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A SUMMARY REPORT OF LIFE HISTORY INFORMATION ON PACIFIC MACKEREL (*SCOMBER JAPONICUS*) FOR THE 2023 BENCHMARK STOCK ASSESSMENT

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A summary report of life history information on Pacific Mackerel (*Scomber japonicus*) for the 2023 benchmark stock assessment

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Abstract

The Pacific mackerel (*Scomber japonicus*) is one of five coastal pelagic species listed in the Pacific Fisheries Management Council (PFMC)'s Coastal Pelagic Species Fishery Management Plan, and has regularly scheduled stock assessments. This report provides a detailed summary of the life history information collected, analyzed, and used in the 2023 benchmark stock assessment for Pacific mackerel. In particular, the goals of this report are to: (1) provide updated age and length data; (2) compute ageing error matrices for use in the stock assessment model; (3) provide updated estimates of the length and age at maturity; and (4) discuss priorities for future life history research to address existing data gaps and assessment needs.

To produce the data included in this report, biological samples from Pacific mackerel were collected during trawl surveys conducted in spring 2010-2021 and summer 2012-2022 by the NOAA Southwest Fisheries Science Center (ovaries and otoliths) and from fishery samples collected monthly by the Port Sampling Program of the California Department of Fish and Wildlife (otoliths only) in 2008- 2022. Sagittal otoliths from individual fish were evaluated whole, and absolute ages were assigned based on a July 1 birthdate and the date of capture. Ovaries from female fish were preserved and histologically processed to permit classification as either immature juveniles or mature adults using established methods and terminology. Maturity ogives were estimated for fork length and age using an analytical method based on logistic, non-linear regression.

Pacific mackerel ages ranged from 0 to 7 years with 0, 1, 2, and 3 year old fish comprising 46%, 29%, 16%, and 6% of sampled fish, respectively. Fish aged 4-7 years made up only 2.3% of otoliths. Ageing agreement for fish 0 to 3 years old were estimated with high precision, whereas fish aged 4 years and older had lower agreement. Difficulty in estimation of age increased in older fish due to reduction in the spacing between annuli and interpretation of a check from an annulus. Length and age at maturity estimates were generated from females that ranged from 174 to 402 mm fork length and 0 to 7 years of age. The estimated average length (L_{50}) and age (A_{50}) at maturity was 274 ± 1.26 mm FL and 1.01 ± 0.06 years, respectively.

1. Introduction

Pacific mackerel (*Scomber japonicus*) are a subtropical and temperate schooling fish that inhabit coastal and offshore waters from the Gulf of Alaska to Banderas Bay, Mexico, including the Gulf of California (Fitch 1951). The largest biomass of Pacific mackerel occurs south of Monterey Bay to southern California and into northern Baja California, Mexico (Parrish et al. 1978). Pacific mackerel are an important coastal pelagic species (CPS) in the California Current Large Marine Ecosystem (CCLME) where they are preyed upon by piscivorous fish, marine mammals, and seabirds (Crone et al. 2019). Their life history is characterized by rapid growth, asynchronous batch spawning, seasonal and annual movements in relation to environmental variability, and foraging on plankton, small teleosts and cephalopods (Crone et al. 2019). While the majority of commercial landings occur in the southern California Bight (SCB), Pacific mackerel are commercially fished throughout their range (Kuriyama et al. 2023).

The primary take of Pacific mackerel occurs in the commercial purse-seine fishery that operates in U.S. and Mexican waters, with the majority of commercial landings occurring in southern California and northern Baja California (Parrish et al. 1978; Crone et al. 2019). Additionally, a small percentage of Pacific mackerel are taken in recreational fisheries in California waters. While Pacific mackerel biomass can increase to relatively high levels during periods of favorable oceanographic conditions, they do not typically represent a large proportion of the CPS biomass in the CCLME (Crone et al. 2019; Zwolinski et al. 2019). Following a steep decline in age class structure that occurred in the mid-1960s the state of California developed the first formal management plan for Pacific mackerel and initiated a fisheries moratorium. After the stock recovered to moderately high abundance, the fishery was reopened in 1977 under a quota system that established harvest control rules based on analyses conducted by MacCall et al. 1985 (Parrish et al. 1978). While commercial landings have not surpassed 5,000 metric tons since 2015 (PFMC Stock Assessment Review Panel Meeting Report 2023), the Pacific mackerel fishery is currently managed as a single unit by the Pacific Fisheries Management Council (PFMC), under the CPS Fishery Management Plan (FMP).

Starting in 2015, the PFMC established a schedule requiring benchmark assessments for Pacific mackerel every 4 years. The base model used in the 2019 benchmark assessment conducted by the Southwest Fisheries Science Center (SWFSC) estimated that Pacific mackerel stock biomass would reach 89,009 metric tons in 2020, with biomass-at-age dominated by fish aged 0 to 2 years old, and age 0 fish represented approximately 37% of the total estimated biomass (Crone et al. 2019). The biomass of fish aged 0 to 2 years old increased in the 2023 Pacific mackerel benchmark assessment to 86.9% of the base model's total biomass estimate of 93,823 metric tons for 2021 (Kuriyama et al. 2023), and the proportion of age 0 fish for forecast years 2024 and 2025 is 56% and 54.5% of the total estimated biomass, respectively (Kuriyama et al. 2023). The projected spawning stock biomass is 46,167 mt for 2023 and 50,372 mt for 2024 (Kuriyama et al. 2023). It is important to note the accuracy of benchmark assessments for Pacific mackerel and other CPS relies upon biomass data produced by the SWFSC California Current Ecosystem Survey (CCES, hereafter referred to as the SWFSC CPS Survey) that uses the Acoustic Trawl Method (ATM) combined with fisheries data and life history information updated annually by SWFSC and California Department of Fish and Wildlife (CDFW).

The objective of this report is to provide a summary of the updated life history information on Pacific mackerel used in the 2023 benchmark stock assessment. The age and length data contained in this report are based on fish sampled monthly by the CDFW and SWFSC CPS surveys conducted in summer from 2012 to 2022. The updated estimates on length and age at maturity were generated from data and gonad samples collected during both spring and summer surveys by SWFSC from 2010 to 2022. In section 2, we provide ageing datasets and estimates of ageing errors for Pacific mackerel. In section 3, we provide an updated estimate of length and age at sexual maturity for Pacific mackerel. In section 4, we identify areas of uncertainty surrounding the life history information used in Pacific mackerel stock assessments and discuss future research opportunities.

2. Age and Length Data

2.1 Background

Historically, biological samples of Pacific mackerel were collected solely from commercial fishery landings by CDFW. Since the 1990s, SWFSC has conducted summer and spring surveys using trawls to collect biological samples in order to better inform the assessment and management of CPS in the CCLME (Dorval et al. 2022). The temporal and spatial frames of these surveys have varied over time, but beginning in 2012, summer surveys have been conducted annually from British Columbia, Canada, to the California-Mexico border, and in recent years expanded south into northern Baja California, Mexico (Stieroff et al. 2020). The SWFSC began archiving Pacific mackerel otoliths in 2007 to provide fishery-independent biological samples for consideration in stock assessments, although this species was not a primary target species at that time. To provide a more robust sample archive for generating length and age compositions for acoustic biomass estimates, Pacific mackerel became a primary target species in 2012 and were sampled following the same protocol as Pacific sardine (*Sardinops sagax*) and northern anchovy (*Engraulis mordax*) (Dorval et al. 2022). In 2021 and 2022, these surveys were extended to sample CPS in Mexican waters down to Punta Eugenia.

2.2 Ageing Methods

2.2.1 Sample Collections

Pacific mackerel otoliths were collected during fishery-dependent and fishery-independent surveys. The fishery-independent survey conducted annually by SWFSC uses an acoustic-trawl method during summer month (July through October) (Dorval et al. 2022; Renfree et al. 2023). Collections spanned from Vancouver Island, British Columbia, Canada to Punta Baja, Baja California, Mexico (2012-2022) (Figure 1). Pacific mackerel were randomly subsampled (n = 50) from the trawl catch, measured for fork length (FL; mm), and weighed (g). If fewer than 50 Pacific mackerel were caught in a single haul, all of these collected fish were measured and weighed. Sagittal otoliths were then extracted from up to 25 Pacific mackerel and stored dry. Fishery-dependent samples were collected from 2008 to 2022 from port landings in southern California (Los Angeles to Santa Barbara) and central California (Monterey Bay). Fish were collected following CDFW standard protocols targeting a sampling unit of 25 fish per landing-boat and a total of 12 samples per month and port during the fishing season (Dorval et al. 2022).

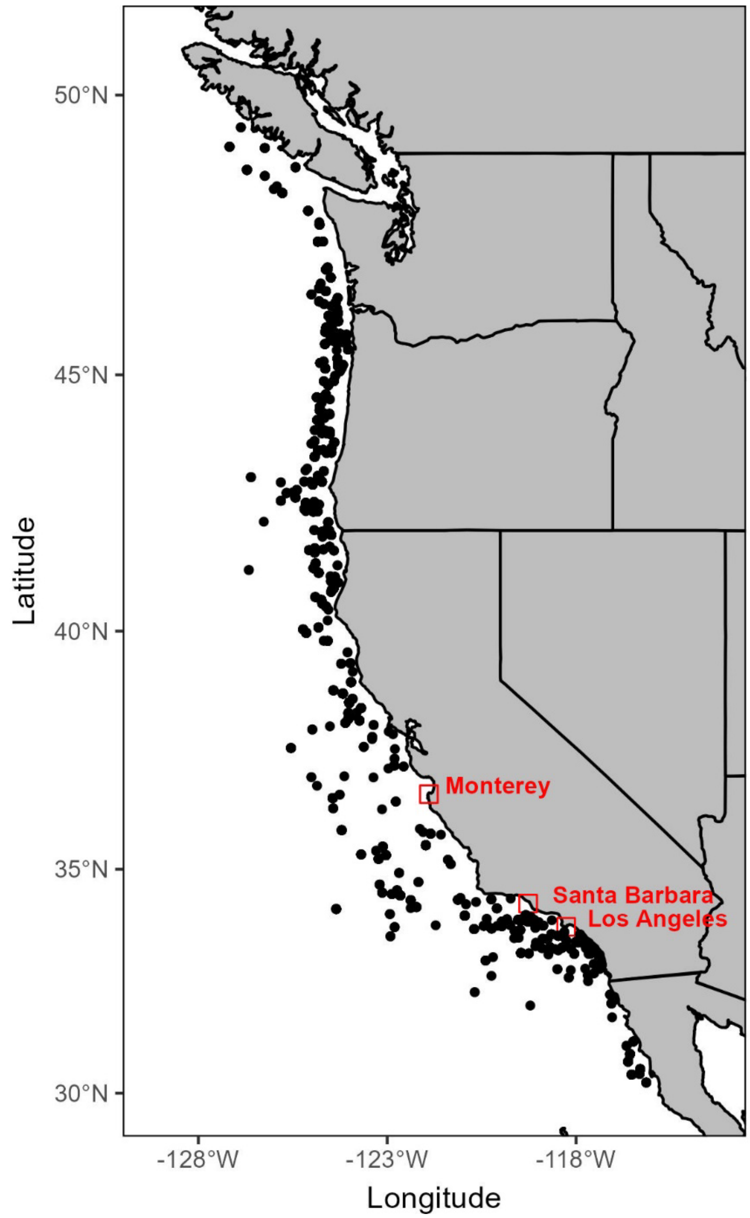

Figure 1. Locations where Pacific mackerel (*Scomber japonicus*) were collected during SWFSC spring and summer fishery-independent surveys (2010 to 2022; black points) and port locations where fishery-dependent samples were collected by CDFW (2008 to 2022; red squares and text).

2.2.2 Age-readings

Pacific mackerel ages were determined using the conventional technique of otolith age-reading described in Yaremko (1996). Whole otoliths were immersed in distilled water with the distal side facing up and then read from the posterior region, using a stereo microscope at 25 X magnification. The method recommends that the age reader immerses the otolith in distilled water in a glass dish with a black background for no longer than three minutes, and using a dissecting microscope with reflected light at a magnification of 25x, counts the number of annuli observed on the distal side of the otolith and determines edge type. An annulus is defined as the interface between an inner translucent growth increment and the successive outer opaque growth increment with the assumption that observable growth increments are deposited during the progression of seasons (Fitch 1951; Yaremko 1996) (Figure 2). Although Pacific mackerel has an extended spawning season, a July 1 birthdate is assigned for all individual Pacific mackerel collected in U.S. waters (Fitch 1951; 1; Yaremko 1996; Carbonara and Follesa 2019), albeit an unknown number of these individual fish could have been born prior to or following this date. After annuli are counted without knowledge of size or sex, the assigned birthdate, capture date, and analysis of the most distal pair of growth increments is used to assign a final age to each fish (see Yaremko 1996).

Three SWFSC age readers (identified as readers 15, 17, and 18) and two CDFW age readers (identified as readers 2 and 25) participated in the age determination process. The lead CDFW age reader (reader 2) was involved in the training process of the three SWFSC readers above. Furthermore, a random set of survey otolith samples (n=317, summer 2012-2017) was assigned to readers 2, 15, 17, and 18 for ageing in order to evaluate bias and precision among these four readers.

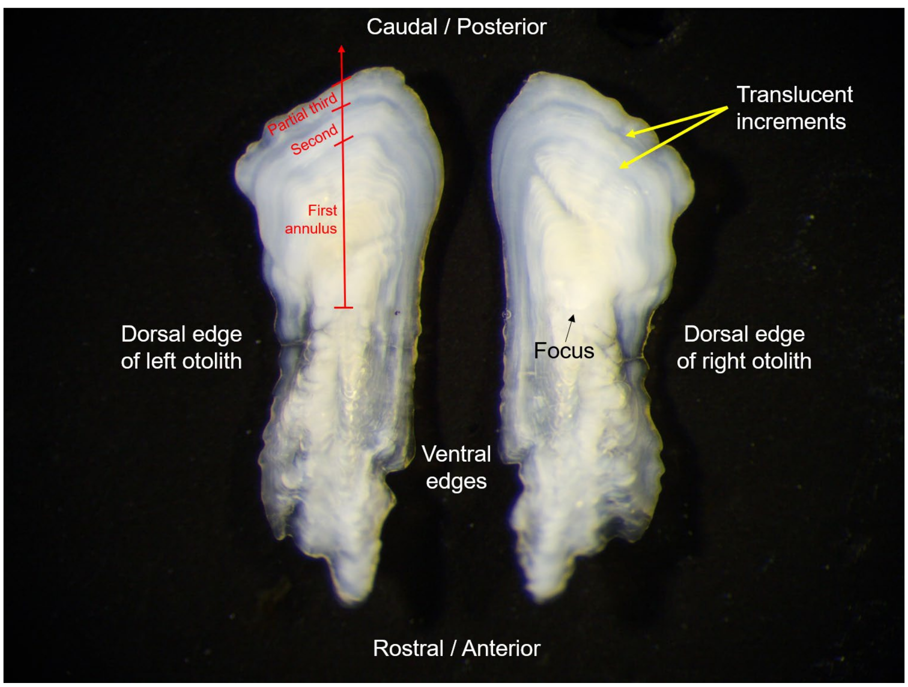

Figure 2. Image of a typical pair of sagittal otoliths from a Pacific mackerel (*Scomber japonicus*) illustrating the overall anatomy and growth features. An annulus is defined as the interface between an inner translucent growth increment (dark band) and the successive outer opaque growth increment (white band). This otolith pair has two fully formed annuli with a third annulus forming. The photo is looking at the distal side of the otolith, and the proximal side with the sulcus into the page.

From 2012 to 2022, a total of 1,762 Pacific mackerel were aged by readers 17 and 18 from the SWFSC CPS survey. From each summer survey, otolith samples were randomly selected by haul and by length bin (50 mm FL), and approximately 50% of the selected samples were randomly allocated to each of these two readers. This selection scheme maintained the spatial and temporal integrity of the trawl sampling and the distribution of length-at-age in space and time. Due to time constraints, a subset of total otoliths collected from 2013 to 2019 were aged that accounted for length bin, year, and geographic location. Each individual fish was assigned a final age based on the capture date, an assumed July 1 birthdate (see Yaremko 1996), and the analysis of the most distal pair of growth increments.

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

A total of 9,035 ages were produced by readers 2 and 25 from the CDFW fishery port sampling from 2008 to 2022. All collected fish samples were randomly assigned to single readers. However, every third or fourth sample (2008-2022) was read by each age reader, deemed an "all-read" sample. Readings were reviewed on all-read samples if disagreement among readers was greater than 25%. As only the first set of all-read-readings were performed without prior knowledge of age composition of the allocated sample sets, they were aggregated and used for computing ageing errors in this report. Further, we selected all-reads conducted in 2008-2017, because not enough all-read-readings were conducted in 2018-2022. Fishery sample datasets were built using only complete reported age-readings among readers 2 and 25 (i.e., observations containing missing values were discarded). Although two readers participated in ageing fishery samples, final age data provided to the stock assessment did not contain reader-specific information.

The computation of age-reading errors was based on the method described by Punt et al. (2008), using the nwfscAgeingError R package (Thorson et al. 2012). For the SWFSC CPS survey data, we computed ageing error matrices based on otoliths that were aged by reader CA, 17, and 18 while assuming that: (1) ageing bias depends on reader and the true age of a fish; (2) the standard deviation (SD) of age-reading error depends on reader and the true age; and (3) age-reading error is normally distributed around the expected age (see Punt et al. 2008). For the purpose of this report, we were mostly interested in estimating the SDs-at-age for age data collected during the 2012-2022 SWFSC CPS surveys, following similar methods used in the past for Pacific sardine and Pacific mackerel assessments (Hill et al. 2011; Dorval et al. 2013; Crone et al. 2019;

Kuriyama et al. 2020). We defined various model scenarios by comparing models that assumed equal or unequal SDs among readers. As in previous assessments, Model C (Dorval et al. 2013) was selected as the best model using Akaike Information Criterion with a correction for finite sample sizes. This model assumed that all three readers (CA, 17, and 18) were unbiased and had equal SDs. A single dataset that included age data from 2012 to 2022 was used to compute ageing errors for the SWFSC CPS surveys. The functional form of random ageing-error precisions was assumed to follow a curvilinear SD and a curvilinear CV based on a three-parameter, Hollings-form relationship of SD or CV with true age (see Punt et al. 2008; Thorson et al. 2012; Dorval et al. 2013). Further, the maximum SD allowed in model runs was 40. Model C was also selected as the best model for computing ageing errors from the fishery dataset (2012-2017), as was also done for the survey data, but assuming that readers 2 and 25 were unbiased and had equal SDs. Note this same fishery dataset was previously used to compute ageing errors for the 2019 Pacific mackerel assessment (Crone et al. 2019), but using the original Agemat model developed in ADMB (Punt et al. 2008).

2.3 Results and Discussion

2.3.1 Age and Length Compositions

Pacific mackerel subsampled and measured during summer SWFSC CPS surveys from 2012 to 2022 ranged in length from 53 mm FL to 402 mm FL (Figure 3a). A total of 1,762 fish were aged, with ages ranging from 0 to 7 years (Figure 3b). Aged samples were composed mostly of young fish, with individuals aged at 0, 1, 2, and 3 years representing 46%, 29%, 16%, and 6% of the total number of fish aged, respectively. Older fish (4-7 years in age) made up only 2.3% of the samples aged, and thus these age classes may not have been well represented in the summer trawl surveys. There were large overlaps in length distributions among age classes (Figure 4). Although ages for Pacific mackerel collected by the SWFSC CPS survey in 2022 were produced, the final assessment model only used ages through 2021 due to no available biomass estimate from the 2022 survey (PFMC 2023).

Pacific mackerel subsampled and measured during CDFW port sampling surveys from 2008 to 2022 ranged in length from 84 mm FL to 429 mm FL (Figure 3a). A total of 9,035 fish were aged, with fish ranging in age from 0 to 9 years (Figure 3b). Aged samples were composed mostly of young fish, with individuals aged at 0, 1, 2, and 3 years representing 47%, 30%, 12%, and 7% of the total number of fish aged, respectively. Older fish (4-9 years in age) made up only 4% of the aged samples. There were large overlaps in length distributions among age classes (Figure 4).

2.3.2 Age-Reading Errors

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

Pacific mackerel aged at 4 years and older (Figure 5) were the only ages from the SWFSC CPS survey that readers agreed 75% of the time or less. Only 26 Pacific mackerel out of 1,762 were in the 4^+ age group. Older age classes generally had lower agreement among readers. Interpreting increments at the edge of older fish otoliths is more challenging, because annuli are much closer together and it is more difficult to differentiate a check from an annulus (Yaremko 1996).

A total of 1,614 otoliths collected from 2008 to 2017 were used to compute age-reading errors for the California fishery (Figure 6). Age 8 was the maximum age estimated by readers 2 and 25. Agreement between these two readers was very high for ages 0 and 1 (94% and 78%, respectively), moderate for ages 2 and 3 (52% and 41%, respectively), and generally low for ages 4-6, ranging from 22% to 30%. However, too few samples were read for fish aged at 6-8 years to make an accurate evaluation (Figure 6), with only two 7 year old and one 8 year old fish observed in the all-read samples. Nevertheless, estimated CVs-at-age were less than 32% across all age classes.

Bias plots showed a high level of agreement among readers 2, 15, 17, and 18 (Figure 7), indicating that all of these readers usually produced the same age compositions given a set of survey or fishery otolith samples. The CDFW ageing-error vector used in the 2023 benchmark stock assessment had higher standard deviations from ages 3 to 7 years than those from the survey data (Figure 8). However, these differences did not result from the application of ageing criteria between the two laboratories; rather they most likely reflected differences in the process of sample selection and in the level of agreement targeted within each lab, when conducting multiple readings for estimating ageing errors. The ageing precision target for CDFW and SWFSC readers is 75% and 100% agreement among readers, respectively (Table 2).

Bias for age agreement among readers could not be assessed due to the absence of an age validation study for Pacific mackerel in the eastern North Pacific. The absence of validation of the periodicity of increment formation in each and every age group can lead to systematic bias in age determination (Campana 2001). Shiraishi et al. (2008) confirmed annual periodicity of annuli in Pacific mackerel from southwest Japan through captive growth of known-age fish up to 2 years old and edge analysis in wild Pacific mackerel up to 6 years old. SWFSC conducted a captive growth experiment of Pacific mackerel, and preliminary results suggest annual periodicity of annuli in fish up to approximately 2 years old (K.C. James et al. unpublished data). While the captive growth experiment did not include fish of every age class, and the possibility of bias from unvalidated ages remains, the results of this study lend confidence to the accuracy of ages provided to the stock assessment.

While Pacific mackerel otolith samples were collected during SWFSC CPS surveys, it is important to note that the survey is designed to produce abundance estimates for multiple CPS based on their acoustic signatures (Zwolinski et al. 2019). Additionally, trawl net avoidance and rates of capture likely varies by species and fish length.

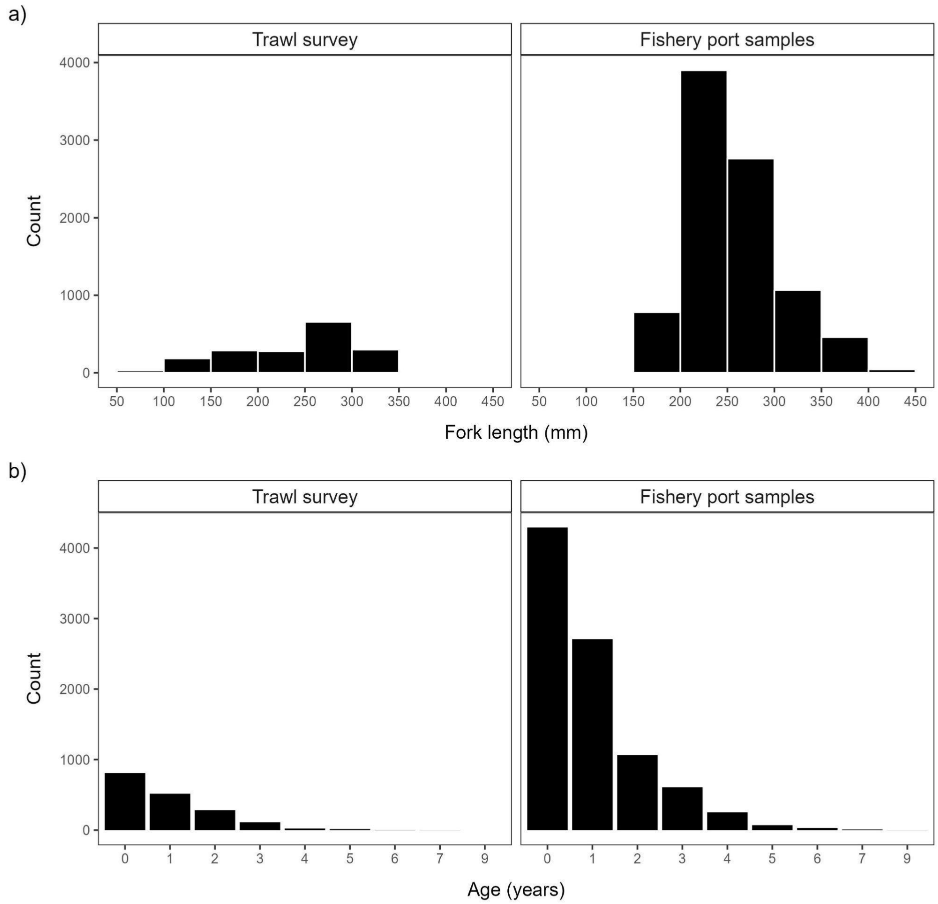

Figure 3. a) Length and b) age distribution of aged Pacific mackerel (*Scomber japonicus*) collected from summer SWFSC CPS surveys (2012-2022) and CDFW fishery port sampling (2008-2022).

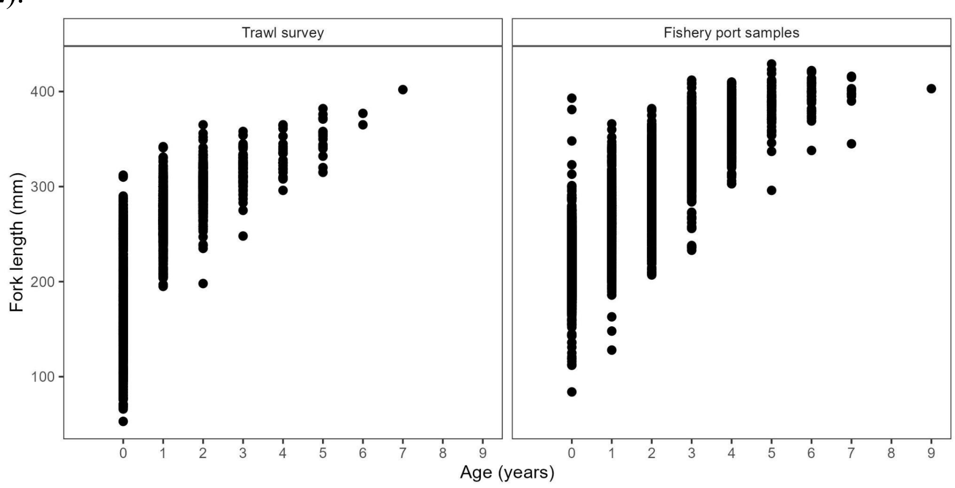

Figure 4. Fork length-at-age for Pacific mackerel (*Scomber japonicus*) collected from summer SWFSC CPS surveys (2012-2022) and CDFW fishery port sampling surveys (2008-2022).

Table 1. Coefficient of variation (CV) and standard deviation (SD) at age estimated for Pacific mackerel (*Scomber japonicus*) collected from summer SWFSC CPS surveys (2012-2022) and CDFW fishery port sampling (2008-2022). All estimates were calculated using the latest version of the nwfscAgeingError R package (Thorson et al. 2012) based on the assumptions that, within the SWFSC laboratory, there was no bias in ageing among readers, and readers had similar SD values.

						Agemat Model	
Survey	**Collection Year**	**Data Set ID**	**Sample Size**	**Number of Readers**	**Age**	**CV**	**SD**
SWFSC CPS Survey	2012-2022	1	643	3	0	0.001	0.001
					1	0.001	0.001
					2	0.074	0.148
					3	0.076	0.229
					4	0.068	0.273
					5	0.060	0.298
					6	0.052	0.311
					7	0.046	0.319
CDFW Port Sampling	2008-2017	2	1614	2	0	0.316	0.316
					1	0.316	0.316
					2	0.276	0.553
					3	0.261	0.783
					4	0.252	1.007
					5	0.245	1.224
					6	0.239	1.435
					7	0.234	1.640
					8	0.230	1.839

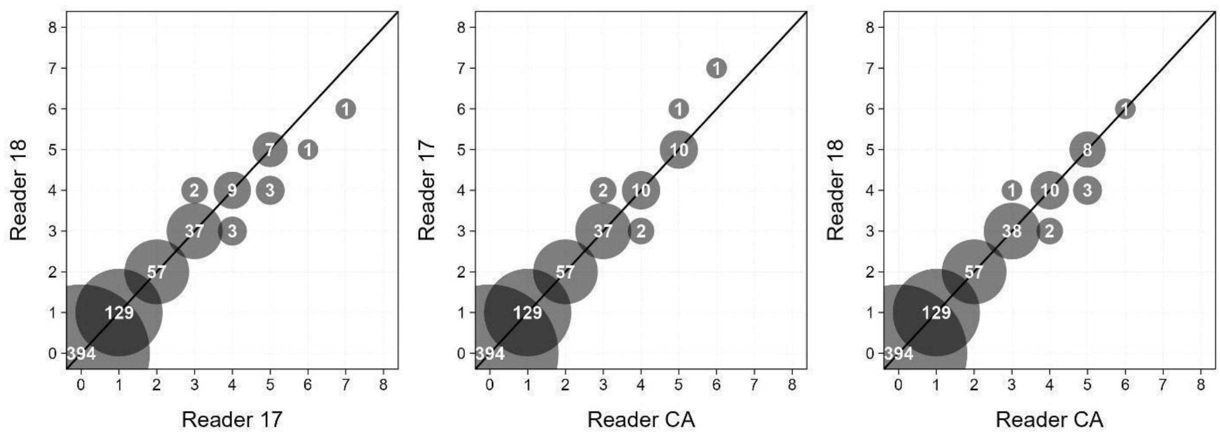

Figure 5. Age bias plots from the Agemat model for readers CA, 17, and 18 for Pacific mackerel (*Scomber japonicus*) collected from summer SWFSC CPS surveys (2012-2022).

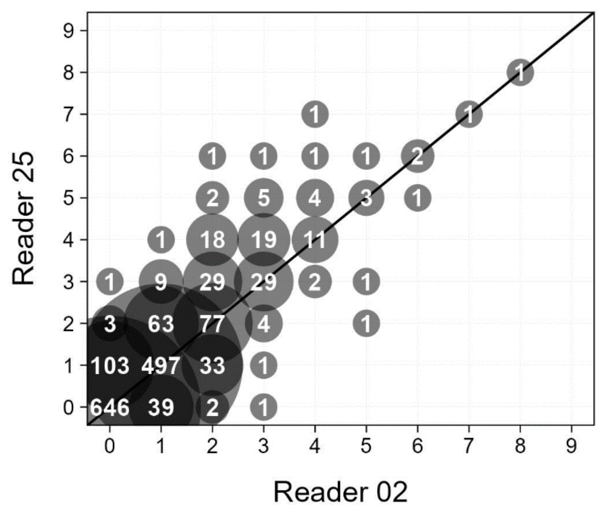

Figure 6. Age bias plots from the Agemat model for readers 2 and 25 for Pacific mackerel collected from CDFW port sampling surveys (2008-2017).

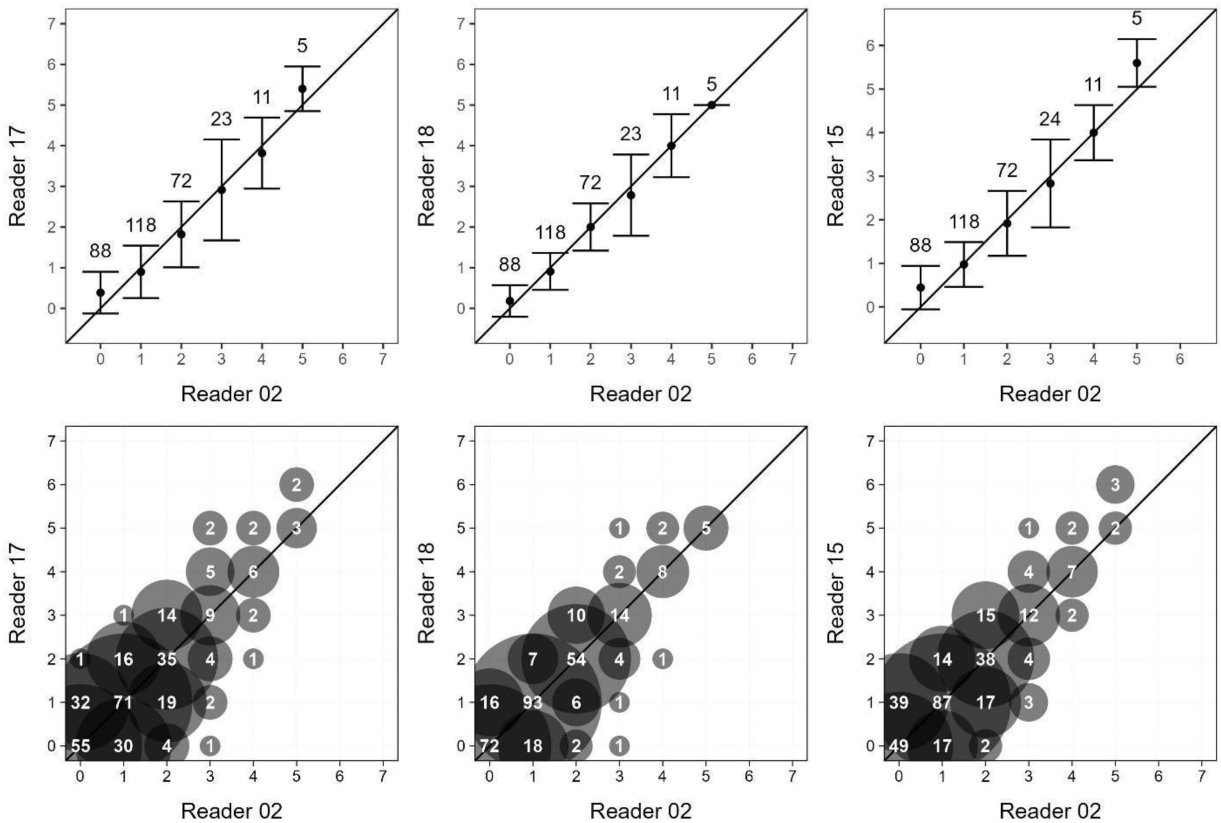

Figure 7. Age bias plots (mean age ± SE and bubble plots) of readers 2, 15, 17,18 for Pacific mackerel (*Scomber japonicus*) collected from summer SWFSC CPS surveys (2012-2022).

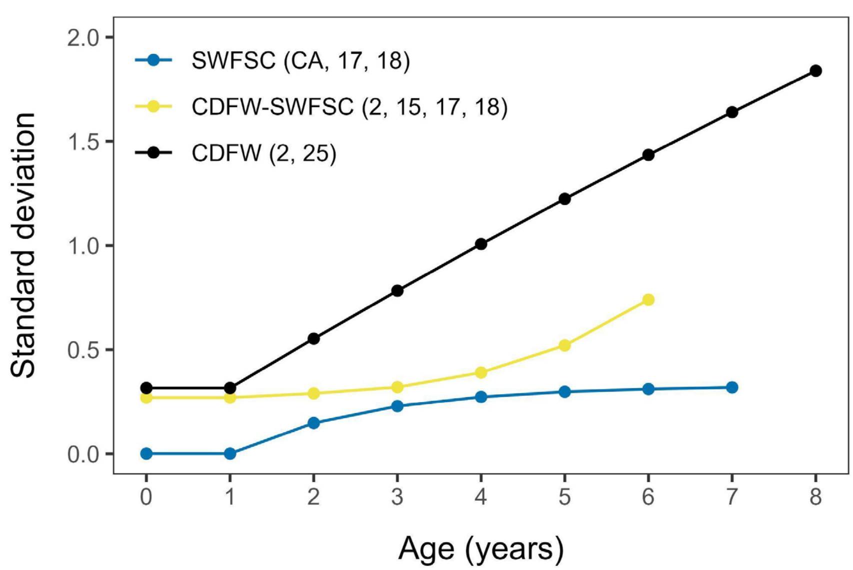

Figure 8. Survey and fishery ageing error vectors used in the final assessment model (CDFW and SWFC vectors) and sensitivity tests (CDFW-SWFSC vector). Blue dotted line shows ageing errors estimated from 2012-2022 summer survey samples; yellow dotted line shows ageing

errors estimated from summer 2012-2017 survey samples; and black dotted line shows ageing error estimated from 2008-2017 fishery samples. Numbers in parentheses indicate SWFSC and CDFW readers that produced age readings for estimating ageing errors.

Table 2. Comparison of CDFW and SWFSC methodologies for computing ageing errors.

Component	Fishery Age Data	Survey Age Data
Ageing criteria	Same as acoustic trawl survey	Same as fishery port sampling
Sample selection for Double readings	From every third - fourth port sample	From every acoustic trawl sample
Target of ageing precision	75% agreement among readers	100% agreement among readers
Data used to compute ageing errors	Double readings before 75% agreement	Double readings at 100% agreement
Rationale	Not possible to adjust or drop assessment ages after double readings	Possible to adjust or drop assessment ages after double readings
	Avoid bias in CV and SD as assessment data cannot be adjusted after double readings	Minimize CV and SD as assessment data can be adjusted after double readings

3. Length and Age at Maturity

3.1 Background

The Pacific mackerel is a multiple batch spawner with indeterminate fecundity, asynchronous oocyte development, and a relatively high spawning frequency (Knaggs and Parrish 1973; Peña et al. 1986; Asano and Tanaka 1989; Dickerson et al. 1992). In the northeast Pacific, spawning of Pacific mackerel typically occurs from Point Conception to Cabo San Lucas from 3 to over 300 km offshore (Moser et al. 1993), although small juveniles have been reported off Oregon and Washington in recent years (Stierhoff et al. 2019). Pacific mackerel have a protracted spawning season throughout their range. Off California, spawning peaks during the spring and summer months, but some spawning occurs during all months of the year. Ahlstrom (1959) reported that Pacific mackerel spawn throughout the year, but peak spawning occurs in April and May. Kramer (1969) estimated that spawning occurs from late April through August based on larval collections. Based on collections and macroscopic examinations of ovaries from commercial catches, Knaggs and Parrish (1973) concluded that Pacific mackerel spawn from March through October off California with a peak from late April through August at depths of 100 m. MacGregor (1976) estimated that 79% of spawning in Pacific mackerel occurs from April through September, but peaks in spawning vary annually and tend to concentrate over a two-month period within a given year. Schaeffer (1980) reported spawning in Pacific mackerel to occur from March through October. Spawning in California occurs in the evening and is estimated to peak at 2200 h (Schaefer 1980). Similar to other broadcast-spawning marine fishes, both spawning frequency and spawning season duration are believed to increase with female size and age (Knaggs and Parrish 1973; Dickerson et al. 1992).

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

3.2 Material and Methods

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

Standardized terminology for describing reproductive development in marine fishes (Brown-Peterson et al., 2011) were used to classify each sampled female Pacific mackerel as either immature (never spawned) or mature (previously spawned or first spawning) (Figure 9). Females with ovaries containing no oocytes undergoing vitellogenesis but numerous oocytes in the cortical alveolar stage of development were classified as mature, because fish sampled at this phase of development usually spawn at some point during the season (Murua and Saborido-Rey 2003; Wright 2007; Lowerre-Barbieri et al. 2011a,b). Additional histological features used to distinguish between immature females and mature, regenerating females included the thickness of the ovarian wall, the presence of muscle bundles or atretic follicles, and the level of organization within the lamellar structure (Lowerre-Barbieri et al. 2011a,b).

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

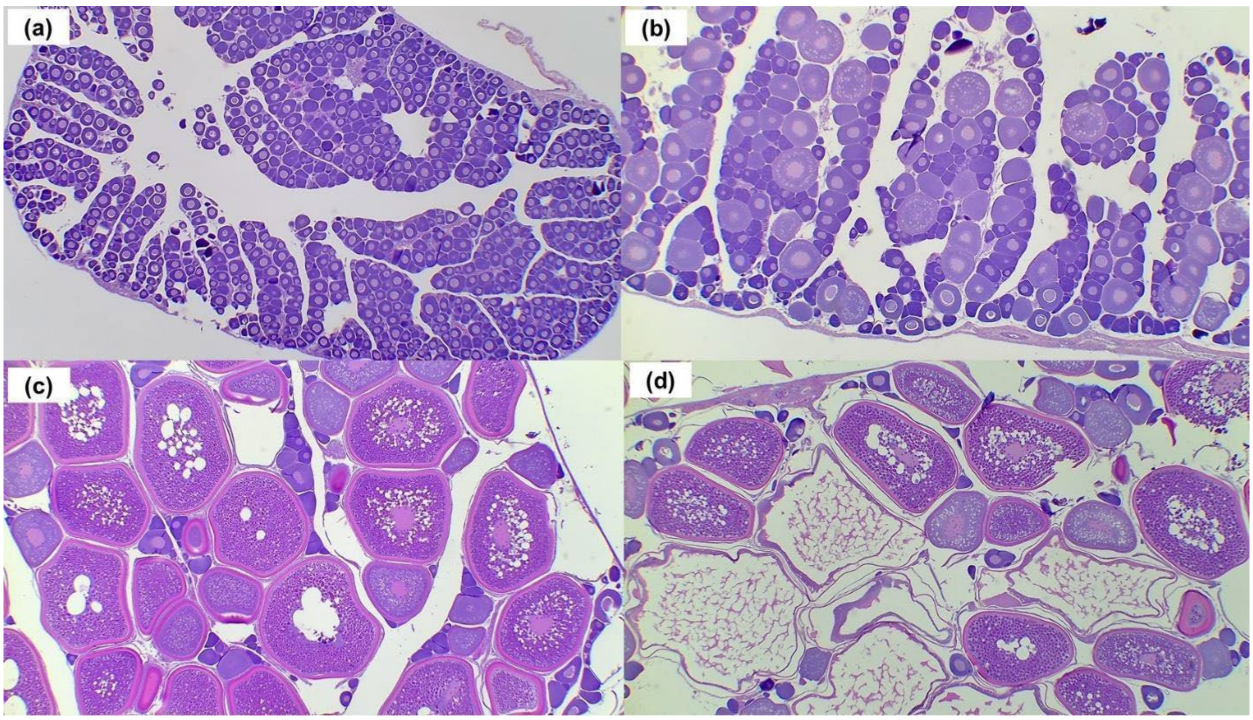

Figure 9. Histological sections of gonads of female Pacific mackerel (*Scomber japonicus*) collected from SWFSC spring and summer trawl surveys (2010 to 2021): (a) Immature female with only previtellogenic oocytes; (b) Mature, developing female with numerous oocytes in early cortical alveoli stage; (c) Mature, spawning capable female with numerous vitellogenic oocytes; (d) Mature, actively spawning female with hydrated oocytes.

3.3 Results and Discussion

A total of 911 gonad samples of female Pacific mackerel were examined histologically, classified as either immature (juvenile) or mature (adult), and then used to generate an estimate of length-at-maturity. Age data were available for 494 of these sampled females from 2012 to 2021 from summer surveys to generate an estimate of age at maturity. Females ranged in length from 174 to 402 mm FL and in age from 0 to 7 years (Figure 10a,b). Immature females ranged in length from 174 to 329 mm FL and in age from 0 to 2 years. Mature females were 207 to 402 mm FL and 0 to 7 years of age.

The estimated length at maturity (L_{50}) for all sampled females (n = 911) was 274 ± 1.26 mm FL with all females (L_{95}) larger than 309 ± 2.60 mm FL predicted to be mature (Figure 11a; Table 3). The estimated age at maturity (A_{50}) for all aged females (n = 494) was 1.01 ± 0.06 years with all females older than 2.52 ± 0.15 years predicted to be mature (Figure 11b; Table 4).

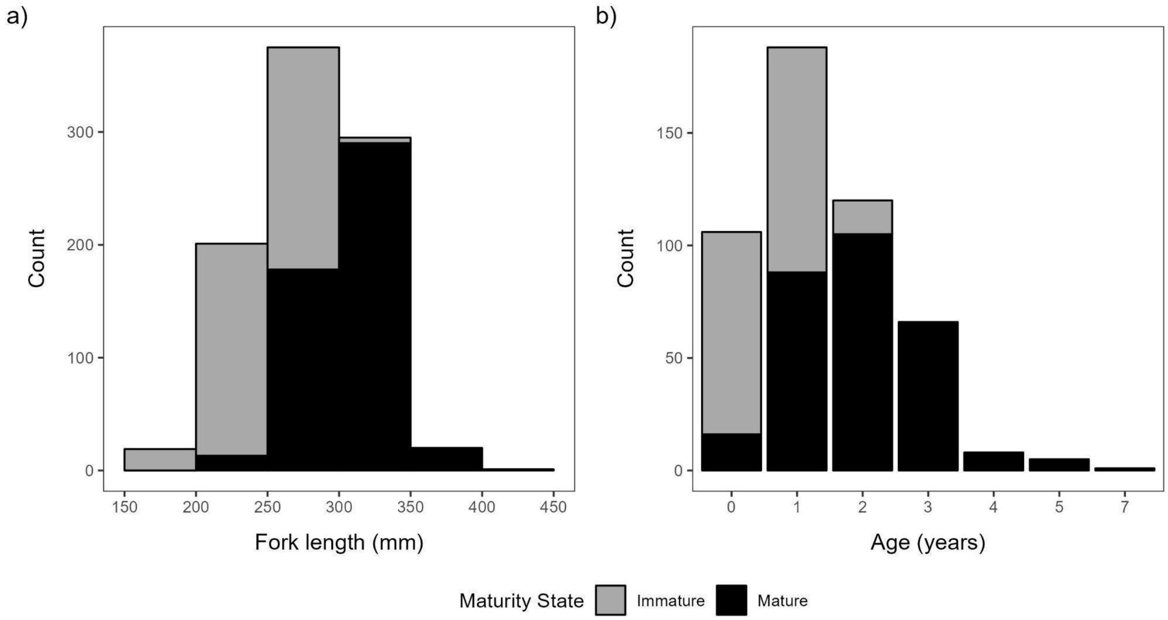

Figure 10. Histograms showing a) length (n = 911) and b) age distribution (n = 494) by maturity state for female Pacific mackerel (*Scomber japonicus*) collected from spring and summer SWFSC CPS surveys (2010 to 2021) and analyzed histologically for reproductive condition.

The estimated length at maturity reported here (274 mm SL) is nearly identical to the value used in recent stock assessments for Pacific mackerel, whereas the estimated age at maturity (1.01 years) is lower than the previous estimate (2.2 years; see Crone et al. 2015, Crone et al. 2019). We attribute the difference in estimated age at maturity to increased precision and accuracy in ageing methods combined with an increase in the availability of smaller age classes to the SWFSC CPS survey. Collectively, the results of this and past studies indicate that maturity schedules in Pacific mackerel off the U.S. Pacific coast have remained constant over the past several decades.

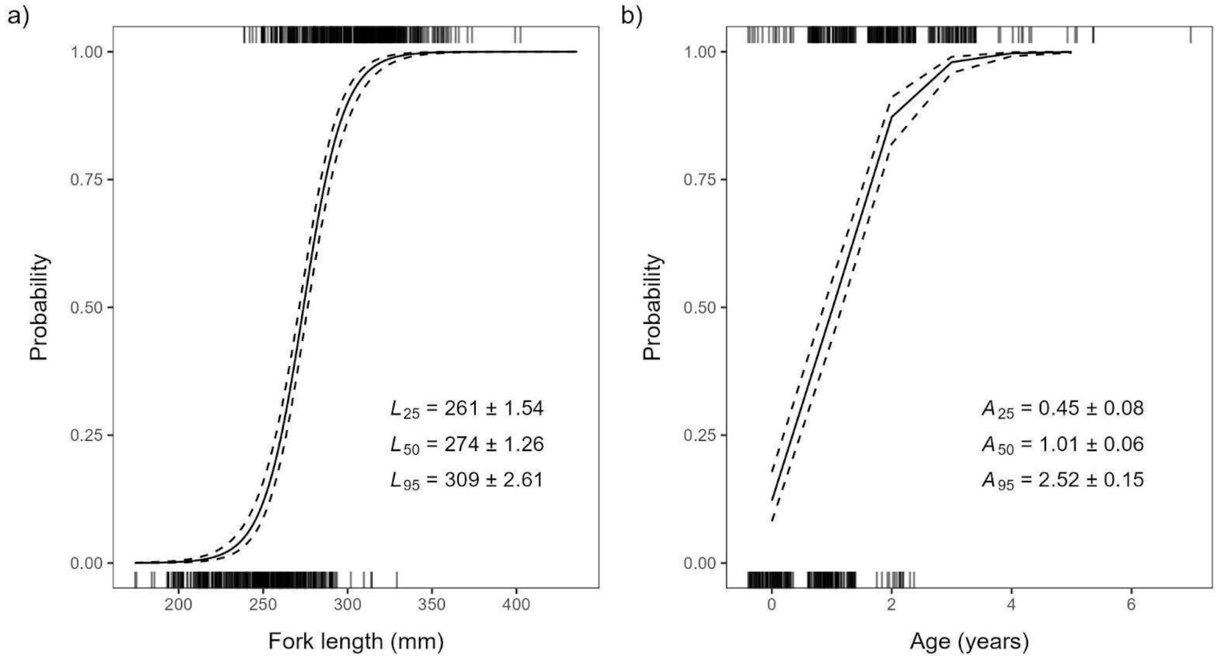

Figure 11. a) Length-based (n = 911) and b) age-based (n = 494) maturity ogives of female Pacific mackerel (*Scomber japonicus*). The length-based maturity ogive was based on samples collected from SWFSC spring and summer trawl surveys (2010 to 2021), whereas the age-based maturity ogive was based on samples collected from summer trawl surveys (2012 to 2021). Data are shown as jittered tick marks along the lower (immature fish) and upper (mature fish) x-axis. The solid line represents the predicted curve, and the dashed lines depict the 95% confidence intervals.

Table 3. Mean predicted probability of being mature and standard deviation for Pacific mackerel (*Scomber japonicus*) in 50 mm fork-length bins from the length-based ogive for samples collected from SWFSC spring and summer trawl surveys (2010 to 2021; n = 911).

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

Table 4. Predicted probability of being mature for each age with 95% confidence intervals for Pacific mackerel (*Scomber japonicus*) from the age-based ogive for samples collected from SWFSC summer SWFSC CPS surveys (2012 to 2021; n = 494).

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

4. Future Research

4.1 Background

Uncertainty pertaining to Pacific mackerel abundance and life history information used in stock assessment models have been identified (PFMC Stock Assessment Review Panel Meeting Report 2023). Similar to other CPS, research is needed to define the drivers of stock structure, understand fluctuations in stock abundance, and improve upon, better understand, or reduce errors related to the methods used to collect and produce life history information for Pacific mackerel. Improvements in these three areas will likely address similar concerns identified in other CPS that inhabit coastal and offshore waters off the west coast of Canada, the U.S., and Mexico. Research topics that could reduce uncertainty and increase our understanding of the biology, ecology, and life history of Pacific mackerel are summarized below.

4.2 Research Topics

1. A significant proportion of the commercial catch of Pacific mackerel occurs in Mexican waters. Collecting data from Mexican waters, whether through collaboration with Mexican scientists or directly obtaining data through surveys, or both, to obtain length, age, and reproductive data would improve efforts to understand the life history, biology, population dynamics, and fishery dynamics of the Pacific mackerel population over the entire extent of their range in the eastern North Pacific.

2. Pacific mackerel stock assessments rely upon the timely production of accurate life history information. To improve age estimates for Pacific mackerel, coordination between ageing laboratories to cross validate efforts and standardize age reads, and refine the approach to quantifying age-reading error on double read otoliths should be prioritized. Consideration should be given to age-reading error matrices by individual readers. Additionally, the development of a fecundity-weight relationship was identified as potentially valuable for consideration in future assessments.

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