Acoustic-Trawl Methods for Surveying Coastal Pelagic Fishes in the California Current Ecosystem

David A. Demer, Juan P. Zwolinski, Kevin L. Stierhoff, Josiah S. Renfree, Danial Palance, Scott Mau, David Murfin, and Steve Sessions

Southwest Fisheries Science Center, Fisheries Resources Division, Advanced Survey Technologies Group, 8901 La Jolla Shores Drive, La Jolla, CA 92037

Contents

1. Introduction

In the California Current, multiple coastal pelagic fish species (CPS; i.e., Pacific sardine *Sardinops sagax*, northern anchovy *Engraulis mordax*, jack mackerel *Trachurus symmetricus*, Pacific mackerel *Scomber japonicus*, and Pacific herring *Clupea pallasii*) comprise the bulk of the forage fish assemblage. These species can attain large biomasses during short periods, comprise prey to marine mammals, birds, and large migratory fishes (Field et al., 2001), and are targets of commercial fisheries. Of particular interest to fishery managers are the northern stock of sardine, the northern and central stocks of anchovy, and Pacific mackerel. This document, and references herein, details the acoustic-trawl method (ATM) as presently used by the Southwest Fisheries Science Center to survey CPS.

The ATM has been used and refined for nearly a half century to survey the distributions and abundances of CPS and their oceanographic environments (e.g., Mais, 1974; Cutter Jr. and Demer, 2008; Demer et al., 2012; Zwolinski et al., 2014). In general terms, the contemporary ATM combines information from satellite-sensed oceanographic conditions, calibrated multi-frequency echosounders, probe-sampled oceanographic conditions, pumped samples of fish eggs, and trawl-net catches of juvenile and adult CPS.

The survey area is initially defined by the potential habitat of a priority stock or stock assemblage, e.g., that for the northern stock of Pacific sardine. Along transects in this area, multi-frequency split-beam echosounders transmit sound pulses down beneath the ship and receive echoes from animals and the seabed in the path of the sound waves. Measurements of sound speed and absorption from conductivity-temperature-depth (CTD) probes allow accurate compensation of these echoes for propagation losses. The calibrated echo intensities, normalized to the range-dependent observational volume, provide indications of the target type and behavior (e.g., Demer et al., 2009).

Echoes from marine organisms are a function of their body composition, shape, and size relative to the sensing-sound wavelength, and their orientation relative to the incident sound waves (e.g.Cutter et al., 2009; Demer et al., 2009; Renfree et al., 2009). Variations in echo intensity across frequencies, known as echo spectra, often indicate the taxonomic groups contributing to the echoes. CPS, with highly reflective swim bladders, create high intensity echoes of sound pulses at all echosounder frequencies (e.g., Conti and Demer, 2003). Krill, with acoustic properties closer to those of the surrounding sea-water, produce much lower intensity echoes, particularly at the lower frequencies (e.g., Demer, 2004). The echo energy attributed to CPS, based on empirical echo spectra (Demer et al., 2012), are apportioned to species using trawl-catch proportions (Zwolinski et al., 2014).

Animal densities are estimated by dividing the summed intensities attributed to a species by the length-weighted average echo intensity – the mean backscattering cross-section – from animals of that species (e.g., Demer et al., 2012). Transects with similar densities are grouped into post-sampling strata that mimic the natural patchiness of the target species (e.g., Zwolinski et al., 2014). An estimate of abundance is obtained by multiplying the average estimated density in the stratum by the stratum area (Demer et al., 2012). The variance is calculated through non-parametric bootstrap of the transect-mean densities. The total abundance in the survey area is the sum of abundances in all strata. The total variance is the sum of the variance in each stratum.

2. Sampling domain

The survey area is defined with consideration to the potential distribution of the target species at the time of the survey, the acceptable estimation uncertainty, and ultimately the availability of ship time and other survey resources. The survey results are for the survey area and period. Consequently, the survey area must span nearly all of a stock for the biomass estimate to be an unbiased representation of the population. Also, the amount of acoustic and trawl sampling must be sufficient in number and placement, relative to the population size and location, for the biomass estimate to be usefully precise.

2.1. Seasonal distributions

During summer and fall, the northern stock of sardine typically migrates to feed in the productive coastal upwelling off Oregon, Washington, and Vancouver Island, for somatic growth and energy storage (Zwolinski and Demer, 2012). The predominantly piscivorous adult mackerels also migrate north in summer, but go farther offshore to feed (Zwolinski et al., 2014). In the winter and spring, the sardine stock typically migrates to the oligotrophic waters that are conducive to larval retention and growth, generally off central and southern California (Demer et al., 2012) and rarely off Oregon and Washington (Lo et al., 2011). These migrations vary in extent with population sizes, fish ages and lengths, and oceanographic conditions (Zwolinski and Demer, 2012).

In contrast, anchovy spawn predominantly during winter and closer to the coast where seasonal downwelling increases retention of their eggs and larvae (Bakun and Parrish, 1982); and herring spawn in intertidal beach areas (Love, 1996). The northern stock of anchovy is located off Washington and Oregon and the central stock is located off central and southern California. Whether a species migrates or remains in an area depends on its reproductive and feeding behavior and its affinity to certain oceanographic or seabed habitats.

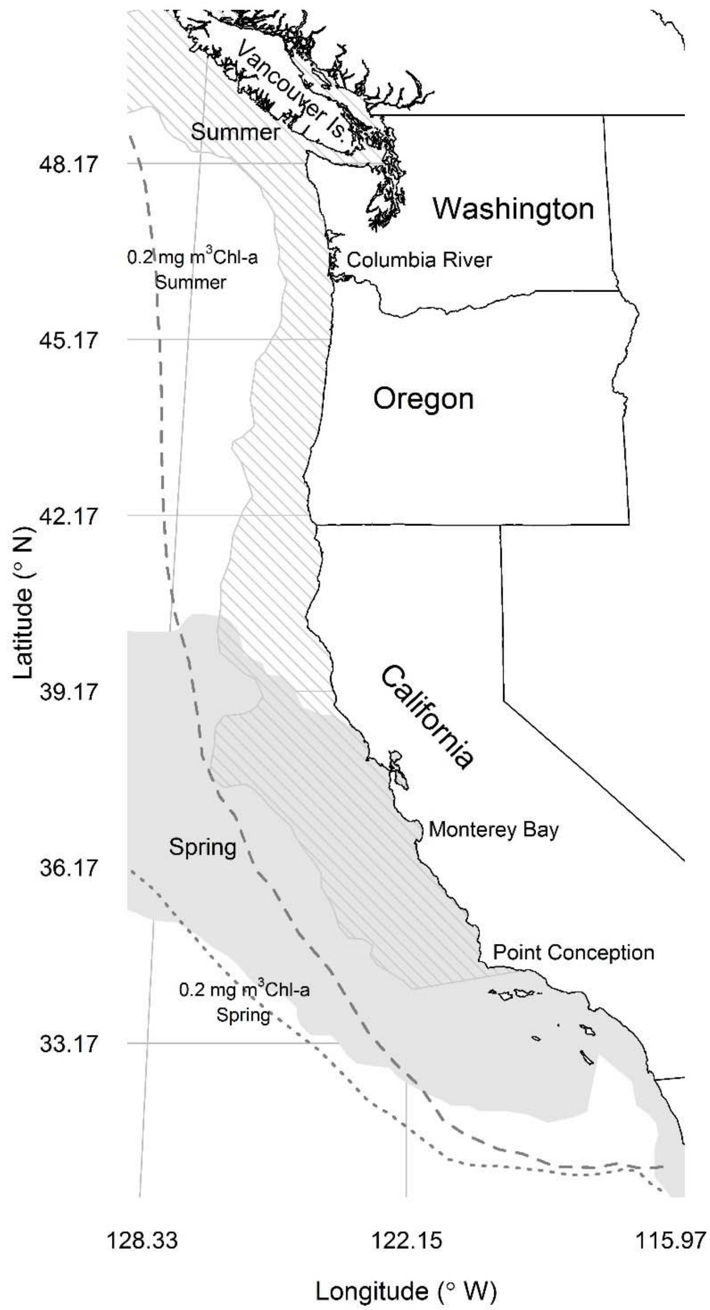

Figure 1. Conceptual map showing the average spring and summer distributions of northern stock sardine habitat along the west coasts of Mexico, the United States, and Canada. The dashed and dotted lines represent, respectively, the approximate summer and the spring position of the 0.2 mg m–3 isoline of chlorophyll-a concentration. This isoline appears to oscillate in synchrony with the transition zone chlorophyll front (Polovina et al., 2001) and the offshore limit of the sardine habitat (Zwolinski et al., 2014).

2.2. Potential Habitats

Sardine potential habitat (**Fig. 1**) is roughly delimited offshore by the 0.18 mg m^{-3} and 15.4 °C surface isolines (Zwolinski et al., 2011), which is typically located to the east and north of the Transition Zone Chlorophyll Front (TZCF), defined by the 0.2 mg m^{-3} surface isoline (Zwolinski et al., 2014). Mackerels are found within and on the edge of the same oceanographic habitat (e.g., Demer et al., 2012; Zwolinski et al., 2012). The TZCF may delineate the offshore and southern limit of both sardine and mackerel distributions, and juveniles may have nursery areas in the Southern California Bight, downstream of upwelling regions. In contrast, Pacific mackerel have a more southerly distribution, probably extending to the southern tip of Baja California and into the Gulf of California (Fry Jr. and Roedel, 1949).

2.3. Survey Period

Spring surveys, typically ~30 days in April to May, target the peak of the sardine spawning season, when the stock is aggregated and modally ~30-m deep offshore of central and southern California (**Fig. 2**; Zwolinski et al., 2012; Demer et al., 2012), and the sardine eggs provide further confirmation of the spatial extent and abundance of the stock (Lo et al., 2009). The spring survey area encompasses the distributions of the northern and central stocks of sardine and anchovy, respectively, and may also include parts of the jack mackerel, Pacific mackerel, and herring populations.

Summer surveys, typically ~50 to ~80 days in June to September, typically span northward of Point Conception, California, to the north end of Vancouver Island, Canada. When resources permit, an area south of Point Conception and north of the US-Mexico border is also sampled. This area encompasses the distributions of the northern subpopulations of sardine and anchovy, and may also include the central subpopulation of anchovy, and parts of the jack mackerel, Pacific mackerel and herring populations. Although the summer surveys require more resources, occur during northward migrations, and are less synoptic, they have the advantages of sampling stocks of multiple species, longer daytime periods, calmer weather, coastal aggregations, more species separation, and coincidence with the majority of the respective commercial fishing efforts.

2.4. Survey Area

Spring surveys typically prioritize the northern stock of sardine, so the survey area is bounded in the north and south to include its potential habitat (**Fig. 2**; Zwolinski et al., 2011) at the time of each survey (http://swfscdata.nmfs.noaa.gov/AST/sardineHabitat/habitat.asp), in the west where the distributions of coastal pelagic fish and their eggs end (often as far as 200 nmi offshore), and in the east by the shallowest navigable depth, typically ~40-m depth and ~2 km from shore.

Summer surveys target the larger CPS community, so the survey area may extend from the north end of Vancouver Island, Canada, to the US-Mexico border in the south, in the west to include the 1500-m isobath (~100 nmi off southern California and ~50 nmi north of Point Conception), and in the east by the shallowest navigable depth.

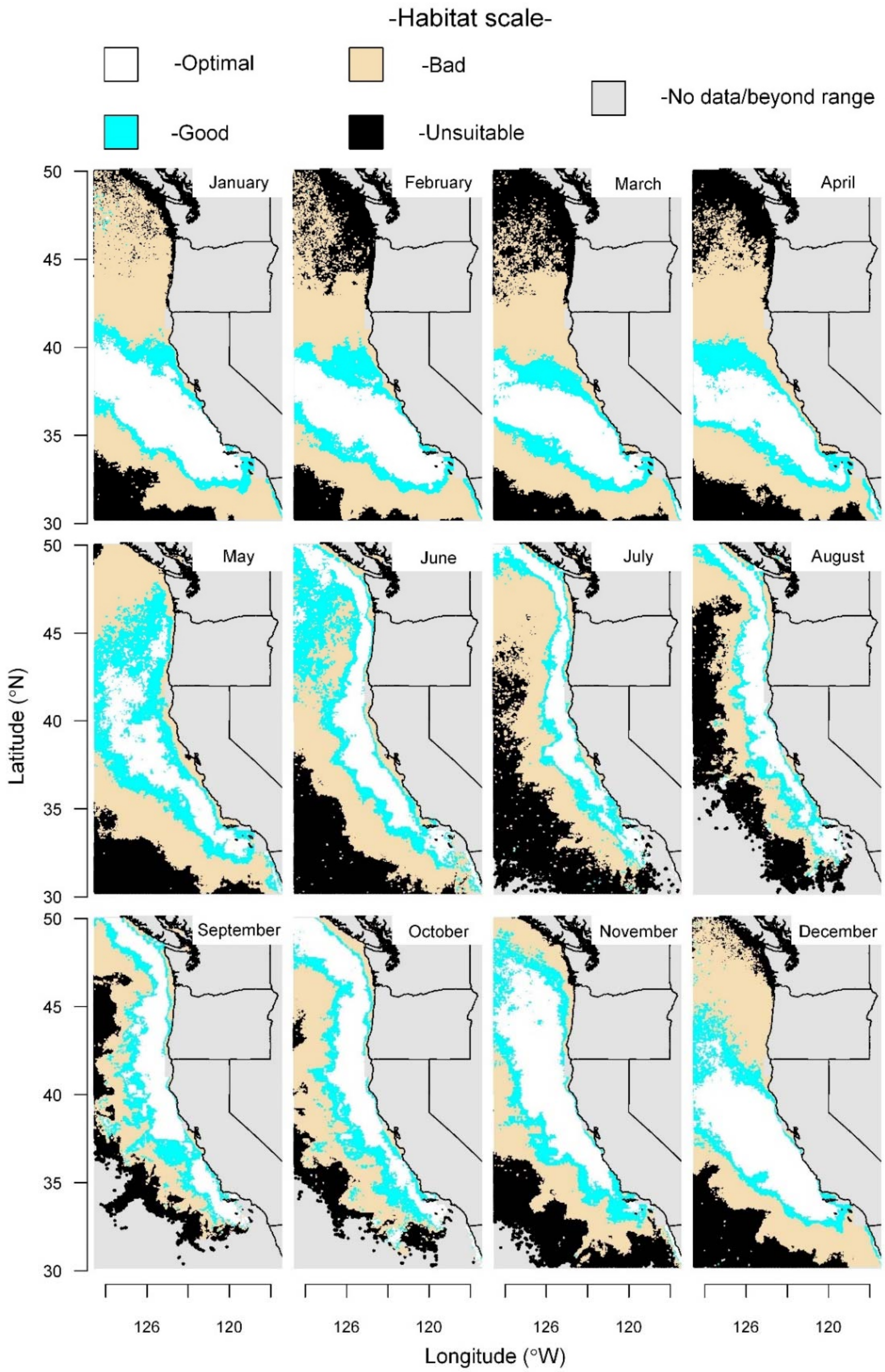

Figure 2. Monthly distribution of potential habitat of the northern stock of Pacific sardine during a typical year (Zwolinski et al., 2011).

3. Sampling

The survey area is spanned by candidate transects, spaced 10 nmi and oriented perpendicular to the coast (**Fig. 3**). Every other transect, spaced 20 nmi, is compulsory. In areas with historically high CPS densities and diversity, i.e., off Washington and Oregon during the summer, all transects, spaced 10 nmi, are compulsory. Sampling is conducted along predetermined transects, at planned stations, and where CPS are located.

The transects are adaptively extended offshore as necessary to map the western extent of CPS based on CPS echoes in echograms, CPS eggs sampled by a Continuous Underway Fish Egg Sampler (CUFES; Checkley et al., 1997), or CPS in survey and commercial catches. Also, in areas with CPS, a minimum of three interstitial transects are added to the compulsory transects (spaced 10-nmi).

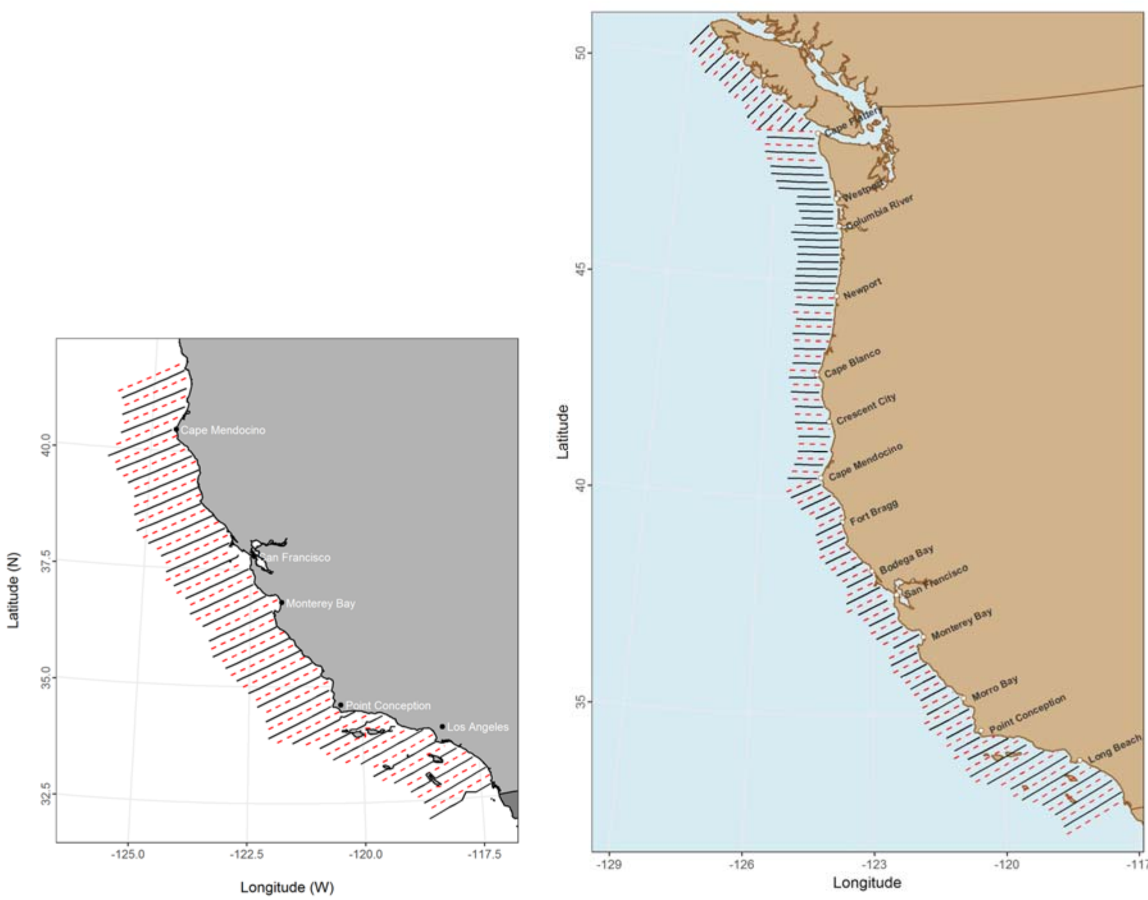

Figure 3. Example transect designs for spring (left) and summer (right) surveys of CPS in the California Current. Black lines represent compulsory transects and the dashed red lines represent adaptive transects.

3.1. CTD Sampling

Seawater temperature and salinity are measured versus depth (0 to 350-m) once each night using a CTD (Seabird SBE-911) and one to five times along each transect using an Underway CTD (UCTD; Teledyne Oceanscience). UCTD deployments are spaced ~15-nmi apart and staggered on adjacent lines to improve sampling coverage. All of these data are used to estimate the time-averaged sound speed (Demer, 2004) used to estimate ranges to the sound scatterers and derive frequency-specific sound absorption coefficients, used for compensating the echo signal for attenuation during propagation of the sound pulse from the transducer to the scatterer range and back (Simmonds and MacLennan, 2005). The CTD also provides measures of chlorophyll-a and dissolved oxygen concentration versus depth, used to estimate the vertical dimension of sardine potential habitat (Zwolinski et al., 2011), particularly the depth of the upper-mixed layer where most epipelagic CPS reside. The latter information is used to inform echo classification (see Section 3.2.3 Data processing).

3.2. Echosounder sampling

Acoustic backscatter measurements are made with multi-frequency (e.g., 18-, 38-, 70-, 120-, 200- and 333-kHz) echosounders comprised of general purpose transceivers (EK60 GPTs) and wide-bandwidth transceivers (EK80 WBTs) multiplexed to an array of split-beam transducers (e.g., Simrad ES18-11, ES38B, ES70-7C, ES120-7C, ES200-7C, and ES333-7C). The transducers are mounted on the bottom of the ship's retractable centerboard (**Fig. 4**). Transducer position and motion are measured at 5 Hz using an inertial motion unit (Trimble/Applanix POS-MV).

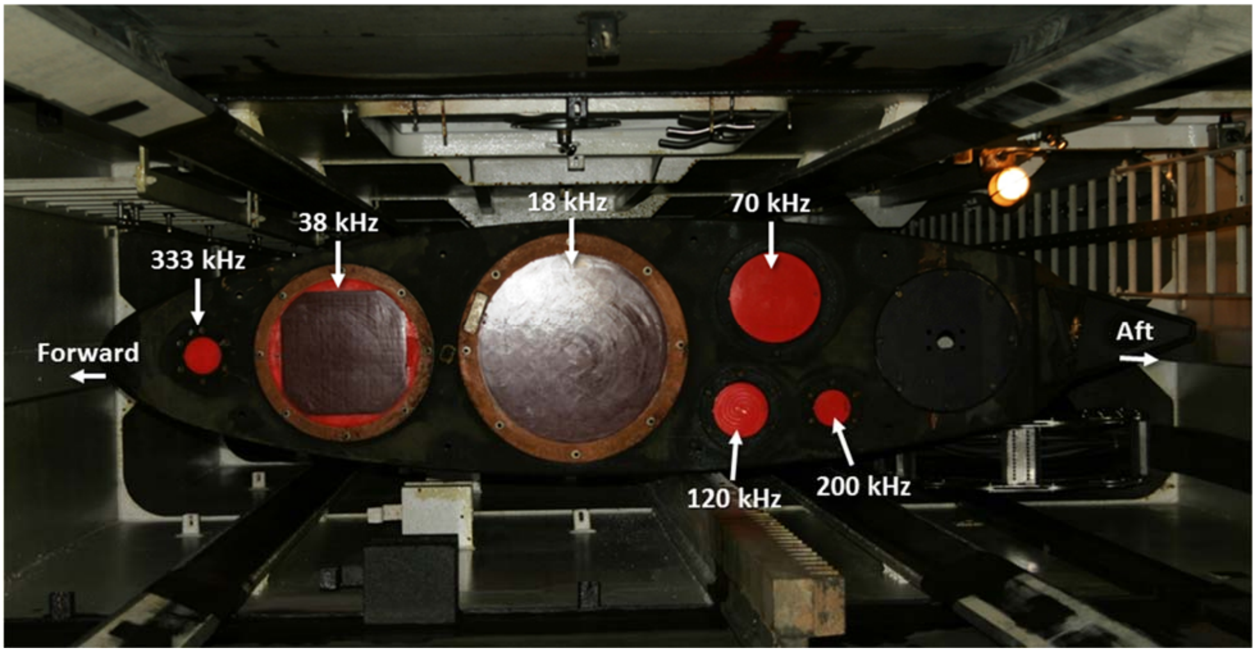

Figure 4. Echosounder transducers mounted on the bottom of the retractable centerboard on *Reuben Lasker*, shown in the maintenance position. During surveys, the centerboard is extended, typically positioning the transducers at ~7-m depth.

3.2.1. Calibration

Within one week prior to the survey, the centerboard is retracted into a dry workspace (maintenance position) and the transducer faces are cleaned of all biofouling. The transducers are then positioned flush with the hull at ~5-m depth (retracted position).

The integrity of each transducer is verified by impedance measurements of each quadrant, both individually and connected in parallel, using either a precision impedance analyzer (Agilent 4294A) or LCR meter (Agilent E4980A) and custom software (Matlab). For each transducer, the magnitude (Z, Ohm) and phase (θ, °) of the impedance, conductance (G, S), susceptance (B, S), and admittance circles (G vs. B) are plotted for each quadrant and for the quadrants in parallel.

Each of the echosounder-transducer pairs are then calibrated using the standard sphere method (Demer et al., 2015). The reference target is a 38.1-mm diameter sphere made from tungsten carbide (WC) with 6% cobalt binder material.

First, the ship is positioned, sometimes dockside, in sufficiently deep water that the sphere is in the far-field of the transducers. A CTD is then cast to measure temperature and salinity versus depth, to estimate sound speeds at the transducer and sphere depths, and the time-averaged sound speed and absorption coefficients for the range between them. The theoretical target strength (*TS*; dB re 1 m^2) of the sphere is calculated using the Standard Sphere Target Strength Calculator (http://swfscdata.nmfs.noaa.gov/AST/SphereTS/) and values for the sphere, sound-pulse, and seawater properties.

The sphere is positioned throughout the main lobe of each of the transducer beams using three motorized downriggers, two on one side of the vessel and one on the other. For each frequency, the calibration results are input to the echosounder software (Simrad ER60) and recorded (Simrad .raw format) with the measures of received power and angles.

3.2.2. Data collection

The ER60 computer clock is set to GMT and synchronized every six hours with the GPS clock using SymmTime (Symmetricon, Inc.). Survey speed is nominally 10 kn, but is decreased in heavy weather, to reduce bubble-induced noise, and increased between transects or during transits.

During the survey, the transducers are typically positioned at ~7-m depth (intermediate position). However, during heavy weather, the depth of the transducers is increased to ~9 m (extended position) to reduce bubble-induced noise. Changes to the transducer depth are logged using the shipboard computing system.

Throughout the survey, the echosounders simultaneously transmit 1.024-ms pulses with transmit powers of 2 kW, 2 kW, 750 W, 250 W, 110 W, and 40 W at 18, 38, 70, 120, 200, and 333 kHz, respectively. To minimize acoustic interference, a synchronization system (Simrad K-

Sync) is used to orchestrate the transmit pulses from the echosounders, two multibeam sonars (Simrad ME70 and MS70), an omni-directional sonar (Simrad SX90), and an acoustic Doppler current profiler (Teledyne RD Instruments Ocean Surveyor Model OS75). All other instruments that produce sound within the echosounder bandwidths are secured during daytime survey operations. Exceptions are made during stations (e.g., plankton sampling and fish trawling) and in shallow water when the vessel's command occasionally operates the bridge's 50- and 200-kHz echosounders (Furuno), the Doppler velocity log (Sperry Marine Model SRD-500A), or both.

An EK Adaptive Logging program (EAL) continuously monitors the echosounder data, detects the seabed depth, and optimizes the echosounder transmit intervals and logging ranges while avoiding aliased seabed echoes (Renfree and Demer, 2016). The logging ranges are from the transducer (~7 or ~9 m depth) to 25 m beyond the detected seabed range, to a maximum of at least 350 m. Received power and angle (EK60) or complex voltage (EK80) measurements are recorded (Simrad .raw), indexed by time and geographic positions provided by the GPS. These are used to derive volume backscattering strength (S_V; dB re 1 m^2 m^{-3}) and *TS*.

3.2.3. Data processing

Data are processed with commercial software (Echoview) using estimates of sound speed and absorption coefficients calculated with data from the nearest CTD cast. Data collected along predetermined transects at speeds exceeding 5 kn and during daylight hours (i.e., not earlier than 30 min before sunrise to not later than 30 min after sunset) are used to estimate CPS densities. Nighttime data are assumed to be negatively biased due to diel-vertical migration (DVM) and disaggregation of the target species' schools (Cutter Jr. and Demer, 2008)

Echoes from schooling CPS are identified with a semi-automated data processing algorithm. The filters and thresholds are based on a subsample of echoes from randomly selected CPS schools. The criteria is to retain at least 95% of their noise-free backscatter while rejecting at least 95% of the non-CPS backscatter.

First, background noise is estimated and subtracted from the backscatter for each echosounder frequency. To reduce stochastic variability, the multiple frequency echo intensities of these candidate CPS echoes are averaged in bins comprising 11 samples vertically (~ 2.1 m) and 3 transmissions horizontally. The horizontal averaging distance is variable due to changes in transmit interval and ship speed. These data are apportioned to CPS and non-CPS (**Fig. 5**), based on comparisons with the following empirical predictions of CPS echo spectra: $-13.85 \le S_{v\ 70\ \mathrm{kHz}} - S_{v\ 38\ \mathrm{kHz}} < 9.89$; $-13.5 \le S_{v\ 120\ \mathrm{kHz}} - S_{v\ 38\ \mathrm{kHz}} < 9.37$; and $-13.51 \le S_{v\ 200\ \mathrm{kHz}} - S_{v\ 38\ \mathrm{kHz}} < 12.53$ dB. For more details see Demer et al. (2009) and Demer et al. (2012).

The provisional CPS regions are ascribed to CPS schools if the standard deviation of each bin is > -50 dB at 120 and 200 kHz. The 38-kHz CPS data with $S_V < -60$ dB (corresponding to a density of approximately three fish per 100 m^3 in the case of 20-cm-long sardine) are set to -999 dB (effectively zero). These two filters serve to exclude echoes from scatterers that are smaller than CPS, but have similar echo spectra (**Fig. 5**).

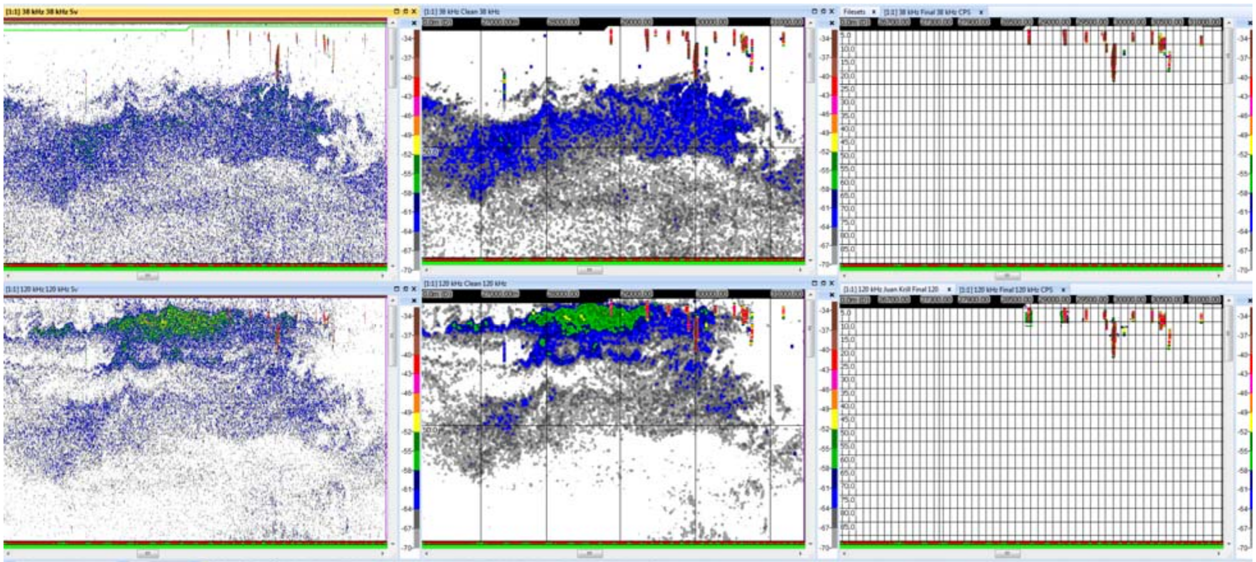

Figure 5. Echogram depicting CPS schools (red) and plankton aggregations (blue and green) at 38 kHz (top) and 120 kHz (bottom). Example data processing steps include the original echogram (left), after noise subtraction and bin-averaging (middle), and filtering to retain only putative CPS echoes (right).

An integration-start line is created at a range of 10-m depth. When necessary, this line is manually modified to exclude reverberation due to bubbles, or to include the tops of shallow CPS schools (**Fig. 5**). An integration-stop line is defined as the range to the bottom of the surface mixed layer (typically between 10 and 12 °C), 3 m above the estimated dead zone (Demer et al., 2009), or to the maximum logging range (e.g., 350 m), whichever is shallowest. The integration stop line is manually adjusted to exclude echoes from demersal fish schools extending more than 3 m above the dead zone.

Between integration start and stop lines, the volume backscattering coefficients (s_V, m^2 m^{-3}) attributed to CPS are integrated over 5-m depths and averaged over 100-m distances. The resulting nautical area scattering coefficients (s_A; m^2 nmi^{-2}) for each transect and frequency are output to comma-delimited text (.csv) files.

3.3. CUFES sampling

Along daytime transects, a continuous underway fish egg sampler (CUFES) collects fish eggs and other plankton in water sampled at a rate of ~640 l min^{-1} from an intake on the hull of the ship at ~3-m depth. The particles in the sampled water are sieved by a 505 µm mesh. Typically, the duration of each CUFES sample is 30 min, corresponding to a distance of 5 nmi at a speed of 10 kn. All fish eggs are identified to lowest taxa, counted, and logged. Because the initial stages of CPS eggs have short duration, the CUFES samples indicate the nearby presence of actively spawning fish. These data are used along with CPS echoes to select trawl locations.

3.4. Trawl sampling

The net, a Nordic 264 rope trawl (NET Systems; Bainbridge Island, WA), has a rectangular opening in the fishing portion of the net with an area of approximately 300 m^2 (~15-m tall x 20-m wide), a variable-sized mesh in the throat, an 8-mm square-mesh codend liner (to retain a large range of animal sizes), and a marine mammal excluder device (MMED) to prevent the capture of large animals, such as dolphins, turtles, or sharks (Dotson et al., 2010). Cameras and lights mounted inside the net are periodically used to evaluate fish behavior inside trawls and the performance of the MMED. The trawl doors are foam-filled and the headrope is lined with floats. The trawl tows at the surface, nominally at 4 kn for 45 min.

During the day, sardine and mackerels form schools in the upper mixed layer, which extends as deep as 70 m in the spring (Kim et al., 2005), but is generally much shallower in summer. After sunset, CPS schools tend to rise and disperse. At that time, with reduced visibility and no schooling behavior, they are less able to avoid a net (Mais, 1974). Therefore, trawl sampling is conducted each night by returning to positions where CPS schools were acoustically observed earlier that day, where CUFES samples indicated egg presences, and reports on the locations of CPS catches by the industry (**Fig. 6**). The first set is ~1 h after sunset, and the last set is concluded prior to sunrise.

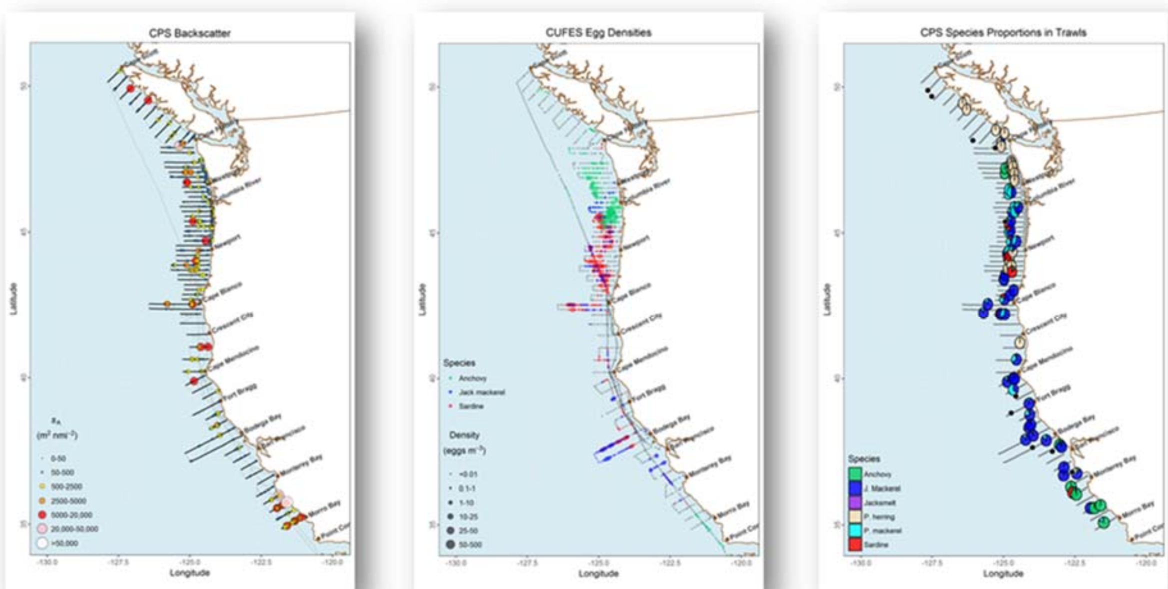

Figure 6. Examples of CPS backscatter (left) and CPS eggs (middle) collected along daytime transects, and species proportions in nighttime trawl catches (right) during summer 2017 (Stierhoff et al., 2018).

The total catch from each trawl is weighed and sorted by species or groups. From the catches with CPS, up to 50 fish from each of the target species are randomly selected. Those are weighed (g), and measured (mm) to either their standard length (L_s) for sardine, northern anchovy, and herring; or fork length (L_f) for jack mackerel and Pacific mackerel. Otoliths from the random sample of fish are removed for age determination. Sex is determined shipboard and female gonads are removed and preserved for laboratory processing.

Catch data from the trawls each night, separated by ~10 nmi, are combined into a "trawl cluster" and used to estimate the species composition, length distributions, and reproductive parameters of sardine, mackerels, anchovy, and herring in that region. After the last trawl of each night, or 30 min prior to sunrise, the ship resumes sampling at the location where the acoustic sampling stopped the previous day.

3.5. Echo classification

The backscattering proportion of CPS in each night's trawl cluster is used to apportion the nearest integrated CPS-backscatter values to each of the dominant epipelagic fish species (**Fig. 7**; see Demer et al., 2012, for details).

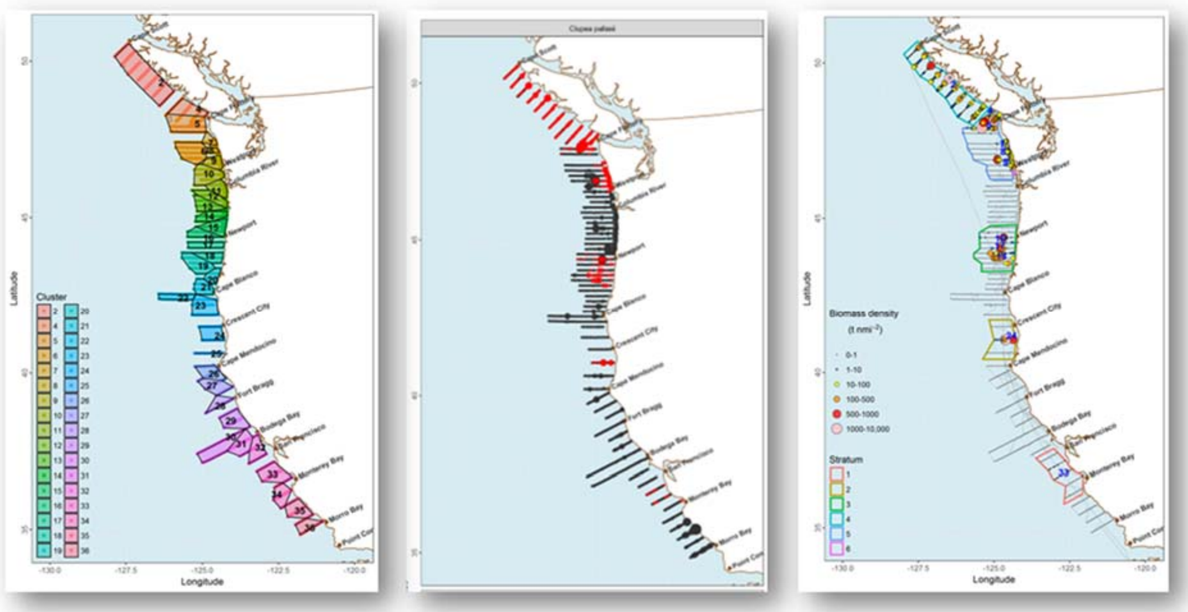

Figure 7. Examples of trawl cluster domains (left) used to apportion nearby CPS backscatter to species, in this case herring (middle), and resulting post-sampling strata (right) during summer 2017.

3.6. *TS* estimation

To estimate the mean backscattering cross-sectional areas (σ_{bs}, m^2, MacLennan et al., 2002) for individual fish of the dominant species within each trawl cluster, the length distributions from each trawl cluster are input to *TS*-versus-length models for sardine (*Sardinops ocellatus/Sardinops sagax*) (Barange et al., 1996), horse mackerel (*Trachurus trachurus*) (Barange et al., 1996), and anchovy (*Engraulis japonicus*) (Kang et al., 2009, compensated for swimbladder compression as in Ona, 2003; Zhao et al., 2008). The model for horse mackerel is also used for jack and Pacific mackerel (Peña, 2008); and the sardine model is also used for herring.

3.7. Density and biomass estimation

Fish biomass densities are calculated by dividing the s_A for each species by their respective spherical cross-section (MacLennan et al., 2002; Simmonds and MacLennan, 2005). The acoustic transects are considered the sample unit (Simmonds and Fryer, 1996). Because each species does not generally span the entire survey area (Zwolinski et al., 2014; Demer and Zwolinski, 2017), their natural patchiness is delineated by statistically-independent, stationary, post-sampling strata (Johannesson and Mitson, 1983; Simmonds et al., 1992). Each stratum has: 1) at least three transects, all of them which have approximately equal spacing, 2) fewer than three consecutive transects with zero-biomass density, and 3) bounding transects with zero-biomass density. The mean biomass density of each stratum is calculated by a transect-length weighted average of the transect-mean densities (Demer et al., 2012; Zwolinski et al., 2012), which is equivalent to the arithmetic mean of all individual samples in the stratum. Total biomass is calculated for each species by summing the products of average biomass density and area for each stratum.

3.8. Sampling precision

Provided that each stratum has spatially independent transect means (i.e., densities on nearby transects are not correlated), random-sampling estimators provide unbiased estimates of variance. Transect-mean densities are treated as replicate samples, and the variance is calculated for each post-sampling stratum using non-parametric bootstrap resampling (Efron, 1981).

The 95%-confidence intervals for the mean biomass densities are estimated as the 0.025 and 0.975 percentiles of the distribution of 1000 bootstrap survey-mean biomass densities. The bootstrap estimates are constructed by resampling, with replacement, the transects within the strata (Efron, 1981). Coefficient of variation (CV) values are obtained by dividing the bootstrapped standard errors by the point estimates (Efron, 1981).

4. Survey time series

Annual or biannual ATM surveys provide time series of potential habitat (Zwolinski et al., 2011; Demer et al., 2012), CPS distributions (**Fig. 8**; e.g., Demer and Zwolinski, 2017; Zwolinski et al., 2017), species and assemblage biomasses (**Fig. 9**; e.g., Zwolinski et al., 2014), length (**Fig. 10**) and conditional-age distributions (**Fig. 11**; e.g., Demer et al., 2013; Hill et al., 2017), natural mortality (**Fig. 12**; Zwolinski and Demer, 2013) and indications of recruitment events (**Figs. 10 and 13**; Zwolinski et al., 2015). Temporal coherence in these estimates serves to bound the survey-estimate uncertainty and prioritize efforts to refine the methods and reduce measurement and sampling uncertainty.

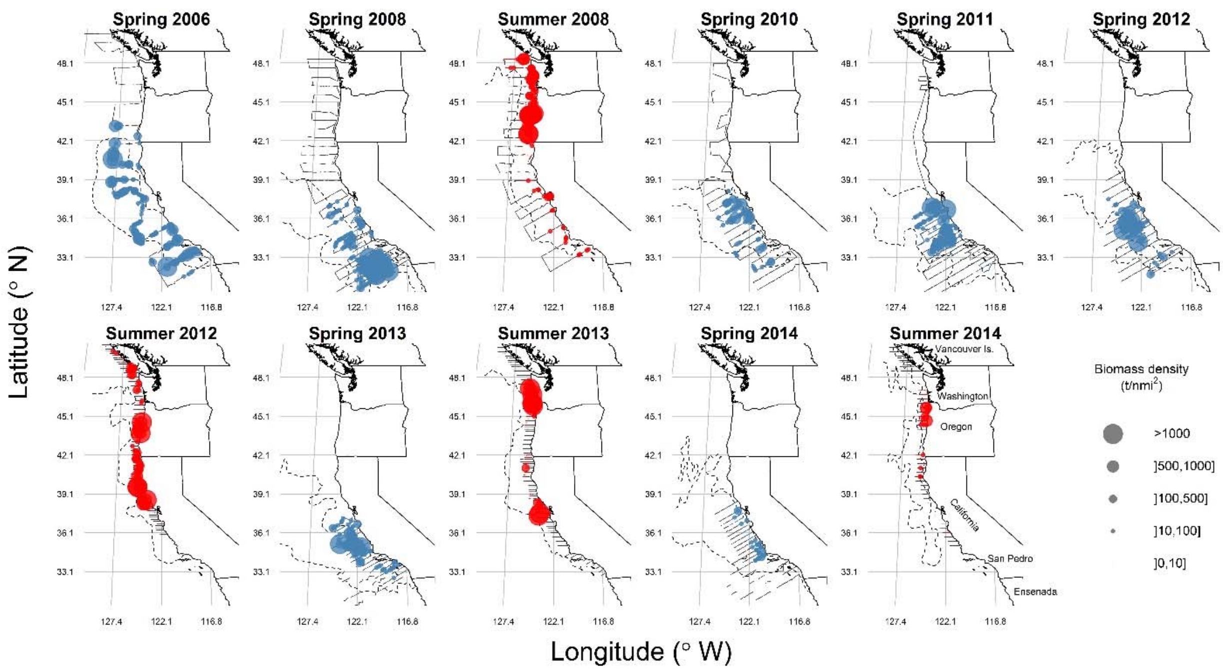

Figure 8. Time series of the distributions of the northern stock of sardine from ATM surveys serve to validate the modeled potential habitat, seasonal migrations, and stock-size dynamics (Demer and Zwolinski, 2017).

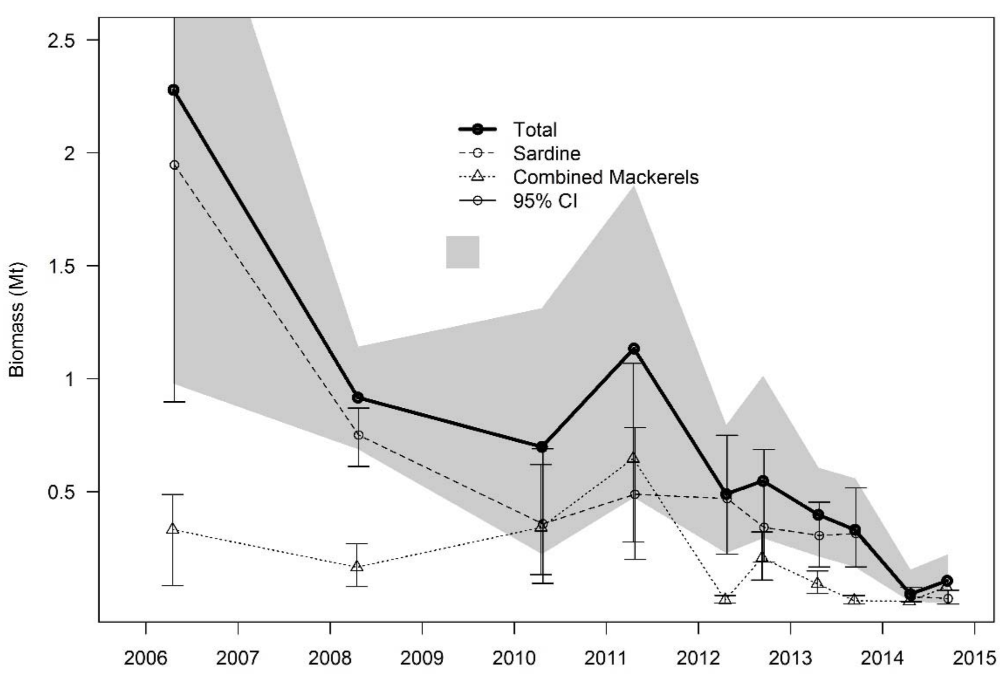

Figure 9. Time series of northern stock sardine, and mackerels (jack and Pacific mackerel combined), and their sum with respective 95% confidence intervals, as estimated from acoustic-trawl method (ATM) surveys (Zwolinski et al., 2015).

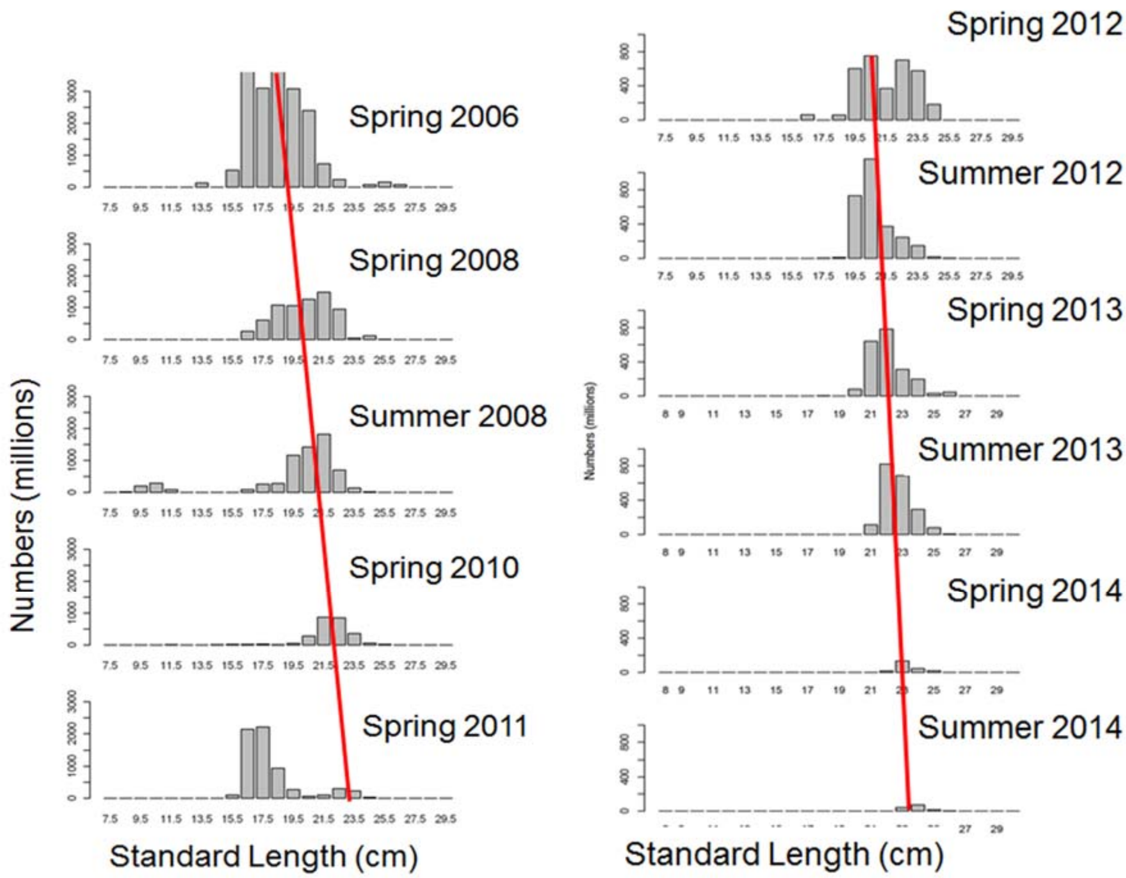

Figure 10. Density-weighted length distributions for northern stock sardine track the 2003-2005 (left) and 2010 cohorts (right) as stock abundance declined (e.g., Demer et al., 2013).

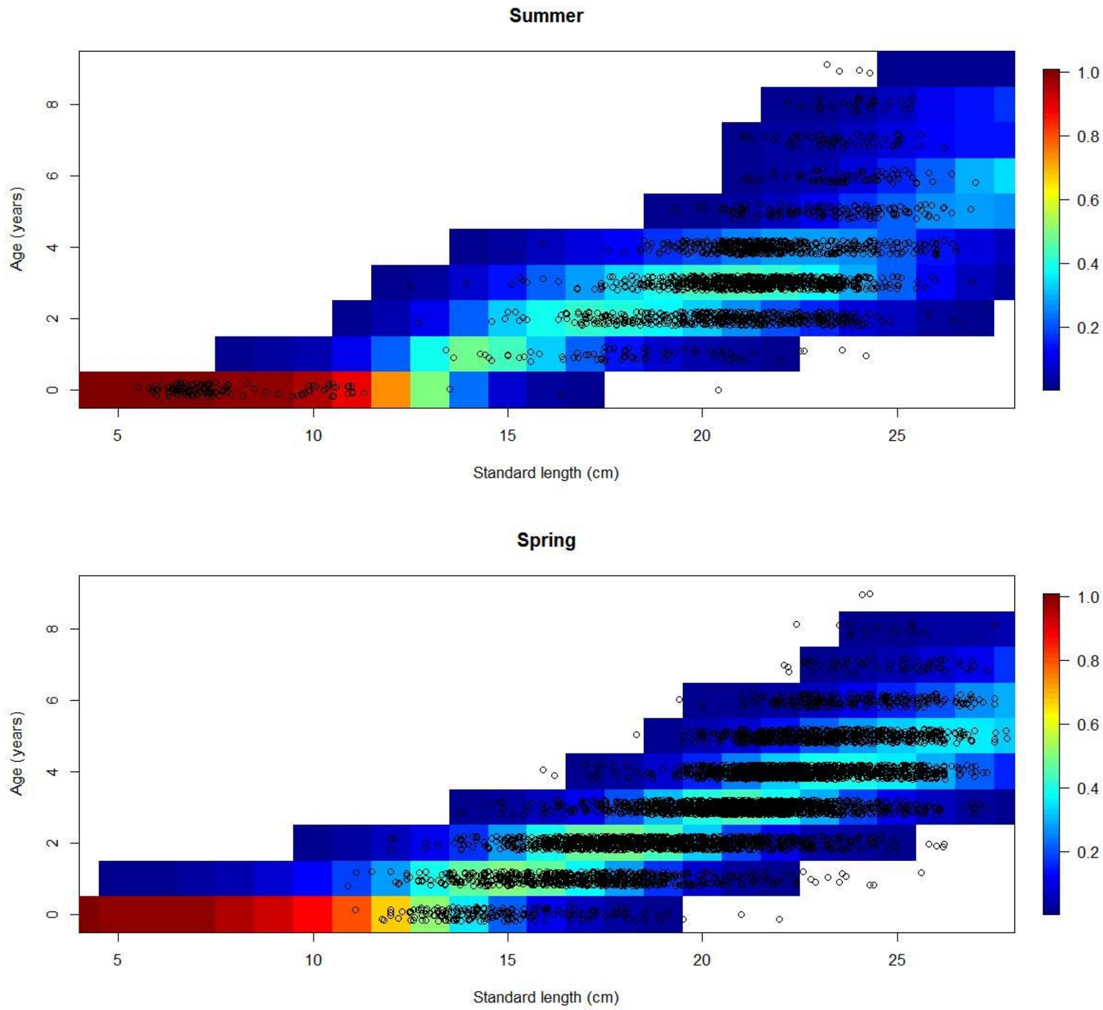

Figure 11. Age-length keys for northern stock sardine sampled during summer and spring ATM surveys, 2004-2016. Colors indicate probabilities from a multinomial surface fit (*multinom* in *nnet* for R; Venables and Ripley, 2002). Circles indicate model-fit data pairs (Hill et al., 2017).

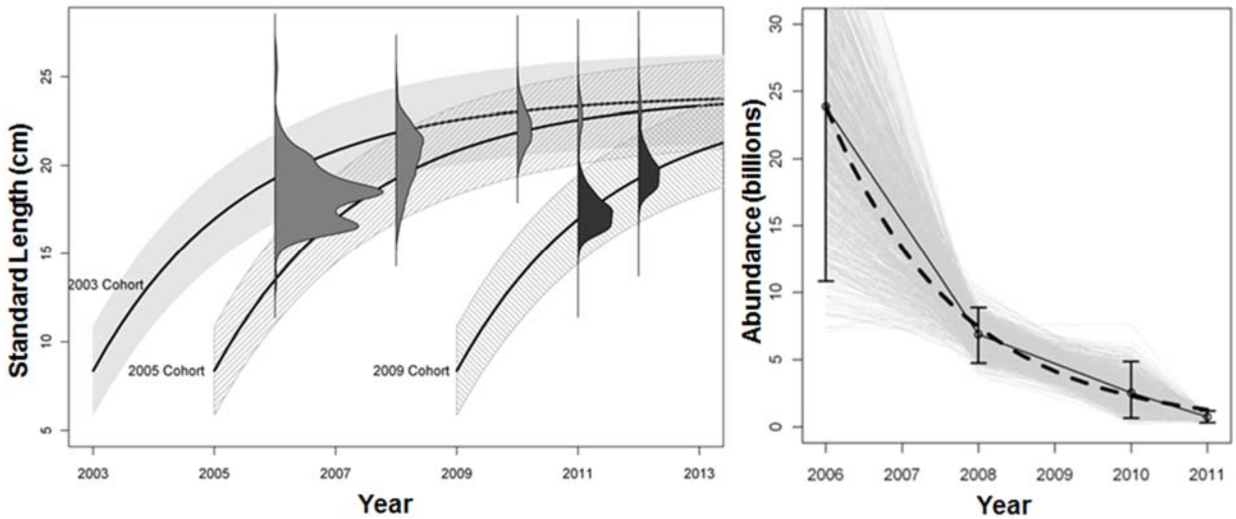

Figure 12. Accounting for growth and fishing mortality, time series of abundance by length provide estimates of natural mortality for a closed "meta-cohort". For the 2003, 2004, and 2005, year-classes, the mean natural mortality for the northern stock of sardine was ~0.52. Larger values are estimated at beginning and end of each cohort (Zwolinski and Demer, 2013). Natural mortality is estimated to be 0.6 in the 2017 assessment (Hill et al., 2017).

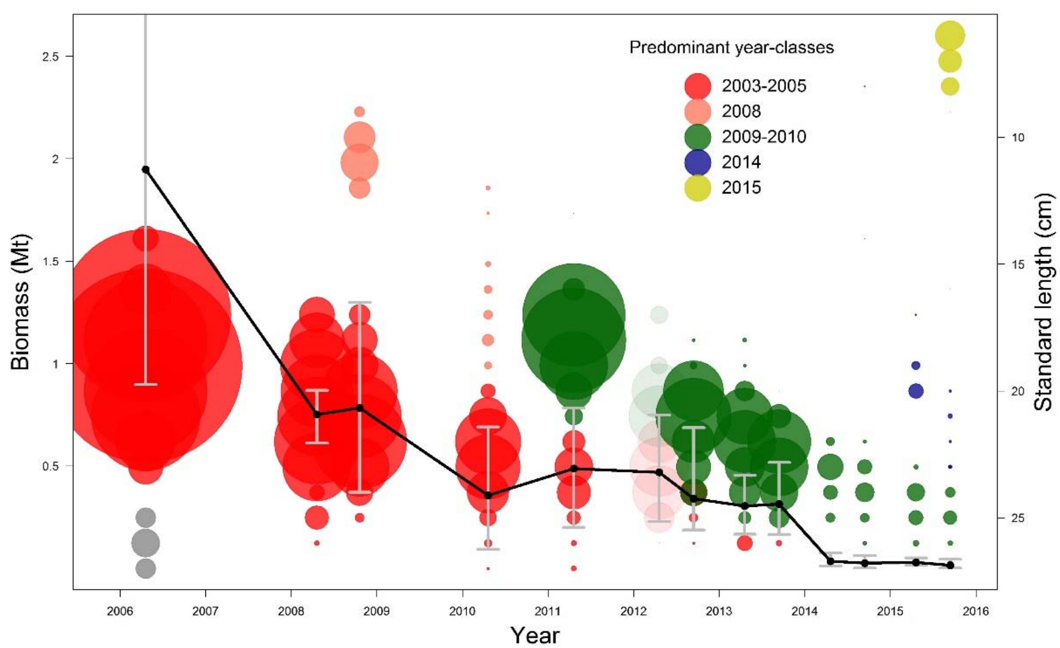

Figure 13. Time series of biomass and density-weighted lengths for the northern stock of sardine indicates that the population was dominated by the 2003-2005 cohort between 2006 and 2010; and the 2009-2010 cohort from 2011 through 2015. Consistent estimates result from spring and summer surveys in the same years (2008, 2012, 2013, 2014, and 2015).

5. Measurement bias

5.1. Fish nearshore and near-surface, and avoiding the vessel

During spring, northern stock sardine are typically farther south, offshore, and deeper compared to summer (**Figs 8 and 14**; Cutter and Demer, 2008), so the potential measurement biases are seasonally different. During spring, a portion of the stock may be south of the survey area, but the adult sardine within the survey area are sampled. During summer, a portion of the stock may be outside of the survey area, to the north and nearshore, and some may be under sampled due to their proximity to the sea-surface or reaction to the survey vessel. Therefore, surveys conducted during both spring and summer of the same year provide two largely independent estimates of the sardine stock abundance (**Fig. 13**; Demer et al., 2012; Zwolinski et al., 2014). The independent estimates validate the estimated sampling variance and provide information to judge the magnitudes of these potential sampling biases.

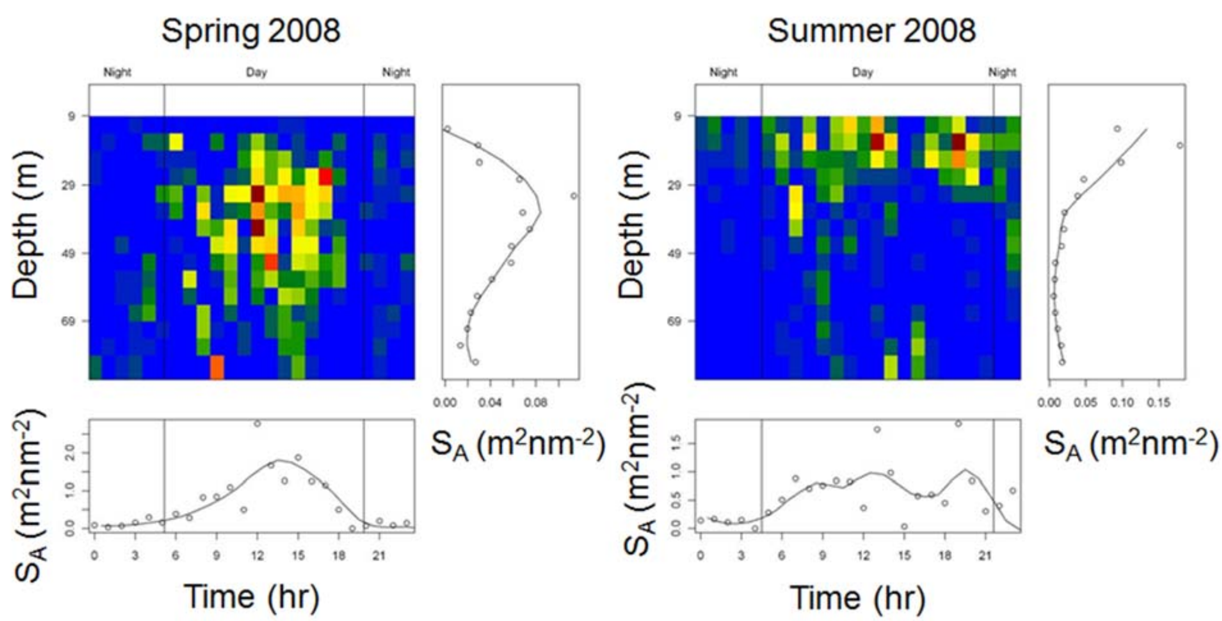

Figure 14. Example CPS backscatter from 2008 surveys averaged over 5-m depth and 1-hr time bins indicate that the fish are deeper in spring when they are farther offshore to spawn (left), compared to summer when they are closer to shore to feed (right).

Throughout the ATM time series, the summer-survey estimates of Pacific sardine biomasses and length distributions are not significantly different from the prior spring-survey estimates (**Fig. 13**), indicating that the potential biases resulting from sardine outside the survey area, near the shore and surface, or avoiding the vessel and trawl, are insignificant (Demer et al., 2012; Zwolinski et al., 2014). Also, the results of a nearshore fishing-vessel survey during the summer 2017 ATM survey (Stierhoff et al., 2018) and annual aerial surveys by the California Department of Fish and Wildlife (e.g., Lynn et al., 2014) corroborate this conclusion.

5.2. Echo classification and target strength estimation

Generally, the two principal sources of bias in ATM surveys are echo classification and *TS* estimation (e.g., Demer, 2004; Simmonds and MacLennan, 2005). These potential biases may be positive or negative. In statistical stock assessments of the northern stock of sardine, the ATM estimates have a catchability (Q) either set to 1 (Hill et al., 2012; Hill et al., 2014; Hill et al., 2015; Hill et al., 2016) or estimated to be ~1 (Hill et al., 2017), which indicate that the measurement and sampling biases are negligible. Nevertheless, research to refine methods for echo classification and *TS* estimation for the various CPS is ongoing.

6. Acknowledgements

The authors greatly appreciate that the acoustic-trawl method surveys require an enormous effort by multiple groups of people, particularly the trawl team (Bev Macewicz, David Griffith, Sue Manion, Amy Hays, Bill Watson, Noelle Bowlin, Sherri Charter, Brian Overcash, and others); the officers and crews of NOAA ships *David Starr Jordan*, *Bell M. Shimada*, and *Reuben Lasker*; and the Fisheries Resources Division administrative staff. Furthermore, the authors acknowledge that the methods used are the culmination of more than a half century of development efforts from numerous researchers from around the globe.

7. References

Bakun, A., and Parrish, R. H. 1982. Turbulence, transport, and pelagic fish in the California and Peru current systems. California Cooperative Oceanic Fisheries Investigations Reports, 23: 99-112.

Barange, M., Hampton, I., and Soule, M. 1996. Empirical determination of in situ target strengths of three loosely aggregated pelagic fish species. Ices Journal of Marine Science, 53: 225-232.

Conti, S. G., and Demer, D. A. 2003. Wide-bandwidth acoustical characterization of anchovy and sardine from reverberation measurements in an echoic tank. Ices Journal of Marine Science, 60: 617-624.

Cutter, G. R., Renfree, J. S., Cox, M. J., Brierley, A. S., and Demer, D. A. 2009. Modelling three-dimensional directivity of sound scattering by Antarctic krill: progress towards biomass estimation using multibeam sonar. Ices Journal of Marine Science, 66: 1245-1251.

Cutter Jr., G. R., and Demer, D. A. 2008. California current ecosystem survey 2006. Acoustic cruise reports for NOAA *FSV Oscar Dyson* and NOAA *FRV David Starr Jordan*. NOAA Technical Memorandum NMFS-SWFSC-, 415: 98pp.

Demer, D., Berger, L., Bernasconi, M., Bethke, E., Boswell, K., Chu, D., Domokos, R., et al. 2015. Calibration of acoustic instruments. ICES Cooperative Research Report, 326: 133.

Demer, D. A. 2004. An estimate of error for the CCAMLR 2000 survey estimate of krill biomass. Deep-Sea Research Part Ii-Topical Studies in Oceanography, 51: 1237-1251.

Demer, D. A., Cutter, G. R., Renfree, J. S., and Butler, J. L. 2009. A statistical-spectral method for echo classification. Ices Journal of Marine Science, 66: 1081-1090.

Demer, D. A., and Zwolinski, J. P. 2017. A method to Consistently Approach the Target Total Fishing Fraction of Pacific sardine and other Internationally Exploited Fish Stocks. North American Journal of Fisheries Management.

Demer, D. A., Zwolinski, J. P., Byers, K., Cutter Jr., G. R., Renfree, J. S., Sessions, S. T., and Macewicz, B. J. 2012. Seasonal migration of Pacific sardine (*Sardinops sagax*) in the California Current ecosystem: prediction and empirical confirmation. Fishery Bulletin, 110: 52-70.

Demer, D. A., Zwolinski, J. P., Cutter Jr., G. R., Byers, K. A., Macewicz, B. J., and Hill, K. 2013. Sampling selectivity in acoustic-trawl surveys of Pacific sardine (*Sardinops sagax*) biomass and length distribution. Ices Journal of Marine Science, 70: 1369-1377.

Dotson, R. C., Griffith, D. A., King, D. L., and Emmett, R. L. 2010. Evaluation of a marine mammal excluder device (mmed) for a Nordic 264 midwater rope trawl. NOAA Technical Memorandum NMFS, NOAA-TM-NMFS-SWFSC-455: 14.

Efron, B. 1981. Nonparametric standard errors and confidence intervals. The Canadian Journal of Statistics, 9: 139-172.

Fry Jr., D. H., and Roedel, P. M. 1949. Tagging experiments on the Pacific mackerel (*Pneumatophorus diego*) 73.

Hill, K., Crone, P., Dorval, E., and Macewicz, B. J. 2016. Assessment of the Pacific sardine resource in 2016 for U.S.A. management in 2016-17. US Department of Commerce. NOAA Technical Memorandum NMFS-SWFSC-562: 184 p.

Hill, K., Crone, P., and Zwolinski, J. P. 2017. Assessment of the Pacific Sardine resource in 2017 for U.S. management in 2017-18. US Department of Commerce. NOAA Technical Memorandum NMFS-SWFSC-576. 262 pp.

Hill, K., Crone, P. R., Demer, D., Zwolinski, J. P., Dorval, E., and Macewicz, B. J. 2014. Assessment of the Pacific sardine resource in 2014 for U.S.A. management in 2014-15. Pacific Fishery Management Council, April 2014 Briefing Book, Agenda Item H.1.b, Portland, Oregon.: 182 p.

Hill, K., Crone, P. R., Lo, N. C. H., Demer, D. A., Zwolinski, J. P., and Macewicz, B. J. 2012. Assessment of the Pacific sardine resource in 2012 for U.S. Management in 2013. Pacific Sardine Assessment Update Report, Agenda Item G.3.b. Supplemental Attachment 1: 51 pp.

Hill, K. T., Crone, P. R., Dorval, E., and Macewicz, B. J. 2015. Assessment of the Pacific Sardine Resource in 2015 for U.S.A. Management in 2015-16.

Johannesson, K. A., and Mitson, R. B. 1983. Fisheries Acoustics - A Practical Manual for Aquatic Biomass Estimation. 240. 249 pp.

Kang, D., Cho, S., Lee, C., Myoung, J. G., and Na, J. 2009. Ex situ target-strength measurements of Japanese anchovy (Engraulis japonicus) in the coastal Northwest Pacific. Ices Journal of Marine Science, 66: 1219-1224.

Kim, H. J., Miller, A. J., Neilson, D. J., and McGowan, J. A. 2005. Decadal variations of Mixed Layer Depth and biological response in the southern California current. *In* Sixth Conference on Coastal Atmospheric and Oceanic Prediction and Processes. San Diego.

Lo, N. C. H., Macewicz, B. J., and Griffith, D. A. 2009. Spawning Biomass of Pacific Sardine (*Sardinops sagax*) of U.S. in 2009. NOAA Technical Memorandum NMFS-SWFSC-449: 31pp.

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

Love, M. S. 1996. Probably more than you want to know about the fishes of the Pacific Coast*,* Really Big Press, Santa Barbara, CA.
Lynn, K., Porzio, D., and Kesaris, A. 2014. Aerial sardine surveys in the Southern California Bight. California Fish and Game, 100: 260-275.
MacLennan, D. N., Fernandes, P. G., and Dalen, J. 2002. A consistent approach to definitions and symbols in fisheries acoustics. Ices Journal of Marine Science, 59: 365-369.
Mais, K. F. 1974. Pelagic fish surveys in the California Current*,* State of California, Resources Agency, Dept. of Fish and Game, Sacramento. 79 p. pp.
Ona, E. 2003. An expanded target-strength relationship for herring. Ices Journal of Marine Science, 60: 493-499.
Peña, H. 2008. In situ target-strength measurements of Chilean jack mackerel (Trachurus symmetricus murphyi) collected with a scientific echosounder installed on a fishing vessel. Ices Journal of Marine Science, 65: 594-604.
Polovina, J. J., Howell, E., Kobayashi, D. R., and Seki, M. P. 2001. The transition zone chlorophyll front, a dynamic global feature defining migration and forage habitat for marine resources. Progress in Oceanography, 49: 469-483.
Renfree, J. S., and Demer, D. A. 2016. Optimizing transmit interval and logging range while avoiding aliased seabed echoes. Ices Journal of Marine Science, 73: 1955-1964.
Renfree, J. S., Hayes, S. A., and Demer, D. A. 2009. Sound-scattering spectra of steelhead (*Oncorhynchus mykiss*), coho (*O. kisutch*), and Chinook (*O. tshawytscha*) salmonids. Ices Journal of Marine Science, 66: 1091-1099.
Simmonds, E. J., and Fryer, R. J. 1996. Which Are Better, Random or Systematic Acoustic Surveys? A Simulation Using North Sea Herring as an Example. Ices Journal of Marine Science, 53: 39-50.
Simmonds, E. J., and MacLennan, D. N. 2005. Fisheries Acoustics: Theory and Practice*,* Blackwell, Oxford. 456 pp.
Simmonds, E. J., Williamson, N. J., Gerlotto, F., and Aglen, A. 1992. Acoustic Survey Design and Analysis Procedures: A Comprehensive Review of Good Practice. ICES Cooperative Research Report, 187: 1-127.
Stierhoff, K. L., Zwolinski, J. P., Renfree, J. S., and Demer, D. A. 2018. Report On The Collection Of Data During The Summer 2017 California Current Ecosystem Survey (1706RL), 19 June To 11 August 2017, Conducted Aboard Fisheries Survey Vessel Reuben Lasker. NOAA Technical Memorandum NMFS-SWFSC-593.
Venables, W. N., and Ripley, B. D. 2002. Modern Applied Statistics with S*,* Springer-Verlag, New York.
Zhao, X. Y., Wang, Y., and Dai, F. Q. 2008. Depth-dependent target strength of anchovy (Engraulis japonicus) measured in situ. Ices Journal of Marine Science, 65: 882-888.
Zwolinski, J. P., and Demer, D. A. 2012. A cold oceanographic regime with high exploitation rates in the Northeast Pacific forecasts a collapse of the sardine stock. Proceedings of the National Academy of Sciences of the United States of America, 109: 4175-4180.
Zwolinski, J. P., and Demer, D. A. 2013. Measurements of natural mortality for Pacific sardine (*Sardinops sagax*). Ices Journal of Marine Science, 70: 1408-1415.
Zwolinski, J. P., and Demer, D. A. 2014. Environmental and parental control of Pacific sardine (*Sardinops sagax*) recruitment. Ices Journal of Marine Science, 71: 2198-2207.

Zwolinski, J. P., and Demer, D. A. submitted. Environmental dependence of Pacific sardine recruitment – reexamining Zwolinski and Demer (2014) Ices Journal of Marine Science.

Zwolinski, J. P., Demer, D. A., Byers, K. A., Cutter, G. R., Renfree, J. S., Sessions, S. T., and Macewicz, B. J. 2012. Distributions and abundances of Pacific sardine (*Sardinops sagax*) and other pelagic fishes in the California Current ecosystem during spring 2006, 2008, and 2010, estimated from acoustic-trawl surveys. Fishery Bulletin, 110: 110-122.

Zwolinski, J. P., Demer, D. A., Cutter Jr., G. R., Stierhoff, K., and Macewicz, B. J. 2014. Building on Fisheries Acoustics for Marine Ecosystem Surveys. Oceanography, 27: 68-79.

Zwolinski, J. P., Demer, D. A., Macewicz, B. J., Mau, S., Murfin, D., Palance, D., Renfree, J. S., Sessions, T. S., Stierhoff, K. S. 2017. Distribution, biomass and demography of the central-stock of Northern Anchovy during summer 2016, estimated from acoustic-trawl sampling NOAA Technical Memorandum NMFS-SWFSC-572.

Zwolinski, J. P., Emmett, R. L., and Demer, D. A. 2011. Predicting habitat to optimize sampling of Pacific sardine (*Sardinops sagax*). Ices Journal of Marine Science, 68: 867-879.