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Pacific Sardine Characteristics Affecting the Conduct of an Acoustic Clutter Experiment off the West Coast of the United States

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14. ABSTRACT

The Office of Naval Research is sponsoring an experiment off the West Coast of the United States during the summer of 2012 that is designed to obtain clutter statistics from biological targets. Schools of fish are the dominant cause of biological clutter. In recent years, Pacific sardines have been by far the most abundant species of schooling fish off the West Coast. Therefore, sardines are the best candidates to be clutter targets. In preparation for the experiment, the characteristics of Pacific sardines that are pertinent to the clutter experiment have been examined. These characteristics include abundance, summertime geographical distribution, depth distribution, size distributions of individual sardines, school size distributions, school shape, sardine packing densities within a school, and spacings between schools. This report contains the results of this examination. In addition, the Pacific sardine fleet in Washington and Oregon waters is described and suggestions are made for locating concentrations of sardines.

15. SUBJECT TERMS

Biological clutter; Fish schools; Pacific sardines

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PACIFIC SARDINE CHARACTERISTICS AFFECTING THE CONDUCT OF AN ACOUSTIC CLUTTER EXPERIMENT OFF THE WEST COAST OF THE UNITED STATES

INTRODUCTION

Fish can adversely affect the performance of Naval active sonar systems. Widely dispersed fish can cause reverberation that can mask target echoes. Groups of fish can produce echoes that can cause clutter or be mistaken for targets. The Office of Naval Research (ONR) is sponsoring an experiment off the West Coast of the United States as part of an effort to mitigate the effects of clutter caused by schooling fish. In order to successfully plan and conduct any at sea experiment that involves scattering from fish and to interpret the results, pertinent characteristics of the major fish species in the region must be known. The best source of that knowledge is the fisheries research community.

The primary goal of most fisheries research is the determination of abundance of commercially important fish species. Accurate abundance information provides a scientific basis for stock management. In the determination of abundance, much supporting information is obtained. This includes seasonal geographic distributions, depth distributions, individual size distributions, and aggregational characteristics. All of this information is helpful to researchers studying scattering from fish.

The fisheries research community has grouped fish off the West Coast in several categories. The categories of interest are Coastal Pelagic Species, Highly Migratory Species, Groundfish, and Salmon. Coastal Pelagic Species include Pacific sardine, Pacific herring, northern anchovy, chub mackerel, jack mackerel, and bonito. Highly Migratory Species include tunas, billfish, and sharks. Groundfish include flatfish, rockfish and midwater fishes such as Pacific hake, Pacific cod, sablefish, grenadiers and walleye pollock.

From an environmental standpoint, the primary requirement for a successful acoustic experiment involving scattering from fish is a dependable supply of fish. Criteria for a species to be considered as a dependable scatterer include abundance, known geographic distribution, and ease of insonifying the fish and interpreting the results. For example, fish living on or very near the bottom might be plentiful but separating returns scattered from the fish from those scattered from the bottom could be very difficult. Generally, abundance is the primary criterion to consider.

Unless a fish species is of little commercial value, catch statistics are a reliable measure of abundance. Figures 1, 2 and 3 show catches of coastal pelagic species, highly migratory species and salmon, and midwater and semi-demersal groundfish, respectively, off Washington, Oregon and California from 1981 through 2011. The data are from the Pacific Fish Information Network (PACFIN), which is funded by the National Marine Fisheries Service (NMFS). [1] These figures show that, during this century, catches of two species, Pacific sardine and Pacific hake, are far greater than those of any other species. Except for grenadiers, all of the species shown are or have been of commercial interest. Therefore, these catch statistics give an accurate indication of abundance. Hence, there are only two fish species to be considered for the planned ONR West Coast experiment.

Pacific sardines form dense schools while Pacific hake are in diffuse aggregations. [2] For a clutter experiment, a schooling species is preferable. Therefore, Pacific sardine is a more suitable target species than Pacific hake for the clutter experiment. The remainder of this report will devoted to describing pertinent characteristics of the Pacific sardine (*Sardinops sagax*) population off the West Coast.

GENERAL CHARACTERISTICS OF PACIFIC SARDINES

The size of the Pacific sardine stock off the West Coast has varied greatly over the last century [3] The fishery began during World War I and peaked in 1936 at over 700,000 mt. The sardine fishery was the largest fishery in the western hemisphere during the 1930s and 1940s. Sardines were caught from northern Mexico to British Columbia. The fishery began to decline in the late 1940s to extremely low levels in the 1970s. Reduced abundance was accompanied by a southward shift in sardine range. No sardines were caught north of San Francisco after 1952. In the early 1980s, sardines began a comeback. In 1986, California lifted a moratorium it had placed on sardines earlier. In 1990 California's catch quota was less than 1000 mt; in 1991 it was more than 10,000 mt; by 1999 it was 120,000 mt.

Pacific sardines off the West Coast are considered to be in three subpopulations. [3] A northern subpopulation can extend from northern Mexico to Alaska. A southern subpopulation can extend from lower Baja California to southern California. A third subpopulation is in the Gulf of California. Although the ranges of the northern and southern population overlap, the stocks move north and south together and do not overlap. It is the northern subpopulation that is of interest.

This northern subpopulation is generally centered off central and southern California but during periods of high abundance and warm ocean temperatures a portion of the population migrates north in late spring to the Pacific Northwest to feed. Larger sardines tend to migrate farther north than smaller ones. The sardines then migrate south in the fall. [4-6] Spawning begins in January off northern Mexico and ends by August in the Pacific northwest, usually peaking off California in April. Sardines spawn in loosely aggregated schools in the upper 50 m. [7-9]

Pacific sardines school at depth during the day and ascend to the surface and disperse at night. [2] Maximum daytime depths are cited as 50, 70 or 100 m, or the thermocline. [2, 4]

The largest Pacific sardine ever caught was 45 cm long. However, the largest caught commercially since 1983 was 33 cm. [3] (It should be noted, that biologists usually use a fish's "standard length", which is measured from the tip of the snout to the base of the tail. Navy acousticians and recreational fishermen tend to use "total length", which is measured from the tip of the snout to the tip of the tail. Standard length is more accurate while total length is more obvious. For Pacific sardines, total length is roughly 10% greater than standard length. Total length is used in this report. Standard lengths are divided by 0.9 when necessary.) Sardines may live up to 15 years, but most of those caught off California are younger than five. Off British Columbia, the most common age has been six to eight years.

PACIFIC SARDINE ABUNDANCE

For fishery researchers, species abundance is an end result. For researchers conducting an experiment on acoustic scattering from fish, it is a good starting point.

In the fall of each year the NMFS Southwest Fisheries Science Center (SWFSC) produces an assessment of the Pacific sardine stock to provide information for managing the stock in the following year. [e.g. 3, 10-13]. The assessments use a combination of fishery data and fishery independent data. The assessments are presented to the Pacific Fishery Management Council (PFMC), whose members represent various fishing industry groups and government agencies, for final approval.

Fishery data include commercial catch statistics and concomitant biological sampling. Catch data are from northern Mexico, southern California, central California, and the Pacific Northwest (Oregon, Washington and British Columbia). Biological data include fish weight, length, age, sex, and maturity.

Sources of fishery-independent data have varied over recent years. One constant, the primary fishery-independent data source, is an annual survey of sardine eggs and larvae conducted off the coast of California by NMFS/SWFSC every April. [8, 14-17] This survey captures eggs and larvae with towed nets, estimates the total number of eggs, and then calculates spawning biomass based on egg numbers. In 2007 and 2008, it was the only fishery-independent source used in the assessment. [11, 12]

In 2009, three additional sources of fishery-independent data were considered. One was a program conducted by the NMFS Northwest Fisheries Science Center (NWFSC). This program consisted of a series of trawl surveys off Washington and Oregon that began in 1998 and continued through 2009. [4] The second was a program conducted by Canada's Department of Fisheries and Oceans (DFO). This program has conducted trawls off the west coast of Vancouver Island since 1992. [18] The third was an aerial survey flown from the Strait of Juan de Fuca to Monterey, CA during the summer of 2009. [19] For various reasons, the data obtained from the trawl surveys were deemed unsuitable for inclusion in the 2009 assessment. However, data from the aerial survey were included.

The aerial survey employs photography to determine the surface area of schools. The aircraft pilots also direct purse seiners to capture selected schools of various sizes. A relationship between school surface area and weight is developed and used to calculate the total weight of all photographed schools. This weight is then used to calculate total biomass in the surveyed area.

The 2010 assessment used only the spring 2010 egg and larvae survey and the 2010 summer aerial survey. [8, 20]

The 2011 assessment used three fishery-independent sources. The spring egg and larvae survey was expanded to include a few trawls of Oregon and Washington. [17] The 2011 aerial survey results were also included. [21] A new source in 2011 was data from an echo sounder/trawl survey conducted by NMFS/SWFSC. [22, 23] Two other data sources were considered but not used. One was the DFO sardine survey off Vancouver Island. [24] The other was a NMFS/SWFSC program surveying juvenile rockfish off central California, which caught sardines incidentally. [10] (The programs that have been considered but not accepted for use in the official sardine assessments are noted because they provide information for the current study.)

The echo sounder/trawl method was developed for sardine surveys by NMFS/SWFSC in response to a 2006 call by PFMC for additional fishery-independent assessment tools. [25] Surveys were conducted in the spring of 2006, 2008, 2010 and 2011, and the summer of 2008. [6, 23, 25] The echo sounder/trawl method has been used for decades to assess various fish populations [e.g. 26], but it took five years and five sardine surveys before the method was accepted as a source of data for the Pacific sardine assessment! This method uses echo sounders to measure the total acoustic backscattering strength along a track at different frequencies. Trawls near the track lines provide information on the species and sizes of fish causing the backscatter. Equations relating the target strength of an individual fish to its size are used to calculate the numbers or weight of fish along a track from total backscattering strength. Then the biomass in the area is estimated.

Information from fishery and fishery-independent sources are combined in a variety of models to produce abundance estimates. The models, which are being improved continually, use time series of data, so that any changes in the models or data change not only the estimate for the current year but also for previous years. Significant changes in the modeling for the fall 2011 abundance estimate and additional data resulted in significant changes in the abundance estimates. Not surprisingly, the assessors believe that the current methodology gives the best estimates for the current and previous years.

Figure 4 shows estimates of spawning stock biomass (those individuals age 1 or greater) from 2000 to 2011 for assessments conducted from 2007 through 2011. [3, 10-13] The estimates in 2007 and 2008 are identical. The 2009 and 2010 estimates follow the same general shape as the 2007 and 2008 estimates but they are lower from 2000 to 2004 and higher from 2006 to 2008 and the peak is shifted from 2005 to 2006. The estimates from all four years show a rapid decline in abundance after 2006. Abundance estimates made in 2011 are much lower than those in previous years for 2000 to 2005 and show a much slower decline in abundance after 2006. Most significantly, the 2011 estimate shows an increase in 2011.

The ratio of stock size in 2007 to that in 2000 was 0.49 fpr the 2007 estimate and 0.83 for the 2011 estimate. The ratio of stock size in 2008 to that in 2000 was 0.34 for the 2008 estimate and 0.74 for the 2011 estimate. The ratio of stock size in 2011 to that in 2000 was 0.66 for the 2011 estimate. Compared to earlier assessments, the 2011 assessment indicates a relatively steady sardine stock biomass from 2000 through 2011, while earlier ones indicate a dramatic decline. The primary factor in this difference is the large drop in the 2011 assessment's estimates for the first half of the decade.

Figure 5 shows the number of juveniles produced by each year class, as estimated during the assessments conducted from 2007 through 2011. [3, 10-13] All estimates are very similar from 2000 to 2003. The difference in the numbers of juveniles estimated for 2004 and 2005 by the 2007-2008 assessments and the 2009-2010 assessments explains why the abundance estimates made in 2009 and 2010 are higher than those made in 2007 and 2008 for 2006 and later. The second factor in the difference in the abundance estimates made in 2011 compared to earlier estimates is that the 2011 estimate of juveniles shows many more juveniles in the 2005, 2007 and 2009 year classes. In particular, the high number of juveniles estimated for the 2009 year class produces the increase in abundance from 2010 to 2011 in the 2011 assessment.

Figure 6 shows sardine catches by area for 2000 through 2010. [10] Although the U.S. catch had some significant variations in this time period, as shown in Figure 1, the total catch from northern Mexico to British Columbia was relatively consistent. There are two interpretations to this relatively consistent total catch. One, which follows from the 2011 assessment, is that catches are consistent because sardine abundance has been relatively consistent. The 2011 assessment states that exploitation rates (ratio of catch to stock biomass) have varied between 10% and 15% between 2000 and 2010. [10] The other, which follows from the 2007 through 2010 assessments, is that a greater fraction of a quickly diminishing population is being caught every year. The 2010 assessment states that exploitation rates have increased from 9% in 2000 to 22.5% in 2010. [13] A recent paper, which was submitted before the 2011 assessment was published, predicts that the Pacific sardine stock could collapse in the near future. [27] This prediction is based on three factors: cooling of the ocean; a precipitous decline in sardine abundance; and poor sardine reproduction conditions. If the 2011 assessment is to be believed, the last two of these factors are not being met, indicating that collapse is not imminent.

PACIFIC SARDINE SIZE

Young Pacific sardines grow rapidly. Average lengths are about 12 cm at 6 months, 16 cm at a year, 20 cm at 2 years and 22 cm at 3 years. They are about 25 cm at 5 years and 26 cm at 7 years. Maximum average length is about 27 cm. [10]

The size distribution of Pacific sardines depends on the relative sizes of different year classes. If the population is dominated by older fish, the distribution is skewed toward large fish. If the population is dominated by younger fish, the size distribution is skewed toward small fish. Of course, it is possible to have two (or more) strong year classes.

Figure 7 shows sardine length distributions from the 2009-2011 aerial survey purse seine catches. [10] Two characteristics are notable. One is that the distribution is very narrow, with a range of only about 5 cm. The other is that the distribution shifts slightly each year. The smallest fish are bigger, the largest fish are bigger and the mean shifts from 22 cm in 2009 to 23 cm in 2010, to 24 cm in 2011. These factors indicate that the sardine population sampled during the aerial surveys was composed primarily of fish that were three years old and older.

Figure 8 shows sardine lengths from the NMFS echo sounder/trawl surveys conducted off California in the spring of 2007 through 2010. [10] The range of sizes is about 10 cm for 2007, 2009, and 2010. In 2008 there is a small population of juveniles 10 to 12 cm long. The younger population is not very evident in 2009, but it dominates the distribution in 2010. Based on their sizes, these 18 to 22 cm long fish would be expected to be 2 or 3 years old. It seems as though there might be a conflict with the data in Figure 5, which indicate that there were large year classes in 2005 and 2009, but not in 2007 or 2008.

In British Columbian waters the modal length for sardines was 24 cm in 2007 and 25 cm in 2008-2010. In 2010, there was also a peak at 15 cm. [23]

Age data were collected off Washington, Oregon and British Columbia between 1999 and 2004. [4, 28] Off Washington and Oregon, the modal age was 2 in 1999, 3 in 2000 and 2001, 4 in 2002, and between 5 and 6 in 2003. Off British Columbia, the modal age was 5 between 1999 and 2002 and 7 in 2004. A comparison of ages and sizes indicates that older and larger fish were generally farther north between 1999 and 2010.

The relationship of sardine weight (W) in grams to its length (L) in cm is given in the 2011 assessment as [10]

$$W = 0.01234\ (L)^{2.94825}.$$

This equation gives the following:

for L = 18 cm, W = 62 gm,
for L = 20 cm, W = 85 gm,
for L = 22 cm, W = 112 gm,
for L = 23 cm, W = 128 gm,
for L = 24 cm, W = 145 gm.

Sardine average lengths and weights were obtained by the Washington Department of Fish and Wildlife (WDFW) for June through September from 2005 through 2010. [29] (Data were not obtained for every month for every year.) There were no apparent trends in sardine weight from month-to-month or year-to-year. The 2011 aerial survey also measured average length and weight. [21] A length-weight plot of WDFW data and the aerial survey data showed that the aerial survey data point fell well within the variability of the WDFW data. Therefore, all these data were combined. An exponential fit to these data gives the following:

for L = 20 cm, W = 87 gm,
for L = 22 cm, W = 119 gm,
for L = 23 cm, W = 137 gm,
for L = 24 cm, W = 159 gm.

A probable explanation for why the assessment equation gives lower weights is that it includes data from throughout the year, while the others include only data from the summer, when the fish are feeding. For an experiment off Oregon and Washington in the summer, the higher weights are more appropriate.

SUMMERTIME GEOGRAPHIC DISTRIBUTION OF PACIFIC SARDINES

The most current and complete set of information on the summertime distribution of Pacific sardines is from the aerial sardine survey program. [19-21] Each survey included a series of east-west aircraft photography transects. The survey plan for each year included three slightly offset replicates of transects. Because of adverse weather conditions, three replicates were completed in only 2010; in 2009 and 2011, only one full set of transects was completed. The transects began north of 48°N and proceeded southward. In 2009, transects were planned to go from 48°10'N to 35°25'N, but poor weather precluded any transects south of 38°10'N. In 2010, transects went from 48°20'N to 33°20'N. In 2011, transects went from 48°15'N to only 42°00'N. Spacing between transects was 15 nm in 2009 and 2010. In 2011, it was 7.5 nm north of 44°30'N and 15 nm south of 44°30'N. Each transect was 33 nm long, extending from 2.6 to 35.6 nm from the coast. The aircraft flew at a nominal altitude of 4000 ft. At this height, the width covered by each photograph was 0.99 nm. There was a significant overlap in photographic coverage.

Sardines were found off the coasts of Washington and Oregon in all three years. However, their distribution with latitude varied from year to year. In 2009, sardines were concentrated off northern Oregon and southern and central Washington. However, there were relatively few off the mouth of the Columbia River. In 2010, sardines were rather uniformly distributed along the Washington coast, with very few south of the Columbia River. In 2011, sardine distribution with latitude had a series of maxima and minima. No fish were found from 45°30'N southward. Between 45°30'N and the Washington-Oregon border, sardines were relatively abundant. There were relatively few sardines off extreme southern Washington. Going northward, there was about a 25 nm band of relatively high density and then a 10 or 20 nm band of low. Sardines were relatively abundant off northern Washington. Table 1 gives the proportion of calculated biomass as a function of latitude for the three years.

A portion of the sardine stock migrates north of Washington into British Columbian waters. Estimates of the percentage of the sardine stock inhabiting British Columbian waters during the summers of 2008, 2009 and 2010 were 27.7%, 33.5%, and 18.4%, respectively. [24]

Along with information on latitudinal variations of sardines, the aerial surveys also provide information on their distance from the coast. Some transects found sardines close to the coast in shallow water. Others did not. Some transects found sardines as close as 3 to 5 nm from shore in 20 to 25 m water depths. Other transects found sardines no closer than 25 nm from shore in water depths well over

100 m. Average minimum distances from shore and the corresponding water depths were very similar in 2009 and 2011: 7 nm and 65 m in 2009 and 8 nm and 60 m in 2011. Average minimum distance and depth were slightly greater in 2010: 13 nm and 70 m. Based on these averages, it can be assumed that 10 nm and 65 m are reasonable working estimates of how far from the coast sardines begin and how deep the water is at that point. An examination of nautical charts for the region indicated that a bottom depth of 65 m 10 nm from shore is a reasonable approximation for Washington. Off northern Oregon, water depths 10 nm from shore are generally greater than 65 m.

The maximum offshore extent of sardines ranged from 10 to 30 nm. Average maximum offshore distances were similar for the three years: 19 nm for 2009, 21 nm for 2010, and 17 nm for 2011. There was also very little variation with latitude. Offshore distances averaged over 30′ of latitude ranged from 17.0 nm to 20.4 nm between 45°N and 48°N. Water depths at the offshore edge of the sardines was generally between 100 and 200 m, although there were several outlying transects where the depths were between 400 and 700 m. Ignoring these outliers for time being, average depths were 150 m in 2009, 140 m in 2010 and 135 m in 2011. The similarity among average maximum distances and depths for the three years indicates that it can be assumed that sardines will often be found over bottom depths of 140 m, 20 nm from shore, with some being found almost as far out as 30 nm.

Off the coasts of Washington and northern Oregon, the 50 fm (90 m) contour is generally quite smooth. Its distance from the coast varies slowly with latitude. The 100 fm (180 m) contour is relatively smooth off Oregon. However, off Washington, its distance from the coast is influenced greatly by the Juan de Fuca, Gray's and Astoria Canyons. Transects that found sardines over these canyons were the ones that registered the depths between 400 and 700 m. This implies that it is distance from shore, rather than bottom depth, that influences the maximum offshore distribution of sardines.

The purse seiners that captured sardine schools during the aerial surveys were homeported in Astoria, OR, which is at 46°11'N, near the mouth of the Columbia River. In 2008 and 2009, the boats fished between about 46°00'N and 46°40'N. In 2011, they fished between about 46°00'N and 47°30'N. In 2009 and 2011, catches were made between about 40 m and 120 m. In 2010, several catches were made in water depths greater than 200 m.

In the decade prior to 2005, NMFS/NWFSC conducted four series of surveys that collected sardines off the coasts of Washington and Oregon. They were the Triennial, Plume, GLOBEC and Predator surveys. [4] The Predator surveys between 1998 and 2004 caught sardines from under 10 nm to over 30 nm from coast. In some years the highest catches were near shore (<10 nm), while in others the highest catches were off shore (20-30 nm). The Triennial surveys of 1995, 1998 and 2001 found that sardines were mainly distributed over the middle and outer shelf. Most fish were caught in water depths of 100 to 200 m, although some were caught in shallower depths. Most of the sardines caught during the August 2000 and 2002 GLOBEC and Plume surveys were in water depths of 200 m or less but a few were caught well off the shelf. The distances from shore and depths found on these earlier NMFS surveys generally agree with those found on the aerial surveys.

A model that predicts optimum habitat of Pacific sardines and, thus, their spatio-temporal distribution off the West Coast throughout the year, has been developed recently. [30] The model uses four satellite-sensed sea surface parameters as inputs: temperature (SST), chlorophyll a (CHLA), surface altitude deviation and surface height gradient. The model was developed by comparing these parameters to the densities and distributions of sardine eggs off California during April estimated by the NMFS/SWFSC surveys. [e.g., 7, 8, 14-17] This effort demonstrated that SST and CHLA were the dominant factors. Sardine eggs were most frequent in areas with SST between 11.5°C and 15.5°C and CHLA between 0.18 mg/m^3 and 3.2 mg/m^3. Low SST (<11.5°C) combined with high CHLA (>3.2 mg/m^3) indicates upwelled water and defined the inshore boundary of eggs. High SST (>15.5°C) and low CHLA (<0.18 mg/m^3) indicate oceanic water and defined the offshore limit of eggs. Where there are sardine eggs, there are spawning adults, so that optimum conditions for eggs are, actually, optimum conditions for adult sardines. It was assumed that the optimum conditions for sardines in April would be the optimum conditions throughout the year. A comparison of SST and CHLA with catches from California, Oregon, Washington, and British Columbia through the year confirmed that this assumption was valid.

The model predicts that optimum sardine habitat is offshore and south of Oregon from January through April. In April, habitat begins to shift north and toward shore. This shift continues through the summer so that in July and August optimum habitat is compressed along the coast from Oregon to British Columbia. This compression is caused by warm, nutrient-poor oceanic water offshore. In early fall, the habitat begins to expand westward and in October and November it begins to move southward and away from the coast. The offshore and southward movement continues throughout the winter.

During the aerial surveys, the purse seiners measured SSTs, usually to the nearest degree Fahrenheit. SSTs ranged from 55°F to 62°F (12.8°C-16.7°C) in 2009, 57°F to 59°F (13.9°C-15.0°C) in 2010, and 55°F to 61°F (12.8°C-16.1°C) in 2011. Median SSTs were similar for the three years, 60°F (15.6°C) in 2009, and 59°F (15.0°C) in 2010 and 2011.

The NMFS Predator surveys showed that most sardines were caught when SSTs were above 12°C. [4] The Plume and GLOBEC surveys showed that along with temperature, CHLA was a factor for juvenile and adult sardines and salinity was a factor for large adults.

In an effort to correlate the springtime arrival of fish off the mouth of the Columbia River with ocean conditions, an acoustic system was deployed in April through June of 2008 and 2009 in the vicinity of a permanently moored oceanographic buoy. [31] The mooring was 13 nm from the coast in 95 m water depth. In 2009, sardines arrived at the site in June, after SSTs were consistently above 12°C.

The range of optimum temperatures predicted by habitat model agrees well with those measured during aerial surveys, the NMFS surveys and the acoustic mooring experiment. This is to be expected, since one of the developers of the model was the lead author of the report on the NMFS surveys and a co-author of the paper on the acoustic mooring experiment.

Sardines follow the predicted optimum habitat but there is a time lag between arrival of optimum habitat and the arrival of sardines in the Pacific northwest. They also start south before the habitat degrades.

The data and the habitat modeling give an indication where sardines might be found during July and August of 2012. They can be expected to be between 10 and 30 nm off the coasts of Oregon and Washington in waters with SSTs between 11°C and 16°C and with CHLA between 0.18 mg/m^3 and 3.2 mg/m^3.

There are two factors that could shift the distribution southward. One would be cool La Nina conditions. The other would be a downward shift in the average size of the sardines. On May 3, 2012 the National Weather Service Climate Prediction Center officially declared that the current La Nina had dissipated during April 2012 and that neutral El Nino/La Nina conditions are expected to persist through the summer. [32] Hence, cool ocean conditions should not be a factor. If the younger sardines evident in the spring 2010 echo sounder/trawl survey data dominate the population, the southern limit of the summertime distribution of sardines could be south of the 45°30'N limit seen by the 2011 aerial survey, in which larger, older fish dominated.

SUMMERTIME DEPTH DISTRIBUTION OF PACIFIC SARDINES

The commonly accepted depth range for Pacific sardines is the upper 70+/-20 m of the water column. [2] They are said to school at depth during the day and rise to near the surface and disperse at night. It is possible that sardines occur at depths deeper than 50 m in the spring when they are off the continental shelf of California and somewhat shallower than 50 m in the summer when they on the continental shelf of the Pacific northwest. When fishery research organizations are assessing species abundance, they want to survey all of that species' habitat, if possible. Therefore, when NMFS/SWFSC conducts its spring sardine echo sounder/trawl surveys off California, they assure that their acoustic system and trawls include the deepest depth they expect to find sardines: 70 m. [2] Likewise, when the Canadian DFO conducts its summer sardine surveys off British Columbia, they assure that their trawls include the deepest depth they expect to find sardines: 30 m. [29]

The aerial sardine surveys were instituted for two reasons. First, the PFMC recommended that additional fishery-independent indices of abundance be developed for the assessment of sardines. Second, the West Coast sardine fishing industry felt that there was strong anecdotal evidence that sardine abundance in the Pacific Northwest was much higher than that given in the official sardine stock assessments. [19] One can assume that, if an assessment method is sponsored by the fishing industry, it will be a method that counts as many fish as possible. Thus, although the survey team acknowledged that some schools might have been missed because they were too deep for the aircraft photographs to detect, the number of missed schools must have been very small for the industry to sponsor this survey method. Therefore, it is reasonable to believe that school depths determined by this method are representative of the vast majority of the schools in the region.

During the aerial surveys, the purse seiners measured the depths of the tops and bottoms of sardine schools as they were capturing them. [19-21] School depths did not differ significantly over the three surveys. School tops ranged from the surface to 9 m, with most being between 4 m and 6 m. School bottoms ranged from 4 m to 16 m, with most being between 8 m and 12 m.

An experiment using a moored upward-looking acoustic system and shipboard echo sounders was conducted in early June 2006 in about 120 to 130 m water depths off the mouth of the Columbia River to examine the diel behavior of pelagic fish schools. [33] Virtually all schools were observed during the day in the upper 20 m. There was essentially no schooling seen at night. Neither were any layers or loose aggregations were seen at night. However, dispersed individuals were detected. Trawling was conducted in the upper 12 m during the day. Pacific sardines and northern anchovies were caught in about equal numbers and, together, made up 90% of the total catch. Since sardines comprised about 45% of the catch, it is reasonable to assume that some fraction of the observed schools was composed of sardines. Since all observed schools were in the upper 20 m, all sardine schools were in the upper 20 m.

NMFS/SWFSC echo sounder/trawl surveys recorded depths of sardine schools. However, these depths were not considered reliable. [34] It is well known that sardines and other Clupeids avoid approaching ships. [35, 36] The fish are affected by the noise and hydrodynamic pressure fields of the ships [37, 38] In general, the larger the ship and the higher its speed, the greater the effect. The NOAA ships used in the echo sounder/trawl surveys ranged from 52 m to 66 m long, with drafts of 4 m to over 6 m, and displacements of about 870 to 1840 GRT. [39] Their speed during echo sounder transects was 10 kt. [22] Multi-beam sonar data indicates that sardines dive to about 3 to 5 m directly below the hulls of the NOAA ships, so that depth information is corrupted but abundance estimates are not. [34] The necessity of the sardines to dive to 7 to 12 m, indicates that the fish are at shallower depths when a ship is not steaming by.

The purse seiners employed during the 2011 aerial survey were 22 to 25 m long with shallow drafts and displacements of 74 to 120 GRT. [21] Their speeds during the purse seining operation are relatively slow. In contrast to the NOAA ships, these small boats have minimal effect on sardine depth behavior.

The trawls off British Columbia, the purse seining off Washington and Oregon, the acoustic experiment, and indirectly, the NMFS echo sounder data all indicate that sardines in the Pacific northwest will be in the upper 30 m, probably the upper 20 m.

PACIFIC SARDINE SCHOOLS

Fish in the ocean can be widely dispersed; in loose aggregations, often termed shoals; or in schools. A fish school is generally defined as a compact group of equally spaced fish of approximately the same size, all swimming synchronously in the same direction. [e.g., 40] Pacific sardines are known to form dense schools during the day and disperse at night. [2, 33]

Two sources of quantitative information on sardine school sizes were found. The experiment conducted off the mouth of the Columbia River in June 2006 calculated mean school lengths of sardine and/or anchovy schools as a function of time of day. [33] Hourly means ranged from 10 m to 60 m. The mean of the hourly means was 30 m. Several schools were longer than 100 m, with the maximum length being 160 m.

The surface areas of many sardine schools were measured during the aerial surveys. [19-21] In addition, the purse seiners measured the height of the schools they captured. Figure 9 shows school size distributions for the 2009, 2010, and 2011 aerial surveys. (Surface areas have been converted into equivalent circular diameters, which will be used throughout the remainder of this report.) Almost 4000 schools were photographed. School size distributions were quite similar in 2010 and 2011, with schools slightly larger in 2010. The mode for both years was 18 m. The medians for 2010 and 2011 were 24 m and 21 m, and the means were 30 m and 25 m, respectively. One difference between these two years was that in 2011 the largest schools had a diameter of 57 m, while in 2010 several schools had diameters larger than 113 m. (A school with a surface area of 10000 m^2 has an equivalent circular diameter of 113 m. Actual sizes were not provided for schools larger than 10000 m^2.) Schools were larger in 2009 than in 2010 and 2011. Bi-modal peaks were at 24 m and 29 m, the median was 40 m and the mean was 46 m. In addition, there were over 100 "schools" larger than 10000 m^2. One "school" seen during the 2009 survey was 504910 m^2 (802 m diameter). [41] Based on the above definition of a school as a "compact group of ... fish", it was assumed that these very large groups we re most likely shoals of loosely aggregated fish and, therefore, they have not been included in the present school size distributions. (During the spring, aircraft pilots have observed huge aggregations of sardines (2-3 nm wide and 20-30 nm long) migrating north. [42])

Purse seiners successfully captured 88 schools. The mean equivalent diameter of these schools was 47 m. The smallest was 16 m and the largest was 98 m. 80% of these schools had diameters between 30 and 70 m. Thus, the size distribution of the schools selected for capture was skewed to larger schools compared to the distribution of all photographed schools.

The measurement of school surface area during the aerial surveys is very precise; to the nearest square meter. The measurement of school height is anything but. [21] While the purse seiners were in the process of capturing schools, the tops and bottoms of the schools and bottom depths were measured to the nearest fathom. Measurements to the nearest fathom are sufficient when determining the depths sardines inhabit or bottom depths, but greater accuracy is desirable when determining school heights. The aerial surveys determine biomass as mt/m^2; school depths are not required.

In fact, school depths were not reported for the 2009 and 2010 aerial surveys. [19, 20] School depths were reported for all three years in the 2011 report, possibly as the result of a request for such information. [21, 42] Even given the limitations of imprecise school height, the aerial surveys still provide the best set of data relating horizontal to vertical dimensions of sardine schools. School height data are available for 79 schools. It is assumed that this is a large enough data set that errors average out. School heights ranged from 2 m to 12 m, with a median and a mean of 6 m. Almost 80% of the schools were between 4 and 8 m high.

Ratios of school diameter to school height varied widely, from 3.4 to 33. The median was 7.7 and the mean was 9.4. Just over 50% of the schools had diameter to height ratios from 5.0 to 10.0.

A major study of schools of Atlantic herring, a species in the same family as Pacific sardine, found that the vertical profile of herring schools was generally circular in the middle of the water column and was somewhat flattened for schools near the surface and bottom. [40] Schools in the upper 20 m had horizontal to vertical dimension ratios from about 1 to 20. The higher ratio decreased to less than 10 below 20 m. The near-surface ratios are similar to the ones determined for the sardine schools and indicate that the imprecision in school height measurement can be tolerated.

Several photographs from the 2009 aerial survey are available for use in estimating school shapes. [41] Generally, the schools had fairly regular shapes. Examination of 31 schools seen in the photographs indicated that, in the horizontal plane, the schools are often shaped like fat hot dogs: rectangles with very rounded corners and slightly bulging sides, something between a rectangle and an ellipse. Some schools were relatively straight, like hot dogs before grilling. Some were curved, like hot dogs that have been grilled. The length-width ratios of these schools varied from 1 to over 5. The distribution of length-width ratios was: 19% between 1 and 1.5, 29% between 2 and 2.5, 23% between 2.5 and 3.5, 16% between 3.5 and 4.5, and 13% between 4.5 and 5.5. The median length-width ratio was 2.7 and the mean was 2.9.

School heights and shapes are not available for any individual schools. However, median and mean length-width and diameter-height ratios can be used to calculate width-height ratios. The medians give a width-height ratio of 4.7 and the means a ratio of 5.5.

Hence, although schools may resemble ellipses from the air, they are not ellipsoids of revolution. The average length-width ratio of the schools is about 2.8 and the average width-height ratio is about 5. Thus, the average length-height ratio is 14. Or, the width of an average school is about 0.36 of its length and its height is about 0.07 of its length.

Most schools of Pacific sardines off Washington and Oregon during the summer will have equivalent circular diameters between 10 m and 40 m, with a few larger than 40 m. On average, a school with an equivalent circular diameter of 10 m will have a length of 17 m, a width of 6 m and a height of just over 1 m. A 40 m diameter school will have a length of 67 m, a width of 24 m and a height of 5 m. A very large, 113 m diameter school will have a length of 188 m, a width of 68 m and a height of 13 m.

The surface areas, heights and weights of schools captured during the aerial surveys have been measured. [19-21] Therefore, densities of fish in the schools can be calculated. However, school shape must be determined before a volume can be calculated. The aforementioned study of Atlantic herring schools assumed that herring schools can be represented as ellipsoids. [40] It will be assumed that Pacific sardine schools can also be represented by this shape.

Densities of fish in schools can be presented in several ways. The primary density is the standard weight per unit volume (kg/m^3), which is the density that usually would be used in abundance estimation. Dividing this density by the mean weight of the fish gives the number of fish per unit volume ($\#/m^3$), which will be termed fish density (FD). Dividing the fish density by the cube of the mean length of the fish produces a fish per body length cubed value ($\#/L^3$), which will be termed fish packing density (PD). Both FD and PD can be of interest when considering fish schools as potential acoustic targets. They are also quantities of major interest in studies of fish schooling. [e.g., 43]

Mean packing densities for the three years of aerial surveys was virtually the same: $0.65/L^3$ in 2009, $0.67/L^3$ in 2010, and $0.66/L^3$ in 2011. Since the mean PD were almost constant and mean sardine lengths increased from 2009 to 2010 to 2011, mean fish densities decreased from $61/m^3$ in 2009 to $55/m^3$ in 2010 to $48/m^3$ in 2011. Over the three years, PD ranged from $0.17/L^3$ to $2.21/L^3$ and FD ranged from $14/m^3$ to $181/m^3$.

The number of sardines in each school was calculated by dividing the weight of a school by the mean weight of an individual. Numbers ranged from 22,500 to 1,077,400. About 10% of the schools had less than 100,000 fish and about 10% had more than 600,000 fish. The primary purpose of catching sardine schools during the aerial surveys was to develop a weight versus surface area relationship that could be applied to all schools. [19-21] However, the purse seiners could not capture schools much larger than 130 mt because of the requirement to completely capture a school and the limitations of the purse seiners (net length, hauling capacity, hold capacity). Based on the mean weights of the sardines caught in 2009, 2010 and 2011, 130 mt corresponds to 1,100,000 to 800,000 fish. Hence, schools with significantly more than 1,000,000 fish were not sampled.

The spacings between schools are of interest in a clutter experiment but are of no concern in assessing a fish stock. Therefore, interschool spacings are not explicitly reported in assessment-related literature. However, it is possible to obtain such information from some survey reports.

Distances between pairs of neighboring schools were estimated from four photographs taken during the 2009 aerial survey. [41] At the nominal flying altitude of 4000 ft, the photographs covered a width of 1829 m. [19] Under the assumption that the pictures presented covered the full width of the photographs, rough estimates of distances could be made. About 10% of the distances between pairs of schools were less than 100 m, about 80% were between 100 m and 400 m, and about 10% were between 400 m and 700 m.

One photograph is available from a satellite survey of sardines conducted in August 2009 off the coast of southern Washington. [44] A scale on the photograph makes it possible to make rough estimates of the distances between schools. Only one pair of schools was less than 200 m apart and only one pair was more than 700 m apart. About 20% were between 200 m and 400 m apart and about 75 % were between 400 m and 700 m apart.

It is estimated that during the NMFS echo sounder/acoustic trawl surveys, distances between schools of sardines along the survey track are about 1 km in areas where sardines are plentiful. [34]

Interschool spacings estimated from the satellite photograph are somewhat larger than those estimated from the aircraft photographs. The mean distance between schools in the satellite photograph is about 500 m and the mean distance in the aircraft photographs is about 250 m. The satellite photograph was to undergo further enhancement. It is possible that more schools would be discernible in the enhanced photograph and the interschool distances would get smaller. The NMFS echo sounder estimate may be based on experience during the spring surveys off California, where most of their work has been done. Sardines are spread over a wider area during the spring and, therefore, interschool spacings would be expected to be larger. [30] Although the three estimates of interschool spacings differ, they are not widely different and it probably can be safely assumed that distances between pairs of sardine schools during the summer will be between 100 and 1000 m. Sardine distribution is patchy. [21, 30] There is no guarantee that any single location that has all the right conditions will contain sardines. Hence, these interschool spacings only apply were sardines are present.

THE PACIFIC SARDINE FISHERY OFF WASHINGTON AND OREGON

The fleet fishing for Pacific sardines off the coasts of Washington and Oregon is not very large. Between 2005 and 2010 only 5 to 11 boats were registered in Washington to fish for Pacific sardines. [45] In that same period, 16 to 22 boats were registered in Oregon to fish for sardines. [46] The boats used to capture schools during the aerial surveys are typical of the boats in both fleets, about 20 m to 25 m long with displacements around 100 GRT. [21] Purse seiners frequently use spotter aircraft to locate and direct them to sardine schools. [46]

The average number of landings (i.e., trips) for each Washington boat increased from 15 to 20 between 2005 and 2007, to 20 to 30 between 2008 and 2010. Conversely, the average number of landings for each Oregon boat decreased from 40 to 70 between 2005 and 2007, to about 20 between 2008 and 2010. The average catch per trip for Washington boats increased from 32 mt in 2005 to 53 mt in 2010. The average catch per trip for Oregon boats increased from 41 mt in 2005 to 55 mt in 2009 but decreased to 51 mt in 2010. The relative consistency in the size of the catches is primarily due to the size of the boats' holds. If the catch per trip is relatively constant and the number of trips changes, it follows that the total catch will change. Thus, in Washington the catch from 2005 to 2008 was between 4400 mt and 6400 mt and increased to 8000 mt in 2009 and to over 12000 mt in 2010. In Oregon, the catch from 2005 to 2007 was between 35,000 mt and 45,000 mt and decreased to between 19,000 mt and 23,000 mt from 2008 to 2010. Between 2005 and 2007 Washington's catch was about 10% to 15% of the combined two state catch. In 2008 and 2009 it was about 25% and in 2010 it increased to 40%. The changes in total catch from year to year reflect not only changes in relative abundance but also changes in fishing regulations. [46]

Oregon boats averaged 1.5 purse seine sets per day and rarely made more than one landing in a day. [46] The most productive Washington boats often made two or even three landings per day. [45]

Being licensed in one state does not preclude fishing in another state's offshore waters. Between 2008 and 2011 most of the fishing effort by the Washington boats was centered off Grays Harbor (46°55'N). In 2008 and 2009 some of the effort extended to the waters off northern Oregon but in 2010 and 2011 virtually all the effort was north of the mouth of the Columbia River. [45] Most of the Oregon catch is landed in Astoria, near the mouth of the Columbia

River. [46] Boats sailing from Astoria are probably just as likely to sail north into Washington waters as they are to sail south into Oregon waters, depending a variety of conditions. Wherever any of the boats go, if they are making one, two or three trips per day, they are not going very far from their landing port.

The sardine fishing season off Washington and Oregon usually runs from June through October. Prior to 2008, the peak months for sardine landings were August and September when the fish were their fattest and most profitable. Due to new harvesting guidelines issued in 2008, the peak month for sardine landings is now July.

LOCATING PACIFIC SARDINES DURING THE SUMMER

At sea experimental time is limited and expensive. Spending a minimal amount of time locating sardine schools is essential. Based on recent history, Pacific sardines can be expected to be 10 to 30 nm off the coasts of Washington and Oregon during the summer in waters shallower than 100 or 200 m. Optimum habitat is predicted to be where sea surface temperatures are between 11°C and 16°C and surface chlorophyll a levels are between 0.18 mg/m^3 and 3.2 mg/m^3. The SeaWiFS satellite can provide these data in real time. [47] Thus, the general location of Pacific sardines can be determined.

However, since sardines are patchy, they will not be found throughout their potential optimum locations. Therefore, patches of sardines must be located within their known habitat. The best way to locate sardine schools would be to use spotter aircraft as the fishing boats do. Another method would be to sail along the coast, about 15 nm offshore in about 100 to 150 m water depths, using a high quality fish finding echo sounder to detect schools. A third method would be to use a high powered horizontal acoustic system to locate schools over a wide area. This method may not be viable due to limitations imposed by marine mammal regulations. Any of these methods should be supplemented with information obtained from knowledgeable persons in the area shortly before the experiment.

SUMMARY

In recent years, Pacific sardines have been by far the most abundant species of schooling fish along the West Coast of the United States. As such, sardine schools are the best candidates to be targets in a sonar clutter experiment planned for summer 2012. During recent summers, sardines have been primarily along the Washington and Oregon coasts. Most schools have been between 10 and 30 nm from the coast in waters with sea surface temperatures between 11°C and 16°C and with moderate levels of chlorophyll a. Water depths at the offshore limit of the schools were generally between 100 and 200 m. Off Washington and Oregon, sardines inhabit the upper 20 or 30 m of the water column during both day and night. Sardine distributions are patchy, so they may not be found even when conditions are ideal. Where sardine schools are found, distances between pairs of schools are usually between 100 and 1000 m.

In the horizontal plane, most summertime sardine schools have equivalent circular diameters between 10 and 40 m, with only a few much larger than 40 m. About 50% of the schools have diameter to height ratios between 5 and 10. On occasion, aggregations of sardines have been seen with diameters much larger than 100 m. The number of sardines in schools captured off Washington and Oregon contained from about 20,000 to over 1,000,000 individuals. These individuals were mostly 20 to 25 cm long.

The Pacific sardine fleet off Washington and Oregon between 2005 and 2011 has consisted of 23 to 28 purse seiners. The boats are 20 to 25 m long with displacements around 100 GRT. Spotter planes are frequently used to locate schools. Most sardines are caught on day trips during the summer.

An efficient method must be devised to locate concentrations of sardine schools to minimize search time and maximize measurement time. Whatever method is chosen, it should be supplemented with current local knowledge.

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Table 1 – Proportion of biomass as a function of latitude for the 2009-2011 aerial sardine surveys

Latitude °N	% of Biomass 2009	2010	2011
>48	0.04	4.5	10.6
47.5-48	0.01	16.8	15.8
47-47.5	22.3	16.6	4.6
46.5-47	49.1	15.3	27.2
46-46.5	0.7	24.7	12.2
45.5-46	23.9	19.8	29.5
45-45.5	0.5	0.2	0
44.5-45	0.03	1.4	0
44-44.5	0	0	0
43.5-44	2.2	0	0
43-43.5	0	0	0
42.5-43	0	0	0
42-42.5	0	0.7	0
41.5-42	0	0	
41-41.5	0	0	
40.5-41	0.25	0	
40-40.5	0	0	
< 40	1.0	0	

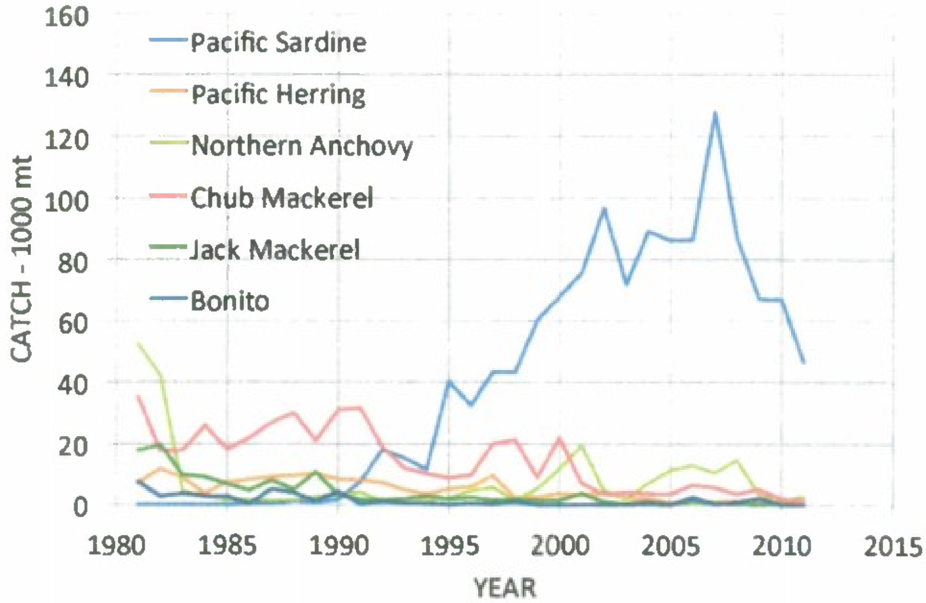

Figure 1 - U5 catches of Coastal Pelagic 5pecies

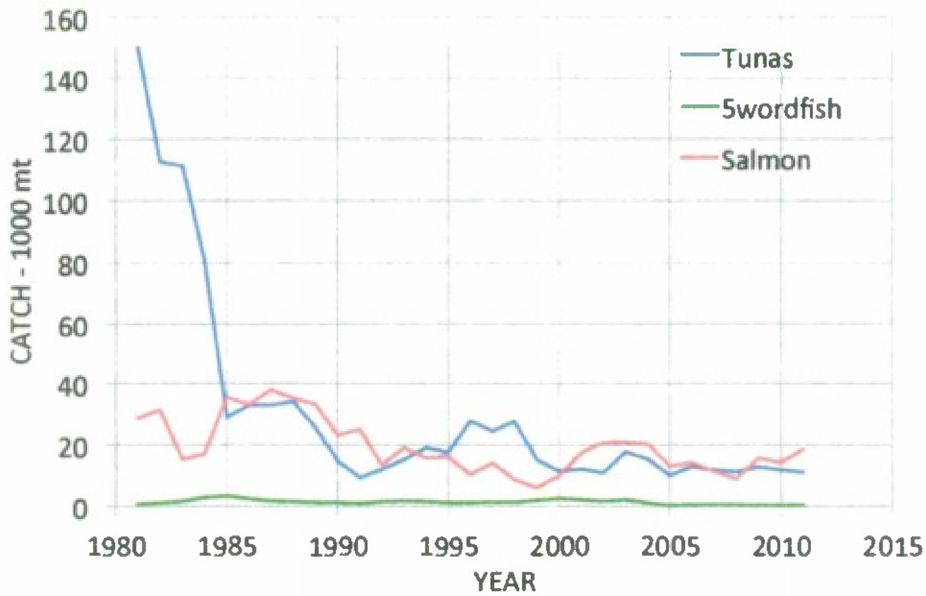

Figure 2 - U5 catches of Highly Migratory 5pecies

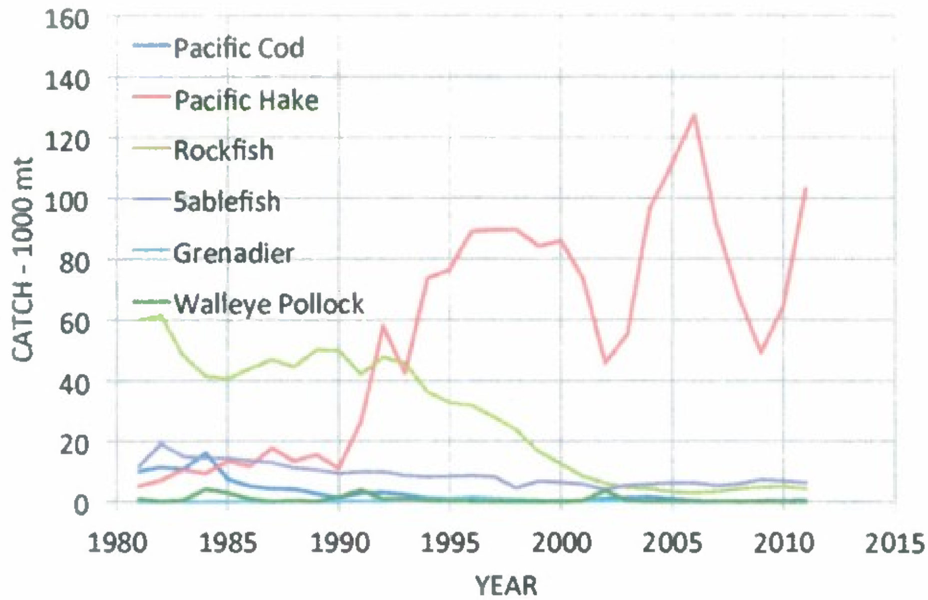

Figure 3 - US catches of midwater and semi-demersal species

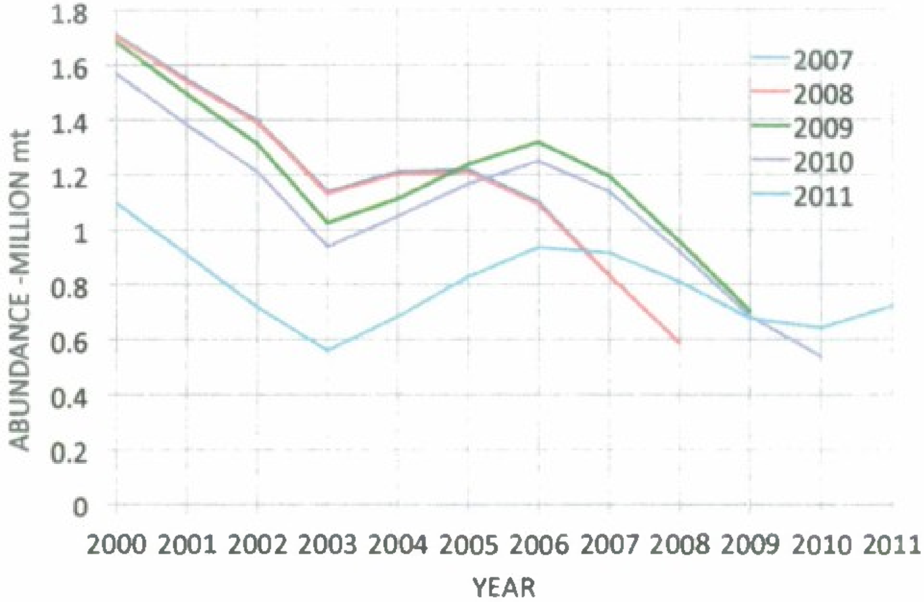

Figure 4 - Estimations of Pacific sardine abundance

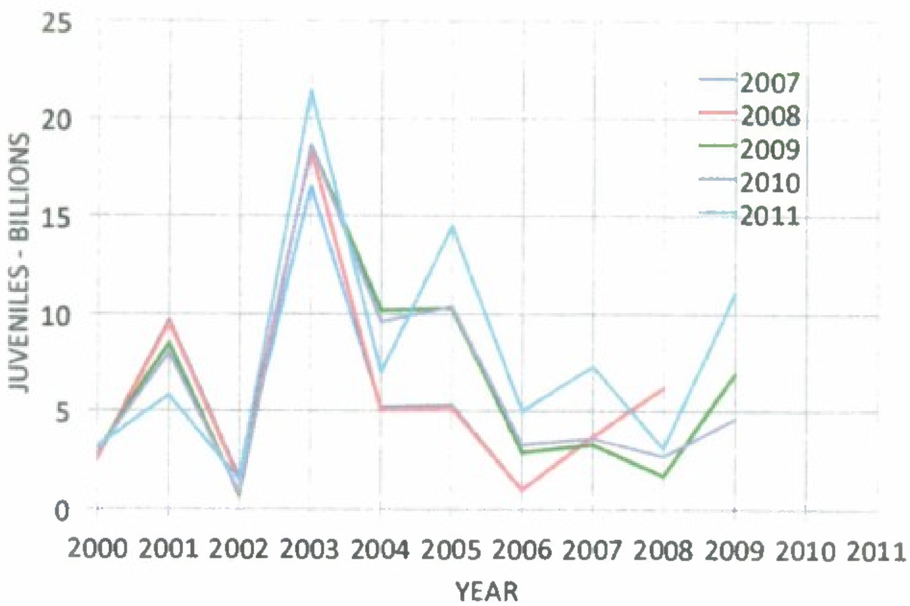

Figure 5 - Estimated numbers of Pacific sardine juveniles

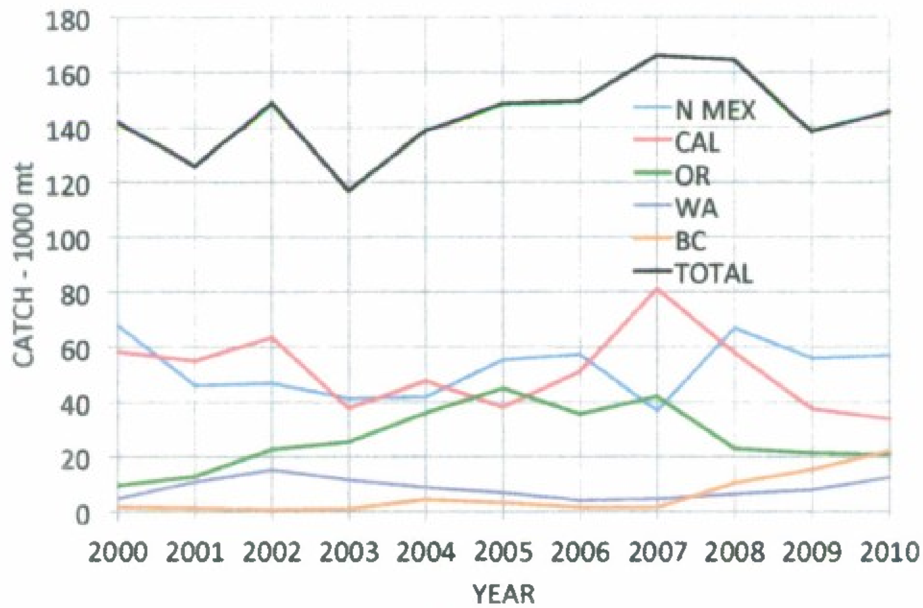

Figure 6 - Pacific Coast catches of Pacific sardines

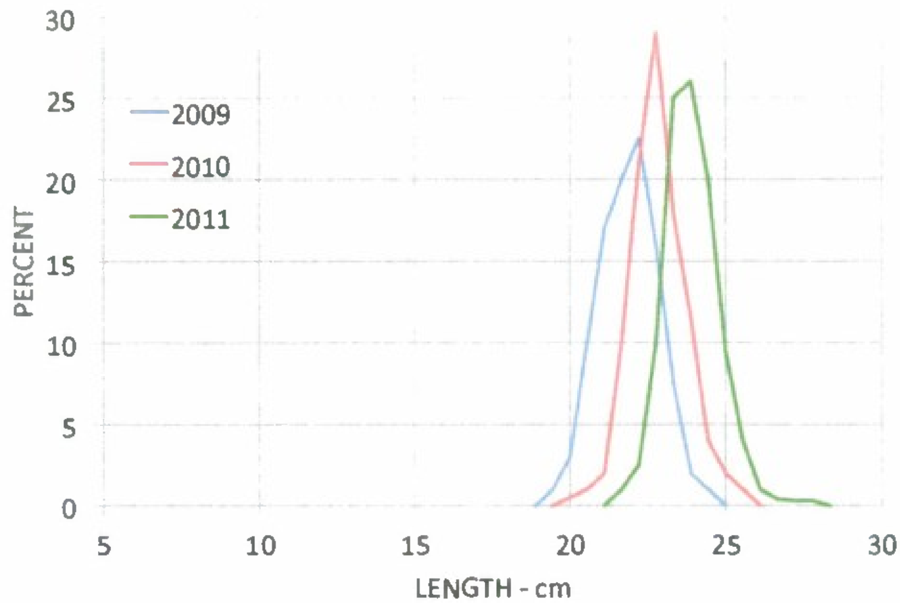

Figure 7 - Aerial survey sardine length distributions

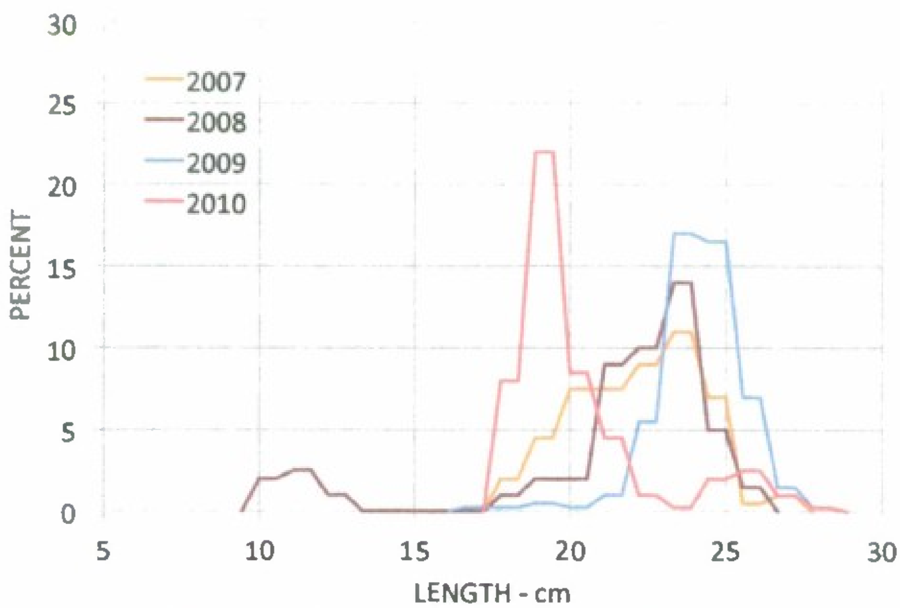

Figure 8 - NMFS spring survey sardine length distributions

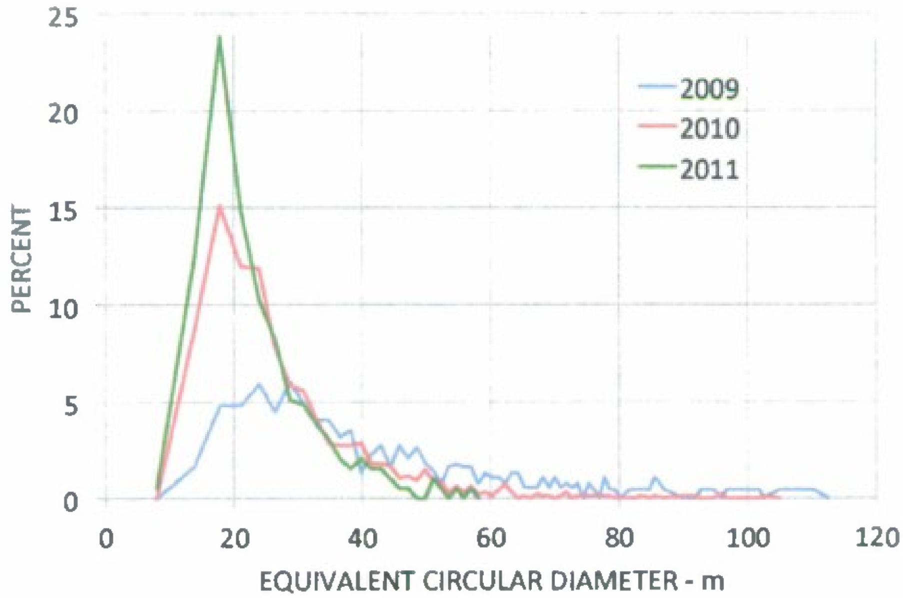

Figure 9 - Aerial survey school size distributions