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

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Abstract—The abundances and distributions of coastal pelagic fish species in the California Current Ecosystem from San Diego to southern Vancouver Island, were estimated from combined acoustic and trawl surveys conducted in the spring of 2006, 2008, and 2010. Pacific sardine (*Sardinops sagax*), jack mackerel (*Trachurus symmetricus*), and Pacific mackerel (*Scomber japonicus*) were the dominant coastal pelagic fish species, in that order. Northern anchovy (*Engraulis mordax*) and Pacific herring (*Clupea pallasii*) were sampled only sporadically and therefore estimates for these species were unreliable. The estimates of sardine biomass compared well with those of the annual assessments and confirmed a declining trajectory of the "northern stock" since 2006. During the sampling period, the biomass of jack mackerel was stable or increasing, and that of Pacific mackerel was low and variable. The uncertainties in these estimates are mostly the result of spatial patchiness which increased from sardine to mackerels to anchovy and herring. Future surveys of coastal pelagic fish species in the California Current Ecosystem should benefit from adaptive sampling based on modeled habitat; increased echosounder and trawl sampling, particularly for the most patchy and nearshore species; and directed-trawl sampling for improved species identification and estimations of their acoustic target strength.

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The California Current Ecosystem (CCE) spans the west coast of North America (GLOBEC, 1992). As in most upwelling ecosystems, the CCE has high primary and secondary productivity and consequently high biomasses of lower- and middle-trophic–level species (Fréon et al., 2009). Four coastal pelagic fish species (CPS) appear to sequentially dominate the epipelagic fish biomass in the CCE: Pacific sardine (*Sardinops sagax*), hereafter sardine; jack mackerel (*Trachurus symmetricus*); Pacific mackerel (*Scomber japonicus*); and northern anchovy (*Engraulis mordax*), hereafter anchovy (MacCall, 1996; Mason, 2004). Sardine dominated in the first half of the 20th century, then declined precipitously and the stock and the fishery collapsed. Jack mackerel were abundant in the 1950s, followed by anchovy in the 1960s and 1970s, and Pacific mackerel in the 1980s. Sardine returned to dominance during the following two decades (Mason, 2004; Moser et al., 2001). These alternations may be driven by natural cycles in the climate and ocean conditions (Chavez et al., 2003) and are perhaps accentuated by fishing pressure (MacCall, 1976; Radovich, 1982).

The distributions of these CPS in the CCE depend on their total abundances, ages, and the season. For example, when the "northern stock" of sardine is large, the older fish can be found offshore of southern and central California during spring spawning; and then nearshore off Oregon, Washington, and Vancouver Island during summer feeding (Clark and Janssen Jr., 1945; Lo et al., 2011; Zwolinski et al., 2011; Demer et al., 2012). In contrast, smaller sardine, age-0 and age-1, rarely venture far from their recruitment areas.

Pacific mackerel are commonly found off southern California, and their distribution extends to southern Baja California (Parrish and MacCall, 1978). During 1980s to 1990s, when their stock abundance was high, Pacific mackerel were present off California and sustained a valuable fishery. Currently, the fishery for Pacific mackerel off the west coast of the United States (U.S.) is small. Although there is a paucity of information about the current size of the Pacific mackerel stock, and its spatial and age distributions, its biomass is thought to be low and mostly residing south of the U.S.–Mexico border

(Crone et al., 2009). Young Pacific and jack mackerel tend to reside in coastal waters and nearshore banks, whereas the older mackerel reside mostly offshore (MacCall and Stauffer, 1983). Pacific and jack mackerel may also migrate seasonally north–south, although not as far north as sardine (Demer et al., 2012).

When the anchovy stocks are low, they tend to remain in certain areas, e.g., in the Southern California Bight (SCB), Monterey Bay, and coastal regions off Oregon and Washington near river plumes. However, when the subpopulations of anchovy increase, their distributions expand to adjacent areas (Messersmith et al., 1969).

Off the U.S. west coast, the fisheries of the aforementioned species are regulated under the Pacific Fishery Management Council (PFMC) CPS management plan. Sardine and Pacific mackerel are "actively managed species," which means that they are regulated by the setting of annual quotas founded on periodic assessments of their populations. In contrast, jack mackerel and anchovy are "monitored species." Although, this status does not require formal assessment and the setting of quotas (which can be set by each state), knowledge of their dynamic stock biomasses is desirable because their exploitation rate and thus their management status may change.

Assessments of actively managed species rely on single-species models that combine catch-at-age statistics from the commercial and sport fisheries, and abundance and demographic information from fishery-independent surveys, when available (Crone et al., 2009; Hill et al., 2010). Although catches may indicate changes in the structure of the CPS community, they are not unbiased indicators of the state of the ecosystem (Pennington and Stromme, 1998; Cotter et al., 2009). This is due to landing data that are affected by both natural variability and market demand (Mason, 2004). For sardine, estimates of spawning-stock biomass (SSB) from surveys with the daily egg production method (DEPM; Lo et al., 2010) comprise the longest fishery-independent time-series. However, owing to uncertainties in the DEPM estimates of SSB, managers called for additional fisheries-independent abundance estimates to include in the stock assessment model (Hill et al., 2006). In response, an acoustic–trawl method (i.e., a method combining echosounder and trawl sampling) was developed and used to survey the abundances and distributions of the dominant CPS in the CCE (Demer et al., 2012).

Acoustic–trawl surveys, conducted periodically and synoptically over the scales of the stocks, can simultaneously provide biomass estimates of multiple actively managed and monitored species, accurately track their distributions and demographics, and provide estimates of recruitment and mortality. Data from these multispecies surveys may be used to monitor epipelagic communities, and provide information for precautionary and ecosystem approaches to the management of exploited and emerging fisheries (FAO, 2003; Rice et al., 2005).

Our goal was to demonstrate the successful use of an acoustic–trawl method to monitor the distributions and abundances of multiple epipelagic fish species in the CCE. Estimates are derived for the most abundant species, i.e., sardine, jack mackerel, and Pacific mackerel. However, the emphasis is on sardine, the dominant, actively managed CPS off the west coast of the United States during these surveys. The resulting estimates of their abundances and demographics are compared to those of the most recent assessment (Hill et al., 2010).

Methods

Three acoustic–trawl surveys of CPS were conducted off the west coast of the United States during April to May of 2006, 2008, and 2010. The surveys were conducted from the U.S. National Oceanic and Atmospheric Administration (NOAA) research vessels *Oscar Dyson* (2006), *David Starr Jordan* (2008), and *Miller Freeman* (2010), and a contracted fishing vessel *Frosti* (2010). The surveys extended south to the Mexican border, and north to the westernmost part of Vancouver Island, Canada, in 2006, and to the Strait of Juan de Fuca in 2008 and 2010 (Fig. 1). The survey transects extended to 250 nmi offshore, south of Point Conception, and to 140 nmi offshore, farther north. Transect spacing varied between 40 and 80 nmi, occasionally with denser sampling off southern California, which is the area of higher expected sardine biomass during the spring (Zwolinski et al., 2011).

Acoustic sampling

Measurements of volume backscattering strength (S_v; dB re 1 m^{-1}) and target strength (TS; dB re 1 m^2) were made by using calibrated echosounders (Simrad EK60, Kongsberg, Norway) configured with split-beam transducers, operating at 38, 70, 120, and 200 kHz (RV *David Starr Jordan* and FV *Frosti*), 18, 38, 70, 120, and 200 kHz (RV *Oscar Dyson*), and 18, 38, 120, and 200 kHz (RV *Miller Freeman*). The echosounder systems were calibrated immediately before the surveys with a 38.1-mm-diameter sphere made from tungsten carbide with 6% cobalt binder material (Foote, 1983). Throughout the surveys, pulses of 1024 µs were transmitted at 0.5-s intervals, except in 2006 when the pulse interval was 2 seconds. Transmit powers were 2000, 2000, 1000, 500, and 120 W at 18, 38, 70, 120, and 200 kHz, respectively (Demer et al., 2012). Received powers were sampled every 256 µs, indexed by time and geographic position, and recorded to at least 250-m range (500 m in 2006).

Trawl sampling

During the night, CPS tend to migrate closer to the sea surface and form loose aggregations (Cutter Jr. and Demer, 2008) facilitating capture and providing better estimates of the proportions of CPS in the area than estimates from directed daytime trawling. Each night during the survey, beginning 30 to 60 min after sunset, as many as four surface trawls were set to sample CPS for the pur-

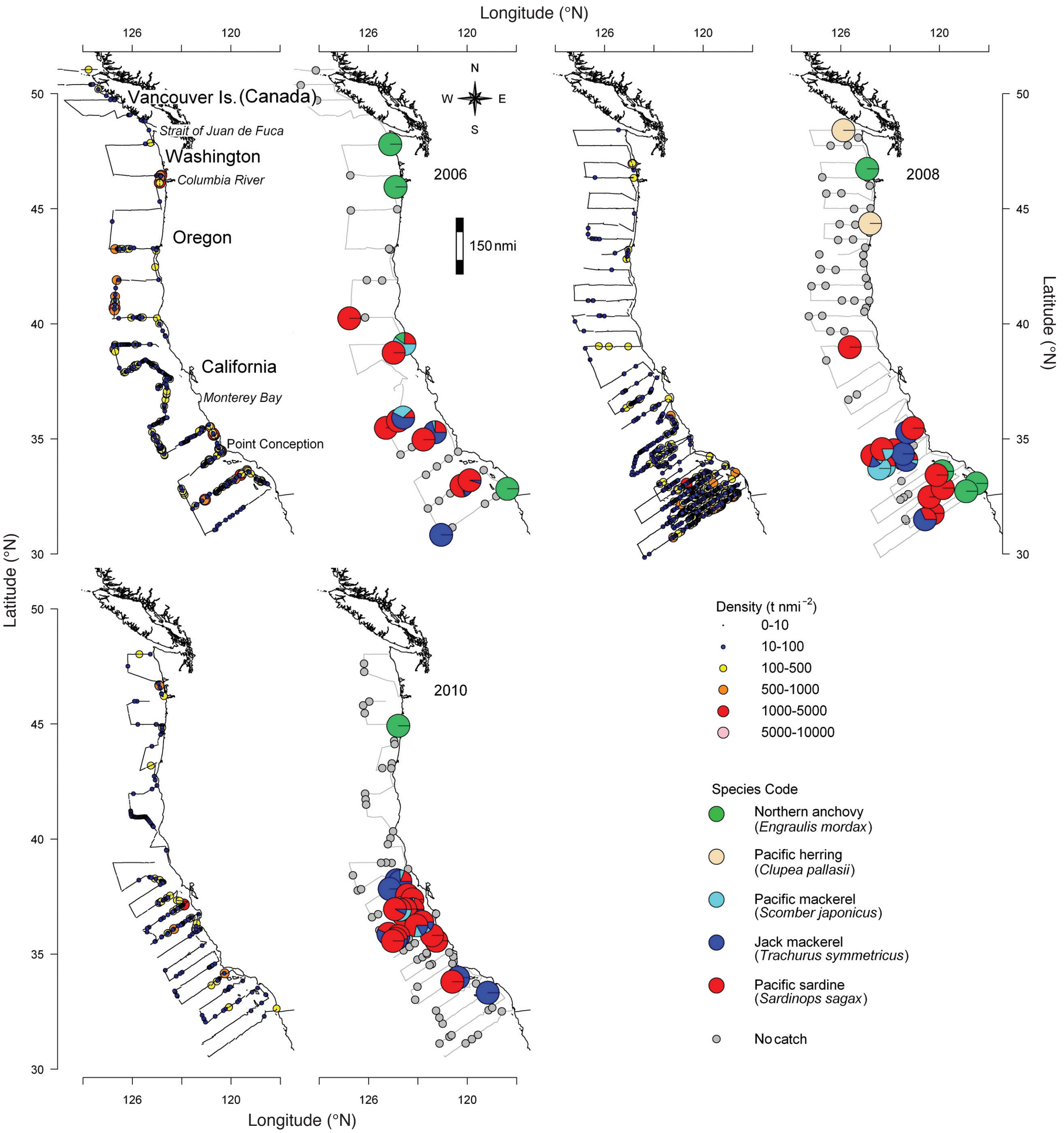

Figure 1

(Left panels) Distributions of biomass densities of acoustically detected coastal pelagic fish species (CPS) (sampling unit=10–70 m depth by 2-km trackline distance), from surveys in spring 2006, 2008, and 2010. (Right panels) Locations and compositions of catches that included at least one CPS specimen; and the locations of trawls with no CPS catch. For each trawl with CPS catch, the proportion of each CPS is represented by the proportion of the area in the circle.

poses of estimating species compositions and fish-length distributions. The trawl locations were generally distributed along the acoustic track, some in the vicinity of predetermined hydrographic stations. The trawl, a Nordic 264 (184 m long; with 24-m by 30-m mouth opening) with floats on the head rope, was towed at the surface at a nominal speed of 3.5 kn for 30 minutes. The trawl catches were sorted by species, counted, and weighed. Measures of standard length (SL; mm; sardine, anchovy, and Pacific herring (*Clupea pallasii*), hereafter herring), fork length (FL, mm; jack and Pacific mackerel), and total weight (W; g) were made of all individuals of each species if catches were less than 75 fish, or, otherwise, of a subsample of 50 fish. On four occasions during the 2010 survey aboard FV *Frosti*, the floats were removed and the net was set on midwater targets. The net was directed to the depth of schools with the aid of a Scanmar trawl eye net sounder (Scanmar AS, Åsgårdstrand, Norway). These trawls were largely unsuccessful as fish avoided the gear and catch numbers were low to none.

Data analysis

Echoes numerically classified as CPS, according to the multifrequency algorithm described in Demer et al. (2012), were integrated vertically from 3 m below the transducer to 70 m depth and were averaged horizontally over 100-m intervals along the survey track. The resulting nautical area scattering coefficients (s_A; m^2 nmi $^{-2}$) at 38 kHz were indexed in space and time. Because most pelagic fish schools disperse and ascend above the transducer depth during night (Cutter Jr. and Demer, 2008), the nighttime acoustic samples were considered negatively biased for CPS and where not used for abundance estimation. Cells sampled during the day, defined here as the time between nautical twilights, had their s_A apportioned to each target species on the basis of the proportion and sizes of the species in the nearest trawl (Demer et al., 2012).

Biomass and numerical densities were obtained from the species-apportioned s_A, as detailed in Demer et al. (2012), by using estimates of average target strength (*TS*; dB re 1 m^2 kg^{-1}; (Barange et al., 1996). Occasionally, echoes ascribed to CPS were not matched with CPS catches. These echoes were often semidemersal, i.e., in contact with the seabed, or in conditions unsuitable for CPS. Therefore, these echoes were likely from other swimbladdered fish species such as hake (also named Pacific whiting; *Merluccius productus*) or rockfishes (*Sebastes* spp.), which tend to reside deeper than CPS, particularly during the day (Dorn et al., 1994; Butler et al., 2003). These echoes, comprising a small fraction of the total s_A initially ascribed to CPS, were excluded from further analysis.

The spatial match between the acoustically detected CPS and the trawl catches was tested by resampling. First, the s_A attributed to CPS during daytime was averaged for spatial bins with various sizes, each centered on the locations of catches with CPS. These values represent the average s_A associated with CPS catches. Then, 1000 sets of points with equal number to those of the CPS catches were drawn randomly within the daytime transect track. The mean acoustic backscatter in the vicinity of those points represents the average s_A ascribed to CPS in the total survey field. The 95% confidence intervals (CI_{95}) for the average s_A of CPS were chosen from the resampled distribution according to the percentile method (Efron, 1981). Association between CPS catches and acoustically detected CPS is strongly supported when the s_A ascribed to CPS in the vicinity of CPS catches is above the confidence intervals.

The potential habitat of sardine in the CCE, defined here as the region expected to contain an average of 90% of all adult sardine (Zwolinski et al., 2011), was predicted for each survey period with a generalized additive model (GAM). The model is based on a 12-year time series of pump-sampled sardine-egg presence and satellite-sensed measurements of sea-surface temperature, chlorophyll-*a* concentration, and the gradient of sea-surface height. The distributions of sardine estimated from the acoustic–trawl surveys were visually compared to those of their potential habitat.

For each target species, the survey area was then stratified into one or two strata with comparable biomass densities and approximately equal transect spacing. To the north and south, the strata extended beyond the exterior transects by half of the intertransect distance. To the east and west, the strata were bounded by the coastline and by the offshore limits of the transects. Occasionally, the inshore and offshore limits were defined by lines parallel to the coast, by excluding large areas of zero densities and ensuring uniformity in the length of the transects within the strata. Mean biomass densities for each strata were obtained by a transect-length-weighted average of the mean transect densities, which is equivalent to the arithmetic mean of all integration cells in each strata. Total biomasses were estimated by multiplying the mean biomass densities by the areas of the respective strata and by summing across strata. Confidence interval (CI) and coefficient of variation (CV) values for total abundance were estimated from bootstrap resampling (Efron, 1981) of the mean biomass densities of the transect means, as described in Demer et al. (2012). Statistical independence between the transect means, required to provide unbiased estimates of variance, was verified for every species and strata through an autocorrelation analysis. Further details of the data processing are provided in Demer et al. (2012).

Sardine-length distributions were estimated by a weighted average of the length distributions from the individual trawls, by using as weights the sardine densities estimated with the nearest acoustic samples. The latter were obtained by converting s_A values into numerical densities with individual TS-to-length equations (Barange et al., 1996). Total sardine numbers were obtained by summing abundances across lengths. Because no new recruits were visible in the time series, the net instantaneous mortality rate of the stock was estimated by fitting an exponential-decay function to the measures of total sardine abundance versus time. For sardine, the only actively managed species distributed throughout most of the survey area, the survey estimates of abundance, demographics, and mortality were compared with those from the independent assessment.

Results

CPS distributions

The results from the multifrequency algorithm provided evidence that CPS were abundant and broadly distributed in 2006. Subsequently, their spatial distributions (Fig. 1) and average s_A values decreased by approximately 70% (Fig. 2). Concurrently, the total area occupied by CPS decreased, but the densities of fewer CPS aggregations remained relatively constant.

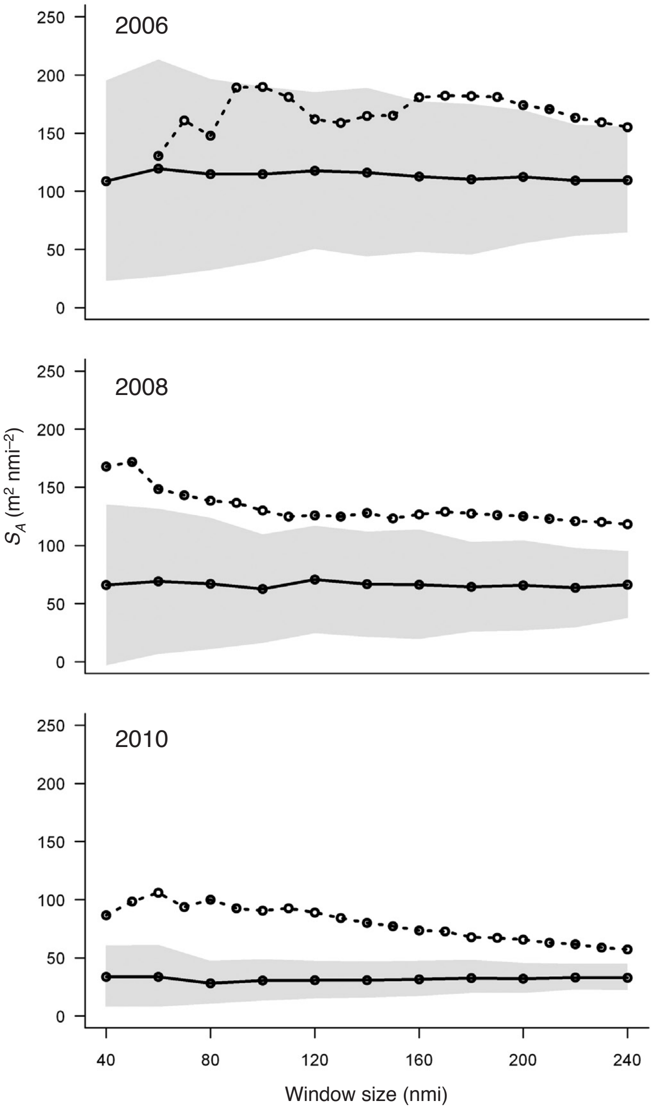

Figure 2

Nautical area scattering coefficient (s_A; m^2 nmi^{-2}) values, sampled during daytime, attributed to coastal pelagic fish species (CPS) in the vicinity of night-time CPS catches, for sampling windows with increasing sizes (dashed line). The solid line represents the mean s_A attributed to CPS for any set of points randomly selected from the survey track with size equal to that of the number of catches with CPS. The shaded area represents the 95% confidence interval of the mean s_A attributed to CPS calculated through resampling. The s_A of CPS in the vicinity of CPS catches is significantly higher than the average, except for 2006, in which CPS were ubiquitous in the survey area. The average s_A for the entire survey area decreased by 70% in the study period.

The acoustically detected CPS during daytime were well matched spatially to the presence of CPS in the night-trawl catches (Fig. 1). CPS catches were located in regions with significantly higher acoustically detected CPS than the overall average, except for 2006, when acoustically detected CPS were abundant throughout the study area and the number of trawls was the lowest (Fig. 2). Therefore, both trawl sampling at night and acoustic sampling during day are effective detectors of CPS when they occur in the same areas. Echoes that were acoustically ascribed to CPS but were not matched with CPS catches comprised a very small fraction of the total $s_{A.}$ (Fig. 1) and were excluded from further analysis.

Sardine were caught offshore of central and southern California, partially overlapping with catches of other species, especially jack and Pacific mackerel (Fig. 1). Sixty-eight percent of the catches containing CPS contained sardine (Table 1). This was the highest "species proportion." The weight of the total sardine catch was also the highest of the CPS catches, except in 2008 when two catches of anchovy totaled more than 500 kg. Sardine ranged in SL between 11 and 27 cm and averaged approximately 21 cm (Table 2). The potential sardine habitat encompassed the area containing echoes attributed to sardine (Fig. 3). In 2006, almost the entire potential sardine habitat was surveyed, but some sardine may have resided to the south of the sampling area (Fig. 3). At that time, sardine were evenly distributed in high densities throughout the potential habitat, allowing the use of a single stratum for estimation. In contrast, in 2008, sardine occupied roughly one fourth of the north–south extent of the survey area, and were concentrated in the southern region of their potential habitat. The potential habitat extended beyond the survey area, mainly offshore, but sardine densities diminished gradually and completely towards the survey-area boundary, indicating that the stock was surveyed entirely. For the 2008 survey, two strata were defined and used for the biomass estimations. In 2010, the estimated sardine densities were again low or null close to the survey boundaries, indicating that most or all of the sardine stock was sampled. In contrast to spring 2008, in 2010, the potential sardine habitat was located farther north and closer to the shore, mainly off San Francisco and Monterey Bay. A single stratum was used for the biomass estimation.

Jack mackerel were common in the trawl catches during each of the surveys (Fig. 1), accounting for the second largest species proportion, and the third largest catches (Table 1). Jack mackerel were the largest of the CPS, some more than 50 cm FL (Table 2). The estimated distributions of jack mackerel were normally more restricted than those of sardine (Fig. 4). In 2006, a single stratum comprising six transects appeared to encompass the entire population of jack mackerel that occupied the southern extension of the survey area. In 2008, jack mackerel again spanned the southern portion of the survey area. In 2010, they were distributed off southern and central California, but closer inshore than in previous years. Similar to sardine, the core of the jack mackerel distribution in 2010 appeared to be off San Francisco and Monterey Bay, with lower abundances to the south.

The trawl catches show Pacific mackerel were mainly mixed with sardine and jack mackerel (Fig. 1) and occurred in lower proportions and numbers (Table 1). Their sizes were between those of sardine and jack mackerel (Table 2). In the three surveys, Pacific mackerel occupied only a fraction of the area occupied by sardine and jack mackerel and were generally found in lower densities (Fig. 5).

Anchovy and herring occurred in isolation in coastal waters off Oregon and Washington, and anchovy were mapped north of Monterey Bay and in the SCB, indicating a higher geographical fidelity than the other species (Fig. 1). Both species were caught in a small number of samples and their catch biomasses were considerably lower than those for sardine and jack mackerel (Table 1), except in 2008, when two catches each yielded more than 500 kg of anchovy. Their apparently low abundances and patchy distributions precluded accurate estimations of their distributions and abundances.

CPS abundances and estimation errors

Transect-mean biomass densities for sardine, jack mackerel, and Pacific mackerel showed no intertransect correlation, thus enabling the use of bootstrap to estimate the variance of the estimates and respective confidence intervals. Sardine were the most abundant CPS throughout the series, ranging from 51% to 85% of the estimated CPS biomass (Table 3). The CV values ranged between 9.2% in 2008, when sardine were evenly distributed over a relatively small region, to 43.3% in 2010, when sardine abundance was the

Table 1

Number (No.) of trawl catches with each coastal pelagic fish species (CPS); their relative proportion (Prop.) in catches with CPS (excluding catches without CPS); total cumulative catch weight (Wt.; kg); and fraction of the combined CPS catch weight.

	Sardine (*Sardinops sagax*)			Jack mackerel (*Trachurus symmetricus*)			Pacific mackerel (*Scomber japonicus*)			Northern anchovy (*Engraulis mordax*)			Pacific herring (*Clupea pallasii*)		
Year	No.	Prop.	Wt. (fraction)	No.	Prop.	Wt. (fraction)	No.	Prop.	Wt. (fraction)	No.	Prop.	Wt. (fraction)	No.	Prop.	Wt. (fraction)
2006	10	0.71	44 (0.68)	5	0.36	9 (0.14)	3	0.21	7 (0.11)	6	0.43	5 (0.08)	0	0	0 (0)
2008	13	0.62	103.4 (0.15)	5	0.24	61 (0.09)	5	0.24	3 (0.004)	4	0.19	532 (0.75)	2	0.10	6 (0.009)
2010	19	0.73	276 (0.54)	15	0.58	217 (0.43)	7	0.27	13 (0.03)	1	0.04	1 (0.00)	0	0	0 (0)

Table 2

Range, mean, and standard deviation (SD) of fish length (SL [standard length]; FL [fork length]; cm) for coastal pelagic fish species caught during the night-time surface trawls. Data not available are indicated by NA.

	Pacific sardine (*Sardinops sagax*)		Jack mackerel (*Trachurus trachurus*)		Pacific mackerel (*Scomber japonicus*)		Northern anchovy (*Engraulis mordax*)		Pacific herring (*Clupea pallasii*)	
Year	SL range	Mean (SD)	FL range	Mean (SD)	FL range	Mean (SD)	SL range	Mean (SD)	SL range	Mean (SD)
2006	11.1–26.8	18.9 (1.8)	7.7–36.0	28.1 (5.3)	20.0–28.0	22.08 (1.6)	6.9–16.1	10.9 (2.4)	18	18 (0)
2008	16.3–25.9	21.2 (1.5)	28.0–58.0	39.6 (4.7)	27.5–34.7	31.9 (2.3)	10.7–4.8	12.5 (0.9)	16–18	17 (1.4)
2010	11.6–26.5	22.0 (1.5)	19.8–44.0	37.0 (4.3)	20.8–36.6	31.8 (3.2)	12.2–15.3	13.7 (0.8)	NA	NA

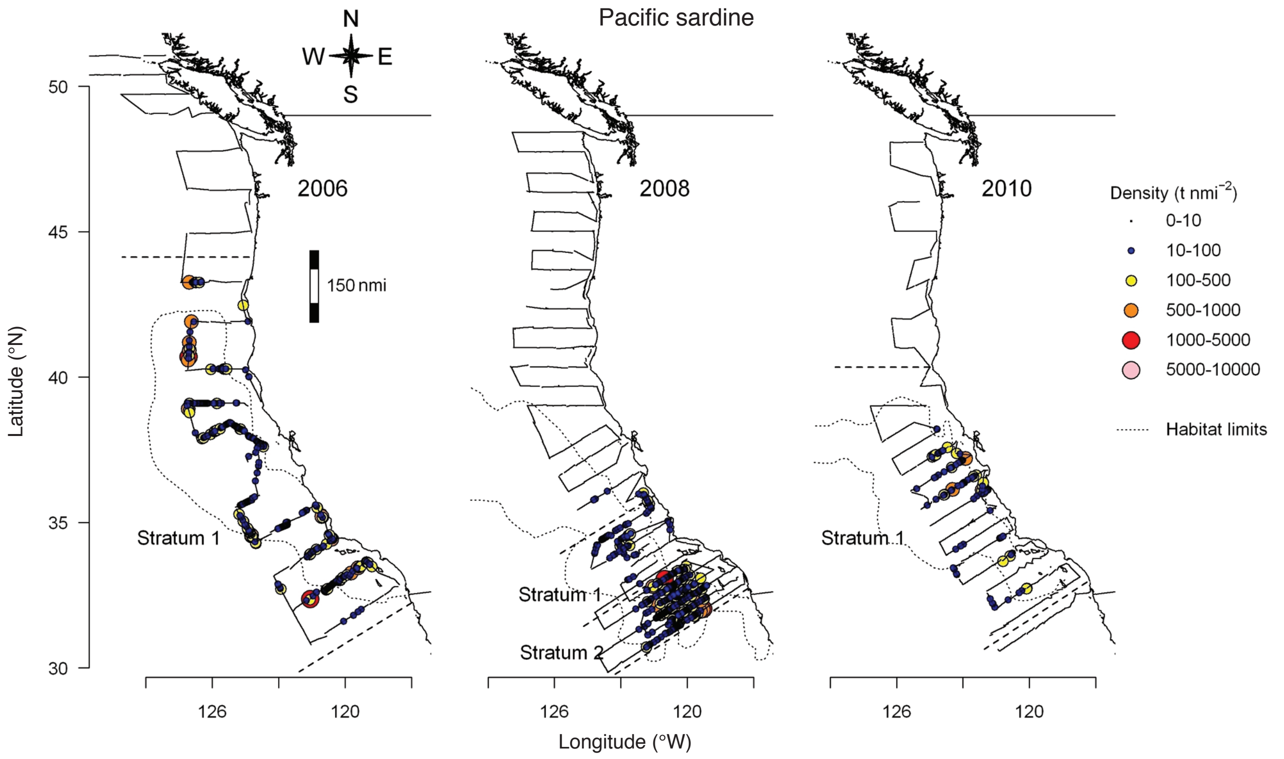

Figure 3

Pacific sardine (*Sardinops sagax*) biomass densities by year estimated by combining information from the acoustic and trawl samples. The northern and southern boundaries of the strata are shown (dashed lines). The boundaries of potential sardine habitat (dotted lines) were estimated with the model in Zwolinski et al. (2011).

Table 3

Estimates of biomass (million metric tons; Mt) for sardine (*Sardinops sagax*), jack mackerel (*Trachurus symmetricus*), and Pacific mackerel (*Scomber japonicus*), and their coefficient of variation (CV) and 95% confidence intervals (CI_{95}) values versus survey year and stratum (see Figs. 2–4).

Species	Spring surveys	Stratum	Biomass (Mt)	CV (%)	CI_{95} (Mt)
Pacific sardine (*Sardinops sagax*)	2006	1	1.947	30.4	0.897–3.139
	2008	1	0.047	45.8	0.017–0.104
		2	0.704	9.3	0.579–0.823
		1+2	0.751	9.2	0.611–0.870
	2010	1	0.357	43.3	0.094–0.690
Jack mackerel (*Trachurus symmetricus*)	2006	1	0.285	35.8	0.078–0.378
	2008	1	0.078	32.1	0.032–0.129
		2	0.069	47.5	0.019–0.140
		1+2	0.147	28.4	0.075–0.232
	2010	1	0.323	36.7	0.132–0.586
Pacific mackerel (*Scomber japonicus*)	2006	1	0.047	61.6	0.006–0.109
	2008	1	0.018	51.8	0.005–0.037
	2010	1	0.018	45.7	0.001–0.034

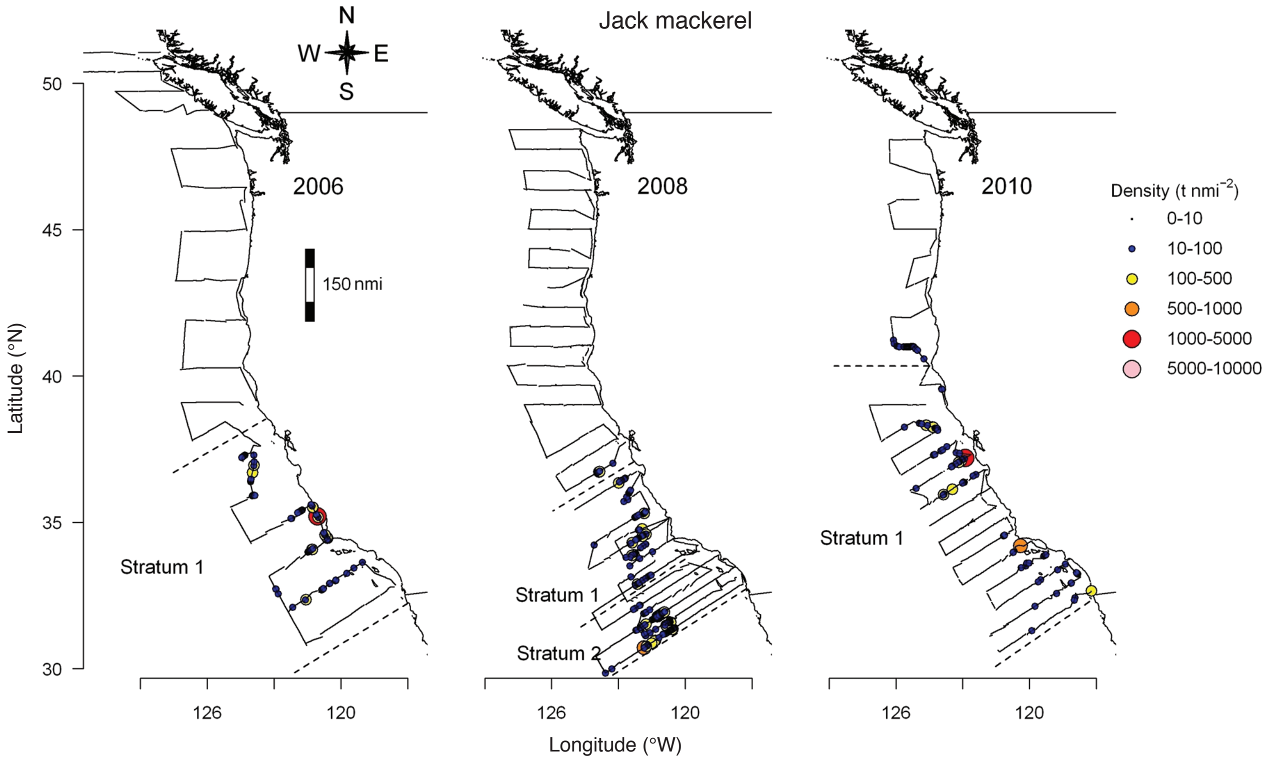

Figure 4

Jack mackerel (*Trachurus symmetricus*) biomass densities estimated by combining information from the acoustic and trawl samples. The northern and southern boundaries of the strata are shown (dashed lines).

lowest and the population was more dispersed. Sardine were distributed within their potential habitat and were generally bounded by it (Fig. 3). In 2006, sardine may have extended slightly beyond the survey limits (Fig. 3), but there was little potential sardine habitat beyond the survey boundary.

Sardine biomass declined monotonically by 80% between 2006 and 2010 (Fig. 6). In 2006 and 2010, the confidence intervals of the acoustic–trawl estimates of sardine biomass encompassed the biomass from the assessment. The length distributions estimated from the acoustic–trawl data matched well the higher mode of those from the assessment, which were derived from the length distributions from the fisheries landings (Fig. 7). However, the acoustic–trawl length distributions lacked age-0 and age-1 fish, i.e., fish less than 15 cm SL, present in the results of the model assessment. Based on the acoustic–trawl length distributions, there was evidence that the cohorts present in 2006 were severely depleted by 2010, and there has not been another strong recruitment (Fig. 7). The instantaneous mortality rate of the sardine population, estimated from the spring acoustic–trawl abundances and the summer 2008 estimate (Demer et al., 2012), was 0.56.

Jack mackerel were the second most abundant CPS (Table 3). Their CV values ranged from 28.4% to 36.7%. Generally, the population of jack mackerel appears to have been encompassed in the survey area. In 2008, however, their densities were high near the southern limit (Fig. 4). During the study period, jack mackerel biomass either increased or remained stable in the survey area, but smaller confidence intervals and CV values are needed to be more certain of change (Fig. 6).

Pacific mackerel, compared with sardine and jack mackerel, comprised a small fraction of the CPS biomass, and their CV values are high, resulting from their sparse and patchy distribution (Table 3). With low biomasses and high CV values, the trajectory of the stock size is uncertain (Fig. 6).

The numbers of anchovy and herring in the catches were too low to allow reliable estimations of their biomasses (Table 1; Fig. 1). Nevertheless, on the basis of the low number of catches with these species and the low acoustic backscatter in the vicinity of those catches, their biomasses were likely much lower than those of sardine, Pacific mackerel, and jack mackerel.

Discussion

Sardine were the most common and abundant CPS in the 2006–10 trawl catches, and the acoustic–trawl estimates

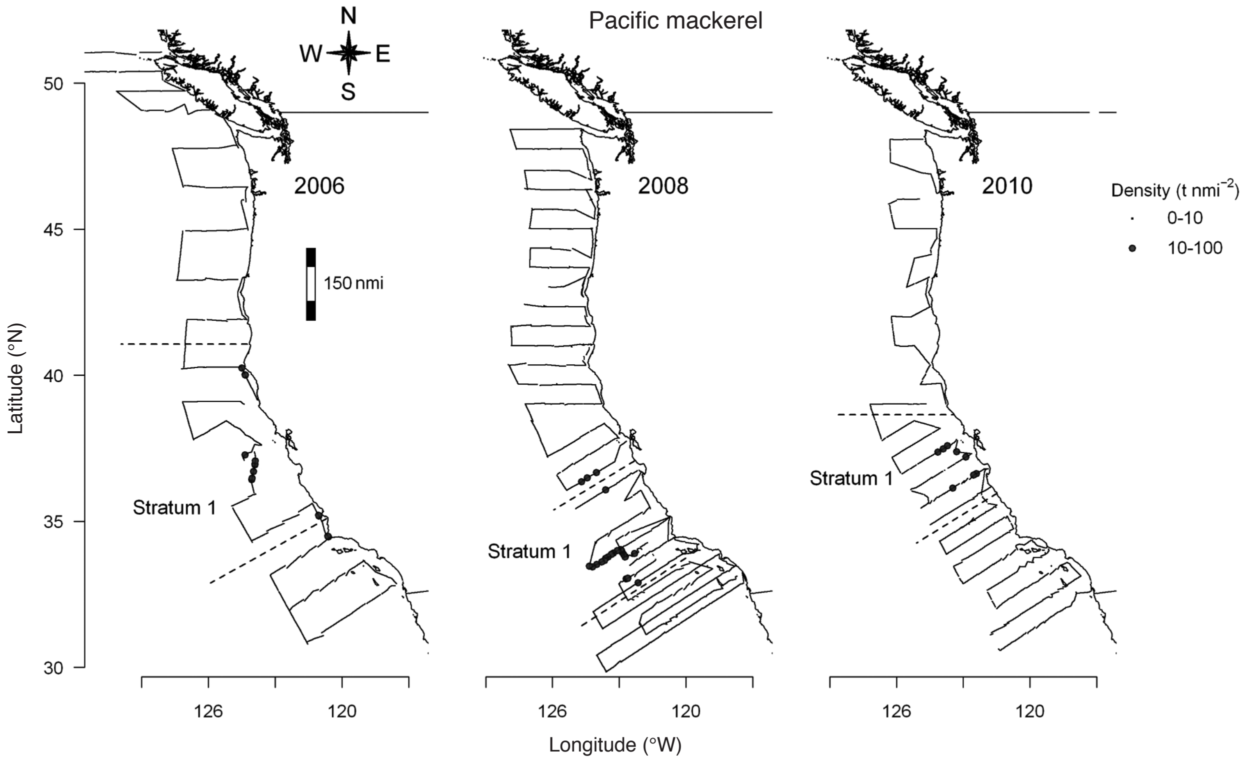

Figure 5

Pacific mackerel (*Scomber japonicus*) biomass densities estimated by combining information from the acoustic and trawl samples. The northern and southern boundaries of the strata are shown (dashed lines).

of their stock biomasses were high, but decreasing, with relatively low CV values (9% to 43%). Their distributions were in close agreement with the predictions of their potential habitat which, during spring, tends to be located off central and southern California (Zwolinski et al., 2011; Demer et al., 2012). Because the large majority of the sardine habitat was encompassed by the survey boundaries, sampling bias appears to be negligible. Acoustic estimates of sardine abundance compare well with those of the 2010 assessment but were higher than those of the DEPM (Fig. 6). Although these higher estimates may be attributed, in part, to the fact that the DEPM provides estimates only of the SSB and the acoustic–trawl surveys allow estimates of total sardine biomass, the discrepancy requires further analysis. Irrespective of the actual sardine biomass, all three time-series share a common, steadily decreasing trend since 2006. The rate of the decay of the sardine population (i.e., the net mortality rate) estimated at –0.56 year^{-1} (Fig. 6) is in close agreement to the summation of the natural mortality rate (–0.4 year^{-1}; corresponding to 33% of the population dying naturally each year) and the fishing mortality rate (–0.26 year^{-1}) estimated for 2010 (Hill et al., 2010).

The acoustic–trawl estimates of sardine demography differ from those of the assessment by the lack of age-0 and age-1 sardine. The latter were rarely caught in the survey trawls and consequently were not represented in the weighted-length distributions. This discrepancy may be related to the very patchy coastal distribution of the younger sardine that are mainly exploited in the California and Ensenada fisheries. Consequently, these fish may be over-represented in the landing statistics, which do not provide a biomass-density–weighted distribution, and are under-sampled in the acoustic–trawl surveys. However, because there is no evidence of small fish growing into the larger size classes during the 2006–10 period, it is more likely that the assessment model is confounded by a variable number of small sardine belonging to the "southern stock" (Félix-Uraga et al., 2005). Like the northern stock, the southern stock also migrates seasonally, and enters the Ensenada and occasionally the southern California fisheries during the summer (Clark and Janssen Jr., 1945; Félix-Uraga et al., 2005).

In the past, when the northern stock of sardine declined, jack mackerel increased rapidly in the CCE and were targeted by the purse-seine fishery (Smith and Moser, 2003; Mason, 2004). Currently, jack mackerel is a monitored species and its stock biomass is largely unknown. Thus, these acoustic–trawl survey results comprise the most comprehensive information on their distribution and abundance in the CCE and may be useful for managing future exploitation

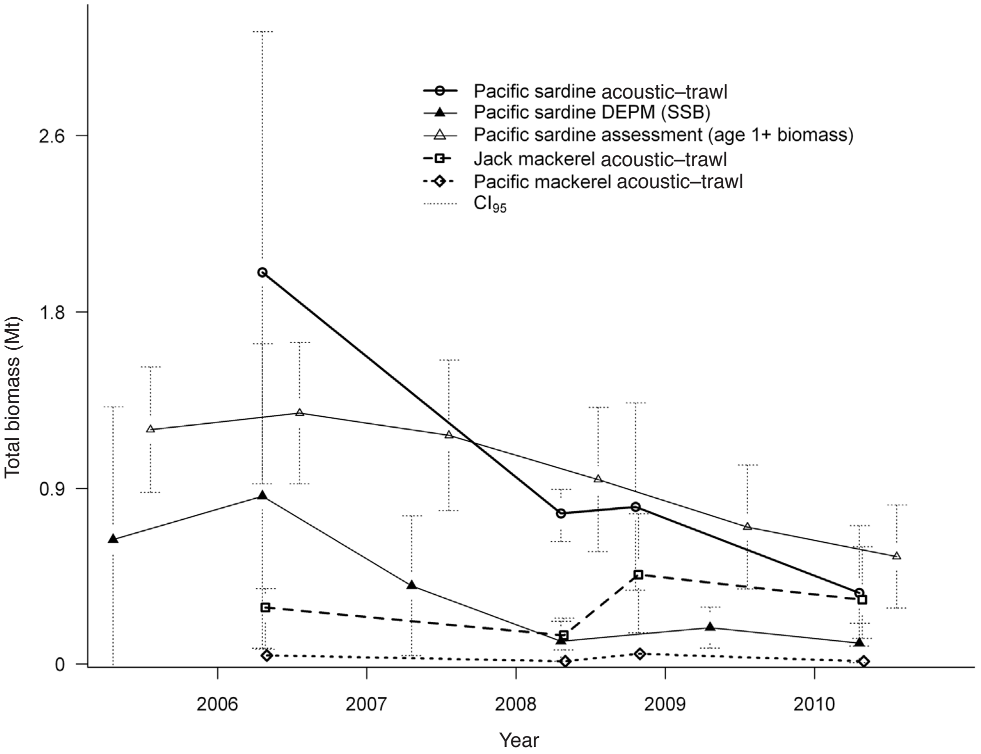

Figure 6

Biomasses (million metric tons; Mt) of the most abundant epipelagic coastal pelagic fish species (CPS) in the California Current Ecosystem (CCE), estimated by the acoustic–trawl method, in spring 2006, 2008, and 2010 (this study), and summer 2008 (Demer et al., 2012). The 95% confidence intervals (CI_{95}) are indicated. Superimposed are the estimates of total sardine (*Sardinops sagax*) biomass from the 2010 assessment (Hill et al., 2010) and the spawning stock biomass (SSB) estimated from the daily egg production method (DEPM; Lo et al., 2010). The biomass estimates from the Pacific mackerel (*Scomber japonicus*) assessment were not included because the distribution of that stock greatly exceeds the sampling area, and estimates for the relevant subpopulation were not available (Crone et al., 2009).

of the stock. From 2006 to 2008, the abundance of jack mackerel appears to have remained constant or increased slightly (Fig. 6). Either the population was stable and entirely contained within the acoustic–trawl survey area, or, less likely, a variable portion of the population within the survey area comprised the same biomass.

Pacific mackerel comprised only a small fraction of the CPS biomass. Their abundances were typically less than 50,000 metric tons (t), which is roughly one-sixth of the total stock biomass estimated by the assessment (>280,000 t; Crone et al., 2009). The large discrepancy between the two estimates is likely a consequence of the stock residing mostly south of the survey area, as far as Cabo San Lucas (Crone et al., 2009). Thus, the acoustic–trawl estimates of Pacific mackerel biomass off the U.S. west coast represents a variable and unknown portion of the entire stock. The high CV values are indicative of high patchiness and could be improved by increasing sampling effort. To reduce the variable systematic error, the survey area should be extended farther south, and also more nearshore, particularly off southern California (Crone et al., 2009; Moser et al., 2001).

Anchovy is currently a monitored species with a residual fishery and unknown abundance (PFMC, 2009). They were caught in a few trawls in each survey, notably off southern California where they were once the most abundant CPS (Mais, 1974; Mason, 2004). Anchovy were also caught, somewhat consistently, close to shore off the Columbia River mouth and Monterey Bay, indicating a higher geographical affinity compared with the other CPS. Improved knowledge of the anchovy stocks will require increased and directed effort in the locations of higher expected abundances.

For all the CPS species combined, the current data do not clearly indicate a relationship between the number and locations of trawls or transects, and the precision of the survey estimates. Therefore, the optimization of future surveys for a desired sampling precision will require simulations of various biomass levels, possible distributions, and sampling strategies (Simmonds and Fryer, 1996). In the meantime, to reduce the sampling variance and improve the description of species demography, acoustic and trawl sampling may be increased in areas of higher expected abundance, which is seasonally dependent (Clark and Janssen Jr., 1945; Zwolinski et al., 2011; Demer et al., 2012). Moreover, target trawling may increase the number of fish samples to better define the demography of the least abundant species. The historical distribution of the dominant CPS and, more recently, model prediction of potential sardine habitat indicate that sampling off Oregon and Washington during the spring is likely useless for the assessment of sardine, jack mackerel, and Pacific mackerel but may be relevant for potentially emerging anchovy and herring populations.

Sardine, mackerels, and anchovy have been shown to alternate dominance in the CCE in response to low-frequency variability in the oceanographic conditions of the North Pacific (MacCall, 1996). While those changes occur naturally and cyclically, they can be exacerbated by extreme fishing pressure. It follows logically that timely management actions may optimize the exploitation of the populations and aid their recovery (Petitgas et al., 2010; Radovich, 1982). Therefore, monitoring by synoptic, periodic, fisheries-independent multispecies surveys is indispensable for a successful transition to ecosystem-based fisheries management (Ecosystem Principles Advisory Panel, 1999; Rice et al., 2005).

Presently, acoustic–trawl surveys uniquely provide synoptic multi-species information over large oceanic areas. Unlike the DEPM, acoustic–trawl surveys do not depend on the timing of spawning. In contrast to trawl surveys, echosounders sample much larger water volumes and ranges of organism sizes. There are, however, some significant challenges when conducting acoustic–trawl surveys. The principal challenge is accurate classification of the echoes. With the frequency-dependent backscatter information, it is possible to objectively separate fluid-like scatterers (e.g., zooplankton, bladderless fish) from gas bearing organisms (e.g., fish with gas-filled swimbladders), and, to some degree, classes of organisms within those groups. However, CPS with similar morphological features and sizes exhibit similar spectral responses, which require, to date, disambiguation by physical sampling.

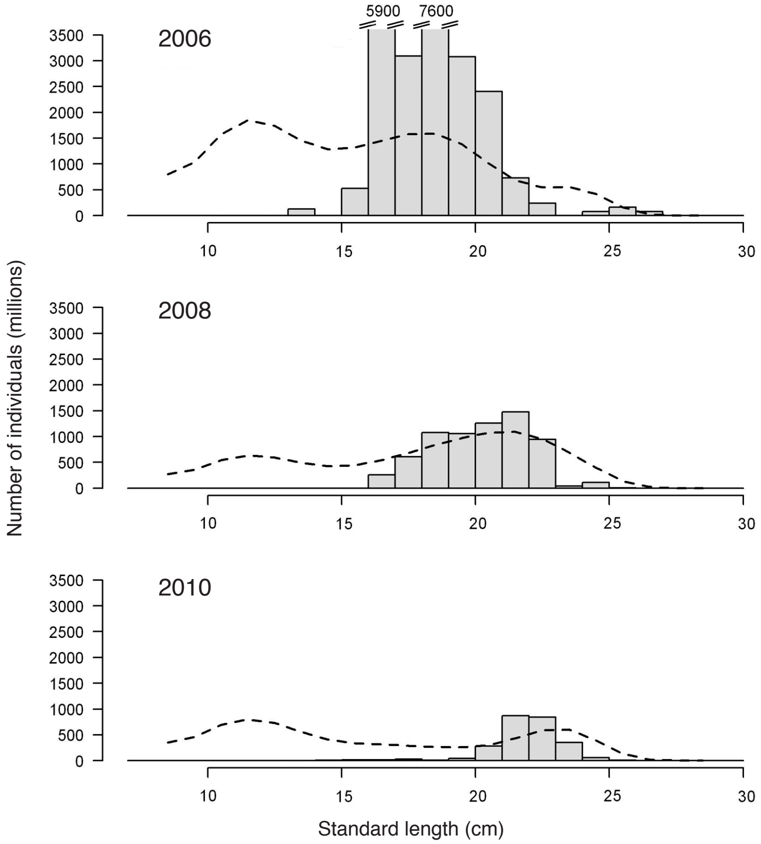

Figure 7

Estimated biomass-weighted length distributions for the northern stock of sardine (*Sardinops sagax*) in the California Current Ecosystem (CCE) during spring 2006, 2008, and 2010 surveys. The dashed lines represent the estimated length composition from the assessment (Hill et al., 2010). There is no indication of significant recruitment. Consequently, the sardine population is aging and declining. The instantaneous net mortality rate was estimate to be 0.56 by fitting an exponential-decay function to abundances derived from acoustic–trawl data.

In the short term, acoustic–trawl surveys for monitoring CPS should include more trawl sampling, both directed and random, and the use of towed optical devices. Data from these will serve to reduce the uncertainty associated with species identification, especially for the less abundant species. Classification algorithms may be refined and the results validated by using data from nonlethal sampling devices, e.g., towed stereo cameras.

The survey design could be optimized for improved acoustic and trawl sampling of species with low or patchily distributed abundances in inaccessible inshore regions (e.g., anchovy and herring) or outside the survey area (e.g., Pacific mackerel). Additionally, the combination of multi-frequency echosounder systems with multibeam (Cutter and Demer, 2008) and omnidirectional sonars may serve to quantify potential biases due to the surface blind zone (Scalabrin et al., 2009) and nearsurface avoidance of fish (De Robertis et al., 2010).

In the medium term, species-specific habitat models, similar to that for sardine (Zwolinski et al., 2011) should be developed, possibly describing the habitat in three-dimensions, for spatial and temporal optimization of sampling designs. Furthermore, TS models should be improved and confirmed for the various species present in the CCE in relation to variable size, physiological characteristics, and environment.

Conclusion

This work provides the first time-series of fisheries-independent estimates of the abundances and distributions of multiple CPS in the CCE. The results emphasize the value of acoustic–trawl surveys for efficient, long-term monitoring of CPS communities in large marine ecosystems. The time series of sardine abundance will be used in the annual assessment of the stock (Hill et al., 2006; PFMC, 2011a, 2011b), and the estimated distributions and abundances of multiple CPS will provide necessary information for a transition from single-species assessments to an ecosystem approach to fisheries management (Ecosystem Principles Advisory Panel, 2001).

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