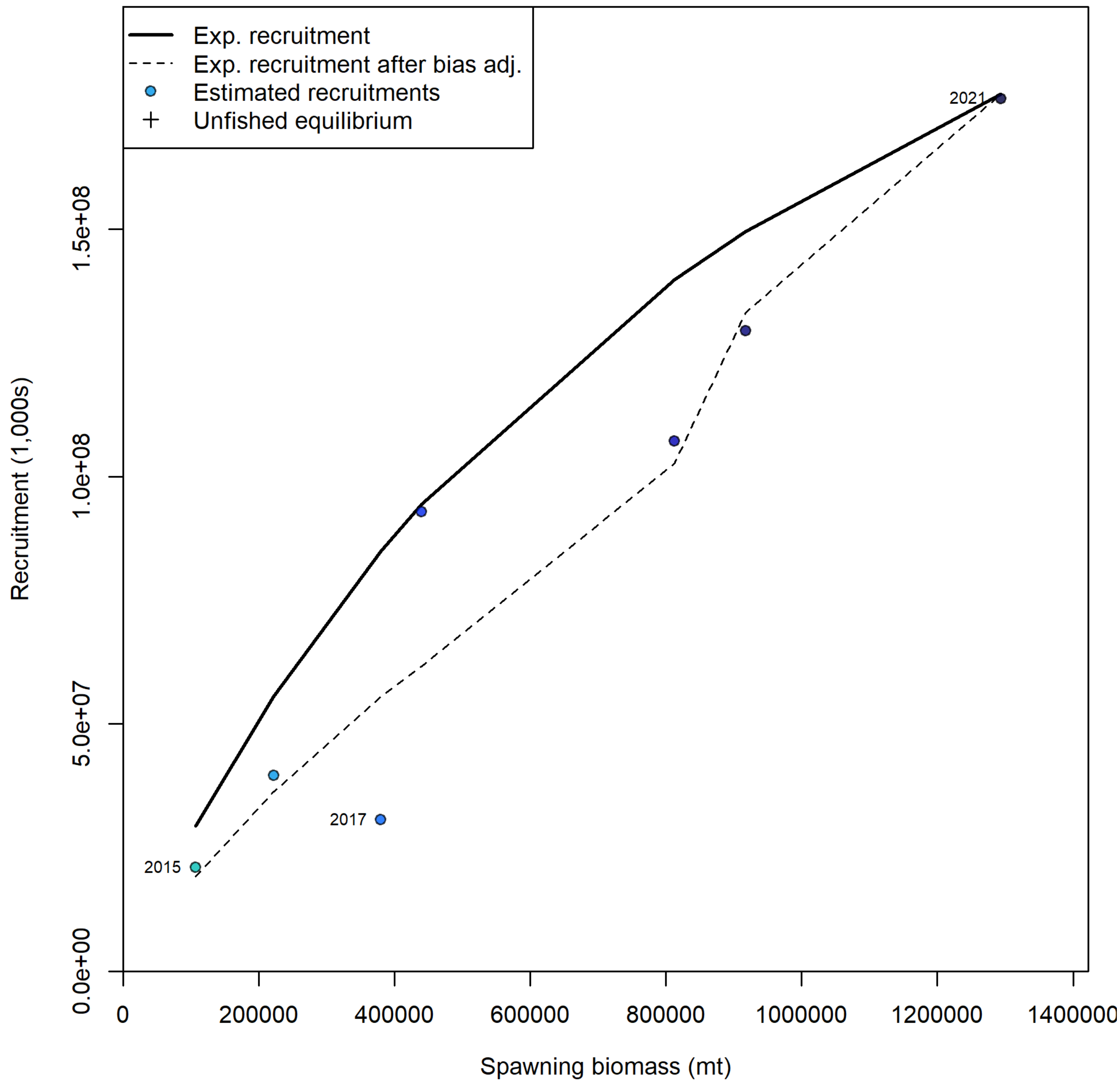

Figure 32: Estimated stock-recruitment (Beverton-Holt) curve with steepness fixed at 0.6. Year numbers indicate the first, last, and years with (log) deviations > 0.5.

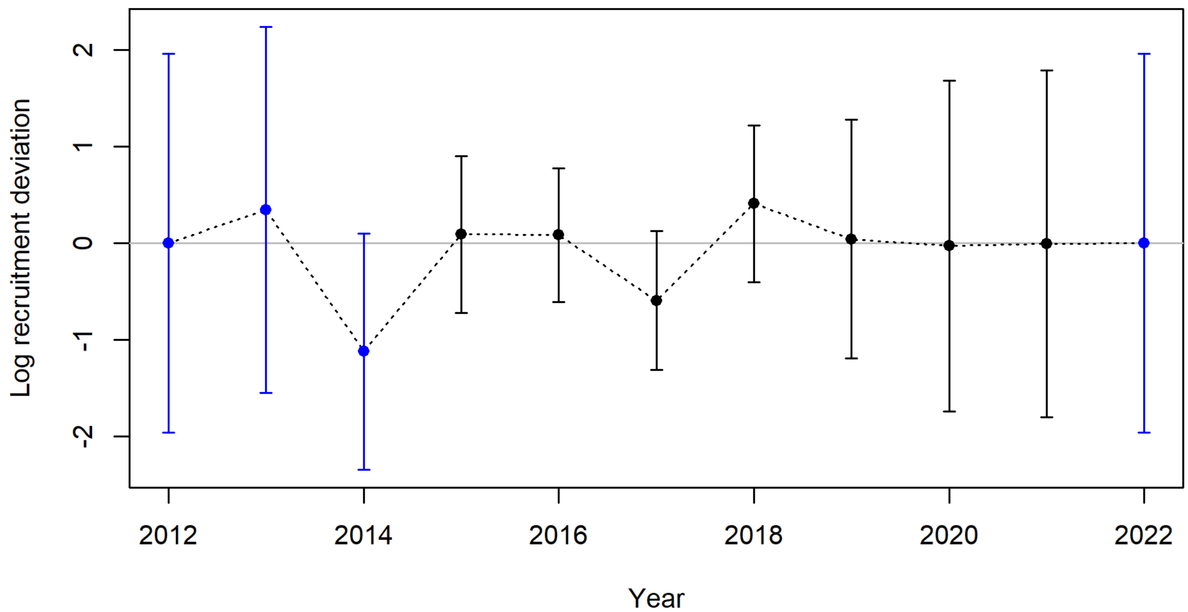

Figure 33: Recruitment deviations with 95% intervals for the base model ($\sigma_R = 1$).

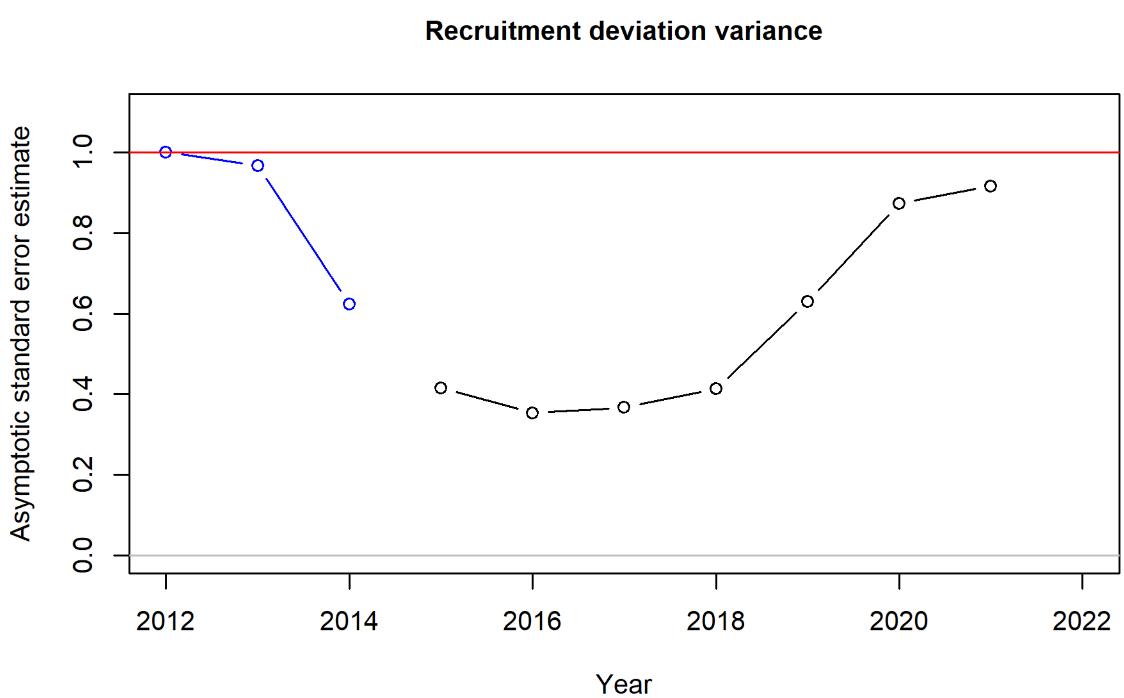

Figure 34: Asymptotic standard errors for the estimated recruitment deviations.

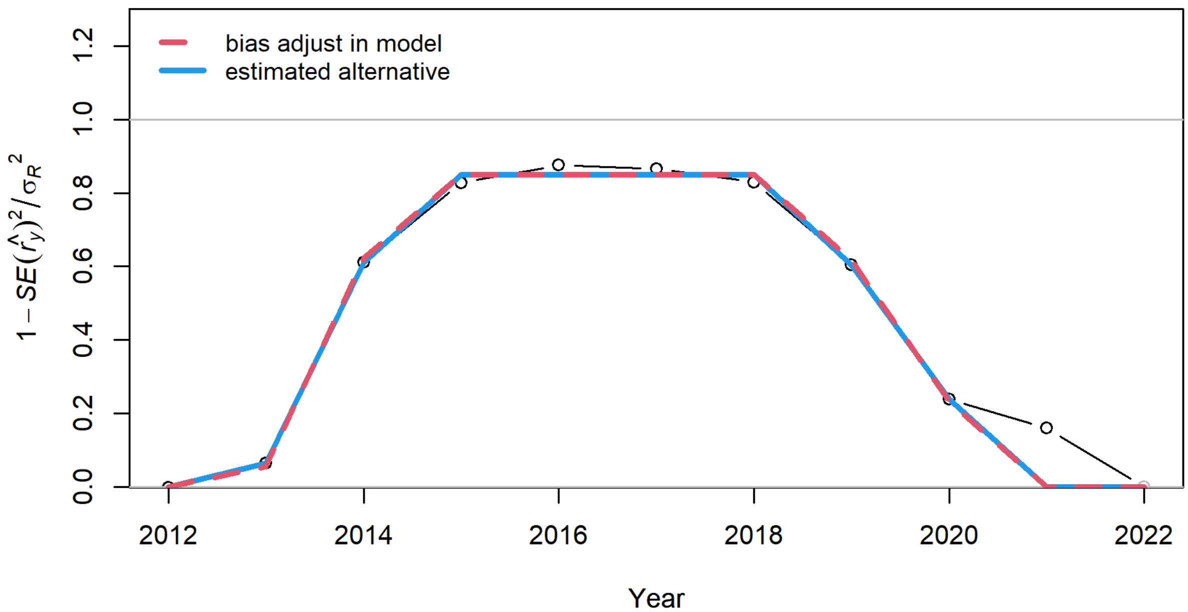

Figure 35: Recruitment bias adjustment plot for early, main, and forecast periods.

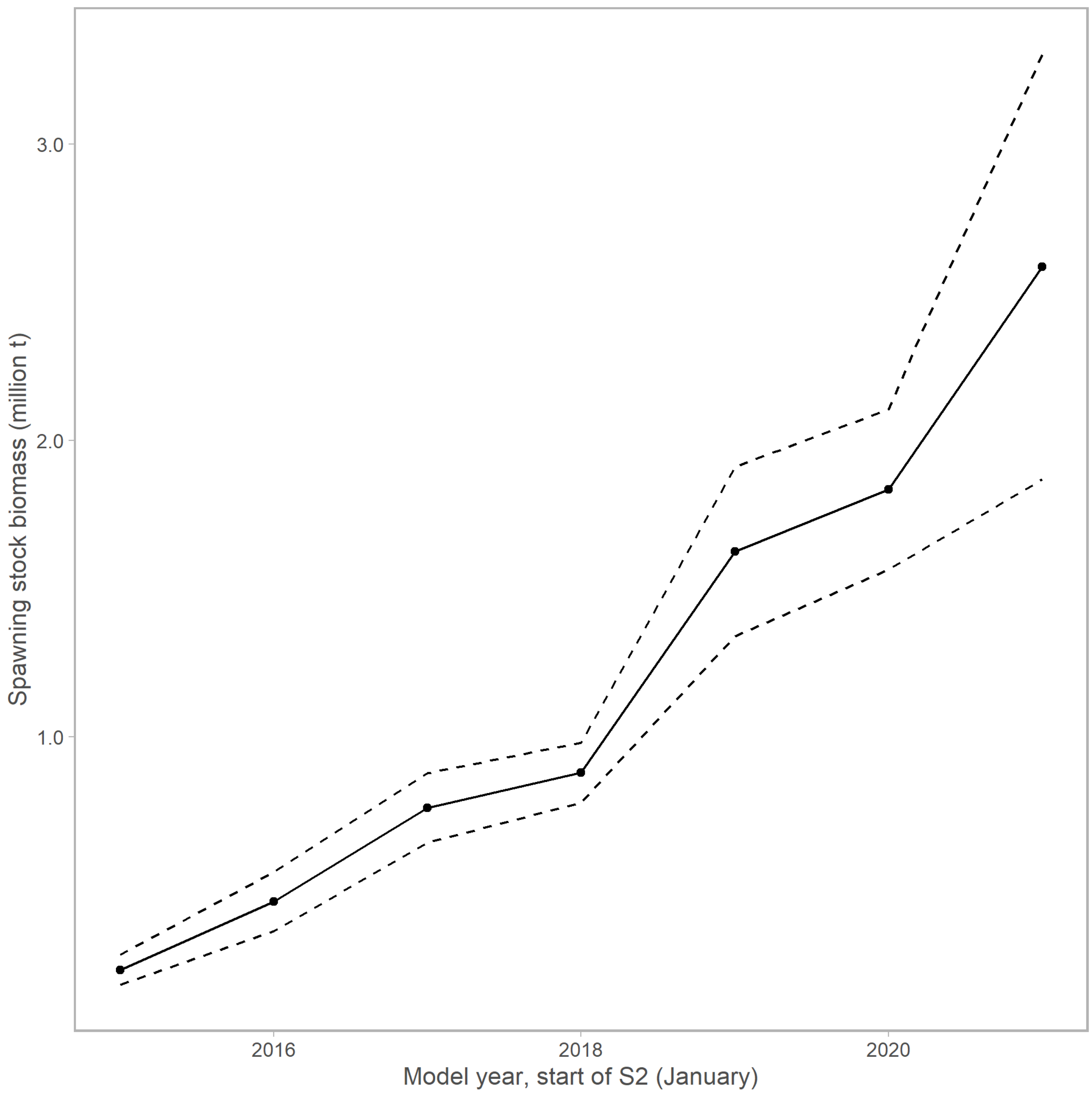

Figure 36: Estimated spawning stock biomass time series (million mt; 95% CI dashed lines).

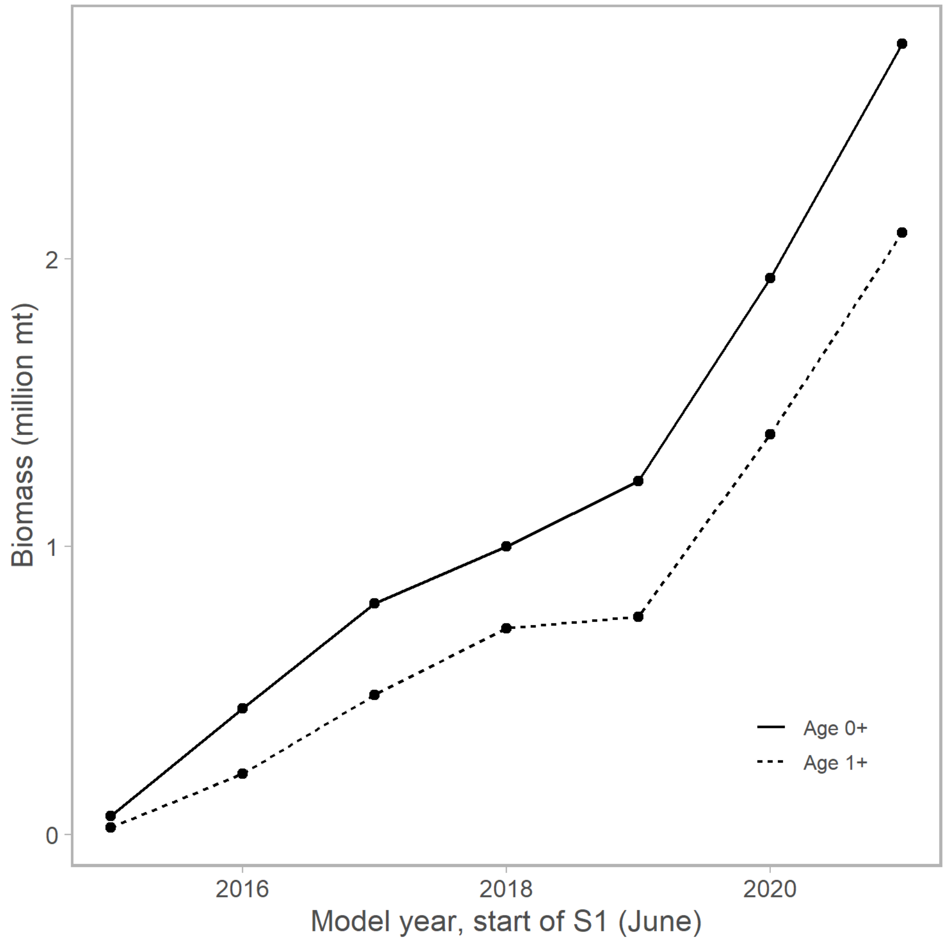

Figure 37: Estimated age-0+ (solid) and age 1+ (dashed) biomass.

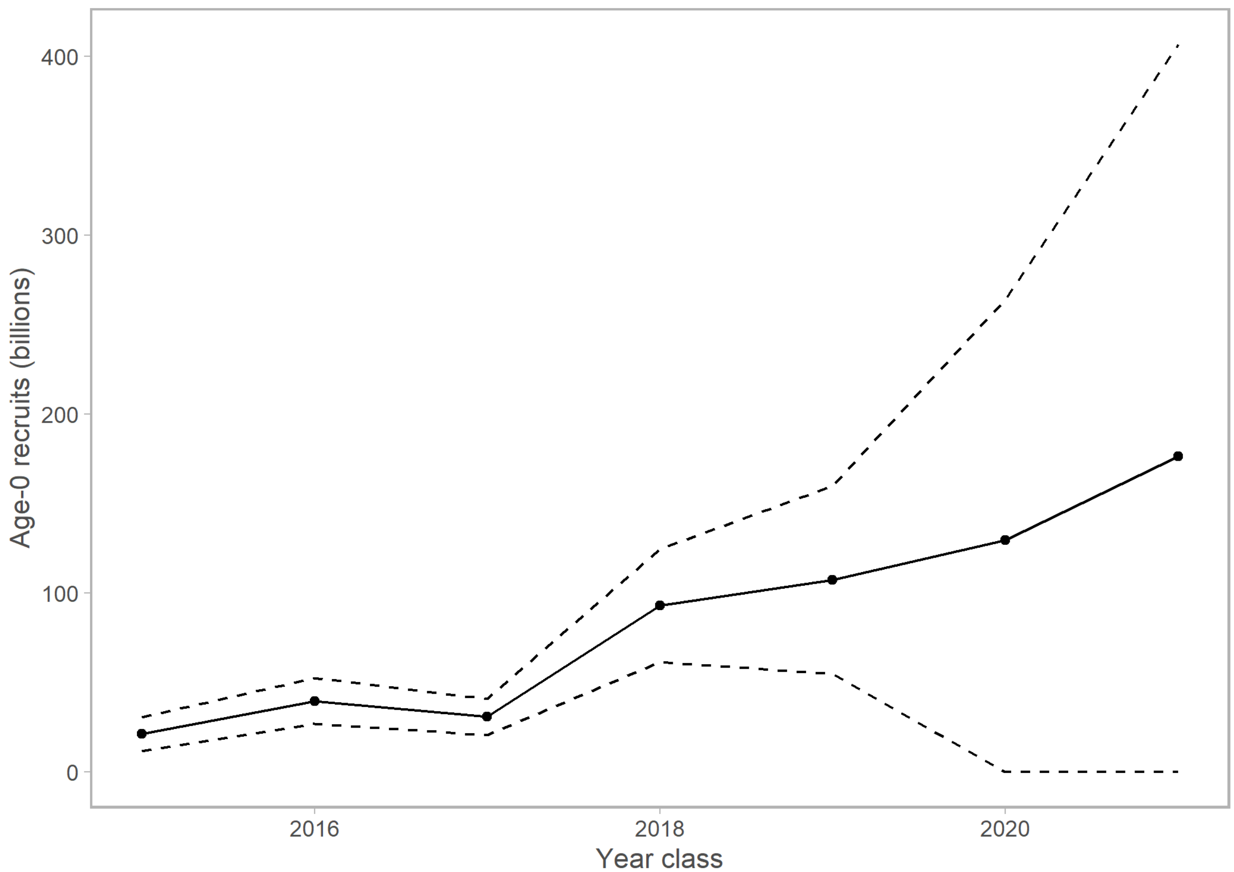

Figure 38: Estimated recruitment time series (billions fish; 95% CI dashed lines).

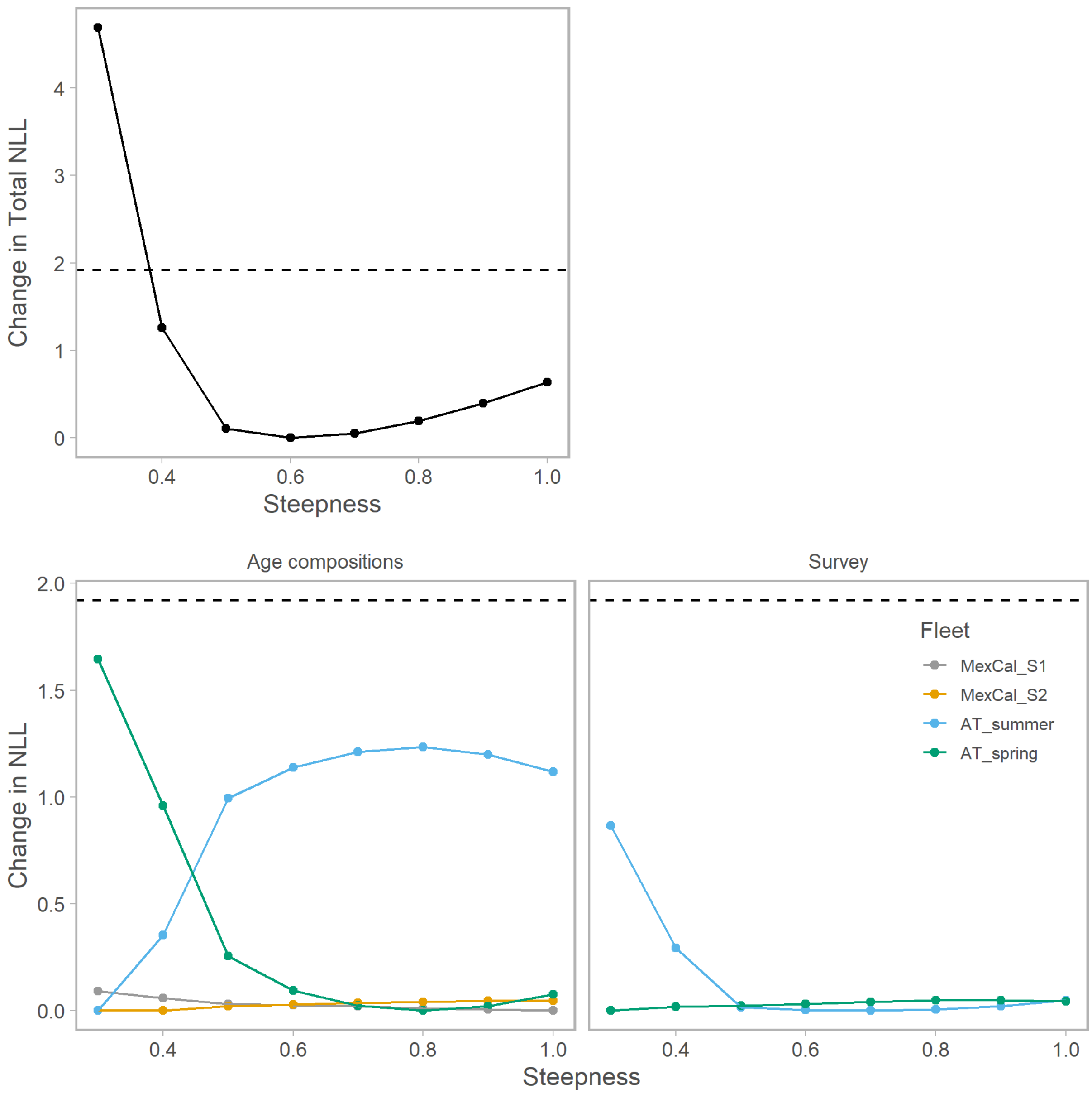

Figure 39: Likelihood profile for values of steepness (h) ranging from 0.3 to 1. Values within 1.92 units of the MLE (dashed horizontal line) are within the 95% confidence interval.

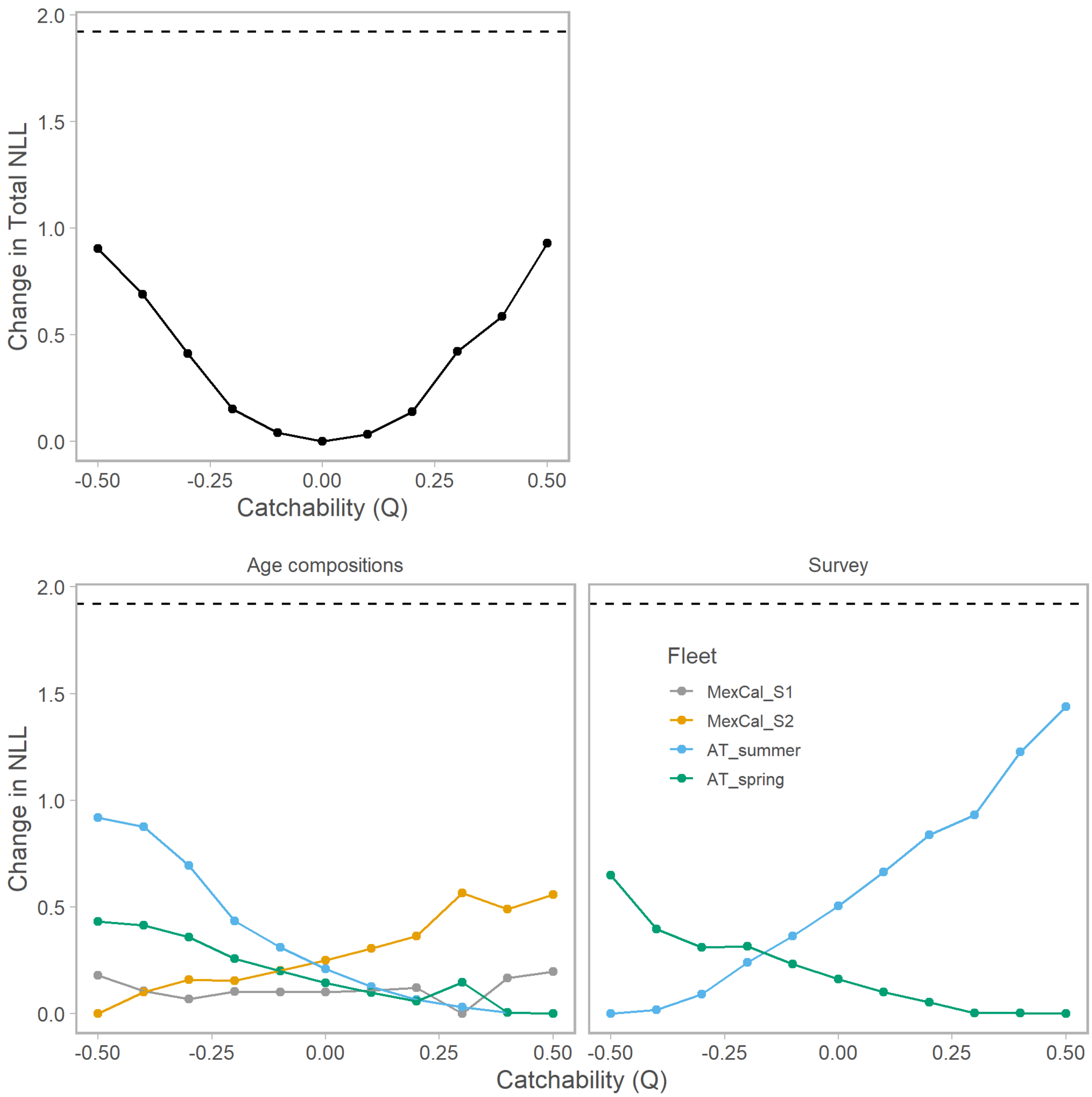

Figure 40: Likelihood profile for values of summer catchability (log Q) ranging from -0.5 to 0.5. Values within 1.92 units of the MLE (dashed horizontal line) are within the 95% confidence interval.

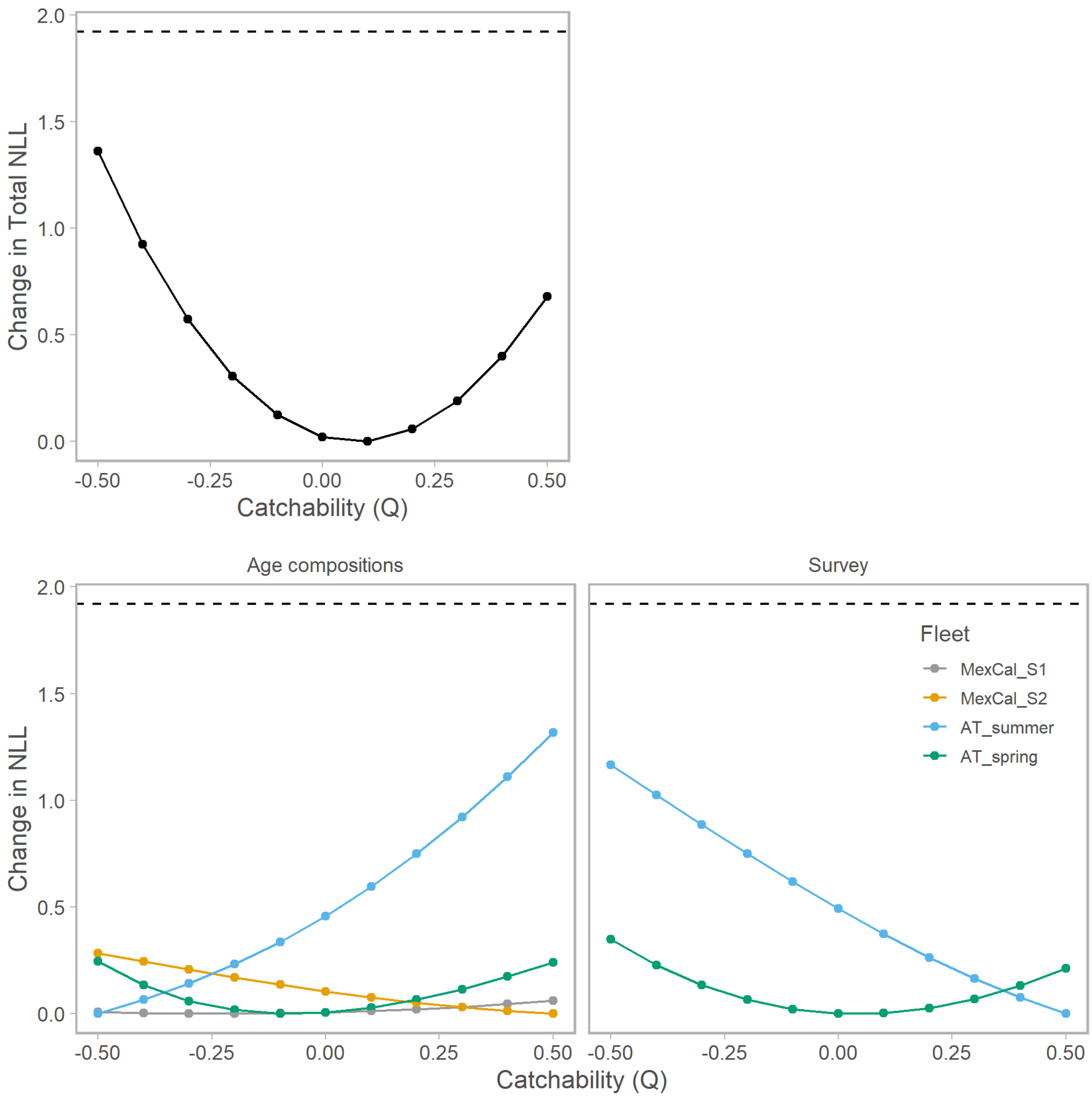

Figure 41: Likelihood profile for values of spring catchability (log Q) ranging from -0.5 to 0.5. Values within 1.92 units of the MLE (dashed horizontal line) are within the 95% confidence interval.

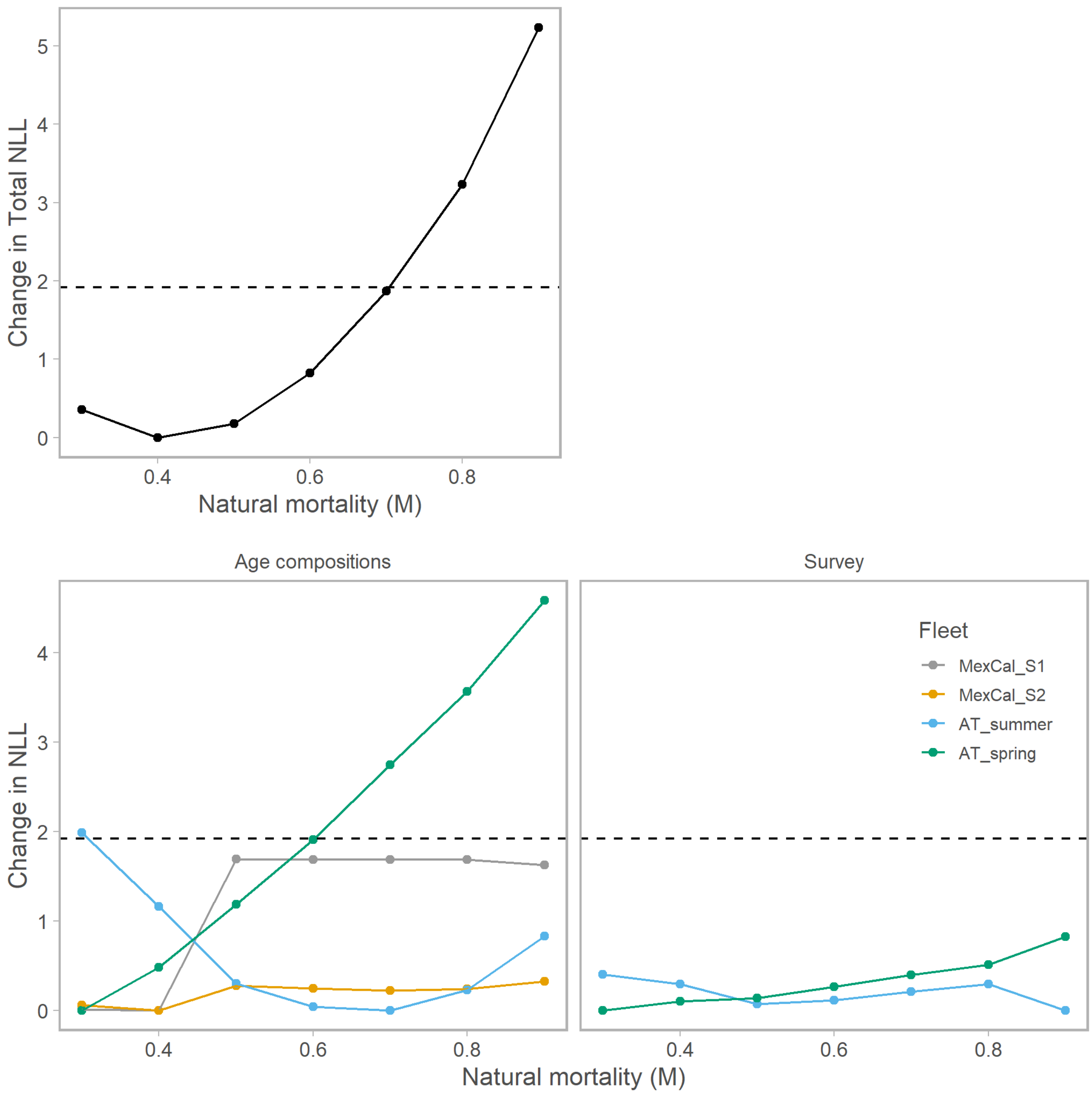

Figure 42: Likelihood profile for values of natural mortality (M) ranging from 0.3 to 0.9 yr^{-1} and steepness fixed at 0.6 (as in the base model). Values within 1.92 units of the MLE (dashed horizontal line) are within the 95% confidence interval.

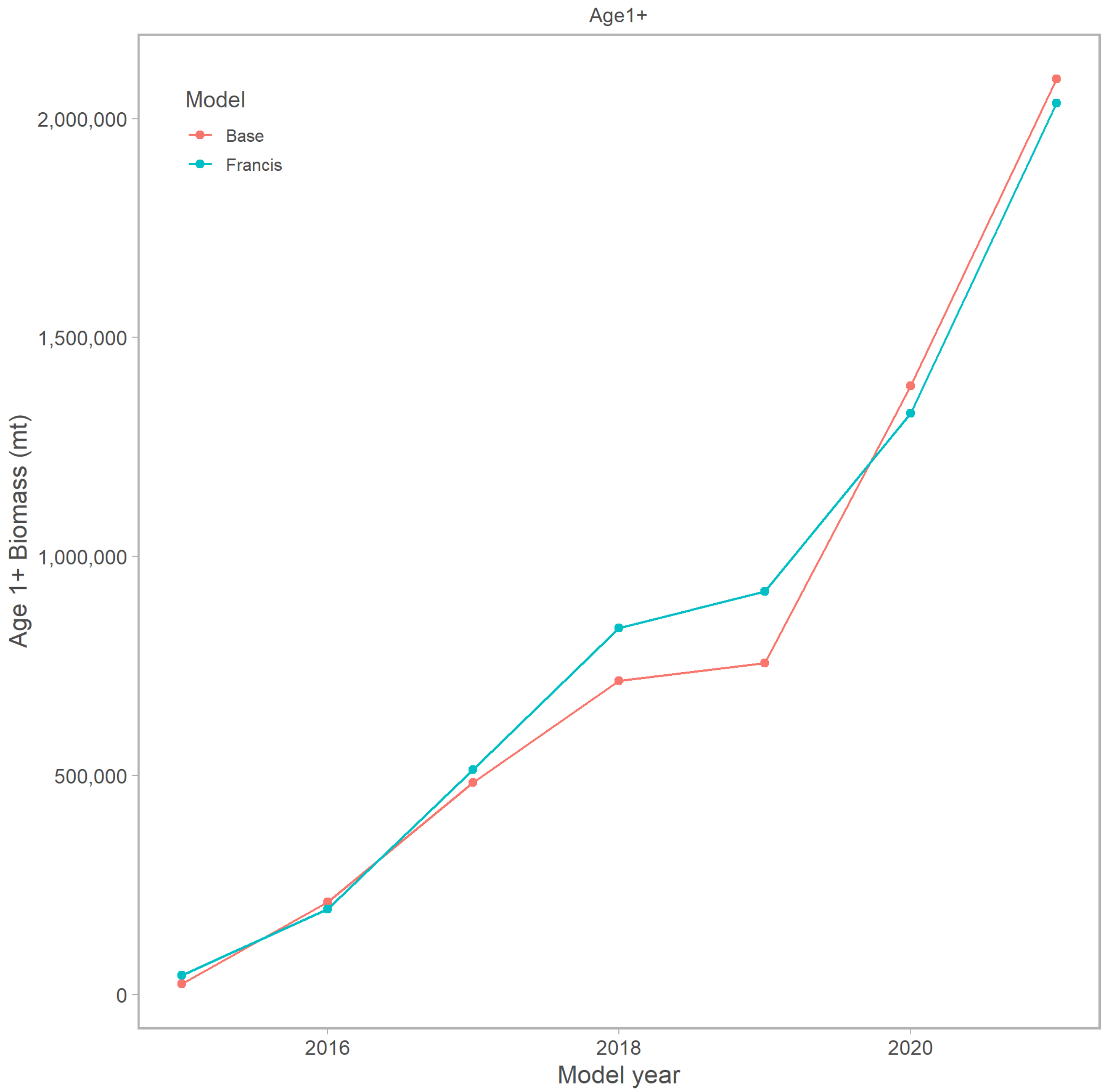

Figure 43: Age-1+ biomass (mt) values estimated from the base model (red line) and the model with Francis reweighting (blue) for the age compositions from all fleets.

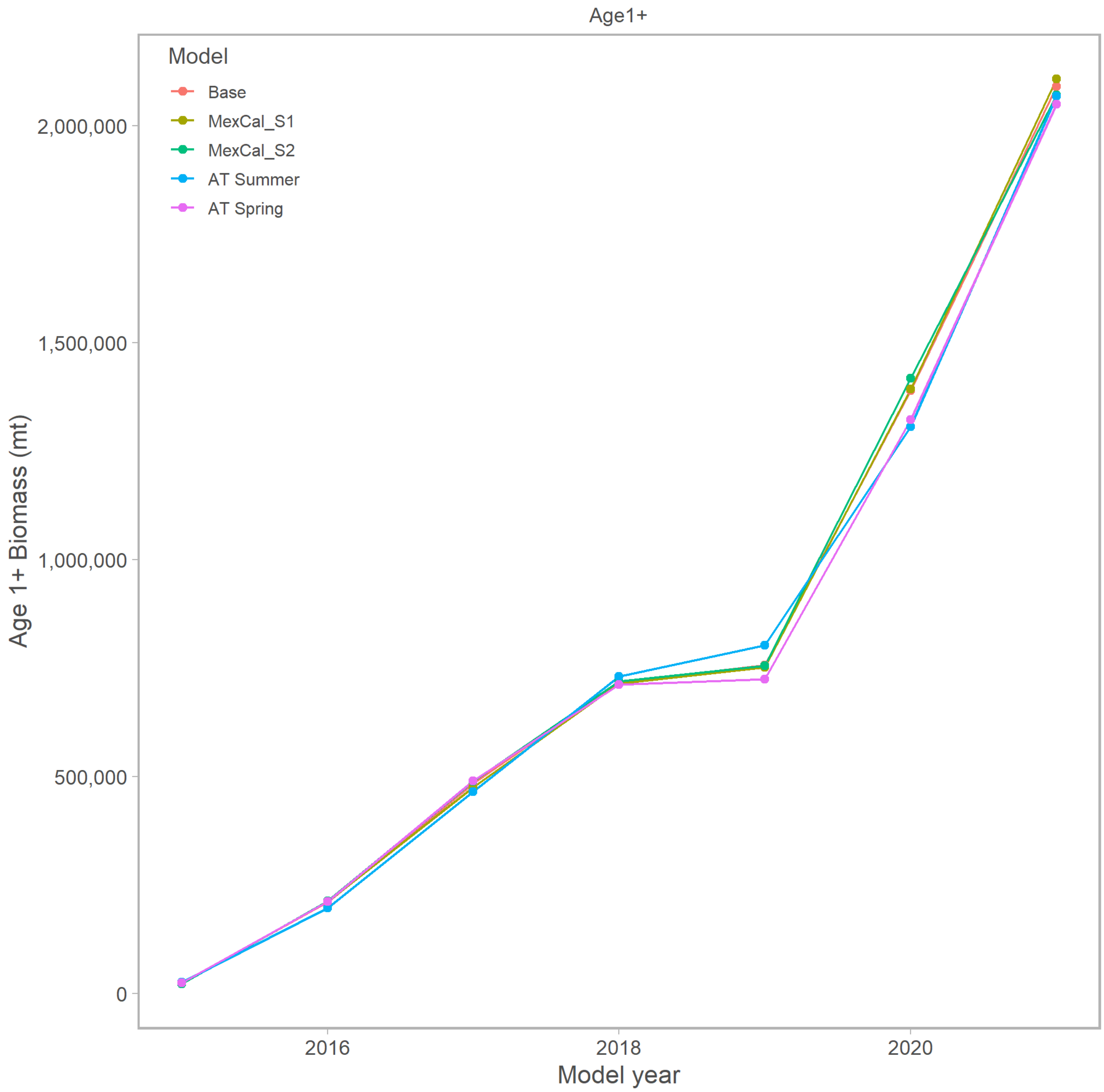

Figure 44: Age-1+ biomass (mt) values estimated from the base model (solid line) and models with downweighted age compositions for each of the MexCal S1, MexCal S2, AT Summer, and AT Spring survey fleets.

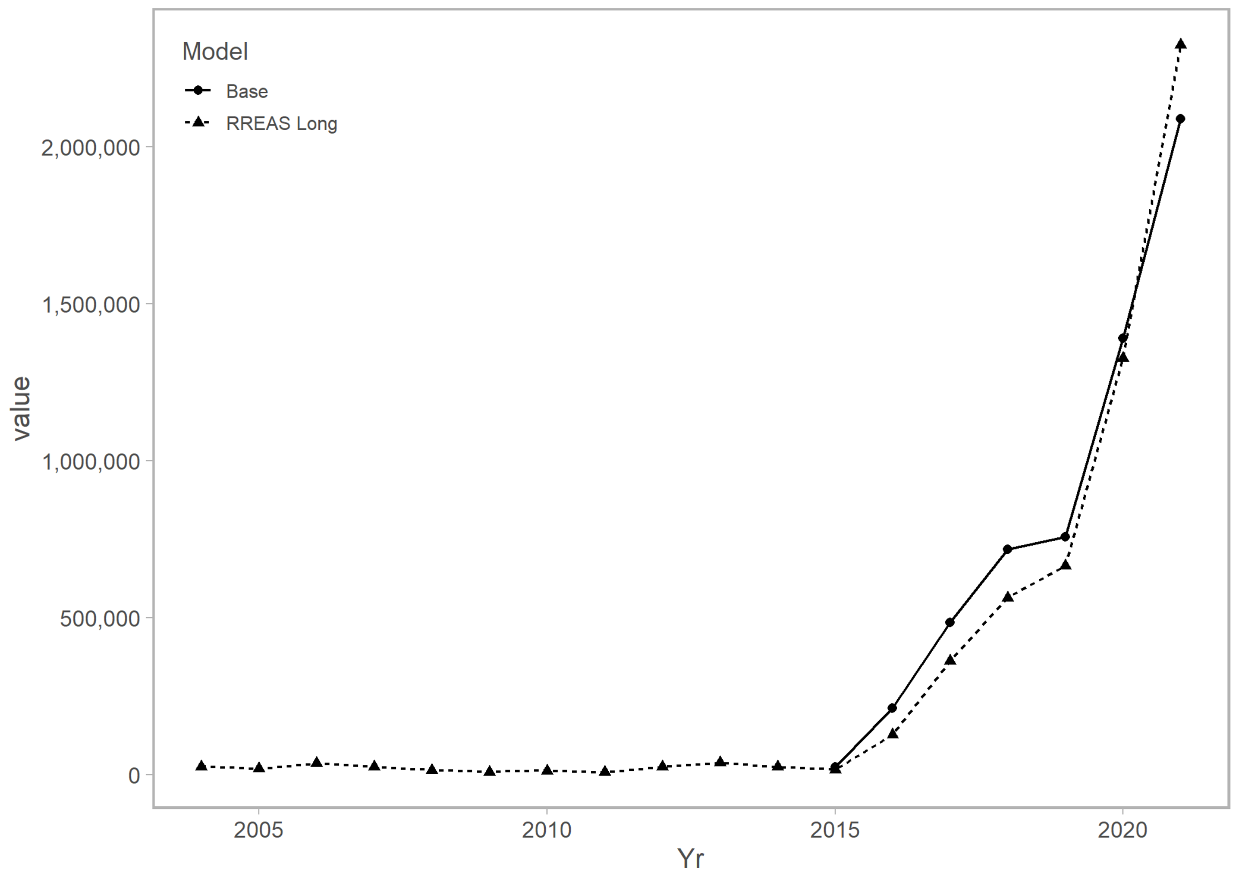

Figure 45: Summary age-1+ biomass (mt) values estimated from the base model (solid line and circles) and longer model with RREAS young-of-year data (dashed line and triangles).

9 References

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10 Appendix A: Calculation of abundance-at-age and weight-at-age from acoustic trawl-method surveys

Two of the outputs of the acoustic-trawl method (ATM) surveys are abundance-at-length and biomass-at-length (Zwolinski et al. 2019). The calculations of abundance-at-age, biomass-at-age, and weight-at-age required for the current anchovy assessment rely on the constructions of age-length keys. An age-length key (ALK) is a model that describes the probability of a fish of a known length belonging to an age-class (Stari et al. 2010). ALKs are used often to calculate abundance and catch-at-age from fisheries-dependent and -independent sources (e.g., Kimura 1977; Clark 1981; Hoenig and Heisey 1987; Robotham et al. 2008). Their use is common when only a subsample of all the fish sampled for lengths are aged, a practice that reduces the time and costs of sampling and analysis. The use of an ALK relies on the assumption that the conditional distribution of ages given length in the subsample is representative of that in the population (Kimura 1977; Westrheim and Ricker 1978).

The sampling scheme to build an ALK necessary requires a sufficient number of individuals to estimate the conditional age-distribution over a set of fixed length intervals. For Northern Anchovy, ALKs were based on individuals from a two-stage sampling procedure. The first level sampling was used to obtain a length-frequency distribution for the population, and a subsample of those individuals was used to derive the distribution of ages-at length (Clark 1981).

When the number of individuals sampled for age is large, an empirical age-length key can be built by computing the proportion of individuals of all ages across all discrete length classes (Ailloud and Hoenig 2019). However, when sample size is small and there is ageing error, empirical age-length keys might be dominated by error (Stari et al. 2010). In these cases creating a smooth ALK relying on some sound underlying process is preferable (e.g., Martin and Cook 1990; Berg and Kristensen 2012).

There are numerous analytical approaches to build smooth or model-based ALK (e.g., references above; Stari et al. 2010; and references therein). Here, we postulated that for ages a (in years) such that $a \in \{0,1,\dots,6+\}$, the probability distribution conditioned on length l, $P_a(l) = \{p_0(l), p_1(l), \dots, p_{6+}(l)\}$, follows an ordered categorical distribution. $P_a(l)$ was modeled using the *gam* function in the *mgcv* package (Wood et al. 2016) for *R*, with distribution *ocat.* Detailed information about the ordered categorical regression used can be found in the supplementary information of Wood et al. (2016). Below is brief explanation of the model fitting in R.

For a data set with a variable *age.ordinal* – coded by natural numbers from 1 to 7, corresponding to ages 0, 1, 2, … 6+ years, and *standard.length* – coded as a continuous variable in mm, the *gam* model can be fitted by

```
R = 7 # number of age categories
model <-   gam(age.ordinal ~ s(standard.length) , data  =  data  , family= ocat(R= R)) # the ordinal model
    as smooth function of length
```

and the resulting ALK can be created by

```
prob.matrix <- predict( model , newdata = data.frame(standard.length = seq(20,200, by =10)), type =
    "response")
```

which results in a 19 by 7 matrix in which each row is the estimated vector of probabilities $P_a(l)$ of a fish of length l (in cm) with $l \in \{2,3,\dots,20\}$ belonging to an age group a, with $a \in \{0,1,\dots,6+\}$. Considering a vector of abundances at length $N_l = n_2, n_3, \dots, n_{20}$, the elements of vector of abundances at age N_a are calculated by $n_a = \sum_{l=2}^{20} P_a(l) n_l$. Similarly, the elements of biomass at age B_a are given by $b_a = \sum_{l=2}^{20} P_a(l) n_l w_l$, where $w_l$is the average weight of anchovy in the l-th length class derived from a length-to-weight relationship. Finally, mean weight-at-age is obtained by dividing B_a by N_a.

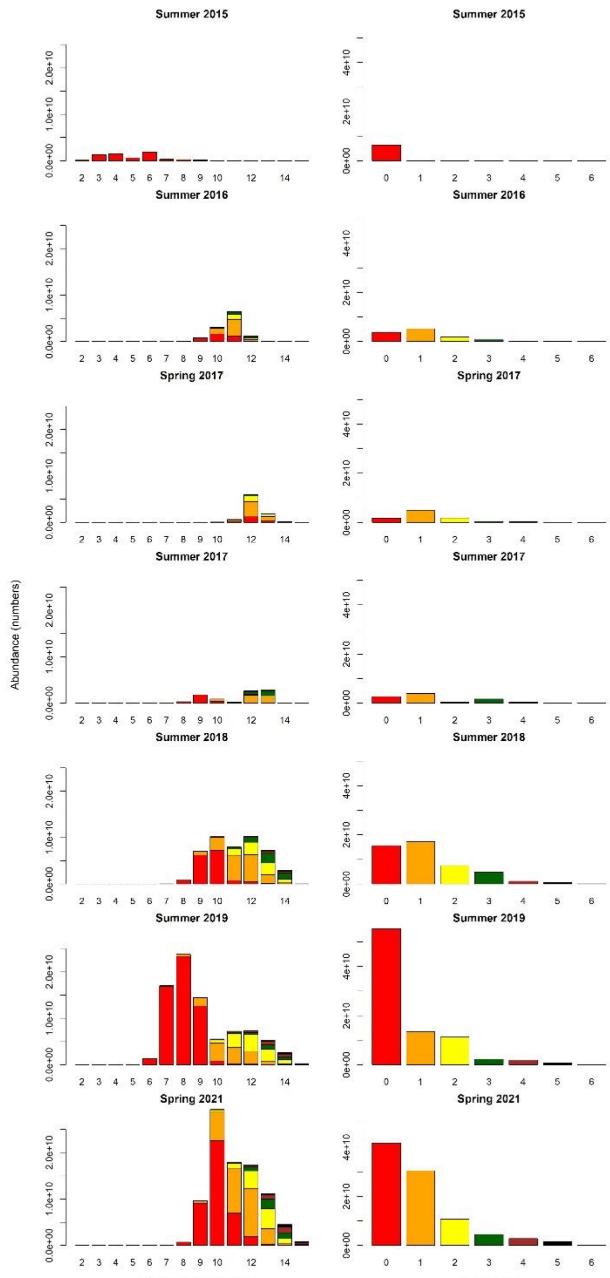

Figure 1 – Left column: abundance-at-length derived from the ATM surveys; Right column: abundance-at-age derived using survey-specific age length keys. The age color code on the right column graphs matches that of the age-disaggregated abundance-at-length on the left column.

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11 Appendix B: Rockfish Recruitment and Ecosystem Assessment Survey (RREAS) CSNA abundance indices

Prepared by John Field, Tanya Rogers, Rebecca Miller and Keith Sakuma

Catch data from the Rockfish Recruitment and Ecosystem Assessment Survey (RREAS) were used to develop relative abundance indices of all anchovy biomass, adult (age 1+) anchovy biomass and young-of-the-year (age 0) abundance from 2004 through 2021. The RREAS began in 1983 in central California waters to assess ocean conditions and the abundance and distribution of young-of-the-year (YOY) rockfish, other young-of-the-year groundfish (such as Pacific hake and sanddabs), and other forage taxa in late spring of each year. Data have been used to inform stock assessment models of rockfish and other groundfish with recruitment indices that improve forecasts of the abundance and availability of strong year classes to commercial and recreational fisheries (Ralston et al. 2013, Field et al. 2021). Since 1990 the survey has also quantified other epipelagic micronekton, with an emphasis on ecologically important forage species, to support a growing array of ecosystem studies and to provide ecosystem indicators to marine resource managers (e.g., Harvey et al. 2021).

From 1983 through 2003 the survey operated solely off of Central California (between approximately 36° N and 38° N latitude), however since 2004 the survey has covered most of the California coastline, from the U.S./Mexico maritime border to the California/Oregon border (Sakuma et al. 2016). Comparable collections have been conducted by the NWFSC since 2001 for YOY groundfish and since 2011 for all taxa (see Field et al. 2021). Mid-water trawls are collected at fixed sampling stations during night using a modified Cobb mid-water with a 9.5 mm cod-end liner, the net design and methods are highly comparable to historical CDFW acoustic trawl surveys (Mais et al. 1974). Standardized fifteen minute tows are made at each station with a headrope depth of 30 m, although for some nearshore stations the shallow bottom depth precludes fishing at that depth, and haul target headrope depths are 10 meters. Trawls are standardized by adjusting the amount of trawl warp deployed and using a Simrad ITI sensor system to adjust the vessel speed in real time to maintain a headrope depth of 30 meters, and thus a constant speed through the water. After each haul, all taxa are identified, enumerated and a subset of key taxa are measured (standard length). Details on methods, routinely encountered taxa, and other data collected during surveys are available at Sakuma et al. (2016) and Santora et al. (2021). For the indices developed here, we focus only on RREAS data from 2004 through 2021, as the limited spatial extent of the pre-2004 data may reduce the information content of the indices (see figures 4 and 5 on relative distribution of both YOY and adult anchovy over time). Table 1 lists the number of trawls conducted, the number of positive trawls by life history stage and year, and the number of length observations collected during the RREAS between 1990 and 2021.

For biomass estimates, length data were expanded from the subset (generally 20-30) of individuals measured in each trawl, and converted to biomass based on published length/weight relationships informed by ontogenetic stage (e.g., YOY, adult). YOY and adults typically distinguished morphologically, and by assuming a 90 mm cutoff between age 0 and age 1 fish at larger sizes. Length data are available for adult life history stages from 1990 through 2021, length data for YOY are only available from 2013 through 2021. While there is some potential for incorrect assignment of some individuals near this size cutoff, the vast majority (>92%) of YOY are between sizes of 15 and 60mm, and clearly recognizable as YOY. Relative abundance indices were estimated using a delta-generalized linear model (GLM) approach (also referred to as a hurdle model), an approach routinely used for developing indices of relative abundance from fisheries survey and catch rate data (Maunder and Punt 2004). The year effects are the parameter of primary interest, with spatial and temporal covariates explored within the model structure, and either included or excluded based on Akaike's Information Criteria (AIC) are also estimated. Covariates explored include station effect, area effects (where station line is a proxy for area), depth effects (inshore and offshore of 200m), Julian day bin effects (typically very important for strongly seasonal YOY groundfish index development, but not significant for CSNA). Uncertainty in the year effects was quantified by running the model in a Bayesian framework using the R package 'rstanarm' to estimate standard error and confidence limits (R project, 2020). Relative abundance indices were developed for total biomass (age 0 and age 1+), and age 0 and age 1+ biomass independently (Figures 1-3).

The trends in relative abundance seen in this dataset are consistent with observations from other data sources such as the acoustic trawl survey, CalCOFI egg and larval abundance data, and predator food habits data. All of these datasets tend to show an increase in relative abundance early in the time series (2004-2006), very low abundance and availability between 2007 and 2014, with a sharp increase in YOY abundance starting around 2014-2015, and an increase in adult abundance trailing the increase in YOY abundance. Spatial patterns indicate considerable spatial autocorrelation in relative catch rates, with the greatest catches of adults typically found around Point Conception and up to Monterey Bay in high abundance years, while YOY are more frequently encountered throughout the Southern California Bight (SCB) at the timing of the survey (Figure 4). The distribution of YOY in 2015 (during the large marine heatwave) was unusual in that YOY were found widespread throughout the survey area, but were not unusually abundant in their (typical) high abundance region (the SCB) during that year (Figure 5). This was consistent with the observation of unusual spatial distributions and abundance patterns of many different taxa during the year of the large marine heatwave (Sakuma et al. 2015, Santora et al. 2017). Note that survey effort was limited in 2020 to a small number of trawls (15) conducted onboard a chartered fishing vessel solely within the core area, thus data are quite thin with respect to this year for the relative abundance indices. However, 2020 and other recent years have seen extremely high abundance of CSNA in both this and other surveys. Data from 1990-2003 in the core area only were not included here as they do not include the core range of the stock, but could be useful in evaluating regional abundance for other investigations.

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Table 1: Number of trawls, number of trawls positive for either YOY or adult northern anchovy, the percentage of positive trawls, and the number of length observations recorded for the RREAS survey, 1990-2021.

year	trawls (south of 40 10)	positive YOY	% positive YOY	YOY length data	positive adult	% positive adults	adult length data
1990	80	2	0.025		24	0.300	
1991	93	10	0.108		0	0.000	
1992	73	27	0.370		21	0.288	
1993	75	50	0.667		9	0.120	
1994	75	47	0.627		8	0.107	
1995	74	14	0.189		23	0.311	
1996	76	35	0.461		13	0.171	
1997	74	36	0.486		15	0.203	
1998	78	6	0.077		23	0.295	
1999	77	3	0.039		19	0.247	322
2000	87	0	0.000		7	0.080	515
2001	80	4	0.050		11	0.138	136
2002	67	1	0.015		4	0.060	106
2003	88	0	0.000		12	0.136	2
2004	119	12	0.101		49	0.412	63
2005	130	26	0.200		71	0.546	905
2006	142	13	0.092		72	0.507	1130
2007	154	15	0.097		33	0.214	1355
2008	95	9	0.095		19	0.200	648
2009	123	11	0.089		6	0.049	298
2010	123	9	0.073		2	0.016	42
2011	58	0	0.000		1	0.017	2
2012	83	2	0.024		0	0.000	1
2013	135	4	0.030	32	6	0.044	38
2014	141	34	0.241	185	3	0.021	16
2015	161	129	0.801	1308	5	0.031	21
2016	131	72	0.550	791	9	0.069	108
2017	91	33	0.363	334	9	0.099	105
2018	126	71	0.563	905	45	0.357	725
2019	102	54	0.529	416	68	0.667	1162
2020	15	5	0.333	28	12	0.800	224
2021	100	27	0.270	310	65	0.650	897

Table 2: RREAS indices of abundance estimated from a delta-generalized linear model. Note, there were insufficient samples to calculate values in 2011 and 2020.

Year	Value	CV
2004	0.029	1.172
2005	0.215	0.878
2006	0.016	1.109
2007	0.024	1.056
2008	0.002	1.286
2009	0.016	1.285
2010	0.006	1.327
2011	-	-
2012	0.009	3.815
2013	0.125	1.762
2014	0.313	0.799
2015	3.644	0.520
2016	1.539	0.601
2017	0.794	0.740
2018	2.014	0.593
2019	0.391	0.637
2020	-	-
2021	0.187	0.887

Table 3: RREAS average individual young-of-year (YOY) masses (g). These values were input to the weight-at-age section of the stock assessment input files in sensitivity runs.

Year	Total YOY mass (g)	Total YOY numbers	Total Pos. Tows	Avg. individual mass (g)
2004	2282.215	2686	12	0.850
2005	31192.823	36700	26	0.850
2006	6006.531	7067	13	0.850
2007	6995.499	8231	15	0.850
2008	127.491	150	9	0.850
2009	177.168	244	11	0.726
2010	16.637	28	9	0.594
2012	23.798	28	2	0.850
2013	6932.533	4973	4	1.394
2014	1607.602	1242	34	1.294
2015	15817.613	12282	118	1.288
2016	104333.379	30524	69	3.418
2017	48577.769	73922	33	0.657
2018	214852.880	212652	71	1.010
2019	6732.146	34668	54	0.194
2020	-	-	-	-
2021	7051.372	23354	27	0.302

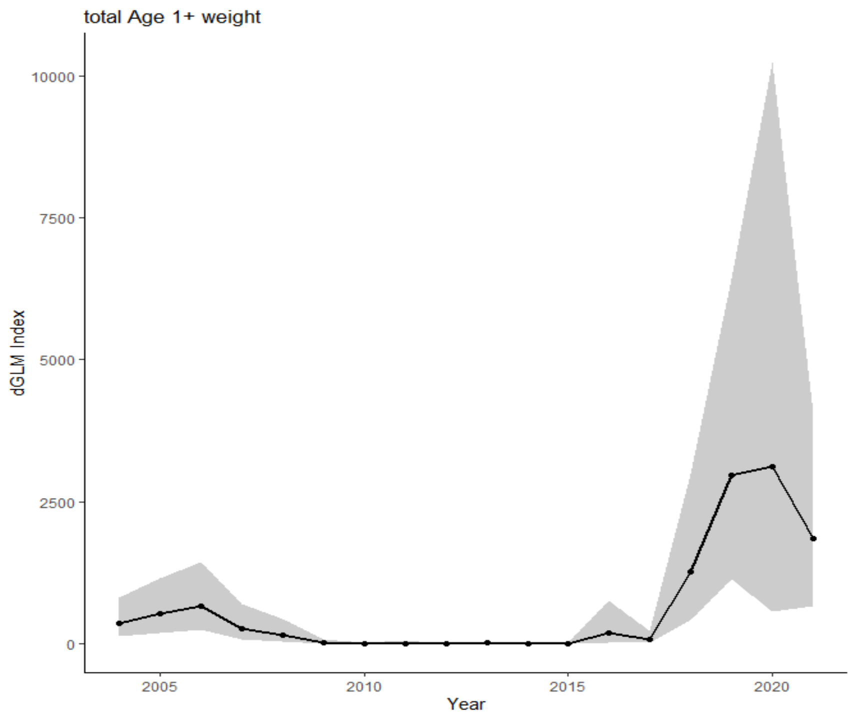

Figure 1: Relative abundance of adult (age 1+) anchovy biomass from the Rockfish Recruitment and Ecosystem Assessment Survey (south of Cape Mendocino to the U.S./Mexico border).

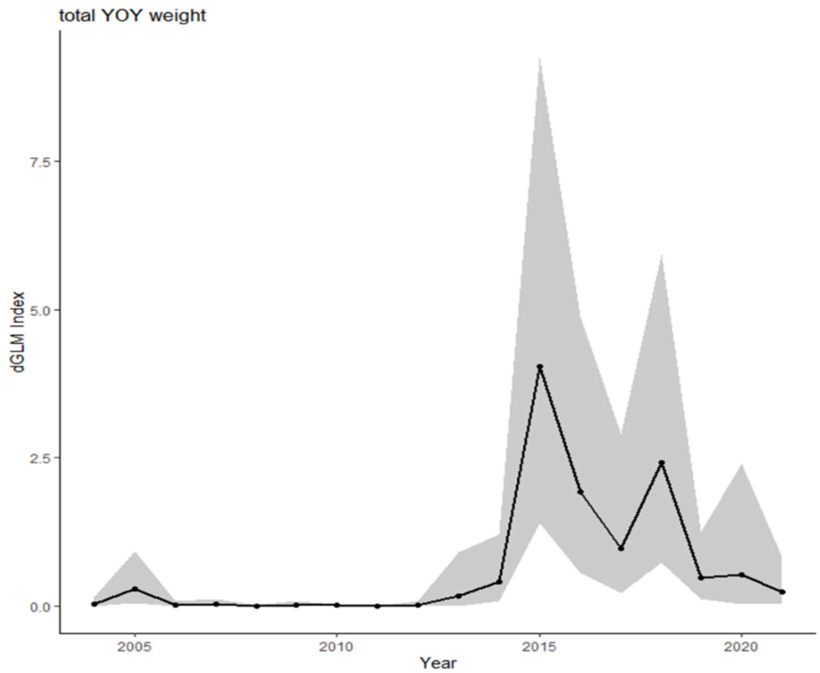

Figure 2: Relative abundance of young-of-the-year (YOY) anchovy from the Rockfish Recruitment and Ecosystem Assessment Survey (south of Cape Mendocino to the U.S./Mexico border).

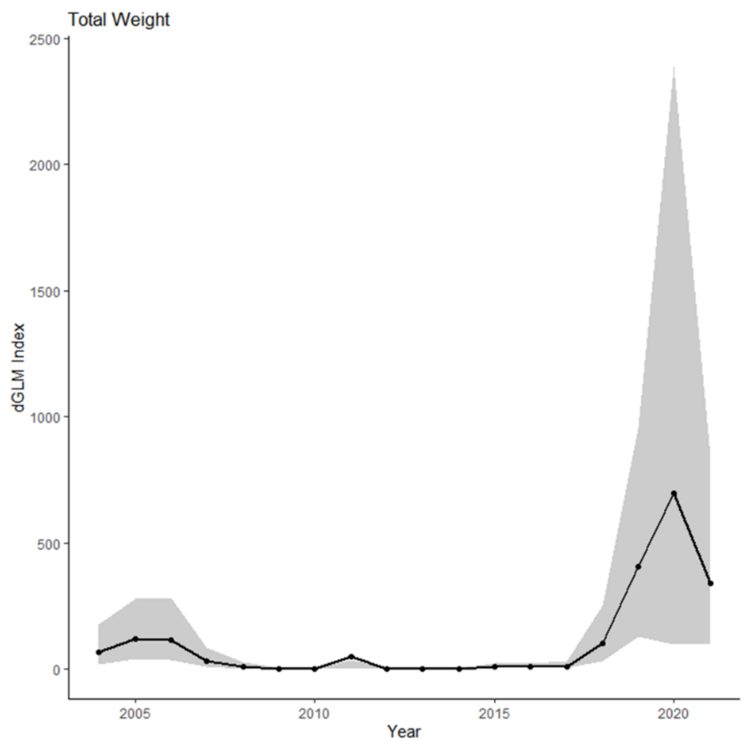

Figure 3: Relative abundance of all anchovy biomass from the Rockfish Recruitment and Ecosystem Assessment Survey (south of Cape Mendocino to the U.S./Mexico border).

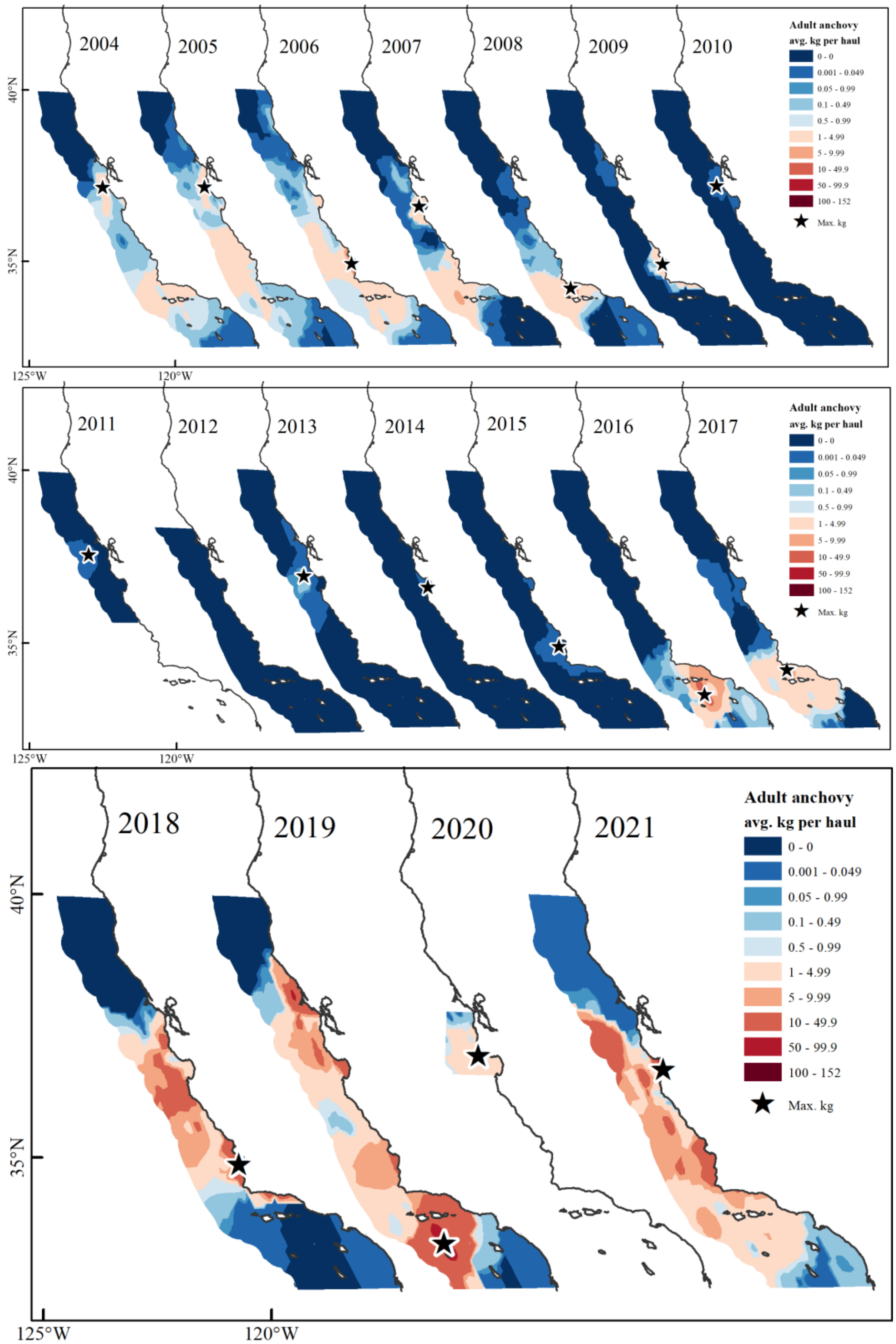

Figure 4: Spatial distribution of adult (age 1+) anchovy catches, 2004-2021

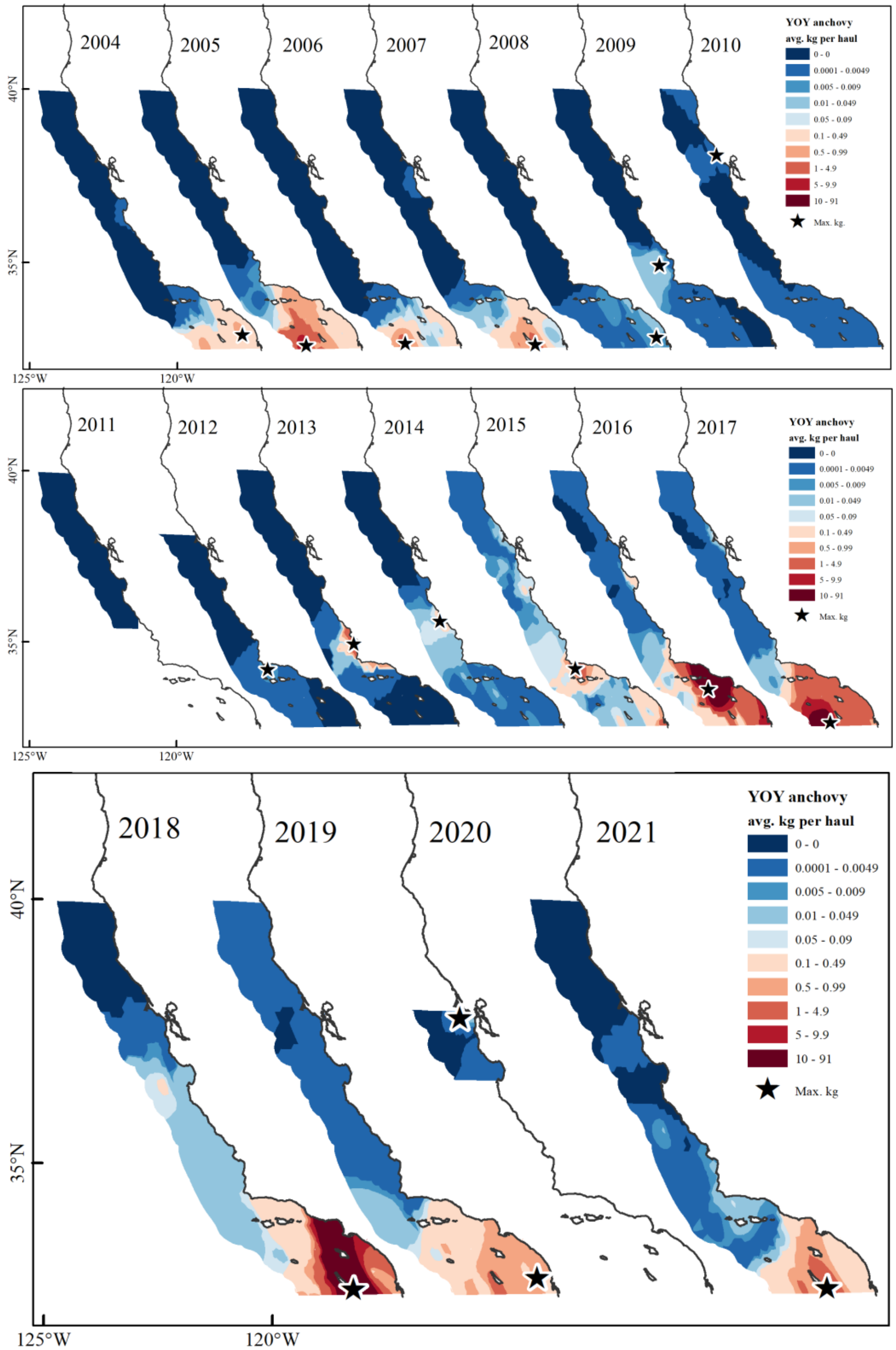

Figure 5: Spatial distribution of young-of-the-year (YOY) anchovy catches, 2004-2021

12 Appendix C: CalCOFI larval and egg indices of abundance

Historical egg or larval abundance data from the California Cooperative Oceanic and Fisheries Investigations (CalCOFI) surveys have been used in previous stock assessments of northern anchovy (Jacobson et al. 1994), as well as several West Coast species including, Boccacio (He and Field 2017), shortbelly rockfish (Field et al. 2007), Cowcod (Dick and MacCall 2014), and California sheephead (Alonzo et al. 2004). The CalCOFI surveys of ichthyoplankton in the California Current began in 1951, with the primary objective of understanding and evaluating the causes of the collapse of Pacific sardine (*Sardinops sagax*) fishery in the late 1940s. Although sardine was the original focus of the surveys, the eggs and larvae of northern anchovy and other species were also identified and quantified. The sampling area and frequency of the surveys have changed over time due to budget constraints. For example, the surveys switched to a triennial cycle after 1969 to maintain spatial coverage at reduced costs. However, this resulted in a lack of sampling during the 1982 El Nino event, and the CalCOFI surveys subsequently switched to an annual, quarterly cycle after 1983, albeit with a smaller spatial coverage limited to central and southern California (McClatchie 2014). Currently, each annual cycle consists of four seasonal surveys although surveys were conducted near-monthly in the early years. The CalCOFI data for this assessment were from oblique larval tows, which sample from approximately 15 m off the bottom to the surface, up to a maximum depth of approximately 210 m. The sampling gear for oblique tows have changed over time, from silk to nylon nets in 1969, and from ring to bongo nets in 1978 (McClatchie 2014).

The spatial extent of the CalCOFI data used to develop this larval index was constrained to the core CalCOFI area, which have been relatively consistently sampled over time and covers the main anchovy larval habitat. This core CalCOFI area consisted of the stations between line 76.7, which abuts the shoreline near Pismo Beach, just north of Point Conception, to line 93.3 to line 93.3, which runs just off of San Diego. Each line was further separated into multiple stations, with a total of 66 line-stations in the core CalCOFI area. The initial and final years for the CalCOFI data in this assessment were 2000 and 2019, respectively, which correspond to the start of the assessment period and the final year of CalCOFI data available. Data from the winter, spring, and summer surveys were used to develop the indices because anchovy spawning peaks in spring. Figure C-1 shows the overall proportions of positive egg and larval samples for the 66 core line-stations during the 2000-2019 period. Figure C-2 shows the overall CPUE of positive egg and larval samples for the 66 core line-stations during the 2000-2019 period.

The CalCOFI larval fish index in this assessment was developed using a similar approach to the CalCOFI index used in the Boccacio assessment (He and Field 2017). The larval fish index used tow-specific information and a delta-GLM approach to derive an index of spawning output. Fixed effects of the model included year, season, line-station. Based on the AIC criteria, we used a lognormal distribution for the positive model and a logit link function for the binomial model. The CalCOFI egg and larval fish index and associated standard errors estimated from a jackknife routine were used as an alternative relative index of spawning output in this assessment (Fig. C-3). The trends suggest that anchovy spawning output have been relatively low over most of the assessment period but increased substantially since summer 2016.

Egg data were also standardized with a vector autoregressive spatio-temporal (VAST) model (Thorson 2019). The models considered full spatiotemporal, spatial, and temporal correlations for both year-season and season-season (code based on the seasonal model code available on the VAST github). The model takes two days to converge with number of knots = 300, using a premade grid. The VAST output showed a similar trend to that from the deltaGLM, particularly in recent years (Figs. C-4 and C-5).

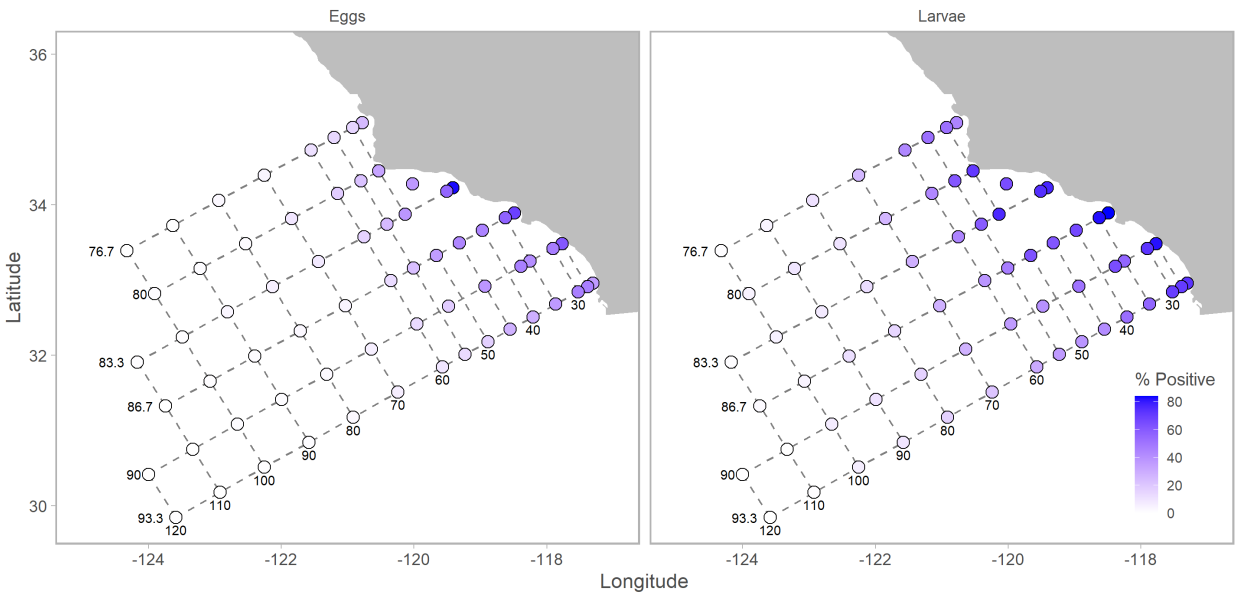

Figure C-1: Percentage positive observations in the core CalCOFI grid averaged from 2000-2019. Percentages for eggs (left) and larvae (right) are displayed. CalCOFI lines are latitudinal and stations are longitudinal, with corresponding lines and stations displayed.Both eggs and larvae tended to be most concentrated nearshore.

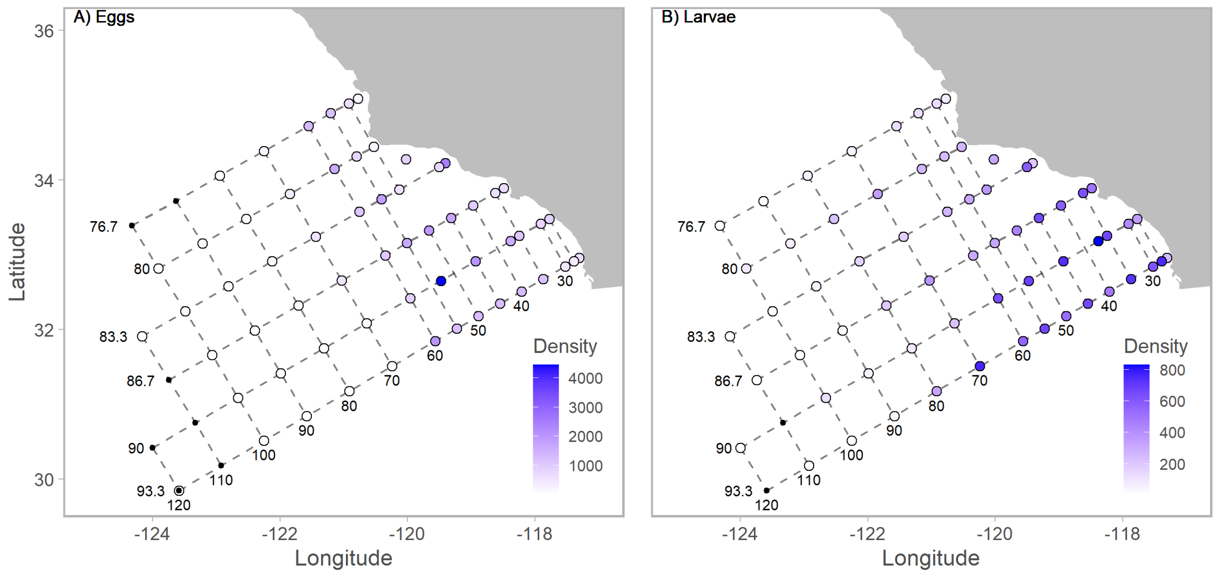

Figure C-2: Average egg (A) and larval (B) densities at CalCOFI stations averaged from 2000-2019. Both eggs and larvae tended to be most concentrated nearshore.

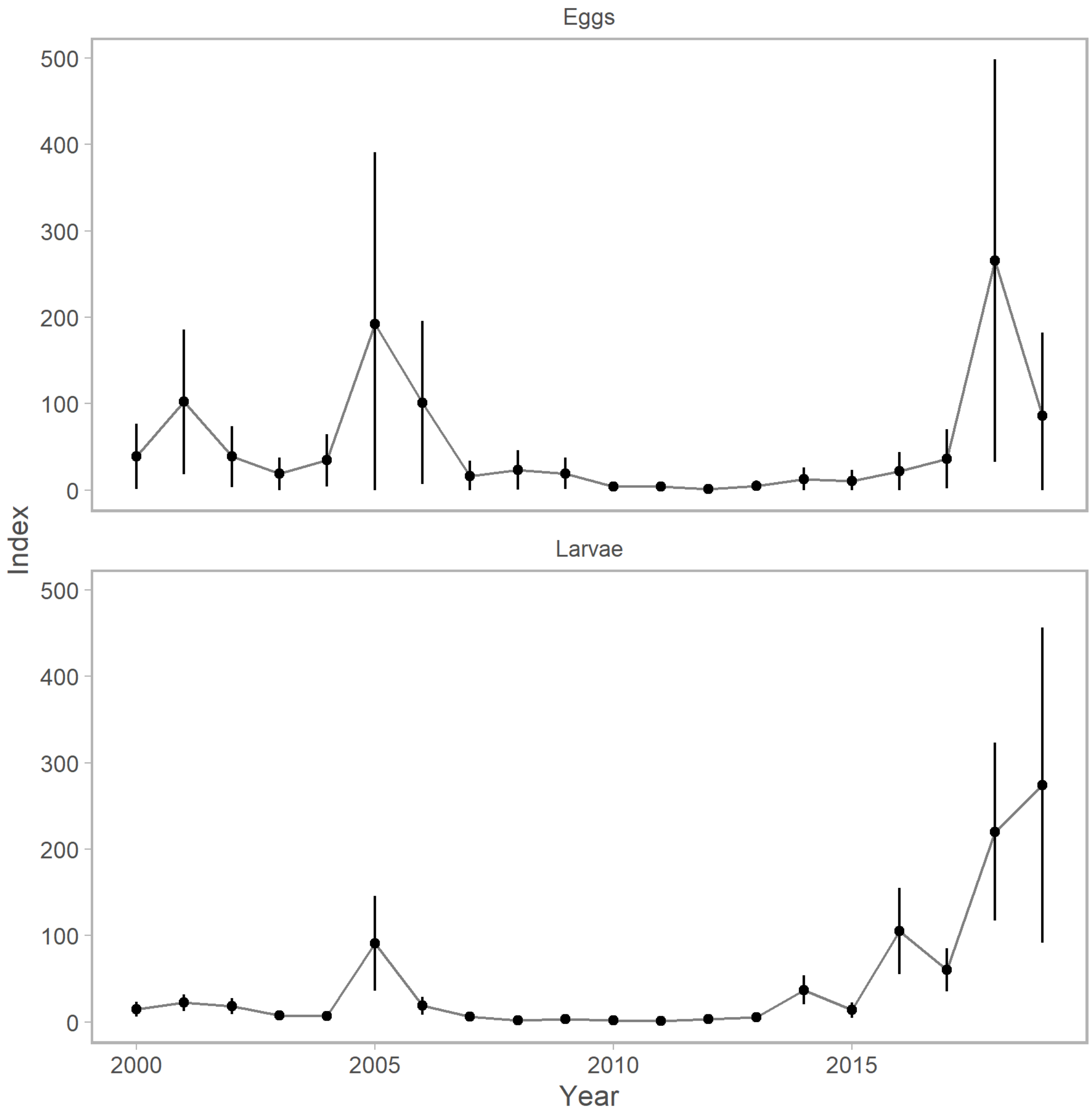

Figure C-3: Standardized CalCOFI indices of abundance for egg (top) and larvae (bottom) data from a delta GLM for 2000-2019.The deltaGLM had effects for year, season, and station.

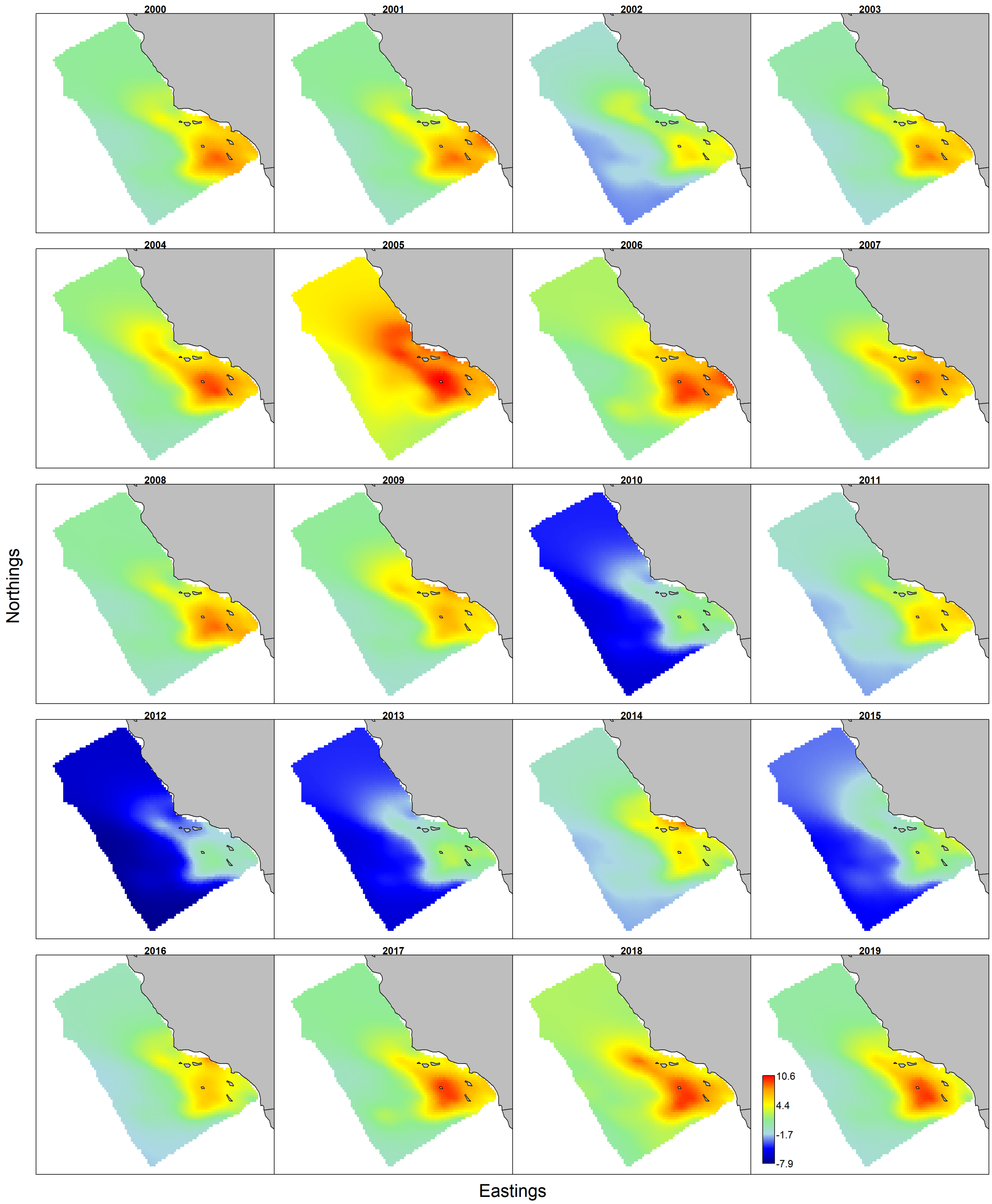

Figure C-4: Spatiotemporal density estimates for CalCOFI eggs.

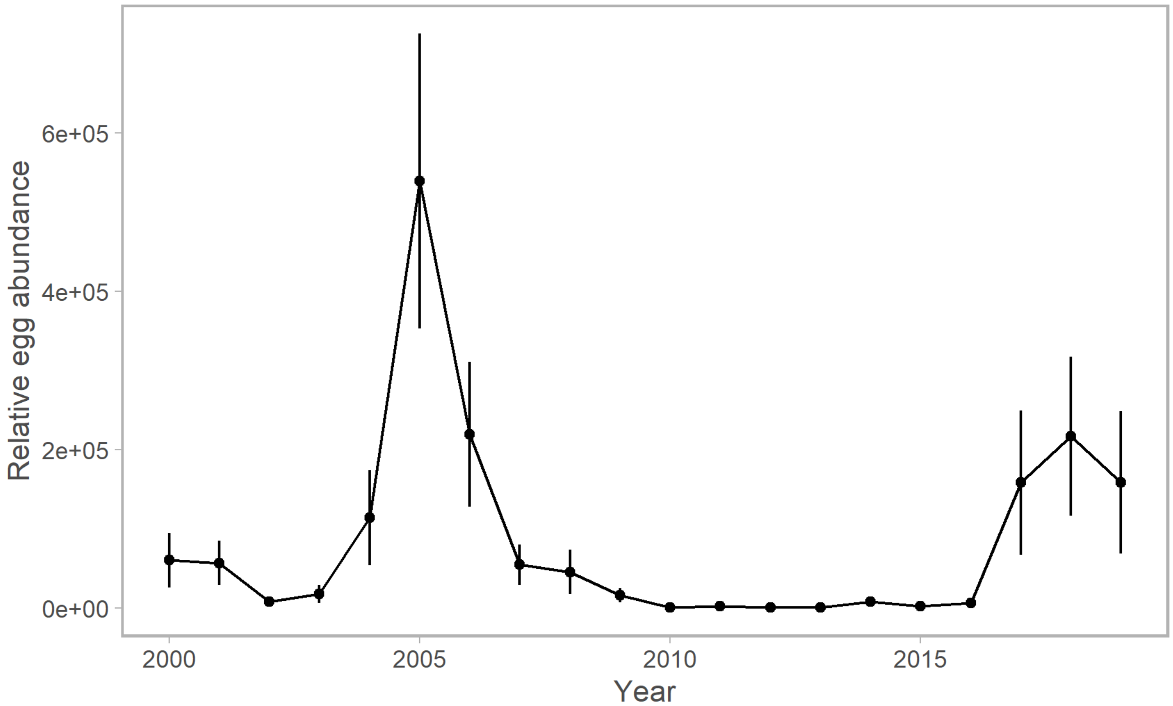

Figure C-5: Relative index of abundance VAST estimates for CalCOFI eggs.

13 Appendix D: California Sea Lion diet time series of anchovy availability

Prepared by Alex Curtis (SWFSC)

California sea lion diet data have been collected at two key southern Channel Islands rookeries on a quarterly basis since 1981 (Fig. 1; Lowry and Carretta 1999). As important predators of small pelagic forage fishes, sea lions provide an index of anchovy relative abundance as well as insight into their relative mortality rates from predation. The time series includes data on frequency of occurrence, numeric abundance, and size of prey (95% of measured anchovy are between 49-153 mm), allowing reconstruction of consumption of specific age classes and relative biomass over time. This data set greatly extends our knowledge of abundance of all anchovy age classes– including non-reproductive – in past decades in the Southern California Bight, an important nursery area that only has been covered by annual trawl surveys in recent years.

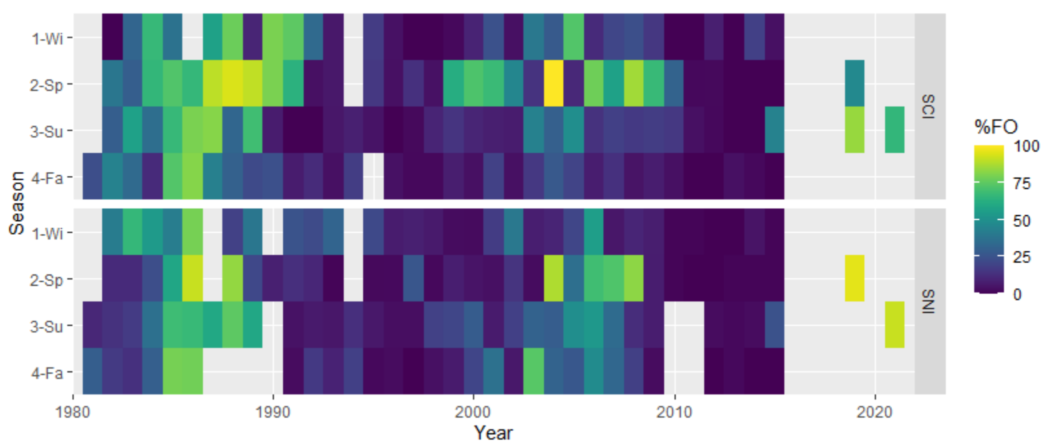

Figure 1. Heat map of percent frequency of occurrence (%FO) of anchovy in California sea lion scats collected quarterly at San Clemente Island (SCI) and San Nicolas Island (SNI). Season abbreviations are 1-Wi = Winter, 2-Sp = Spring, 3-Su = Summer, and 4-Fa = Fall. Apparent gaps in 2010 and recent years are largely an artefact due to a backlog in sample processing, with the exception of spring 2020 through winter 2021, a true gap attributable to COVID-19 sampling restrictions.

References

Lowry M. S., Carretta, J. V. 1999. Market squid (*Loligo opalescens*) in the diet of California sea lions (*Zalophus californianus*) in southern California (1981-1995). *CalCOFI Reports*, 40: 196-207.

14 Appendix E: Calculation of E_{MSY} with SS3.30.19

The exploitation rate that corresponds to Maximum Sustainable Yield (E_{MSY}) was calculated to be 0.493 with the assumed fixed steepness value of 0.6 in the base model (Table E-1 and Figure E-1). The E_{MSY} was calculated to be catch/summary age 1+ biomass and not the fully selected fishing mortality corresponding to MSY. In this case, E_{MSY} can exceed 1 because selectivity for age-0 fish is non-zero. E_{MSY} values associated with steepness values from 0.3 to 1.0 were also calculated.

The steepness profile for E_{MSY} was conducted with SS3.30.19, while the base model was conducted with SS3.30.17. Parameter estimates, biomass values, and E_{MSY} values were identical between both versions of SS3 (Figure E-2). SS3.30.17 did not seem to be calculating seasonal recruitment values correctly in the MSY routine. This calculation was corrected (thanks to Rick Methot) in SS3.30.19, and did not affect any management quantities.

Table E-1: E_{MSY} values with fixed steepness values between 0.3 and 1.0. The total negative log-likelihood (NLL) values and difference from the minimum NLL (steepness=0.6) are also shown.

Steepness	Emsy	Total NLL	Change in NLL
0.3	0.194	59.135	4.691
0.4	0.323	55.702	1.258
0.5	0.380	54.549	0.105
0.6	0.493	54.444	0.000
0.7	0.647	54.494	0.050
0.8	0.900	54.637	0.193
0.9	1.182	54.841	0.397
1.0	1.319	55.080	0.636

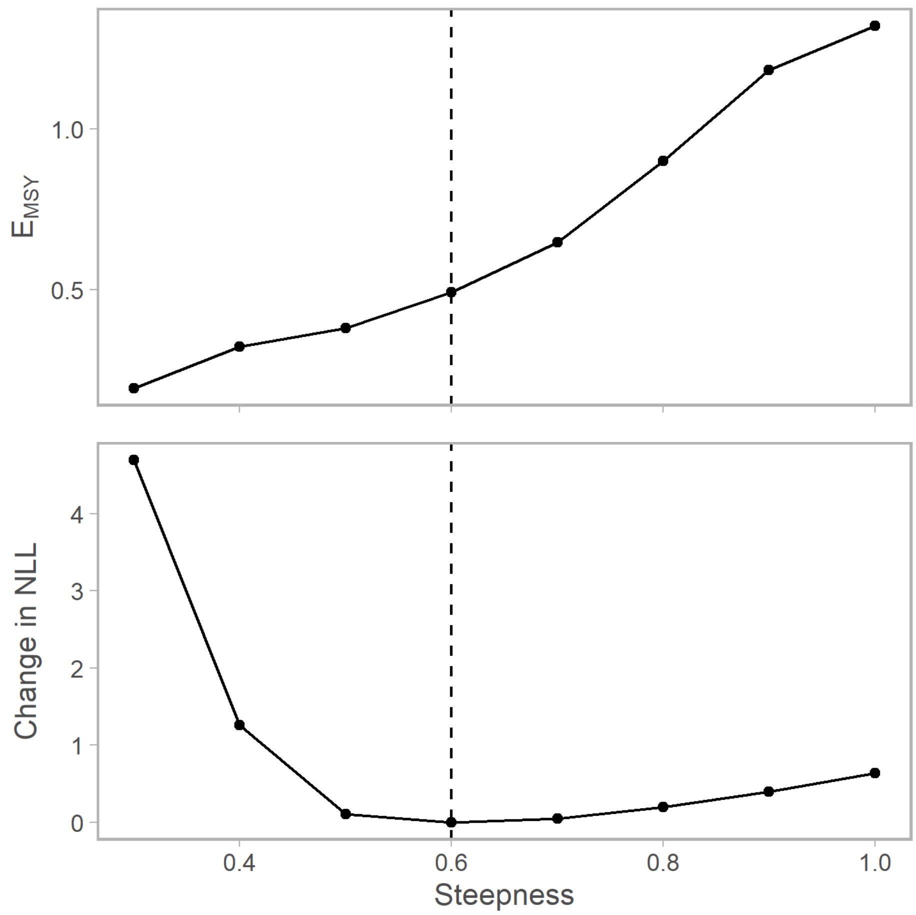

Figure E-1: E_{MSY} values (top) and change in negative log-likelihood values (bottom) with fixed values of steepness from 0.3 to 1.0.

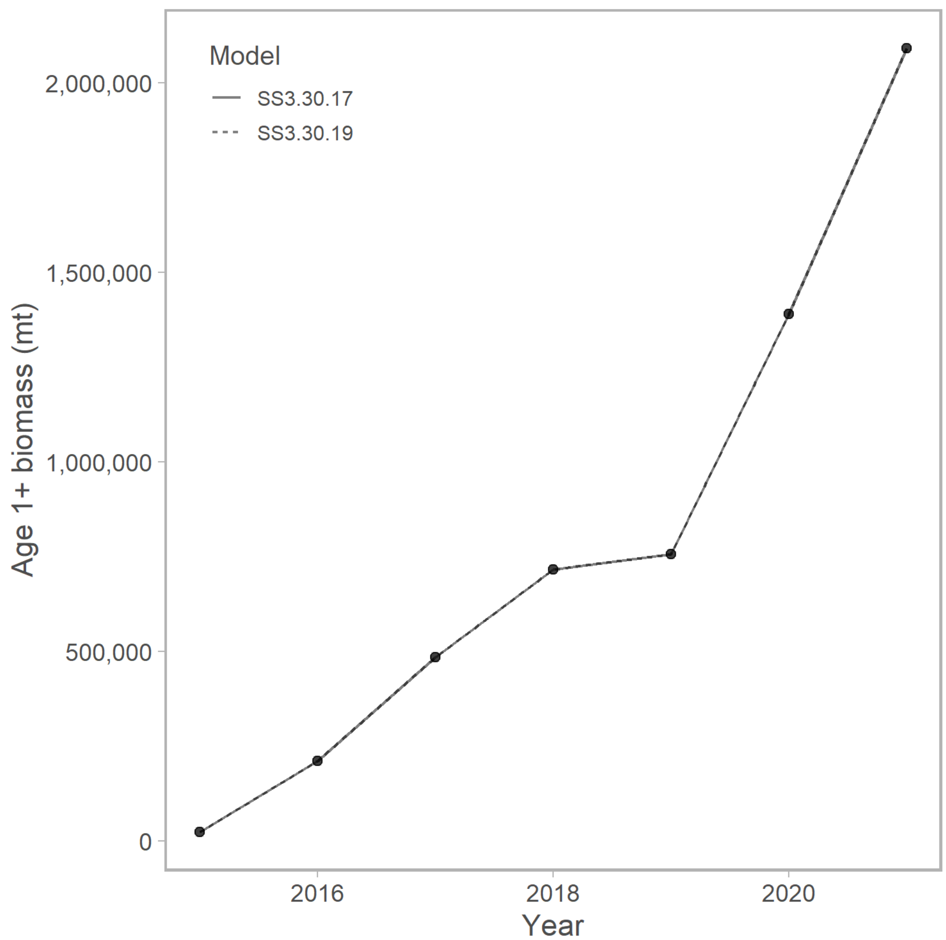

Figure E-2: Comparison of the age 1+ biomass estimated from SS3.30.17 (previous) and SS3.30.19 (current). The values are identical between the two versions.