Computing bias and variance for Pacific Sardine (*Sardinops sagax*) biomass estimated from aerial surveys in California nearshore waters

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Abstract

Pacific sardine (*Sardinops sagax*) stocks off the U.S. Pacific coast undergo boom and bust cycles modulated by decadal changes in oceanic and atmospheric conditions. During periods of low abundance, Pacific sardine may contract into nearshore waters, making it more challenging to be surveyed by research vessels that cannot operate in the shallowest habitats, 0 to 40.00 m. In response, a new transect-based design and methods were developed to compute bias and variance of biomass estimated from a collaborative aerial survey implemented in nearshore waters. From experimental aerial surveys conducted in 2010 and from 2018 to 2020, two professional aerial fish spotters underestimated school biomass by 10.5% and 12.6%, whereas most of the variability of aerial biomass was due to within-transect variance, with no significant contribution from the among-transect variance. Implementation of the new transect-based design to aerial surveys from 2020 to 2023 in southern and northern California showed that a substantial biomass of Pacific sardine occurred in nearshore waters, representing 69.9% of total biomass estimated from acoustic surveys in spring 2021, and 36.5% in summer 2021. Seasonal biomass estimates were variable within each region, affected by school dynamics during daytime in nearshore waters and the timing of aerial surveys as determined by weather and environmental conditions. Given that nearshore aerial biomass comprised a measurable proportion of total biomass estimates for Pacific sardine during the recent period of low abundance, it has been used to inform acoustic survey catchability, which is no longer assumed to be 1.0 in recent Pacific sardine stock assessments.

Keywords: Pelagic fish, Aerial spotters, Sardine, School biomass, Variance estimator, Bootstrap.

1. Introduction

Pacific sardine, *Sardinops sagax*, is a small pelagic schooling species that is distributed from southeastern Alaska, U.S., to the tip of Baja California, Mexico, including the Gulf of California (McFarlane et al., 2005; Nevárez-Martínez et al., 2019; Schultz et al., 1932). This species exhibits a boom and bust life history strategy, hence its abundance fluctuates in 20 to 30-year cycles based on temperature regime shifts (Baumgartner et al., 1992; McClatchie et al., 2017), although the environmental drivers of its abundance are subject to current debate (e.g., Muhling et. al., 2013; Politikos et al., 2018; Qiu, 2015). In the California Current Ecosystem, the geographic distribution of Pacific sardine is highly dependent on population abundance and migratory behavior (Murphy, 1977; Scharwtzlose et al., 1999). In periods of high abundance, the species likely occupies all potential habitats along the northeastern Pacific, extending spawning habitats to > 250.00 km offshore (Nieto et al., 2014). In contrast, periods of low abundance are characterized by contraction of the species distribution southward and shoreward (McFarlane et al., 2000; Schwartzlose et al., 1999). For example, during the cool temperature regime of the 1960s, 1970s, and 1980s Pacific sardine stock size was low in U.S. waters and the species was not found north of Point Conception (McFarlane et al., 2005), whereas during the warm temperature regime of the 1990s and 2000s Pacific sardine stock biomass (age-1^+ biomass) rebounded, peaking to 1.7 million mt in 2000 (Hill et al., 2007) and leading to recolonization of habitats from northern California and British Columbia to northern Alaska (McFarlane et al., 2005). Since 2013 Pacific sardine has not been fished off British Columbia, while stock biomass has dramatically declined off Washington, Oregon, California, and northern Baja California from 1.50 million mt in 2007 to 28276.00 mt in 2020 (Kuriyama et al., 2020).

For management purposes, Pacific sardine is assumed to consist of three separate stocks, namely, a northern stock from northern Baja California to Alaska, a southern stock ranging from southern California to Baja California, and a Gulf of California stock. In the U.S., the northern stock has been federally managed since 2000 by the Pacific Fishery Management Council under the Coastal Pelagic Species (CPS) Fishery Management Plan (PFMC, 2019). In 2019, the National Marine Fisheries Service (NMFS) declared the northern stock overfished, leading to the establishment of a rebuilding plan in 2021 (PFMC, 2021).

High temporal and spatial variations in the abundance of the northern stock of Pacific sardine present various challenges for assessing and managing this stock. In periods of high abundance, Pacific sardine juveniles tend to mostly recruit in shallow nearshore waters that serve as nursery grounds (Takahashi and Checkley, 2008), whereas older and larger fish tend to migrate further north and in offshore waters compared to younger and smaller fish (McDaniel et al., 2016). During this period the CPS fishery operates in nearshore shallow waters within 3 nautical miles (nm) from the shoreline, capturing mostly 1 to 3 year-old fish, whereas all ages and size fish are available to fishery-independent surveys that use large vessels and operate in offshore waters (> 40.00 m). However, in periods of low abundance Pacific sardine tend to be more abundant southward and shoreward, with fewer larger and older age classes (Murphy, 1977; MacCall, 1979; Kuriyama et al., 2022a). Under these conditions, not all age and size classes are likely to be available to fishery-independent surveys operating in deeper offshore waters. From 1994 to 2008 eleven age classes (0-10 years) were present in survey samples collected during the spring from the Daily Egg Production Method (DEPM); but beginning in 2009, older fish (7-10 years) became less frequent off California (Dorval et al., 2015). During the recent low biomass period (2015 to 2022), the maximum age in summer acoustic trawl surveys was 8 years old, but the dominant age classes were 2- and 3-year-old fish off Oregon and California (Kuriyama et al., 2022a).

Under these highly variable environmental conditions, several methods have been developed to sample Pacific sardine in U.S. waters in order to collect data to develop age composition and abundance indices for Pacific sardine stock assessments (Dorval et al., 2022). These methods have involved fishery-dependent surveys such as the California Department of Fish and Wildlife (CDFW) port sampling program and the Southwest Fisheries Science Center (SWFSC) Aerial Marine Resources Monitoring System (Caruso et al., 1983; Squire et al., 1993); fishery-independent surveys such as trawl surveys (DEPM; and Acoustic Trawl Method, ATM), aerial surveys such as the Northwest Sardine Survey (Jagielo et al., 2010), and the California Coastal Pelagic Species Survey (CCPSS; Lynn et al., 2022). As such, aerial survey methods have historically represented a significant component of CPS stock assessment and management, although their importance has varied over time based on stock status and/or the ability to address environmental factors that may affect their precision and accuracy.

Several studies have reported that professional aerial fish spotters can estimate pelagic school tonnage and identify pelagic species with reliable precision and accuracy (Taylor, 2015; Wiley et al., 2021). Inaccurate species identification and poor biomass estimates can lead to loss of revenue to fishermen (Lo et al., 1992), and thus only accurate spotters are employed in the fishing industry. Nevertheless, several factors may affect the quality of aerial survey data. Visual biomass estimates can be biased, because substantial portions of pelagic schools can be distributed below surface waters and thus their entire biomass is not always fully observable. Pelagic fish species often occur in mixed or clustered schools, including two or more species. Mixed schools typically comprise a dominant species that may entrain individuals from lesser abundant fish species (Bakun and Cury, 1999). Pelagic prey and predators may also form multispecies clusters, with the schools of predators influencing the shape, stability, and distribution of schools of prey fish that occur in their vicinity (e.g., Massé et al., 1996). As both the degree of school mixing and clustering varies with abundance, they can affect the accuracy of species-specific aerial biomass estimates. Pelagic fish also tend to school during daylight hours to avoid predation and disperse at night during feeding, but these dynamics may vary among regions (Fréon et al., 1996; Kaltenberg and Benoit-Bird, 2009). Kaltenberg and Benoit-Bird (2009) reported that acoustic observations off Oregon detected no schooling of Pacific sardine at night; rather, this pelagic species was dispersed both horizontally and vertically throughout the water column and began forming schools at dawn. In that study, although fish schools displayed diel formation and dispersal in Monterey Bay, distinct schools were observed at nighttime and peak formation of schools might begin 3 to 4 hours before sunrise in this region. Off Oregon, the Pacific sardine purse seine fishery primarily operates during daytime, using spotter planes to detect large Pacific sardine schools that are observed at the surface, whereas in Monterey Bay individual purse seine vessels fish both at night and day (Kaltenberg and Benoit-Bird, 2009). Thus, regional dynamics may affect aerial biomass estimates if the timing of the survey does not synchronize well with the diurnal occurrence of Pacific sardine schools in surface waters. Furthermore, both size and packing density of Pacific sardine schools may increase with stock biomass (Barange et al., 1999; Curtis, 2004; Love et al., 2016, Furuichi et al., 2022), which influence their dynamics in surface and deep waters and consequently the precision and accuracy of aerial biomass estimates in periods of high abundance. In addition, differences among spotters in estimating school biomass may confound variations in abundance estimates when spotters change from survey to survey (Lo et al., 1992). However, most of these constraints can be addressed in design-based aerial surveys, and some authors such as Taylor (2015) provide methodologies to implement modern aerial surveys and quantify bias and precision of school biomass estimates.

The CCPSS is a daytime visual aerial survey that was developed by CDFW and the California Wetfish Producers Association (CWPA) based on known CPS school dynamics in California coastal waters (Kaltenberg and Benoit-Bird, 2009; Lynn et al., 2022). Data collected from this survey from 2012 to 2019 provided evidence that substantial fractions of Pacific sardine biomass occur in nearshore waters of < 40.00 m deep off California, compared to offshore biomass estimated from the SWFSC ATM surveys that use large research vessels operating in waters > 40.00 m deep. These findings first led to the development of synoptic surveys between CCPSS and the ATM survey beginning in 2017, allowing the integration of Pacific sardine biomass estimated from these surveys in stock assessments (Kuriyama et al., 2020; Kuriyama et al., 2022a). Secondly, in 2021 the SWFSC started a small vessel acoustic survey in nearshore waters off California, but this survey is limited to water depth of > 10.00 m, and hence does not fully cover the nearshore distribution of Pacific sardine that typically extends to the shoreline. Thus, the development of synoptic CCPSS and acoustic nearshore and offshore surveys provides a robust set of complementary approaches to survey Pacific sardine schools that are mostly concentrated close to shore off California during periods of low abundance. Questions about the application of the CCPSS to estimate nearshore biomass of Pacific sardine have been raised and discussed during various workshops and stock assessment review panels (e.g., PFMC, 2020). Recommendations from these meetings were addressed, resulting in the creation of a new design implemented in 2020.

The goal of this study was to develop a new transect survey design and methodology for quantifying the level of bias and uncertainty of nearshore Pacific sardine aerial biomass estimates off California. Specifically, we aimed to: (1) conduct experimental purse-seine vessel point set surveys to compute bias for biomass estimated by aerial survey spotters; (2) develop an experimental transect survey to partition and quantify within- and among-transect variances for school biomass estimated by two spotters; and (3) apply the aerial survey to estimate Pacific sardine biomass in two regions, southern and northern California (SCA and NCA, respectively) from 2020 to 2023, using bootstrap methods to compute variance for the biomass estimated in each region. Aerial surveys were conducted during the spring in SCA and summer in SCA and NCA based on Pacific sardine dynamics off California.

2. Materials and methods

Aerial survey data were collected and analyzed based on three distinct research components: a) experimental point set surveys performed in nearshore waters off California in 2010 and 2018-2020; b) experimental transect aerial surveys conducted in California nearshore waters from 2018 to 2020; and c) knowledge and data acquired from the above two components were then used to design and implement a new seasonal aerial survey in nearshore waters of California from summer 2020 to spring 2023. Two professional aerial fish spotters from the CWPA participated in collecting data during the experimental components of this study, but only one was involved in the application of the new aerial survey design. Sampling area, collection and analytical methods of aerial data for each research component are described below (sections 2.1 and 2.2).

2.1 Experimental surveys

2.1.1. Point set sampling (2010 and 2018-2020)

Point set surveys were defined as sampling surveys that were conducted concurrently by chartered fishing vessels (F/V) and aerial spotter planes to quantify Pacific sardine school biomass in the same area and day. In SCA waters, point set surveys were conducted in summer 2010 and 2018, in spring and summer 2019, and in spring 2020 (Table 1). The summer 2010 survey was a pilot study by Jagielo et al. (2010) that lacked some of the biological and environmental data collected from 2018 to 2020. In NCA, point set surveys occurred in summer 2019 and in fall 2020. A total of six chartered vessels (F/V's *Cape Blanco*, *Eileen*, *Triton*, *Provider*, *Sea Wave*, and *King Philip*) participated in sampling using purse seine gear. These boats were equipped with two or four wells (holds), which allowed for separation of schools collected from different point sets. Purse seine nets ranged from 365.00 m to 420.00 m in length and from 37.00 m to 54.00 m in depth, but all nets had the same mesh size of 1.75 cm. The boats were equipped with echo-sounders (Furuno FCV 295/582, Furuno TZ 12/14) and/or SONAR (Furuno CH 37, 270 or 250, WESMAR HD 800) allowing the detection of schools distributed within the water column. In particular, sounders and SONAR provided the top and bottom depths of each school, which were averaged to determine the mean depth (i.e., the depth of the middle of each school).

During the 2018 to 2020 point set surveys, the pilot (Spotter 1) and an additional observer (Spotter 2) flew in a Cessna 175A aircraft ahead of the fishing vessels, and determined the distribution of CPS schools over the survey area. The pilot then communicated the location of observed schools and directed the purse seine fishing vessels to wrap selected individual schools. For each fish school, the spotters independently identified school species composition, estimated tonnage, and determined the proportion of each school that was effectively wrapped and caught by each purse seine vessel. Vessel captains recorded school depth distribution as detected by shipboard echo-sounder or SONAR. Catches from each set were landed at the closest port, San Pedro or Ventura in SCA and Monterey or Moss Landing in NCA, as soon as the boat reached well capacity or at the end of the sampling day. During offloading of schools at the processing facility, the processor staff took bucket samples per established protocols for commercial fishing operations (CDFW, 2020) to determine species composition. The weight of the catch by species in each well was recorded separately for each point set, facilitating the determination of total weight and species composition of each captured school.

During surveys conducted in 2018 to 2020, CDFW scientific staff collected biological samples from each point set to estimate length and age compositions of captured Pacific sardine schools. In summer 2018, fish samples were collected onboard the fishing vessels throughout the pumping and onboarding of fish from each purse seine set. In 2019 and 2020, biological sampling was conducted at the dock during pumping and offloading of each set. Fish were sampled four times at equal intervals throughout the pumping of each set using 5-gallon buckets to collect fish samples. The contents of each bucket were sorted by species and weighed in aggregate by species. All four subsamples were mixed in a basket, and up to 50 fish per species and per set were randomly selected, stored in plastic bags and preserved on ice. All collected fish samples were processed at the CDFW laboratories and measured and analyzed for biological characteristics (length, weight, sex, maturity, and age). The maturity stage of individual fish was determined from visual analysis of gonad samples based on methods developed by Macewicz et al. (1996). Fish were aged from surface ageing of whole otoliths using methods described in Yaremko (1996).

2.1.2. Bias estimation

Schools included in the computation of bias were selected using a criterion of ≥ 90.0% wrapping during point set sampling. A total of 81 point sets were conducted on Pacific sardine schools during this experiment, including 66 valid sets (≥ 90.0%) and 15 non-valid sets (< 90.0%) that were attempted but whose catches were unsuccessful due to issues with the purse seine nets during capture and onboarding. The percent of each school wrapped by purse seine was estimated independently by each spotter. After each valid point set, the total weight of each school caught during sampling was adjusted based on the estimated percent of the school that was effectively captured and expressed as adjusted landed catch (ALC). For each spotter, a weighted least-squares linear model with no intercept was used to compute the ratio of estimated school biomass to the adjusted landed catch for sardine schools captured during point set sampling. Intercepts of these two linear models were not significantly different than zero, and thus they were set to zero. Hence, all regression analyses were performed using intercepts equal to zero, with the slope of the regression providing the ratio between the true school size and the estimated size by each spotter. The R software (version 4.1.1) was used for regression analyses (R Core Team, 2020). The target number of point set samples for this study (n =23 per fishing year and per Exempted Fishing Permit due to closure of the fishery) was established from a power analysis on 2010 point set school biomass data, which were estimated by Spotter 1 only (PFMC, 2018).

2.1.3. Experimental transect surveys (2018-2020)

Experimental transect aerial surveys were conducted in the SCA and NCA regions to improve survey design and efficiency and evaluate aerial biomass variance within and among transects. These aerial surveys were performed aboard the same Cessna 175A aircraft and with the same two spotters (including the pilot) that participated in the point set surveys. From 2018 to 2020, the pilot was asked to conduct daily aerial surveys on strata of different sizes located in SCA and NCA. Each stratum comprised three transects of equal length located at 1200.00 m, 2400.00 m, and 3600.00 m from the shoreline. The plane flew at 457.00 m altitude to optimize school detections on each transect based on a field of view of 1200.00 m as determined from prior aerial surveys conducted on CPS schools off California (Lynn et al., 2022). Weather conditions determined which stratum was sampled each day. Acceptable conditions for conducting aerial surveys were defined as maximum wind speed of approximately 10–12 knots and visibility at least 90.0% clear of cloud cover (Lynn et al., 2022). If similar weather and fishing conditions existed for all strata, one stratum was randomly selected by the pilot using a random number table. The plane flew transects in the direction that minimized the effects of sun glare to optimize the ability of spotters to detect CPS schools and assess their biomass. Each morning (between 8 am and 10 am, depending on weather conditions) the pilot randomly determined by a coin flip whether to start with the most inshore or offshore transect in a given stratum. At the end of the selected transect the pilot continued flying over the middle and then the third transect and repeating this sequence for a total of three replicated flights per transect. Once a stratum was surveyed, priority was given to the next unsurveyed strata until all strata were flown. A total of three replicated flights was conducted over each transect within a stratum. By design, experimental strata were of variable lengths and areas and were labeled from A to I (Table 2). Total area of all strata was estimated using geographic information system (GIS) software (ArcMap Version 10.5.1).

During the survey each spotter identified CPS schools, providing independent estimates of the number of schools, their biomass, and their species composition. However, in many cases when a large number of schools were seen at once, individual school biomass could not be estimated due to schools constantly shifting positions and shapes. In these instances, the spotters reported the total biomass and the number of schools present in the aggregation.

During experimental aerial surveys a forward motion compensating (FMC) system designed by Aerial Imaging Solutions, LLC (AIS; Version 12.3.1) was used to record aerial and environmental data. The FMC system consists of a Nikon D700 Camera with a 24.0 mm Sigma lens (f-stop 1.4), attached to a mount capable of sliding outside of the plane from a cutout of the side door, providing a downward view of the sea surface. From a laptop computer, all settings on the camera were automatically controlled by the AIS software, including the frame overlap at which the camera captured photos. When CPS schools were identified and confirmed, the plane flew over schools and photos were taken, with the camera system set at 80.0% overlap. The camera system software recorded time, school GPS location, plane speed and altitude, and other information with each image.

2.1.4. Within and among transect (Spatial) variance estimation

Assuming that each observer detected all schools that were present at the surface on a transect line during a given replicate flight, and considering that the sampling unit was a flight on a given transect, the total biomass estimated on the j^{th} transect during the k^{th} flight in the s^{th} stratum by a given spotter was calculated as:

$$b_{j,k,s} = \sum_{i=1}^{n_{i,j,k,s}} b_{i,j,k,s} \quad , \tag{1}$$

where $b_{i,j,k,s}$ is the biomass estimated for the i^{th} individual (or aggregated) school observed on the j^{th} transect during the k^{th} *flight* in stratum *s*, and $n_{i,j,k,s}$ is the total number of schools observed on transect *j,* during flight *k* in stratum *s*. Then:

The mean of daily total biomass estimated on the j^{th} transect in the s^{th} stratum was:

$$\bar{B}_{j,s} = \frac{\sum_{k=1}^{n_{k,j,s}} b_{j,k,s}}{n_{k,j,s}} \quad , \tag{2}$$

where $n_{k,j,s}$ is the number of flights on the j^{th} transect in stratum *s;*

and the grand mean of daily total biomass across the transects was estimated as:

$$\bar{\boldsymbol{B}}_s = \frac{1}{N_{j,s}} \sum_{j=1}^{N_{j,s}} \bar{B}_{j,s} \quad , \tag{3}$$

where $N_{j,s}$ is the number of transects in stratum *s*.

Therefore, the spatial variance (here and thereafter among-transect) variance is the variance of the grand mean, which was estimated as:

$$Var(\bar{\boldsymbol{B}}_s) = \frac{1}{N_{j,s} - 1} \sum_{j=1}^{N_{j,s}} (\bar{B}_{j,s} - \bar{\boldsymbol{B}}_s)^2 \ , \tag{4}$$

which was also used to compute the coefficient of variation (CV) of total biomass per stratum in the results section.

And the between-flight (here and thereafter within-transect) variance was estimated as:

$$Var(\bar{B}_{j,s}) = \frac{1}{N_{k,s} - N_{j,s}} \sum_{j=1}^{N_{j,s}} \sum_{k=1}^{n_{k,j,s}} (b_{i,j,k,s} - \bar{B}_{j,s})^2 \tag{5}$$

where $N_{k,s}$ is the total number of flights in stratum *s,* with each flight referring to a transect being flown.

Hence, for each spotter we computed the ratio $F_0 = {Var(\bar{\boldsymbol{B}}_s)}\big/{Var(\bar{B}_{j,s})}$ to test whether the expected value of the among-transect variance was significantly different from zero in a given stratum. Significance was determined using critical values from the *F* distribution statistical table at α = 0.05 and based on the degree of freedom (*df*) of each variance component (Kuehl, 1994; Rohlf and Sokal, 1995).

2.2 Application of the nearshore aerial survey in 2020-2023

Based on the results of the experimental surveys from 2018 to 2020 presented below (see section 3.3.), a new design was implemented for the nearshore aerial survey off California. In this design, the sampling frame of the aerial survey was defined as the nearshore coastal waters from the shoreline out to a distance of 3600 m from the shoreline. This area was divided in two regions: (1) the NCA region, which measures 2352.00 km^2 and spans from about north of Point

Arena to about north of Port San Luis; and (2) the SCA region, which measures 1692.00 km^2, starting from Point Conception to about north of San Diego. Each region was stratified in planned and expansion survey strata (Fig. 1A and 1B). Planned survey strata were areas that were pre-determined to be flown prior to each survey (N1-N8 and S1-S6). These planned strata covered 69.0% of the NCA area and 78.0% of the SCA area, and these proportions were set as the optimal spatial coverage of the aerial survey in each season and region. Expansion strata were not prescribed to be surveyed (N1E-N7E and S1E-S4E), but for which post-survey expansion of biomass was estimated based on density measured from the planned strata in each region (see section *2.3.2*).

Locations and sizes of strata were selected to maximize coastline coverage while avoiding restricted flight zones and to allow sufficient time for completing at least one stratum in a single day. Hence, the maximum size of strata (200.00 km^2 for N1 and S1) was the maximum area the pilot could fly within one day under acceptable weather conditions (as defined above). In addition, airspace restrictions surrounding the Los Angeles International Airport limit the surveyable areas in the vicinity. Therefore, the two smallest planned survey areas (S3 and S4) were set to be 99.76 km^2 and 95.00 km^2, respectively, allowing the expansion stratum S3E (191.00 km^2) to coincide with the restricted flight zone.

Aerial surveys were conducted during spring and summer in each region over a maximum of two weeks. As Pacific sardine populations tend to move northward in summer-fall and southward in winter-spring (Clark and Janssen,1945), spring surveys were only conducted in SCA, whereas summer surveys were conducted in both SCA and NCA. During spring surveys, except in 2021, the selection of which strata to be flown in a given day was based on local weather conditions or random selection. However, summer surveys (except in 2020 due to the

COVID-19 pandemic) and the spring 2021 survey were conducted synoptically with the fishery survey vessel (FSV) *Reuben Lasker* during the SWFSC ATM survey. Under this constraint, the selection of which strata to be flown in a given day was based, in order of priority, on the proximity of the FSV *Reuben Lasker*, weather conditions, and random selection. Further details on the methodology to conduct synoptic surveys can be found in Lynn et al. (2023).

From summer 2020 to spring 2023, CDFW aircraft were used to survey the SCA and NCA regions. The planes were flown by a CDFW Warden-Pilot, with Spotter 1 and a CDFW biologist observing and collecting data onboard. In 2020, a Partenavia P68 (N28FG) equipped with an FMC system (see section *2.1.3*) was used. The Partenavia P68 (N28FG) was retired by CDFW in 2021, thus the 2021 through 2023 surveys used a Cessna 185 Skywagon or a Partenavia P68 (N37FG), which were not configured to fit the FMC system. Therefore, a new method was developed for surveys conducted in 2021 to 2023. This method used the ArcGIS QuickCapture application (2019; Version 1.17.47) and focused on collecting the geographic location of schools without taking photos. The QuickCapture application is integrated with ArcGIS, allowing customization and collection of field data during aerial survey flights. In particular, the application was used to record the GPS location of CPS schools using an iPad 9 (iOS version 16.5) or an iPhone 11 (iOS version 16.5). The application was monitored by the CDFW biologist who recorded the GPS location of CPS schools on each transect flown in a stratum during daily aerial surveys. The onboard biologist also recorded the number and biomass of schools as estimated by Spotter 1. These aerial survey data were stored on the tablet or mobile device until the user uploaded the data to ArcGIS, creating shapefiles analyzed using ArcMap (Version 10.5.1). As for the experimental surveys, the plane flew at 457 m altitude, surveying three transects located at 1200.00 m, 2400.00 m, and 3600.00 m from the shoreline. However, due to limited funding, transects within each stratum were flown only twice per day.

2.2.1 Stratum biomass, density and variance

Based on equation 3, an estimator of the total biomass of stratum during the daily survey was:

$$B_s^{tot} = N_{j,s} \times \overline{\boldsymbol{B}}_s \ , \tag{7}$$

whose variance was estimated as:

$$Var(B_s^{tot}) = (N_{j,s})^2 \times Var(\overline{\boldsymbol{B}}_s), \tag{8}$$

Hence, the biomass density in stratum *s* was estimated as follows:

$$D_s = \frac{B_S^{tot}}{A_s} \quad , \tag{9}$$

where A_s was the area in km^2 effectively flown by the pilot during the aerial survey of stratum *s*.

And the variance of the density estimated in each stratum was computed as:

$$Var(D_s) = \frac{1}{(A_s)^2} \times Var(B_s^{tot}) \tag{10}$$

2.2.2 Regional biomass and variance estimation

If *n* strata were sampled in region *r* during a season, then the mean density over these strata during each seasonal survey was estimated as:

$$\overline{D}_{s,r} = \frac{\sum_{s=1}^{N_{s,r}} D_s}{N_{s,r}} \ , \tag{11}$$

where $N_{s,r}$ is the number of strata surveyed in region r.

Therefore, the regional biomass in each seasonal survey was estimated as:

$$B_r^{tot} = \sum_{s=1}^{N_{s,r}} \overline{D}_{s,r} \times A_{s,r} \quad , \qquad (12)$$

where $A_{s,r}$ is the area of stratum s in region r.

Prior to the start of each season a pre-determined number of areas was selected to be surveyed. However, not all planned strata could be effectively surveyed because of weather conditions and delays in synoptic ATM survey legs, which ultimately affected airplane and pilot availability, and hence may have reduced the number of days (14 per season) available to conduct each seasonal survey. Consequently, not all possible nearshore strata were always sampled, and therefore final estimates of variance for the mean daily density in equation 11 could not be based on a full stratified random sampling design. However, unbiased estimates of regional density variances could be approximated by: a) assuming the number of transects measured (N) in a given region was a random sample of the total number of transects of that region; b) assuming each replicated flight was an independent measurement of biomass within a given stratum for a given day; and c) using bootstrap methods to resample with replacement the replicated (k) flights that have been surveyed within each stratum of a given region. Accordingly, for each season the collected aerial biomass data computed for each replicated flight by region, stratum, and transect were resampled with replacement using bootstrap methodology. For each replicated flight, a biomass sample was randomly selected from a normal distribution with mean equal to $b_{j,k,s}$ and its standard deviation (SD) derived from the standard error of the bias correction of Spotter 1. A summary of the resampling scheme for each iteration is presented in Fig. 2. Ten thousand iterations were conducted and for each iteration (i) mean biomass density for the region was computed as:

$$\overline{D}_{s,r,i} = \frac{1}{N_{s,r,i}} \sum_{s=1}^{N_{s,r,i}} D_{s,r,i} \qquad (13)$$

These resampled means were then used to compute the variance, standard deviation, and CV for mean density estimated in equation 11 for each of the two regions (NCA and SCA) per season (spring and summer). Finally, equation 11 and its variance (computed as the variance of the resampled means) was applied to expand aerial biomass to all areas within the region (bounded by surveyed strata) that were not surveyed either by design (i.e., expansion strata) or due to inclement weather or restricted areas.

3. Results

3.1. Point set school composition and distribution

A total of 66 Pacific sardine schools were collected from point set sampling off California during daytime, including 26 schools from 2010 and 40 schools from 2018 to 2020 (Table 1). In the 2010 point sets, targeted Pacific sardine schools ranged from a minimum size of 2.80 mt to a maximum size of 84.90 mt, whereas from 2018 to 2020 point sets school biomass varied from 2.14 mt to 80.08 mt. No data on the occurrence of other species in Pacific sardine schools were recorded during the 2010 point set survey. Only one captured school off NCA in 2020 was significantly mixed, comprising 7.03 mt of northern anchovy and 43.21 mt of Pacific sardine. Three schools of Pacific sardine captured in 2019 and 2020, which measured 6.00 mt, 18.00 mt, and 22.00 mt, contained small sampled amounts of northern anchovy, 49 g, 26 g and 30 g, respectively. Jack mackerel were also sampled in small amounts (31 g, 132 g, 138 g, and 161 g) in Pacific sardine schools whose biomass were 32.00 mt, 13.00 mt, 9.00 mt, and 6.00 mt respectively. Small samples of Pacific mackerel, varying from 37 g to 2479 g, were also collected in 20 Pacific sardine schools, which varied in biomass from 2.70 mt to 58 mt.

On average, Pacific sardine schools collected from 2018 to 2020 in the SCA comprised smaller and younger fish than those captured in the NCA (Fig. 4). In the SCA region, Pacific sardine measured on average 141.8 mm (SD =19), with a mean age of 0.6 years old (SD= 0.7). In contrast, mean length and age in NCA were estimated to be 168.0 mm (SD= 10.4) and 1.6 years old (SD= 0.7), respectively. The oldest fish collected during point set surveys were 4 years old, but they were infrequent, representing only 0.3% of the total number of fish (*N* = 1,908) aged from the valid sets.

From 2018 to 2020, point sets were conducted during daytime in nearshore waters ranging from 9.00 m to 36.00 m of bottom depth. Prior to capture, Pacific sardine schools observed across all years from SONAR were distributed throughout the water column at mean depths ranging from 4.58 m to 18.29 m (Fig. 5). Top depths of these schools ranged from 1.83 m to 9.14 m, whereas their bottom depths ranged from 7.32 m to 36.58 m.

3.2. Bias correction factor

Pacific sardine school biomass estimated by both aerial survey spotters were negatively biased (Fig. 6). Spotter 1 underestimated the ALC by about 10.5% (bias correction factor (BCF) = 0.895, Fig. 6A), whereas Spotter 2 underestimated the ALC by 12.6% (BCF= 0.874, Fig. 6B). The slope of each regression model was an estimate of the ratio of school biomass estimated by spotter to the ALC, and therefore it was set as the bias correction factor.

3.3. Experimental transect surveys

Spotters 1 and 2 observed 406 and 395 Pacific sardine schools, respectively, during experimental surveys. A paired-t test conducted on the number of Pacific sardine schools that were simultaneously observed on transects showed no significant difference between spotters (p= 0.584, df= 89). However, the true mean difference between transect biomass estimated by the two spotters during aerial flights were not equal to 0 (p= 0.010, df= 89). Thus, as expected from the calibration curves there was significant difference between transect school biomass estimated by spotters during the experimental surveys. In absolute values, differences in total biomass estimated by the two spotters appeared to increase with increasing stratum biomass, but there was relatively little change in these differences with the magnitude of biomass. For example, in stratum A, the absolute difference between Spotter 1 and 2 in estimated biomass was 1568.17 mt in August 2019, compared to 12.94 mt when biomass was lower in April 2020 (Table 2). However, ratios estimated between Spotter 1 and 2 in stratum A changed only from 0.84 to 0.78, respectively in August 2019 and in April 2020. Nevertheless, the CV of total biomass estimated in each stratum by the two spotters was similar, but their magnitude indicated high variability in the biomass of Pacific sardine in nearshore areas off California.

For the purpose of this study, comparison of within- and among-transect variances of biomass was performed based on experimental aerial surveys conducted in three strata (A-C) in NCA and six strata (D-I) in SCA (Table 2). By design, these strata varied in size and each transect within the strata was surveyed three times during daily aerial surveys. Regardless of region, season, and stratum size, no values of the ratio F_0 estimated from data collected by Spotters 1 and 2 were significantly greater than the critical F value of 5.14, based on the degrees of freedom of the among-transects variance ($df=2$) and the within-transect variance ($df=6$). These results indicated that the expected value of the among-transect variance was not significantly different than zero; thus the variance among transects contributed little to the total variability of biomass estimated during aerial surveys.

3.4. Regional biomass estimation

In NCA, total biomass and CV were estimated only during summer surveys. The total surveyed area (planned and expansion area) was higher in 2020 (2259.18 km^2) than in 2021 (1372.76 km^2), because in 2021 synoptic surveys could not be conducted over the whole region

(Table 3). In contrast, the SCA region was surveyed in both spring and summer and the total surveyed area remained the same during the 2020-2023 period. Out of 637 pure schools observed in NCA, 12 had a biomass > 100.00 mt, with the maximum school size estimated to be 420.00 mt (Fig. 3A). In SCA, nine out of 3971 observed pure schools had a biomass > 100.00 mt, including four schools of 1750.00 mt and one school of 2600.00 mt (Fig. 3B and 3C). Across the three years of this study, large aggregations of Pacific sardine schools (> 800.00 mt) were observed off Bodega Bay, Santa Cruz, and Monterey Bay in NCA (Fig. 1C), and off Long Beach, Newport Beach, Oceanside, and San Diego in SCA (Fig. 1D).

Nearshore biomass estimated from aerial surveys was highly variable among seasons in both regions (Table 3). Although the total surveyed area of NCA was lower in 2021, total biomass was estimated to be higher in 2021 (14963.30 mt) than in 2020 (8699.31 mt). Only two strata (N1 and N5) were surveyed in summer 2022 in NCA, representing 17.0% of the planned survey area. As these two strata were too far apart and this spatial coverage was much lower than the 69.0% target in this region, it was not appropriate to expand biomass based on their mean density into any non-surveyed areas. In 2021, biomass in SCA was higher in spring (18433.86 mt) than in summer (13159.23 mt). However, this pattern reversed in 2022 when estimated biomass in SCA was lowest in spring 2022 (1326.21 mt) and highest in summer 2022 (24400.84 mt).

Coefficient of variation of biomass estimated from bootstrap resampling of the aerial surveys ranged from 0.02 to 0.22 (Table 3). Fourteen percent of replicated flights recorded no Pacific sardine on transects surveyed in the SCA region across the three seasons (spring 2021, summer 2021 and spring 2023) and had the lowest CVs (0.05, 0.02, and 0.04 respectively). In contrast, 32.0% of replicated flights recorded no Pacific sardine across both the SCA and NCA regions in seasons with the highest CVs (0.13-0.22). Further, mean density computed from resampling data was equal to the mean density computed from survey data collected in each season and region (Table 3, Fig. 7 and 8), and thus no bias was caused by bootstrapping the data. As expected from the resampling scheme (Fig. 2), the distribution of mean density estimated from each iteration approximated a normal distribution in most seasons (Fig. 7 and Fig. 8), except for summer 2020 and spring 2023 in the SCA where bootstrapping resulted into two multimodal distributions, containing three modes each.

4. Discussion

4.1 *Experimental surveys*

This study was the first to simultaneously evaluate bias and variance for Pacific sardine aerial biomass estimated by professional spotters based on experimental surveys conducted in nearshore waters off California. In particular, this study corroborated assumptions made by previous studies that professional spotters exhibited low bias (10.5% or 12.6% in this study) in identifying and estimating the biomass of pelagic fish schools (Squire, 1993; Taylor, 2015; Wiley et al., 2021). Although small, the difference in bias between spotters can lead to large differences in biomass estimates when population abundance is high, underscoring the need to quantify bias for each spotter that may be involved in future aerial surveys. This study also addresses concerns raised by previous authors and assessment review panels (e.g., PFMC 2017; Taylor 2015) about the need to develop better methods to quantify and account for all variance components when estimating aerial survey biomass. Replication from experimental surveys showed that most of the variability of nearshore aerial biomass off California was due to within-transect variance. Thus, future surveys could focus on increasing the number of replicate flights per transect, and possibly increasing the frequency of the survey in each season, while maintaining current spacing of the three transects that define the east-west boundary of the nearshore survey along the California coastline. Although there was a significant difference in biomass estimated by spotters, CVs between the two spotters for total biomass estimated within a stratum were large and similar in magnitude. For the range of school sizes observed during the experimental surveys, biomass data from either spotter could be used, particularly in this period of low abundance. However, as school size increases with fish abundance, we expect that the variability in Pacific sardine biomass will increase, and therefore variance among spotters will need to be specified if aerial biomass data are produced by two or more spotters, as suggested by Taylor (2015).

In this study we assumed that transect biomass estimated by spotters during experimental surveys were independent, although the two spotters flew in the same plane throughout these surveys. Recognizing that this assumption may have included some bias in the estimation of variance, no attempt was made to compute between spotter variance or to pool spotter data to compute mean biomass per stratum. Rather, all biomass estimates were computed separately on each individual spotter, and statistical methods applied to these data accounted for this lack of independence. Although it was cost prohibitive for this study, future experimental surveys should consider a design where spotters fly in different planes, which would allow the computation of all variance components of nearshore aerial surveys.

A limitation of the experimental point set survey was that sampling was conducted in a period of very low Pacific sardine abundance, with the exception of 2010 (Hill et al. 2018; Kuriyama et al. 2020). In such periods, Pacific sardine would tend to form smaller schools (Curtis, 2004; Furuichi et al., 2022), comprising younger age classes (Kuriyama et al., 2022a), thus the calibration curves for spotters were based on schools of less than 90.00 mt. From point set surveys on northern anchovy, it is known that CPS purse seine vessels can capture schools as large as 111.00 mt (Lynn et al., 2022; Lynn et al., 2023), but no Pacific sardine schools ≥ 90.00 mt were observed during the point seine survey period. Nevertheless, the calibration curves established in this study are suitable to correct bias in aerial surveys conducted by Spotter 1 and/or 2 in this period of low abundance. However, when stock biomass increases the demography of Pacific sardine is expected to shift toward the formation of larger and faster-moving schools (Curtis, 2004; Furuichi et al., 2022), and thus alternative methods should be considered to collect data on these larger schools to update these calibration curves. Due to the maximum capacity of CPS fishing vessels at approximately 120 mt, chartering larger purse seine boats could be considered for future point set surveys. Further, as the availability of professional spotters may limit the ability to conduct aerial surveys, an alternative method being evaluated by CDFW is the use of remote sensing techniques such as multi-spectral sensors to estimate biomass from aerial images.

Point set survey data collected from 2018 to 2020 provided valuable information on Pacific sardine school depth distributions during a period of low stock biomass. During the daytime, Pacific sardine schools occurred in shallow waters and extended their distribution from surface waters down to 27.00 m of depth. All aerial surveys in this study were conducted between 11 am to 5 pm. Likewise, these surveys were conducted during optimal hours to detect Pacific sardine schools whose formation begins in surface waters off California 3 to 4 hours before sunrise and ends after dawn (Kaltenberg and Benoit-Bird, 2009). Hence, school depth distribution patterns, as revealed in this study, may be useful in improving future aerial surveys or developing new approaches to compute bias. For example, this information can be valuable in developing remote sensing methodology and in making adequate assumptions on school packing density when developing photogrammetric techniques (e.g., Love et al., 2016).

4.2 *Application of the aerial nearshore survey*

The level of biomass and its variance estimated from daily aerial surveys from 2020 to 2023 was dependent not only on Pacific sardine stock dynamics (e.g., Clark and Janssen, 1954), but also on the timing of each survey coupled with weather and environmental conditions in each season and region. As stated above, along the U.S.-Mexico coast, adult Pacific sardine (~ 2+ years old) tend to migrate northward (McDaniel et al., 2016) in summer and fall, and southward in winter and spring. In the past two decades Pacific sardine were observed year-long in the Southern California Bight but were often found to be less abundant north of Monterey or San Francisco, California, during the spring compared to summer (e.g., Lo et al. 2008, Dorval et al. 2014, Stierhoff et al., 2020). Accordingly, aerial surveys were conducted in both NCA and SCA in summer, but only in spring in SCA, coinciding with the greater seasonal abundance of Pacific sardine in each region, given limited survey resources.

Aerial flights were only replicated twice in each stratum per survey season, as it was beyond our objectives and capability to survey strata across multiple days or weeks. This lack of temporal replication within a season may have affected the level of estimated regional seasonal biomass, while making it difficult to compare biomass among seasons and years. For example, the lower biomass estimated in summer 2020 compared to 2021 in NCA was likely due to the timing of aerial surveys and logistical constraints in both seasons. The summer 2020 survey was conducted in September 5-16, whereas the summer 2021 survey was conducted much earlier in the season (August 6-11). As Pacific sardine tend to move northward in summer, part of this difference in biomass between the two surveys could be explained by mismatch between the timing of this migration and the aerial survey in a given year. This difference could be exacerbated by differential mortality and growth rates among year classes, affecting their abundance and migration. In addition, the summer 2020 survey off NCA coincided with the "California Dolan Fire" (August 18-December 31, ArcGIS, 2021), hence portions of planned strata were not able to be flown due to flight restrictions imposed by firefighting efforts. In contrast, no fires were reported off NCA during summer 2021, but synoptic surveys with the FSV *Reuben Lasker* dictated the start of the survey in August and its completion in a smaller portion of the NCA region. Therefore, replicating the aerial survey monthly in a given season could be one of the best alternatives to reduce the influence of unexpected weather conditions and logistical constraints on seasonal aerial biomass estimates.

Similarly, patterns in mean density and CVs estimated in each season and region were likely associated with fish movements and the timing of survey flights. Aerial flights took longer to be completed when more schools were present on a given transect, due to the time needed to identify and quantify fish schools. Thus, when transects had no or few schools, the pilot would have returned in a shorter amount of time to conduct the next replicated flight on any other transects where schools were previously observed. Returning sooner on a transect would have increased the likelihood of seeing the same schools during the replicated flight on that transect, leading to lower within-transect variance, regardless of the total biomass observed. Further, in some seasons the strata within a region were surveyed in as few as three days (e.g., summer 2020 in the SCA), whereas in other seasons it took many more days to complete flights for a region (e.g., 11 days in SCA in spring 2021) due to weather conditions or logistical problems.

While a maximum of 14 days was set to complete the survey in each of the regions based on known Pacific sardine school movement, surveys that lasted more than 7 days may have affected variance more in SCA than NCA. The NCA region is much larger and spread out closer to a straight line, with stratum size and spacing designed to follow natural breaks along the coast and to minimize the likelihood of schools moving among strata before the surveys ended. In contrast, SCA strata were determined in part based on flight restrictions around the Los Angeles International Airport, and thus this region comprised the two smallest surveyed strata, 95.07 km^2 and 99.76 km^2, which were nearly half of the size of any other strata (187.38 - 202.50 km^2) used during the application of the aerial survey. Clark and Janssen (1945) found that tagged Pacific sardine may migrate approximately 6.00 nm to 7.00 nm per day. These movement rates fall within the range of migration speed of South African Pacific sardine (as identified by Teske et al., 2021) schools, which was estimated to be as little as 1.13 to 3.30 nm per day (Newman, 1970; Blaxter and Hunter, 1984) to as much as 27.00 nm per day (Cram and Hampton, 1976). Assuming similar maximum speed for Pacific sardine off California, surveys that were conducted in a shorter period of time in SCA should provide more accurate variance for biomass. These patterns in estimated variances also indicated the need for more than two daily replicated flights in each stratum per region. Although experimental surveys demonstrated that within-transect variance accounted for most of the variability of stratum biomass, due to limiting funding and logistical constraints only two replicated flights were conducted on transects for 2020 to 2023 surveys. Thus, future aerial surveys should consider increasing the number of replicated flights to ensure the temporal variability of biomass within and among strata is captured.

While the survey design of this study allowed for synoptic aerial and acoustic trawl surveys, due to logistical constraints it was not possible to conduct point set sampling during any of the seasonal synoptic surveys. As only one CDFW plane was available to survey in each season, point set surveys were conducted prior or after synoptic aerial and acoustic trawl surveys. Therefore, age and length samples collected from point sets might not be fully representative of the nearshore areas during 2020-2022 synoptic surveys, potentially limiting the use of these biological data in Pacific sardine stock assessments. Although school sizes estimated during point sets were largely within the range of observed Pacific sardine schools during synoptic surveys, it remained difficult to compare the spatial distribution of schools and their behavior during point set sampling and during synoptic surveys. As seasonal variations in environmental conditions may affect school distribution in the water column, there may be additional bias that may not be accounted for when applying the spotter calibration curves to correct biomass estimated in strata and regions during aerial synoptic surveys. This level of unaccounted bias may be exacerbated when large aggregations of schools become more prevalent in nearshore waters.

Given the constraints outlined above, nearshore aerial biomass estimated in this study should be considered as a fraction of the total biomass of Pacific sardine that occurred in southern and northern California. As the aerial survey was designed to occur outside of the SWFSC ATM survey footprint, this conceptual definition allowed the nearshore aerial biomass to be used as a means to inform catchability of the SWFSC ATM survey in recent Pacific sardine stock assessments (Kuriyama et al., 2020; Kuriyama et al., 2022a) when both surveys were conducted synoptically. Under this conceptual framework, Kuriyama et al. (2020) used aerial survey biomass to adjust catchability of the ATM survey from 2015 to 2019. Biomass from this new design was further used by Kuriyama et al. (2022) to estimate catchability of the ATM surveys conducted in spring and summer 2021. Total acoustic biomass for spring and summer 2021 were estimated to be 26369 mt and 40983 mt (Kuriyama et al., 2022), respectively, compared to 18434 mt and 14942 mt of aerial biomass estimated from this study. Total acoustic biomass included those estimated from offshore acoustic surveys using the FSV *Reuben Lasker* and nearshore acoustic biomass estimated from saildrones and small vessel acoustic surveys (Stierhoff et al., 2020). Results from this study showed that substantial amounts of Pacific sardine occurred in nearshore waters, and that in the likelihood component of Pacific sardine stock assessments the catchability of the ATM survey cannot be assumed to be 1.0. Hence, accounting for nearshore biomass estimated by aerial surveys will significantly contribute to avoiding bias in fisheries parameters estimated from stock assessment models especially when biomass is in a period of low abundance.

While Pacific sardine biomass estimated from nearshore small vessel acoustic surveys (newly implemented, beginning in 2021) and aerial surveys in spring and summer 2021 were significantly different, northern anchovy biomass computed in spring and summer 2021 were not significantly different between the two methods (Kuriyama et al., 2022a, 2022b; Lynn et al., 2023). Recognizing the limitation of existing synoptic survey data, we expect that the continuation of these surveys will provide improved data and longer time series to conduct more robust comparisons between the two methods. However, current observations suggest that there may be species-specific differences among these survey methods, which may have resulted from the ability of each species to avoid acoustic detection in shallow waters. Previous studies have shown that conducting acoustic surveys in shallow nearshore habitats is challenging due to constraints and limitations posed by the ship's draft. For example, fish avoidance of vessels, primarily due to noise and turbulence, can bias acoustics survey abundance estimates in nearshore waters (De Robertis and Handegard, 2013; DuFour et al., 2018). In addition, off California the distribution of lobster and crab pots in nearshore waters may limit access for saildrones, while the small vessels acoustic survey cannot operate in shallow waters of less than 5.00 m depth. Aerial surveys are subject to their own biases and limitations (e.g., varying bias with spotter's experience, and inability to fly spotter planes during bad weather conditions), but in shallow nearshore waters where nearly the entire water column can be observed from the spotter plane, they can provide a more representative estimate of biomass, especially during periods of low abundance when Pacific sardine are more commonly found in such habitats.

5. Conclusion

In summary, this study provided new methods to implement aerial surveys for Pacific sardine in nearshore waters off California and developed bias and variance estimators for different components of this survey. Biomass estimated by two professional aerial fish spotters were negatively biased by 10.5% and 12.6 %, respectively, emphasizing the need to quantify bias for each spotter being used in a survey. It was also shown that among-transect variance did not significantly contribute to the total variance. Thus, future aerial surveys should ideally focus more on increasing the number of replicated flights, with the current number of transects (N=3) providing adequate spatial coverage of the nearshore habitat. Lastly, this study demonstrated that there was measurable Pacific sardine biomass in nearshore waters off California, and therefore catchability of acoustic trawl surveys cannot be assumed to be 1.0 in stock assessments. Given these results and the current Pacific sardine stock status in U.S. waters, nearshore aerial survey biomass is an important component of surveying the total biomass of Pacific sardine. Future work should consider temporal replications of the survey (across multiple weeks within seasons) to develop a time series of relative abundance in northern and southern California.

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Table 1. Number and proportion of Pacific sardine schools collected in southern (SCA) and northern (NCA) California during 2010 and the 2018-2020 point set sampling. All point sets met the criteria of ≥ 90.0% of school wrapped.

School size (mt)	Collection year				
	2010	2018	2019	2020	Total
0-20	10	16	4	3	33
20-40	5	0	4	3	12
40-60	6	0	4	4	14
60-80	3	0	1	0	4
80-100	2	0	0	1	3
Total	26	16	13	11	66
Proportion (SCA)	1.00	1.00	0.62	0.10	
Proportion (NCA)	0.00	0.00	0.38	0.90	

Table 2. Total biomass and F_0 ratios estimated by stratum and spotter for experimental aerial surveys conducted in 2018-2020 in nearshore waters of southern (SCA) and northern California (NCA). $N_{j,s}$ is the number of transects per stratum, and $N_{k,s}$ the total number of daily flights per stratum. None of the F_0 values were significantly greater than the critical F value (5.14) at an alpha level of 0.05, with $df = 2$ for the among-transect variance and $df = 6$ for the within-transect variance.

Date	Region	Stratum	Area (km^2)	$N_{j,s}$	$N_{k,s}$	Spotter 1		Spotter 2	
						Biomass (CV, mt)	F_0	Biomass (CV, mt)	F_0
08/23/18	SCA	G	62.29	3	9	7.77 (1.73)	0.33	6.92 (1.73)	0.33
08/29/18		I*	221.17	3	9	59.46 (0.18)	0.05	55.7 (0.18)	0.04
03/16/19		D	271.83	3	9	8.45 (1.73)	0.33	8.30 (1.73)	0.33
03/17/19		F	63.68	3	9	8.78 (0.87)	0.17	8.30 (0.87)	0.17
03/17/19		H	113.84	3	9	995.71 (0.95)	0.48	990.9 (0.95)	0.48
03/23/19		I	214.24	3	9	136.16 (0.88)	1.09	133.89 (0.87)	1.1
05/27/19		D	271.83	3	9	474.71 (0.97)	0.72	420.72 (0.93)	0.66
04/19/20		I	250.32	3	9	333.82 (0.99)	1.22	310.69 (1.02)	1.34
04/20/20		G	62.29	3	9	48.66 (1.73)	1.23	48.09 (1.73)	1.08
04/21/20		E	261.62	3	9	1471.21 (0.75)	0.46	1249.40 (0.79)	0.50
04/23/20		I	223.08	3	9	3205.05 (0.74)	0.73	2996.27 (0.78)	0.74
07/30/19	NCA	C	215.61	3	9	1069.03 (1.57)	1.57	892.65 (1.57)	1.76
08/15/19		A	219.77	3	9	10872.87 (1.33)	1.61	9304.70 (1.30)	1.65
09/19/19		B	156.6	3	9	2169.64 (1.14)	1.48	1879.41 (1.10)	1.63
04/10/20		C	215.61	3	9	1501.50 (0.87)	0.68	1413.37 (0.87)	0.73
04/13/20		A	219.77	3	9	57.64 (1.73)	1.25	44.70 (1.73)	1.85

Note: * Area flown in stratum I varied among dates due to flight restrictions.

Table 3. Pacific sardine regional biomass estimated by region and season for aerial surveys conducted in NCA and SCA from 2020 to 2023 by Spotter 1.

Region	Season	Year	Total surveyed area (km^2)	Mean density (mt/km^2)	Biomass (mt)	CV
NCA	Summer	2020	2259.18	3.85	8699.31	0.17
		2021*	1372.76	10.90	14963.30	0.15
SCA	Summer	2020	1514.68	11.38	17243.80	0.22
	Spring	2021		12.17	18433.86	0.05
	Summer	2021*		8.67	13159.23	0.02
	Spring	2022		0.88	1326.12	0.17
	Summer	2022*		16.11	24400.84	0.13
	Spring	2023		7.32	11082.78	0.04

Note: *Indicate season and year when synoptic surveys were conducted with the SWFSC acoustic trawl method.

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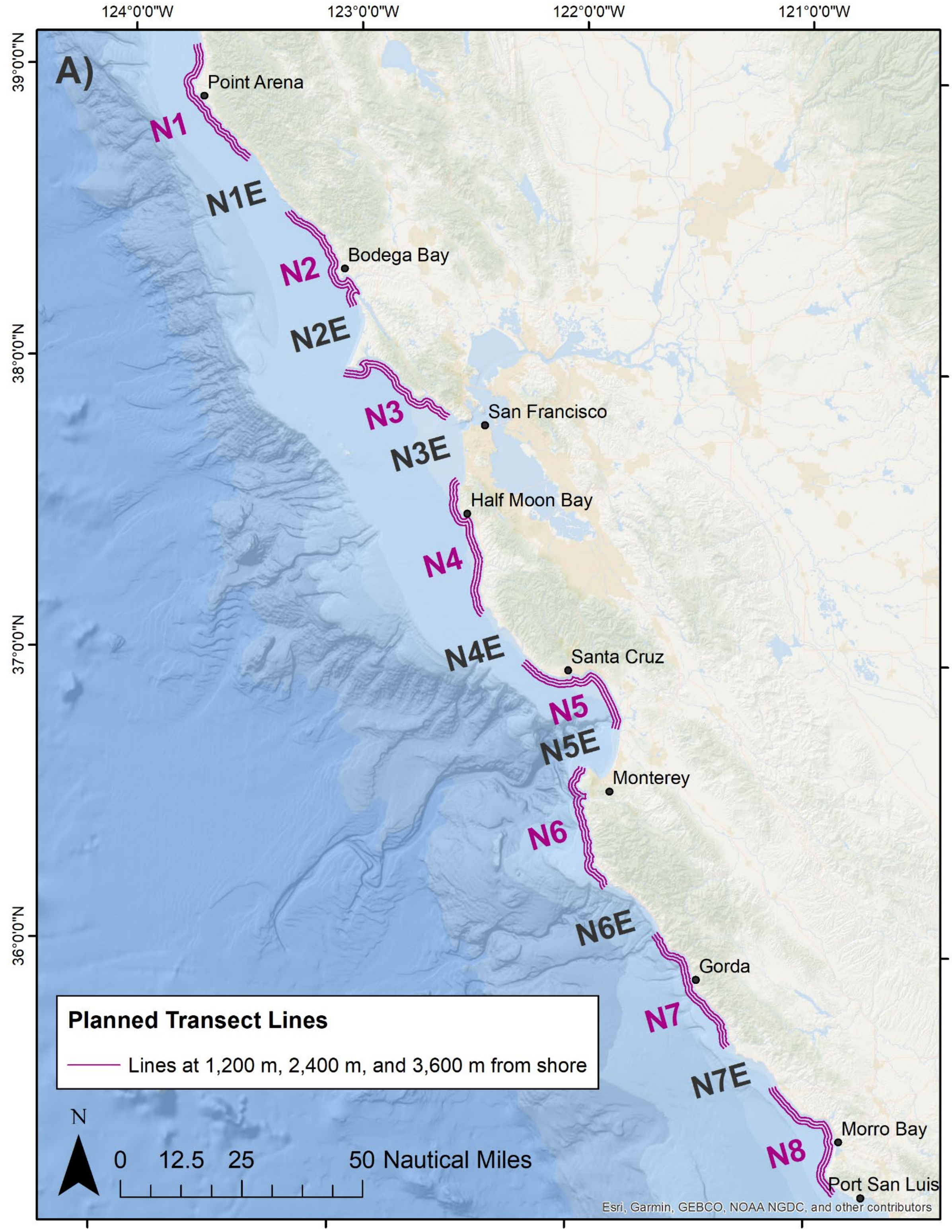
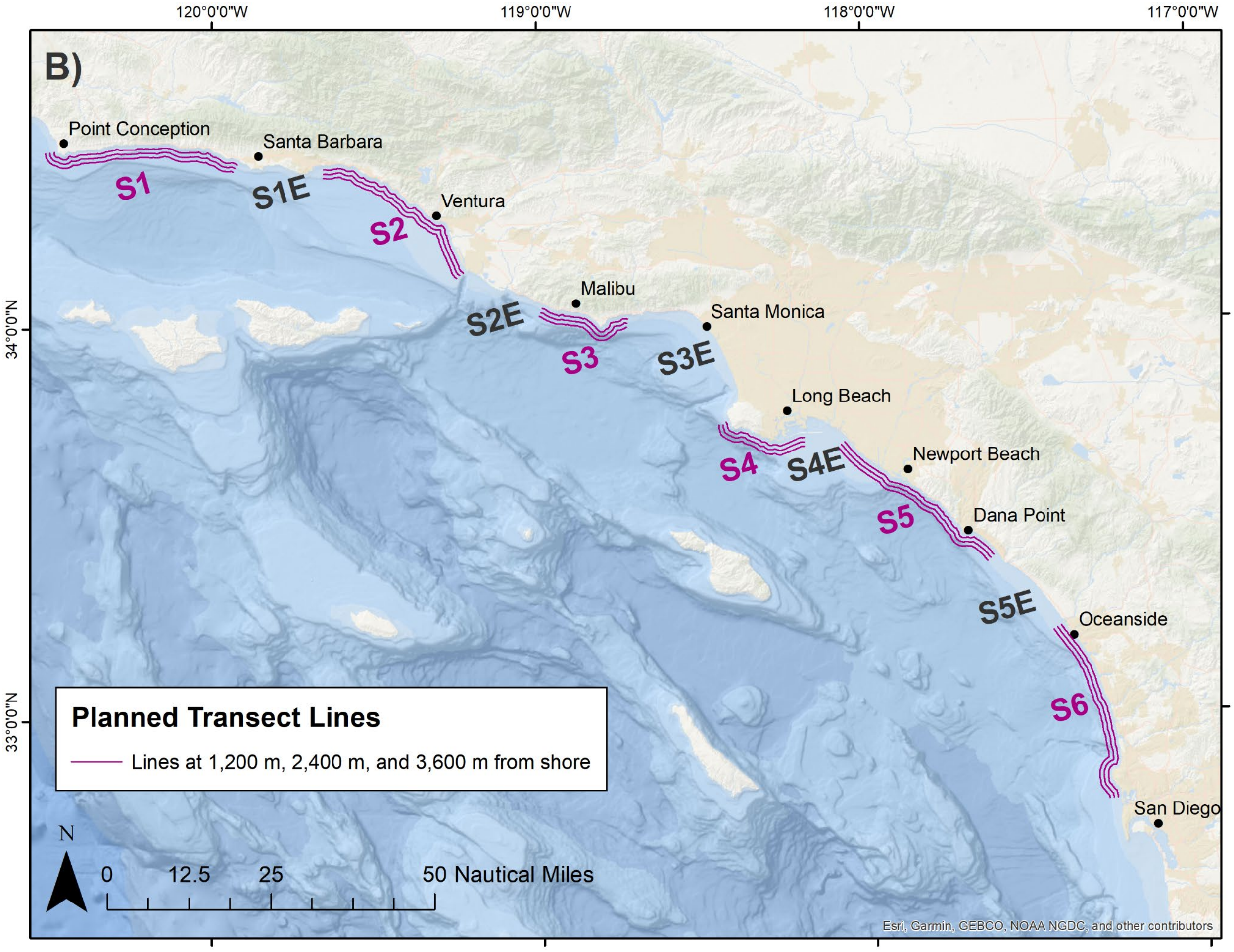
Fig. 1.

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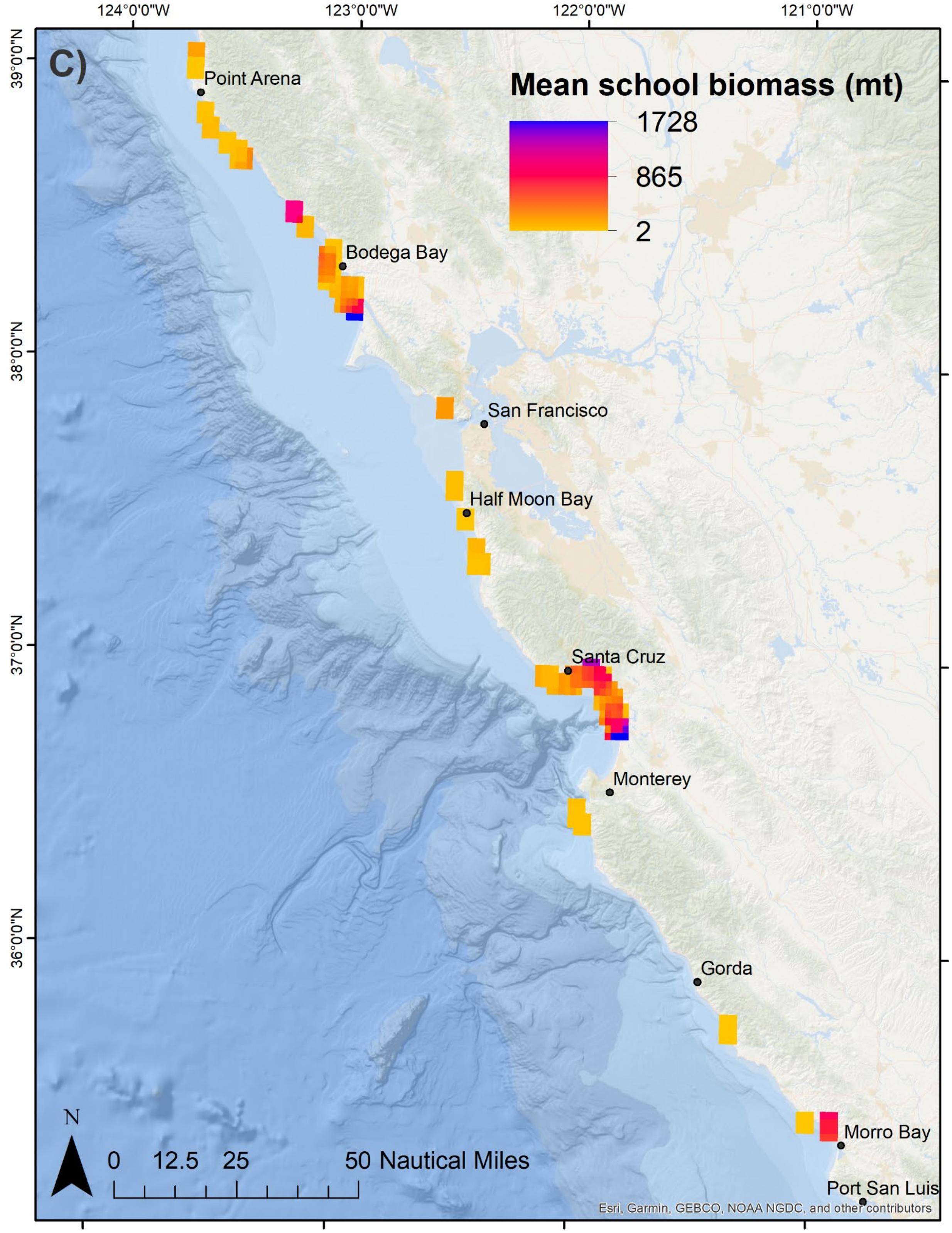
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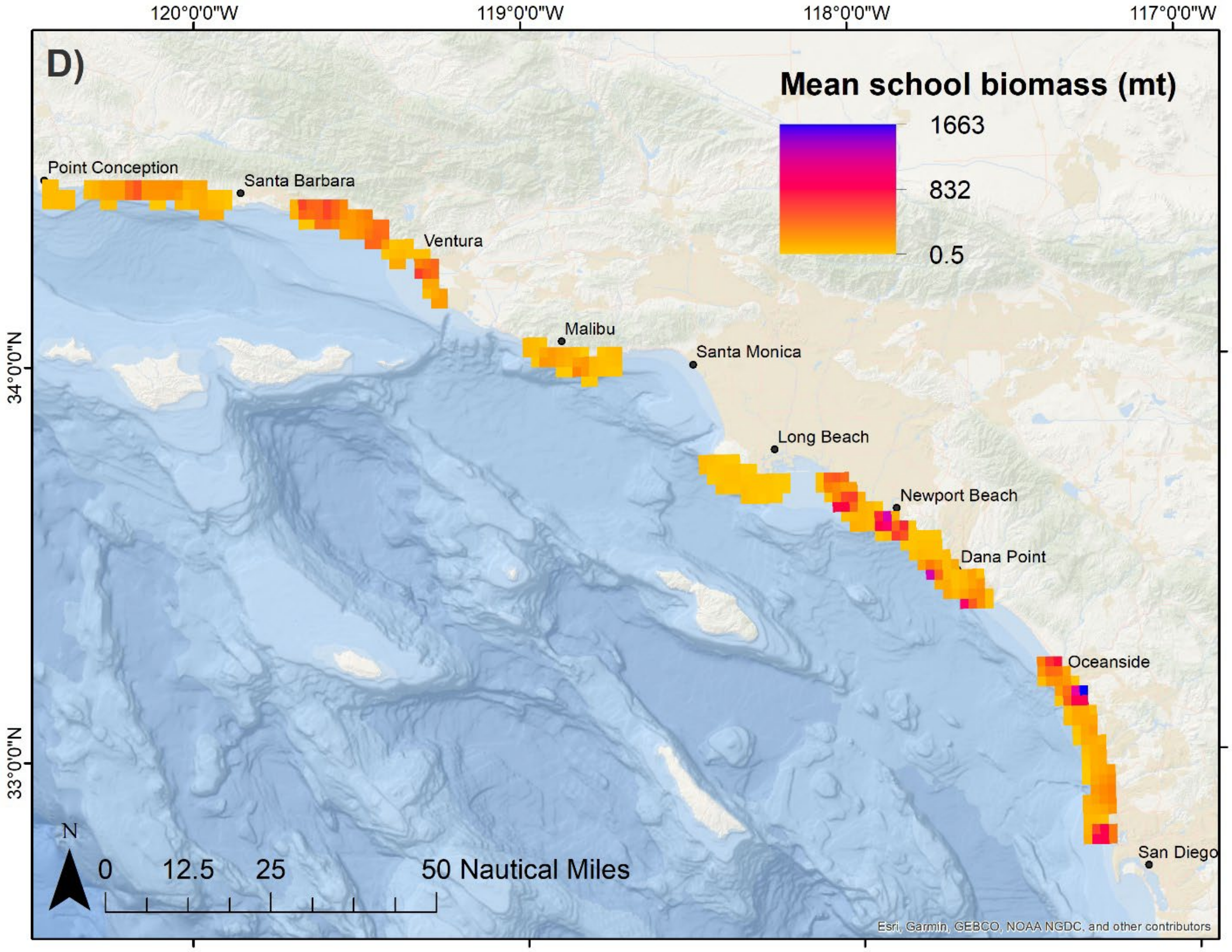
Esri, Garmin, GEBCO, NOAA NGDC, and other contributors



(Panel A-D)**.** Spatial distribution of strata flown (Panels A and B) and Pacific sardine schools observed (Panels C and D) off northern California (NCA) and southern California (SCA) during the application of the new aerial survey design in 2020 to 2023. In Panels A and B, planned survey strata are in pink; and strata for expansion of biomass are in black and denoted with "E" label. Note strata S3 and S4 are smaller to circumvent airspace restrictions near the Los Angeles Airport. In Panels C and D, colors denote the mean biomass (mt) of all schools (including aggregated schools) observed from 2020 to 2023 by Spotter 1 on transects during aerial surveys.

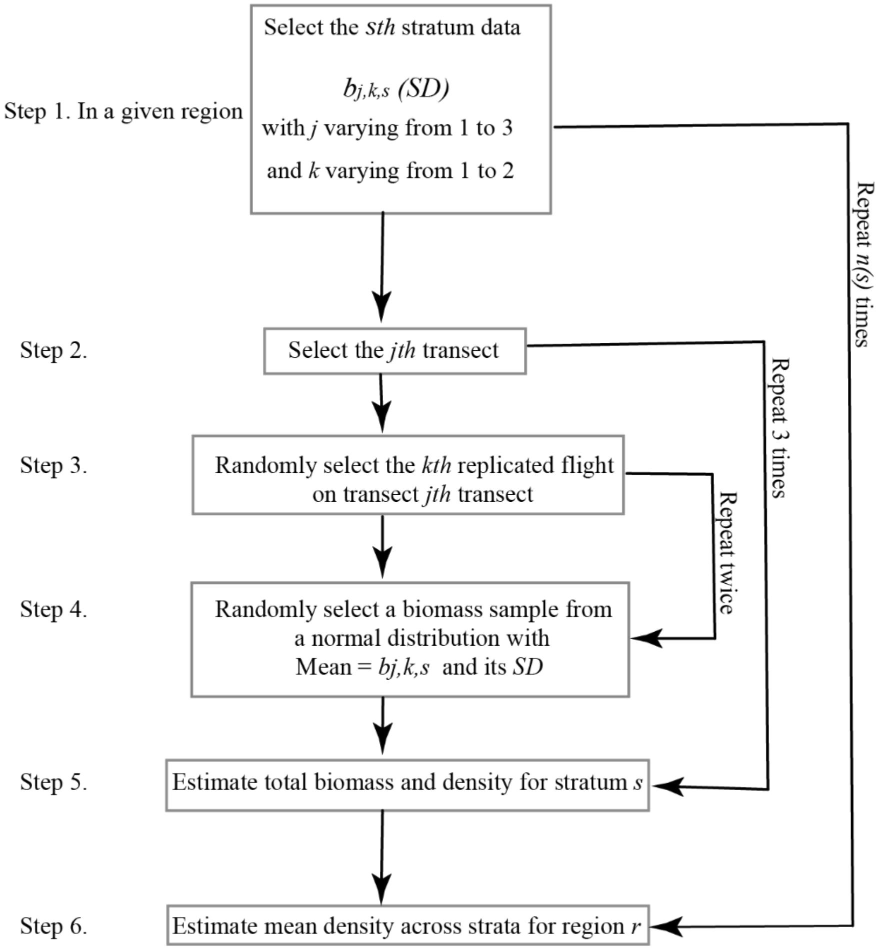


Fig. 2. Diagram of the steps used to compute regional mean density in each iteration during resampling of seasonal aerial survey data.

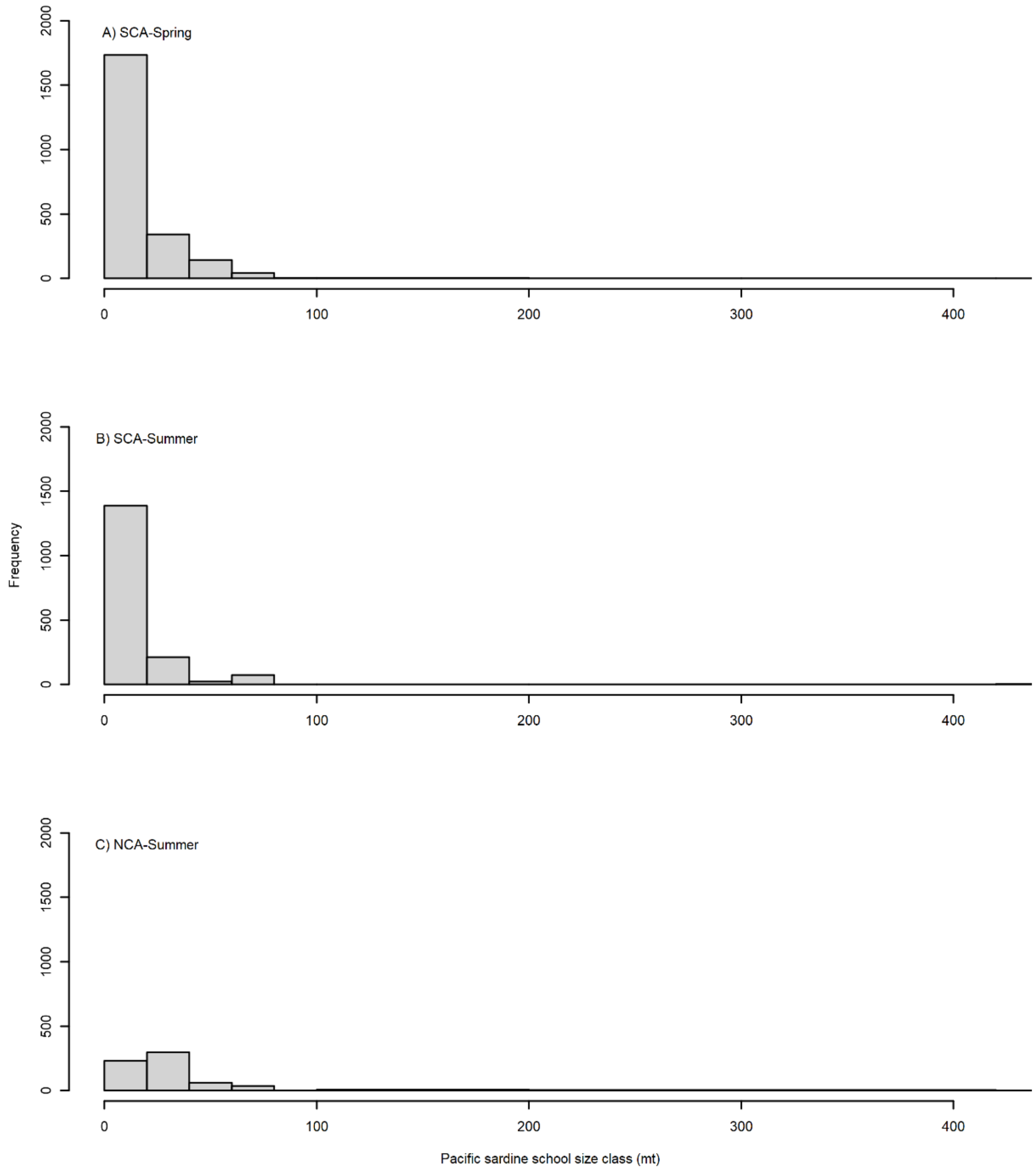


Fig. 3. Frequency of observed pure Pacific sardine schools in aerial surveys conducted off southern California from 2020 to 2023 in spring and summer (SCA, Panels A, B), and in summer off northern California (NCA, Panel C). Bin size for each class is 20.00 mt from 0 to 100.00 mt, and 100.00 mt thereafter. For clarity of the figure, Pacific sardine school > 420.00 mt are not shown on the x-axis of Panel B, which contains four schools of 1750.00 mt and one school of 2600.00 mt.

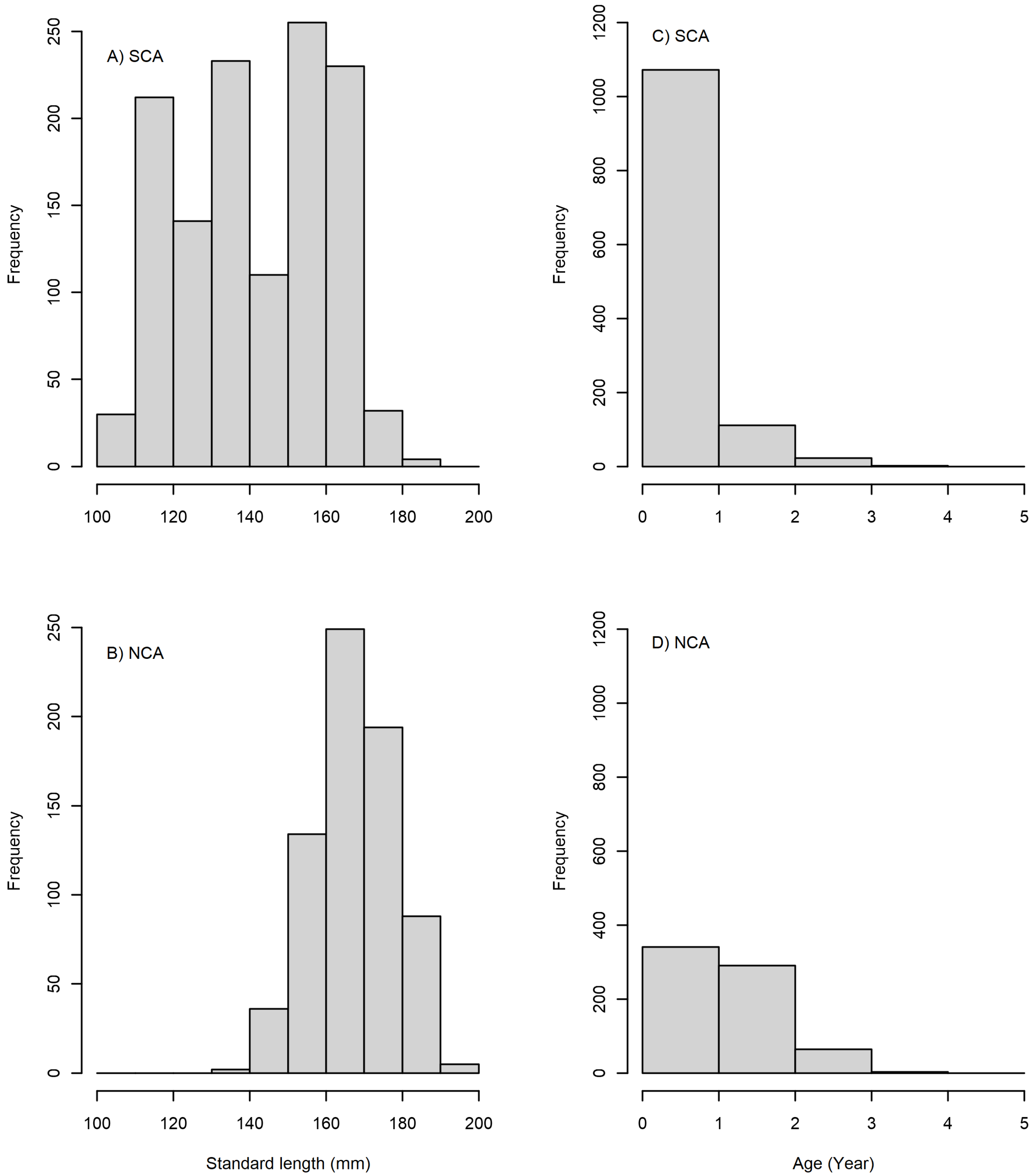


Fig. 4. Length and age distribution of Pacific sardine schools collected during point set sampling in southern (SCA) and northern (NCA) California from 2018 to 2020.

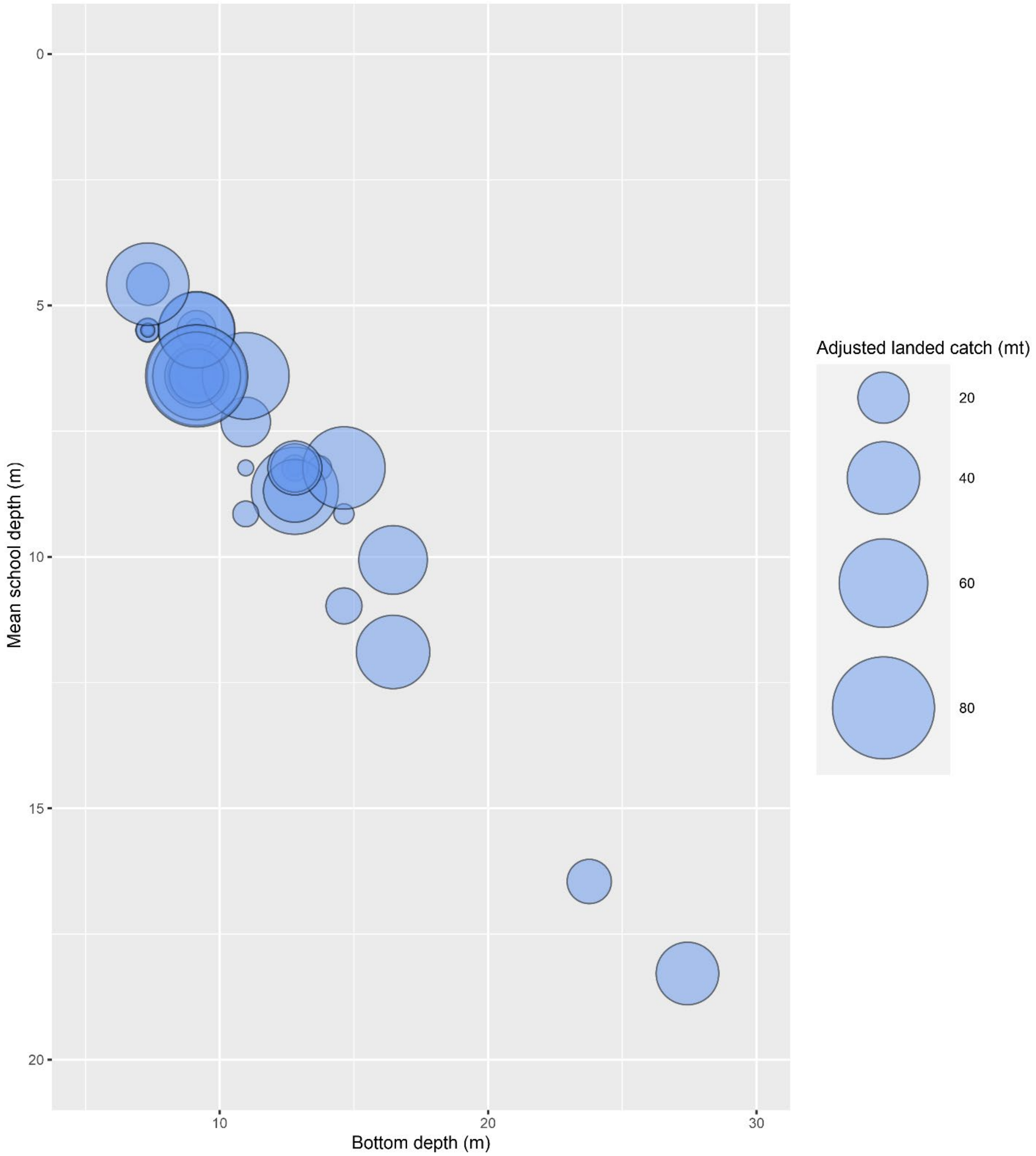


Fig. 5. Mean depth distribution and adjusted landed catch (ALC) of Pacific sardine schools observed at different bottom depths from 2018 to 2020. Bubble plot sizes indicate the biomass of each school collected during point set sampling.

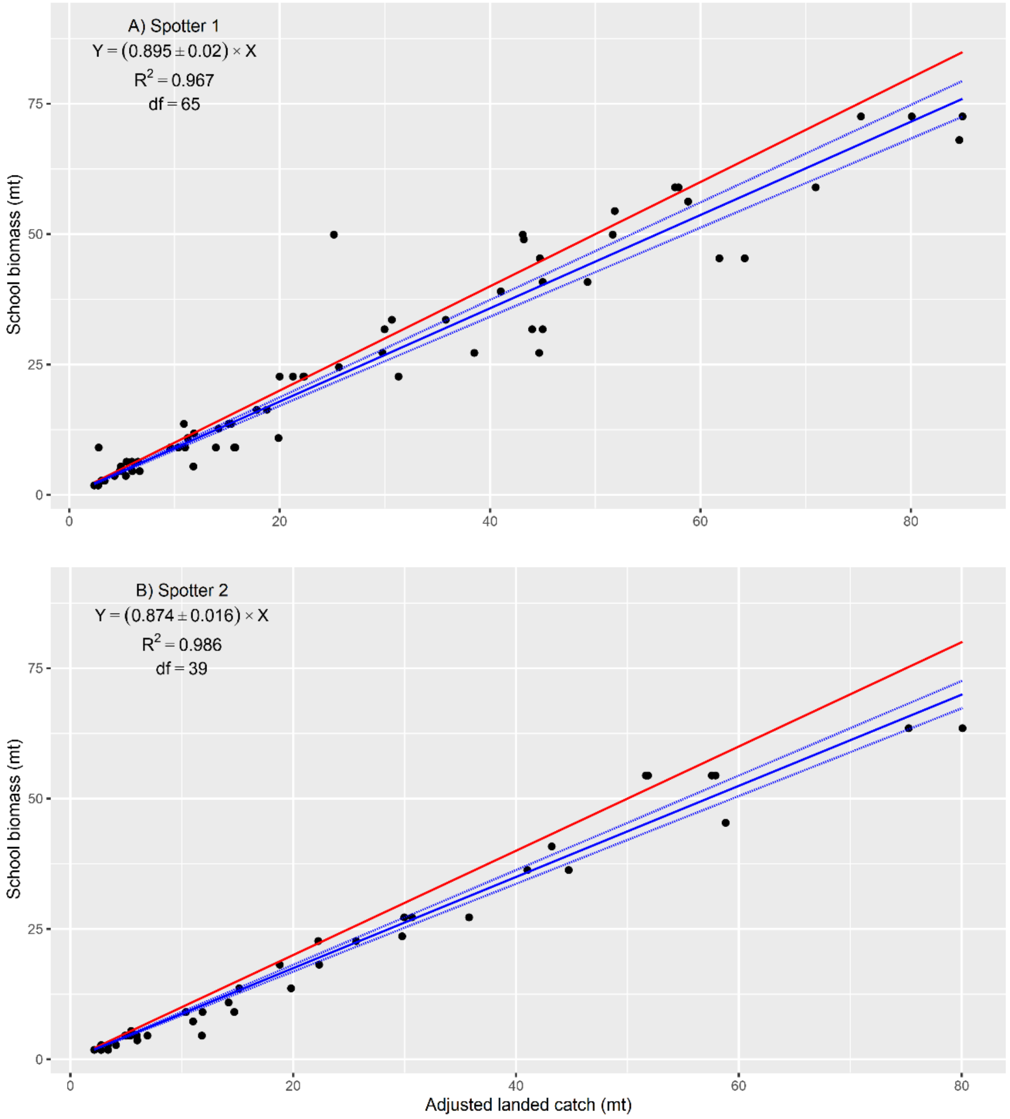


Fig. 6. Calibration curves for Spotters 1 and 2 derived from Pacific sardine point set data collected in 2010 and in 2018-2020. Adjusted landed catch (ALC) is the landed biomass tonnage for each Pacific sardine school corrected by the percent capture by the fishing vessel. Note that Spotter 2 provided observations only during the 2018-2020 period. In each panel, the red line indicates the 1:1line, the solid blue line is the predicted curve, and dashed blue lines show the upper and lower 95% confidence intervals for the predicted curves.

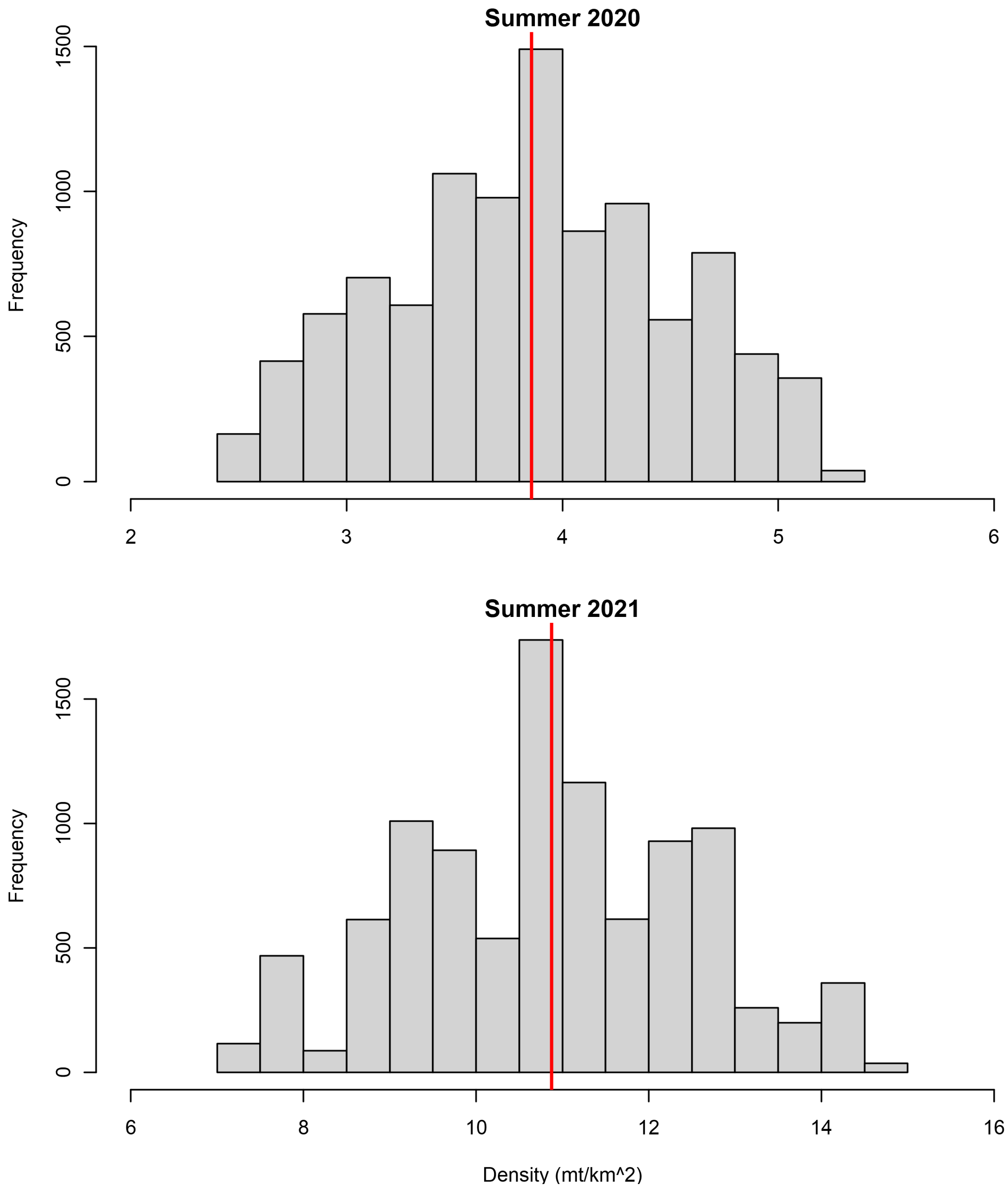


Fig. 7. Distributions of mean densities (mt/km^2) of Pacific sardine in NCA from bootstrap resampling analysis (*N*=10,000 iterations) for aerial surveys conducted in summer 2020 and 2021. The vertical red line represents the bootstrap mean density.

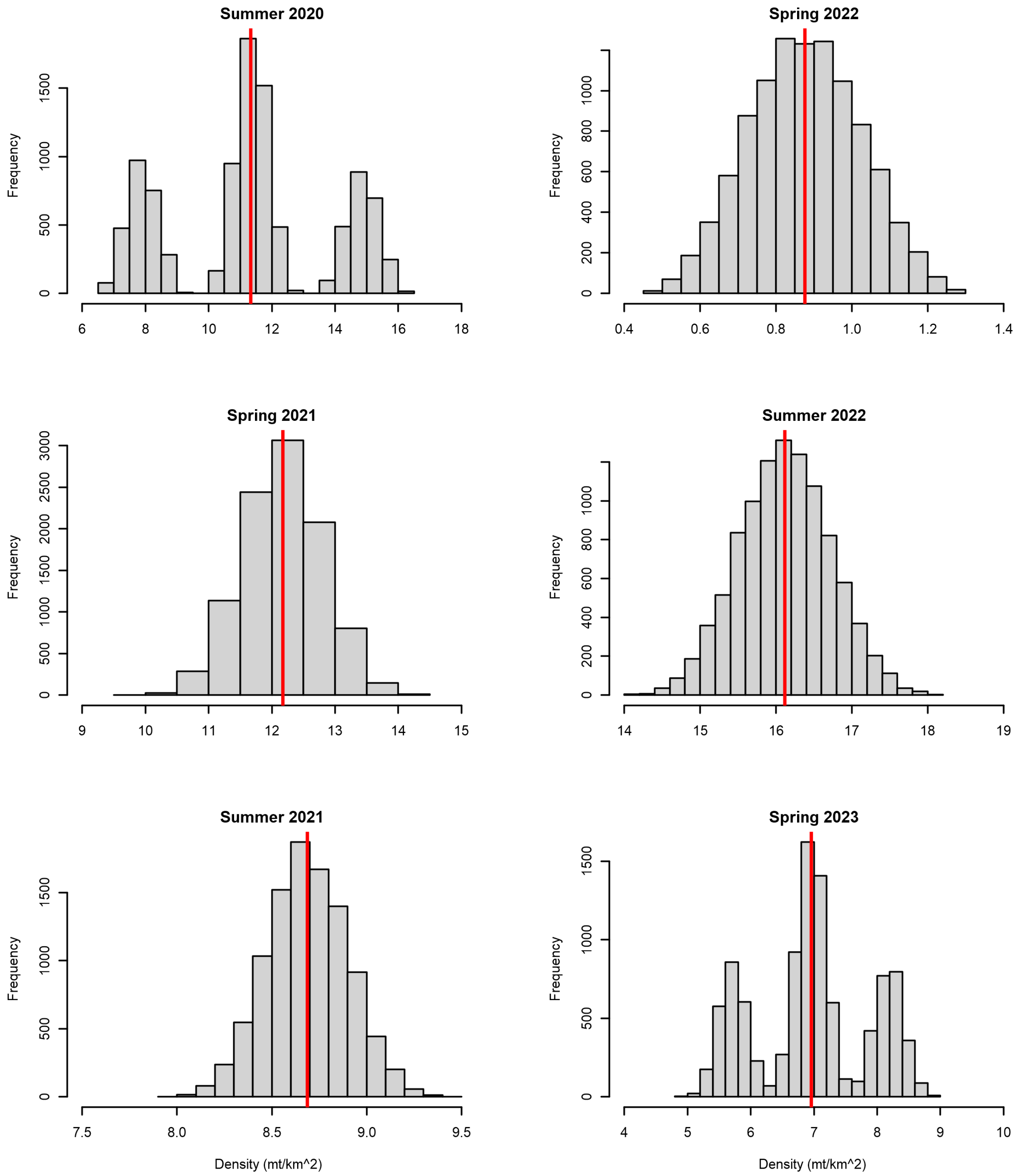


Fig. 8. Distributions of mean densities (mt/km^2) of Pacific sardine in SCA from bootstrap resampling analysis (*N*=10,000 iterations) for aerial surveys conducted in spring and summer from 2020 to 2023. The vertical red line represents the bootstrap mean density.

5. References

ArcGIS, 2021. Dolan fire, southern California. NWS San Francisco/Monterey, CA. https://storymaps.arcgis.com/stories/d409a75c8c9a4253997a7dca71314860

Barange, M., Hampton, I., Roel, B. A., 1999. Trends in the abundance and distribution of anchovy and sardine on the South African continental shelf in the 1990s deduced from acoustic survey. https://doi.org/10.2989/025776199784126088

Baumgartner, T. R., Soutar, A., Ferreira-Bartrina, V., 1992. Reconstruction of the history of Pacific sardine and Northern anchovy populations over the past millennia from sediments of the Santa Barbara Basin, California. CalCOFI Rep., 33, 24-40.

Bakun, A., Cury, P., 1999. The “school trap”: a mechanism promoting large amplitude out-of-phase population oscillation of small pelagic species. Ecol. Lett., 2, 349-351.

Blaxter, J. H. S., Hunter, J. R., 1984. The biology of the Clupeoid fishes. Adv. Mar. Biol., 20, 1-223. https://doi.org/10.1016/S0065-2881(08)60140-6

Caruso, J.P., Meyer, C.D., Iacometti, S., 1983. Aerial marine resources monitoring system. Southwest Fisheries Science Center, Administrative Report LJ-79-09.

CDFW (California Department of Fish and Wildlife), 2020. Coastal Pelagic Species Project, Pelagic Fish Monitoring: A Guide to Port Sampling, Laboratory Sample Processing, and Databases for the CPS Finfish Fishery. California Department of Fish and Wildlife, 4665 Lampson Ave., Suite C, Los Alamitos, CA 90720.

Clark, F. N., Janssen, J. F. Jr., 1945. Movement and abundance of sardine as measured by tag returns. California Department of Fish and Game. Fish. Bull., 61, 7–43.

Cram, D. L., Hampton, I., 1976. A proposed aerial/acoustic strategy for pelagic fish stock assessment. ICES J. Mar. Sci., 37, 91-97.

Curtis, A., 2004. Fine scale spatial pattern of Pacific sardine (*Sardinops sagax*) and northern anchovy (Engraulis mordax) eggs. Fish. Oceanogr., 13, 239-259. https://doi.org/10.1111/j.1365-2419.2004.00291.x

De Robertis, A., Handegard, N. O., 2013. Fish avoidance of research vessels and the efficacy of noise-reduced vessels: a review. ICES J. Mar. Sci., 70, 34-35. https://doi.org/10.1093/icesjms/fss155

Dorval, E, Macewicz, B. J., Griffith, D. A., Lo, C. H., Gu, Y. 2014. Spawning biomass of Pacific sardine (*Sardinops sagax*) estimated from the daily egg production method off California in 2013. NOAA Technical Memorandum, NOAA-TM-NMFS-SWFSC-535.

Dorval, E., McDaniel, J. D., Macewicz, B. J., Porzio, D. L., 2015. Changes in growth and maturation parameters of Pacific sardine Sardinops sagax collected off California during a period of stock recovery from 1994 to 2010. J. Fish. Biol., *87*, 286-310. https://doi.org/10.1111/jfb.12718

Dorval, E., Porzio, D., Schwartzkopf, B. D., James, K. C., Vasquez, L., Erisman, B., 2022. Sampling methodology for estimating life history parameters of coastal pelagic species along the U.S. Pacific coast. NOAA-TM-NMFS-SWFSC-660. https://doi.org/10.25923/e8wq-xf39

DuFour, M. R., Mayer, M. C., Qiana, S. S., Vandergoot, S. C., Krausc, T. R., Kocovskyc, M. P., Warner, M. D., 2018. Inferred fish behavior its implications for hydroacoustic surveys in nearshore habitats. Fish. Res., 199, 63-75. https://doi.org/10.1016/j.fishres.2017.11.018

Fréon, P., Gerlotto, F., Soria, M., 1996. Diel variability of school structure with special reference to transition periods. ICES J. Mar. Sci., 53, 459-464.

Furuichi, S., Kamimura, Y., Suzuki, M., Yukami. R., 2022. Density-dependent attributes of schooling in small pelagic fishes. Sci. Nat., 109, https://doi.org/10.1007/s00114-022-01819-4

Jagielo, T. H., Hanan, D., Howe, R., Mikesell, M., 2010. West coast aerial survey: sampling results in 2010. Prepared for Northwest Sardine Survey and the California Wetfish Producers Association. Submitted to Pacific Fishery Management Council, Portland, OR, October 15, 2010. 51 p.

Hill, K. T., Crone, P.R., Zwolinski, J.P., 2018. Assessment of the Pacific sardine resource in 2018 for U.S. Management in 2018-19. NOAA-SWFSC-600.

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

Kaltenberg, A., Benoit-Bird, K., 2009. Diel behavior of sardine and anchovy schools in the California Current System. Mar. Ecol. Progr. Ser., 394, 247-262. https://doi.org/10.3354/meps08252

Kuehl, R. O. 1994. Statistical principles of research design and analysis. Wadsworth Publishing Company, Belmont, California. 686 p.

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

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

Kuriyama, P. T., Zwolinski, J. P., Teo, S. L. H., Hill, K. T., 2022b. Assessment of the Northern anchovy (*Engraulis mordax*) central subpopulation in 2021 for U.S. management in 2021-2022. NOAA-SWFSC-665.

Lo, N. C.-h., Jacobson, L. D., Squire, J. L., 1992. Indices of relative abundance from fish spotter data based on delta-lognormal models. Can. J. Fish. Aquat. Sci., 49, 2515-2526.

Lo, N. C. H., Macewicz, B. J., Griffith, D. A., Charter, R.L, 2008. Spawning biomass of Pacific sardine (*Sardinops sagax*) off U.S. and Canada in 2008. U.S. Dep. Commer., NOAA Tech. Memo., NOAA-TM-NMFS-SWFSC-430.

Love, R. H., Fialkowski, J. M., Jagielo, T. H., 2016. Target strength distributions of Pacific sardine schools: Model results at 500 Hz to 10 kHz. J. Acoust. Soc. Am., 140, 4456. https://doi.org/10.1121/1.4966553

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

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

Macewicz, B. J., Castro-González, J. J., Hunter, J. R. 1996. Adult reproductive parameters of Pacific sardine (*Sardinops sagax*) during 1994. CalCOFI Rep., 37, 140-151.

Massé, J., Koutsikopoulos, C, Patty, W. 1996. The structure and spatial distribution of pelagic schools in multispecies clusters: an acoustic study. ICES J. Mar. Sci., 53, 155-160

MacCall, A. D., 1979. Population estimates for the waning years of the Pacific sardine fishery. CalCOFI Rep., 20, 72-82.

McClatchie, S., Hendy, I. L., Thompson, A. R., Watson, W., 2017. Collapse and recovery of forage fish populations prior to commercial exploitation. Geophys. Res. Lett. https://doi.org/10.1002/2016gl071751

McDaniel, J., Piner, K., Lee, H. H., Hill, K., 2016. Evidence that the migration of the northern subpopulation of Pacific sardine (*Sardinops sagax*) off the west Coast of the United States is age-based. PLoS One, 11, e0166780. https://doi.org/10.1371/journal.pone.0166780

McFarlane, G. A., King, J. R., Beamish, R. J., 2000. Have there been recent changes in climate? Ask the fish. Progr. Oceanogr., 47, 147-169. https://doi.org/10.1016/S0079-6611(00)00034-3

McFarlane, G. A., MacDougall, L., Schweigert, J., Hrabok, C., 2005. Distribution and biology of Pacific sardines (*Sardinops sagax*) off British Columbia, Canada. CalCOFI *Rep.*, 46, 144-160.

Muhling B. A, Brodie S, Smith J. A., 2020. Predictability of species distributions deteriorates under novel environmental conditions in the California current system. 2020. Front. Mar. Sci. doi: http://dx.doi.org/10.3389/fmars.2020.00589.

Murphy, G., 1977. Clupeoids. *In* Fish Population Dynamics., ed. J. Gulland. John Willey, New York. Pp. 37-41.

Nevárez-Martínez, M. O., Arzola-Sotelo, E. A., López-Martínez, J., Santos-Molina, J. P., Angeles, M. Z. D. L., 2019. Modeling growth of the Pacific sardine *Sardinops caeruleus* in the Gulf of California, Mexico. CalCOFI Rep., *60*, 1-13.

Newman, G. G., 1970. Migration of the Pilchard (*Sardinops ocellata*) in Southern Africa. Investigational Report, Division of Sea Fisheries, South Africa 86,1–6.

Nieto, K., McClatchie, S., Weber, E. D., Lennert-Cody, C. E., 2014. Effect of mesoscale eddies and streamers on sardine spawning habitat and recruitment success off Southern and central California. *J. Geophys. Res.: Oceans*, 6330-6339. https://doi.org/10.1002/2014JC010251

PFMC (Pacific Fishery Management Council), 2017. Southern California coastal pelagic species aerial survey methodology review. Methodology Review Panel Report. PFMC, Portland, Oregon. Available: https://bit.ly/3S9NkFS.

PFMC, 2018. Revised application for experimental fishery permit to allow take of Pacific sardine in 2018 nearshore research program. Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 101, Portland, Oregon 97220-1384.

PFMC, 2019. Coastal pelagic species fishery management plan as amended through Amendment 17. Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 101, Portland, Oregon 97220-1384.

PFMC, 2020. Pacific sardine stock assessment review panel meeting report. PFMC April 2020 Briefing Book. Agenda Item D.3, Attachment 2. Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 101, Portland, Oregon 97220-1384.

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

Politikos D. V, Curchitser E. N, Rose K. A, Checkley, David M. Jr, Fiechter J. 2018. Climate variability and sardine recruitment in the California current: A mechanistic analysis of an ecosystem model. Fish. Oceanogr. 27, 602-622. doi: http://dx.doi.org/10.1111/fog.12381

Qiu Y. 2015. Iron fertilization by Asian dust influences north Pacific sardine regime shifts. Prog. *Oceanogr*., 134, 370-378. doi: 10.1016/j.pocean.2015.03.011

R Core Team, 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna.

Rohlf, F. J., Sokal, R. R., 1995. Statistical tables. Third edition. W. H. Freeman and Company. New York. 199 p.

Schultz, L. P., Hart, J. L., Gunderson, F. J., 1932. New Records of Marine West Coast Fishes. *Copeia* (2), 65-68.

Schwartzlose, R. A., Alheit, J., Bakun, A., Baumgartner, T. R., Cloete, R., Crawford, R. J. M., Fletcher, W. J., Green-Ruiz, Y., Hagen, E., Kawasaki, T., Lluch-Belda, D., Lluch-Cota, S. E., MacCall, A. D., Matsuura, Y., Nevárez-Martínez, M. O., Parrish, R. H., Roy, C., Serra, R., Shust, K.V., Ward, M.N., Zuzunaga, J. Z., 1999. Worldwide large-scale fluctuations of sardine and anchovy populations. S. Afr. J. Mar. Sci., 21, 289-347. https://doi.org/10.2989/025776199784125962

Squire, J. L. J., 1993. Relative abundance of pelagic resources utilized by the California purse-seine fishery: Results of an airborne monitoring program, 1962-90. Fish. Bull., *93*, 348-361.

Stierhoff, K. L., Zwolinski, J. P., Demer, D. A., 2020. Distribution, biomass, and demography of coastal pelagic fishes in the California Current Ecosystem during summer 2019 based on acoustic-trawl sampling. NOAA-TM-SWFSC-626.

Takahashi, M., Checkley, D. M. J., 2008. Growth and Survival of Pacific sardine (Sardinops sagax) in the California Current Region. J. Northwest Atl. Fish. Sci., 41, 129-136. https://doi.org/10.2960/J.v4110.2960/J.v41.m626

Taylor, P. R., 2015. Investigating a multi-purpose aerial method for surveying inshore pelagic finfish species in New Zealand. New Zealand Government. https://www.mpi.govt.nz/dmsdocument/10745-FAR-201536-Investigating-a-multi-purpose-aerial-method-for-surveying-inshore-pelagic-finfish-species-in-New-Zealand

Teske, P. R. Emami-Khoyi, A., Golla, T. R., Sandoval-Castillo, J., Lamont, T., Chiazzari, B., McQuaid, C. D., Beheregaray, L. C., van der Lingen, C.D, 2021. The sardine run in southeastern Africa is a mass migration into an ecological trap. Sci. Adv., 7, eabf4514.

Wiley, J., Sabater, M., Langseth, B., 2021. Aerial survey as a tool for understanding bigeye scad (*Selar crumenophthalmus*) dynamics around the island of O'ahu, Hawai'i. Fish. Res., *236, 105866*. https://doi.org/10.1016/j.fishres.2020.105866

Yaremko, M. L. 1996. Age determination in Pacific sardine, *Sardinops sagax*. NOAA Technical Memorandum, NMFS SWFSC-223. 33 p.