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RESOURCE IN 2011 FOR U.S. MANAGEMENT IN 2012

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ACRONYMS AND ABBREVIATIONS

ABC	acceptable biological catch
ACL	annual catch limit
ACT	annual catch target
ALK	age-length key
BC	British Columbia (Canada) fishery
CA	California fishery
CalCOFI	California Cooperative Oceanic Fisheries Investigations
CCA	Central California fishery
CDFG	California Department of Fish and Game
CDFO	Canada Department of Fisheries and Oceans
CICIMAR	Centro Interdisciplinario de Ciencias Marinas
CONAPESCA	Comisión Nacional de Acuacultura y Pesca (México's National Commission of Aquaculture and Fishing)
CPS	Coastal Pelagic Species
CPSAS	Coastal Pelagic Species Advisory Subpanel
CPSMT	Coastal Pelagic Species Management Team
CV	coefficient of variation
DEPM	Daily egg production method
ENS	Ensenada (México) fishery
FMP	fishery management plan
HG	harvest guideline, as defined in the CPS-FMP
INAPESCA	Instituto Nacional de la Pesca (México's National Fisheries Institute)
Model Year	July 1 (year) to June 30 (year+1)
mt	metric tons
mmt	million metric tons
MexCal	southern 'fleet' based on ENS, SCA, and CCA fishery data
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
ODFW	Oregon Department of Fish and Wildlife
OFL	overfishing limit
OR	Oregon fishery
PacNW	northern 'fleet' based on OR, WA, and BC fishery data
PFMC	Pacific Fishery Management Council
S1 & S2	Model Season 1 (Jul-Dec) and Season 2 (Jan-Jun)
SCA	Southern California fishery
SS	Stock Synthesis
SSB	spawning stock biomass
SSC	Scientific and Statistical Committee
SST	sea surface temperature
STAR	Stock Assessment Review
STAT	Stock Assessment Team
SWFSC	Southwest Fisheries Science Center
TEP	Total egg production
WA	Washington fishery
WDFW	Washington Department of Fish and Wildlife

PREFACE

The Pacific sardine resource is assessed each year in support of the Pacific Fishery Management Council (PFMC) process that, in part, establishes annual harvest specifications for the U.S. fishery. The following assessment was conducted using the 'Stock Synthesis 3' (SS3) model, and includes fishery and survey data from updated and new sources. A draft assessment was reviewed by a STAR panel 4-7 October, 2011, in La Jolla, California. Modifications to input data and model parameterization were incorporated during the STAR, resulting in changes to population estimates and derived management outcomes. This final draft reflects changes made during the STAR process. The report was presented to the PFMC's advisory bodies (SSC, CPSMT, CPSAS) and the Council at their November 2011 meetings in Costa Mesa, CA, and was subsequently adopted for U.S. Pacific sardine management in 2012. Reports of the STAR panel and PFMC advisory bodies are provided in Appendix 6.

EXECUTIVE SUMMARY

Stock

The Pacific sardine (*Sardinops sagax caerulea*) ranges from southeastern Alaska to the Gulf of California, México, and is thought to comprise three subpopulations. In this assessment, we presumed to model the northern subpopulation which ranges seasonally from northern Baja California, México, to British Columbia, Canada, and up to 300 nm offshore. All U.S., Canada, and México (Ensenada) landings were assumed to be taken from a single northern stock. Future modeling efforts may explore a scenario where Ensenada and San Pedro catches are parsed into the northern and southern stocks using some objective criteria.

Catches

The assessment includes sardine landings from six major fishing regions: Ensenada, southern California, central California, Oregon, Washington, and British Columbia.

Calendar year	ENS	SCA	CCA	OR	WA	BC	Total
2000	67,845	46,835	11,367	9,529	4,765	1,721	142,063
2001	46,071	47,662	7,241	12,780	10,837	1,266	125,857
2002	46,845	49,366	14,078	22,711	15,212	739	148,952
2003	41,342	30,289	7,448	25,258	11,604	978	116,919
2004	41,897	32,393	15,308	36,112	8,799	4,438	138,948
2005	55,323	30,253	7,940	45,008	6,929	3,232	148,684
2006	57,237	33,286	17,743	35,648	4,099	1,575	149,588
2007	36,847	46,199	34,782	42,052	4,663	1,522	166,065
2008	66,866	31,089	26,711	22,940	6,435	10,425	164,466
2009	55,911	12,561	25,015	21,482	8,025	15,334	138,328
2010	56,821	29,382	4,306	20,853	12,381	22,223	145,965

Data and assessment

This assessment was conducted using 'Stock Synthesis' version 3.21d and includes fishery and survey data collected from mid-1993 through mid-2011. The model uses a July-June 'model year', with two semester-based seasons per year (S1=Jul-Dec and S2=Jan-Jun). Catches and biological samples for the fisheries off Ensenada, southern California, central California were pooled into a single 'MexCal' fleet, in which selectivity was modeled separately for each season (S1 & S2). Catches and biological samples from Oregon, Washington, and British Columbia were modeled as a single 'PacNW' fleet. Four indices of relative abundance were included in the base model: daily egg production method and total egg production estimates of spawning stock biomass off California (1994-2011), aerial survey estimates of biomass off Oregon and Washington (2009-2011), and acoustic estimates of biomass observed from California to Washington (2006-2011). Catchability coefficient (*q*) for the acoustic survey was fixed at 1 in the base model. All other survey *q*s were freely estimated.

Unresolved problems and major uncertainties

As in the past, the sardine model can be sensitive with regard to scaling of population estimates. While model likelihoods were robust to large changes in scale (i.e., flat likelihood surface), some model scenarios (e.g. extended time series, or treating Canadian fishery separately) resulted in implausibly high fishing mortality rates at the start and/or end of the modeled time series. In the 2009 and 2010 assessments, the scaling problem was addressed by fixing the aerial survey

catchability coefficient (*q*) to equal 1. For the current assessment, model scaling and stability were improved, in part, by simplifying overall model structure (e.g. fewer time-varying elements and fleets) and reducing the number of estimated parameters. Final base model stability was further improved by fixing *q* for the acoustic time series to equal 1. The acoustic biomass survey was chosen due to the more synoptic nature and longer time series available for the survey. A more detailed listing of modeling issues and uncertainties may be found in the body of this report as well as in the STAR (2011) panel report.

Spawning Stock Biomass and Recruitment

Recruitment was modeled using the Ricker stock-recruitment relationship (σ_R=0.62). The estimate of steepness was high (*h*=2.96), and virgin recruitment (R_0) was estimated to be 6.2 billion age-0 fish. Virgin SSB was estimated to be 0.969 mmt. Spawning stock biomass (SSB) increased throughout the 1990s, with peaks at 1.13 mmt in 1999 and 0.936 mmt in 2006. Recruitment (year-class abundance) peaked at 15.5 billion fish in 1997, 14.9 billion in 1998, 21.4 billion in 2003, and 14.5 billion in 2005. The 2009 year class was estimated to be 11.1 billion fish, higher than the recent average.

Model year	SSB (mt)	SSB Std Dev	Year class abundance (billions)	Recruits Std Dev
2000	1,099,300	156,590	3.176	0.441
2001	910,030	134,710	5.774	0.611
2002	717,380	112,480	1.453	0.280
2003	559,170	93,958	21.444	2.198
2004	683,570	103,390	7.007	0.927
2005	828,760	120,630	14.502	1.573
2006	936,130	132,590	4.968	0.714
2007	915,230	134,720	7.299	0.987
2008	809,350	128,620	3.081	0.584
2009	675,810	119,320	11.107	2.028
2010	642,830	124,630	---	---
2011	720,420	134,540	---	---

Stock biomass

Stock biomass, used for calculating harvest specifications, is defined as the sum of the biomass for sardine ages 1 and older. Biomass increased rapidly throughout the 1990s, peaking at 1.45 mmt in 1999 and 1.27 mmt in 2006. Stock biomass was estimated to be 988,385 mt as of July 2011.
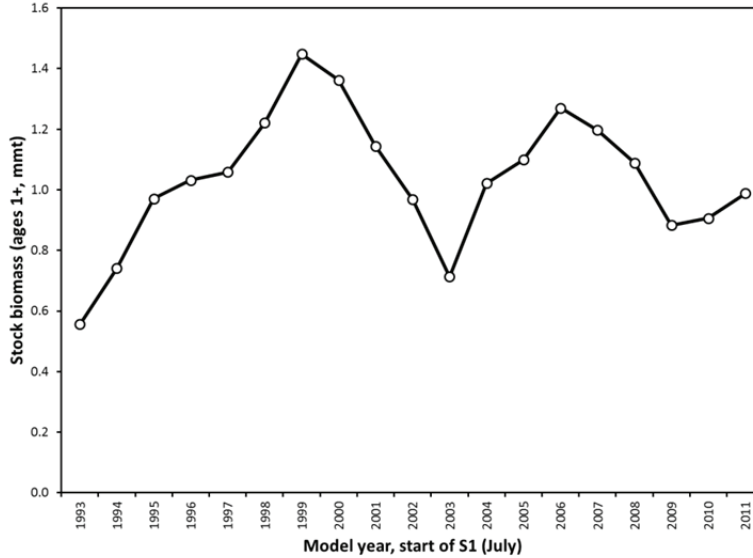
Exploitation status

Exploitation rate is defined as calendar year catch divided by total mid-year biomass (July-1, ages 0+). U.S. exploitation rate has averaged 7.6% since 2000 and is currently about 6.6%. Total coast-wide exploitation rate has averaged 12.8% since 2000 and is currently about 14.5%.
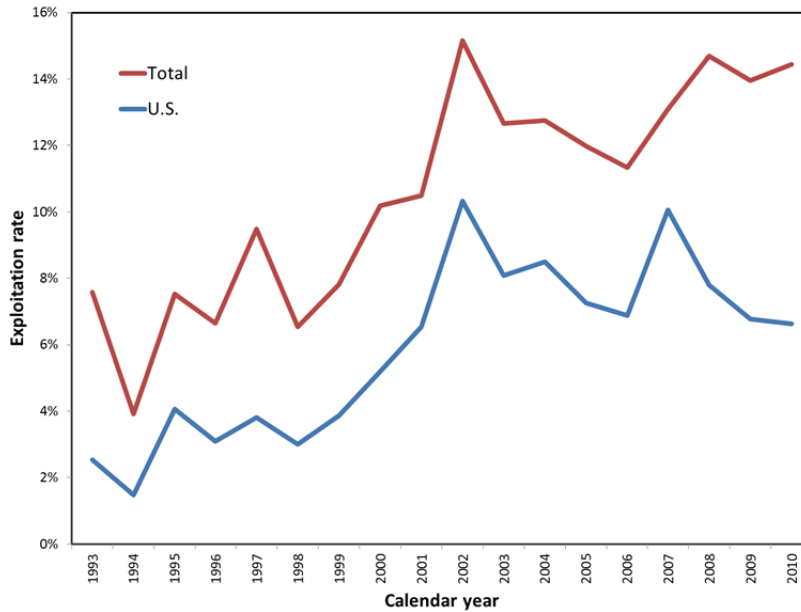
Calendar year	U.S. rate	Total rate
2000	5.20%	10.19%
2001	6.54%	10.48%
2002	10.32%	15.16%
2003	8.08%	12.67%
2004	8.50%	12.75%
2005	7.26%	11.98%
2006	6.88%	11.34%
2007	10.06%	13.09%
2008	7.79%	14.70%
2009	6.77%	13.95%
2010	6.62%	14.45%

Harvest Specifications

Harvest Guideline for 2012

Using results from the final base model ('X5'), the harvest guideline for the U.S. fishery in calendar year 2012 would be 109,409 mt. To calculate the HG for 2012, we used the harvest control rule defined in Amendment 8 of the Coastal Pelagic Species-Fishery Management Plan (PFMC 1998). This formula is intended to prevent Pacific sardines from being overfished and maintain relatively high and consistent catch levels over the long-term. The Amendment 8 harvest guideline for sardines is calculated:

$$HG_{2012} = (BIOMASS_{2011} - CUTOFF) \cdot FRACTION \cdot DISTRIBUTION;$$

where HG_{2012} is the total U.S. (California, Oregon, and Washington) harvest guideline for 2012, $BIOMASS_{2011}$ is the estimated July 1, 2011 stock biomass (ages 1+) from the assessment (988,385 mt), CUTOFF is the lowest level of estimated biomass at which harvest is allowed (150,000 mt), FRACTION is an environmentally-based percentage of biomass above the CUTOFF that can be harvested by the fisheries, and DISTRIBUTION (87%) is the average portion of BIOMASS assumed in U.S. waters.

The following formula has been used to determine FRACTION value:

$$FRACTION = 0.248649805(T^2) - 8.190043975(T) + 67.4558326;$$

where T is the running average sea-surface temperature at Scripps Pier, La Jolla, California during the three preceding seasons (July-June). Under Option J (PFMC 1998), F_{MSY} is constrained and ranges between 5% and 15%. Based on T values observed throughout the period covered by this stock assessment, the appropriate exploitation fraction has consistently been 15%; and this remains the case under current conditions ($T_{2011} = 17.7$ °C). U.S. harvest guidelines and catches since 2000 are displayed below.

OFL and ABC

The Magnuson-Stevens Reauthorization Act requires fishery managers to define an overfishing limit (OFL), allowable biological catch (ABC), and annual catch limit (ACLs) for species managed under federal FMPs. By definition, ABC must always be lower than the OFL based on uncertainty in the assessment approach. The PFMC's SSC recommended the 'P^*' approach for buffering against scientific uncertainty when defining ABC, and this approach was adopted under Amendment 13 to the CPS-FMP.

The estimated biomass of 988,385 (ages 1+, mt), an F_{MSY} estimate of 0.18 based on an analysis presented in Appendix 4, and an estimated distribution of 87% of the stock in U.S. waters results in a U.S. OFL of 154,781 mt for 2012. For Pacific sardines, the SSC has recommended that scientific uncertainty (σ) be set to the maximum of either (1) the CV of the biomass estimate for the most recent year or (2) a default value of 0.36, which was based on uncertainty across full sardine assessment models. Model CV for the terminal year biomass was equal to 0.187 (σ =0.185); therefore scientific uncertainty (σ) was set to the default value of 0.36. The Amendment 13 ABC buffer depends on the probability of overfishing level chosen by the Council (P^*). Uncertainty buffers and ABCs associated with a range of discreet P^* values are presented in the table below.

Harvest Formula Parameters	Value			
BIOMASS (ages 1+, mt)	988,385			
Pstar (probability of overfishing)	0.45	0.40	0.30	0.20
BUFFER$_{Pstar}$ (Sigma=0.36)	0.95577	0.91283	0.82797	0.73861
F_{MSY} (stochastic, SST-independent)	0.18			
FRACTION	0.15			
CUTOFF (mt)	150,000			
DISTRIBUTION (U.S.)	0.87			

Harvest Formulas	MT
OFL = BIOMASS * F_{MSY} * DISTRIBUTION	154,781
ABC$_{0.45}$ = BIOMASS * BUFFER$_{0.45}$ * F_{MSY} * DISTRIBUTION	147,935
ABC$_{0.40}$ = BIOMASS * BUFFER$_{0.40}$ * F_{MSY} * DISTRIBUTION	141,289
ABC$_{0.30}$ = BIOMASS * BUFFER$_{0.30}$ * F_{MSY} * DISTRIBUTION	128,153
ABC$_{0.20}$ = BIOMASS * BUFFER$_{0.20}$ * F_{MSY} * DISTRIBUTION	114,323
HG = (BIOMASS - CUTOFF) * FRACTION * DISTRIBUTION	109,409

INTRODUCTION

Distribution, Migration, Stock Structure, Management Units

Information regarding Pacific sardine (*Sardinops sagax caerulea*) biology is available in Clark and Marr (1955), Ahlstrom (1960), Murphy (1966), MacCall (1979), Leet et al. (2001), and in references cited below.

The Pacific sardine has at times been the most abundant fish species in the California Current. When the population is large it is abundant from the tip of Baja California (23° N latitude) to southeastern Alaska (57° N latitude) and throughout the Gulf of California. Occurrence tends to be seasonal in the northern extent of its range. When sardine abundance is low, as during the 1960s and 1970s, sardines do not occur in commercial quantities north of Baja California.

It is generally accepted that sardines off the West Coast of North America consists of three subpopulations or 'stocks'. A northern subpopulation (northern Baja California to Alaska), a southern subpopulation (outer coastal Baja California to southern California), and a Gulf of California subpopulation were distinguished on the basis of serological techniques (Vrooman 1964) and in a study of temperature-at capture (Felix-Uraga et al., 2004; 2005). An electrophoretic study (Hedgecock et al. 1989) showed, however, no genetic variation among sardines from central and southern California, the Pacific coast of Baja California, or the Gulf of California. Although the ranges of the northern and southern subpopulations overlap, the adult spawning stocks may move north and south in synchrony and do not overlap significantly. The northern subpopulation is exploited by fisheries off Canada, the U.S., and northern Baja California and is included in the Coast Pelagic Species Fishery Management Plan (CPS-FMP; PFMC 1998).

Pacific sardines probably migrated extensively during historical periods when abundance was high, moving north as far as British Columbia in the summer and returning to southern California and northern Baja California in the fall. Tagging studies indicate that the older and larger fish moved farther north (Janssen 1938, Clark & Janssen 1945). Migratory patterns were probably complex, and the timing and extent of movement were affected by oceanographic conditions (Hart 1973) and stock biomass. During the 1950s to 1970s, a period of reduced stock size and unfavorably cold sea surface temperatures apparently caused the stock to abandon the northern portion of its range. In recent decades, the combination of increased stock size and warmer sea surface temperatures resulted in the stock re-occupying areas off Central California, Oregon, Washington, and British Columbia, as well as distant-offshore areas off California. During a cooperative U.S.-U.S.S.R. research cruise for jack mackerel in 1991, several tons of sardines were collected 300 nm west of the Southern California Bight (Macewicz and Abramenkoff 1993). Resumption of seasonal movement between the southern spawning habitat and the northern feeding habitat has been inferred by presence/absence of size classes in focused regional surveys (Lo et al. 2011).

Life History Features Affecting Management

Pacific sardines may reach 41 cm in length, but are seldom longer than 30 cm. They may live up to 15 years, but fish in California commercial catches are usually younger than five years. Sardines are typically larger and two to three years older in regions off the Pacific northwest. There is evidence for regional variation in size-at-age, with size increasing from south to north and from inshore to offshore (Phillips 1948, Hill 1999). Size- and age-at-maturity may decline with a decrease in biomass, but latitude and temperature are also likely important (Butler 1987). At relatively low biomass levels, sardines appear to be fully mature at age one, whereas at very high biomass levels only some of the two-year-olds are mature (MacCall 1979).

Sardines ages three and older were fully recruited to the fishery until 1953 (MacCall 1979). Recent fishery data indicate that sardines begin to recruit at age zero and are fully recruited to the southern California fishery by age two. Age-dependent availability to the fishery likely depends upon the location of the fishery; young fish are unlikely to be fully available to fisheries located in the north, and old fish are less likely to be fully available to fisheries south of Point Conception.

Age-specific mortality estimates are available for the entire suite of life history stages (Butler et al. 1993). Mortality is high at the egg and yolk sac larvae stages (instantaneous rates in excess of 0.66 d^{-1}). Adult natural mortality rate has been estimated to be $M=0.4$ yr^{-1} (Murphy 1966; MacCall 1979) and 0.51 yr^{-1} (Clark and Marr 1955). A natural mortality rate of $M=0.4$ yr^{-1} means that 33% of the adult sardine stock would die each year of natural causes if there were no fishery.

Pacific sardines spawn in loosely aggregated schools in the upper 50 meters of the water column. Northern subpopulation spawning activity begins in January off northern Baja California and ends by August off the Pacific northwest, typically peaking off California in April. Sardine eggs are most abundant at sea surface temperatures of $13^{o}C$ to $15^{o}C$, and larvae are most abundant at $13^{o}C$ to $16^{o}C$. The spatial and seasonal distribution of spawning is influenced by temperature. During periods of warm water, the center of sardine spawning shifts northward and spawning extends over a longer period of time (Butler 1987; Ahlstrom 1960). Recent spawning has been concentrated in the region offshore and north of Point Conception (Lo et al. 1996 & 2005). Sardines are oviparous, multiple-batch spawners with annual fecundity that is indeterminate and age- or size-dependent (Macewicz et al. 1996).

Abundance, Recruitment, and Population Dynamics

Extreme natural variability is characteristic for clupeoid stocks such as the Pacific sardine (Cushing 1971). Estimates of sardine abundance from the years 300 through 1970 have been reconstructed from the deposition of fish scales in sediment cores from the Santa Barbara basin off southern California (Soutar and Issacs 1969, 1974; Baumgartner et al. 1992). Significant sardine populations existed throughout the period with biomass levels varying widely. Both sardine and anchovy populations tend to vary over periods of roughly 60 years, although sardines have varied more than anchovies. Sardine population declines were characterized as lasting an average of 36 years; recoveries lasted an average of 30 years. Biomass estimates inferred from

scale-depositions in the 19th and 20th centuries suggest that the biomass peaked at about six mmt in 1925 (Soutar and Isaacs 1969; Smith 1978).

Sardine spawning biomass estimated from catch-at-age analysis averaged 3.5 million mt from 1932 through 1934, fluctuated from 1.2 to 2.8 million mt over the next ten years, then declined steeply from 1945 to 1965, with some short-term reversals following periods of particularly successful recruitment (Murphy 1966, MacCall 1979). During the 1960s and 1970s, spawning biomass levels were thought to be less than about five thousand to ten thousand mt (Barnes et al. 1992). The sardine stock began to increase by an average rate of 27% per annum in the early 1980s (Barnes et al. 1992).

Pacific sardine recruitment is highly variable. Analyses of the sardine stock recruitment relationship have been controversial, with some studies showing a strong density-dependent relationship (production of young sardines declining at high levels of spawning biomass) and others finding no relationship (Clark and Marr 1955; Murphy 1966; MacCall 1979). Jacobson and MacCall (1995) found both density-dependent and environmental factors to be important.

Relevant History of the Fishery

The sardine fishery was first developed in response to demand for food during World War I. Landings increased from 1916 to 1936, peaking at over 700,000 mt. Pacific sardines supported the largest fishery in the western hemisphere during the 1930s and 1940s, with landings in British Columbia, Washington, Oregon, California, and México. The population and fishery declined, beginning in the late 1940s and with some short-term reversals, to extremely low levels in the 1970s. There was a southward shift in catch as the fishery collapsed, with landings ceasing in the Pacific Northwest in 1947 through 1948, and in San Francisco in 1951 through 1952. Sardines were primarily used for reduction to fish meal, oil, and as canned food, with small quantities taken for bait.

In the early 1980s, sardines were taken incidentally with Pacific and jack mackerel in the southern California mackerel fishery. As sardines continued to increase in abundance, a directed purse-seine fishery was reestablished. The sardine incidental fishery ended in 1991. Besides San Pedro and Monterey, California, substantial Pacific sardine landings are now made in the Pacific northwest and in Baja California, México. Total annual harvest by the Mexican fishery is not regulated by quotas, but there is a minimum legal size limit.

Recent Management Performance

In January 2000, management authority for the U.S. Pacific sardine fishery was transferred to the Pacific Fishery Management Council. The Pacific sardine was one of five species included in the federal CPS-FMP (PFMC 1998). The CPS-FMP includes a maximum sustainable yield (MSY) control rule intended to prevent Pacific sardines from being overfished and to maintain relatively high and consistent catch levels over a long-term horizon. The harvest formula for sardines is provided at the end of this report ('Harvest Guideline for 2012' section). A thorough description of PFMC management actions for sardines, including harvest guidelines, may be found in the most recent CPS SAFE document (PFMC 2011). U.S. harvest guidelines and

resultant landings since calendar year 2000 are displayed in Table 1 and Figure 1a. Coast-wide harvests for major fishing regions from Ensenada to British Columbia are provided in Table 2 and Figure 1b.

ASSESSMENT

Data

Biological Parameters
Stock structure
For purposes of this assessment, we model the northern subpopulation ('cold stock') that ranges from northern Baja California, México to British Columbia, Canada and extends up to 300 nm offshore (Macewicz and Abramenkoff 1993). Specifically, all landings, biological samples, and survey data collected between Ensenada (Mexico) and Vancouver Island (British Columbia, Canada) are assumed to be taken from a single stock. Future modeling scenarios may consider an alternative case that separates the catches in Ensenada and San Pedro into respective northern ('cold') and southern ('temperate') stocks using temperature-at-catch and otolith morphometric criteria proposed by Felix-Uraga et al. (2004, 2005). Subpopulation differences in growth, maturation, and natural mortality would also be taken into account.

Growth
The weight-length relationship for Pacific sardines (combined sexes) was modeled using fishery samples collected from 1981 to 2011 and the standard power function:

$$W = a \, (L^b);$$

where W is weight (kg) at length L (cm), and a and b are regression coefficients. The estimated coefficients were a = 1.68384e-05 and b = 2.94825 (corrected R^2 = 0.928; n = 155,814). Coefficients a and b were fixed parameters in all models (Figure 2a).

The largest recorded Pacific sardine was 41.0 cm long (Eschmeyer et al. 1983), but the largest Pacific sardine taken by commercial fishing since 1981 was 29.7 cm long. The heaviest sardine weighed 0.323 kg. The oldest recorded age is 15 years, but commercially-caught sardines are typically less than seven years old.

Sardine otolith ageing methods were first described by Walford and Mosher (1943) and further clarified by Yaremko (1996). Pacific sardines are routinely aged by fishery biologists in México, California, and the Pacific Northwest using annuli enumerated in whole sagittae. A birth date of July 1 is assumed when assigning year class. Lab-specific ageing errors were calculated and applied as described in 'Conditional age-at-length compositions' and in Appendix 2.

Sardine growth was first estimated outside the SS model to provide initial parameter values and CVs for length at Age_{min} (0.5 yrs), length at Age_{max} (15 yrs), and the growth coefficient K. An analysis of size-at-age from fishery samples (1993-2010) revealed no evidence for sexual dimorphism (Figure 2b), so a single-sex model was applied in SS.

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During the 2009 STAR panel, examination of residuals for the age- and length-composition data revealed that growth was apparently not constant over time. Specifically, there was evidence for a shift in growth rates in 1991. To address this in past assessments, growth parameters were modeled in two time blocks: 1981-1990 and 1991-2009 (Hill et al. 2009, 2010). It is still unclear whether this shift in growth rate was due to density-dependence (compensatory growth) during the early stages of population recovery or some other factor. For example, the early difference in size-at-age could have been due to size-selective schooling, as many of these sardines were sampled from incidental catches (mixed with larger mackerel). Uncertainty around growth and representativeness of early samples was one of several reasons for starting the model in a later period (base model currently begins 1993).

Maturity

Maturity-at-length was estimated using sardines sampled from survey trawls conducted from 1986 to 2011. Reproductive state was primarily established through histological examination, although some immature individuals were simply identified through gross visual examination. Maturity parameters were estimated over two blocks of time to match different SS model scenarios. The full range of available samples was included for models beginning in the early 1980s, resulting in an inflexion = 16.05 cm and slope = -0.78849. A subset of survey samples (1994 to 2011) was used to parameterize maturity in abbreviated SS models (i.e. base case), where inflexion = 15.88 cm and slope = -0.90461. Parameters for the logistic maturity function were fixed in SS, where:

$$\text{Maturity} = 1/(1+\exp(slope*L-L_{\text{inflexion}})))$$

Fecundity was fixed at 1 egg/gram body weight. Resultant maturity and fecundity-at-size and age during the spawning season derived from the final base model are presented in Figure 3.

Natural mortality

Adult natural mortality rate has been estimated to be M=0.4 yr^{-1} (Murphy 1966; MacCall 1979) and 0.51 yr^{-1} (Clark and Marr 1955). A natural mortality rate of M=0.4 yr^{-1} means that 33% of the stock would die of natural causes each year if there were no fishery. Consistent with all previous sardine assessments, the base-case value for the instantaneous rate of natural mortality was taken as 0.4 yr^{-1} for all ages and years (Murphy 1966, Deriso et al. 1996, Hill et al. 1999).

Fishery Data
Overview

Available fishery data include commercial landings and biological samples from six regional fisheries: Ensenada (ENS), Southern California (SCA), Central California (CCA), Oregon (OR), Washington (WA), and British Columbia (BC). Standard biological samples include individual weight (kg), standard length (cm), sex, maturity, and otoliths for age determination (most but not all cases). A complete list of available landings and port sample data by fishing region, model year, and season is provided in Table 3.

Ensenada sardine samples have been collected by INAPESCA since 1989. Sampling has been comparable to that of the U.S. with respect to randomness, frequency, and types of biological

data. INAPESCA has collected approximately 10 random samples of 25 fish per month for size, sex, and reproductive condition, with a random subset being aged using otoliths (Table 3). Our previous sardine assessments have used the subset data for both length and conditional age-at-length compositions as provided by Dr. Roberto Felix-Uraga (CICIMAR-IPN), since the full complement of sample data were not available from INAPESCA. For this assessment, we include newly-available length compositions (catch-weighted aggregates provided by INAPESCA) representing the full set of INAPESCA samples collected from mid-1988 through mid-2009. INAPESCA also provided a full series of conditional age-at-length compositions. However, those data were not included this year due to unresolved issues.

CDFG currently collects 12 random port samples (25 fish per sample) per month from each region. CDFG has collected sardine samples on a regular basis since 1981 (Table 3). ODFW has collected port samples since 1999, and WDFW since 2000 (Table 3). Oregon and Washington fishery samples are typically collected more frequently due to a compressed fishing season, but each sample contains 25 fish.

CDFO has sampled the BC sardine fishery since 1998. CDFO collects 100 fish per sample and requires 100% observer coverage, so most of the BC loads are sampled. CDFO's protocol does include collection of otoliths. However, their ageing efforts have primarily focused on survey samples, so no fishery ages were available for this assessment.

All fishery catches and compositions were compiled based on the sardine's biological year ('model year') to match the July-1 birth date assumption used in age assignments. Each model year is labeled with the first of two calendar years spanned (e.g. model year '1993' includes data from July 1, 1993 through June 30, 1994). Further, each model year had two six-month seasons, where 'S1'=Jul-Dec and 'S2'=Jan-Jun. For the final base model, major fishery regions were pooled to represent a southern 'MexCal' fleet (ENS+SCA+CCA) and a northern 'PacNW' fleet (OR+WA+BC), where the MexCal fleet was treated with semester-based selectivities ('MexCal_S1' and 'MexCal_S2'). Rationale for this design is provided in the 'Model Description' section.

Landings
Ensenada monthly landings, 1981 to 2002, were compiled using the 'Boletín Anual' series previously produced by INAPESCA's Ensenada office (e.g. Garcia and Sánchez, 2003). Monthly landings from 2003 to 2010 were taken from CONAPESCA's web archive of Mexican fishery yearbook statistics (CONAPESCA 2011). Ensenada catch for 2011 was unavailable, so was assumed identical to the catch of 2010.

California (SCA & CCA) commercial landings were obtained from CDFG. CDFG catch data are based on dealer landings receipts which, in some cases, were augmented with special sampling for mixed-load portions. During California's incidental sardine fishery (1981 through 1990), many processors reported sardines as mixed with jack or Pacific mackerel, but in some cases sardines were not accurately reported on landing receipts. For these years, sardine landings data were augmented by CDFG with shore-side 'bucket' sampling of mixed-load fish bins to estimate species portions by weight and track compliance with incidental allowance regulations. CDFG reported these landings statistics in 'Wetfish Tables', which are still distributed by the

Department on a monthly basis. These tables are considered more accurate than PacFIN for California CPS statistics and so were used for this assessment.

Oregon (OR) and Washington (WA) landings were obtained from the PacFIN database. British Columbia monthly landing statistics, 1999 to 2010, were provided by CDFO (Jake Schweigert, pers. comm.). Catch data for 2011 were unavailable, so were assumed identical to those for 2010.

The current SS base model includes landings from 1993 to 2011 and aggregates regional fisheries into a southern 'MexCal' fleet and a northern 'PacNW' fleet (see Model Desciption section for rationale). Landings by model year, semester, and fleet are presented in Table 4 and Figure 4.

Length composition
Length compositions for each fishery and semester were the sums of catch-weighted length observations, with monthly landings within semester being the sampling unit. Length compositions were comprised of 0.5-cm bins ranging from 9 cm to 28 cm standard length (39 bins total). The 9-cm bin reflects all fish $\leq$9.49 cm, the 28-cm bin reflects all fish $\geq$28 cm, and all other bins (9.5 to 27.5 cm) reflect the lower end of the respective 0.5-cm interval (e.g., the 9.5-cm bin includes fish ranging 9.5 to 9.99 cm).

Total numbers of lengths observed in each fishery-semester stratum were divided by the typical number of fish collected per sampled load (25 fish per sample for most regions, 100 fish per sample in Canada) to calculate effective sample sizes (ESS). Compositions having fewer than two samples per semester were omitted from the model. Length-compositions were input as proportions. While raw sample data were not available from the ENS and BC regional fisheries, catch-weighted length distributions, assembled per above, were made available by INAPESCA and CDFO. Once the decision was made to pool ENS with SCA-CCA data (='MexCal') and to combine BC with OR-WA data (='PacNW'), the respective length distributions and effective sample sizes were weighted by catch from each region at the semester level. Landings and ESS by model year, semester, and fleet are provided in Table 4. Length-compositions by fleet are displayed in Figures 5a-c.

Age composition
Implied ('ghost') age compositions were compiled based on the same fishery samples and weighting methods described above in 'Length composition'. Implied age-compositions were included as model inputs with effective sample sizes set to "-1". Inclusion of these input data facilitated comparison of model predictions of age-composition to the inferred values through examination of model residual patterns. Implied age composition data are presented adjacent to corresponding length compositions in Figures 6a-c.

Conditional age-at-length compositions were constructed from the same fishery samples and weighting methods described above. Age bins included 0, 1, 2, 3, 4, 5, 6, 7, 8-10, 11-15 (10 bins total). The age 11-15 bin served as an accumulator allowing growth to approach L_∞. Age-compositions were input as proportions of fish in 1-cm length bins. As per the length-compositions, the number of individuals comprising each bin was divided by number of fish per

sample to set the initial effective sample size. In most cases, age data were available for every length observation. Conditional age-at-length compositions for each fishery are presented in Figures 7a-c.

Ageing error

Ageing error vectors (std. dev. by age, Figure 8) were calculated and linked to fishery-specific conditional age-at-length compositions following methods recommended during the 2009 STAR panel. The past four stock assessments of Pacific sardines (i.e., Hill 2007-2010) relied on traditional methods to estimate and include age-reading precisions in the Stock Synthesis 3 model. The traditional methods assumed that all agers were unbiased and computed standard deviation-at-age (SDa) by averaging across all fish that were assigned a given age a by one or more readers. In addition these estimates of SDa were limited because: (1) they were based solely on age-readings from a 2004 Tri-national workshop, including agers from Mexico, the US and Canada, and thus they were a snap shot in time; and (2) they did not account for difference in age estimation from different fisheries and laboratories. As age-reading errors can impact the performance of stock assessment models, and with the advent of new statistical models that can simultaneously estimate bias and precision, the 2009 Pacific sardine Stock Assessment Review panel recommended that new analyses should be conducted to allow for better estimation and integration of age-reading errors in future Pacific sardine assessment models.

In this assessment, we estimated SD for three fisheries (Ensenada, California, Pacific Northwest) and the DEPM survey. Age-reading data sets (i.e., sets of otoliths that were aged by the same set of agers) were built by fishery and date of fish collection. These data were produced by four ageing laboratories: CICIMAR-IPN (Baja California Sur, Mexico); CDFG (CA, US); SWFSC (CA, US); and WDFW (WA, US). For each fishery and the DEPM survey, we compared SD estimated from the traditional method and the Age-Reading Error Matrix Estimator (Agemat model), a statistical model developed by Punt et al. (2008). The Agemat model uses the maximum likelihood method to estimate ageing errors and typically compute SD by age-reader. However, age data and age-reading errors cannot be included in the Stock Synthesis 3 model by ager. As an alternative, we defined various model scenarios, comparing models that assumed equal or unequal SD among agers for each fishery and the DEPM survey. Then, we used AICc (Akaike Information Criterion with a correction for finite sample sizes) to select the best model and thus determined whether there was enough evidence to support the assumption of equality of SD among agers for the age-reading data sets considered in a given model. We refer the reader to Appendix 2 for more details regarding age-reading data sets, model development and assumptions.

Estimates of standard deviation-at-age from the traditional method and the Agemat model were different. Estimates from the Agemat model were derived from models that assumed equality of SD among agers. These models were selected because they had the lowest AICc when compared to models that did not assume equality of SD among agers (Appendix 2, Table 8).

Final model runs of the Stock Synthesis model were based on SD estimated from the Agemat model (Figure 8). Although SDs estimated for the Ensenada and the PNW fisheries were based on a single year of fish collection; time-series of age data used in this assessment for these two fisheries were produced by the same agers. Thus we could assume that for the Ensenada and the

PNW fisheries, age-reading errors did not change over time. In contrast for the California fishery and the DEPM survey, multiple readings of otolith samples were performed on a yearly basis, but there was turnover among agers. Therefore, in this assessment we used time-varying estimates of SDa for the California fishery and the DEPM survey.

Fishery-Independent Data
Overview
This assessment includes four time series obtained from fishery-independent surveys: 1) Daily Egg Production Method (DEPM) estimates of female spawning biomass; 2) Total Egg Production (TEP) estimates of total spawning biomass; 3) Aerial photogrammetric surveys of biomass; and 4) Acoustic-trawl surveys of biomass. The DEPM, TEP, and Aerial surveys and estimation methods were previously reviewed and included in recent sardine assessments. The SWFSC acoustic-trawl time series of biomass is new to this assessment model, and the survey and estimation approach was rigorously reviewed in February 2011. All surveys were initially treated as time series of relative abundance in the base model (pre-STAR model 'Ld'). Following recommendations of the 2011 STAR panel, the acoustic survey series is now modeled with a catchability coefficient (q) of 1 to provide further stability in scaling population estimates. Survey estimates and standard errors are presented in Table 5.

Daily egg production method spawning biomass
DEPM and TEP estimates of SSB were based on SWFSC ship-based surveys conducted each April between San Diego and San Francisco. The DEPM index of female SSB is used when adult daily-specific fecundity data are available from the survey. The total egg production (TEP) index of SSB is used when survey-specific fecundity data are unavailable. The DEPM and TEP series have been used for sardine stock assessment since the 1990s, and the surveys and estimation method were reviewed by a STAR panel in May 2009. Both time series are treated as indices of relative SSB, with catchability coefficients (q) being estimated (Figure 15).

The SWFSC conducted a coastwide California Current Ecosystem (CCE) survey from March 23 to April 29, 2011 aboard the NOAA ship *Bell M. Shimada* and the F/V *Frosti*. The survey, which ranged from Cape Flattery, Washington to San Diego, California (Figure 9a) including the primary CalCOFI area (CalCOFI lines 76.7 to 93.3), employed all the usual methods for estimating sardine SSB via the DEPM (Lo et al. 2010). The survey included a complete sampling of the 'standard' area for the assessment models' DEPM time series, i.e. San Francisco to San Diego (Figure 9b).

The standard DEPM index area off California (San Diego to San Francisco; CalCOFI lines 95 to 60) was 314,481 km^2, and the egg production (P_0) estimate was 1.16/0.05m^2 (CV = 0.29)(Lo et al. 2011). Even though only a small area close to Astoria, Washington (47.1° - 45.9° N) was sampled by the *Bell M. Shimada*, no eggs and only two immature sardines were collected in the area north of CalCOFI line 63.3. Female spawning biomass for the standard area was taken as the sum of female spawning biomasses in regions 1 and 2 (Table 6). The female spawning biomass and total spawning biomass (sum) for the standard DEPM area were estimated to be 219,386 mt (CV = 0.28) and 373,348 mt (CV = 0.28), respectively (Table 6). Adult reproductive parameters for the survey are presented in Table 7. The daily specific fecundity was calculated as 19.04 (number of eggs/population weight (g)/day) using the estimates of reproductive parameters

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from 244 mature females collected from 30 positive trawls, where mean batch fecundity (F) was 38369 eggs/batch (CV = 0.07), fraction spawning (S) was 0.1078 females spawning per day (CV = 0.18), mean female fish weight (W_f) was 127.6 g (CV = 0.05), and sex ratio of females by weight (R) was 0.587 (CV = 0.06). Since 2005, trawling has been conducted randomly or at CalCOFI stations, which resulted in sampling adult sardines in both high (Region 1) and low (Region 2) sardine egg density areas. During the 2011 survey, the number of tows positive for mature female sardines was similar in Regions 1 and 2 (14 and 16 respectively), while four additional tows in Region 2 contained solely immature sardines (Lo et al. 2011).

In SS, the DEPM series was taken to represent female SSB (length selectivity option '30') in the middle of S2 (April). Since 2009, the time series of spawning biomass was replaced by female spawning biomass for years when sufficient trawl samples were available and the total egg production for other years as inputs to the stock assessment of Pacific sardines. The 2011 DEPM estimate is considerably higher than in the previous few years, primarily due to the relative high egg production (Tables 5 & 6; Figure 15).

Total egg production spawning biomass
Adult sardine samples are needed to calculate daily specific fecundity for true DEPM estimates. Sardine trawls were not always conducted during the egg production surveys. Beginning in 2007, we chose to include these data as a Total Egg Production (TEP) series, which is simply the product of egg density (P_0) and spawning area (km^2). Calculated TEP values are provided in Table 5 & 6 and displayed in Figure 15. TEP was also taken to represent relative SSB (length selectivity option '30') in the model, but in this case the female fraction was unknown (Tables 5 & 6; Figure 15).

Aerial survey
The Pacific sardine industry has funded aerial photogrammetric surveys of sardine abundance off the coast of Oregon and Washington, beginning with a pilot survey in summer 2008. The 2008 survey methodology and results were reviewed by a STAR panel in May 2009. Full surveys were subsequently conducted during summers of 2009, 2010, and 2011 (Jagielo et al. 2009-2011).

The Aerial survey employs two sampling elements: 1) high-resolution photographs collected by spotter planes to estimate the number and surface area of sardine schools, and 2) using fishing vessels to conduct point sets on schools to determine the relationship between surface area and biomass and to determine size composition of the schools. Maps of the 2009 and 2010 biomass distributions and point set locations are displayed in Figure 10 and 11. Weighted length compositions from the three surveys are displayed in Figure 12. A complete description of the methods and results can be found in Jagielo et al. (2009-2011).

The past two assessments (Hill et al. 2009 & 2010) have treated the aerial biomass estimates as absolute (q=1), with length selectivity being dome-shaped. The current assessment continued using domed-selectivity but now treats the time series as relative (Figure 15), i.e. catchability (q) is now estimated.

Acoustic survey

The Acoustic-trawl time series is based on SWFSC surveys conducted coast-wide (most years) between San Diego and Cape Flattery, Washington since 2006. The acoustic-trawl surveys and estimation methods were reviewed by an independent review panel in February 2011. Following the methodology review, recommended revisions were made and additional survey data (April 2011) were incorporated (Demer et al. 2011; Zwolinski et al. 2011a,b).

Sardine size and age composition data were available from survey trawls. Survey length compositions were based on biomass-weighted length distributions from each haul (Demer et al. 2011; Zwolinski et al. 2011a,b) (Figure 14a). Conditional age-at-length compositions were available for surveys conducted in spring of 2006, 2008, and 2010 (Figure 14b). Survey-specific ageing error vectors were also included in the model (Figure 8). Acoustic trawl biomass estimates were treated as absolute ($q = 1$), with asymptotic length selectivity assumptions (Figure 15).

Data Sources Considered But Not Used

Pacific sardines are routinely collected during two additional surveys: 1) CDFO's swept area trawl survey for sardines, conducted each summer along the west coast of Vancouver Island (Canada), and 2) the SWFSC's juvenile rockfish mid-water trawl survey, conducted during late spring along the central and southern California coast. CDFO's trawl survey was described by MacFarlane et al. (2005) and has been proposed for potential methodology review during 2012 (Schweigert & Flostrand 2011). The SWFSC juvenile rockfish survey was described by Sakuma et al. (2006) and Field et al. (2010), and a preliminary analysis of sardine CPUE and size data has been summarized by Crone (2011) in Appendix 3 of this report. As noted in the 2011 STAR panel report, any substantial new data source would likely need to be reviewed during a Council-sponsored Methodology Review panel before it could be included in the sardine stock assessment.

History of modeling approaches

The Pacific sardine population (pre-collapse) was first modeled by Murphy (1966). MacCall (1979) refined Murphy's VPA analysis using additional data and prorated portions of Mexican landings to exclude the southern subpopulation. Deriso et al. (1996) modeled the recovering population (1982 forward) using CANSAR, a modification of Deriso's (1985) CAGEAN model. CANSAR was subsequently modified by Jacobson (NOAA) into a *quasi* two-area model 'CANSAR-TAM' to account for net losses from the core model area. CANSAR and CANSAR-TAM were used for annual stock assessments and management advice from 1996 through 2004 (e.g. Hill et al. 1999, Conser et al. 2003). In 2004, a STAR panel endorsed use of the ASAP model for routine assessments. ASAP was used for sardine assessment and management advice for calendar years 2005 to 2007 (Conser et al. 2003 & 2004, Hill et al. 2006a,b). In 2007, a STAR panel reviewed and endorsed an assessment using 'Stock Synthesis 2' (Methot 2005, 2007), and the results were adopted for management in 2008 (Hill et al. 2007) as well as an update for 2009 management (Hill et al. 2008). The sardine model was transitioned to Stock Synthesis version 3.03a in 2009 (Methot 2009) and was again used for an updated assessment in 2010 (Hill et al. 2009 & 2010).

Responses to 2009 STAR Panel and 2010 SSC CPS-Subcommittee Recommendations

A. Future assessments should consider the fishery-independent mid-water trawl surveys off the west coast of Vancouver Island. This data set is potentially valuable as it provides abundance information for a large area within Canadian waters. However, it needs to be analyzed further before it can be included in a future assessment. The STAT should confer with the lead investigator for the WCVI survey to obtain further information, including raw data. If necessary, the lead investigator should be invited to attend the next STAR panel to present results for this time series.

   <u>STAT Response</u>: The PFMC reviewed a number of requests for CPS survey methodology reviews during 2011 (SWFSC's Acoustic survey, Southern California Aerial-LIDAR Survey, and Pacific NW Satellite Imagery Survey). However, CDFO's swept area trawl survey was not formally proposed for review. From the STAT's perspective, CDFO's swept area trawl survey would be of limited utility in the assessment for two reasons: (1) spatial coverage is limited to areas off Vancouver Island, the northern tail of the stock's distribution, and (2) CDFO's biomass estimates (nighttime trawls, 2006-2010) have large CVs (1.5~3.0), so the survey would not be an informative time series within an assessment model.

B. Further review the sampling protocols and analysis methods for other potential indices of abundance (such as the SWFSC juvenile rockfish survey and the acoustic surveys, which have been conducted in conjunction with egg surveys since 2003) and consider inclusion of such data in future assessments.

   <u>STAT Response</u>: The STAT (Crone) has conferred with the lead scientist for the SWFSC's Pelagic Juvenile Rockfish Survey (Dr. John Field) regarding potential use of sardine data as a time series in the assessment. A delta-GLM model was used to generate a time series of sardine abundance for the core and broader survey areas. Raw (i.e. un-weighted) length distributions were also developed. A summary analysis is provided in Appendix 3 of this report (Crone 2011). Overall, the STAT concludes that this survey will require further evaluation, and potentially a methodology review, before being adopted as an index in an ongoing assessment for sardine.

C. Density-dependent changes in growth or reproduction have not been identified nor evaluated. Maturity at length is variable from year to year, although adult sampling has not been consistent, and young fish may be under-represented. Available maturation ogives could be compared to biomass estimates to identify possible density-dependent effects, although environmental variation is likely to be a major factor in growth and maturation, so inference may be weak.

   <u>STAT Response</u>: Length-at-maturity (L_{50}) can change considerably among survey years, likely due to a combination of sampling bias and movement. This recommendation suggests looking for density-dependence, but this will be difficult unless sources of potential bias are identified and addressed. Smaller, immature fish are under-represented in the regressions.

D. Fecundity at age is based on weight and does not account for the total number of batches of eggs produced during a season (annual fecundity). While the spawning frequency during the peak season does not appear to be age-dependent, the length of the spawning season may be longer in older fish. This may affect the stock-recruitment relationship. Whether visual

estimates of activity (presence of developed gonads) from port-collected samples can be used to estimate length-specific timing and duration of spawning across the stock's range should be explored.

STAT Response: The STAT examined visual maturity data available from port-samples collected 1981 to 2010 (CA, OR, WA) and found some evidence for size-dependence in duration of spawning season (Figure 3c). Data from the SWFSC's egg production surveys (not presented here) also indicate a size-dependence in spawning frequency. Given this preliminary evidence for size-dependence in annual fecundity, it is not entirely clear how this relationship should best be modeled in SS. That is, should this information by captured in the fecundity equation (eggs/gram), or should an age-specific fecundity vector be applied? Time did not permit further exploration of this problem prior to the conclusion of this draft.

E. There continues to be uncertainty in the DEPM survey as a key indicator of spawning stock biomass trends coastwide. Expand coastwide sampling of adult fish to further refine the estimate of the proportion spawning.

STAT Response: The SWFSC continues to pursue coast-wide surveys as frequently as possible. The most recent coast-wide survey, conducted in 2010, found little evidence of sardines (ichthyoplankton, trawled adults, or acoustic backscatter) outside of the standard DEPM area (Figure 9b). Plans are underway to conduct a synoptic survey in 2012.

F. Temperature at catch could provide insight in stock structure and the appropriate catch stream to use for assessments, because the southern subpopulation is thought to prefer warmer water. Conduct tests of alternative assumptions regarding the fraction of the ENS and SCA catch that comes from the northern subpopulation.

STAT Response: This is a potentially important research exercise, but not one that will soon translate into a model for management advice. Felix et al. (2004, 2005) used course grid (2-degree) SST data from the Hadley Centre (U.K.). Additional work is needed to look at the best oceanographic data and spatial scope for parsing the catch and comp data. This topic is currently being studied by a graduate student at CICIMAR-La Paz.

G. The assessment would benefit not only from data from Mexico and Canada, but also from a joint assessment, which includes assessment team members from these countries.

STAT Response: A joint INP-NMFS sardine assessment workshop was held in La Paz during September, 2010. The workshop resulted in exchange of information regarding the SS modeling platform, as well as standardized data sets for the respective fisheries off Mexico and the U.S.

H. Re-evaluate the magnitude of discards in each fishery, and account for discards in future assessments.

STAT Response: No extensive work has been undertaken on this topic. In general, the small purse seine fisheries are relatively 'clean' with regard to discards, given the nature of the fishing procedure (i.e. purse contents being pumped into the hold) and the practical difficulties incurred by dumping entire loads. Under-reporting on landing receipts has been documented by enforcement agents. However, it would be problematic to apply some expansion factor to the entire catch.

I. Otolith and microchemistry studies are useful tools for evaluating stock structure. Results should be evaluated to determine if the spatial distribution is purely age-dependent or due to an alternate life history strategy. These evaluations could be combined with a traditional tagging study (which has not been done since the 1940s) to provide useful information about fish migration and distribution.
   STAT Response: No data were available.

J. The relationship between environmental correlates and abundance should be examined. In particular, the relationship between environmental covariates and recruitment deviations should be explored further.
   STAT Response: This is a currently-funded project under the FATE program. However, no new time series is yet available.

K. Further evaluate the appropriate form of stock-recruitment relationship for Pacific sardine, including appropriate environmental covariates.
   STAT Response: The STAT has explored alternative S-R functions in SS (e.g. Beverton-Holt, CAA), however, all have resulted in poorer overall fits to the data, with worsening trends in the recruitment deviations. McClatchie et al. (2010) have raised doubts regarding applicability of SST data collected at the SIO pier. No alternative environmental covariate has been identified.

L. Consider spatial models for Pacific sardine, which can be used to explore the implications of regional recruitment patterns and region-specific biological parameters. These models could be used to identify critical biological data gaps.
   STAT Response: This is the focus of a current Washington SeaGrant project (PI: Andre Punt), and is been being studied intensively by Dr. Punt's graduate student, Felipe Hurtado.

M. Re-estimate age-reading error matrices and include them in updated assessments.
   STAT Response: This item has been addressed and fully documented in Appendix 2 (Dorval et al. 2011).

N. During the May 2009 STAR panel review of the DEPM survey, the panel recommended applying Bayesian hierarchical models to estimate adult spawning fraction in years when survey collections are less than adequate. This request has been studied by Lo et al. (2011) and is attached as Appendix 5.

O. During the SSC CPS-Subcommittee review of the 2010 assessment update (October 2010), the subcommittee made a recommendation to "Explore model configurations in which the selectivity pattern for the aerial survey in the north is asymptotic, as is the case for the fishery, rather than dome-shaped." The subcommittee's recommendation was based on the STAT's analysis of selectivity assumptions (asymptotitc vs. domed) presented during the update review and further summarized in the 2010 update report (Hill et al. 2010). Selectivity shape can be quite important when an index is taken to represent absolute abundance (e.g. aerial survey q=1), as was demonstrated in the 2010 assessment update (Hill et al. 2010). The aerial survey was not modeled with $q = 1$ during the 2011 assessment, so this recommendation was not explored further.

Model Description

Assessment program with last revision date

Stock Synthesis version 3.21d (Methot 2005, 2011) is based on the AD Model Builder software environment (Otter Research 2001). The SS model framework allows the integration of both size and age structure. The general estimation approach used in the SS model accounts for most relevant sources of variability and expresses goodness of fit in terms of the original data, potentially allowing final estimates of model precision to capture most relevant sources of uncertainty.

The SS model comprises three sub-models: 1) a population dynamics sub-model, where abundance, mortality and growth patterns are incorporated to create a synthetic representation of the true population; 2) an observation sub-model that defines various processes and filters to derive expected values for the different type of data; and 3) a statistical sub-model that quantifies the difference between observed data and their expected values and implements algorithms to search for the set of parameters that maximizes the goodness of fit. These sub-models are fully integrated, and the SS model uses forward-algorithms, which begin estimation prior to or in the first year of available data and continues forward up to the last year of data (Methot 2005, 2011).

Definitions of fleets and areas

Data from major fishing regions are aggregated to represent southern and northern fleets. The southern 'MexCal' fleet includes data from three major fishing areas at the southern end of the stock's distribution: northern Baja California (Ensenada, Mexico), southern California (Los Angeles to Santa Barbara), and central California (Monterey Bay). Fishing can occur throughout the year in the southern region. However, availability-at-size/age changes due to migration. Selectivity for the southern 'MexCal' fleet was therefore modeled separately for seasons 1 and 2 ('S1' & 'S2').

The 'PacNW' fleet includes data from the northern range of the stock's distribution, where sardines are typically abundant between late spring and early fall. The PacNW fleet includes aggregate data from Oregon, Washington, and Vancouver Island (British Columbia, Canada). The majority of fishing in the northern region typically occurs between July and October (S1).

Likelihood components and model parameters

A complete list of model parameters is provided in Table 8. The objective function for the base model included likelihood contributions from 1) fits to catch, 2) fits to the DEPM, TEP, Aerial, and Acoustic surveys; 3) fits to length compositions from the three fleets, Aerial and Acoustic surveys; 4) fits conditional age-at-length data from the three fleets and the Acoustic survey; 5) deviations about the spawner-recruit relationship; and 6) minor contributions from parameter soft-bound penalties (Table 9).

The final base model (X5) incorporates the following specifications:
- model year spans July 1-June 30 (July 1 birth date assumption);
- two seasons (S1=Jul-Dec and S2=Jan-Jun) (assessment years 1993 to 2011);

- sex is ignored;
- two fleets (MexCal, PacNW), with an annual selectivity pattern for the PacNW fleet, and seasonal selectivity patterns for the MexCal fleet;
- length-frequency and conditional age-at-length data for all fisheries;
- length-based, double-normal selectivity with time-blocking (1993-1998, 1999-2011) for the MexCal fleet; asymptotic length-selectivity for the PacNW fleet;
- Ricker stock-recruitment relationship with estimated "steepness"; $\sigma_R = 0.622$ (tuned);
- virgin (R_0) and initial recruitment offset (R_1) were estimated;
- spawning occurs in S2 and recruitment in S1;
- initial recruitment estimated; recruitment residuals estimated for 1987-2009;
- initial Fs set to 0 for all fleets;
- hybrid-F fishing mortality (option 3);
- $M = 0.4 \text{ yr}^{-1}$ for all ages;
- DEPM and TEP measures of spawning biomass; q estimated;
- aerial survey biomass, 2009-2011, q estimated, domed selectivity; and
- acoustic survey biomass, 2006-2011, $q=1$, asymptotic selectivity.

Selectivity assumptions

Length data from the MexCal and PacNW fleets were fit using a length-based selectivity. The MexCal fleet was fit using the domed selectivity (double-normal function), as we assumed that not all larger sardines were available to the Baja California and California fisheries from 1993 onward. At that stage in the population's recovery, large spawning events were observed off central California (Lo et al. 1996), and sardines were captured in trawls 300 nm off the California coast (Macewicz and Abramenkoff 1993). Selectivity for the MexCal fleet was estimated by season and in two time blocks (1993-1998, 1999-2011) to better account for both seasonal- and decadal-scale shifts in sardine availability to the southern region.

PacNW fleet lengths were fit using asymptotic selectivity (simple logistic). Large sardines are typically found in the northern region, and it is assumed the largest sardines are best able to migrate to northern feeding habitats in summer. The 2007 STAR recommended fitting PacNW lengths over two time blocks (break at 2003/2004) to better fit a decrease in length observed following the large 2003 recruitment event. While the additional time block had resulted in slightly better fit to the PacNW lengths (Hill et al. 2007), we decided to remove this time block from the current base model as there was no theoretical basis for its application.

Stock-recruitment constraints and components

Pacific sardines are believed to have a broad spawning season, beginning in January off northern Baja California and ending by July off the Pacific Northwest. The SWFSC's annual egg production surveys are timed to capture (as best is possible) the peak of spawning activity off the central and southern California coast during April. In our semester-based model, we calculated SSB at the beginning of S2. Recruitment was specified to occur in Semester-1 of the following model year (consistent with the July-1 birth date assumption).

As per past assessments (Hill et al. 2007, 2009), we explored models fit with Ricker and Beverton-Holt S-R functions. Models based on the Ricker function were ultimately more stable

and improved the trend in recruitment deviations. Jacobson and MacCall (1995) found that Pacific sardines were best modeled using Ricker assumptions, and past assessments using CANSAR and CANSAR-TAM included a modified Ricker S-R function (e.g. Deriso et al. 1996, Hill et al. 1999, Conser et al. 2003).

Virgin recruitment (R_0), initial recruitment offset (R_1), and steepness (h) were all freely estimated. Recruitment variability (σ_R) was initially set at a high value (0.9), and later fixed at 0.622 to match the model RMSE. Recruitment deviations were estimated as separate vectors for the early and main data periods. Early recruitment deviations for the initial population were estimated from beginning in 1987 (start year minus 6). A recruitment bias adjustment ramp was applied to the early period (Figure 32d).

The last year for the main recruitment deviations was set at 2008, which means that the 2009 year class was freely estimated from the data and the 2010 and 2011 year classes were derived from the Ricker curve. This is a change from past assessments, which estimated recruitments until end year minus one. Our rationale for this change is that there is very little information on recent recruitment available from the last two years of data. Implied age-selectivities (product of length selectivity and the age-length key) from the fisheries and surveys are displayed in Figures 18b and 25b. The Acoustic survey is about ~85% selected by age-2, and other surveys are selected at older ages (Figure 25b). The MexCal_S2 fleet (1999-2011 block) is fully selected by age-1, but these fish are approaching their second birthday. The MexCal_S1 fleet (same block) is fully selected at age-2.

Selection of first modeled year and treatment of initial population
Recent assessments started the model in 1981 (Hill et al. 2007-2010). However, we chose to begin the base model in 1993. This year was chosen for several reasons: 1) as stated previously, there is some uncertainty regarding representativeness of the early (1981-1990) composition data, which was a mixture of samples from incidental and directed fisheries (Table 3); 2) egg production surveys of the mid-1980s were conducted between June and August within the Southern California Bight (Table 5), so they covered a smaller geographic range and might have sampled summer spawning of the southern subpopulation; and 3) scaling problems encountered in models using the full time series may be exacerbated by starting the population at a such low levels (1,000s of tons) relative to 'recovered' conditions (>1 mmt).

The initial population was calculated by estimating early recruitment deviations from 1987-1992, six years prior to the model start year. In the pre-STAR assessment model ('Ld'), initial F was estimated for the MexCal_S1 fleet and fixed at low values for the MexCal_S2 and PacNW fleets, and non-equilibrium conditions were assumed (i.e. lambdas for equilibrium catch were set to zero). The initial F parameter for MexCal_S1 was consistently estimated at $F=4$ yr^{-1}, a value that was not credible. Moreover, the fishery selectivity used to calculate initial F appeared to be taken from a later time block (1999-2011) instead of the early period (1993-1998), indicating a potential SS coding error. To address this problem, the STAR panel recommended starting the model with all initial F parameters set to zero (STAR 2011; request 'N'). The new model had a trend in biomass that was nearly identical, scaled 40-50% higher, and had survey q estimates that were more reasonable than model 'Ld'.

The implications of assuming initial $F=0$ yr^{-1} (as opposed to some value >0) were not explored during the STAR, but the STAT did note there was a fishery occurring during the initial modeled period (late 1980s and early 1990s). Following the STAR, the STAT tested a model where initial F for MexCal_S1 was fixed at a moderate level ($F=0.5$ yr^{-1}). The terminal year stock biomass for that model scaled lower by a minor amount (3%) relative to the base model ('X5') where initial $F=0$.

Convergence criteria and status
The iterative process for determining numerical solutions in the model was continued until the difference between successive likelihood estimates was <0.0001. Final gradient for the base model was 0.00003444.

Base model changes made during the 2011 STAR panel
The STAT explored a wide range of model designs and parameterizations and conducted suites of sensitivity analyses throughout the 2011 STAR panel (see STAR 2011 for complete details). Resultant changes from the preliminary model (pre-STAR model 'Ld') to the final STAR base model ('X5') were as follows:
1) Smoothed the ageing error vector for CA-2007 (STAR request 'B');
2) Minor correction to the summer 2008 acoustic biomass estimate (changed from 783,740 mt to 801,000 mt) (STAR request 'F');
3) Set the Initial-F parameters to 0 (STAR request 'N');
4) Acoustic survey q fixed to equal 1(STAR request 'X.5')

The first two changes (requests 'B' and 'F') were trivial corrections to model inputs and had no detectable effect on population estimates or model fits. The third change (request N), which resulted in upward scaling of population estimates, was discussed above in the section 'Selection of first modeled year and treatment of initial population' and in the STAR (2011) report. The fourth change (request 'X5') was incorporated to provide scaling stability to the final base model (STAR 2011).

Base Model Results

Parameter estimates and errors
Base model parameter estimates and standard errors are presented in Table 8. Most model parameters were within a reasonable range of bounds and had relatively small standard errors.

Growth
Modeled length-at-age is displayed in Figure 16. Length at age 0.5 was estimated to be 11.2 cm SL, L_∞ was 24.0 cm, and the growth coefficient K was 0.399. Standard deviations for the growth parameters are provided in Table 8. Fits to fleet and survey conditional age-at-length data are shown in Figures 17a-d. Most conditional age-at-length compositions fit reasonably well, with the exceptions of MexCal_S1 in 1993 and 2002-2003 (Figure 17a) and PacNW in 2008-2010 (Figure 17c).

Selectivity estimates and fits to composition data

Length selectivity estimates for each fleet and time period are displayed in Figure 18a. Implied age selectivities (product of length selectivity and the age-length key) for each fleet and period are shown in Figure 18b. The MexCal fleets (S1 & S2) captured progressively smaller fish between the early and latter time blocks (Figure 18a).

Model fits to fleet length frequencies, implied age-frequencies, Pearson residuals, and observed and effective samples sizes are displayed in Figures 19-24. Results are grouped by fleet so, for example, the reader can examine fits to length compositions, bubble plots of the input data, and bubble plots of Pearson residuals across facing pages. Corresponding fits to implied age compositions for the same fishery are found on the following two pages. Results indicate random residual patterns for most data and fleets. The PacNW fleet displayed notable residuals patterns for strong year classes (1997, 1998, 2003) moving through the fishery (Figure 23c,d).

Length selectivity estimates for each survey are displayed in Figure 25a, and implied age selectivities are shown in Figure 25b. Model fits to Aerial and Acoustic survey compositions, Pearson residuals, and observed and effective samples sizes are displayed in Figures 26-28. A clear trend is evident in the residual pattern for the Aerial length data (Figure 26a,d). Fits to the Acoustic-trawl survey length and age data are likewise less than optimal (Figures 27-28).

Fits to indices
Model fits to the DEPM, TEP, Aerial and Acoustic survey time series are displayed in Figure 29a-d. Model expected values all fit within error bounds of the observed data. The acoustic survey series showed evidence for under-fitting at the start (2006) and over-fitting at the end (2010-2011) (Figure 29d). Runs in residuals for the acoustic survey are difficult to interpret due to the abbreviated nature of this time series. Catchability coefficient (q) for the DEPM series of female SSB was estimated at 0.18. The TEP series was best fit with q=0.49. The Aerial best fit with q=0.89.

Spawning stock biomass
Base model estimates of total SSB are presented in Tables 10-11 and Figure 31a. SSB increased throughout the 1990s, peaking at 1.13 mmt in 1999 (=Jan of calendar year 2000) and at 0.936 mmt in 2006. Virgin SSB was approximately 0.969 mmt.

Recruitment
Time series of recruit (age-0) abundance are provided in Tables 10-11 and Figure 31b. Virgin recruitment (R_0) was estimated at 6.2 billion age-0 fish. Recruitment increased rapidly through the mid-1990s, peaking at 15.4 billion fish in 1997, 14.9 billion in 1998, and 21.4 billion fish in 2003. The 2009 year-class was estimated to be 11.1 billion fish (Figure 31b).

Stock-recruitment relationship
The Ricker stock-recruitment relationship for the base model is displayed in Figure 32a. The estimate of steepness (h) was 2.96 for the base model (Table 8). Recruitment deviations (main period) were estimated from 1993 through 2008 (2009 Year Class). There was no evidence for trend in the recruitment deviations over time (Figure 32b). Recruitments for 2010 and 2011 were drawn from the stock-recruitment curve. Sigma-R was fixed at 0.622 in the final tuned model. Recruitment deviations and their asymptotic standard errors are shown in Figure 32b,c.

Stock biomass (ages 1+) for PFMC management
Stock biomass, used for setting management specifications, is defined as the sum of the biomass for ages 1 and older. Base model estimates of stock biomass are provided in Table 11 and displayed in Figure 33. Stock biomass increased rapidly through the 1990s, peaking at 1.45 mmt in 1999 and 1.27 mmt in 2006. Stock biomass was estimated at 988,385 mt as of July 1, 2011.

Harvest and exploitation rates
Harvest rates (catch per selected biomass, 'continuous-F') by fleet are displayed in Figure 30a. F estimates were all within a plausible range of values, and most were less than 0.6 in any given season.

Exploitation rates (calendar year catch/total mid-year biomass, ages 0+) for the U.S. and total fisheries are displayed in Figure 30b. The U.S. exploitation rate trended upwards from 3% in 1993 to approximately 10% in 2007. Total exploitation rate has trended upward since 2001, reaching 14.5% in 2010.

Uncertainty and Sensitivity Analyses

Profile on recruitment variance (σ_R)
The base model (X5) had been tuned with $\sigma_R = 0.622$, a value considered by some to be low for a small pelagic species. Sensitivity of the base model to recruitment variability was examined by profiling across σ_R values ranging from 0.4 to 1.0 (STAR 2011, requests Y.4-Y.6). Biomass estimates for the range of σ_R values are displayed in Figure 34. Biomass scaling did not differ greatly between the base case and runs having higher σ_R values. The model with $\sigma_R = 0.4$ scaled appreciably lower than the others (Figure 34).

Sensitivity to survey q and data weighting assumptions
During the 2011 STAR, the panel requested a series of model runs to address two issues: 1) scale of the biomass in the assessment, which was not well-determined, and 2) the weighting of length and conditional age-at-length data relative to the survey indices of abundance. Variants of STAR model N (all survey q's estimated; default data weighting) were run by sequentially fixing q=1 for each of three indices (DEPM, Aerial, Acoustic) and applying the default versus Francis data weighting methods to each of the variants (STAR 2011, requests X.1-X.6). Biomass trajectories for these models are displayed in Figure 35. Survey q estimates for models N and X.1-X.6 are provided in Table 12.

The estimate of terminal year (2011) stock biomass was higher for model N (all q's estimated) than for models X.1-X.6. Biomass trends were similar for models N, X.1, X.3, and X.5, in which default data weightings were used, but biomass scaling differed widely among runs that fixed survey q=1. Biomass trajectories were similar across models using down-weighted composition data (Francis wtg; models X.2, X.4, X.6), but the trend differed from default weighting runs, in that the second biomass peak was higher than the first (Figure 35). The estimated q's for the aerial and acoustic surveys were most plausible for runs X.3 through X.6

but were implausibly high for runs that treated DEPM as absolute (q's ranged 2.32-4.74; Table 12).

Likelihood profile on *M*

Natural mortality (*M*) was profiled for the base model (X5, *M*=0.4) using values ranging from 0.25 yr^{-1} to 0.75 yr^{-1} in 0.125 yr^{-1} increments (STAR 2011, request Z.2). Model component likelihoods, terminal year (2011) stock biomass, and the 2010 exploitation rate are summarized in Table 13. Likelihood profiles for key model components (surveys, lengths, ages, and total) are displayed in Figure 36. The total likelihood, length likelihoods, and conditional length-at-age likelihoods all favored higher natural mortality rates than the base model. The survey likelihoods indicated overall better fits with *M*'s equal to or lower than the base model (Figure 36). Results were consistent with the *M* profiles conducted for the 2007 and 2009 assessments (Hill et al. 2007, 2009).

Likelihood profile on acoustic survey *q*

Acoustic survey *q* was profiled for the base model (X5; *q*=1) using *q* values ranging from 0.25 to 2.00 in 0.25 increments (STAR 2011, request Z.3). Model component likelihoods, terminal year (2011) stock biomass, the 2010 exploitation rate, and *q*'s for the DEPM, TEP, and Aerial surveys are summarized in Table 14. Likelihood profiles for key model components (surveys, lengths, ages, and total) are displayed in Figure 37. The profile on acoustic *q* indicated that the length compositions were not informative to the choice of *q*, but the conditional age-at-length data did favor *q*'s in the range of 0.75-1.50 (Figure 37). The overall likelihood surface was quite flat, changing by only 2-3 units across the modeled range of *q*'s (Figure 37).

Retrospective analysis

Retrospective analysis can provide another means of examining model properties and characterizing uncertainty. A retrospective analysis of the base model (X5) was performed, where data were incrementally removed from the end year back to 2007 (STAR 2011, request Z.4). Stock biomass and recruitment series from these analyses are displayed in Figure 38. The model displayed no systematic pattern of under- or over-estimation, however there was appreciable variability, with changes of up to 377,000 mt from one year to the next (e.g. 2010 to 2009 end years; Figure 38).

Prospective analysis

A prospective analysis was conducted over the first five years of the base model (1993-97; STAR 2011, request Z.5). Stock biomass and recruitment time series are displayed in Figure 39. The model showed only modest changes in early period biomass estimates and minimal changes in terminal year biomass estimates, and no systematic pattern was evident (Figure 39).

Historical analysis

Base model estimates of stock biomass and recruitment were compared to recent assessment models (Figures 40a,b). Full and updated models from Hill et al. (2007-2010) were included in the comparison, in addition to alternative models where aerial survey estimates (*q* fixed at 1) were either excluded or de-emphasized. Trends in biomass and recruitment were generally comparable among models, with some departure in scale and trajectory of the current base model (X5) for the final few years.

HARVEST CONTROL RULES

Harvest Guideline for 2012
Using results from the final base model ('X5'), the harvest guideline for the U.S. fishery in calendar year 2012 would be 109,409 mt. To calculate the HG for 2012, we used the harvest control rule defined in Amendment 8 of the Coastal Pelagic Species-Fishery Management Plan (PFMC 1998). This formula is intended to prevent Pacific sardines from being overfished and maintain relatively high and consistent catch levels over the long-term. The Amendment 8 harvest guideline for sardines is calculated:

$$HG_{2012} = (BIOMASS_{2011} - CUTOFF) \bullet FRACTION \bullet DISTRIBUTION;$$

where HG_{2012} is the total U.S. (California, Oregon, and Washington) harvest guideline for 2012, $BIOMASS_{2011}$ is the estimated July 1, 2011 stock biomass (ages 1+) from the assessment (988,385 mt), CUTOFF is the lowest level of estimated biomass at which harvest is allowed (150,000 mt), FRACTION is an environmentally-based percentage of biomass above the CUTOFF that can be harvested by the fisheries, and DISTRIBUTION (87%) is the average portion of BIOMASS assumed in U.S. waters.

The following formula has been used to determine FRACTION value:

$$FRACTION = 0.248649805(T^2) - 8.190043975(T) + 67.4558326;$$

where T is the running average sea-surface temperature at Scripps Pier, La Jolla, California during the three preceding seasons (July-June). Under Option J (PFMC 1998), F_{MSY} is constrained and ranges between 5% and 15%. Based on T values observed throughout the period covered by this stock assessment, the appropriate exploitation fraction has consistently been 15% and this remains the case under current conditions ($T_{2011} = 17.7$ °C). U.S. harvest guidelines and catches since 2000 are displayed in Figure 1a.

OFL and ABC
The Magnuson-Stevens Reauthorization Act requires fishery managers to define an overfishing limit (OFL), allowable biological catch (ABC), and annual catch limit (ACLs) for species managed under federal FMPs. By definition, ABC and ACL must always be lower than the OFL based on uncertainty in the assessment approach. The PFMC's SSC recommended the '$P*$' approach for buffering against scientific uncertainty when defining ABC, and this approach was adopted under Amendment 13 to the CPS-FMP.

The estimated biomass of 988,385 (ages 1+, mt), an F_{MSY} estimate of 0.18 based on an analysis presented in Appendix 4, and an estimated distribution of 87% of the stock in U.S. waters results in a U.S. OFL of 154,781 mt for 2012 (Table 15b). For Pacific sardines, the SSC has recommended that scientific uncertainty (σ) be set to the maximum of either (1) the CV of the biomass estimate for the most recent year or (2) a default value of 0.36, which was based on uncertainty across full sardine assessment models. Model CV for the terminal year biomass was equal to 0.187 ($\sigma = 0.185$) therefore scientific uncertainty (σ) was set to the default value of 0.36. The Amendment 13 ABC buffer depends on the probability of overfishing level chosen by the

Council (*P**). Uncertainty buffers and ABCs associated with a range of discreet *P** values are presented in Table 15a. Table 15b provides complementary OFL and ABC values using an alternative estimate of F_{MSY} (0.18) that is independent of the SIO-SST environmental time series (see Hill 2011; Appendix 4 of this report).

RESEARCH AND DATA NEEDS

The following research recommendations are excerpted from 2011 STAR panel report:

A. Explore additional fishery-independent data sources for possible inclusion in the assessment, e.g. CDFO's mid-water trawl survey off Vancouver Island and the SWFSC's juvenile rockfish survey. Inclusion of a substantial new data source would likely require review during a Council-sponsored Methodology panel.

B. Continue expansion of coast-wide sampling of adult fish for use when estimating parameters in the DEPM method and when computing biomass from the acoustic-trawl surveys. Pursue collaborative survey sampling in Mexican and Canadian waters.

C. Temperature-at-catch could provide insight into stock structure and the appropriate catch stream to use for assessments, because the southern subpopulation is thought to prefer warmer water. Conduct tests of sensitivity to alternative assumptions regarding the fraction of the MexCal (in particular, Ensenada and Southern California) catch that comes from the northern subpopulation.

D. The assessment would benefit not only from data from Mexico and Canada, but also from joint assessment, which includes assessment team members from these countries.

E. Conduct additional studies on stock structure – otolith morphometry and microchemistry studies are potential tools for this purpose.

F. The relationship between environmental correlates and abundance should be examined. In particular, the relationship between environmental covariates and overall recruitment levels as well as recruitment deviations should be explored further.

G. Consider spatial models for Pacific sardines, which can be used to explore the implications of regional recruitment patterns and region-specific biological parameters. These models could be used to identify critical biological data gaps as well as better represent the latitudinal variation in size-at-age.

H. Explore models which consider a much longer time-period (e.g. 1931 onwards) to determine whether it is possible to model the entire period and determine whether this leads to a more informative assessment and provides a broader context for evaluating changes in productivity.

L. Consider a model which explicitly models the sex-structure of the population and the catch.

M. Reconsider a model which has separate fleets for Mexico, California, Oregon-Washington and Canada.

N. Develop a relationship between egg production and age which accounts for the duration of spawning, batch fecundity, etc. by age.

O. Consider model configurations which use age-composition rather than length-composition and conditional age-at-length data given evidence for time- and spatially-varying growth.

P. Further explore methods to reduce between-reader ageing bias. In particular, consider comparisons among laboratories and assess whether the age-reading protocol can be improved to reduce among-ager variation.

Q. Reasons for the discrepancy between the observed and expected proportions of old animals in the length and age compositions should be explored further. Possible factors to consider in this investigation include ageing error / ageing bias and the way dome-shaped selectivity has been modeled.

ACKNOWLEDGMENTS

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TABLES

Table 1. Sardine harvest guidelines and U.S. landings since the onset of federal management. Landings for 2011 are provisional.

Year	HG (mt)	Landings (mt)
2000	186,791	67,981
2001	134,737	75,800
2002	118,442	96,896
2003	110,908	71,922
2004	122,747	89,350
2005	136,179	86,463
2006	118,937	86,609
2007	152,564	127,788
2008	89,093	87,189
2009	66,932	67,084
2010	72,039	66,920
2011	50,526	*43,695*

Table 2. Pacific sardine landings (mt) for major fishing regions off northern Baja California (Mexico), the United States, and Canada, calendar years 1981 to 2010[1].

Calendar year	ENS	SCA_Inc	SCA_Dir	CCA	OR	WA	BC	Grand Total
1981	0.0	5.8	0.0	0.0	0.0	0.0	0.0	5.8
1982	0.0	131.1	0.0	0.0	0.0	0.0	0.0	131.1
1983	273.6	352.4	0.0	0.0	0.0	0.0	0.0	626.0
1984	0.0	170.6	0.0	63.9	0.0	0.0	0.0	234.5
1985	3,722.3	558.6	0.0	34.4	0.0	0.0	0.0	4,315.2
1986	242.6	721.1	330.1	112.9	0.0	0.0	0.0	1,406.7
1987	2,431.6	1,691.8	363.9	38.9	0.0	0.0	0.0	4,526.2
1988	2,034.9	2,790.3	984.3	10.2	0.0	0.0	0.0	5,819.7
1989	6,224.2	2,605.1	838.2	237.7	0.0	0.0	0.0	9,905.2
1990	11,375.3	1,266.1	1,241.9	306.6	0.0	0.0	0.0	14,189.9
1991	31,391.8	1,174.9	5,599.1	975.7	0.0	0.0	0.0	39,141.5
1992	34,568.2	0.0	16,061.0	3,127.6	3.9	0.0	0.0	53,760.7
1993	32,044.9	0.0	15,487.7	704.5	0.2	0.0	0.0	48,237.3
1994	20,877.0	0.0	10,345.9	2,359.0	0.0	0.0	0.0	33,581.9
1995	35,396.2	0.0	36,561.4	4,927.9	0.0	0.0	22.7	76,908.1
1996	39,064.7	0.0	25,170.9	8,885.1	0.0	0.0	0.0	73,120.7
1997	68,439.0	0.0	32,836.8	13,360.8	0.0	0.0	70.8	114,707.3
1998	47,812.2	0.0	31,974.6	9,080.8	1.0	0.0	488.1	89,356.7
1999	58,569.4	0.0	42,863.0	13,884.0	775.1	0.0	24.5	116,115.9
2000	67,845.3	0.0	46,834.8	11,367.3	9,529.0	4,765.4	1,721.3	142,063.1
2001	46,071.3	0.0	47,661.7	7,241.4	12,780.0	10,837.0	1,265.9	125,857.3
2002	46,845.3	0.0	49,365.9	14,077.8	22,711.0	15,212.1	739.4	148,951.5
2003	41,341.8	0.0	30,289.1	7,448.3	25,258.0	11,603.9	977.7	116,918.7
2004	41,896.9	0.0	32,393.4	15,308.3	36,111.8	8,799.4	4,438.0	138,947.9
2005	55,322.5	0.0	30,252.6	7,940.1	45,008.1	6,929.0	3,231.8	148,684.2
2006	57,236.9	0.0	33,285.8	17,743.1	35,648.2	4,099.0	1,575.4	149,588.4
2007	36,846.8	0.0	46,198.6	34,782.1	42,052.3	4,662.5	1,522.3	166,064.6
2008	66,866.1	0.0	31,089.3	26,711.0	22,939.9	6,435.2	10,425.0	164,466.4
2009	55,911.2	0.0	12,561.1	25,015.0	21,481.6	8,025.2	15,334.3	138,328.4
2010	56,820.9	0.0	29,381.5	4,305.9	20,852.6	12,381.1	22,223.1	145,965.0

[1] Southern and central California landings (incidental and directed) are from CDFG's monthly 'Wetfish' tables, which included bucket sampling of mixed loads to account for incidental catches not included on landing receipts. OR and WA landings were obtained from the PacFIN database. British Columbia landings were provided by the Canada Department of Fisheries and Oceans. Ensenada (Mexico) landings were obtained from INAPESCA annual reports, INAPESCA scientists, and CONAPESCA (2005-2010).

Table 3. Pacific sardine landings (mt) and corresponding number of fish sampled (available length and/or age data) for major fishing regions off northern Baja California (Mexico), the United States, and Canada, by model year and season, 1981 to 2011[1]. Base model begins 1993-1.

Model year	Model sem	ENS mt	ENS N_len	ENS N_age	SCA Inc mt	SCA Inc N_fish	SCA Dir mt	SCA Dir N_fish	CCA mt	CCA N_fish	OR mt	OR N_fish	WA mt	WA N_fish	BC mt	BC N_len
1981	1	0	0	0	6	179	0	0	0	0	0	0	0	0	0	0
1981	2	0	0	0	57	204	0	0	0	0	0	0	0	0	0	0
1982	1	0	0	0	74	361	0	0	0	0	0	0	0	0	0	0
1982	2	150	0	0	263	580	0	0	0	0	0	0	0	0	0	0
1983	1	124	0	0	89	411	0	0	0	0	0	0	0	0	0	0
1983	2	0	0	0	159	188	0	0	0	0	0	0	0	0	0	0
1984	1	0	0	0	12	0	0	0	64	0	0	0	0	0	0	0
1984	2	3,174	0	0	312	214	0	0	10	0	0	0	0	0	0	0
1985	1	548	0	0	247	371	0	0	24	0	0	0	0	0	0	0
1985	2	99	0	0	530	482	325	297	65	0	0	0	0	0	0	0
1986	1	143	0	0	191	447	5	14	48	0	0	0	0	0	0	0
1986	2	975	0	0	918	767	364	289	22	0	0	0	0	0	0	0
1987	1	1,457	0	0	773	728	0	0	17	0	0	0	0	0	0	0
1987	2	620	0	0	2,028	1,365	984	762	8	0	0	0	0	0	0	0
1988	1	1,415	0	0	763	562	0	0	3	0	0	0	0	0	0	0
1988	2	461	34	34	1,081	810	838	262	235	0	0	0	0	0	0	0
1989	1	5,763	97	97	1,524	1,018	0	0	3	0	0	0	0	0	0	0
1989	2	5,900	73	69	645	556	1,242	588	245	0	0	0	0	0	0	0
1990	1	5,475	395	94	621	350	0	0	62	92	0	0	0	0	0	0
1990	2	9,271	1,216	303	601	441	4,481	1,514	90	113	0	0	0	0	0	0
1991	1	22,121	1,073	242	574	0	1,118	412	885	495	0	0	0	0	0	0
1991	2	3,327	469	139	0	0	5,884	912	1,113	221	0	0	0	0	0	0
1992	1	31,242	1,195	356	0	0	10,177	2,098	2,014	0	4	0	0	0	0	0
1992	2	18,648	853	239	0	0	11,759	1,585	369	0	0	0	0	0	0	0
1993	1	13,397	2,068	124	0	0	3,729	363	335	0	0	0	0	0	0	0
1993	2	5,712	816	222	0	0	7,738	785	629	0	0	0	0	0	0	0
1994	1	15,165	913	264	0	0	2,607	644	1,730	0	0	0	0	0	0	0
1994	2	18,227	958	230	0	0	28,122	3,024	443	0	0	0	0	0	0	0
1995	1	17,169	1,283	317	0	0	8,439	863	4,485	0	0	0	0	0	23	0
1995	2	15,666	665	183	0	0	14,409	1,492	2,486	271	0	0	0	0	0	0
1996	1	23,399	1,065	320	0	0	10,762	837	6,399	2,182	0	0	0	0	0	0
1996	2	13,498	534	158	0	0	11,524	1,441	343	49	0	0	0	0	44	0
1997	1	54,941	1,250	354	0	0	21,313	1,325	13,018	1,374	0	0	0	0	27	0
1997	2	20,239	458	131	0	0	19,094	1,482	2,747	124	1	0	0	0	0	0
1998	1	27,573	1,034	189	0	0	12,881	1,315	6,334	1,286	0	0	0	0	488	175
1998	2	34,760	1,461	348	0	0	24,050	1,514	7,741	348	50	31	0	0	24	165
1999	1	23,810	1,014	265	0	0	18,813	1,215	6,143	0	725	76	62	0	0	290
1999	2	33,933	1,156	288	0	0	34,119	1,457	1,285	0	205	106	0	0	162	0

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Table 3. (cont'd). Pacific sardine landings (mt) and corresponding number of fish sampled (available length and/or age data) for major fishing regions off northern Baja California (Mexico), the United States, and Canada, by model year and season, 1981 to 2011[VI]. Base model begins 1993-1

Model year	Model Sem	ENS mt	ENS N_len	ENS N_age	SCA Inc mt	SCA Inc N_fish	SCA Dir mt	SCA Dir N_fish	CCA mt	CCA N_fish	OR mt	OR N_fish	WA mt	WA N_fish	BC mt	BC N_len
2000	1	33,912	1,281	298	0	0	12,716	1,405	10,082	0	9,324	796	4,703	899	1,559	2,909
2000	2	16,545	1,145	214	0	0	29,343	1,699	774	92	2,288	168	49	100	0	648
2001	1	29,526	720	145	0	0	18,318	1,670	6,467	690	10,492	702	10,789	1,350	1,265	1,206
2001	2	17,422	930	217	0	0	26,621	1,621	1,575	302	2,724	250	412	419	1	300
2002	1	29,424	891	55	0	0	22,745	1,153	12,503	758	19,987	1,249	14,800	3,113	739	9,323
2002	2	15,514	460	0	0	0	20,380	1,739	5,086	471	503	25	94	186	0	300
2003	1	25,827	1,036	0	0	0	9,909	1,511	2,363	195	24,755	943	11,510	2,726	977	9,227
2003	2	11,213	5,028	0	0	0	15,232	1,669	2,146	197	2,204	124	235	298	180	0
2004	1	30,684	5,113	0	0	0	17,161	1,715	13,163	563	33,908	872	8,564	1,578	4,258	6,689
2004	2	17,323	4,191	0	0	0	15,419	1,756	115	23	692	50	324	147	0	0
2005	1	38,000	2,885	0	0	0	14,834	1,810	7,825	587	44,316	349	6,605	1,348	3,231	6,451
2005	2	17,601	1,336	0	0	0	17,158	3,322	2,033	1,530	102	0	0	0	0	0
2006	1	39,636	1,154	0	0	0	16,128	1,517	15,711	1,446	35,547	300	4,099	375	1,575	0
2006	2	13,981	553	0	0	0	26,344	1,789	6,013	1,138	0	75	0	0	0	0
2007	1	22,865	1,138	0	0	0	19,855	1,802	28,769	1,701	42,052	1,999	4,663	250	1,522	2,336
2007	2	23,488	1,080	0	0	0	24,127	1,318	2,515	370	0	0	0	0	0	0
2008	1	43,378	2,074	0	0	0	6,962	637	24,196	746	22,940	2,000	6,435	360	10,425	22,894
2008	2	25,783	1,251	0	0	0	9,251	497	11,080	497	0	0	0	0	0	0
2009	1	30,128	0	0	0	0	3,310	325	13,935	575	21,482	2,050	8,025	300	15,334	28,527
2009	2	12,989	0	0	0	0	19,457	1,550	2,909	925	437	84	511	50	0	200
2010	1	43,832	0	0	0	0	9,925	625	1,397	325	20,416	1,599	11,870	200	22,223	28,689
2010	2	12,989	0	0	0	0	12,515	549	2,643	275	0	0	0	0	0	0
2011	1	43,832	0	0	0	0	3,173	300	9,070	301	12,779	0	11,252	0	21,801	0

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\1 Southern and central California landings (incidental and directed) are from CDFG's monthly 'Wetfish' tables, which included bucket sampling of mixed loads to account for incidental catches not included on landing receipts. OR and WA landings were obtained from the PacFIN database. British Columbia landings were provided by the Canada Department of Fisheries and Oceans. Ensenada (Mexico) landings were obtained from INAPESCA annual reports, INAPESCA scientists, and CONAPESCA (2005-2010).

Table 4. Pacific sardine landings (mt) and effective sample sizes (ESS) by model year, semester, and fishery for the base model. The base model begins in 1993-1.

Model year	Model sem	MexCal mt	MexCal ESS	PacNW mt	PacNW ESS	Model year	Model sem	MexCal mt	MexCal ESS	PacNW Mt	PacNW ESS
1981	1	5.8	7.16	0.0	0.00	1997	1	89,272.0	72.64	27.2	0.00
1981	2	57.2	9.52	0.0	0.00	1997	2	42,079.7	42.44	0.8	0.00
1982	1	73.9	14.44	0.0	0.00	1998	1	46,787.9	67.85	488.5	0.00
1982	2	412.8	23.32	0.0	0.00	1998	2	66,550.5	66.15	74.4	0.00
1983	1	213.2	16.84	0.0	0.00	1999	1	48,765.8	44.67	725.1	3.04
1983	2	159.1	7.52	0.0	0.00	1999	2	69,337.6	52.39	429.6	4.24
1984	1	75.4	0.00	0.0	0.00	2000	1	56,709.8	53.24	15,586.2	63.93
1984	2	3,495.8	8.64	0.0	0.00	2000	2	46,662.7	62.74	2,336.6	10.72
1985	1	819.4	15.00	0.0	0.00	2001	1	54,311.7	58.90	22,546.0	78.15
1985	2	1,019.0	33.40	0.0	0.00	2001	2	45,617.1	62.32	3,137.2	26.75
1986	1	387.7	20.20	0.0	0.00	2002	1	64,671.9	73.64	35,525.7	172.79
1986	2	2,278.9	44.32	0.0	0.00	2002	2	40,979.6	62.30	597.3	8.44
1987	1	2,247.3	29.40	0.0	0.00	2003	1	38,099.6	50.43	37,242.3	145.33
1987	2	3,639.8	87.72	0.0	0.00	2003	2	28,590.6	124.63	2,618.4	16.88
1988	1	2,179.9	22.76	0.0	0.00	2004	1	61,008.2	149.06	46,730.8	95.17
1988	2	2,614.8	46.80	0.0	0.00	2004	2	32,857.3	122.39	1,016.3	7.88
1989	1	7,290.5	12.65	0.0	0.00	2005	1	60,658.0	108.68	54,152.6	67.68
1989	2	8,031.5	15.49	0.0	0.00	2005	2	36,791.2	77.23	101.7	0.00
1990	1	6,158.4	16.11	0.0	0.00	2006	1	71,474.7	78.73	41,220.9	27.00
1990	2	14,443.5	64.03	0.0	0.00	2006	2	46,338.3	91.44	0.0	3.00
1991	1	24,698.0	42.48	0.0	0.00	2007	1	71,489.2	109.86	48,237.1	87.86
1991	2	10,323.5	64.38	0.0	0.00	2007	2	50,130.3	56.13	0.0	0.00
1992	1	43,433.3	61.18	3.9	0.00	2008	1	74,536.0	71.40	39,800.1	129.64
1992	2	30,776.4	46.21	0.2	0.00	2008	2	46,113.9	45.51	0.0	0.00
1993	1	17,460.8	68.60	0.0	0.00	2009	1	47,373.4	36.00	44,841.2	159.41
1993	2	14,078.9	75.58	0.0	0.00	2009	2	35,354.6	99.08	948.1	5.36
1994	1	19,503.0	34.15	0.0	0.00	2010	1	55,153.7	38.00	54,508.8	159.59
1994	2	46,792.1	184.41	0.0	0.00	2010	2	28,147.9	32.96	0.0	0.00
1995	1	30,093.3	54.40	22.7	0.00	2011	1	56,074.7	24.04	45,832.8	73.60
1995	2	32,561.2	50.12	0.0	0.00	2011	2	12,989.1	0.00	0.0	0.00
1996	1	40,559.5	76.02	0.0	0.00						
1996	2	25,364.6	39.90	43.5	0.00						

Table 5. Fishery-independent indices of Pacific sardine relative abundance. Complete details regarding estimation of DEPM and TEP values can be found in Tables 6 and 7. In the SS model, indices had a lognormal error structure with units of standard error of $\log_e$(index). Variance of the observations was only available as a CV, so the S.E. was approximated as sqrt($\log_e(1+CV^2)$). The current base model begins in 1993.

Model year	DEPM	S.E. ln(index)	TEP	S.E. ln(index)	TEP_full	S.E. ln(index)	Aerial	S.E. ln(index)	Acoustic	S.E. ln(index)
1981	---	---	---	---	---	---	---	---	---	---
1982	---	---	---	---	---	---	---	---	---	---
1983	---	---	---	---	---	---	---	---	---	---
1984	---	---	---	---	---	---	---	---	---	---
1985	---	---	---	---	---	---	---	---	---	---
1986	4,061	0.60	---	---	11,220	0.73	---	---	---	---
1987-1	8,661	0.56	---	---	24,883	0.48	---	---	---	---
1987-2			17,266	0.35	17,266	0.35	---	---	---	---
1988	---	---	---	---	---	---	---	---	---	---
1989	---	---	---	---	---	---	---	---	---	---
1990	---	---	---	---	---	---	---	---	---	---
1991	---	---	---	---	---	---	---	---	---	---
1992	---	---	---	---	---	---	---	---	---	---
1993	69,065	0.29	---	---	73,374	0.21	---	---	---	---
1994	---	---	---	---	---	---	---	---	---	---
1995	---	---	97,923	0.40	97,923	0.40	---	---	---	---
1996	---	---	482,246	0.21	482,246	0.21	---	---	---	---
1997	---	---	369,775	0.33	369,775	0.33	---	---	---	---
1998	---	---	332,177	0.34	332,177	0.34	---	---	---	---
1999	---	---	1,252,539	0.39	1,252,539	0.39	---	---	---	---
2000	---	---	931,377	0.38	931,377	0.38	---	---	---	---
2001	---	---	236,660	0.17	236,660	0.17	---	---	---	---
2002	---	---	556,177	0.18	556,177	0.18	---	---	---	---
2003	145,274	0.23	---	---	307,795	0.24	---	---	---	---
2004	459,943	0.55	---	---	486,950	0.40	---	---	---	---
2005	---	---	651,994	0.25	651,994	0.25	---	---	1,947,063	0.30
2006	198,404	0.30	---	---	306,297	0.26	---	---	---	---
2007	66,395	0.27			128,118	0.21	---	---	751,075	0.09
2008-1	---	---	---	---	---	---	---	---	801,000	0.30
2008-2	99,162	0.24	---	---	162,188	0.22	---	---	---	---
2009	58,447	0.40	---	---	97,838	0.39	1,236,911	0.90	357,006	0.41
2010	219,386	0.27	---	---	364,798	0.26	173,390	0.40	493,672	0.30
2011	---	---	---	---	---	---	201,888	0.29	---	---

Table 6. The spawning biomass related parameters: daily egg production/0.05m² (P_0), daily mortality rate (z), survey area (km²), two daily specific fecundities: (RSF/W), and (SF/W); s. biomass, female spawning biomass, total egg production (TEP) and sea surface temperature for 1986, 1987, 1994, 2004, 2005 and 2007-2011.

Calendar year	Season	Region	[1]P_0/0.05m² (cv)	Z (CV)	[2]RSF/W based on S_1	[3]RSF/W based on S_{12}	[3]FS/W based on S_{12}	[4]Area (km²)	[5]S. biomass (cv)	S. biomass females (cv)	S. biomass females (Sum of R1andR2) (cv)	Total egg production (TEP)	Mean temperature (°C) for positive eggs	Mean temperature (°C) from Calvet
1986(Aug)	1986	[6]S	1.48(1)	1.59(0.5)	38.31	43.96	72.84	6478	4362 (1.00)	2632 (1)		9587.44		
		N	0.32(0.25)		8.9	13.34	23.89	5333	2558 (0.33)	1429 (0.28)		1706.56		
		whole	0.95(0.84)		23.61	29.89	49.97	11811	7767 (0.87)	4491 (0.86)	4061 (0.66)	11220.45	18.7	18.5
1987 (July)	1987	1	1.11(0.51)	0.66(0.4)	38.79	37.86	57.05	22259	13050 (0.58)	8661 (0.56)		24707.49		
		2	0					15443	0	0		0		
		whole	0.66(0.51)		38.79	37.86	57.05	37702	13143 (0.58)	8723 (0.56)	8661 (0.56)	25637.36	18.9	18.1
1994	1993	1	0.42(0.21)	0.12(0.91)	11.57	11.42	21.27	174880	128664 (0.30)	69065 (0.30)		73449.6		
		2	0(0)	-				205295	0	0		0		
		whole	0.193(0.21)		11.57	11.42	21.27	380175	128531 (0.31)	68994 (0.30)	69065 (0.30)	73373.775	14.3	14.7
2004	2003	1	3.92(0.23)	0.25(0.04)	27.03	26.2	42.37	68204	204118 (0.27)	126209 (0.26)		267359.68		
		2	0.16(0.43)		-	-	-	252416	30833 (0.45)	19065 (0.44)		40386.56		
		whole	0.96(0.24)		27.03	26.2	42.37	320620	234958 (0.28)	145297 (0.27)	145274 (0.23)	307795.2	13.4	13.7
2005	2004	1	8.14(0.4)	0.58(0.2)	31.49	25.6	46.52	46203	293863 (0.45)	161685 (0.42)		376092.42		
		2	0.53(0.69)		3.76	3.2	7.37	207417	686168 (0.86)	298258 (0.89)		109931.01		
		whole	1.92(0.42)		15.67	12.89	27.11	253620	755657 (0.52)	359209 (0.50)	459943 (0.60)	486950.4	14.21	14.1
2007	2006	1	1.32(0.2)	0.13(0.36)	12.06	13.37	27.54	142403	281128 (0.42)	136485 (0.36)		187971.96		
		2	0.56(0.46)		24.48	23.41	38.94	213756	102998 (0.67)	61919 (0.62)		119703.36		
		whole	0.86(0.26)		15.68	16.17	31.52	356159	380601 (0.39)	195279 (0.36)	198404 (0.31)	306296.74	13.7	13.6
2008	2007	1	1.45(0.18)	0.13(0.29)	57.4	53.89	68.54	53514	29798 (0.20)	22642 (0.19)		77595.3		
		2	0.202(0.32)		13.84	12.6	22.57	244435	78359 (0.45)	43753 (0.42)		49375.87		
		whole	0.43(0.21)		21.82	20.31	32.2	297949	126148 (0.40)	79576 (0.35)	66395 (0.28)	128118.07	13.1	13.1
2009	2008	1	1.76(0.22)	0.25(0.19)	19.50	20.37	36.12	74966	129520 (0.31)	73048 (0.29)		131940.16		
		2	0.15(0.27)		14.25	14.34	22.97	199929	41816 (0.38)	26114 (0.38)		29989.35		
		whole	0.59(0.22)		17.01	17.53	29.11	274895	185084 (0.28)	111444 (0.27)	99162 (0.24)	162188.05	13.6	13.5
2010	2009	1	1.70(0.22)	0.33(0.23)	21.08	24.02	51.56	27462	38875 (0.44)	18111 (0.39)		46685.4		
		2	0.22(0.42)		14.55	16.20	26.65	244311	66345 (0.58)	40336 (0.58)		53748.42		
		whole	0.36(0.29)		16.08	18.07	31.49	271773	108280 (0.46)	62131 (0.46)	58447 (0.42)	97838.28	13.7	13.9
2011	2010	1	5.57(0.24)	0.51(0.14)	19.03	24.26	41.16	41878	192332 (0.31)	113340 (0.30)		233260.5		
		2	0.487(0.33)		11.40	14.67	25.04	272603	181016 (0.48)	106046 (0.49)		132757.7		
		whole	1.16(0.26)		14.85	19.04	32.40	314481	383286 (0.32)	225155 (0.32)	219386 (0.28)	364798.0	13.5	13.6

1: P_0 for the whole is the weighted average with area as the weight.

2. The estimates of adult parameters for the whole area were unstratified and RSF/W was based on original S_1, data of day-1 spawning females. For 2004, 27.03 was based on sex ratio= 0.618 while past biomass used RSF/W of 21.86 based on sex ratio = 0.5. (Lo et al. 2008)

3. The estimates of adult parameters for the whole area were unstratified. Batch fecundity was estimated with error term. For 1987 and 1994, estimates were based on S_1 using data of day-1 spawning females. For 2004, all trawls were in region 1 and value was applied to region 2,

4. Region 1, since 1997, is the area where the eggs/min from CUFES ≥1 and prior to 1997, is the area where the eggs/0.05m² >0 from CalVET tows

5: For the spawning biomasses, the estimates for the whole area uses unstratified adult parameters

6. Within southern and northern area, the survey area was stratified as Region 1 (eggs/0.05m2>0 with embedded zero) and Region 2 (zero eggs)

Table 7. Pacific sardine female adult parameters for surveys conducted in the standard daily egg production method (DEPM) sampling area off California (1994 includes females from off Mexico).

		1994	1997	2001	2002	2004	2005	2006	2007	2008	2009	2010	2011
Midpoint date of trawl survey		22-Apr	25-Mar	1-May	21-Apr	25-Apr	13-Apr	2-May	24-Apr	16-Apr	27-Apr	20-Apr	8-Apr
Beginning and ending dates of positive collections		04/15-05/07	03/12-04/06	05/01-05/02	04/18-04/23	04/22-04/27	03/31-04/24	05/01-05/07	04/19-04/30	04/13-04/27	04/17-05/06	04/12-04/27	03/23-04/25
N collections with mature females		37	4	2	6	16	14	7	14	12	29	17	30
N collection within Region 1		19	4	2	6	16	6	2	8	4	15	3	14
Average surface temperature (°C) at collection locations		14.36	14.28	12.95	12.75	13.59	14.18	14.43	13.6	12.4	12.93	13.62	13.12
Female fraction by weight	R	0.538	0.592	0.677	0.385	0.618	0.469	0.451	0.515	0.631	0.602	0.574	0.587
Average mature female weight (grams): with ovary	W_f	82.53	127.76	79.08	159.25	166.99	65.34	67.41	81.62	102.21	112.40	129.51	127.59
without ovary	W_{of}	79.33	119.64	75.17	147.86	156.29	63.11	64.32	77.93	97.67	106.93	121.34	119.38
Average batch fecundity[a] (mature females, oocytes estimated)	F	24283	42002	22456	54403	55711	17662	18474	21760	29802	29790	39304	38369
Relative batch fecundity (oocytes/g)		294	329	284	342	334	270	274	267	292	265	303	301
N mature females analyzed		583	77	9	23	290	175	86	203	187	467	313	244
N active mature females		327	77	9	23	290	148	72	187	177	463	310	244
Spawning fraction of mature females[b]	S	0.074	0.133	0.111	0.174	0.131	0.124	0.0698	0.114	0.1186	0.1098	0.1038	0.1078
Spawning fraction of active females[c]	S_a	0.131	0.133	0.111	0.174	0.131	0.155	0.083	0.134	0.1187	0.1108	0.1048	0.1078
Daily specific fecundity	$\dfrac{RSF}{W}$	11.7	25.94	21.3	22.91	27.04	15.67	8.62	15.68	21.82	17.53	18.07	19.04

[a] 1994-2001 estimates were calculated using $F_b = -10858 + 439.53\ W_{of}$ (Macewicz et al. 1996), 2004 used $F_b = 356.46 W_{of}$ (Lo and Macewicz 2004), 2005 used $F_b = -6085 + 376.28\ W_{of}$ (Lo and Macewicz 2006), 2006 used $F_b = -396 + 293.39\ W_{of}$ (Lo et al. 2007a); 2007 used $F_b = 279.23 W_{of}$ (Lo et al. 2007b), 2008 used $F_b = 305.14 W_{of}$ (Lo et al. 2008), 2009 used $F_b = -4598 + 326.78 W_{of} + e$ (Lo et al. 2009), and 2010 used $F_b = 5136 + 287.37 W_{of} + e$ (Lo et al. 2010).

[b] Mature females include females that are active and those that are postbreeding (incapable of further spawning this season). S_l was used for years prior to 2009 and S_{12} was used staring 2009.

[c] Active mature females are capable of spawning and have ovaries containing oocytes with yolk or postovulatory follicles less than 60 hours old.

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Table 8. Base model parameters and asymptotic standard deviations.

Parameter	Phase	Min	Max	Initial Value	Final Value	Std Dev
NatM_p_1_Fem_GP_1	-3	0.3	0.7	0.4	0.400000	_
L_at_Amin_Fem_GP_1	3	3	15	10	11.205900	0.176972
L_at_Amax_Fem_GP_1	3	20	30	25	23.956000	0.206533
VonBert_K_Fem_GP_1	3	0.05	0.99	0.40	0.398582	0.019772
CV_young_Fem_GP_1	3	0.05	0.3	0.14	0.150130	0.005995
CV_old_Fem_GP_1	3	0.01	0.1	0.05	0.054534	0.003000
Wtlen_1_Fem	-3	-3	3	1.68384E-05	0.000017	_
Wtlen_2_Fem	-3	-3	5	2.94825	2.948250	_
Mat50%_Fem	-3	9	19	15.88	15.880000	_
Mat_slope_Fem	-3	-20	3	-0.90461	-0.904610	_
Eggs/kg_inter_Fem	-3	0	10	1.00	1.000000	_
Eggs/kg_slope_wt_Fem	-3	-1	5	0.00	0.000000	_
SR_LN(R0)	1	3	25	16.00	15.644400	0.127072
SR_Ricker	6	0.2	4	2.50	2.959450	0.661916
SR_sigmaR	-3	0	2	0.622	0.622000	_
SR_R1_offset	2	-15	15	0.00	-1.026230	0.206755
Early_InitAge_6	_	_	_	_	-0.711711	0.476840
Early_InitAge_5	_	_	_	_	-0.775153	0.462862
Early_InitAge_4	_	_	_	_	-0.756781	0.458298
Early_InitAge_3	_	_	_	_	0.053468	0.365529
Early_InitAge_2	_	_	_	_	0.728308	0.253221
Early_InitAge_1	_	_	_	_	1.427700	0.202966
Main_RecrDev_1993	_	_	_	_	-0.039491	0.347683
Main_RecrDev_1994	_	_	_	_	-0.664052	0.250149
Main_RecrDev_1995	_	_	_	_	-0.104942	0.168600
Main_RecrDev_1996	_	_	_	_	0.830296	0.126283
Main_RecrDev_1997	_	_	_	_	0.751775	0.113416
Main_RecrDev_1998	_	_	_	_	-0.366219	0.157222
Main_RecrDev_1999	_	_	_	_	-0.164342	0.259925
Main_RecrDev_2000	_	_	_	_	0.371005	0.233258
Main_RecrDev_2001	_	_	_	_	-1.397970	0.185927
Main_RecrDev_2002	_	_	_	_	0.943127	0.104668
Main_RecrDev_2003	_	_	_	_	-0.409594	0.216045
Main_RecrDev_2004	_	_	_	_	0.496969	0.117325
Main_RecrDev_2005	_	_	_	_	-0.323344	0.146036
Main_RecrDev_2006	_	_	_	_	0.267517	0.214102
Main_RecrDev_2007	_	_	_	_	-0.636362	0.252510
Main_RecrDev_2008	_	_	_	_	0.445624	0.212131
InitF_1MexCal_S1	-1	0	4	0.00	0.000000	_
InitF_2MexCal_S2	-1	0	4	0.00	0.000000	_
InitF_3PacNW	-1	0	4	0.00	0.000000	_
Q_base_4_DEPM	5	-3	3	-1.39	-1.727120	0.284961
Q_base_5_TEP	5	-3	3	-0.69	-0.695249	0.239106
Q_base_7_Aerial	5	-3	3	0.00	-0.114855	0.462752
Q_base_8_Acoustic	-5	-3	3	0.00	0.000000	_

Table 8 (cont'd). Base model parameters and asymptotic standard deviations.

Parameter	Phase	Min	Max	Initial Value	Final Value	Std Dev
SizeSel_1P_1_MexCal_S1	4	10	28	18.00	18.997800	0.344970
SizeSel_1P_2_MexCal_S1	4	-5	3	3.00	-3.362570	1.579730
SizeSel_1P_3_MexCal_S1	4	-1	9	2.50	2.376110	0.138967
SizeSel_1P_4_MexCal_S1	4	-1	9	4.00	1.056540	0.391492
SizeSel_1P_5_MexCal_S1	-4	-10	10	-10.00	-10.000000	_
SizeSel_1P_6_MexCal_S1	4	-10	10	10.00	-5.566430	4.552130
SizeSel_1P_1_MexCal_S1_BLK1repl_1999	4	10	28	18.00	16.831400	0.125793
SizeSel_1P_2_MexCal_S1_BLK1repl_1999	-4	-5	3	-5.00	-5.000000	_
SizeSel_1P_3_MexCal_S1_BLK1repl_1999	4	-1	9	2.50	2.121320	0.075526
SizeSel_1P_4_MexCal_S1_BLK1repl_1999	4	-1	9	4.00	1.552330	0.124518
SizeSel_1P_5_MexCal_S1_BLK1repl_1999	-4	-10	10	-10.00	-10.000000	_
SizeSel_1P_6_MexCal_S1_BLK1repl_1999	4	-10	10	10.00	-3.903470	0.401022
SizeSel_2P_1_MexCal_S2	4	10	28	18.00	16.503800	0.231807
SizeSel_2P_2_MexCal_S2	-4	-5	3	-4.90	-4.900000	_
SizeSel_2P_3_MexCal_S2	4	-1	9	2.50	1.820640	0.143881
SizeSel_2P_4_MexCal_S2	4	-1	9	4.00	2.374640	0.233013
SizeSel_2P_5_MexCal_S2	-4	-10	10	-10.00	-10.000000	_
SizeSel_2P_6_MexCal_S2	4	-10	10	10.00	-2.693700	0.721403
SizeSel_2P_1_MexCal_S2_BLK1repl_1999	4	10	28	18.00	15.217400	0.145741
SizeSel_2P_2_MexCal_S2_BLK1repl_1999	-4	-5	3	-5.00	-5.000000	_
SizeSel_2P_3_MexCal_S2_BLK1repl_1999	4	-1	9	2.50	1.651470	0.115971
SizeSel_2P_4_MexCal_S2_BLK1repl_1999	4	-1	9	4.00	2.240940	0.117707
SizeSel_2P_5_MexCal_S2_BLK1repl_1999	-4	-10	10	-10.00	-10.000000	_
SizeSel_2P_6_MexCal_S2_BLK1repl_1999	4	-10	10	10.00	-3.647030	0.389847
SizeSel_3P_1_PacNW	4	10	28	18.00	18.623100	0.175019
SizeSel_3P_2_PacNW	4	1	16	4.00	2.181730	0.203663
SizeSel_7P_1_Aerial	4	10	28	18.00	20.974100	0.458331
SizeSel_7P_2_Aerial	4	-5	3	3.00	-4.909180	2.734450
SizeSel_7P_3_Aerial	4	-1	9	2.50	0.889258	0.477407
SizeSel_7P_4_Aerial	4	-1	9	4.00	0.228393	0.924095
SizeSel_7P_5_Aerial	-4	-10	10	-10.00	-10.000000	_
SizeSel_7P_6_Aerial	4	-10	10	10.00	-3.341490	1.915570
SizeSel_8P_1_Acoustic	4	10	28	18.00	17.452300	0.448059
SizeSel_8P_2_Acoustic	-4	-5	3	3.00	3.000000	_
SizeSel_8P_3_Acoustic	4	-1	9	2.50	0.219768	0.630375
SizeSel_8P_4_Acoustic	-4	-1	9	4.00	4.000000	_
SizeSel_8P_5_Acoustic	-4	-10	10	-10.00	-10.000000	_
SizeSel_8P_6_Acoustic	-4	-10	10	10.00	10.000000	_

Table 9. Likelihood components and input variance adjustments for the base model.

COMPONENT	-log(L)	MexCal_S1	MexCal_S2	PacNW	DEPM	TEP	Aerial	Acoustic
Catch	2.98E-10	1.50E-15	1.38E-15	2.98E-10	---	---	---	---
Survey	-1.31068	---	---	---	0.372788	-0.0280109	0.0325582	-1.68802
Length comp	1060.54	399.058	318.83	233.857	---	---	19.1359	89.6555
Age comp	712.701	267.064	231.061	182.407	---	---	0.000	32.1695
Recruitment	11.0596							
Parm softbounds	0.00990076							
TOTAL	1783							

INPUT VARIANCE ADJUSTMENTS		MexCal_S1	MexCal_S2	PacNW	DEPM	TEP	Aerial	Acoustic
Index_extra_CV		---	---	---	0.377	0.288	0.274	0.171
effN_mult_Lencomp		2.003	1.882	0.64	---	---	0.445	2.416
effN_mult_Agecomp		0.8	0.8	0.25	---	---	---	0.25

Table 10. Derived SSB (mt) and recruits (year-class abundance, billions of age-0 fish) for the base model. SSB estimates are calculated at the beginning of Season 2 of each model year, e.g. the 2011 value is SSB January 2012. Recruits are age-0 fish calculated at the beginning of each model year (July).

Model year	SSB (mt)	SSB Std Dev	Year class abundance (billions)	Recruits Std Dev
Virgin	968,740	125,630	6.227	0.791
1993	425,720	84,036	2.232	0.563
1994	590,020	108,710	11.904	1.671
1995	753,910	132,160	5.217	0.850
1996	839,030	140,980	7.067	1.068
1997	816,720	138,010	15.450	2.020
1998	941,340	146,640	14.884	1.689
1999	1,128,200	161,320	3.833	0.555
2000	1,099,300	156,590	3.176	0.441
2001	910,030	134,710	5.774	0.611
2002	717,380	112,480	1.453	0.280
2003	559,170	93,958	21.444	2.198
2004	683,570	103,390	7.007	0.927
2005	828,760	120,630	14.502	1.573
2006	936,130	132,590	4.968	0.714
2007	915,230	134,720	7.299	0.987
2008	809,350	128,620	3.081	0.584
2009	675,810	119,320	11.107	2.028
2010	642,830	124,630	---	---
2011	720,420	134,540	---	---

Table 11. Pacific sardine biomass and population numbers-at-age (1,000s) by model year and semester for the base model.

Model year	Sem	BIOMASS (mt) Total (0+)	Stock (Age 1+)	SSB	POPULATION NUMBERS-AT-AGE (1,000s of fish) 0 (R)	1	2	3	4	5	6	7	8	9	10+
VIRG	1	1,221,710	1,160,880		6,227,090	4,174,140	2,798,010	1,875,560	1,257,230	842,745	564,909	378,670	253,830	170,147	345,951
VIRG	2	1,204,900	1,091,000	968,738	5,098,310	3,417,500	2,290,820	1,535,580	1,029,330	689,981	462,508	310,028	207,818	139,305	283,241
INIT	1	437,807	416,007		2,231,510	1,495,830	1,002,680	672,118	450,534	302,002	202,438	135,698	90,961	60,973	123,974
INIT	2	431,782	390,967	347,153	1,827,010	1,224,680	820,927	550,284	368,866	247,259	165,742	111,100	74,473	49,921	101,501
1993	1	636,749	556,488		8,215,490	5,507,000	1,880,430	658,056	201,122	135,695	99,357	135,698	90,961	60,973	123,974
1993	2	705,515	555,274	425,724	6,725,220	4,432,750	1,466,180	511,248	158,561	108,499	80,147	109,995	73,928	49,630	101,060
1994	1	857,328	741,032		11,903,900	5,468,340	3,526,510	1,169,150	411,659	128,486	88,203	65,259	89,637	60,273	122,911
1994	2	951,388	733,686	590,016	9,745,020	4,422,540	2,787,330	921,696	327,980	103,415	71,445	53,045	73,001	49,139	100,315
1995	1	1,021,880	970,915		5,216,830	7,838,350	3,363,010	2,132,290	722,954	261,490	83,136	57,672	42,911	59,123	121,185
1995	2	1,053,020	957,615	753,914	4,270,610	6,324,070	2,639,760	1,668,510	572,906	209,753	67,196	46,810	34,909	48,160	98,841
1996	1	1,100,960	1,031,920		7,066,960	3,459,990	4,956,230	2,076,150	1,331,850	461,741	169,885	54,556	38,053	28,398	119,667
1996	2	1,091,820	962,588	839,033	5,785,000	2,783,620	3,858,690	1,610,430	1,048,810	368,935	136,976	44,209	30,920	23,111	97,537
1997	1	1,209,670	1,058,730		15,449,900	4,692,820	2,192,960	3,049,340	1,289,310	846,837	299,177	111,315	35,967	25,171	98,280
1997	2	1,211,710	929,243	816,715	12,644,300	3,678,870	1,584,830	2,183,570	958,478	652,626	235,811	88,835	28,899	20,302	79,597
1998	1	1,366,710	1,221,290		14,884,200	10,192,700	2,823,250	1,222,630	1,721,860	766,688	525,842	190,686	71,970	23,437	81,110
1998	2	1,448,270	1,176,090	941,344	12,183,800	8,165,990	2,171,410	935,787	1,342,560	608,606	422,125	154,026	58,331	19,031	66,005
1999	1	1,485,630	1,448,190		3,832,790	9,800,370	6,210,650	1,661,290	734,018	1,070,340	489,234	340,724	124,589	47,238	68,955
1999	2	1,466,790	1,396,750	1,128,220	3,135,230	7,717,000	4,811,090	1,316,220	591,856	869,557	398,587	277,904	101,668	38,557	56,295
2000	1	1,393,700	1,362,670		3,176,150	2,459,280	5,740,310	3,718,690	1,049,870	478,317	706,196	324,336	226,329	82,835	77,311
2000	2	1,272,840	1,214,820	1,099,280	2,596,930	1,897,830	4,301,540	2,864,790	827,767	380,965	564,634	259,716	181,356	66,397	61,986
2001	1	1,200,600	1,144,190		5,774,400	2,022,800	1,389,310	3,290,080	2,271,510	666,260	308,361	458,048	210,898	147,339	104,342
2001	2	1,076,030	970,655	910,035	4,716,920	1,497,940	979,706	2,434,840	1,749,760	522,259	243,321	362,383	167,042	116,765	82,726
2002	1	982,277	968,081		1,453,050	3,599,100	1,046,910	728,400	1,904,630	1,398,010	420,592	196,573	293,169	135,230	161,581
2002	2	823,587	797,106	717,378	1,185,370	2,512,270	674,334	504,687	1,403,580	1,058,410	321,708	150,969	225,555	104,131	124,498
2003	1	922,867	713,370		21,443,900	894,507	1,713,610	494,805	393,178	1,121,080	853,304	260,328	122,365	182,967	185,577
2003	2	960,865	569,837	559,167	17,503,600	640,051	1,137,220	345,612	287,695	837,488	642,533	196,644	92,558	138,490	140,536
2004	1	1,090,130	1,021,680		7,006,860	13,880,100	487,492	889,470	276,312	232,120	678,030	520,909	159,519	75,106	226,468
2004	2	1,090,860	962,917	683,573	5,726,900	10,505,600	346,512	634,204	199,559	168,784	494,392	380,253	116,502	54,866	165,466
2005	1	1,241,230	1,099,550		14,502,000	4,593,010	8,210,540	275,654	511,927	162,065	137,385	402,785	309,919	94,972	179,645
2005	2	1,247,560	982,667	828,757	11,857,300	3,534,740	5,985,820	200,139	374,152	118,929	100,992	296,300	228,056	69,897	132,229
2006	1	1,319,000	1,270,470		4,968,080	9,470,290	2,737,810	4,740,590	161,422	304,073	96,929	82,403	241,881	186,217	165,079
2006	2	1,254,380	1,163,660	936,129	4,061,170	7,227,040	1,993,700	3,508,050	121,693	231,241	73,964	62,965	184,934	142,416	126,281
2007	1	1,268,830	1,197,530		7,298,760	3,218,250	5,500,340	1,562,600	2,816,530	98,690	188,234	60,297	51,365	150,912	219,320
2007	2	1,162,560	1,029,310	915,233	5,964,450	2,421,040	3,921,630	1,140,210	2,105,970	74,626	142,959	45,874	39,108	114,943	167,093
2008	1	1,118,830	1,088,740		3,080,490	4,647,930	1,774,760	3,005,530	906,300	1,699,550	60,567	116,289	37,353	31,859	229,852
2008	2	979,231	923,037	809,353	2,515,410	3,382,720	1,210,780	2,147,670	675,049	1,289,430	46,277	89,101	28,655	24,455	176,515
2009	1	991,425	882,913		11,107,100	1,940,100	2,423,240	915,249	1,696,580	543,139	1,044,610	37,593	72,467	23,319	163,642
2009	2	930,980	728,307	675,809	9,072,280	1,429,020	1,673,660	653,181	1,250,820	406,405	786,114	28,355	54,713	17,615	123,666
2010	1	1,010,480	906,627		10,630,300	7,090,560	1,054,220	1,286,570	519,367	1,008,670	329,457	638,608	23,056	44,508	114,984
2010	2	979,318	785,315	642,833	8,684,180	5,253,580	727,402	902,167	372,597	731,661	240,026	466,075	16,840	32,521	84,045
2011	1	1,097,640	**988,385**		11,183,300	6,933,440	4,065,910	575,853	727,585	302,826	596,374	195,869	380,525	13,752	95,217
2011	2	1,092,010	887,795	720,421	9,141,400	5,275,290	2,924,950	416,984	534,247	223,933	442,261	145,420	282,656	10,218	70,760

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Table 12. Survey catchability coefficient (q) estimates for STAR models N, X1-X6.

Model	DEPM	TEP	Aerial	Acoustic
N (default wtg)	0.15	0.43	0.73	0.81
X1 (default wtg)	1 (fixed)	0.79	3.29	2.32
X2 (Francis wtg)	1 (fixed)	1.36	4.74	2.91
X3 (default wtg)	0.17	0.48	1 (fixed)	0.92
X4 (Francis wtg)	0.12	0.42	1 (fixed)	0.67
X5 (default wtg)	0.18	0.49	0.89	1 (fixed)
X6 (Francis wtg)	0.18	0.59	1.5	1 (fixed)

Table 13. Likelihood profile for a range of natural mortality rates (*M*) in the base model.

Natural Mortality Rate (*M*):	0.250	0.375	0.400	0.500	0.625	0.750
TOTAL LIKELIHOOD	1840.27	1788.75	1783.00	1768.68	1762.43	1793.14
SURVEY Likelihoods	2.5228	-1.2864	-1.3107	0.4542	2.5333	0.2692
DEPM	0.5409	0.3958	0.3728	1.3500	2.3474	0.4486
TEP	-0.2147	-0.0967	-0.0280	2.0087	3.2330	0.4158
Aerial	0.0517	0.0405	0.0326	-0.1388	-0.1734	0.1391
Acoustic	2.1449	-1.6259	-1.6880	-2.7657	-2.8737	-0.7343
LENGTH Likelihoods	1068.45	1060.81	1060.54	1051.49	1057.70	1089.06
MexCal_S1	404.61	399.41	399.06	392.96	394.06	387.66
MexCal_S2	319.33	318.66	318.83	314.70	318.10	313.66
PacNW	235.26	233.96	233.86	235.09	235.67	275.41
Aerial	18.77	19.04	19.14	18.80	19.42	18.65
Acoustic	90.48	89.74	89.66	89.94	90.44	93.67
AGE Likelihoods	748.35	717.20	712.70	704.43	689.56	696.12
MexCal_S1	281.21	268.96	267.06	263.84	256.71	264.16
MexCal_S2	247.37	233.24	231.06	228.20	219.55	227.68
PacNW	186.02	182.54	182.41	179.84	182.12	175.82
Acoustic	33.75	32.47	32.17	32.55	31.19	28.47
DERIVED QUANTITIES						
DEPM *Q*	0.308	0.190	0.178	0.154	0.131	0.050
TEP *Q*	0.966	0.546	0.499	0.270	0.192	0.140
Aerial *Q*	1.447	0.931	0.891	1.338	1.376	0.263
Acoustic *Q* (fixed)	1.000	1.000	1.000	1.000	1.000	1.000
Exploitation rate (2010)	0.246	0.154	0.144	0.202	0.202	0.024
Biomass_ages_1+ (2011)	570,437	923,087	988,385	574,765	644,435	5,527,460

Table 14. Likelihood profile for a range of acoustic survey *q*s.

Acoustic survey *q*:	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00
TOTAL LIKELIHOOD	1784.74	1783.36	1782.88	1783.00	1783.46	1784.11	1784.84	1785.56
SURVEY Likelihoods	-0.8050	-0.9983	-1.2050	-1.3107	-1.3238	-1.2829	-1.2191	-1.0890
DEPM	0.3630	0.3729	0.3750	0.3728	0.3702	0.3756	0.4079	0.4941
TEP	-0.0428	-0.0540	-0.0536	-0.0280	0.0108	0.0697	0.1607	0.2797
Aerial	0.1047	0.0797	0.0557	0.0326	0.0083	-0.0196	-0.0538	-0.0920
Acoustic	-1.2299	-1.3970	-1.5821	-1.6880	-1.7131	-1.7086	-1.7339	-1.7709
LENGTH Likelihoods	1060.69	1060.27	1060.40	1060.54	1060.66	1060.58	1060.09	1059.17
MexCal_S1	394.21	396.55	398.10	399.06	399.67	399.99	400.00	399.72
MexCal_S2	320.23	319.66	319.28	318.83	318.37	317.82	317.09	316.22
PacNW	236.52	234.96	234.15	233.86	233.82	233.96	234.22	234.52
Aerial	18.53	18.76	18.96	19.14	19.29	19.42	19.54	19.62
Acoustic	91.20	90.34	89.90	89.66	89.51	89.38	89.24	89.08
AGE Likelihoods	715.02	713.81	712.96	712.70	712.71	712.99	713.62	714.57
MexCal_S1	267.60	267.33	267.13	267.06	267.09	267.21	267.48	267.89
MexCal_S2	232.35	231.77	231.31	231.06	230.94	230.96	231.17	231.56
PacNW	182.13	182.09	182.16	182.41	182.64	182.83	182.97	183.06
Acoustic	32.95	32.62	32.36	32.17	32.04	31.98	32.00	32.07
DERIVED QUANTITIES								
DEPM *Q*	0.050	0.099	0.142	0.178	0.209	0.237	0.263	0.289
TEP *Q*	0.156	0.298	0.412	0.499	0.566	0.616	0.652	0.675
Aerial *Q*	0.225	0.460	0.684	0.891	1.096	1.314	1.573	1.878
Acoustic *Q* (fixed)	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00
Exploitation rate (2010)	0.043	0.083	0.116	0.144	0.170	0.196	0.226	0.261
Biomass_ages_1+ (2011)	3,277,040	1,710,860	1,223,820	988,385	839,514	724,772	620,323	524,737

Table 15a. Pacific sardine harvest control rules for the 2012 management year based on stock biomass estimated in the base model 'X5' and temperature-dependent F_{MSY} per Amendment 8 to the CPS-FMP (PFMC 1998).

Harvest Formula Parameters	Value			
BIOMASS (ages 1+, mt)	988,385			
Pstar (probability of overfishing)	0.45	0.40	0.30	0.20
BUFFER$_{Pstar}$ (Sigma=0.36)	0.95577	0.91283	0.82797	0.73861
F_{MSY} (upper quartile SST)	0.1985			
FRACTION	0.15			
CUTOFF (mt)	150,000			
DISTRIBUTION (U.S.)	0.87			

Harvest Formulas	MT
OFL = BIOMASS * F_{MSY} * DISTRIBUTION	170,689
ABC$_{0.45}$ = BIOMASS * BUFFER$_{0.45}$ * F_{MSY} * DISTRIBUTION	163,140
ABC$_{0.40}$ = BIOMASS * BUFFER$_{0.40}$ * F_{MSY} * DISTRIBUTION	155,810
ABC$_{0.30}$ = BIOMASS * BUFFER$_{0.30}$ * F_{MSY} * DISTRIBUTION	141,325
ABC$_{0.20}$ = BIOMASS * BUFFER$_{0.20}$ * F_{MSY} * DISTRIBUTION	126,073
HG = (BIOMASS - CUTOFF) * FRACTION * DISTRIBUTION	109,409

Table 15b. Pacific sardine harvest control rules for the 2012 management year based on stock biomass estimated in the base model 'X5' and stochastic F_{MSY} per Hill (2011; see Appendix 4).

Harvest Formula Parameters	Value			
BIOMASS (ages 1+, mt)	988,385			
Pstar (probability of overfishing)	0.45	0.40	0.30	0.20
BUFFER$_{Pstar}$ (Sigma=0.36)	0.95577	0.91283	0.82797	0.73861
F_{MSY} (stochastic, SST-independent)	0.18			
FRACTION	0.15			
CUTOFF (mt)	150,000			
DISTRIBUTION (U.S.)	0.87			

Harvest Formulas	MT
OFL = BIOMASS * F_{MSY} * DISTRIBUTION	154,781
ABC$_{0.45}$ = BIOMASS * BUFFER$_{0.45}$ * F_{MSY} * DISTRIBUTION	147,935
ABC$_{0.40}$ = BIOMASS * BUFFER$_{0.40}$ * F_{MSY} * DISTRIBUTION	141,289
ABC$_{0.30}$ = BIOMASS * BUFFER$_{0.30}$ * F_{MSY} * DISTRIBUTION	128,153
ABC$_{0.20}$ = BIOMASS * BUFFER$_{0.20}$ * F_{MSY} * DISTRIBUTION	114,323
HG = (BIOMASS - CUTOFF) * FRACTION * DISTRIBUTION	109,409

FIGURES
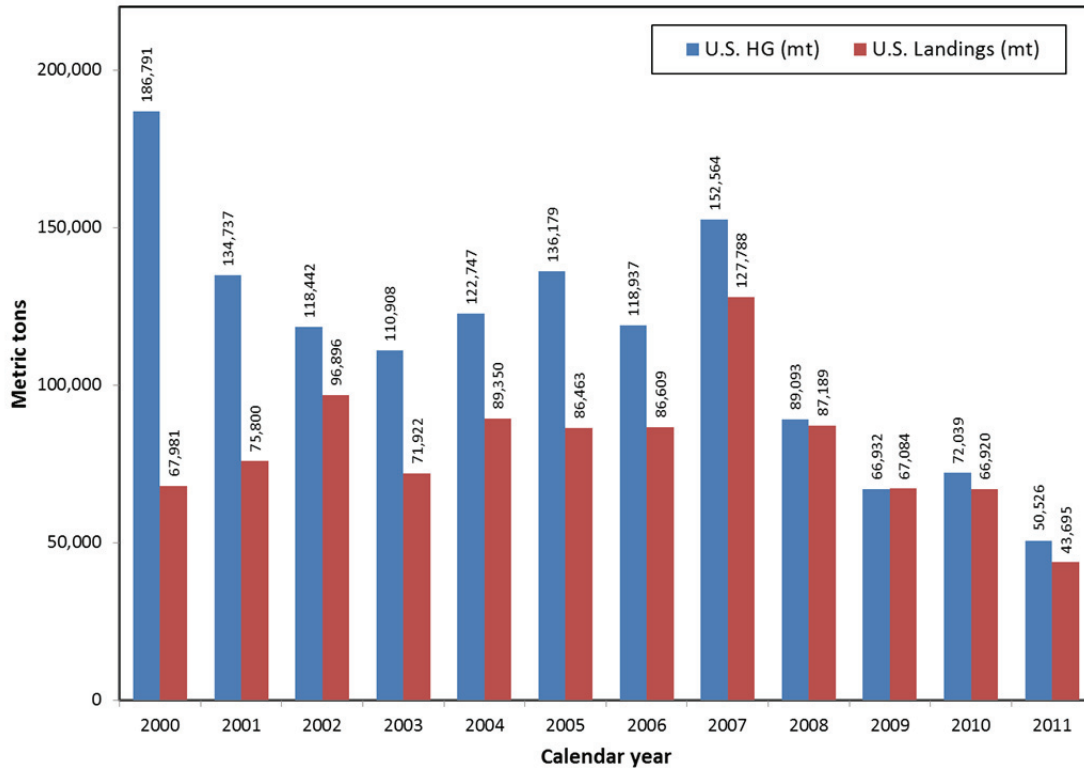
Figure 1a. U.S. harvest guidelines and landings since calendar year 2000.
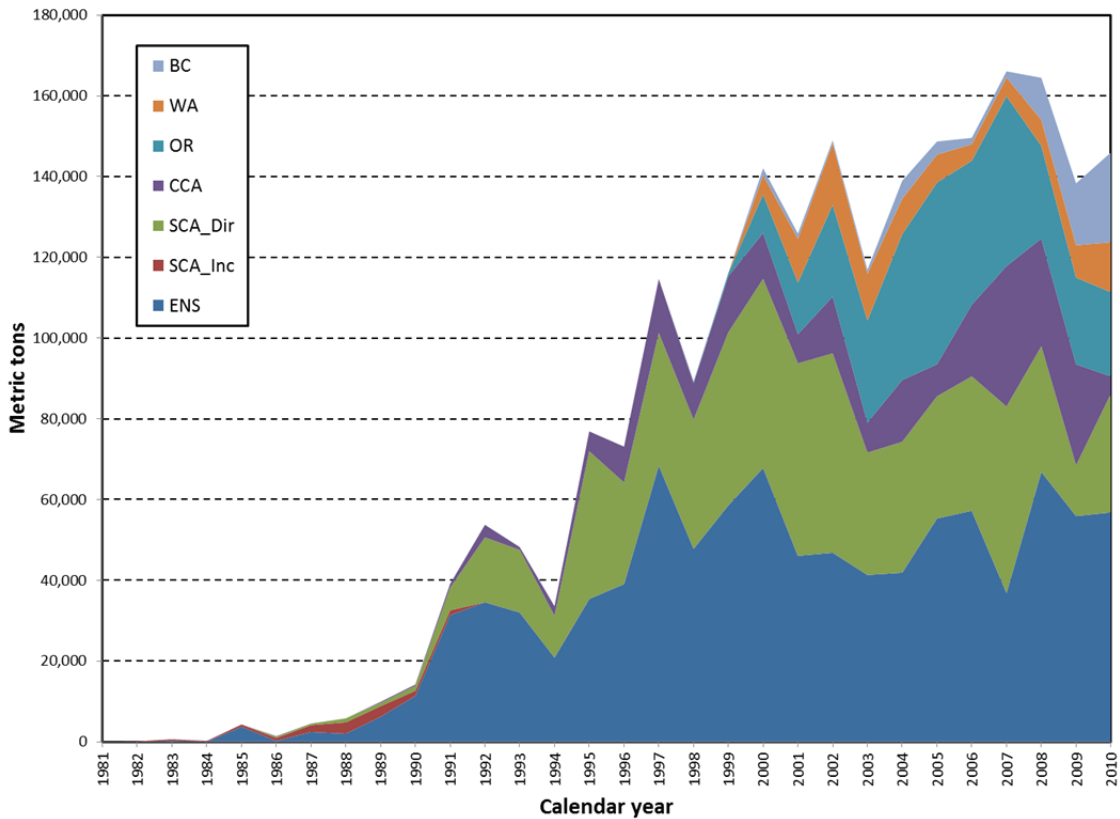
Figure 1b. Pacific sardine landings (mt) by major fishing region and calendar year.
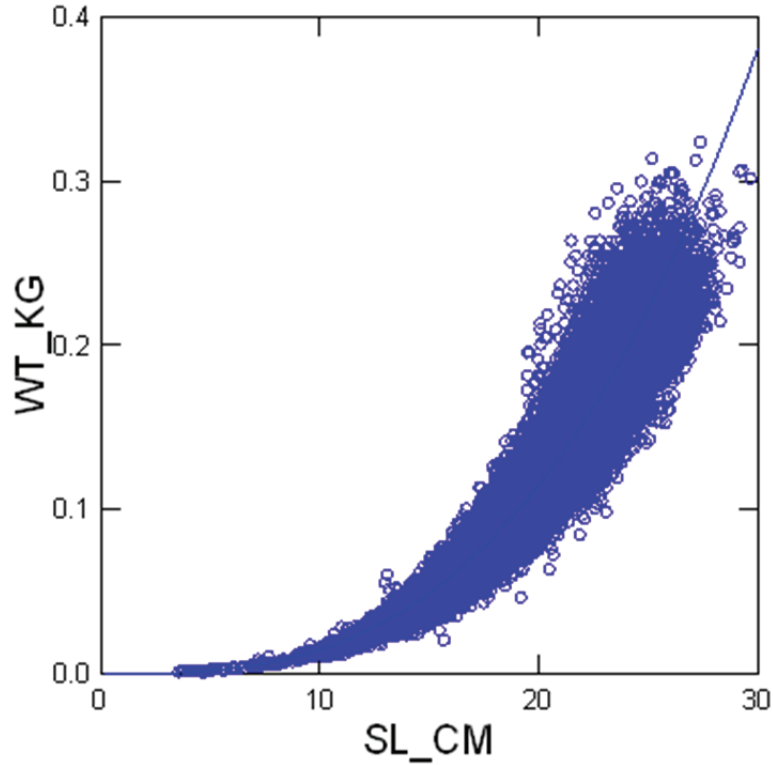
Figure 2a. Weight-at-length regression from fishery samples as applied in the base model, where: a = 1.68384E-05 and b = 2.94825 (n=155,814, R^2 = 0.928).
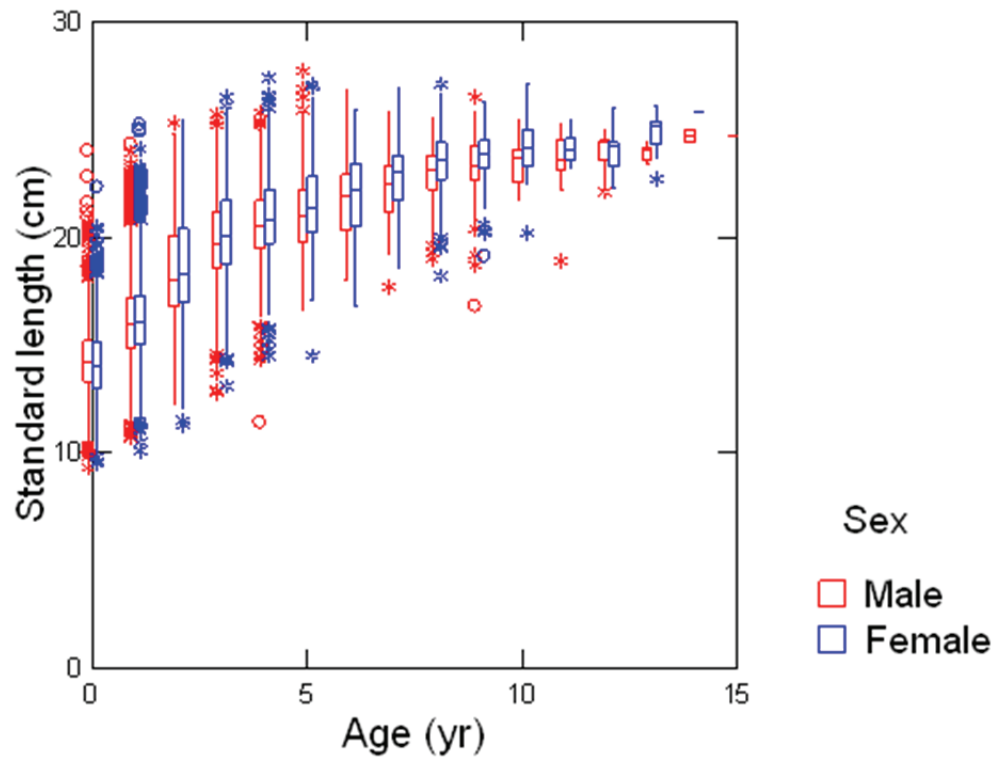
Figure 2b. Length-at-age by sex from fishery samples. Box symbols indicate median and quartile ranges for the raw data. The SS base model is based on pooled sexes.
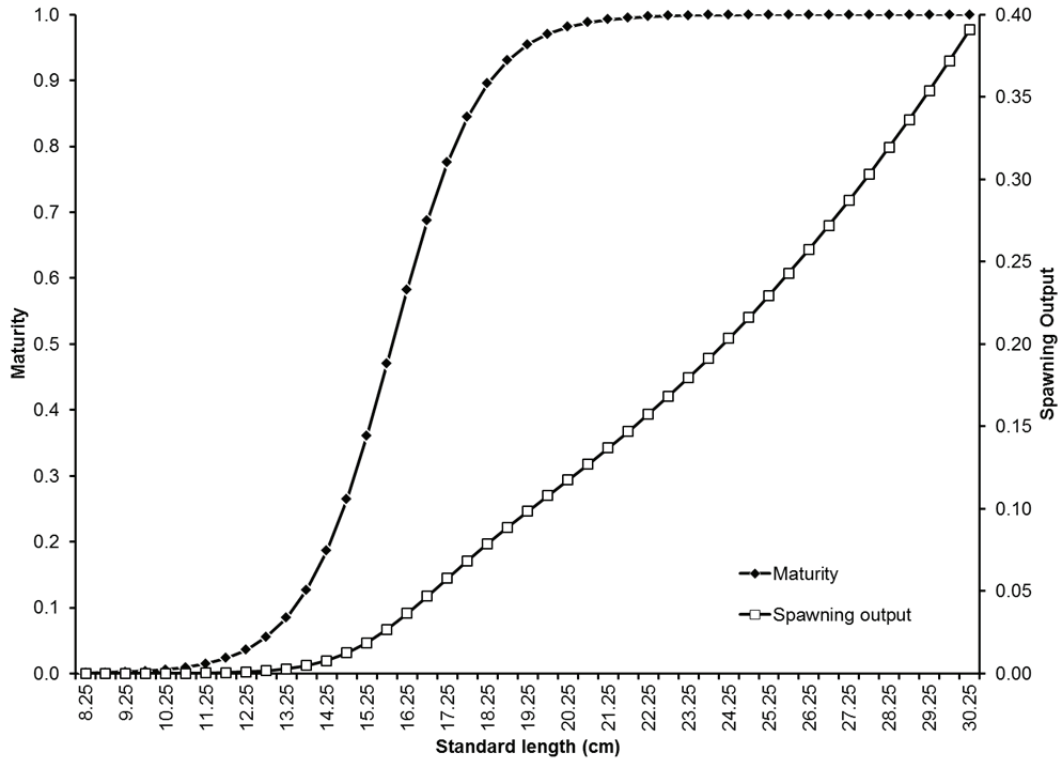
Figure 3a. Maturity (L_{50} = 15.88 cm) and spawning output as a function of length in base model.
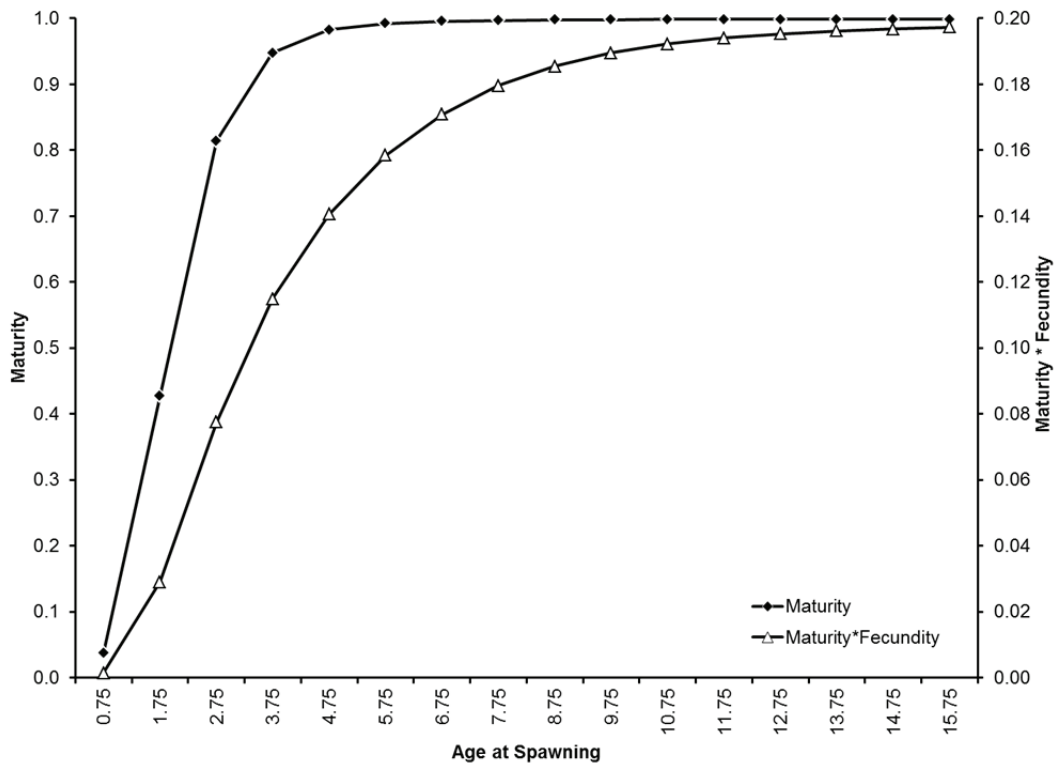
Figure 3b. Maturity and fecundity as a function of age, as derived from the base model.

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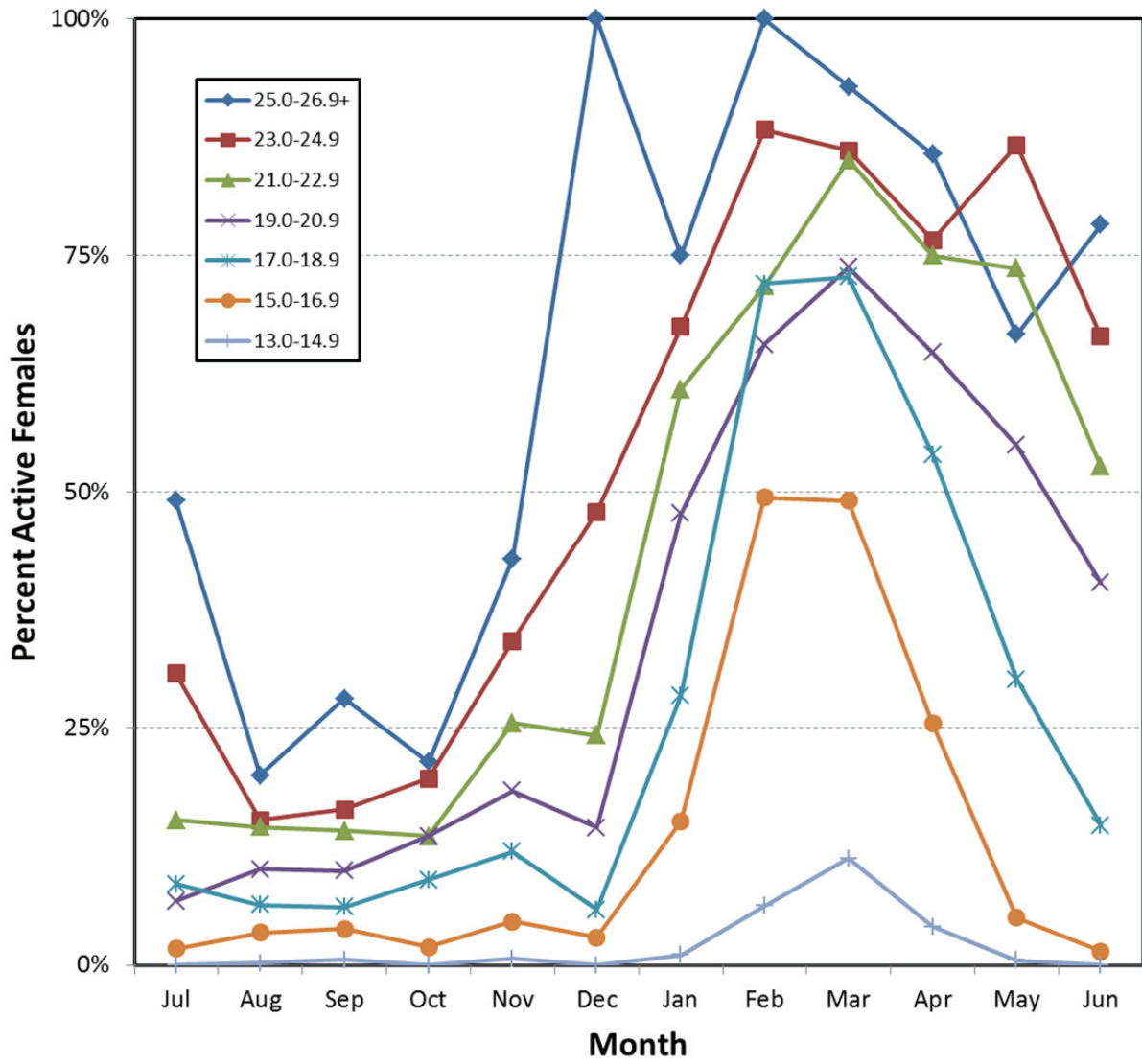
Figure 3c. Spawning activity by size (2-cm categories) and month based on visual inspection of gonads collected from U.S. port samples, 1981-2010.
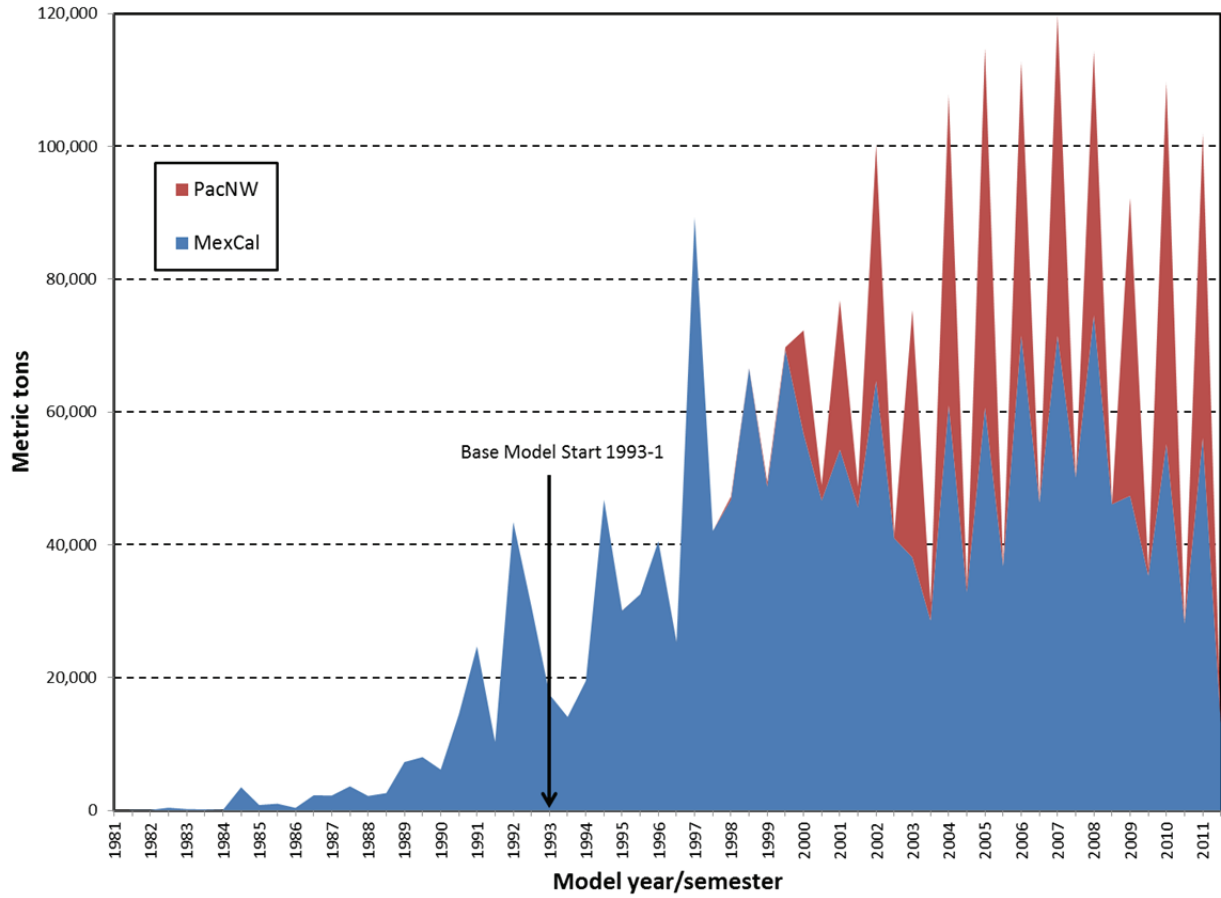
Figure 4. Pacific sardine landings (mt) by fishery, model year and semester as used in SS. The base model begins in 1993-1.

length comp data, sexes combined, whole catch, MexCal_S1
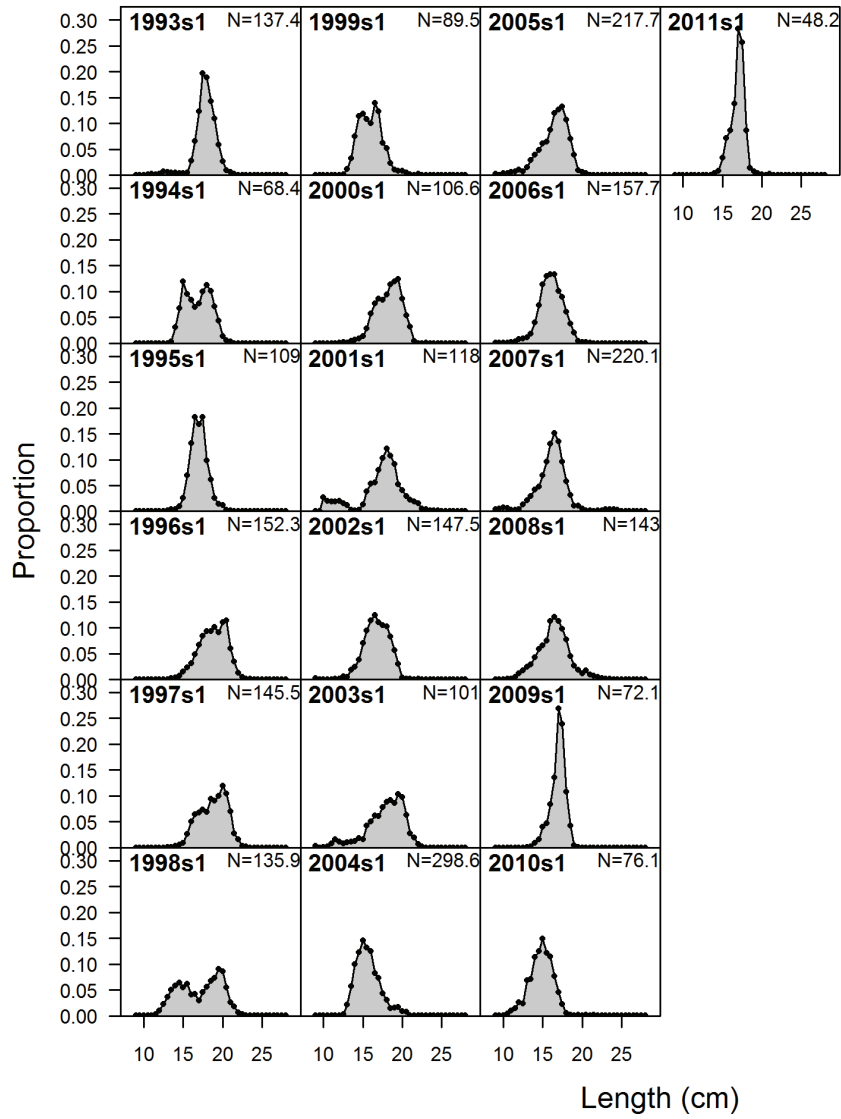
Figure 5a. Length-composition and effective sample size data for the MexCal_S1 fishery.

ghost age comp data, sexes combined, whole catch, MexCal_S1
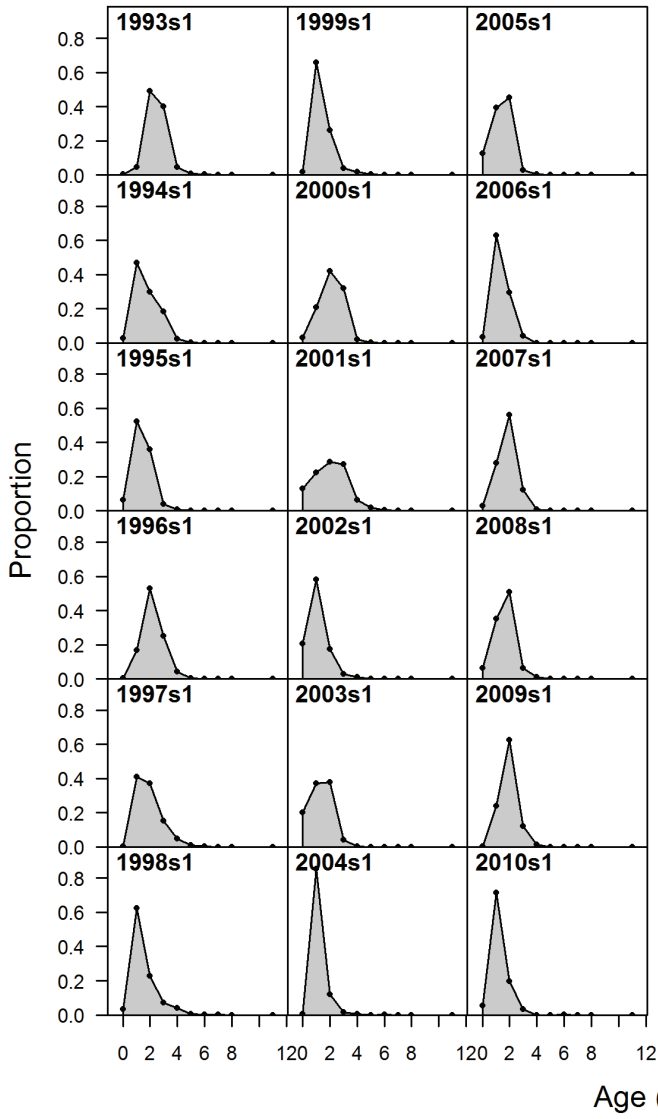
Figure 6a. Implied age-composition data for the MexCal-S1 fishery.

length comp data, sexes combined, whole catch, MexCal_S2
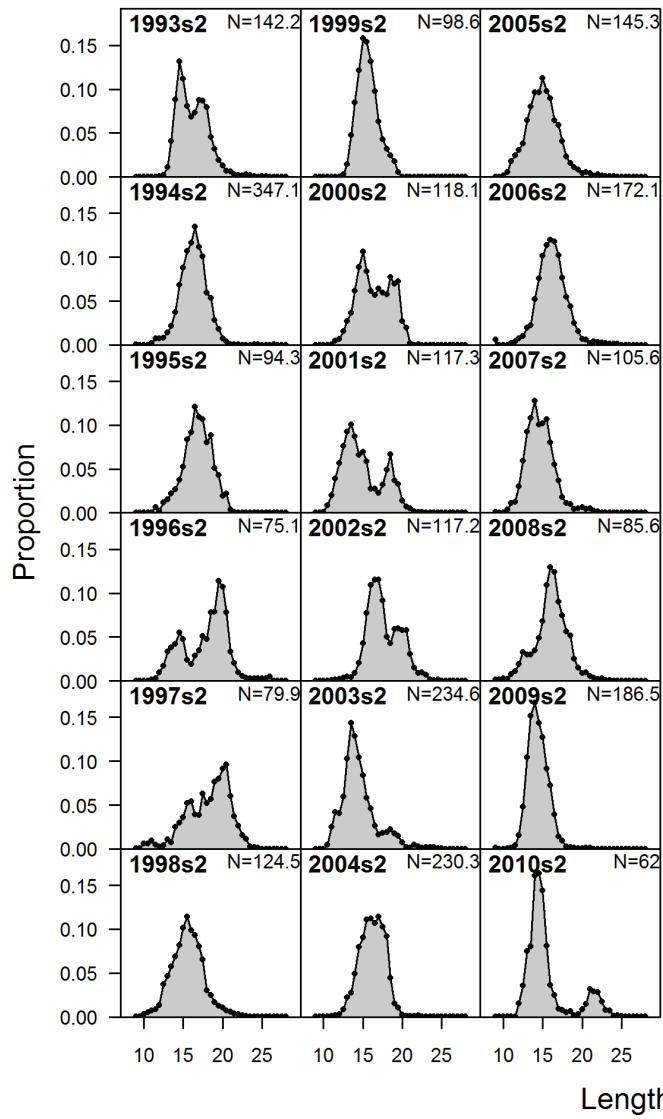
Figure 5b. Length-composition data and effective sample size for the MexCal_S2 fishery.

ghost age comp data, sexes combined, whole catch, MexCal_S2
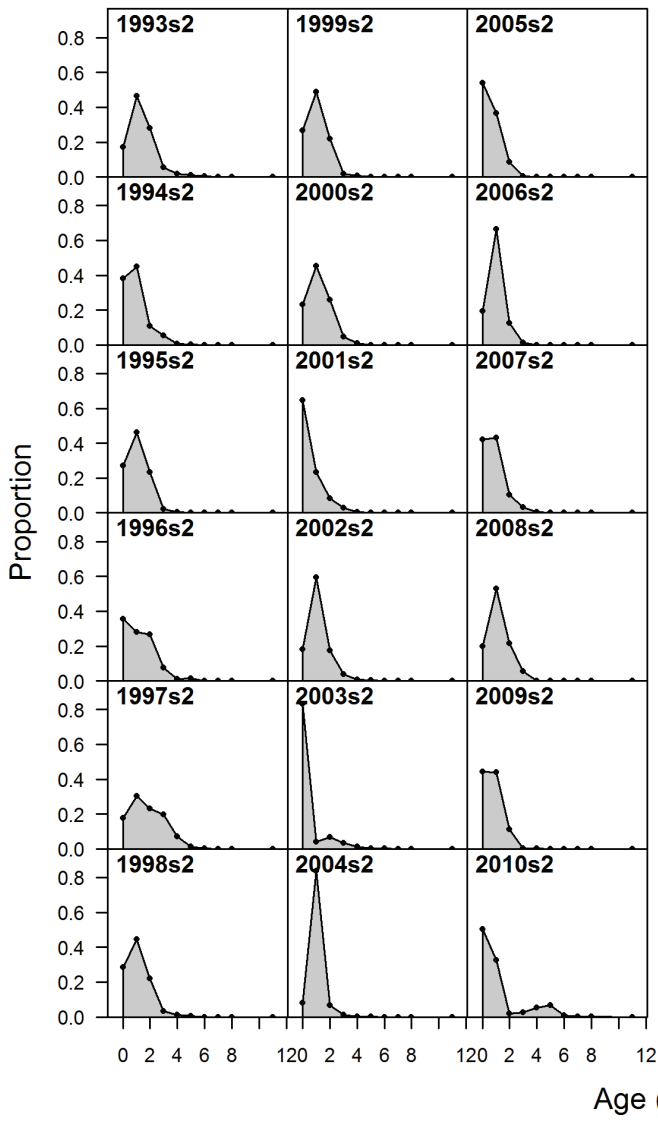
Figure 6b. Implied age-composition data for the MexCal_S2 fishery.

length comp data, sexes combined, whole catch, PacNW
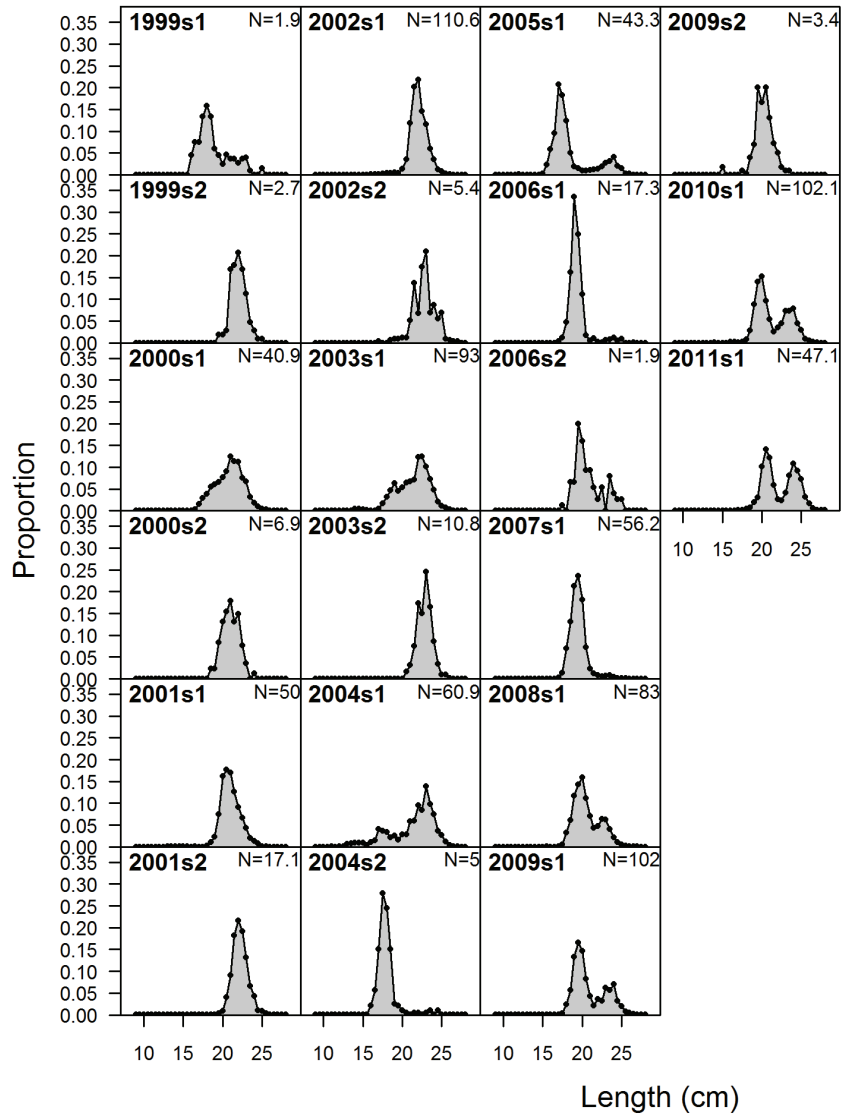
Figure 5c. Length-composition and effective sample size data for the PacNW fishery.

ghost age comp data, sexes combined, whole catch, PacNW
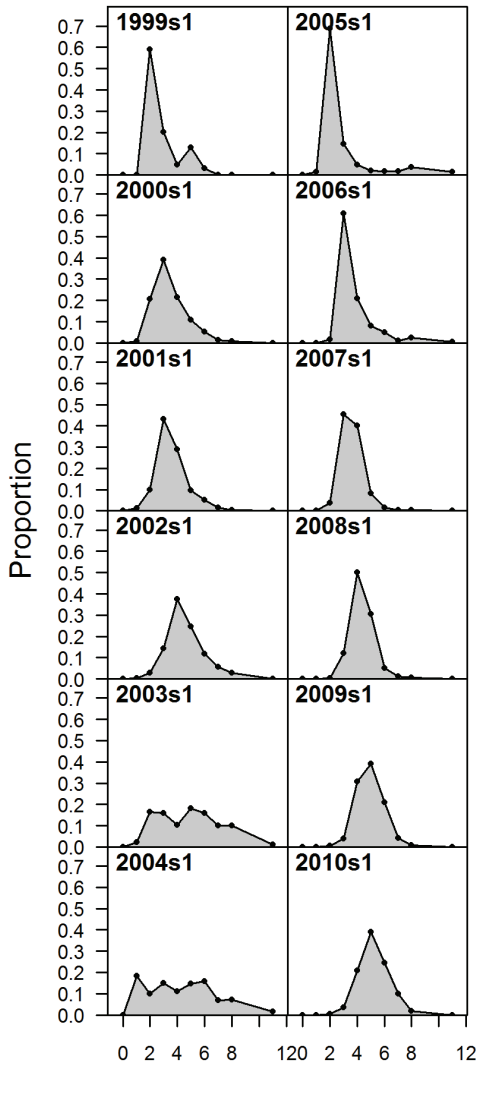
Figure 6c. Implied age-composition data for the PacNW fishery.

conditional age-at-length data, sexes combined, whole catch, MexCal_S1 (max=1)
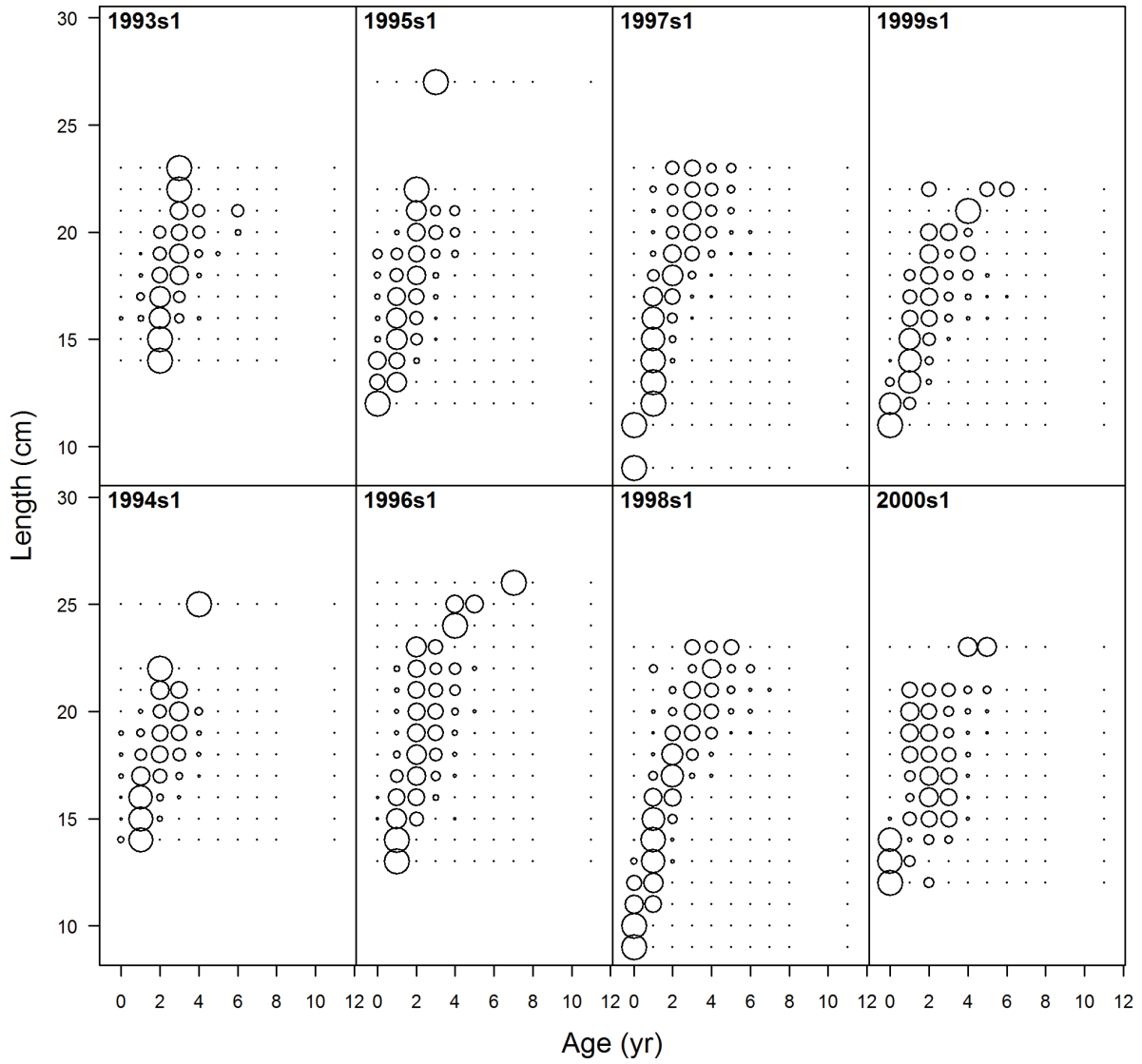
Figure 7a. Conditional age-at-length data for the MexCal_S1 fishery, 1993-2000.

conditional age-at-length data, sexes combined, whole catch, MexCal_S1 (max=1)
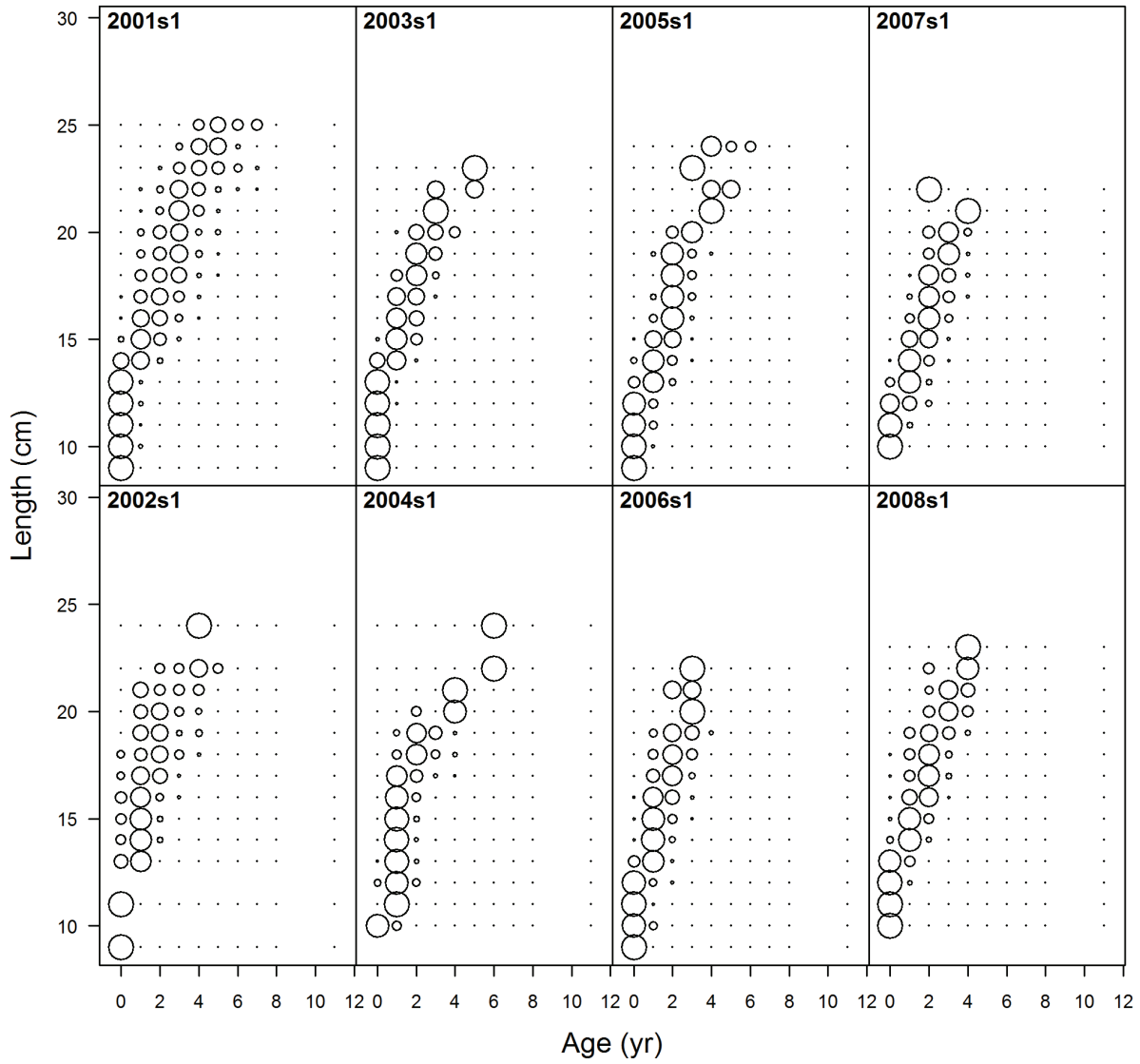
Figure 7a (cont'd). Conditional age-at-length data for the MexCal_S1 fishery, 2001-2008.

conditional age-at-length data, sexes combined, whole catch, MexCal_S1 (max=1)
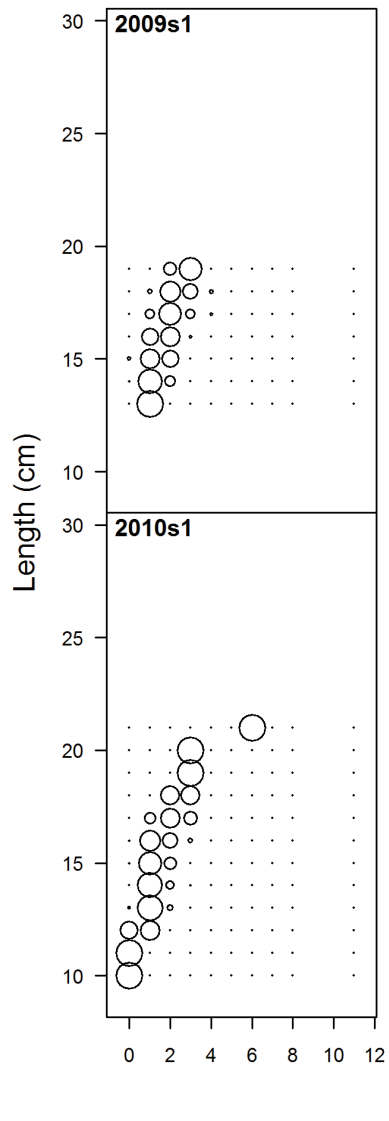
Figure 7a (cont'd). Conditional age-at-length data for the MexCal_S1 fishery, 2009-2010.

conditional age-at-length data, sexes combined, whole catch, MexCal_S2 (max=1)
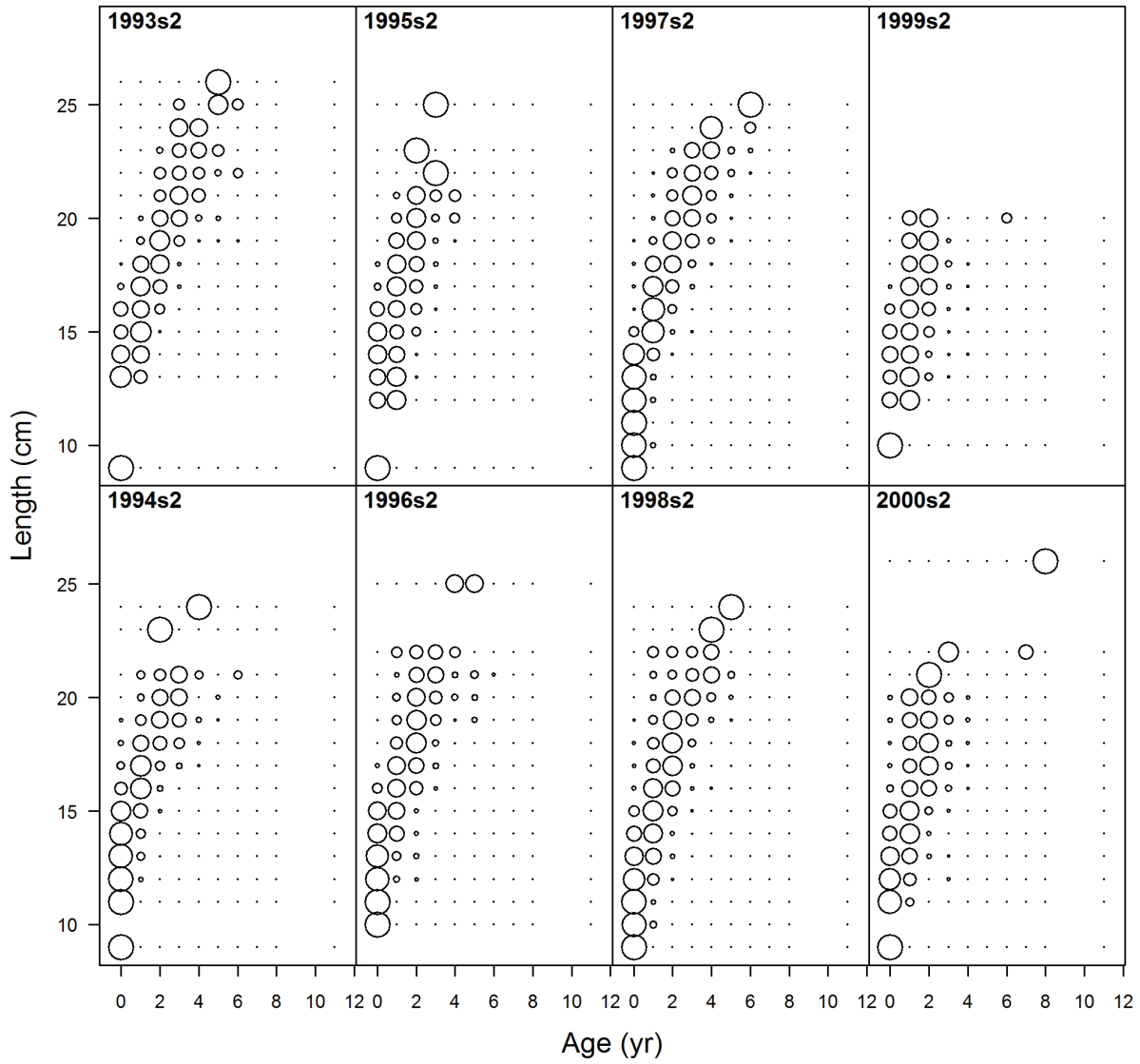
Figure 7b. Conditional age-at-length data for the MexCal_S2 fishery, 1993-2000.

conditional age-at-length data, sexes combined, whole catch, MexCal_S2 (max=1)
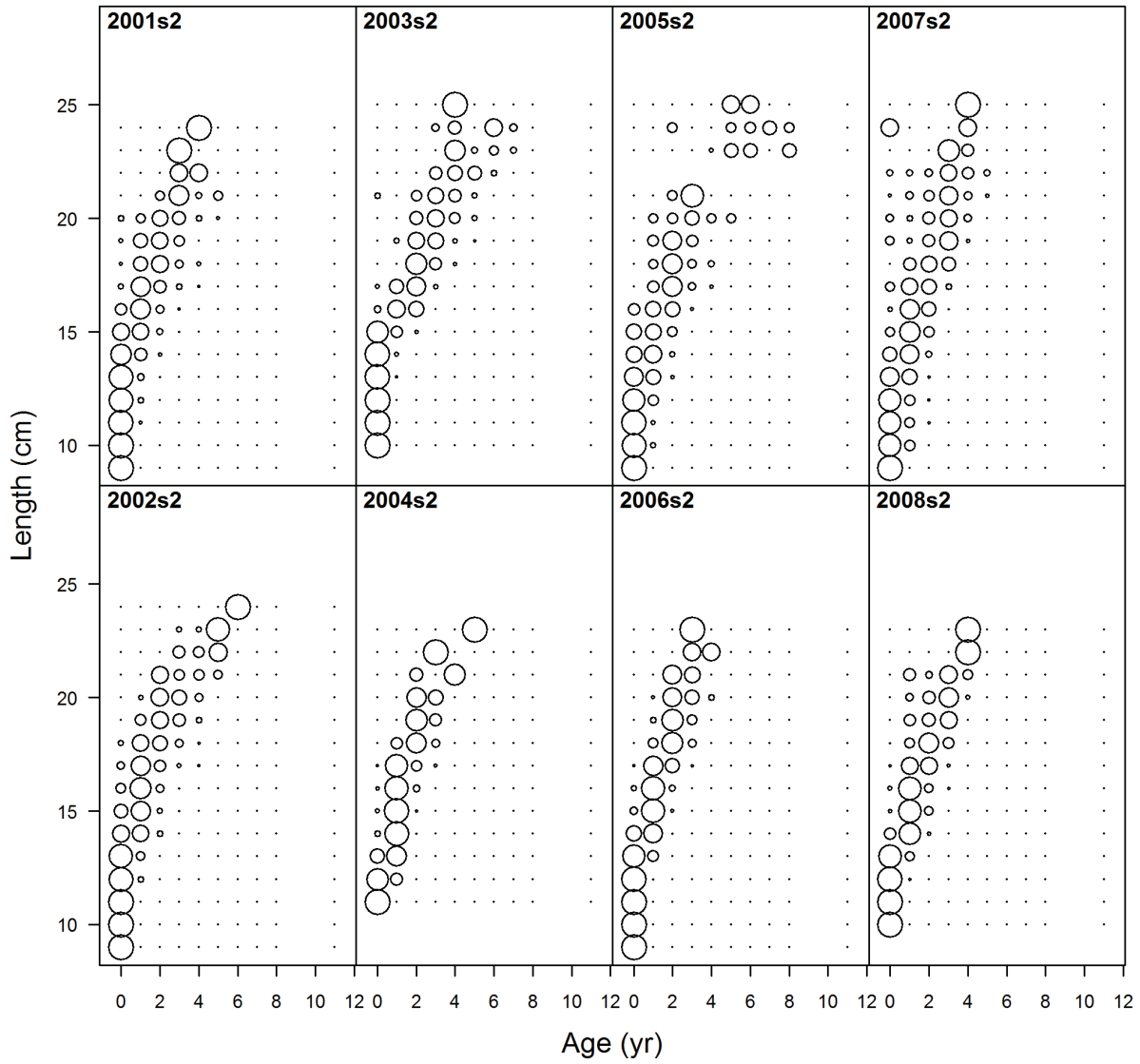
Figure 7b (cont'd). Conditional age-at-length data for the MexCal_S2 fishery, 2001-2008.

conditional age-at-length data, sexes combined, whole catch, MexCal_S2 (max=1)
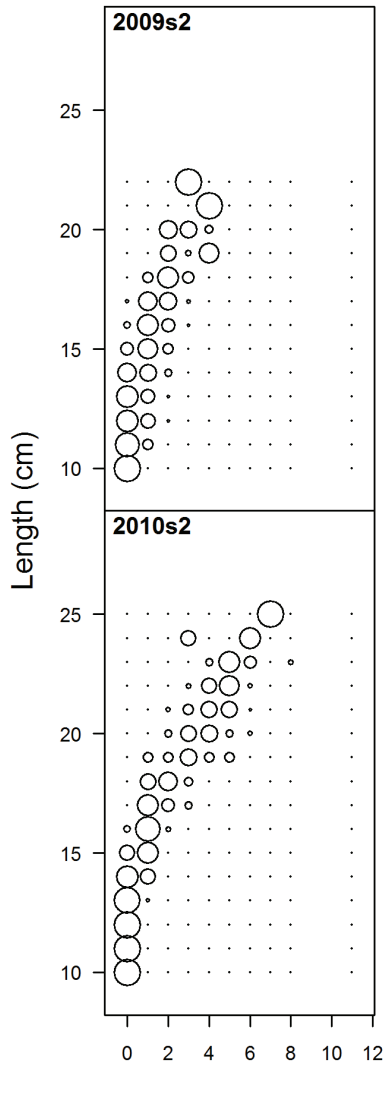
Figure 7b (cont'd). Conditional age-at-length data for the MexCal_S2 fishery, 2009-2010.

conditional age-at-length data, sexes combined, whole catch, PacNW (max=1)
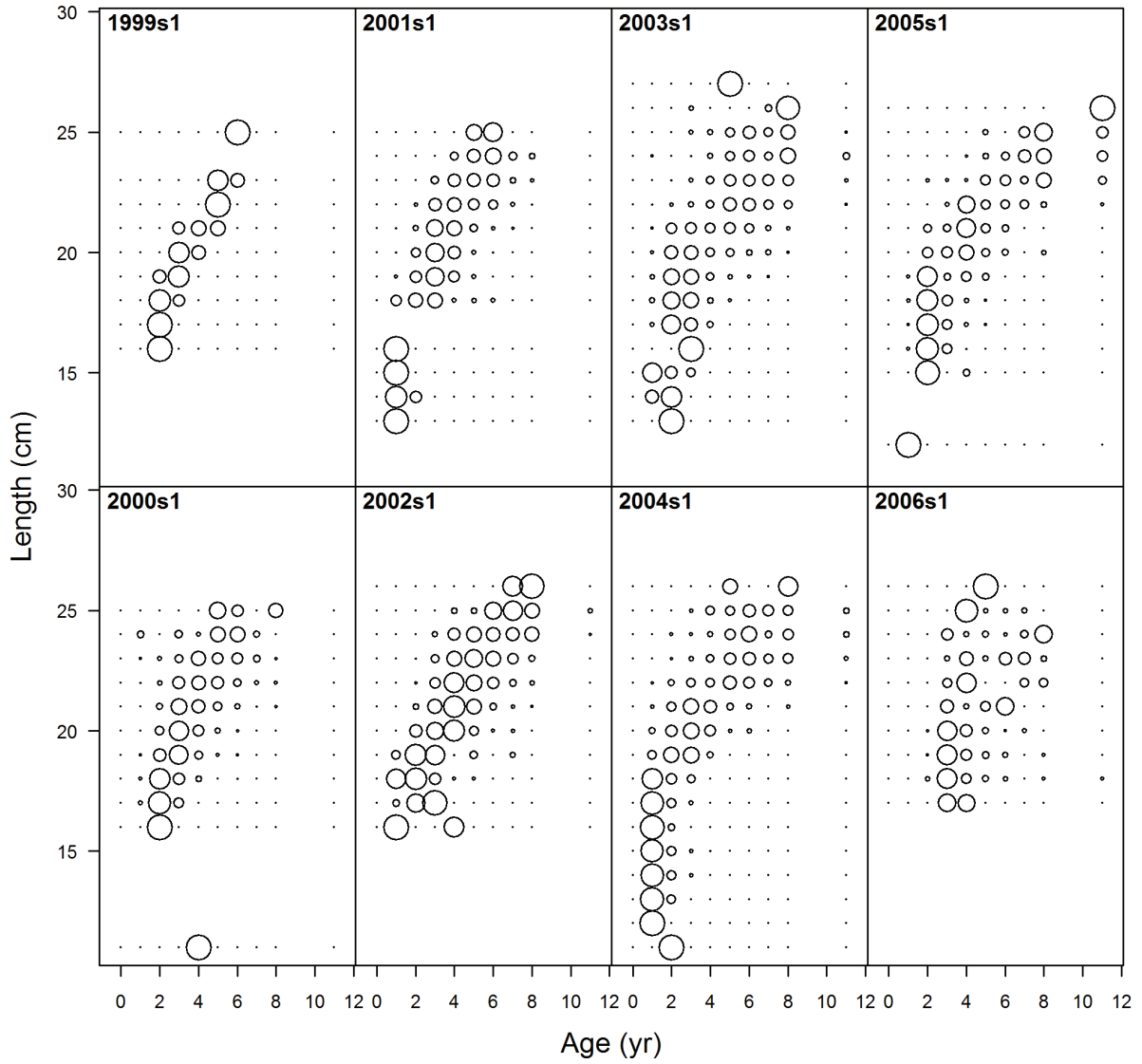
Figure 7c. Conditional age-at-length data for the PacNW fishery, 1999-2006.

conditional age-at-length data, sexes combined, whole catch, PacNW (max=1)
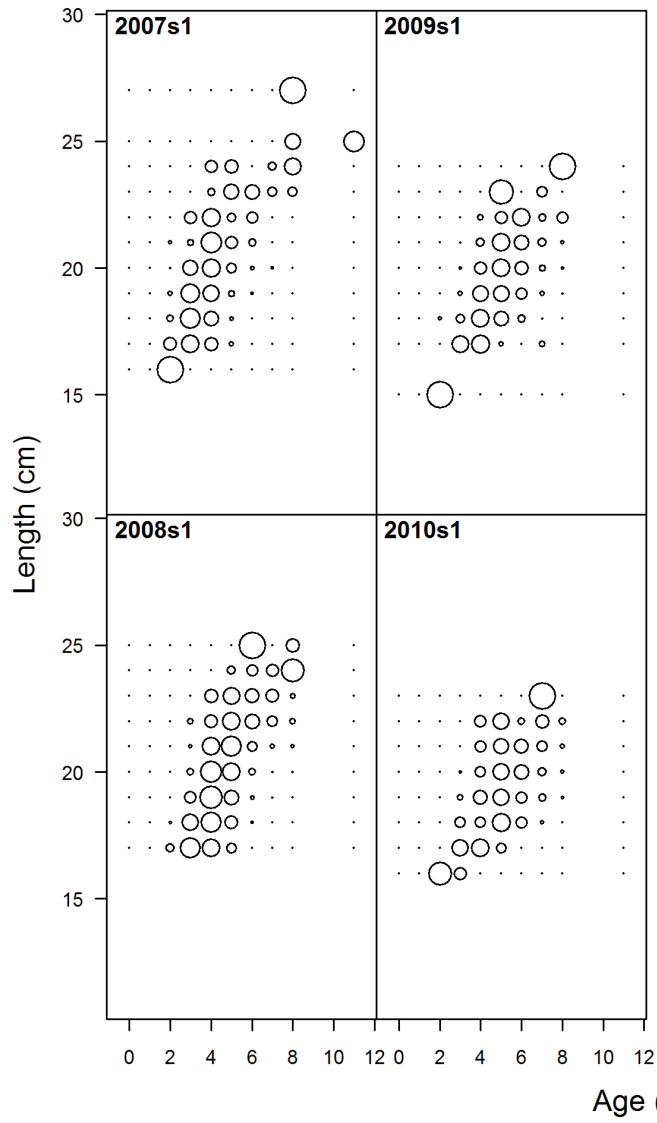
Figure 7c (cont'd). Conditional age-at-length data for the PacNW fishery, 2007-2010.
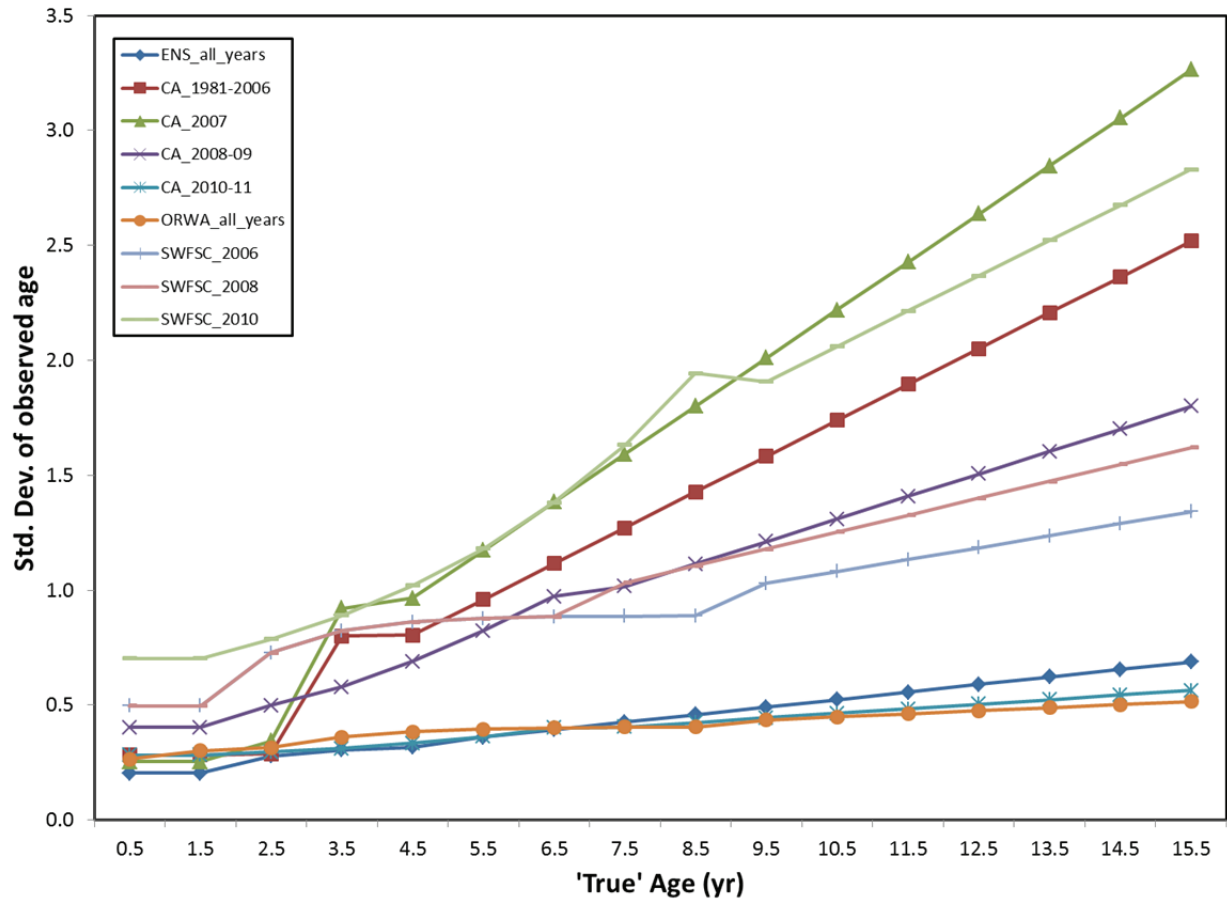
Figure 8. Laboratory- and year-specific ageing errors.
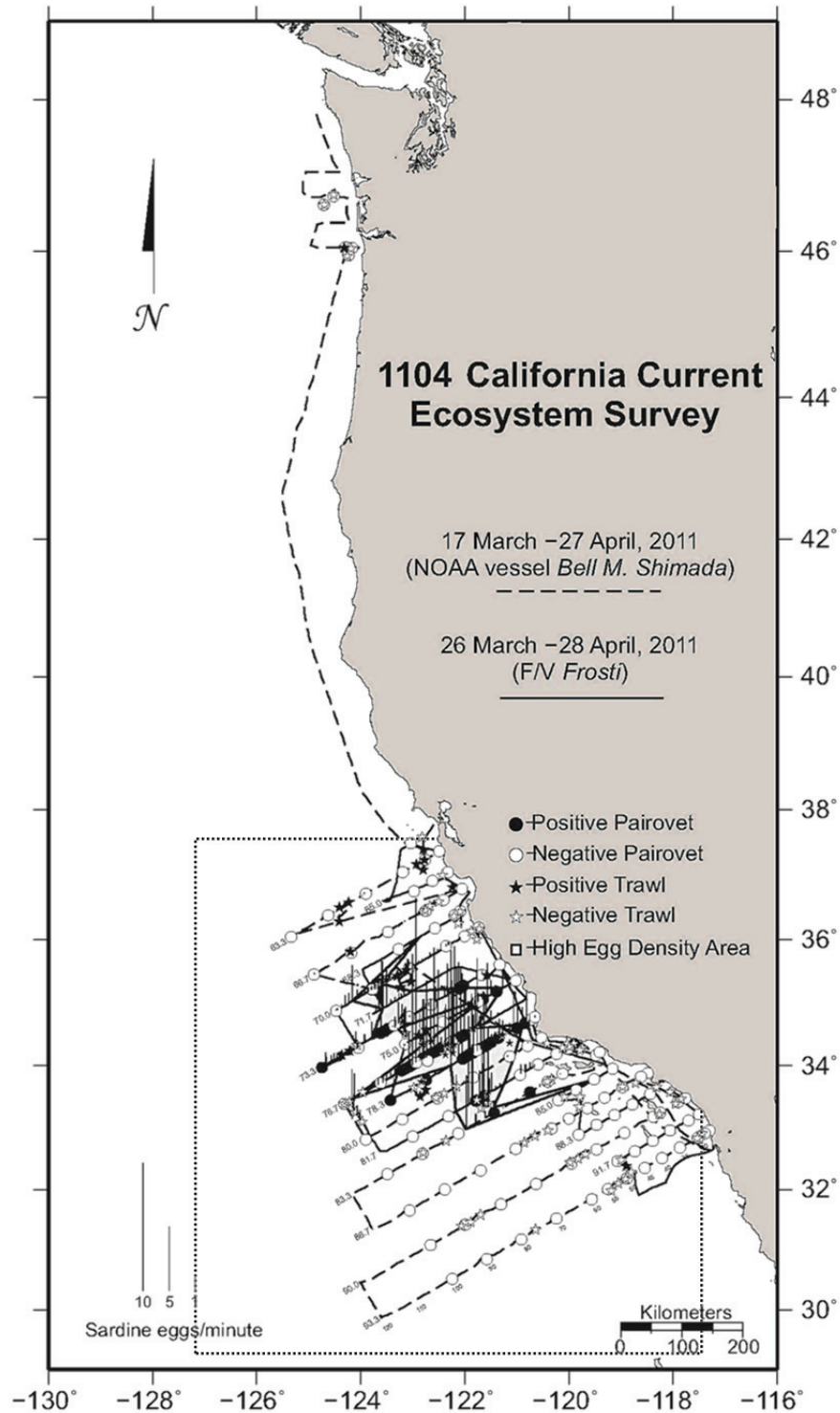
Figure 9a. Distribution of CUFES, Pairovet and Bongo ichthyoplankton collections, and adult trawl samples from the SWFSC 1104 sardine survey (coast-wide), conducted onboard the F/V *Frosti* and NOAA ship *Bell M. Shimada* during spring of 2011. Standard sampling area for the DEPM/TEP index (inset) is displayed on the following page.
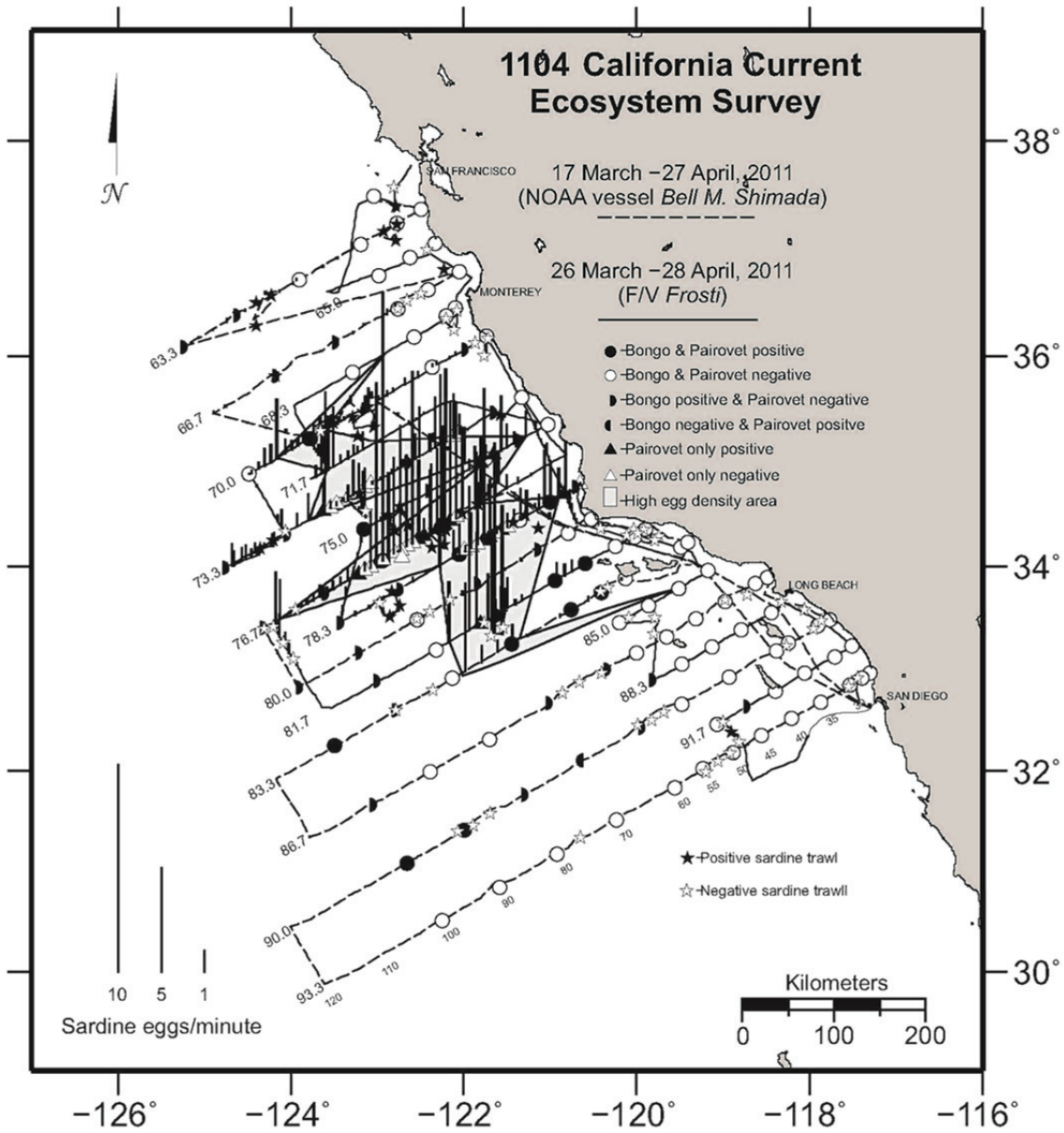
Figure 9b. Distribution of CUFES, Pairovet, and Bongo collections, and adult trawl samples from the SWFSC 1104 sardine survey in the standard sampling area for the DEPM index, conducted onboard the F/V *Frosti* and the NOAA ship *Bell M. Shimada* during spring 2011.
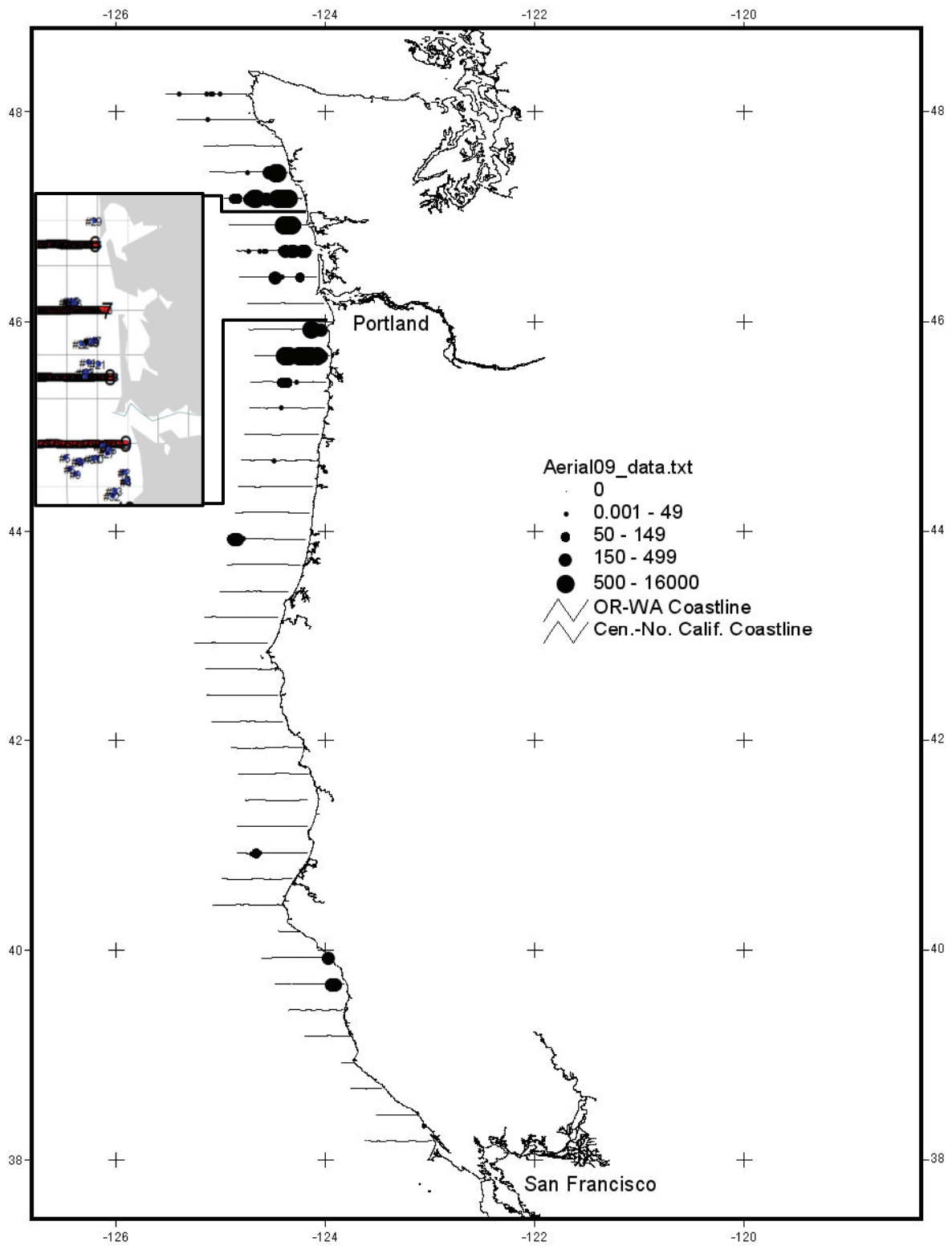
Figure 10. Distribution of sardine schools observed in the 2009 Aerial Sardine Survey (data from Jagielo et al. 2009).
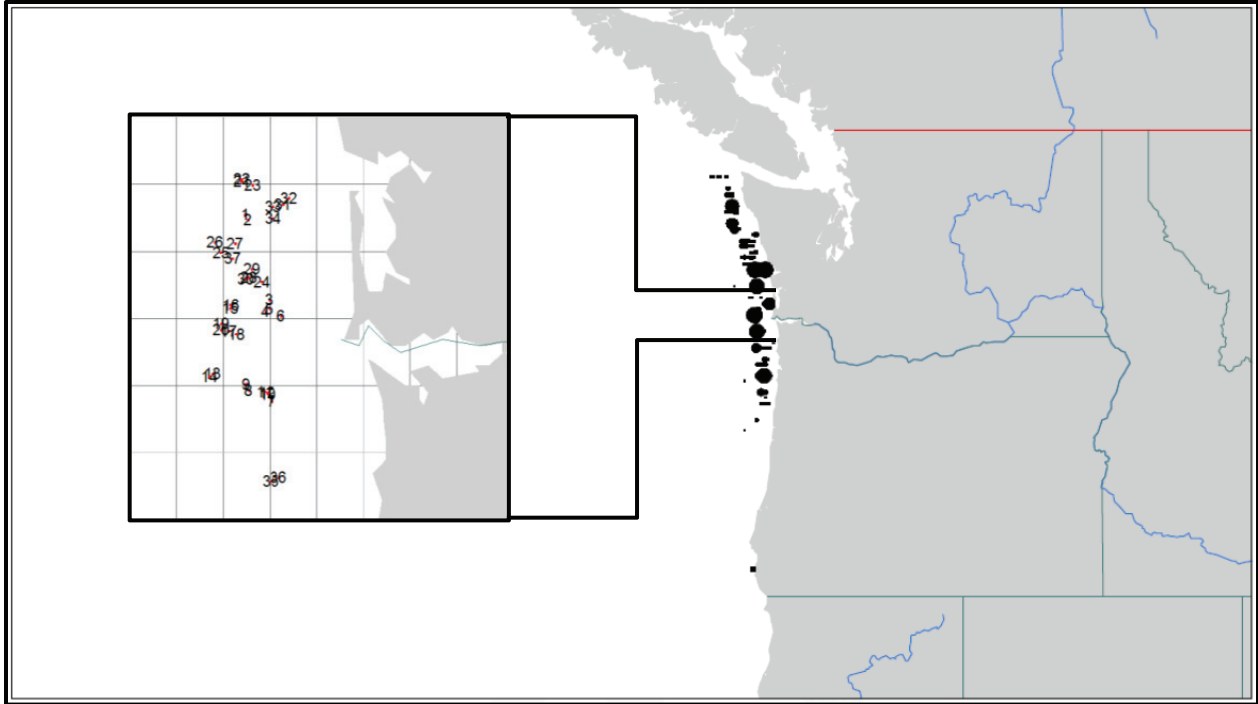
Figure 11. Distribution of sardine schools observed in the 2010 Aerial Sardine Survey (from Jagielo et al. 2010). Inset displays distribution of point sets to determine surface area to biomass relationship and length composition.
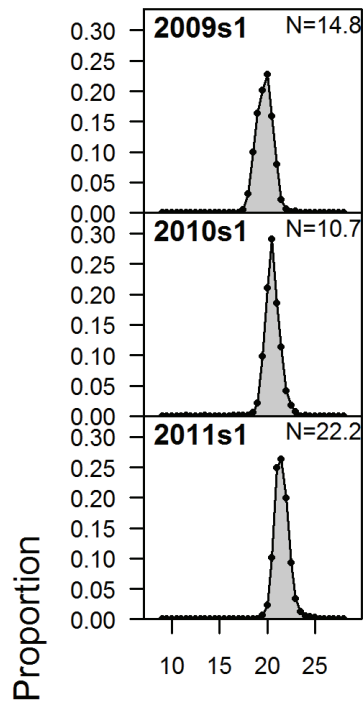
Figure 12. Length-composition data (SL-cm) for the aerial survey.
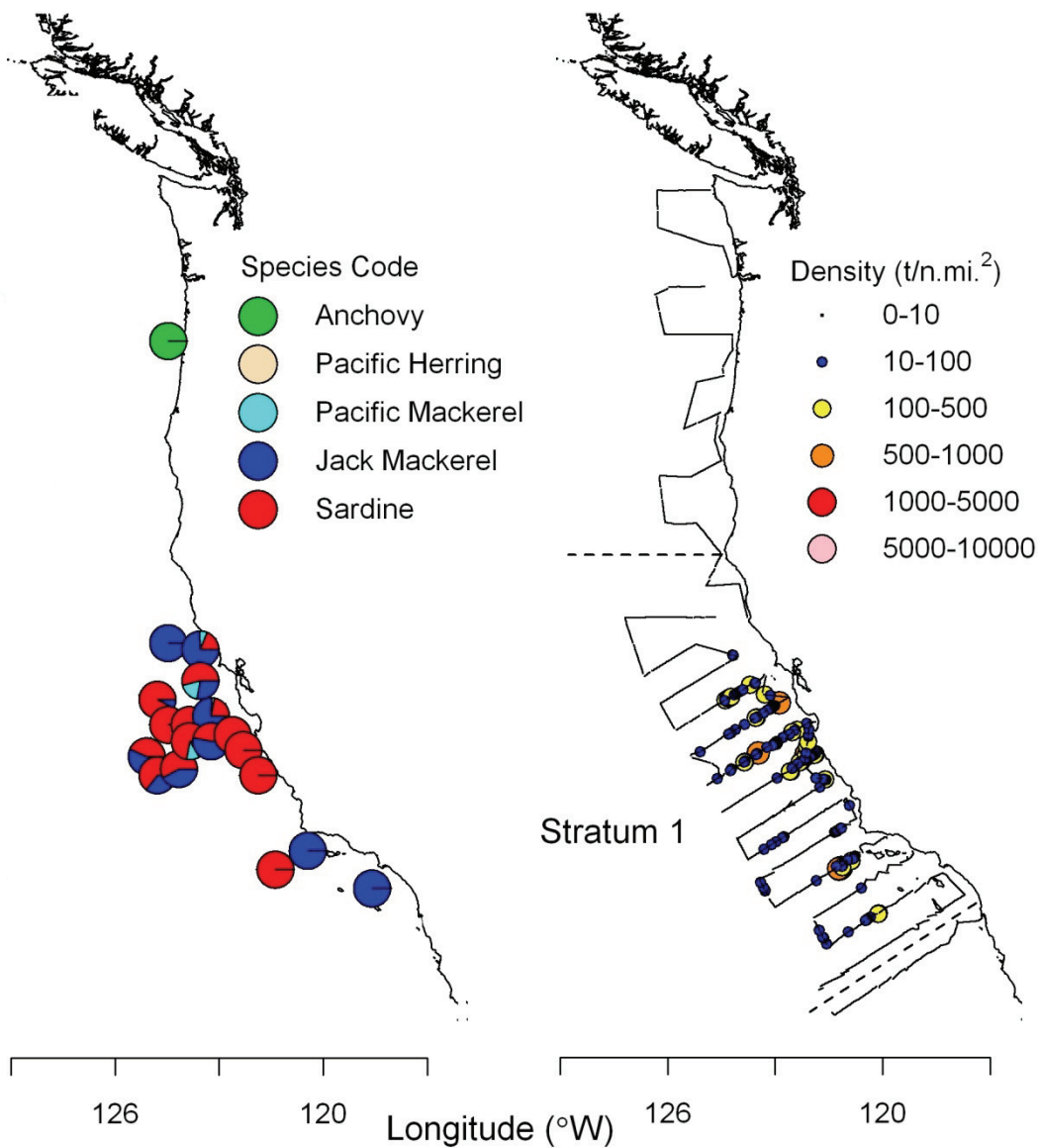
Figure 13. Trawl species composition (left) and Pacific sardine density (right) measured by acoustic backscatter during the SWFSC 1004 sardine survey (coast-wide), conducted onboard the F/V *Frosti* and NOAA ship *Miller Freeman* during spring of 2010. Maps provided by Drs. David Demer and Juan Zwolinski (SWFSC Advanced Survey Technologies).

length comp data, sexes combined, whole catch, Acoustic
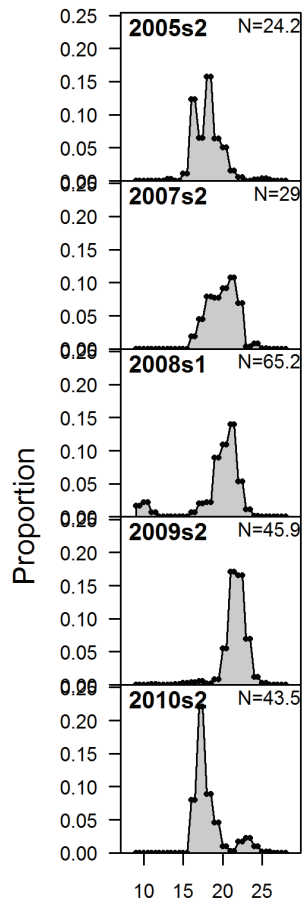
Length (cm)

Figure 14a. Length-composition data (1-cm resolution) for the acoustic survey, 2005-2010.

conditional age-at-length data, sexes combined, whole catch, Acoustic (max=1)
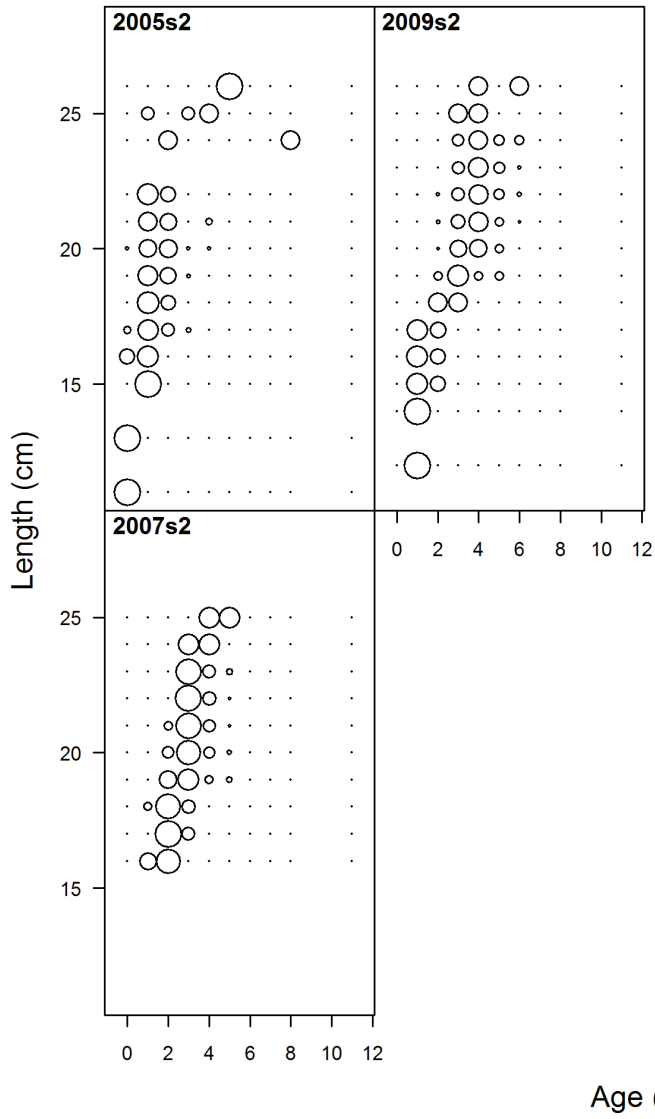
Figure 14b. Conditional age-at-length data for the Acoustic-trawl survey, 2005-2009.
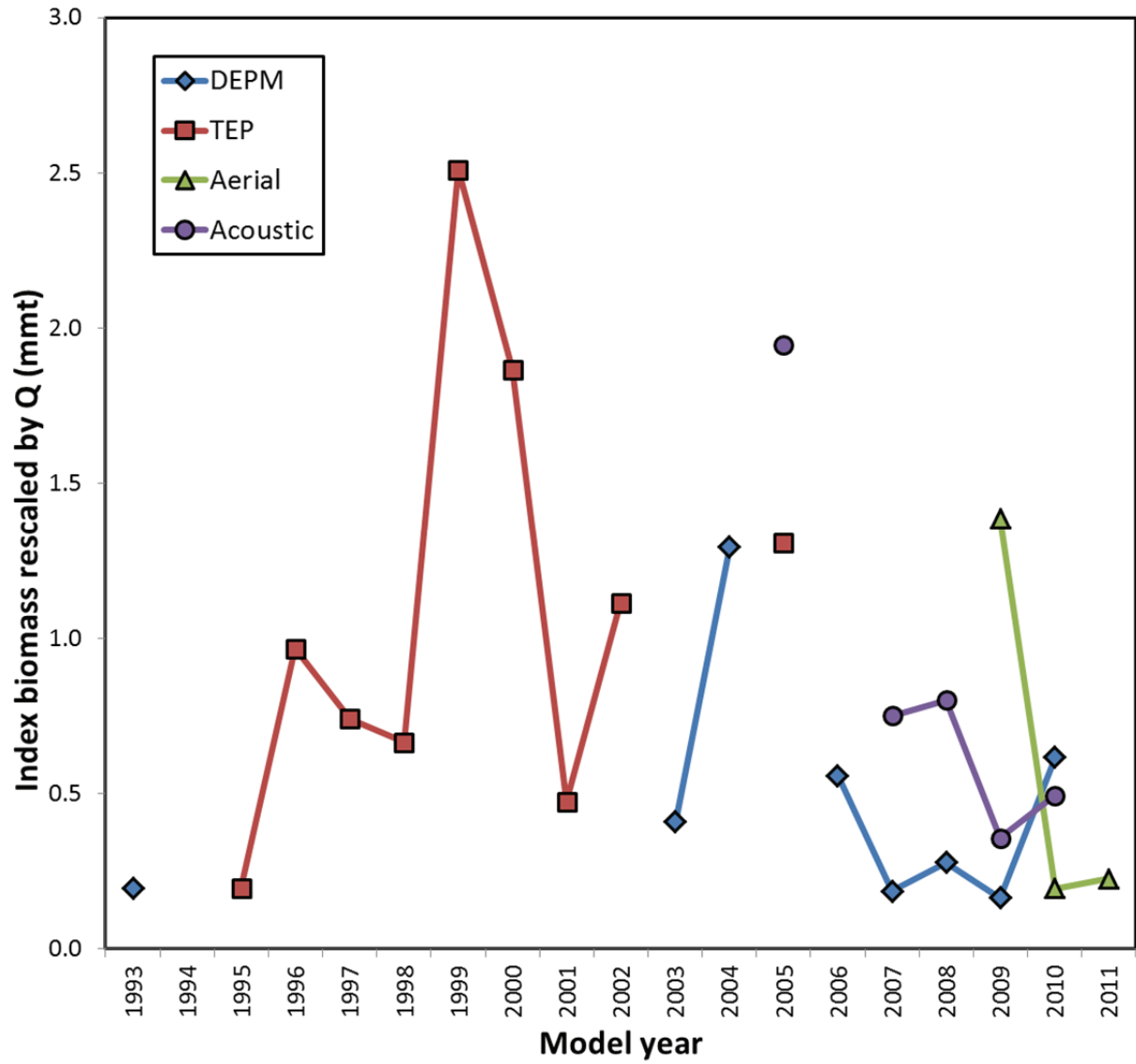
Figure 15. Survey indices of relative abundance standardized by base model estimates of q for each survey.
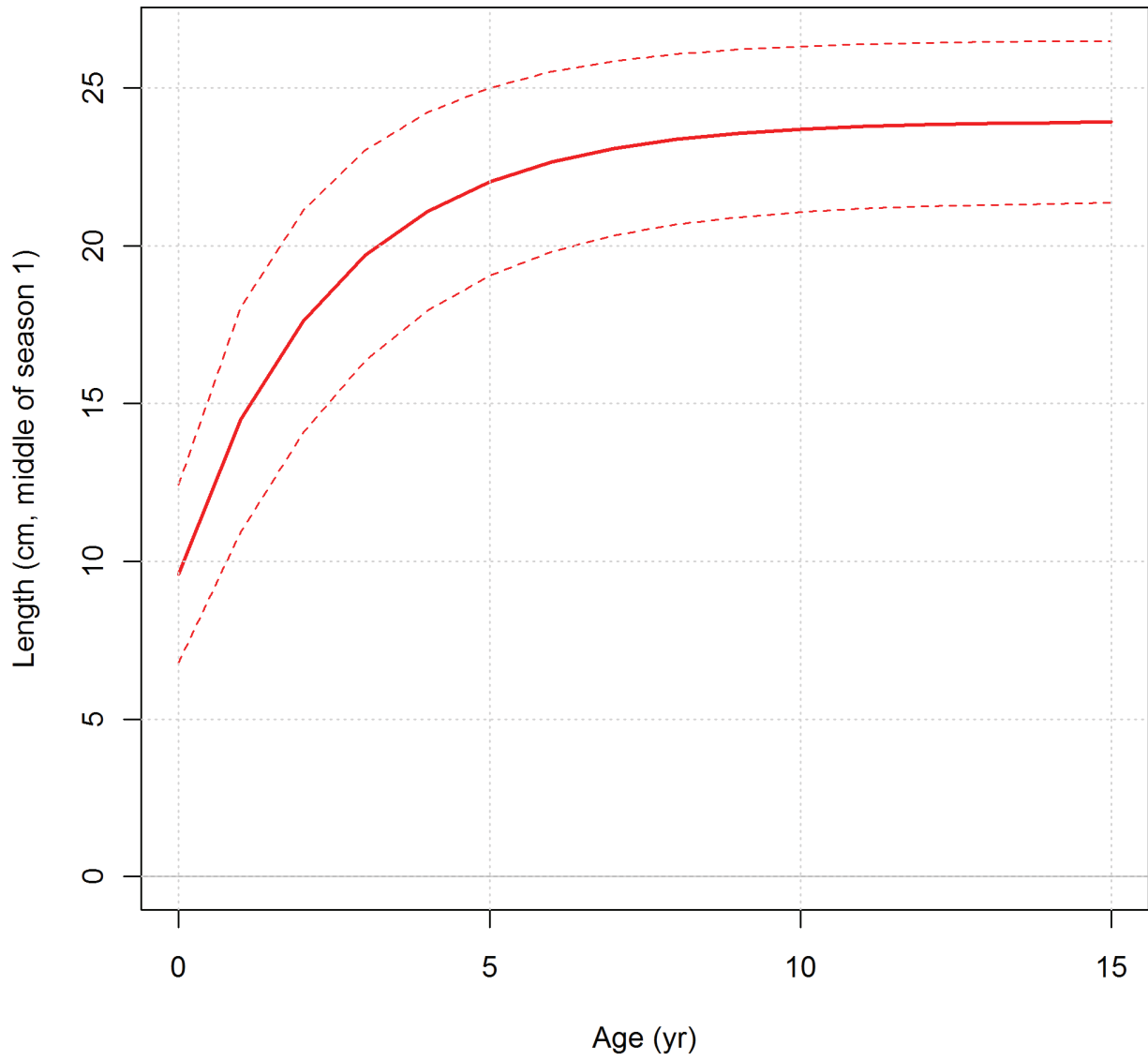
Figure 16. Length-at-age as estimated in the base model ($L_{0.5yr}$ = 11.2, L_∞ = 24.0, K = 0.399).
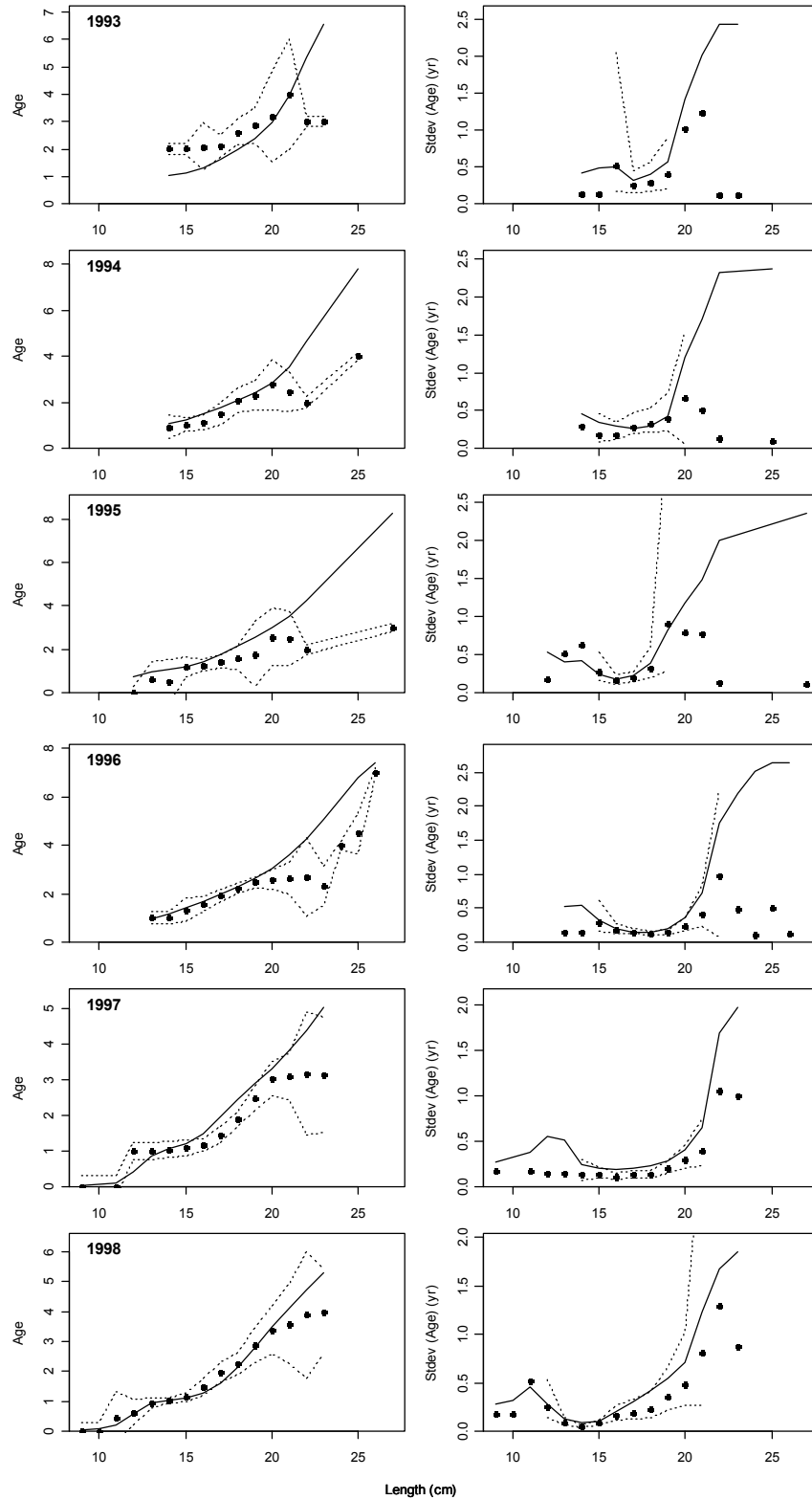
Figure 17a. Fit to conditional age-at-length data, MexCal_S1, 1993-1998.
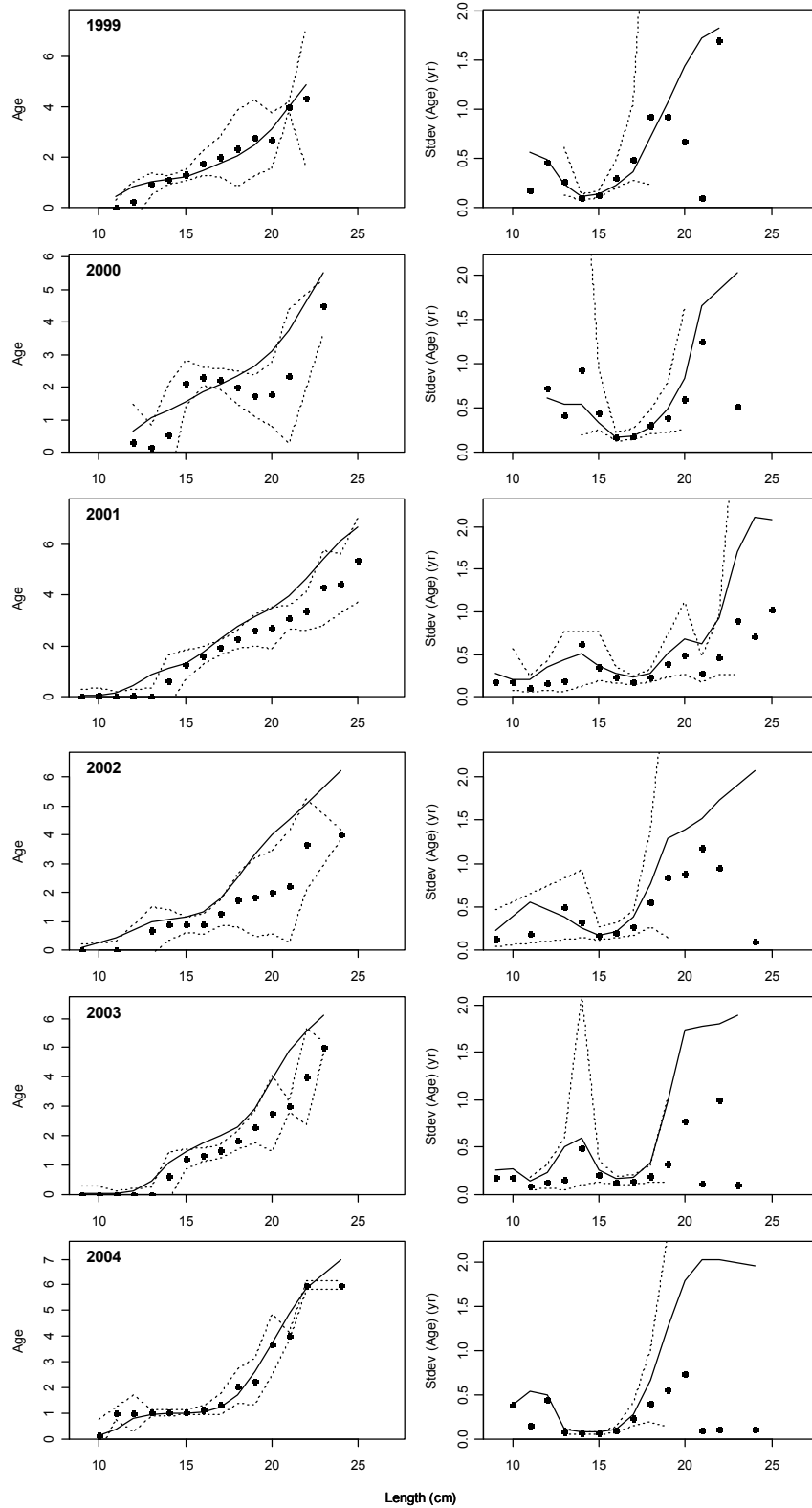
Figure 17a (cont'd). Fit to conditional age-at-length data, MexCal_S1, 1999-2004.
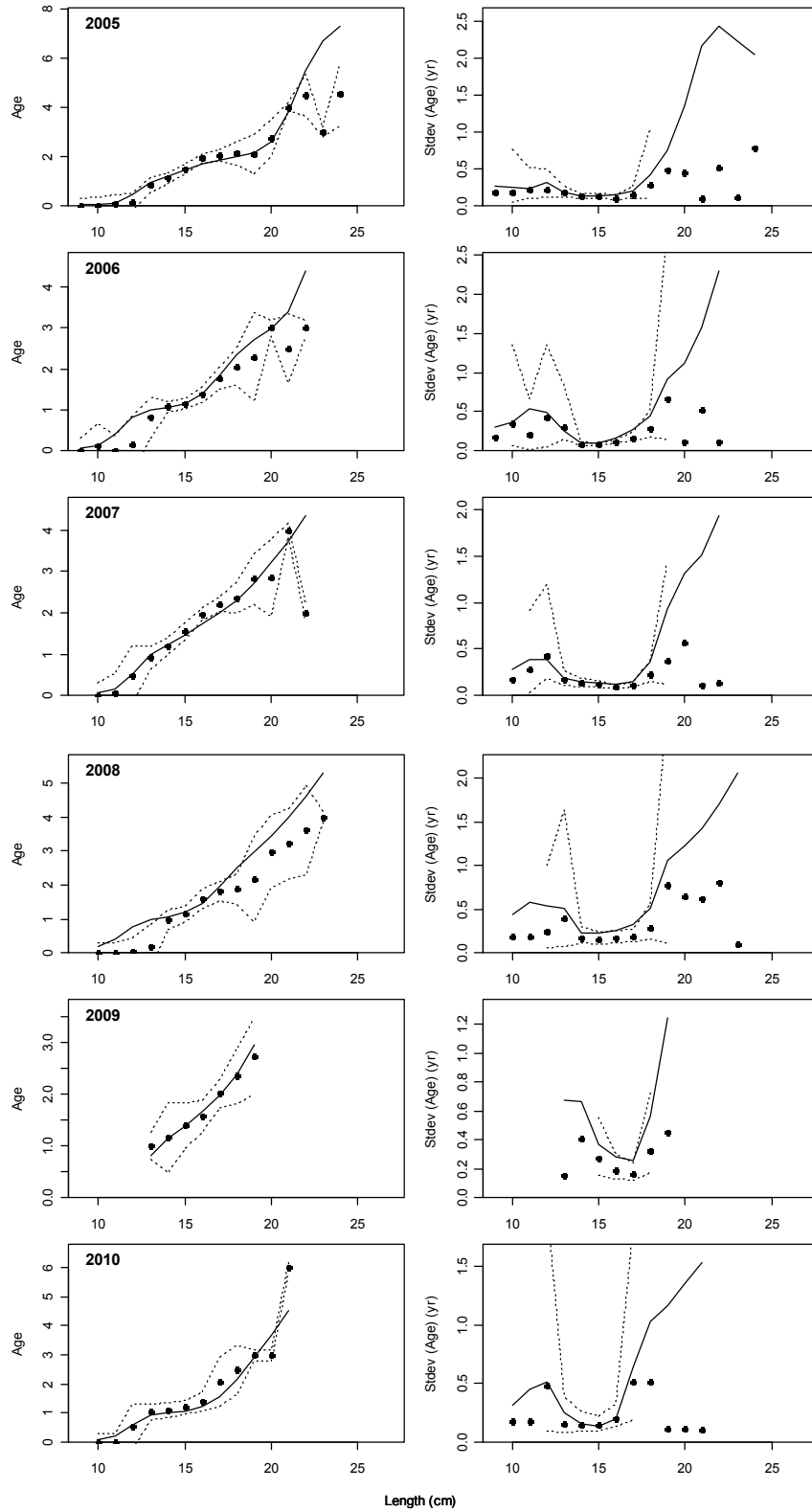
Figure 17a (cont'd). Fit to conditional age-at-length data, MexCal_S1, 2005-2010.
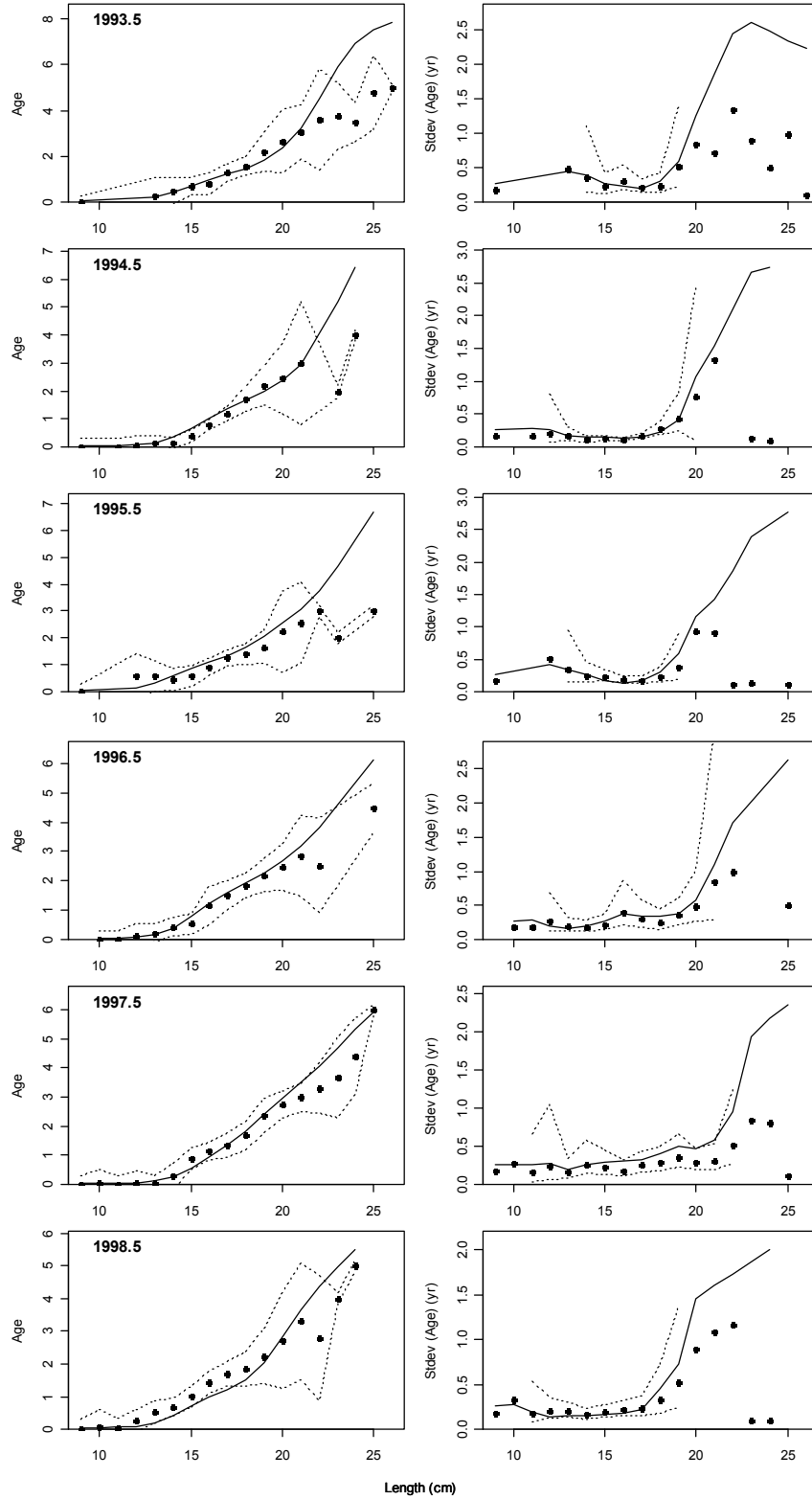
Figure 17b. Fit to conditional age-at-length data, MexCal_S2, 1993-1998.

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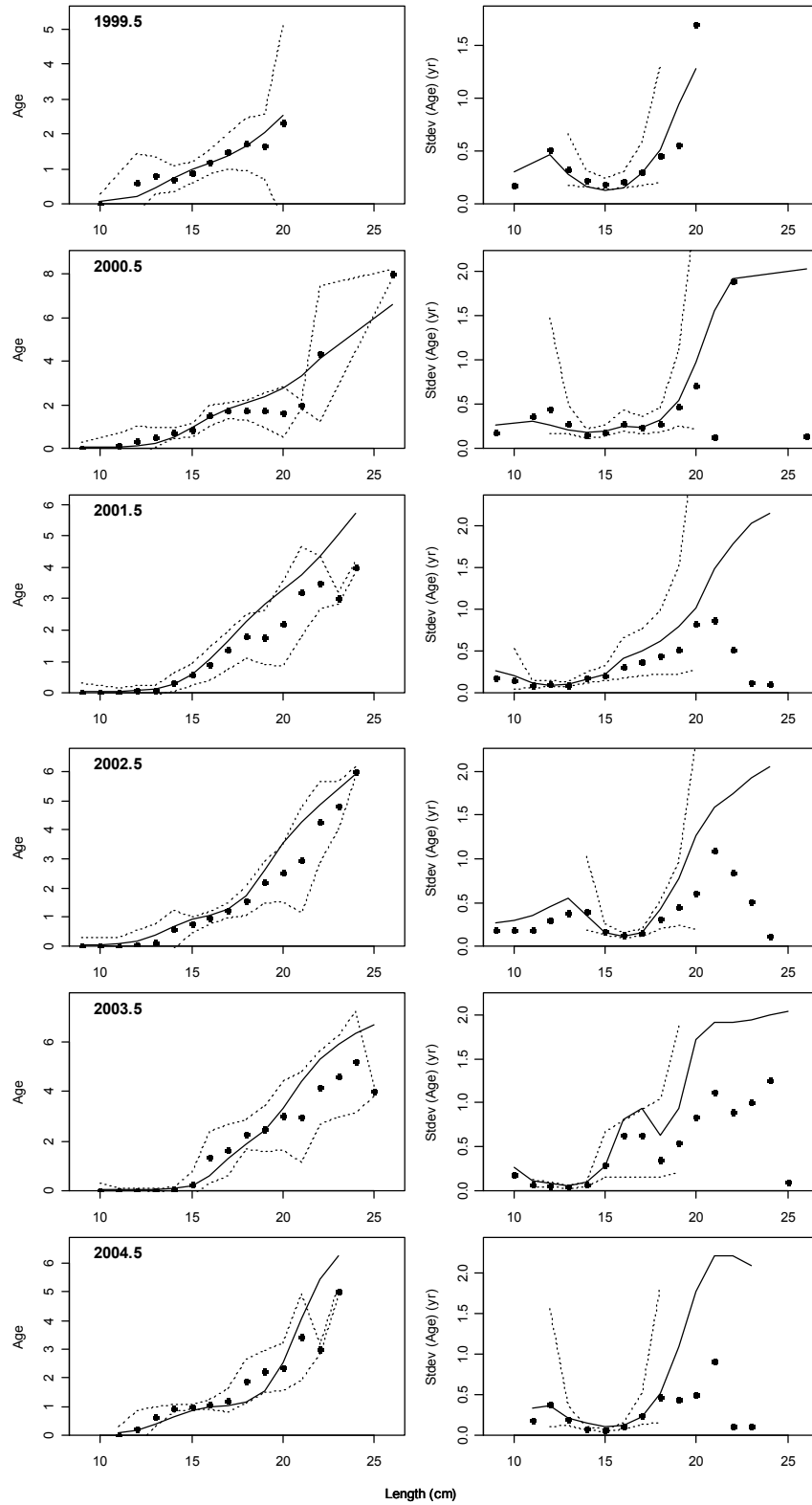
Figure 17b (cont'd). Fit to conditional age-at-length data, MexCal_S2, 1999-2004.

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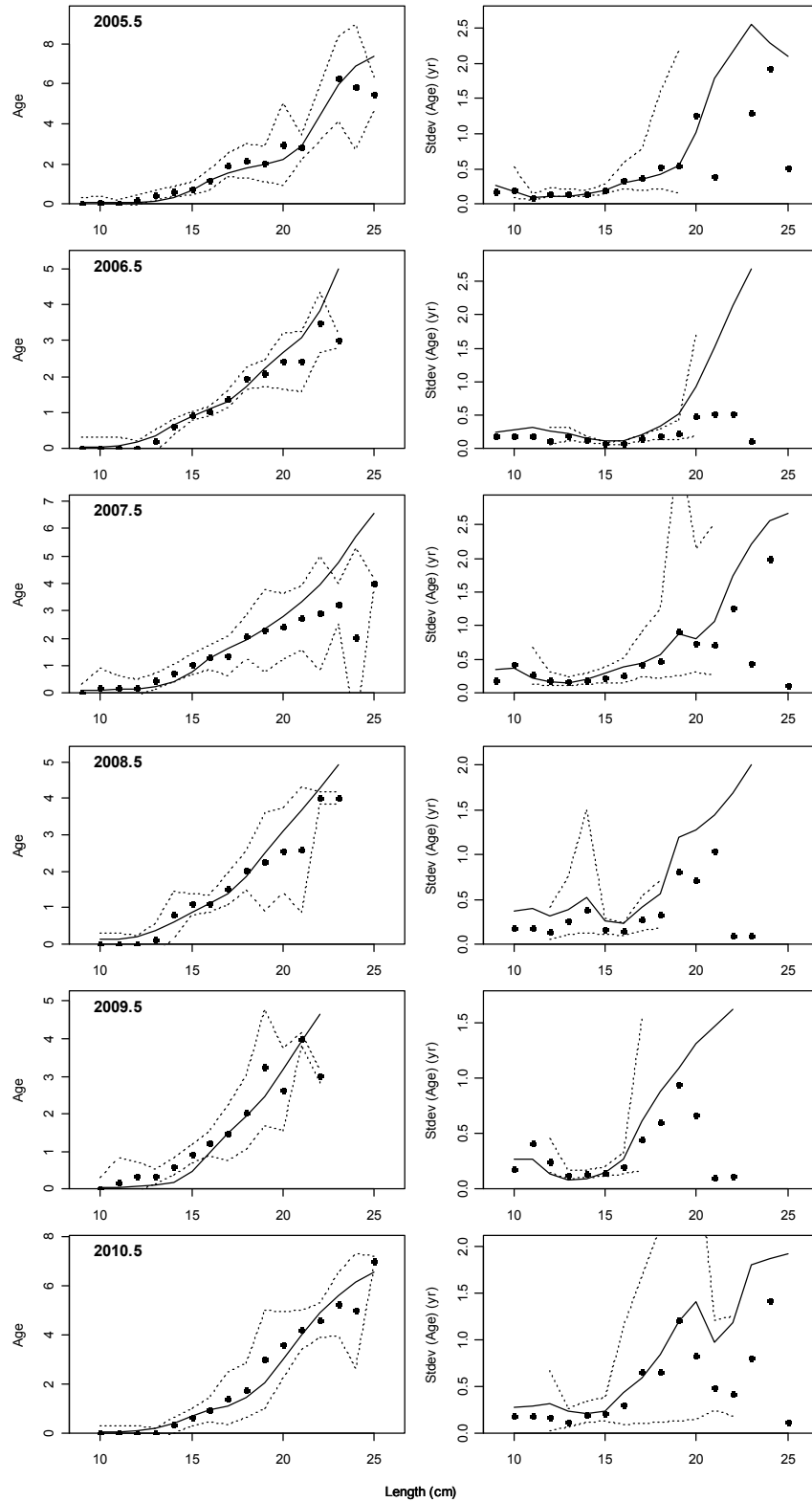
Figure 17b (cont'd). Fit to conditional age-at-length data, MexCal_S2, 2005-2010.
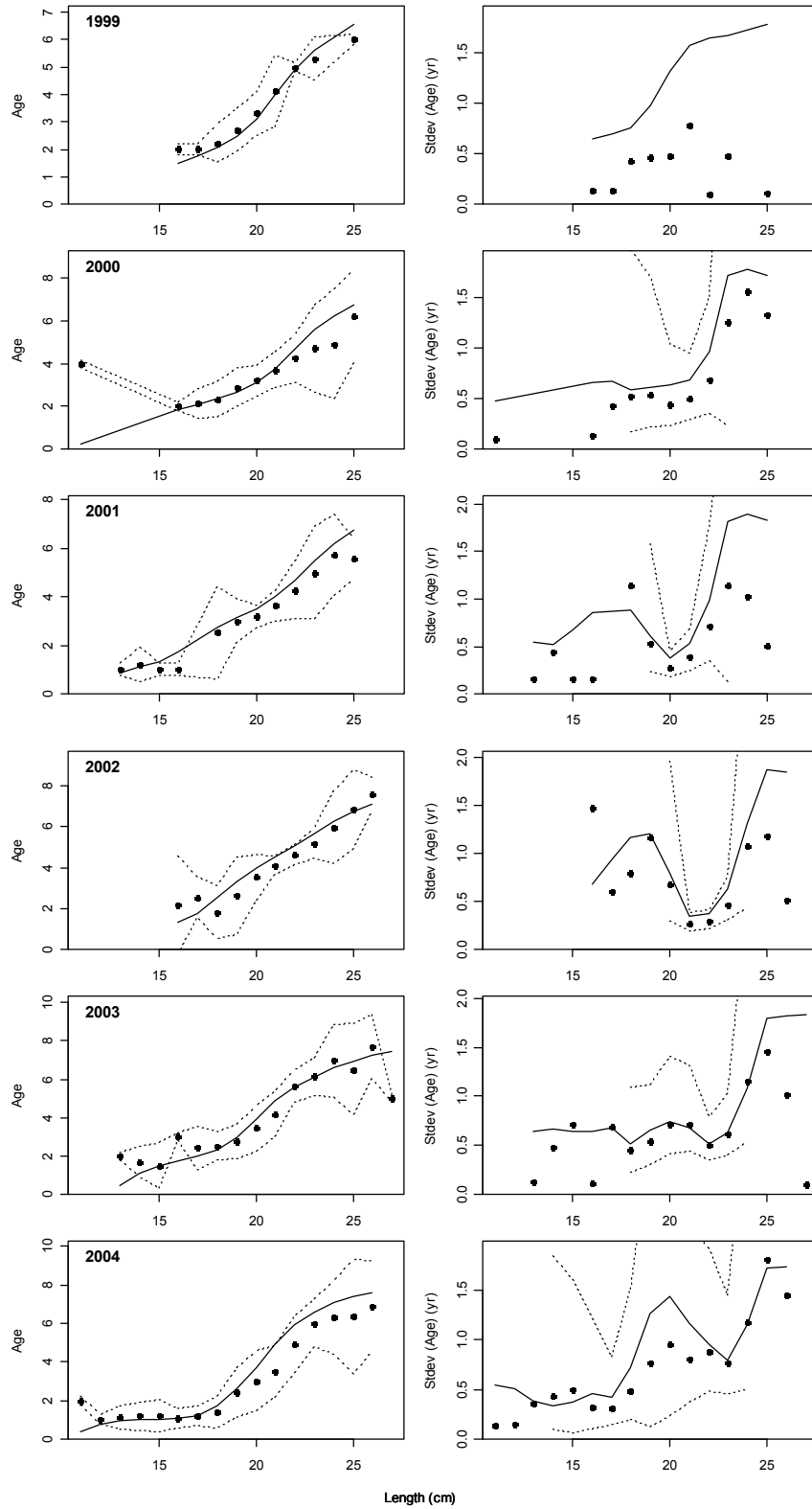
Figure 17c. Fit to conditional age-at-length data, PacNW, 1999-2004.
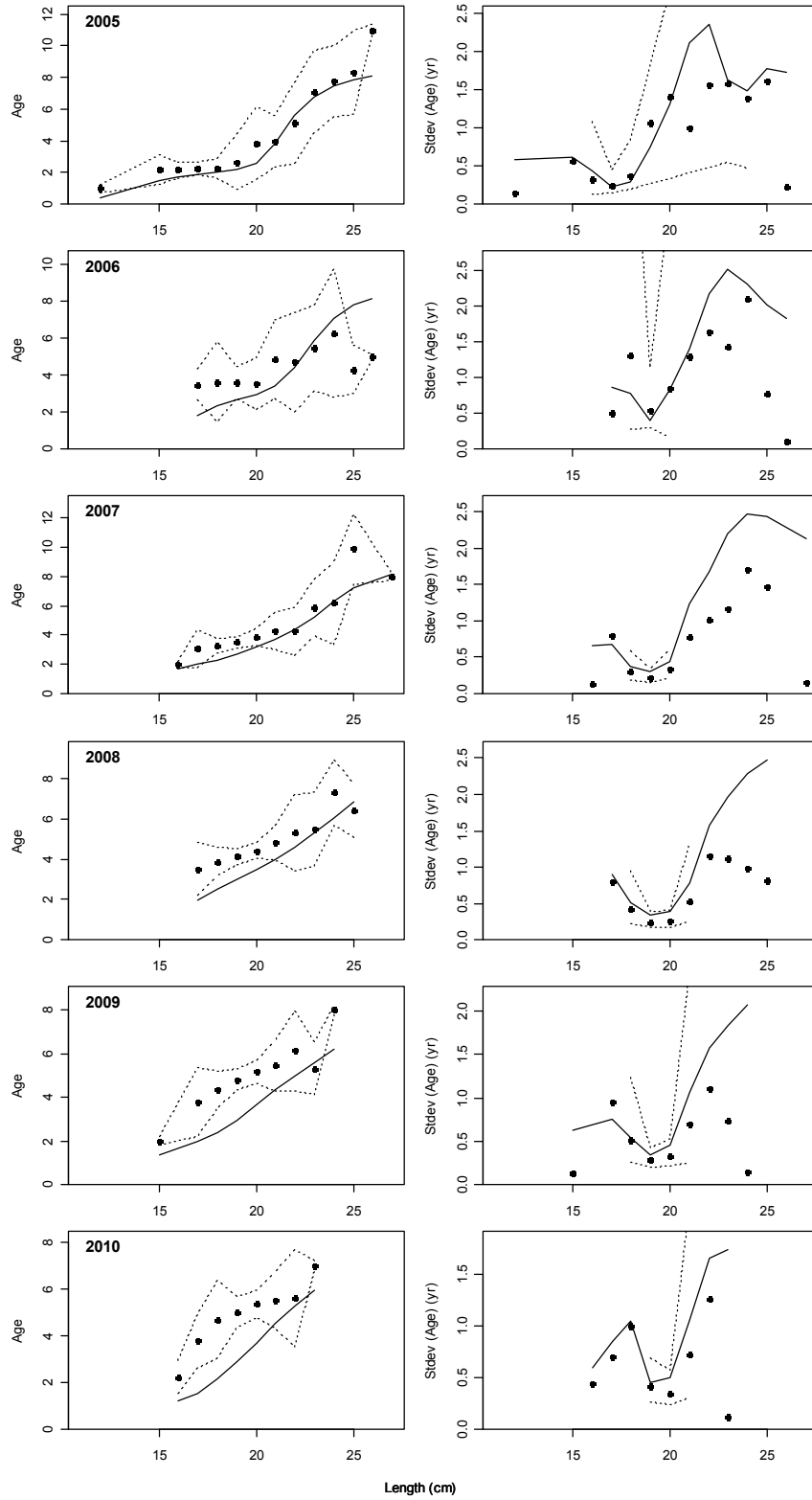
Figure 17c (cont'd). Fit to conditional age-at-length data, PacNW, 2005-2010.
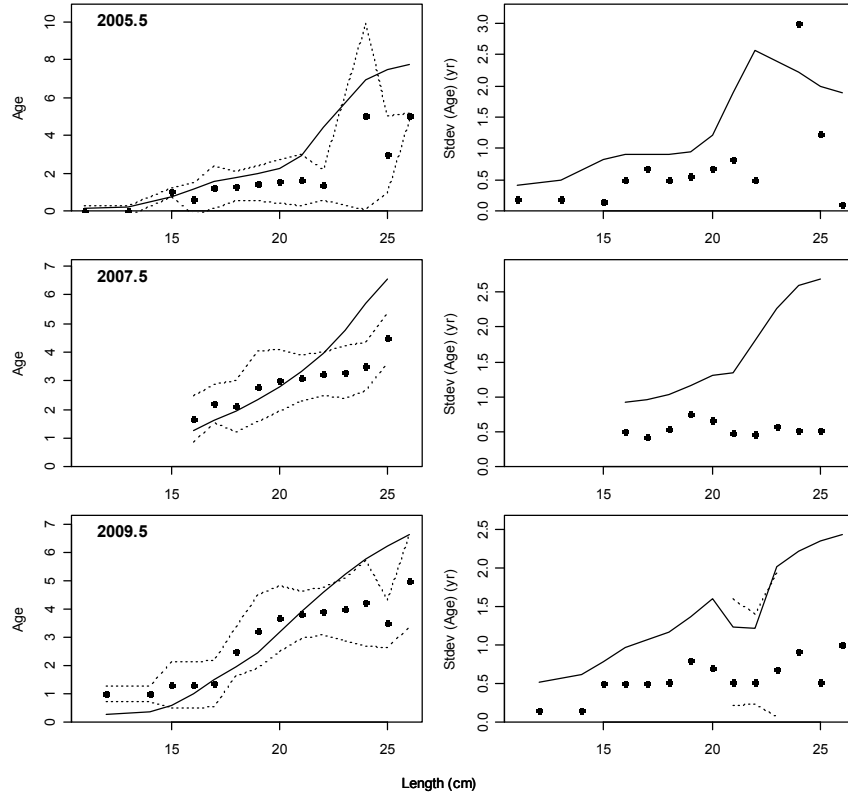
Figure 17d. Fit to conditional age-at-length data, Acoustic survey, 2005-2009.
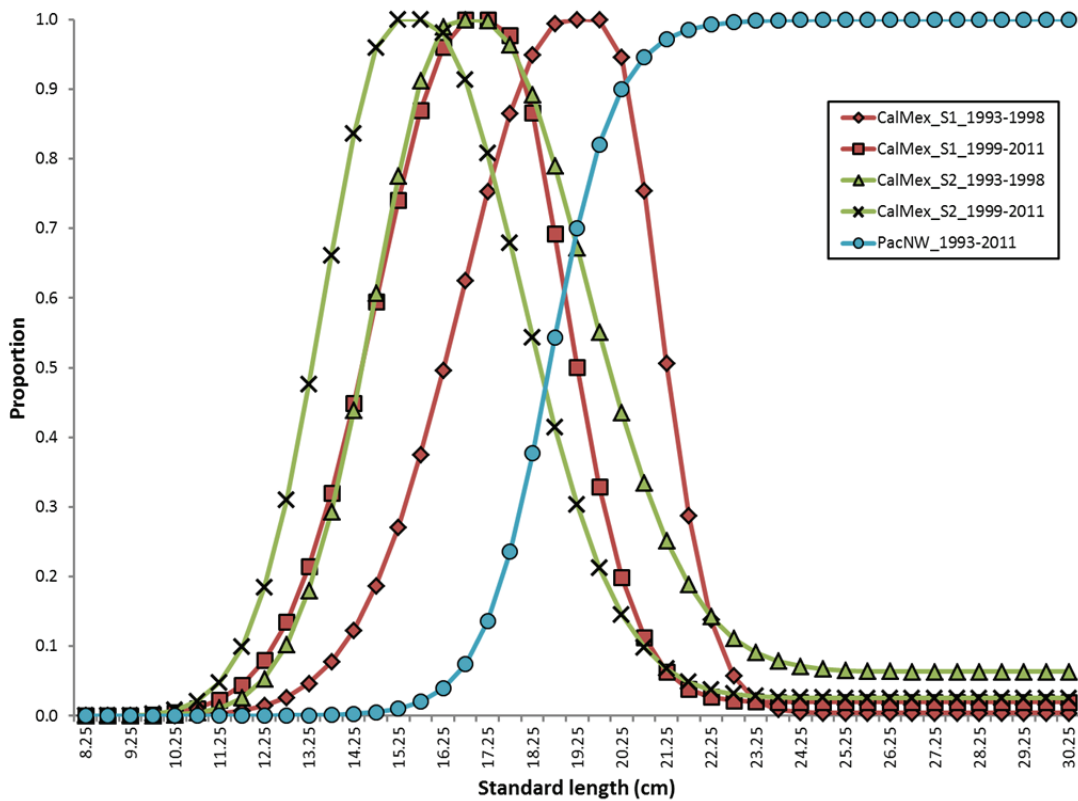
Figure 18a. Fishery length selectivities estimated by SS.
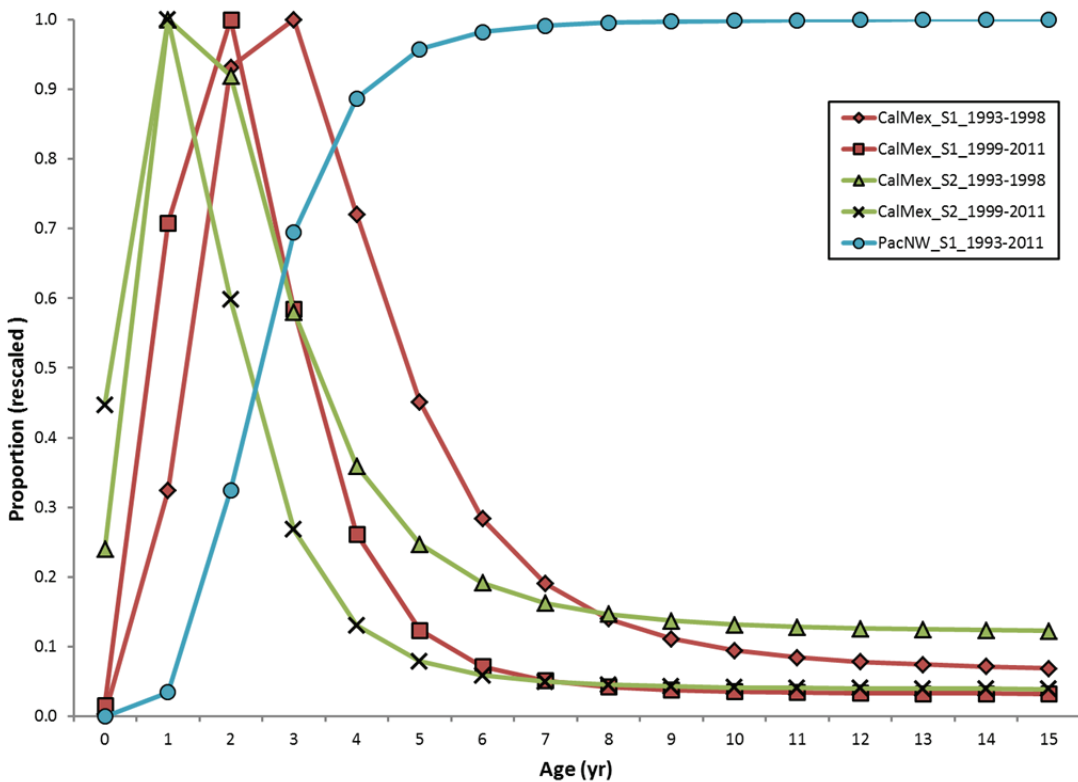
Figure 18b. Fishery age selectivities as implied by the product of length selectivity and the ALK.
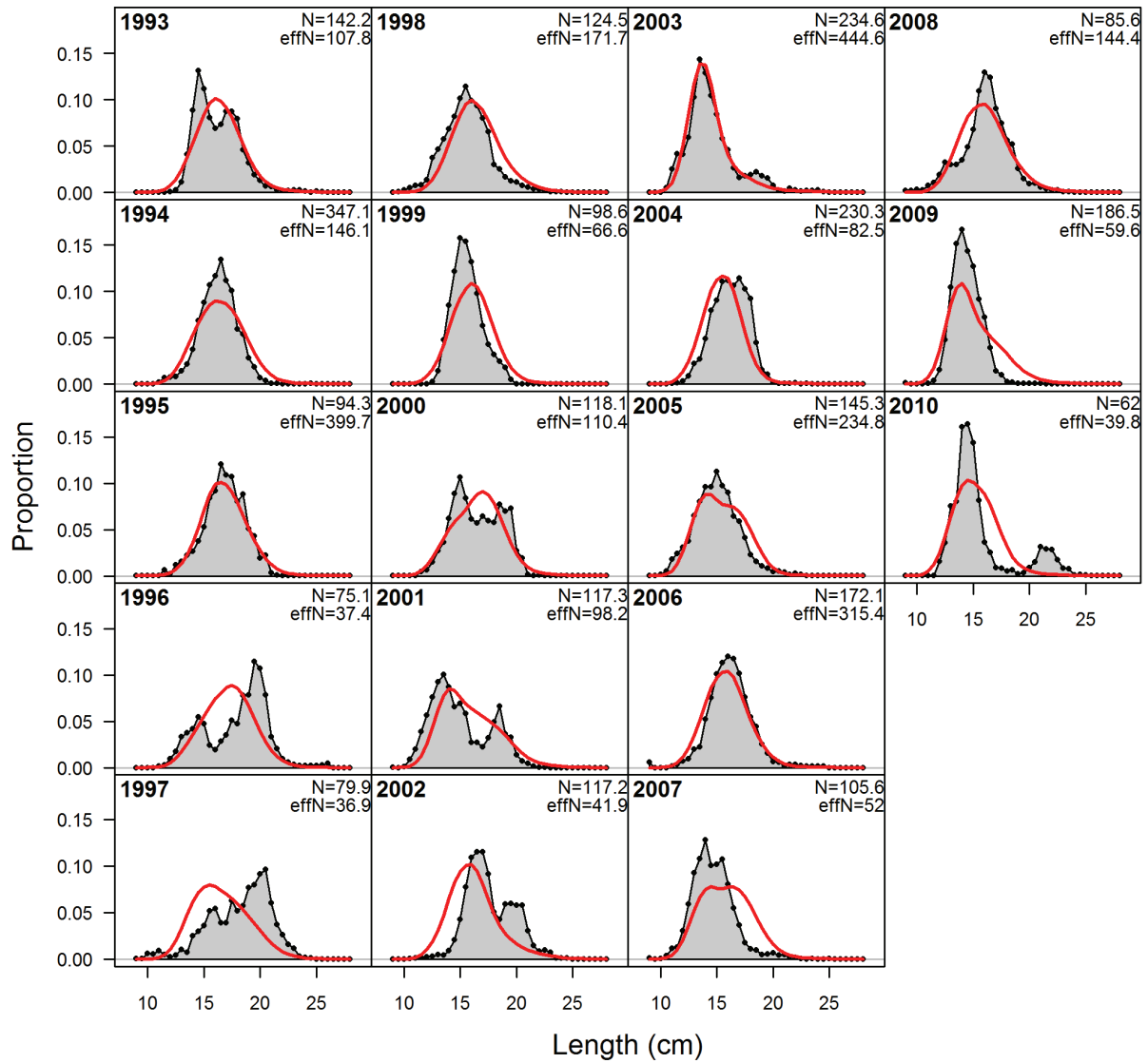
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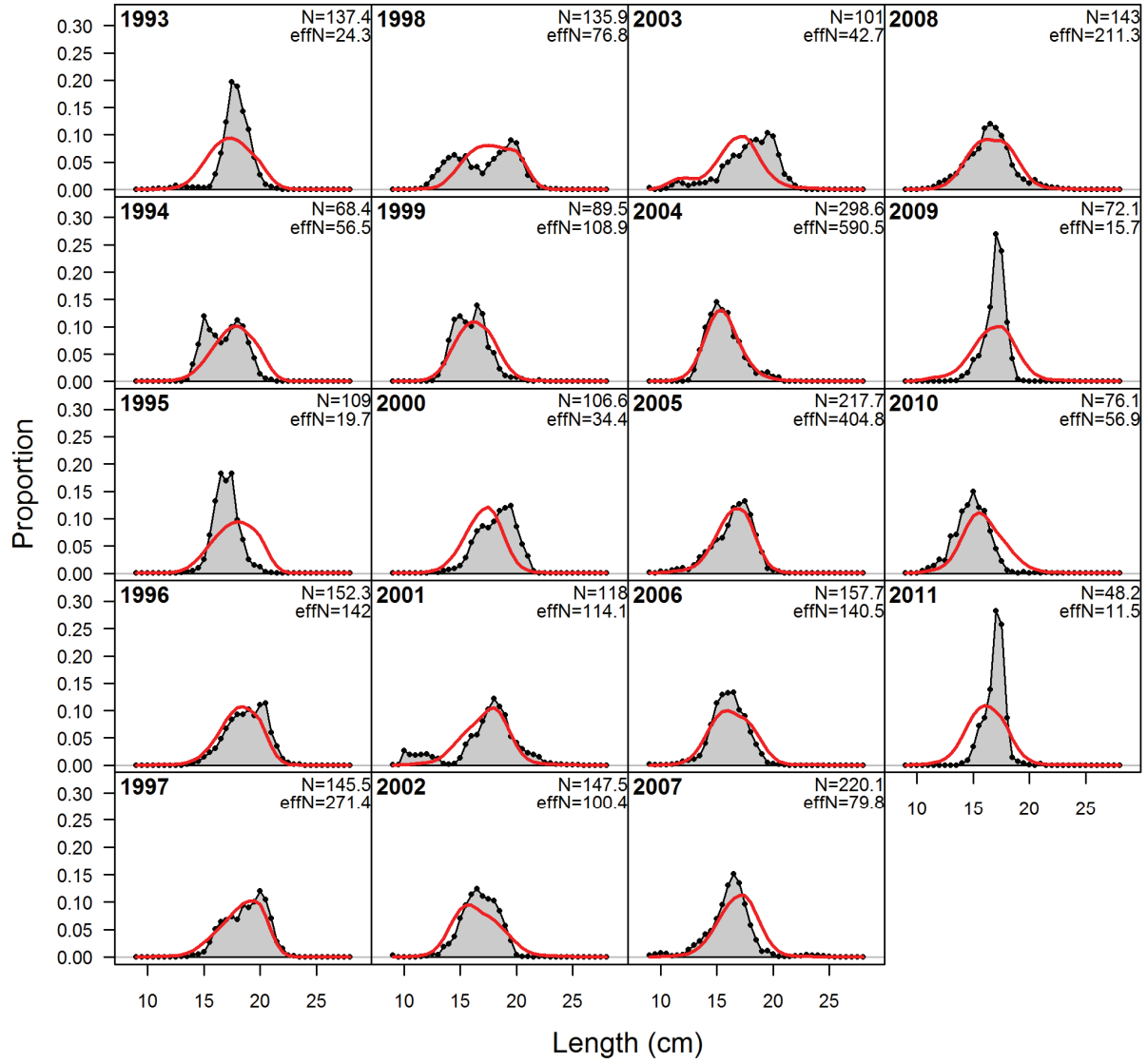
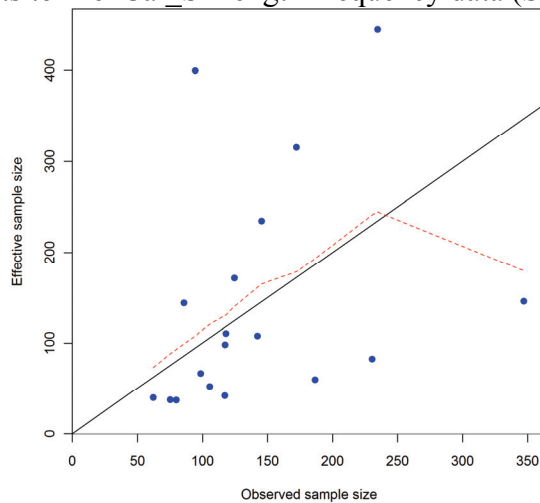Figure 19a. Base model fits to MexCal_S1 length-frequency data (Season 1).
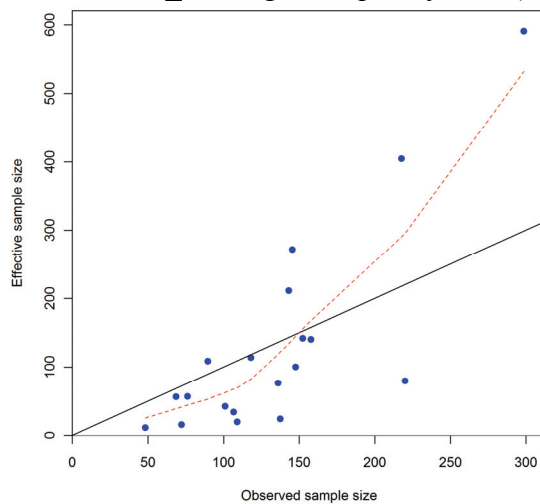
Figure 19b. Observed and effective sample sizes for MexCal_S1 fishery length-frequency data.
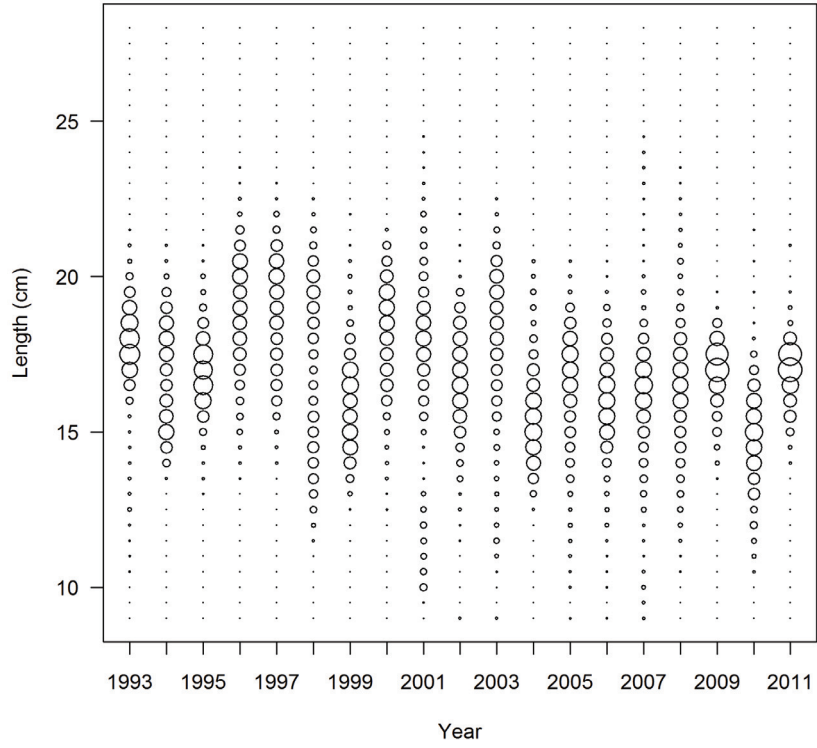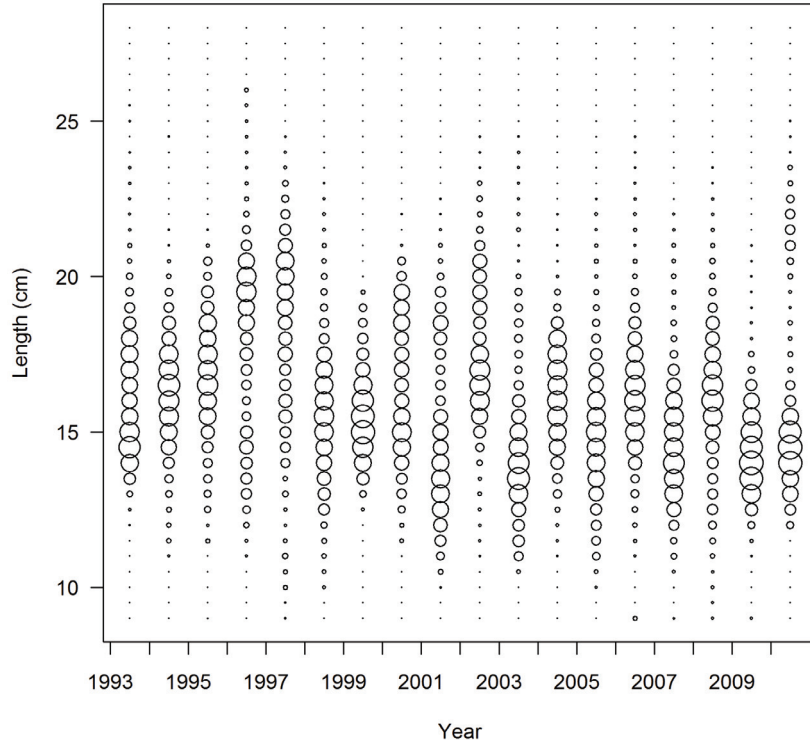
Figure 19c. Bubble plot of MexCal_S1 length-frequency data (Season 1).
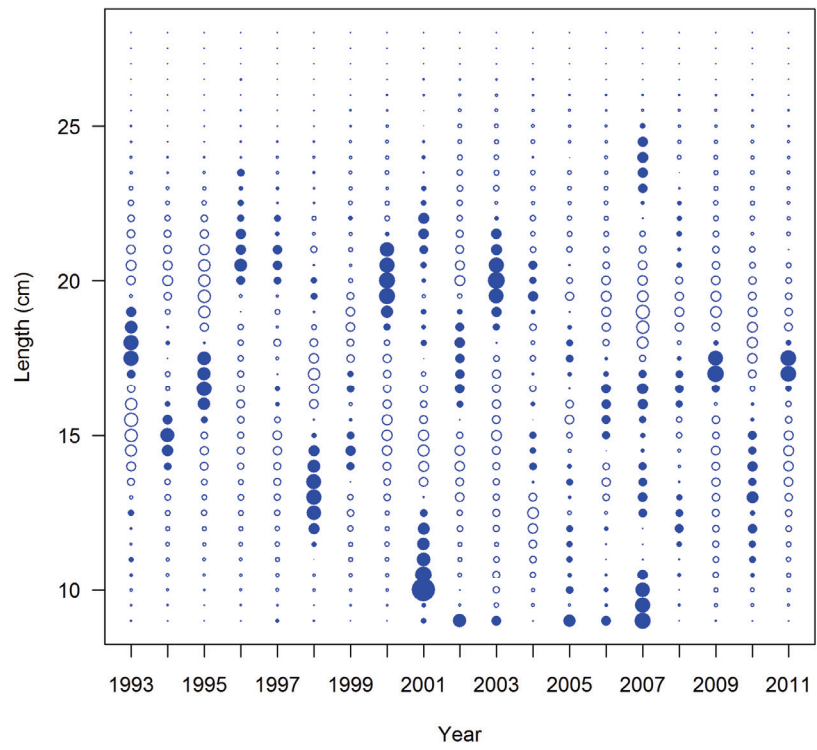
Figure 19d. Pearson residuals (max=9.19) for fit to MexCal_S1 length-frequency data.
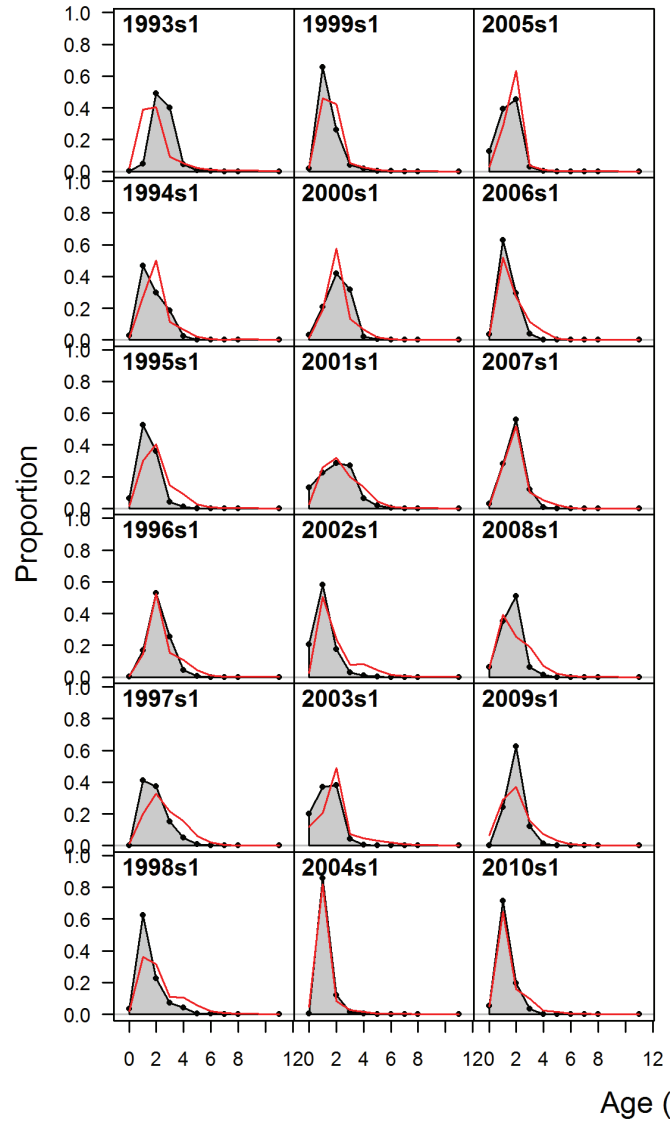
Figure 20a. Base model fits to MexCal_S1 implied age-frequency data (Season 1).
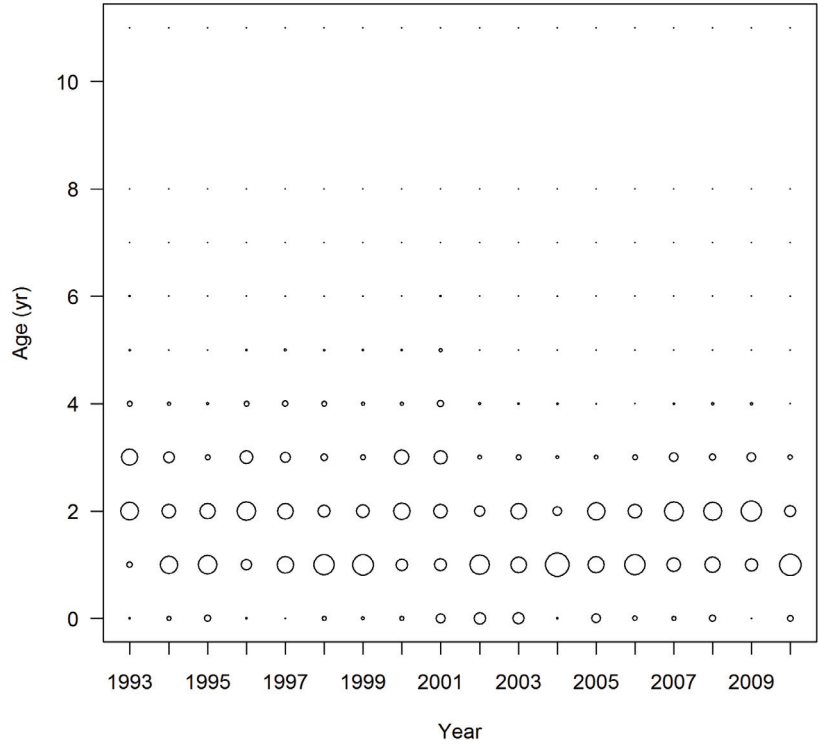
Figure 20b. Bubble plot of MexCal_S1 implied age-frequency data (Season 1).
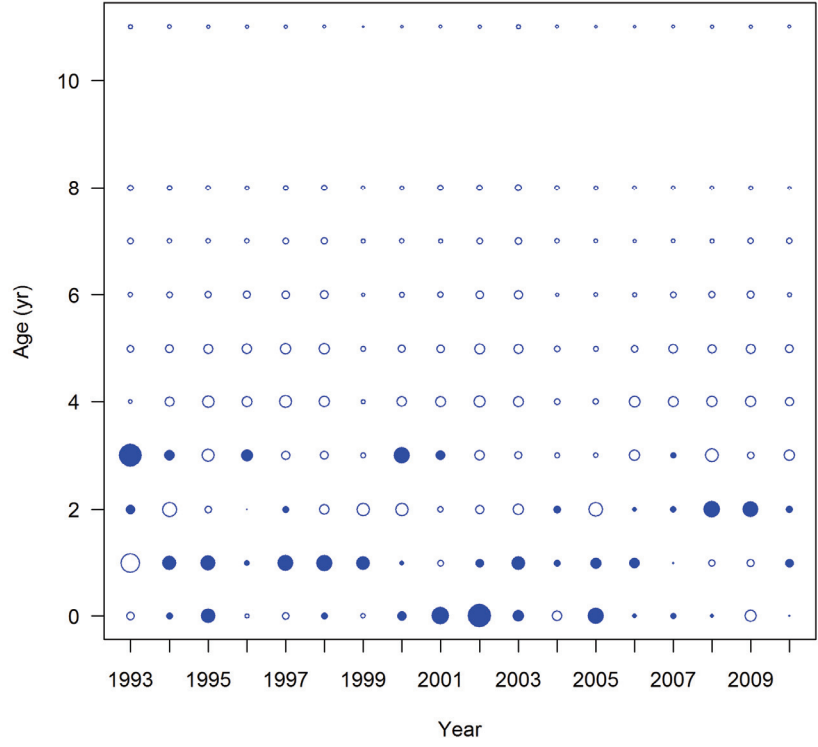
Figure 20c. Pearson residuals (max=1.13) for fit to MexCal_S1 implied age-frequency data.

Figure 21a. Base model fits to MexCal_S2 length-frequency data (Season 2).

Figure 21b. Observed and effective sample sizes for MexCal_S2 fishery length-frequency data.

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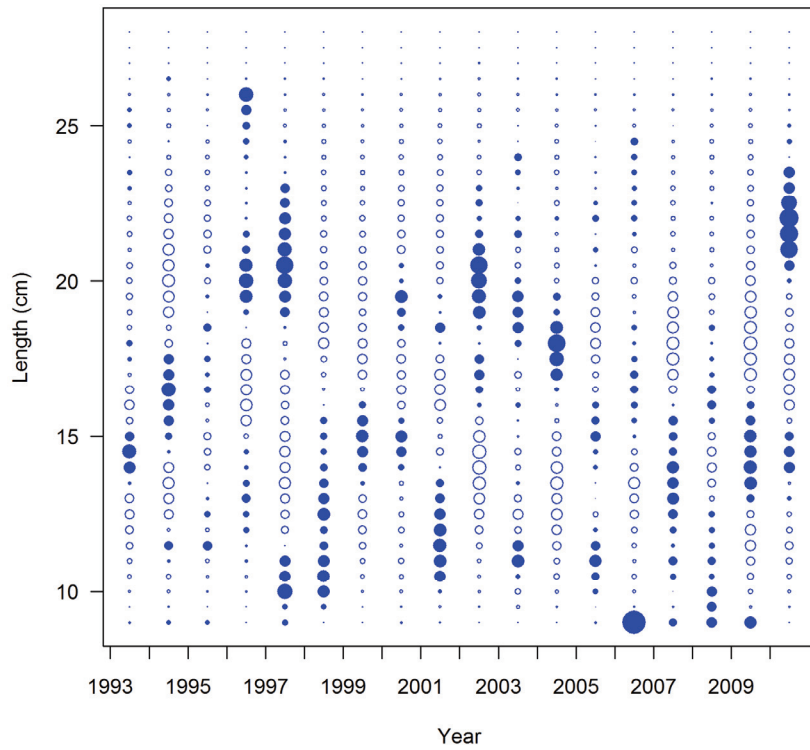Figure 21c. Bubble plot of MexCal_S2 length-frequency data (Season 2).

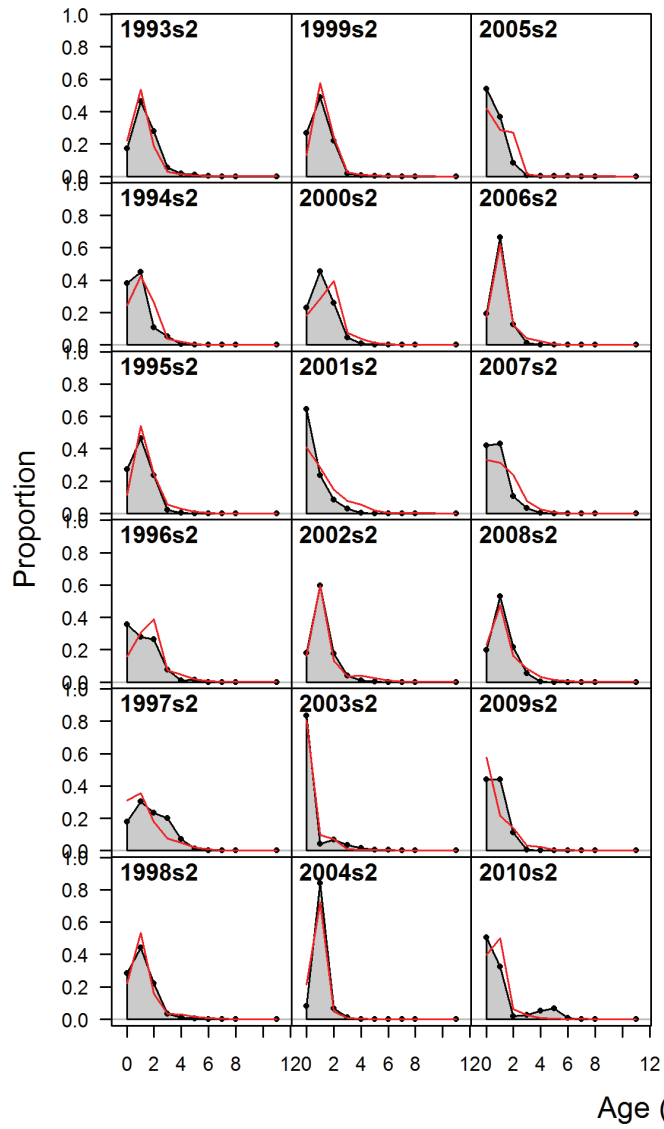Figure 21d. Pearson residuals (max=7.62) for fit to MexCal_S2 length-frequency data.

Figure 22a. Base model fits to MexCal_S2 implied age-frequency data (Season 2).
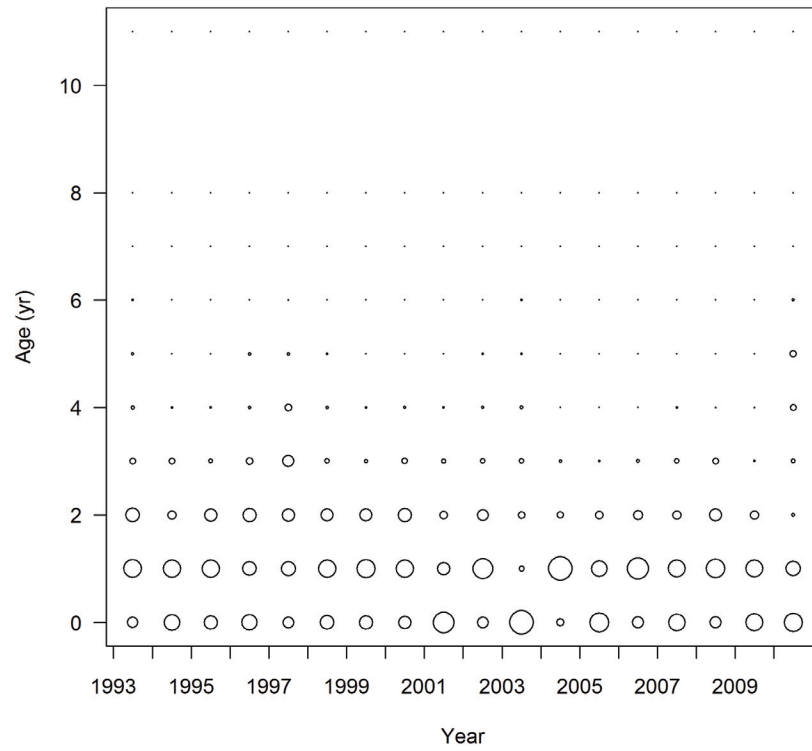
Figure 22b. Bubble plot of MexCal_S2 implied age-frequency data (Season 2).
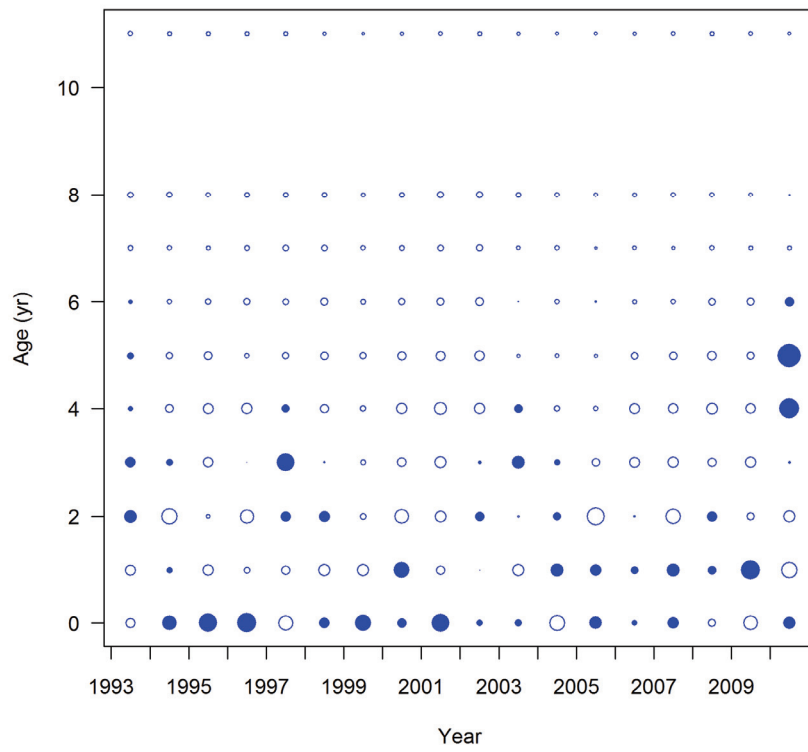

Figure 22c. Pearson residuals (max=0.81) for fit to MexCal_S2 implied age-frequency data.
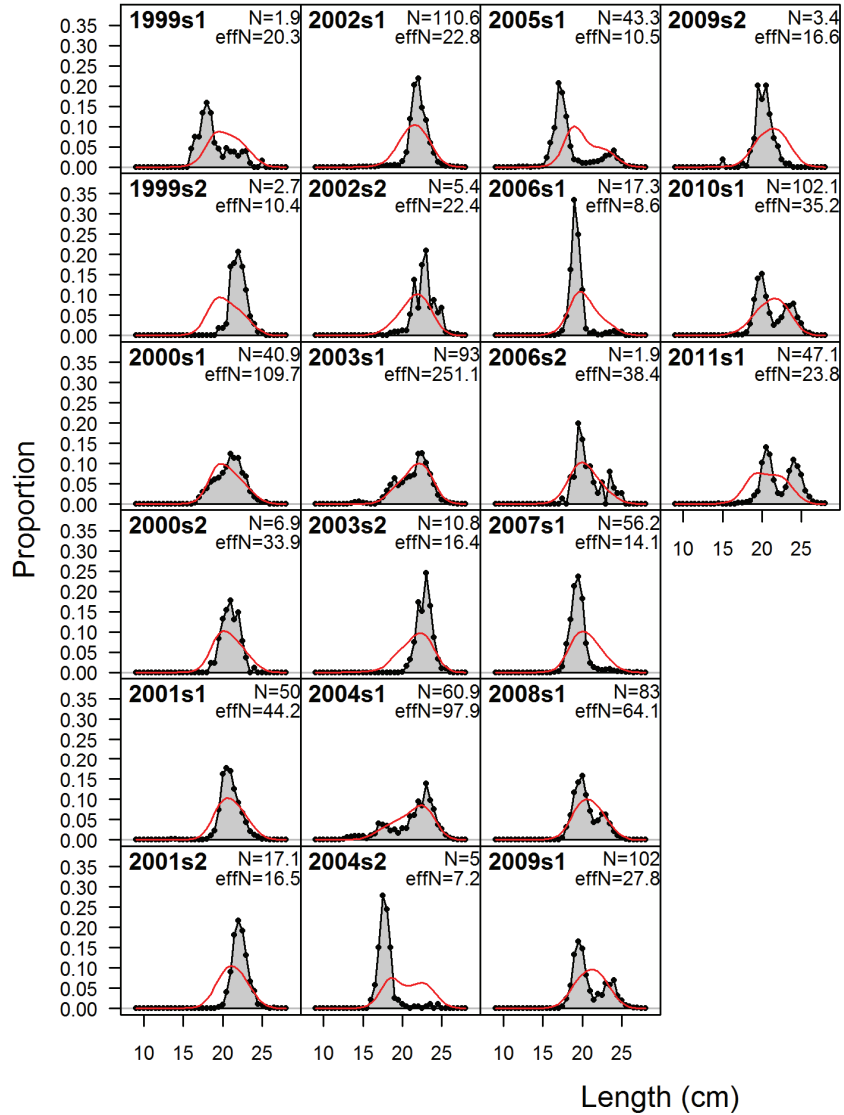
Figure 23a. Base model fits to PacNW length-frequency data.
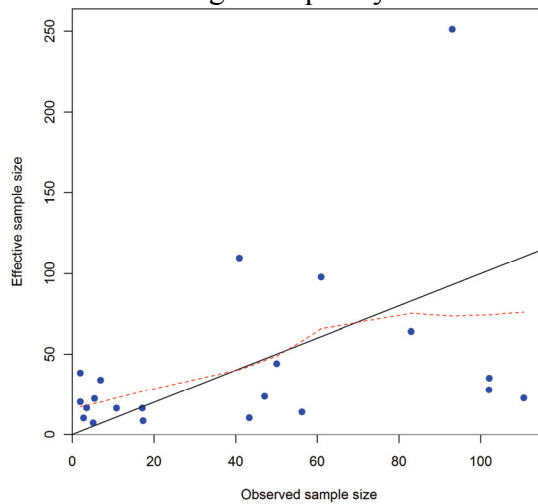
Figure 23b. Observed and effective sample sizes for PacNW fishery length-frequency data.
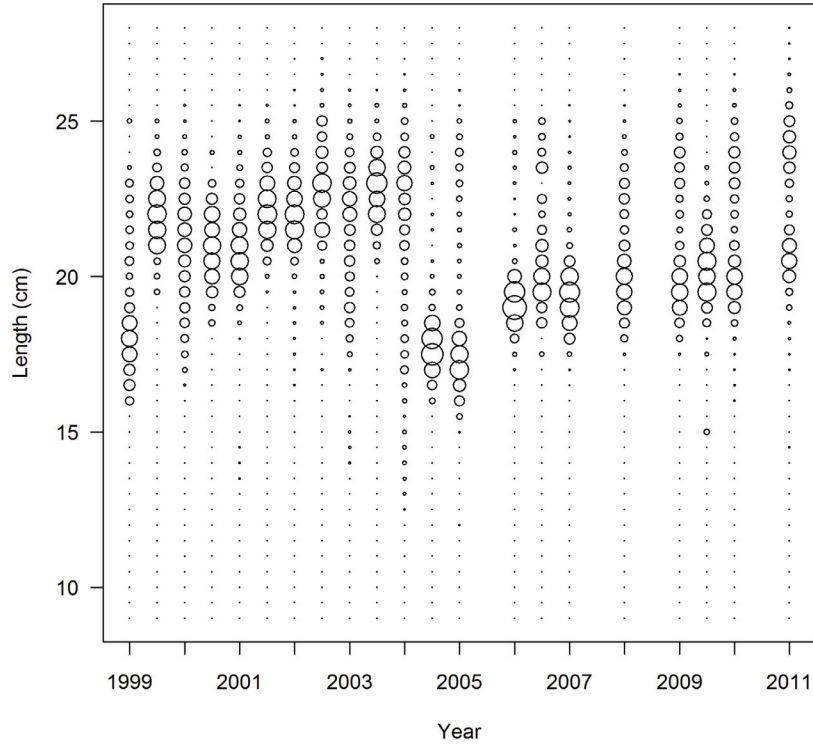
Figure 23c. Bubble plot of PacNW length-frequency data.
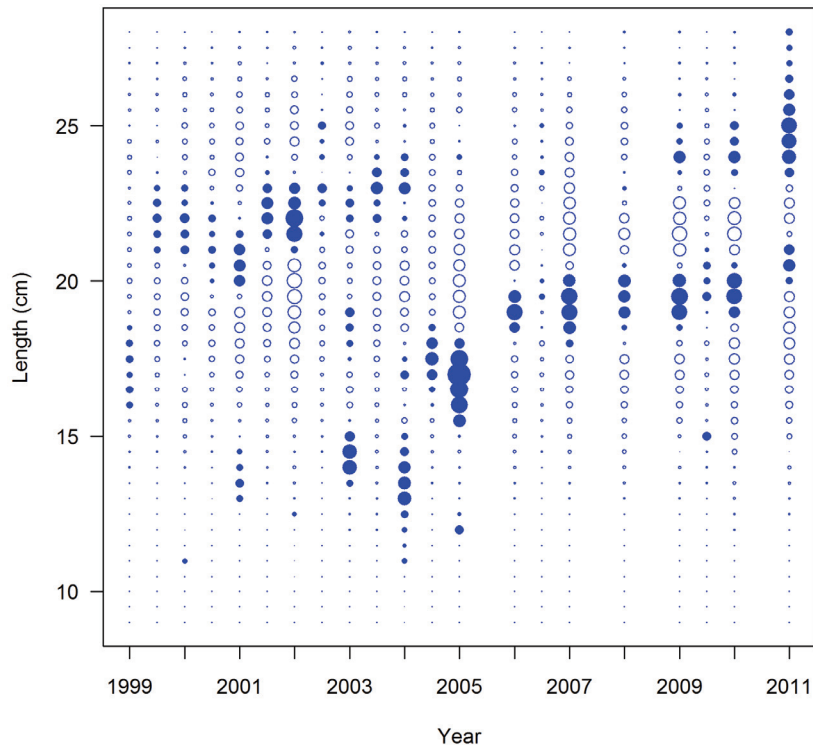
Figure 23d. Pearson residuals (max=6.72) for fit to PacNW length-frequency data.
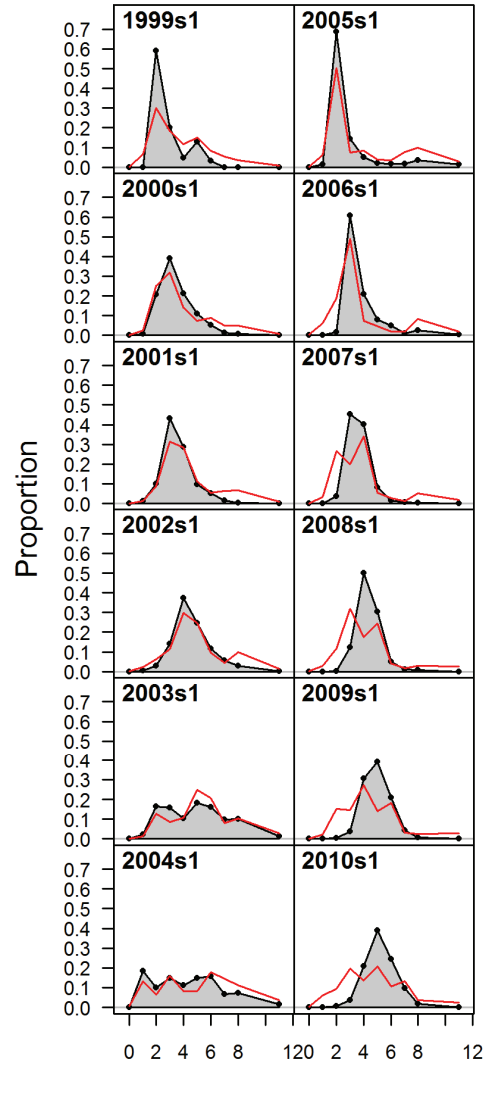
Figure 24a. Base model fits to implied age-frequency data for the PacNW fishery.
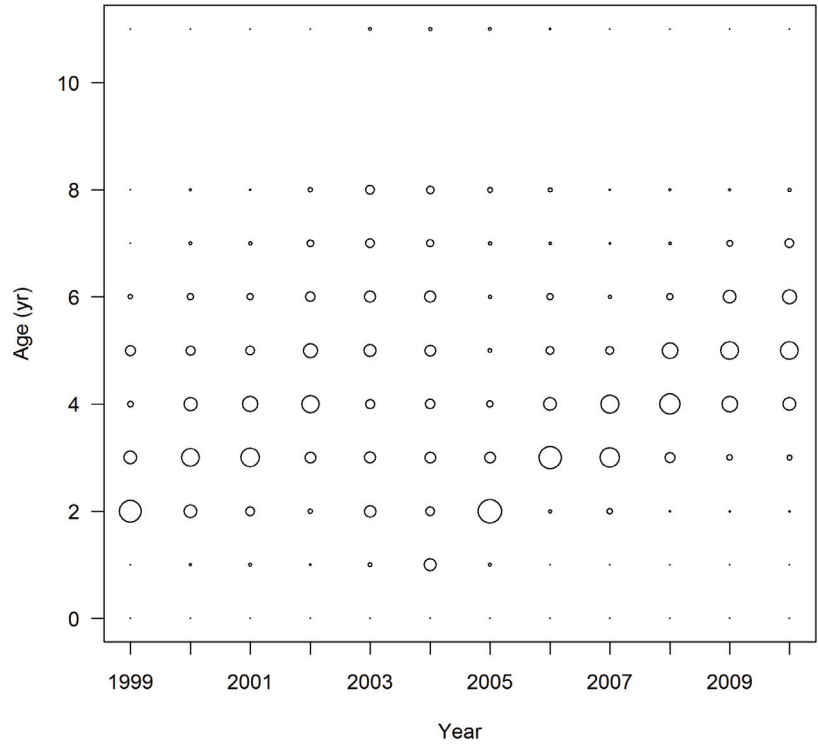
Figure 24b. Bubble plot of PacNW implied age-frequency data.
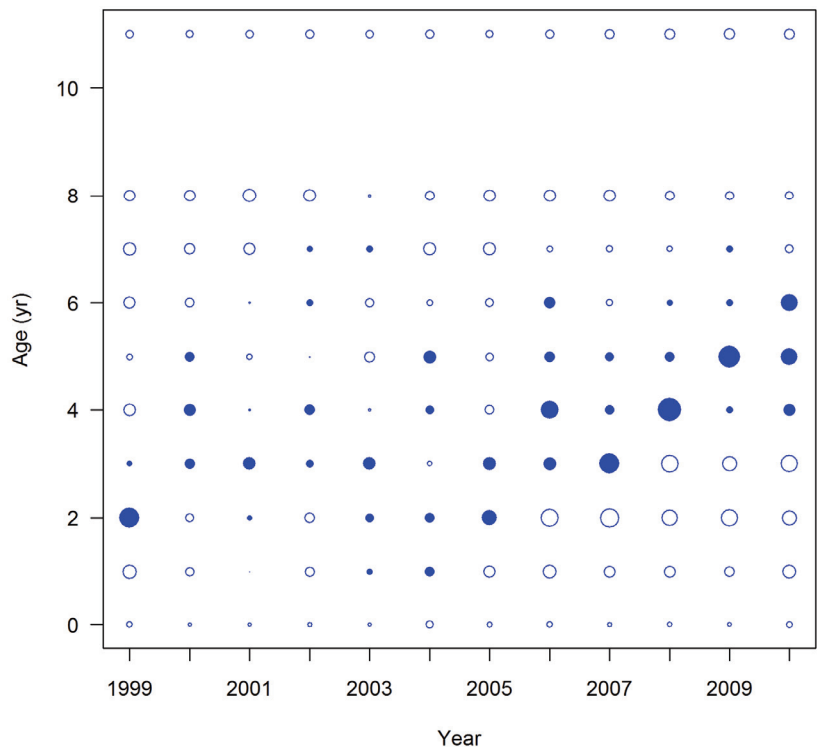
Figure 24c. Pearson residuals (max=0.86) for fit to PacNW implied age-frequency data.
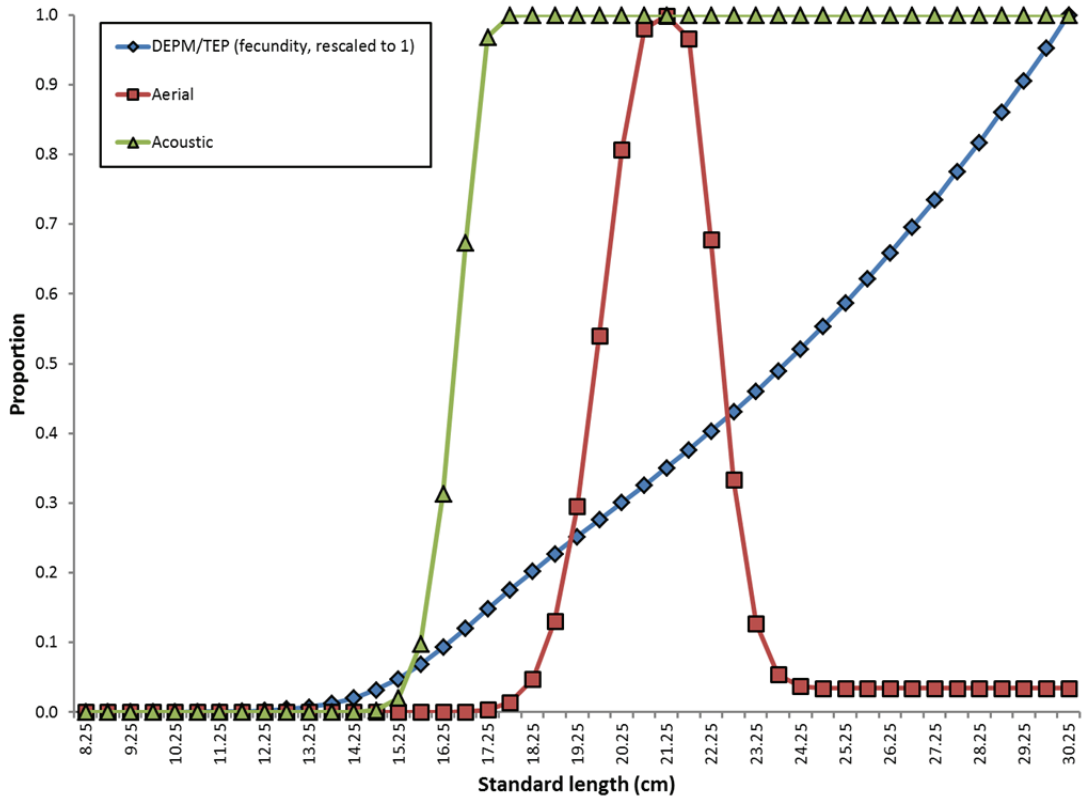
Figure 25a. Survey length selectivities estimated by SS.
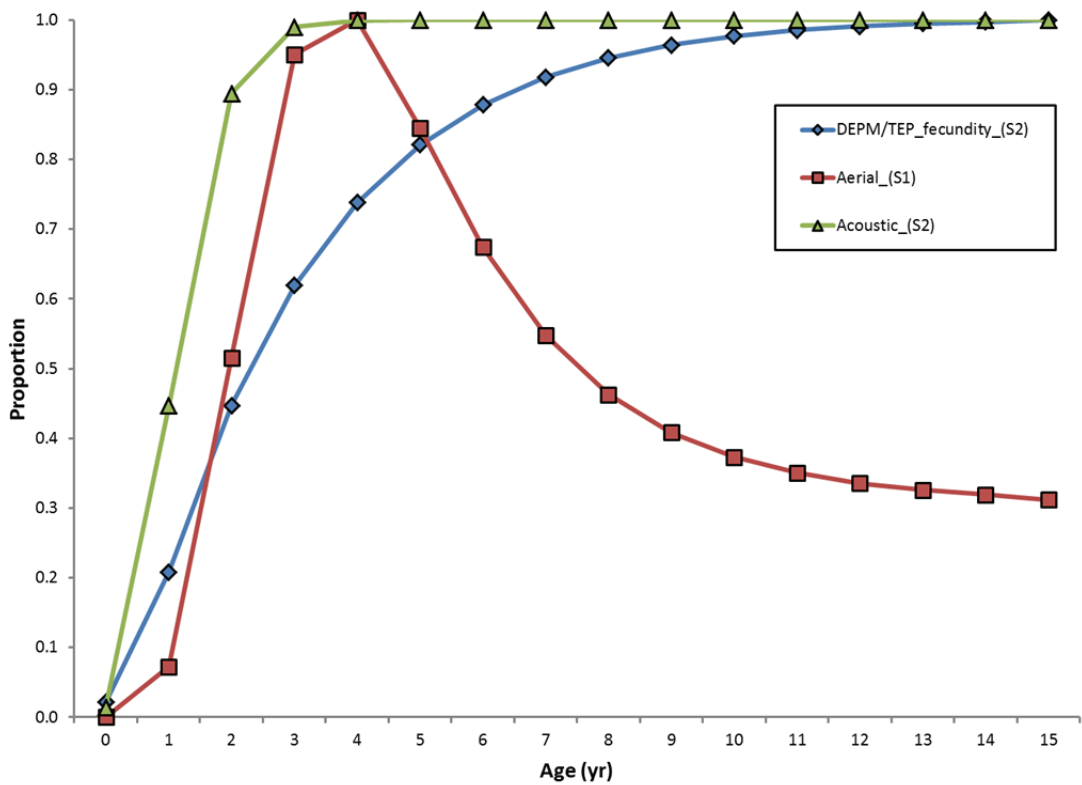
Figure 25b. Survey age selectivities as implied by the product of length selectivity and the ALK.

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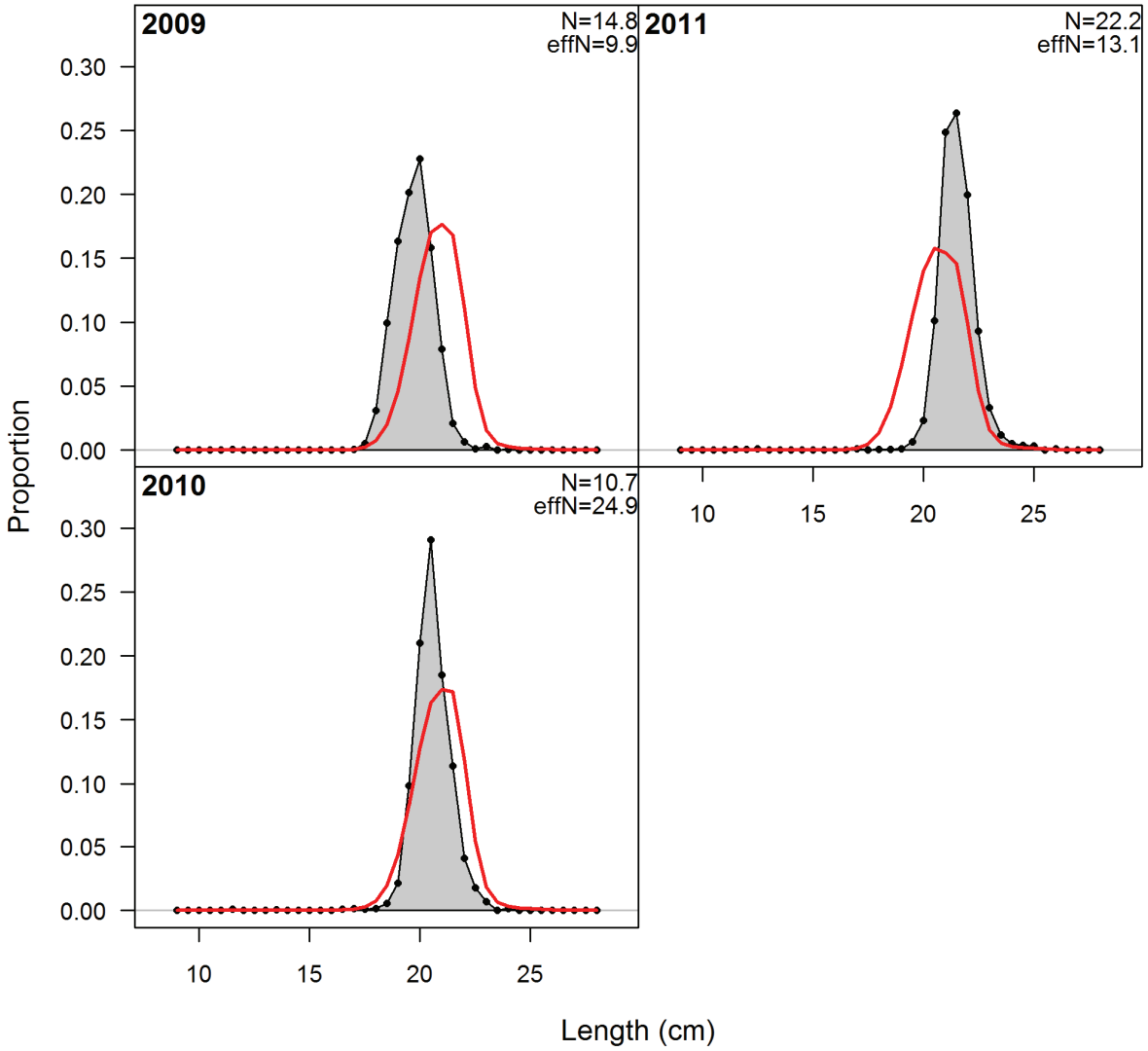
Figure 26a. Base model fits to Aerial survey length-frequency data.
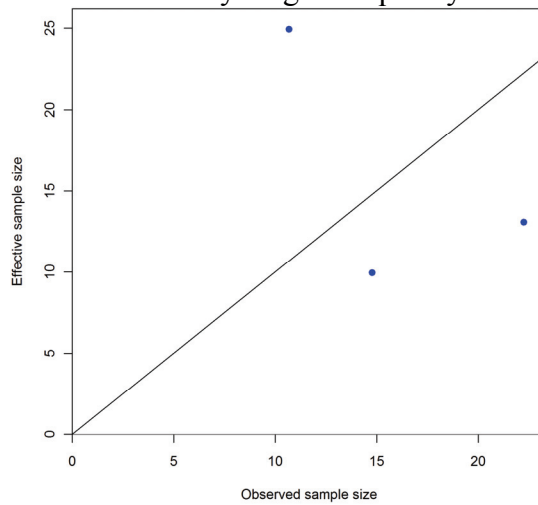
Figure 26b. Observed and effective sample sizes for Aerial survey fishery length-frequency data.
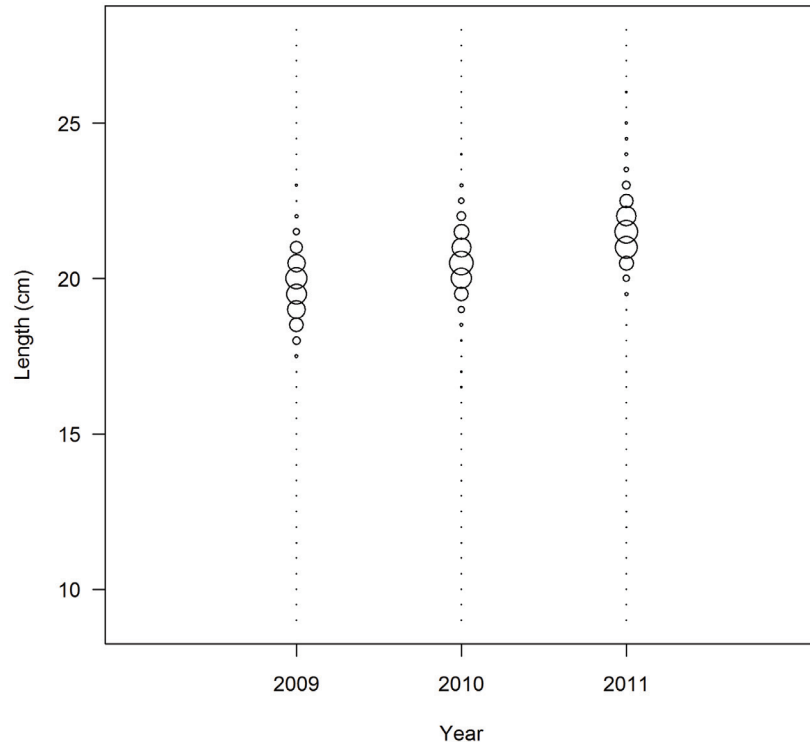
Figure 26c. Bubble plot of Aerial survey length-frequency data.
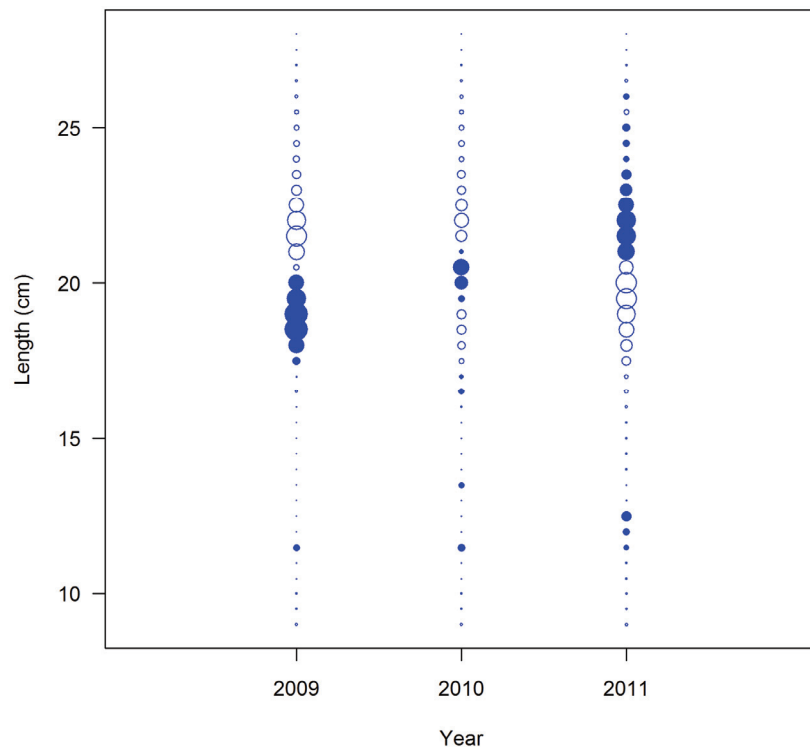
Figure 26d. Pearson residuals (max=2.19) for fit to Aerial survey length-frequency data.
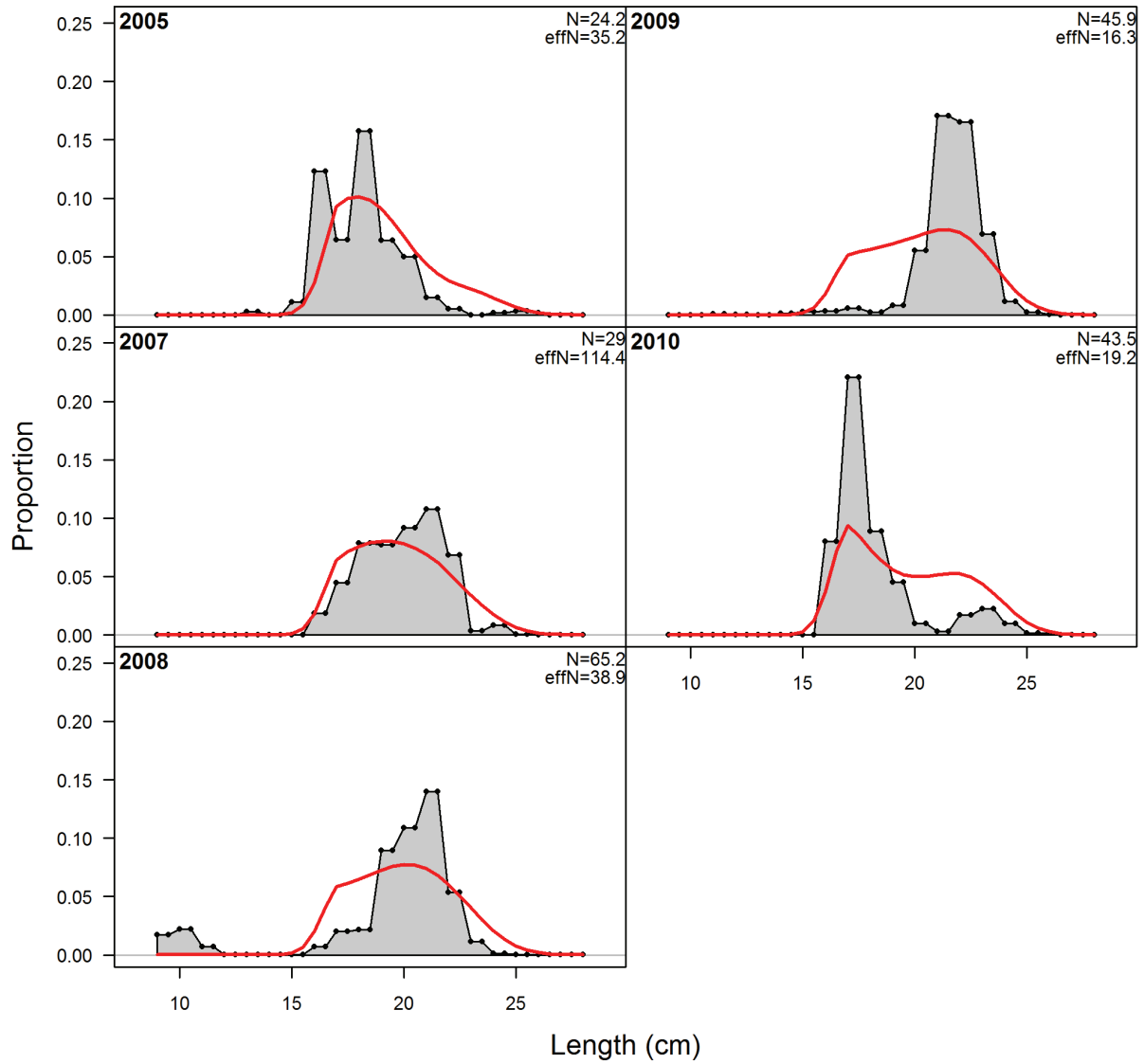
Figure 27a. Base model fits to Acoustic survey length-frequency data.
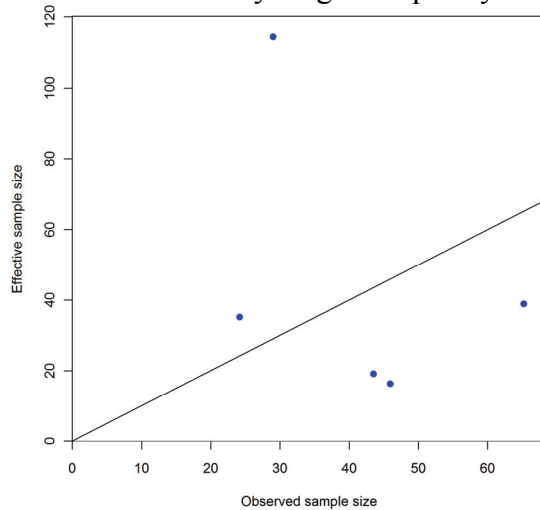
Figure 27b. Observed and effective sample sizes for Acoustic survey fishery length data.

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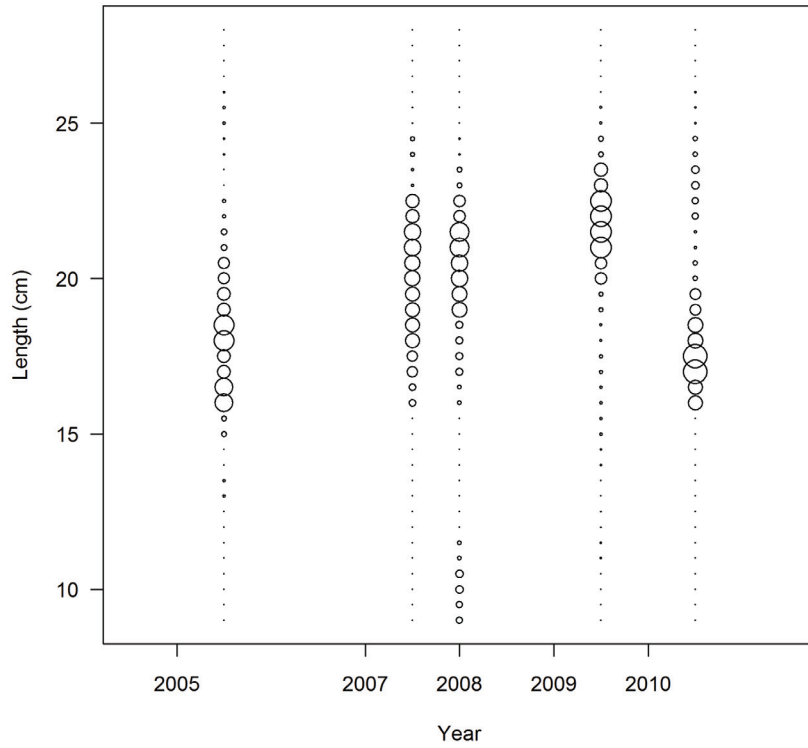
Figure 27c. Bubble plot of Acoustic survey length-frequency data.
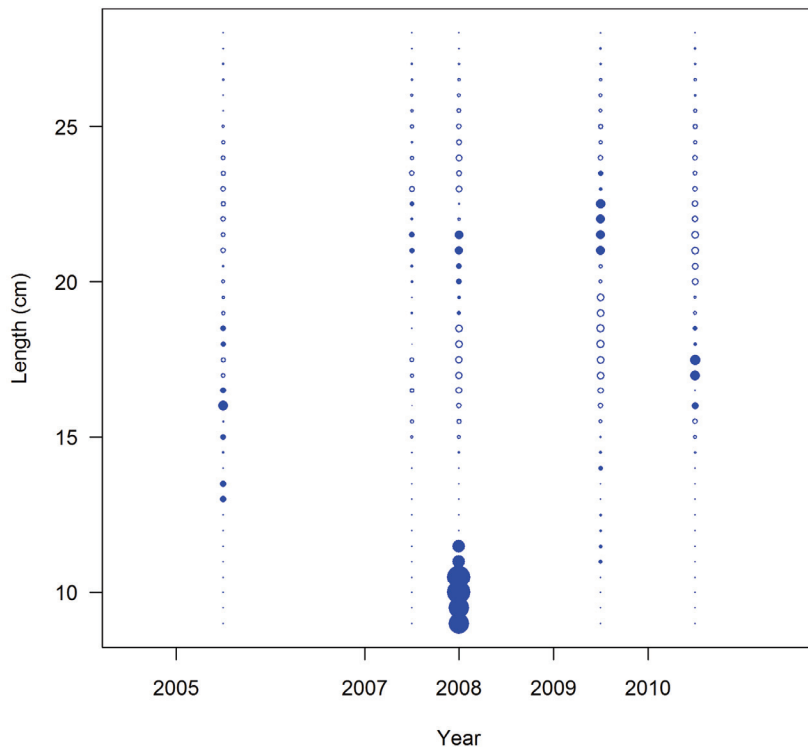
Figure 27d. Pearson residuals (max=17.62) for fit to Acoustic survey length-frequency data.

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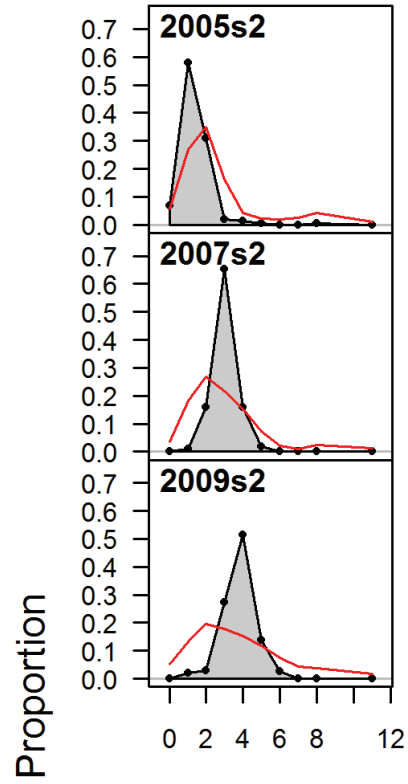
Figure 28a. Base model fits to Acoustic survey implied age-frequency data.
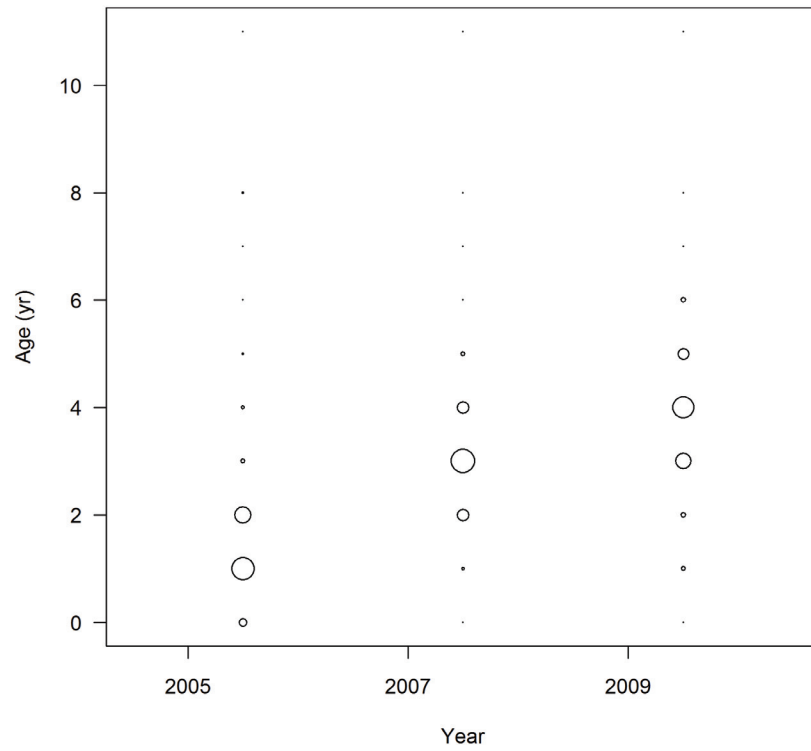
Figure 28b. Bubble plot of Acoustic survey implied age-frequency data.
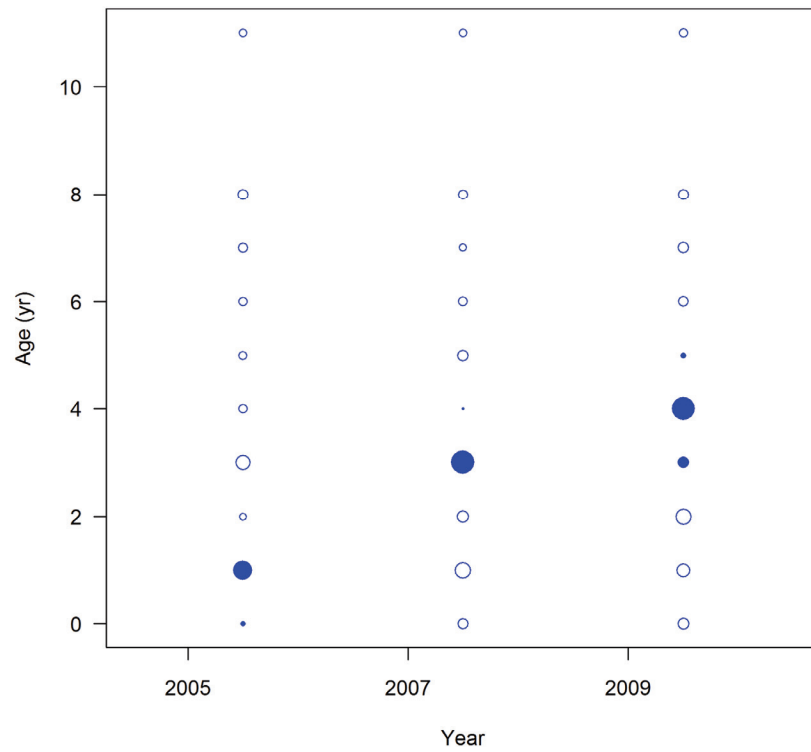
Figure 28c. Pearson residuals (max=1.07) for fit to Acoustic survey implied age-frequency data.
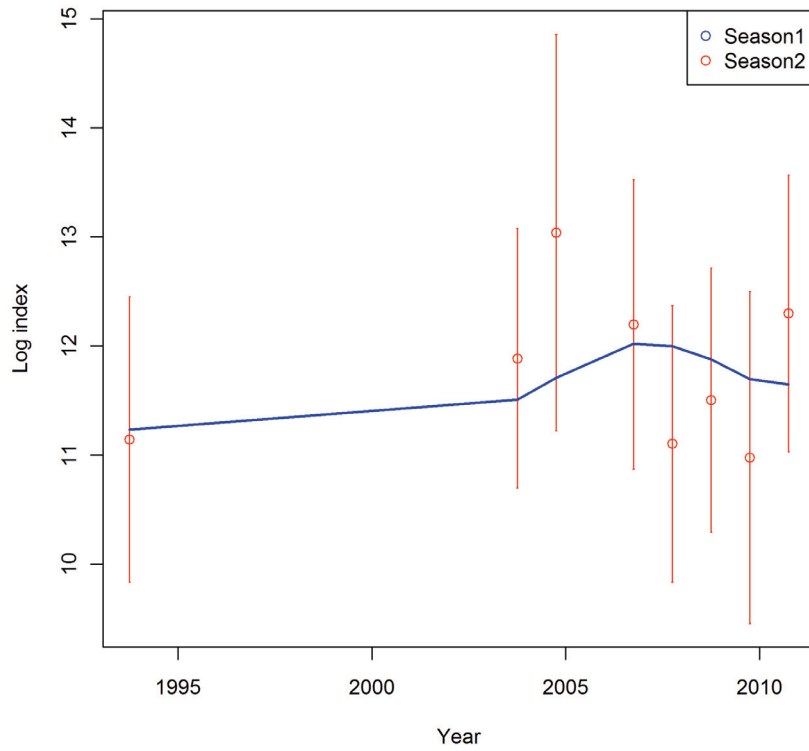
Figure 29a. Base model fit to the Daily Egg Production Method (DEPM) series of female SSB (q=0.18).
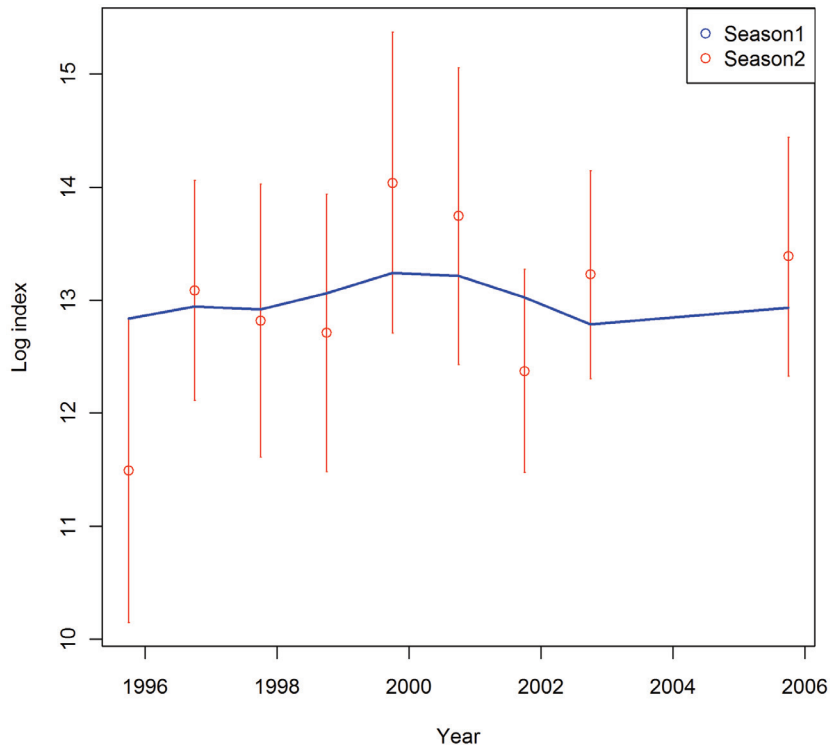
Figure 29b. Base model fit to the Total Egg Production (TEP) series of total SSB (q=0.49).
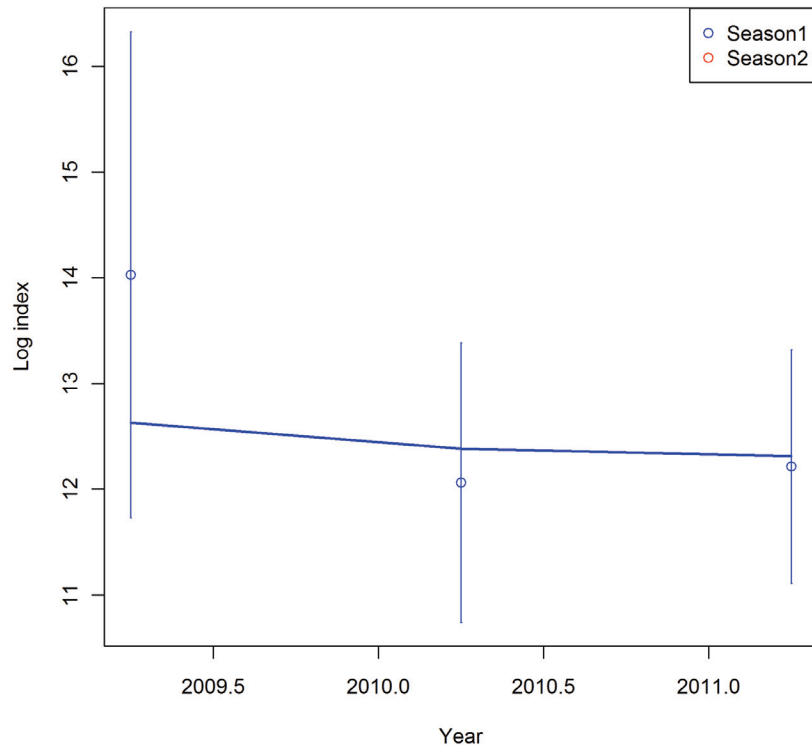
Figure 29c. Base model fit to Aerial survey estimates of biomass ($q = 0.89$).
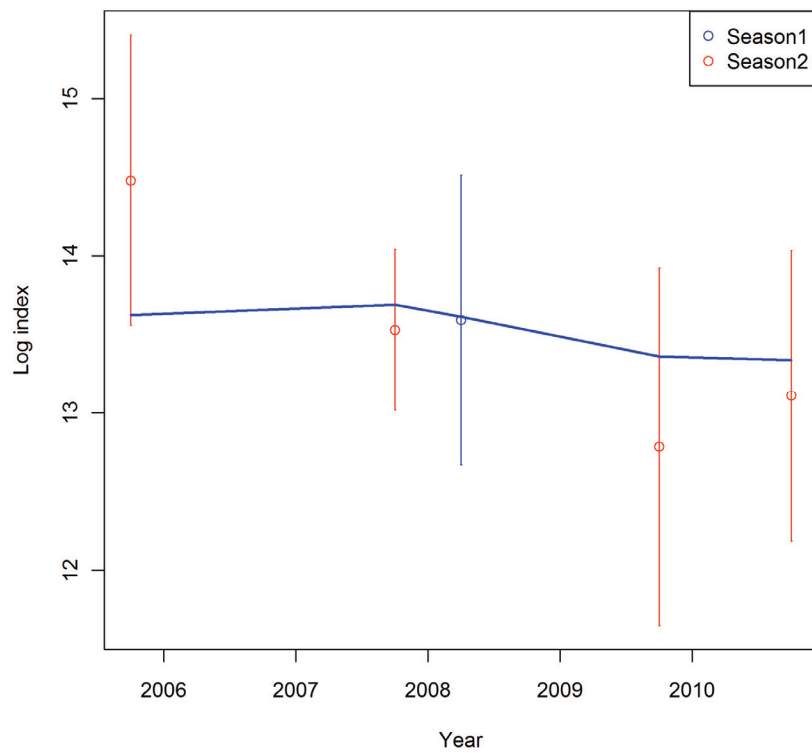
Figure 29d. Base model fit to the Acoustic survey biomass series ($q = 1$; fixed).

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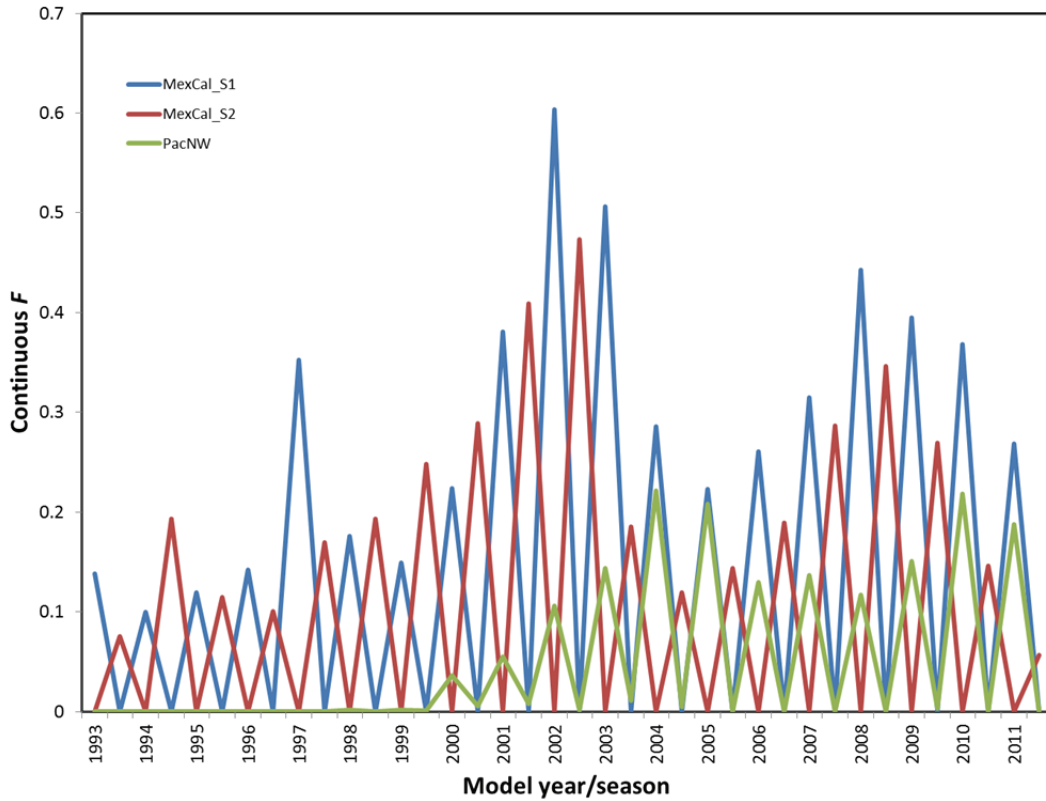
Figure 30a. Base model fishing mortality rate (continuous F; SS method 3) by fishery.
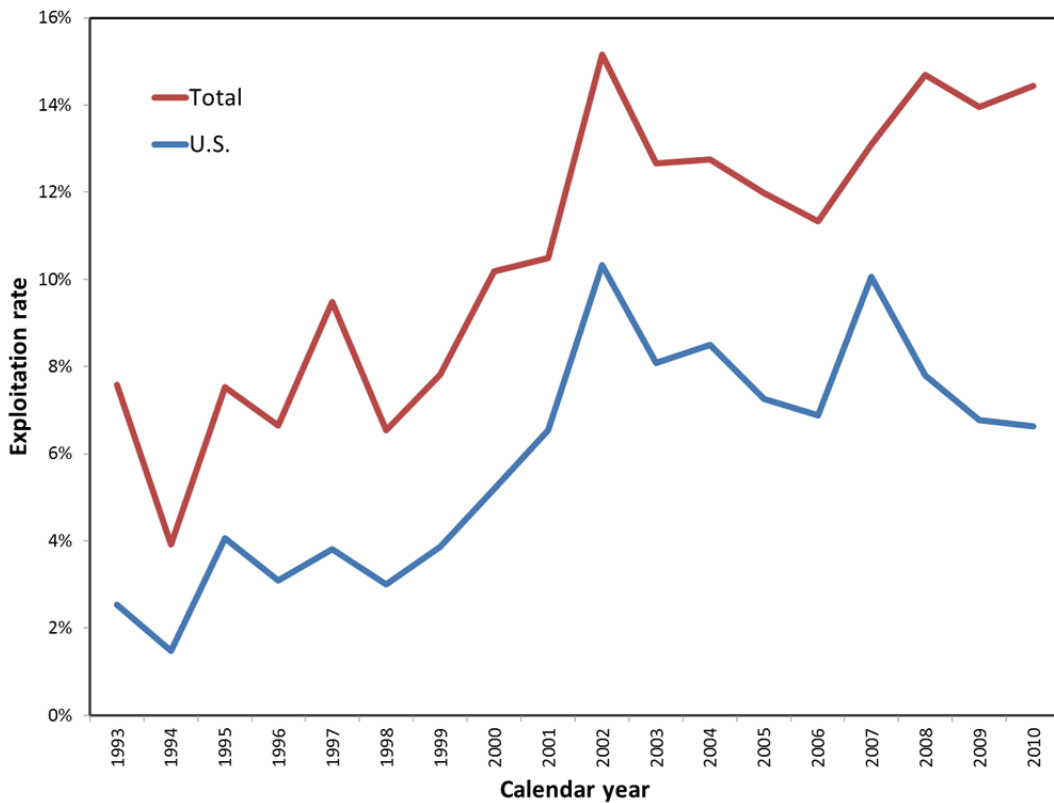
Figure 30b. Exploitation rate (CY landings / July total biomass) for the base model.

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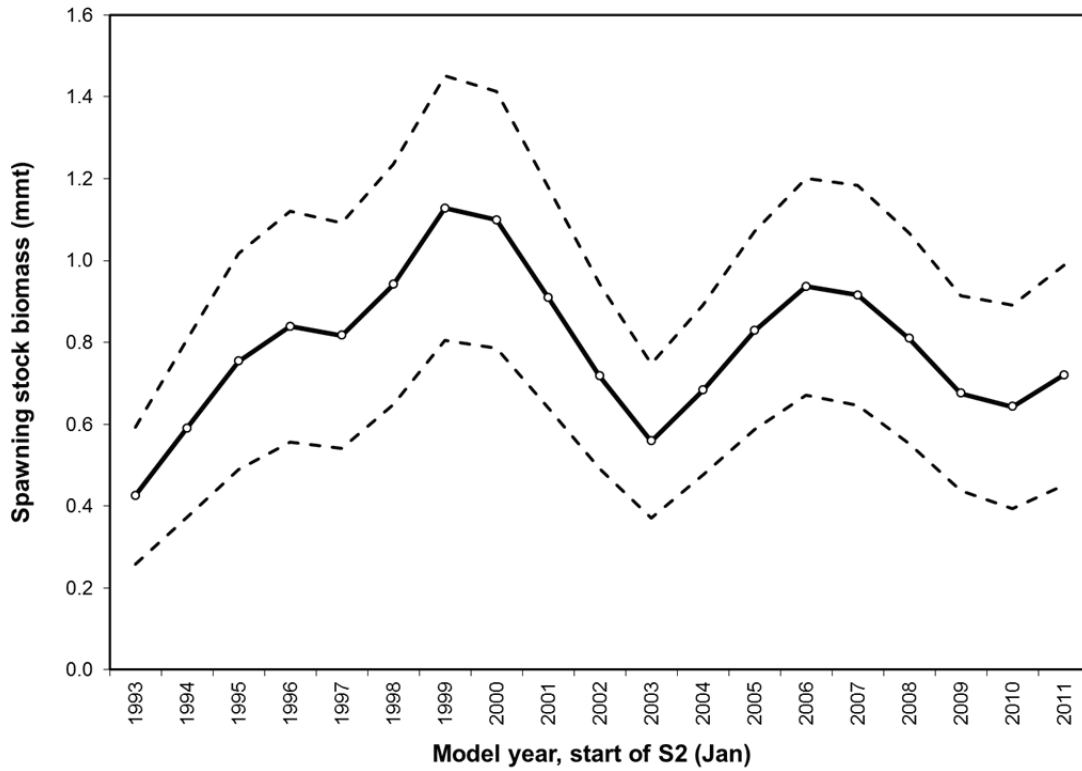
Figure 31a. Base model spawning stock biomass with ~95% asymptotic confidence intervals.
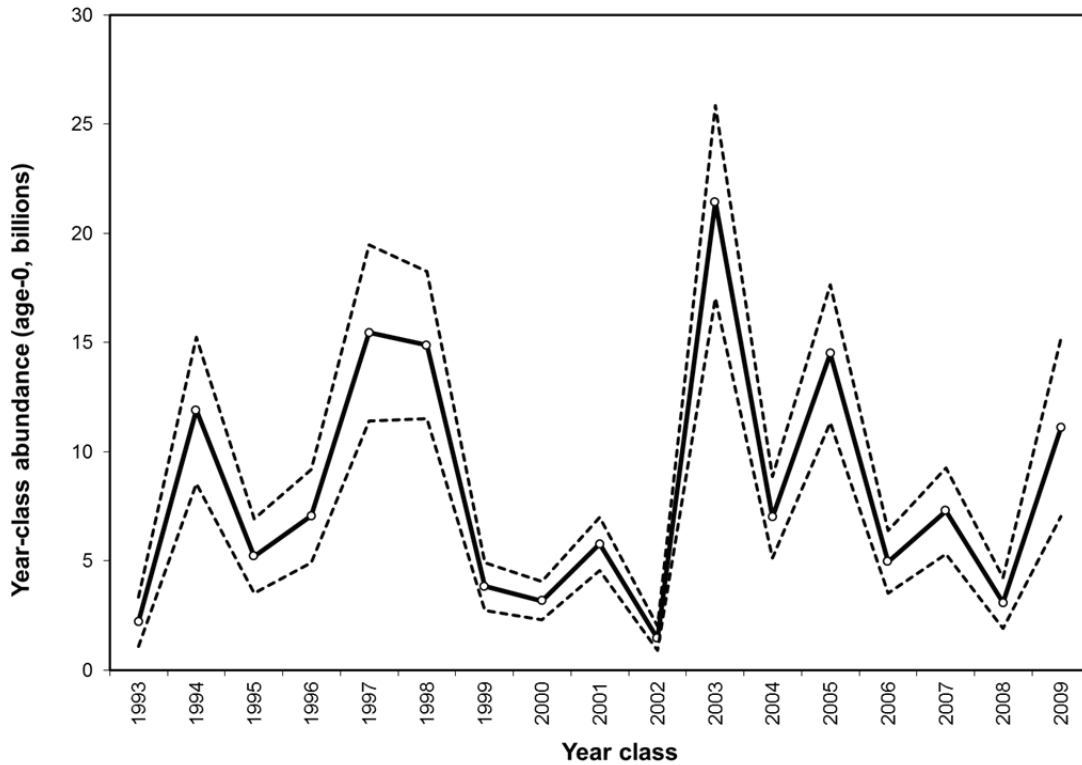
Figure 31b. Base model year-class abundance with ~95% asymptotic confidence intervals.
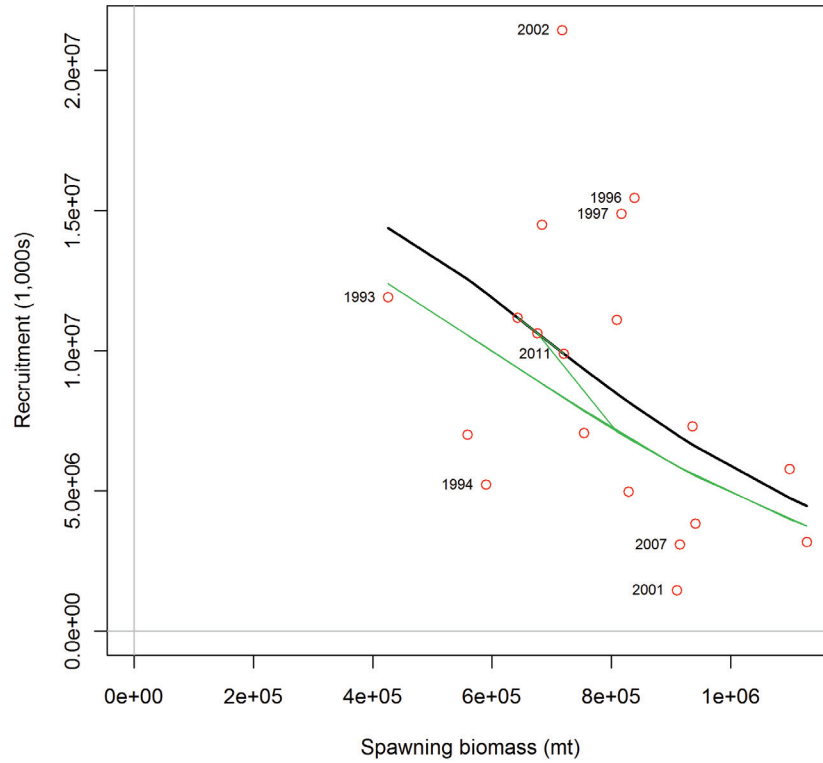
Figure 32a. Spawner-recruitment relationship for the base model, showing Ricker function fit with bias correction. Steepness (h) = 2.96, R_0 = 6.23 billion age-0 fish, and σ_R = 0.622. Year labels indicate year of spawning season (S2) prior to recruitment season in the following S1, e.g. '1996' is season prior to production of the 1997 year-class.
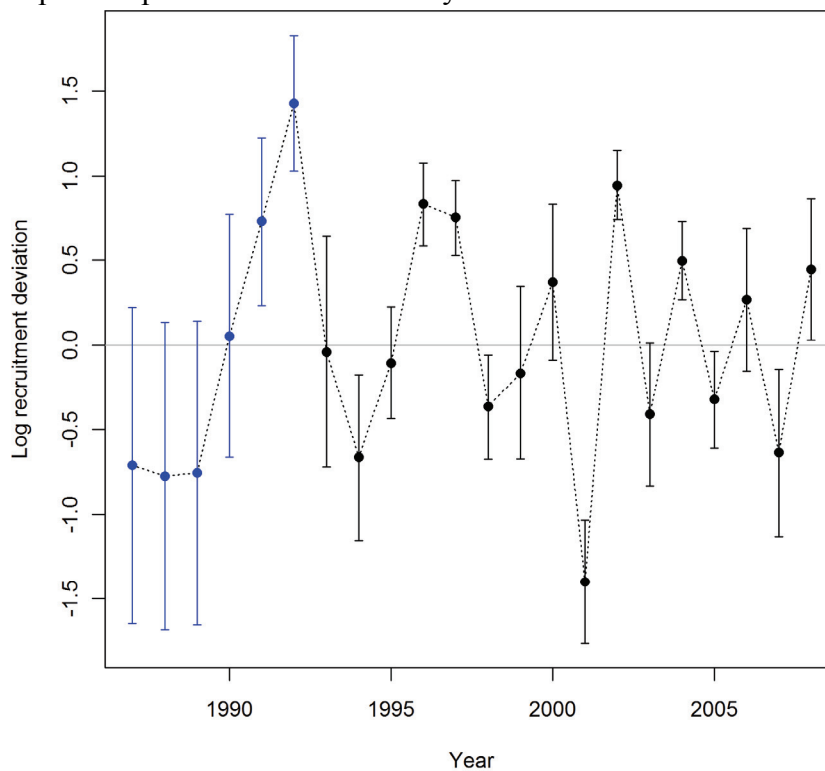
Figure 32b. Recruitment deviations and standard errors estimated in the base model (σ_R = 0.622).
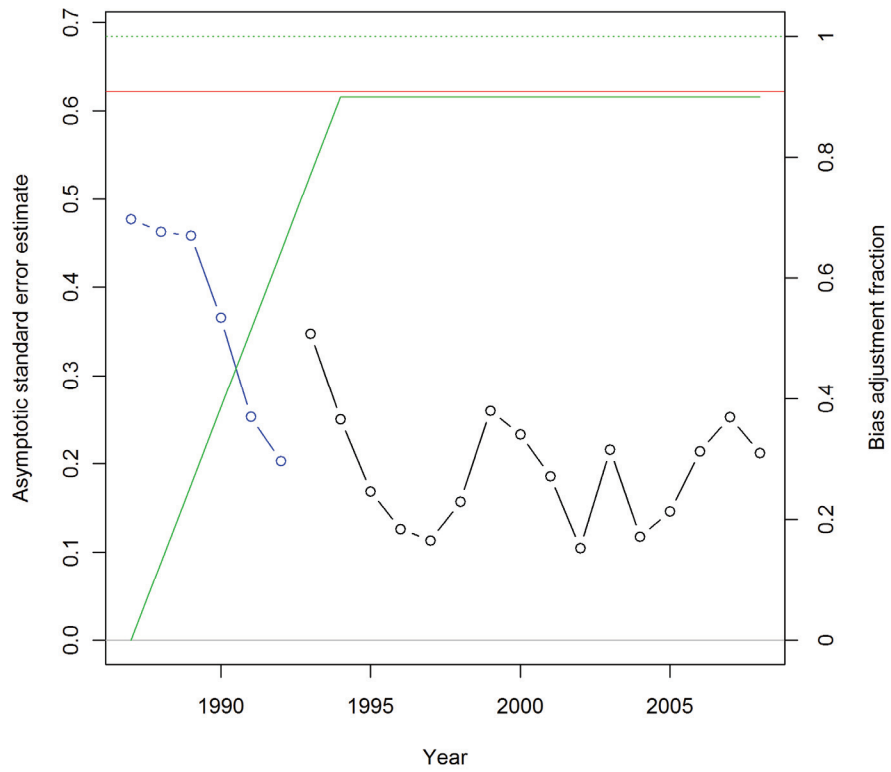
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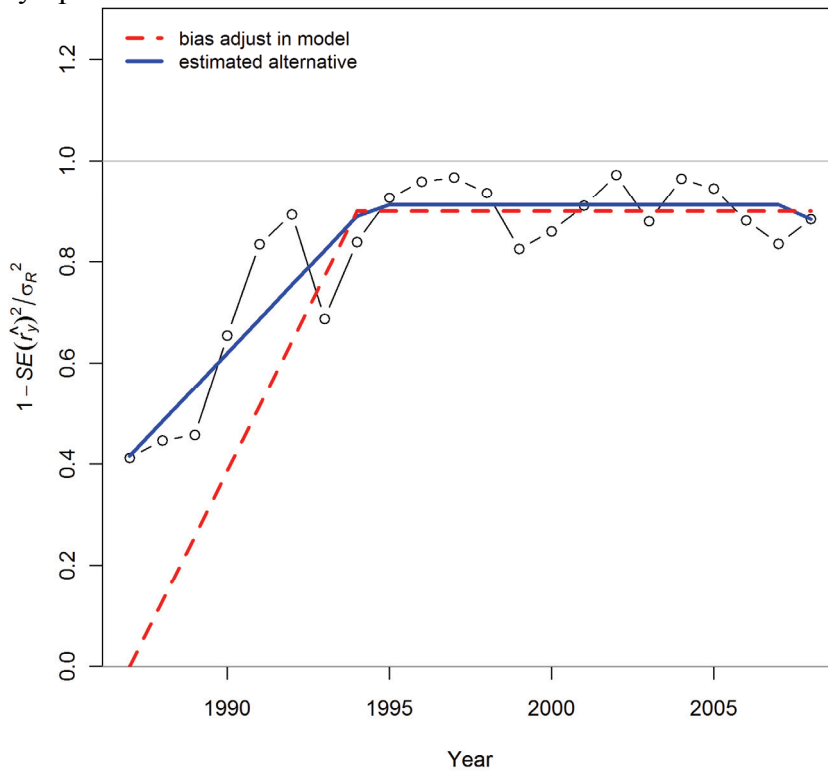
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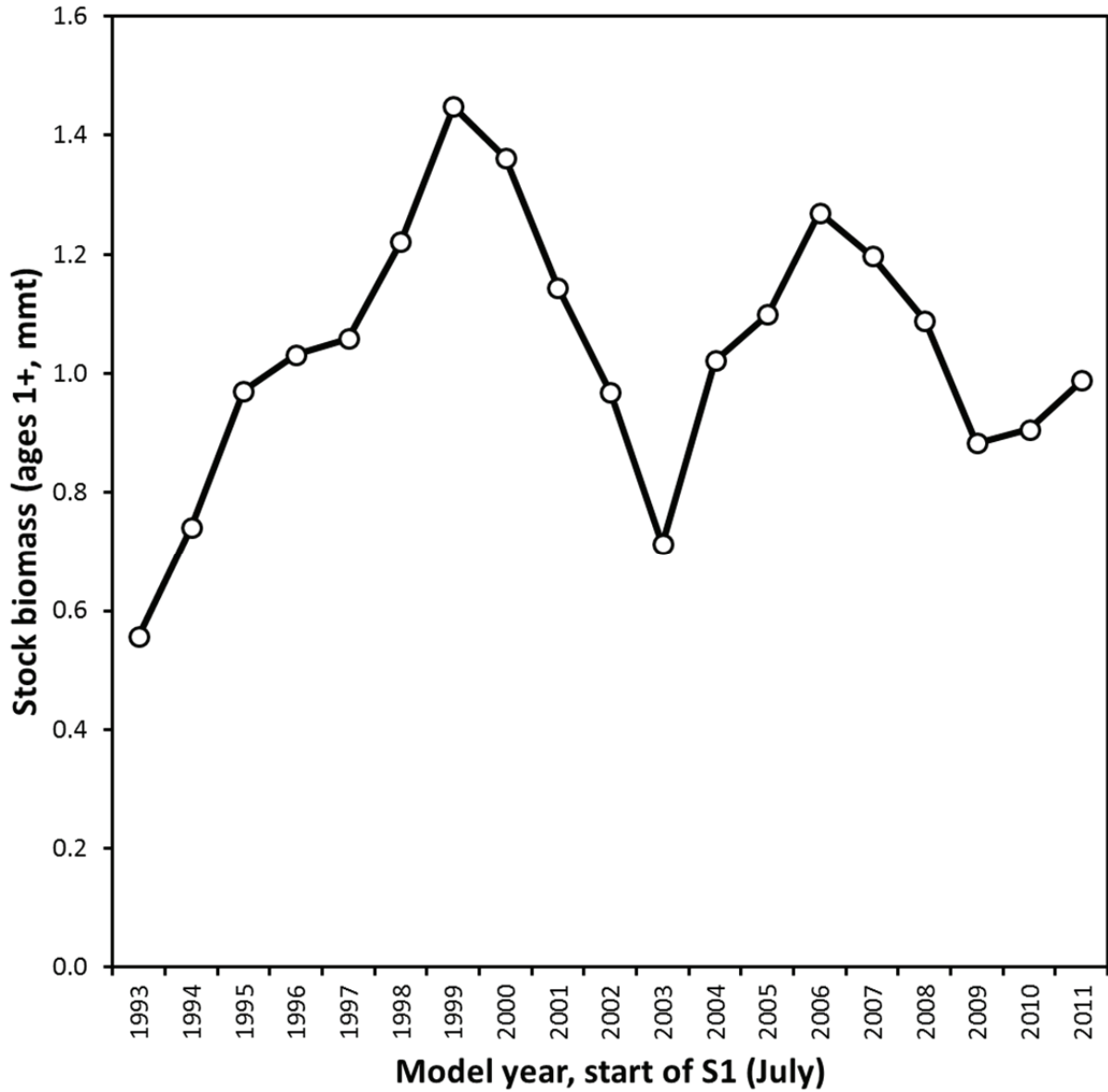
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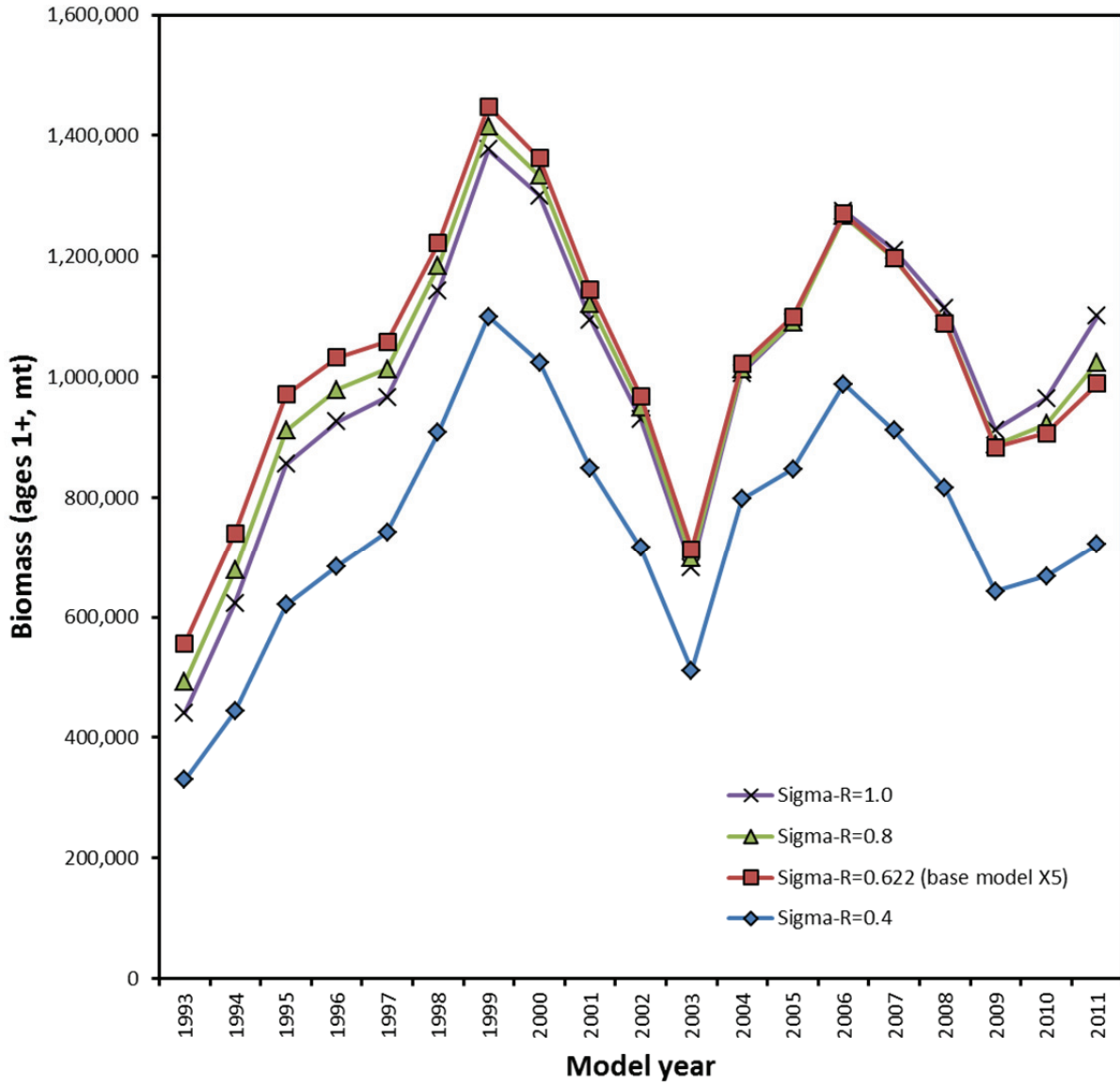
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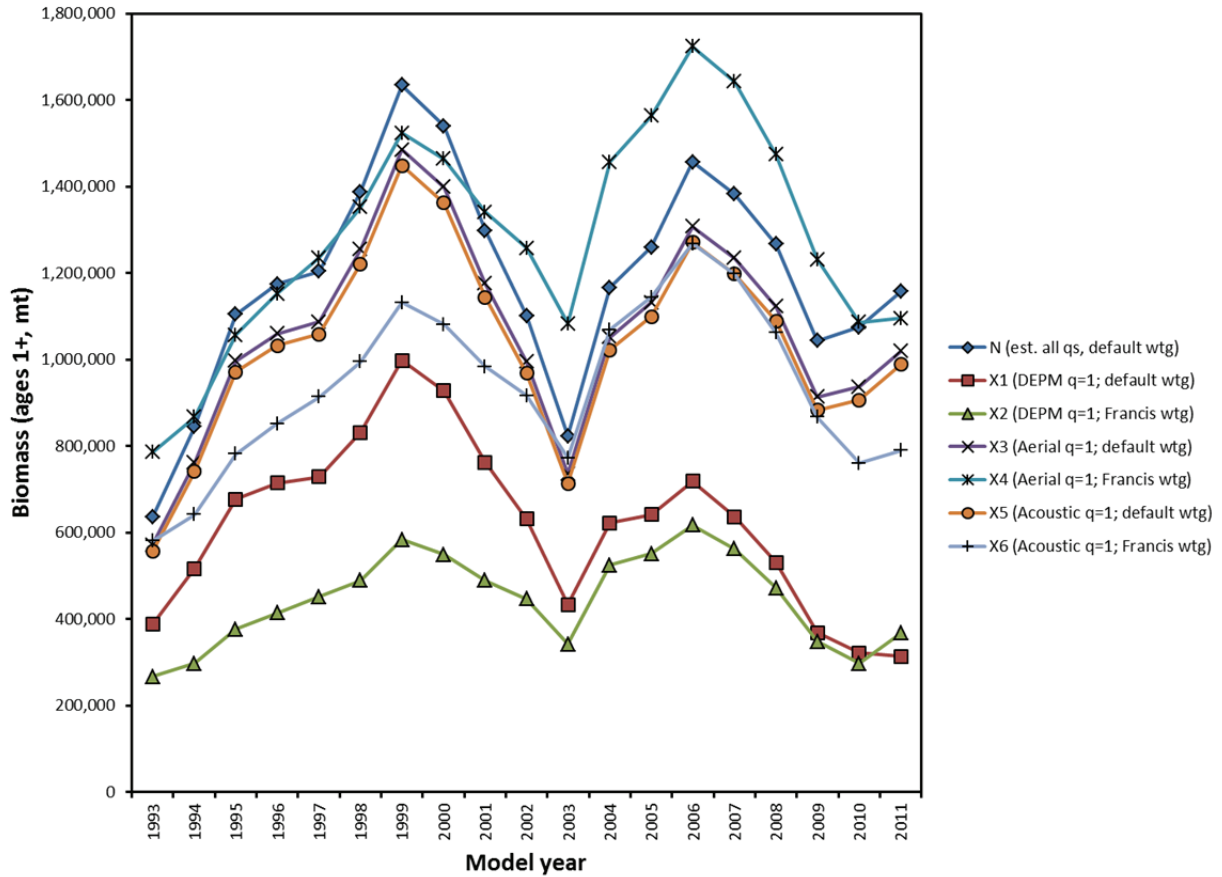
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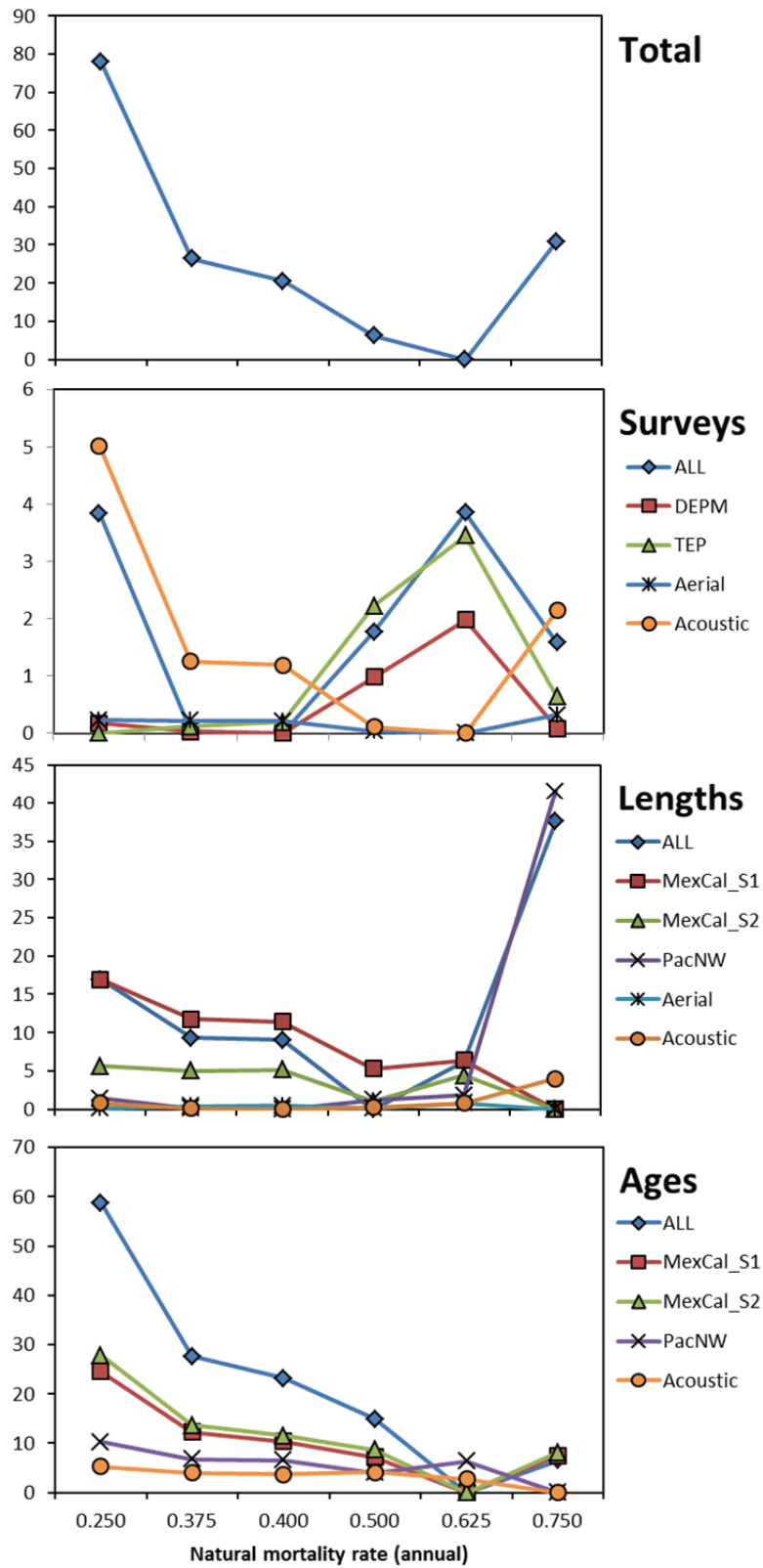
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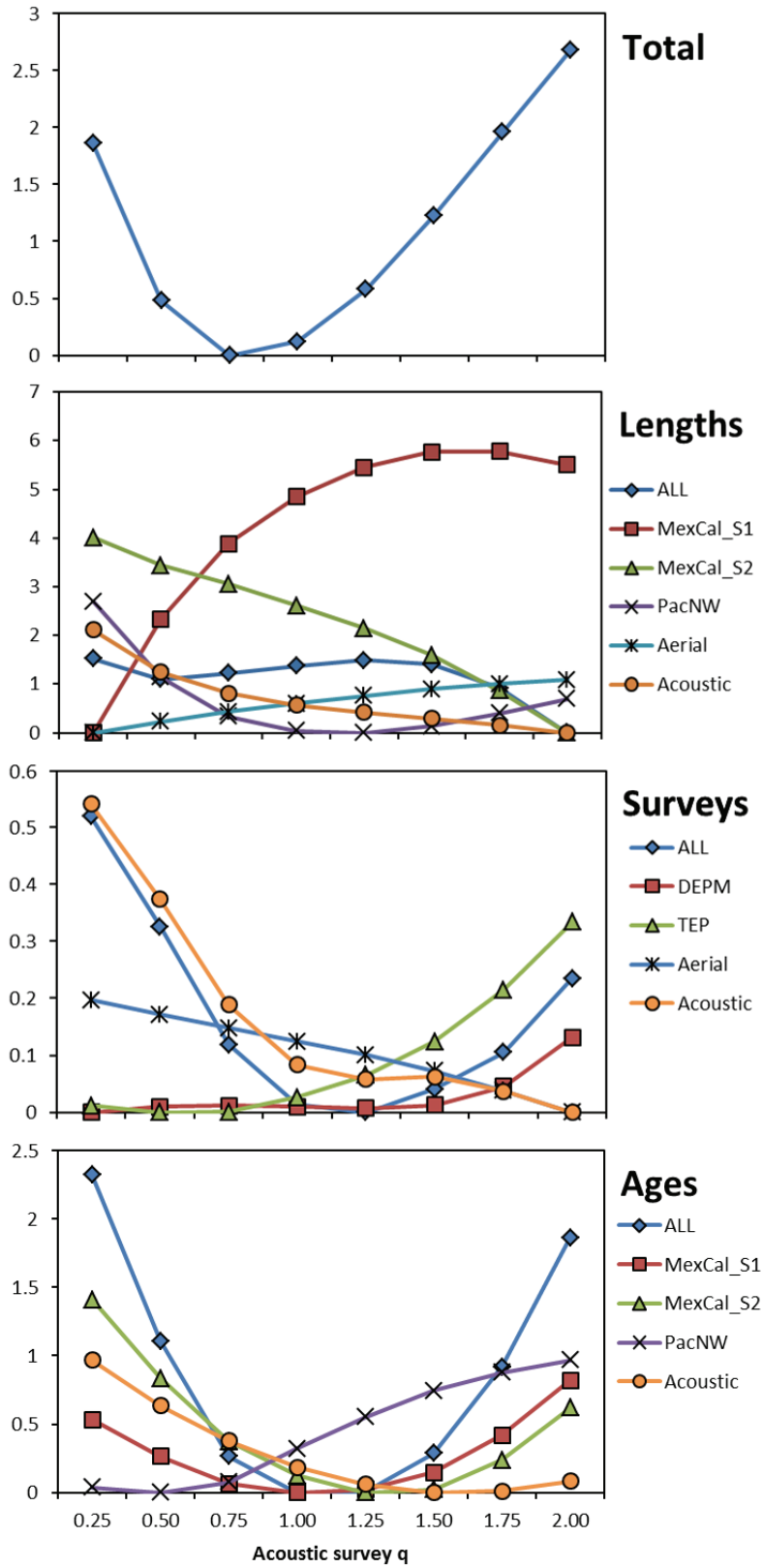
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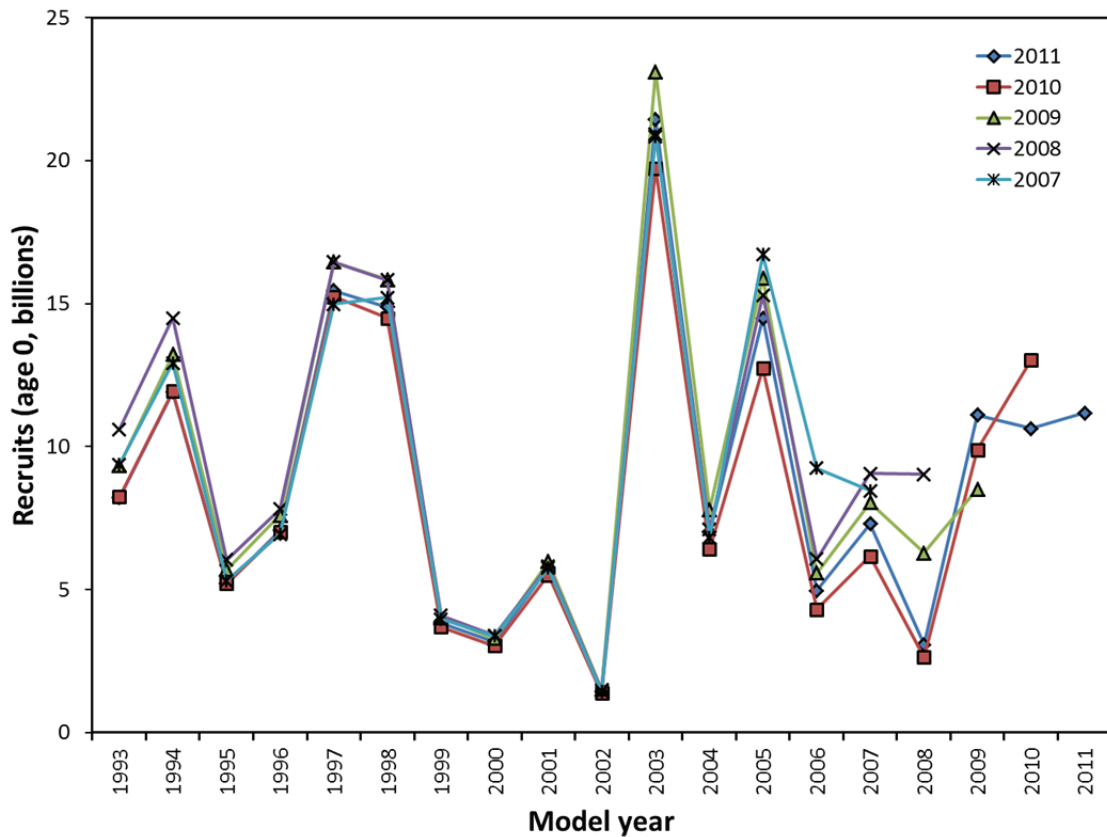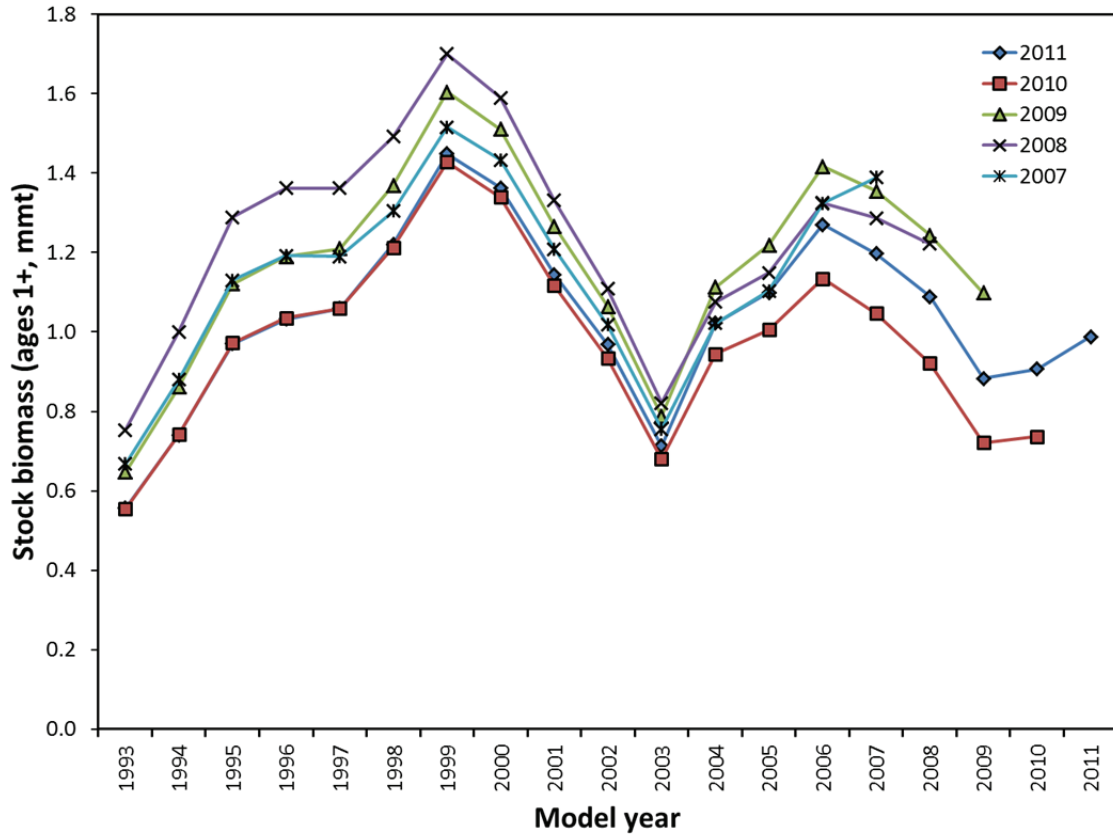
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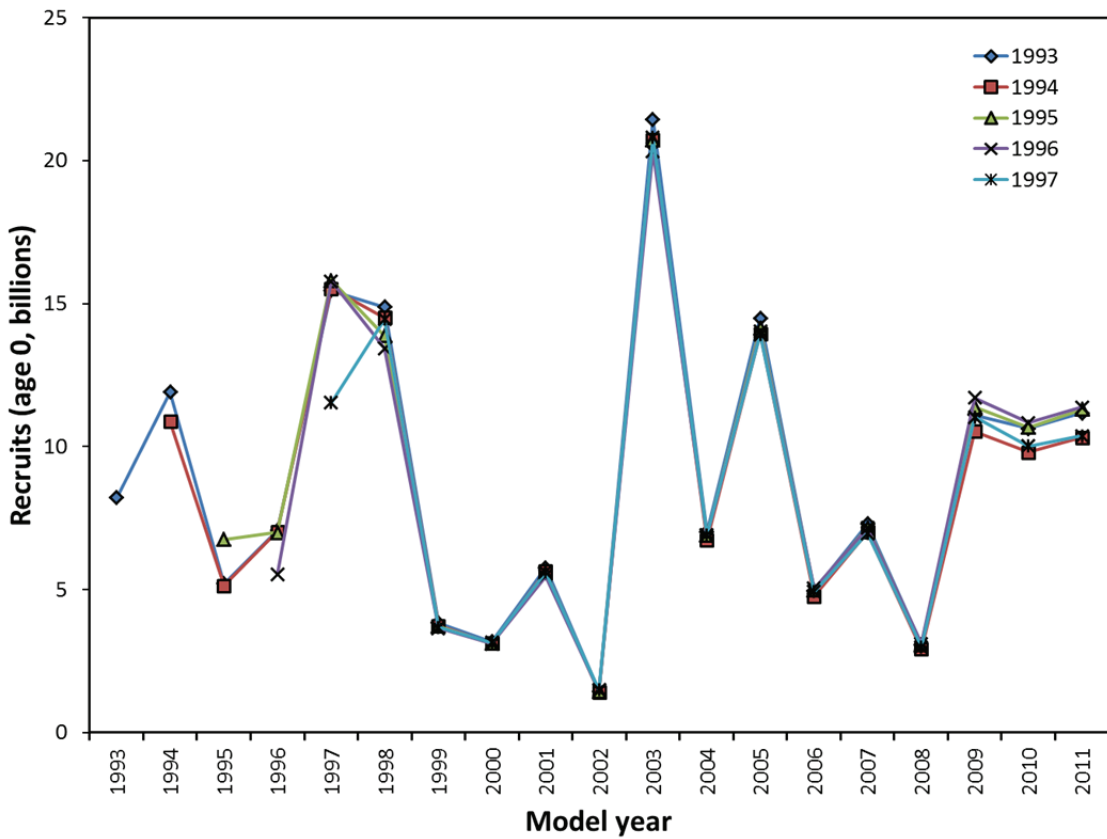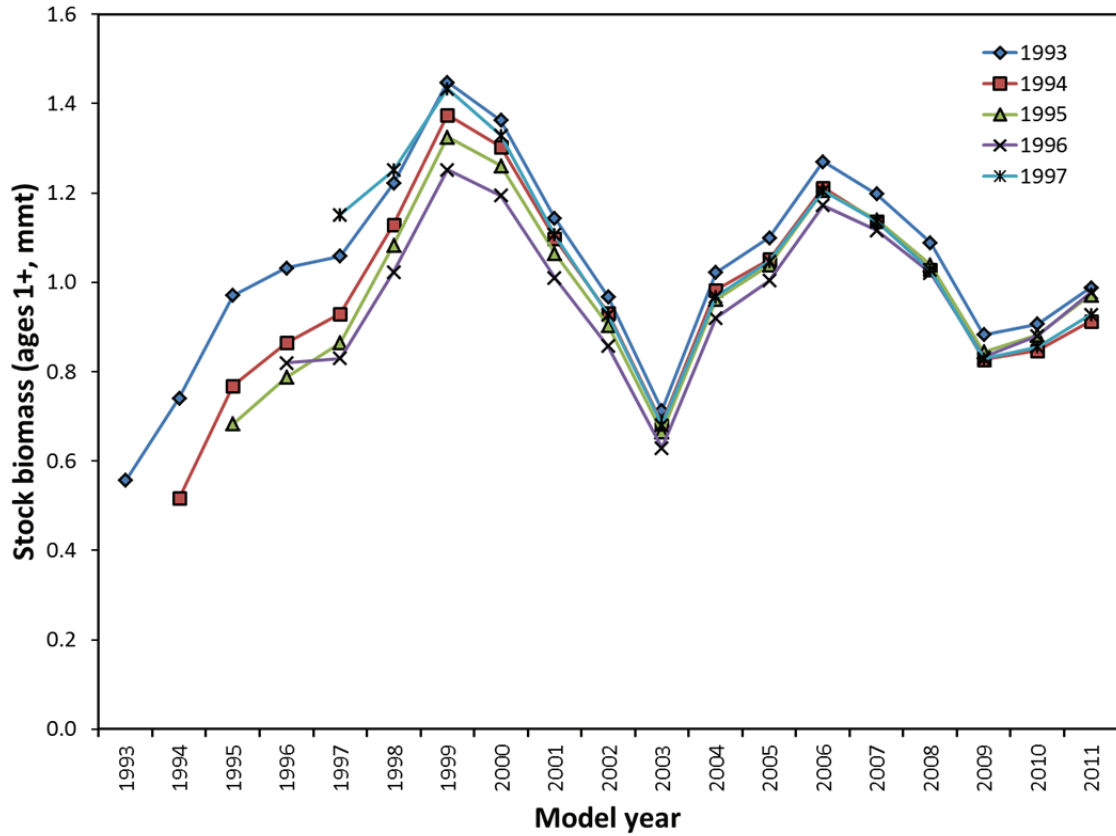
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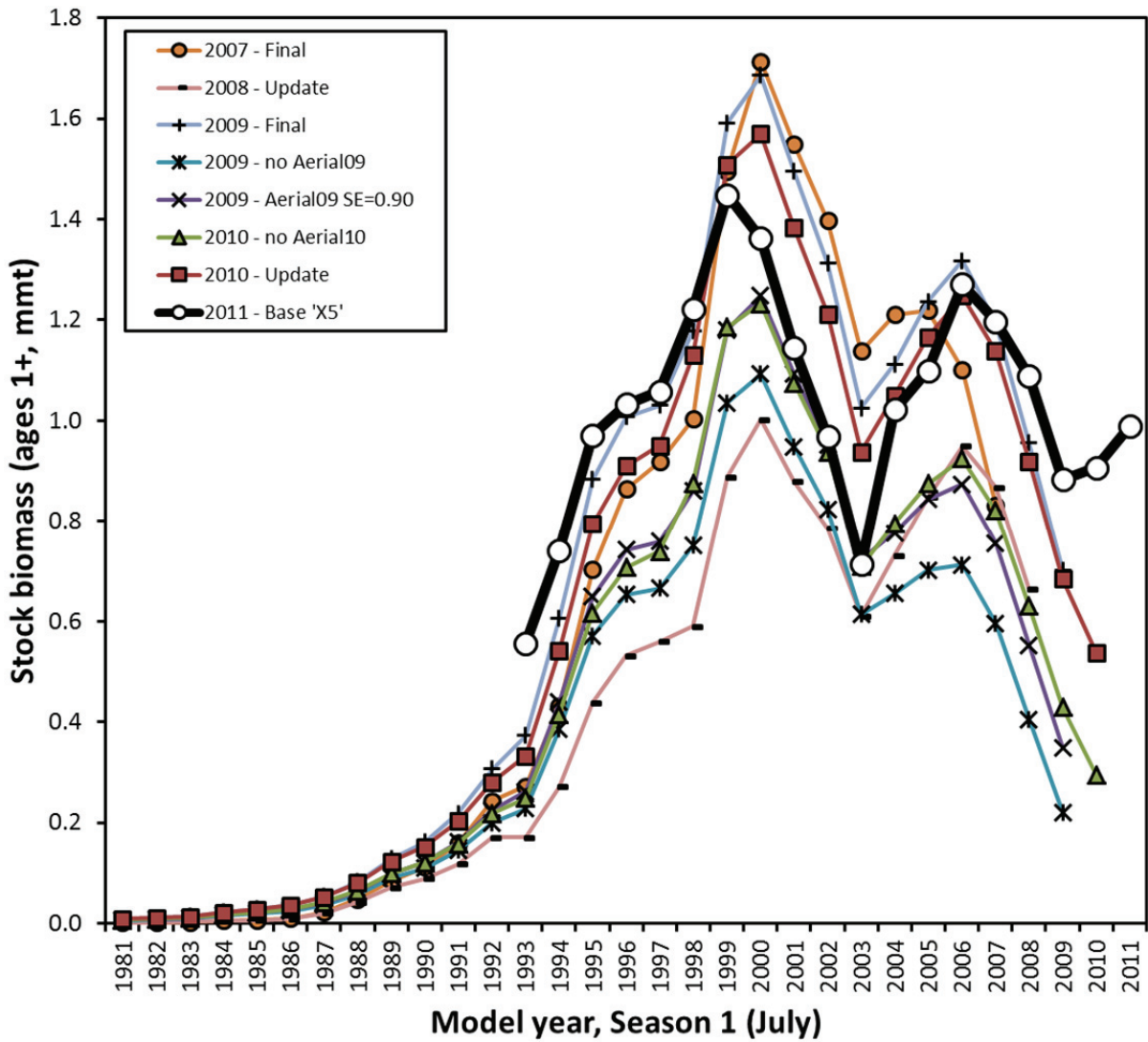
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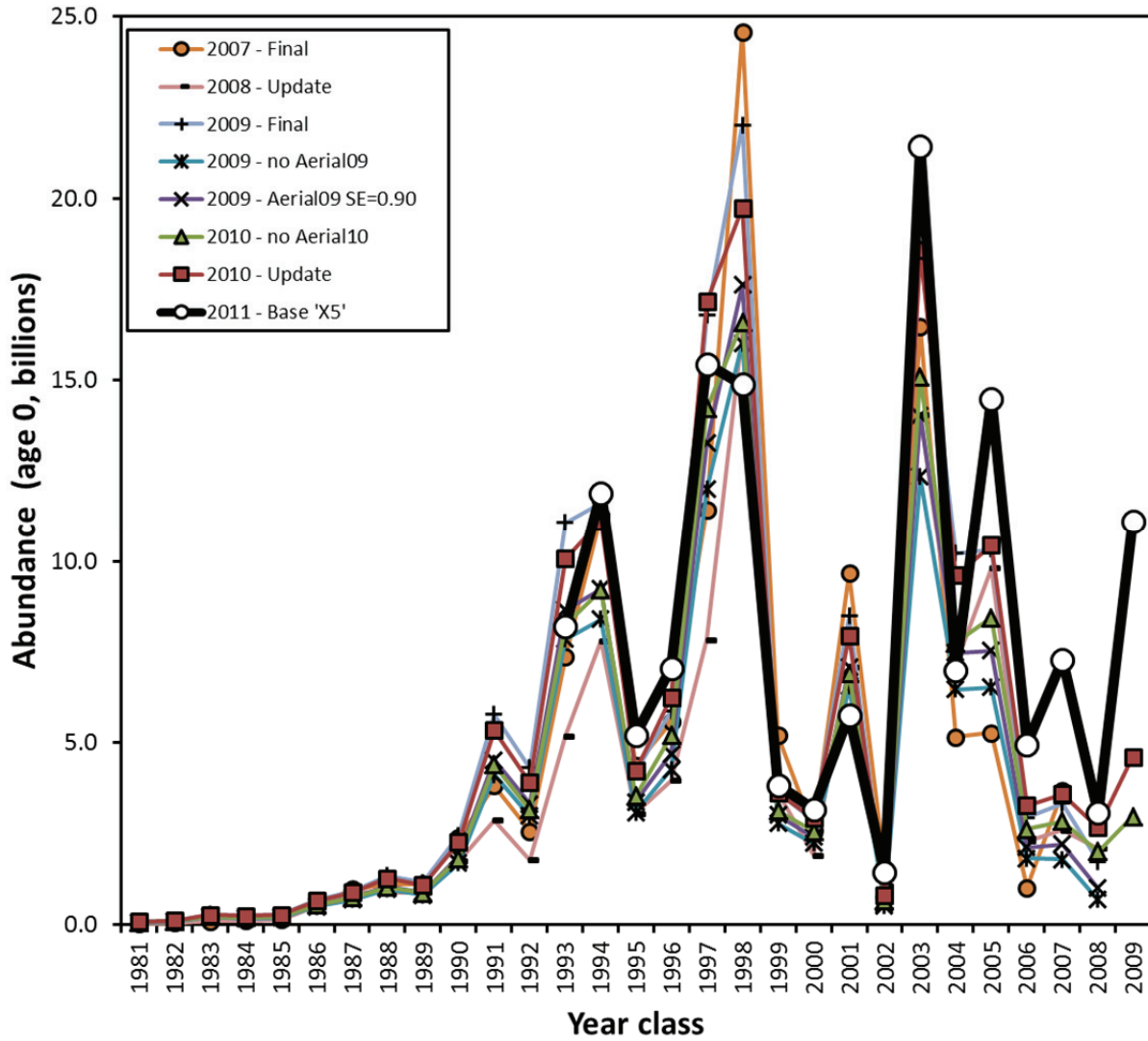
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APPENDICES

Appendix 1. SS inputs for the base model (PS11_X5).

Appendix 2. An Evaluation of the Consistency of Age-determination of Pacific Sardine (*Sardinops sagax*) Collected from Mexico to Canada. E. Dorval, J. McDaniel, and K. Hill

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Appendix 6. PFMC scientific peer reviews and advisory body reports

Appendix 1 – SS inputs for the base model (PS11_X5)

A complete listing of SS inputs (Starter, Forecast, Data, and Control files) is available in the PFMC's briefing book version of this report (pp. 136-199):

http://www.pcouncil.org/wp-content/uploads/F2b_SUP_ATT8_2011_Pacific_Sardine_Assessment_FINAL_Draft1.pdf

Appendix 2

An Evaluation of the Consistency of Age-determination of Pacific Sardine (*Sardinops sagax*) Collected from Mexico to Canada

By

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1. Introduction

Since the 1990's Pacific sardine (*Sardinops sagax*) stocks have been assessed using age-structured models (Deriso et al. 1996, Conser et al. 2004, Hill et al. 2007, 2009). Although many of these models could include age-reading errors, a systematic estimation of these errors has never been conducted for sardine samples collected from both fishery dependent and independent surveys. Butler et al. (1996) used traditional methods (i.e., Beamish and Fournier 1981, Chang 1982) to assess age-reading imprecisions for fish collected during the 1994 Daily Egg Production Method (DEPM) survey, however these estimates could not be applied to fishery age-data time series used in past assessment models. Hill et al. (2007, 2009) also used traditional methods to compute the mean standard deviation-at-age (SD_a) for all agers that participated in a 2004 Tri-national sardine ageing workshop (i.e., involving age-readers from Mexico, the US and Canada). These estimates were included in Hill et al. (2007, 2009) assessment models, but they represented a snap shop in time and did not account for differences in age estimation between fisheries or laboratories. A major problem with using traditional methods is that these methods generally focused on computing either precision (i.e. Beamish and Fournier 1981, Chang 1982) or bias (Campana et al. 1995, Morison et al. 1998), but not on both. Thus, these methods are not appropriate to develop age-reading error matrices for use in stock assessment models (Punt et al. 2008).

The Pacific sardine 2009 Stock Assessment Review (STAR) panel recommended that more systematic age-reading comparisons should be conducted in each of the major sardine ageing laboratories and that new analyses should be conducted to allow for better estimation and integration of age-reading errors in future assessment models. These recommendations were made based on two main reasons: (1) Age-reading errors can impact the performance of stock assessment models, smoothing out estimates of recruitment and total allowable catch (Reeves 2003), and potentially masking important stock-recruit relationship and the effects of environmental factors on year-class strength (Fournier and Archibald 1982, Richards et al. 1992); (2) New statistical models that can take account of both bias and precisions in estimating age-reading error matrices are now available (eg., Richards et al. 1992, Punt et al. 2008). These newer methods can estimate the true age distribution of a population, based on multiple age-readings of individual fish. Age-reading errors are represented using classification matrices that quantify the probability of a fish of true age *a* to be assigned an age *a* or some other age *a'*, *P(a'|a)*. These models can estimate the parameters of various functions that can be used to determine the relationship between true age and estimated age. Because these statistical models are based on the maximum likelihood method, they can allow for considerable flexibility in the relationship between true age and the expectation and imprecision of the estimated age (Richards et al. 1992, Punt et al. 2008).

The otolith is the primary hard part used for ageing Pacific sardines collected in Mexico, the US and Canada. A methodology for determining age of Pacific sardine from whole (i.e., un-sectioned) otoliths was established by Yaremko (1996), and is currently used in ageing laboratories of Mexico and the US, although with slight variations among laboratories (see section 2.2. below). The method is straightforward and generally recommends that: (1) the age reader immerses the otolith in distilled water for about three minutes; and (2) the age reader counts the number of annuli observed on the proximal side of the otolith using a light microscope. An annulus is defined as the interface between an inner translucent growth increment and the successive outer opaque growth increment (Fitch 1951, Yaremko 1996). The

method assumes a July 1 birthdate for all individual fish hatched in US waters within a calendar year. Pacific sardine have a prolonged spawning season, but in the early 1990s the majority of spawning used to occur in summer, justifying the assumption of a July 1 birthdate for the population off the west coast of the United States. Age assignment by readers is based on the capture date and the interpretation of the most distal pair of increments:

(1) Fish caught in the first semester of a calendar year have not yet reached their July 1 birth date; therefore their most distal pair of opaque and translucent increments should not be counted, even if exhibiting the early beginning of a second opaque increment (Yaremko 1996, Page 12).

(2) Fish caught in the second semester of a calendar year have completed a year since their last birthdate; therefore their age is equal to the number of annuli counted in their otolith.

(3) The marginal increment is categorized as opaque or translucent, wide or narrow, allowing a confidence rating to be assigned to the age determination.

The California Fish and Game (CDFG), the Washington Department of Fish and Wildlife (WDFW) and the Southwest Fisheries Science Center (SWFSC) have used this method for annual production ageing of Pacific sardine samples collected from the California, Oregon and Washington commercial fisheries, and from the DEPM survey since the 1990s. However, McFarlane et al. (2010) proposed an alternative method to age fish older than 1 collected in British Columbia waters. McFarlane et al. (2010) method consists in:

(1) Fixing the otolith on a microscope slide (sulcus side down) using the thermal resin Crystalbond^{TM} ;

(2) Polish the otolith using fine sand paper (600-800 grit);

(3) Age the otolith under a microscope using reflected light.

Comparing their method to Yaremko (1996)' otolith surface ageing, McFarlane et al. (2010) found that the polished otolith method could improve the identification of the first and the second annulus. In addition fish aged from the polished otolith method were found to be 1 to 3 years older than when aged from surface ageing. However, the polished otolith method is not currently being used for ageing fish collected off British Columbia (BC), because the method needs further evaluation particularly for fish collected in US and Mexico waters. Hence, the otolith surface ageing remains the primary method used for production ageing at the Pacific Biological Station (PBS, Nanaimo-BC).

The general goal of this paper was to summarize Pacific sardine age-reading works that have been conducted since 2004 in various ageing laboratories, and to estimate age-reading errors matrices that are suitable to be integrated in current assessment models. In particular we had three main objectives:

1) Estimate ageing-error matrices for the major fisheries and surveys of Pacific sardine. More specifically we compared ageing precision estimated from traditional methods to estimates derived from the Age-reading Error Matrix Estimator developed by Punt et al. (2008, here and thereafter referred as the Agemat model).

2) Determine which sets of ageing error matrices to be used in the 2011 stock assessment, given age data reporting from different laboratories and Stock Synthesis 3 model configurations.

3) Identify potential issues in the current ageing process and determine future research
needs for improving the consistency of age determination of Pacific sardines.

2. Method

2.1. Sample Collection

Pacific sardines were collected from the DEPM survey and from port sampling of commercial fishery landings from Mexico to Canada. DEPM samples were collected during the 2004-2010 April surveys from San Diego to San Francisco (CA). Port sampling data were collected using various designs (Hill et al. 2009), but were assumed to be representative of four major fisheries: Ensenada (ENS, Mexico), California (CA, including the southern and central California fisheries), the Pacific Northwest (PNW, including Oregon, Washington) and British the Columbia (BC) fisheries. For details about the surveys and port samplings we refer the readers to Nancy et al. (2009), Hill et al. (2009), and McFarlane et al. (2010).

2.2. Age-reading Data

Pacific sardines were aged from otoliths by agers located at five ageing laboratories: (1) The Centro Interdisciplinario de Ciencas Marinas-Instituto Politécnico Nacional (CICIMAR-IPN, Baja California Sur, Mexico); (2) The California Department of Fish and Game (CDFG, CA, US); (3) The Southwest Fisheries Science Center (SWFSC, CA, US); (4) The Washington Department of Fish and Wildlife (WDFW, WA, US); and (5)The Pacific Biological Station (PBS) of the Department of Fisheries and Ocean (DFO, BC, Canada). All laboratories used the conventional technique of otolith age-readings described in Yaremko (1996) with slight variations. Age-reading data from each fishery and survey were organized in data sets, which were defined as sets of otoliths that were aged by the same set of agers. Each ager was provided with a unique identification number, and the number of readers per data set is presented in Table 1. All agers used in this study were certified agers, but with varying degree of experience.

2.2.1. ENS Fishery Age-readings

Pacific sardines samples were collected in Magdalena Bay during the 2005 fishing season. Fish collected in the Magdalena and Ensenada fisheries were aged by a single age reader (Ager 13), and thus we assumed that age-reading errors for Magdalena fish can be applied to the Ensenada fishery. Whole sardine otoliths were fixed on glass slides (sulcus side down) using glue. Otoliths were first read on December 2006 and then double-read on June 2011. A summary of the age-reading data, along with frequency of observations, is presented in Table 2. Ager 13 reported the final age assigned to an individual fish based on the number of annuli counted, and thus no birthdates were assumed.

2.2.2. CA Fishery Age-readings

Pacific sardines samples were collected from port landings of the southern California fishery (San Pedro to Santa Barbara) and central California fishery (Monterey Bay region) from 2005 to 2011. Whole otoliths were immersed in distilled water and then read multiple times from the distal side. Depending on the year of collection 3 to 5 CDFG agers participated in the age reading process. Data sets were built based on time of collection (one to two years) using only complete reported age-readings among agers (i.e., observations containing one or more missing values were discarded). The CA age-reading data sets, including frequency of observations, are

summarized in Table 3. Each ager reported the final age assigned to an individual fish caught in California based on the capture date and a July 1 birthdate.

2.2.3. PNW Fishery Age-readings
Pacific sardines samples were collected from port landings in Oregon. Landings were sampled in July and September of 2009. Whole otoliths were immersed in alcohol and then read from the distal side using a light microscope. All otoliths were read by two WDFW age readers (Ager 8 and 9). The PNW age-reading data set, including frequency of observations, is presented in Table 4. Agers 8 and 9 reported the final age assigned to an individual fish based on the capture date and a July 1 birthdate.

2.2.4. BC fishery Age-readings
British Columbia samples were collected from July to September of 2007. Whole otoliths were first read separately by two age readers (Ager 10 and 11). Then, each otolith was re-read again simultaneously by both agers to estimate a best/resolved age (RA). Age data from these three readings, including frequency of observations, are presented in Table 5. Final age was assigned to individual fish based on the capture date and a January 1 birthdate. Finally, in this paper we assumed that the resolved age was more likely to be unbiased.

2.2.5. DEPM Survey Age-readings
Pacific sardine samples were collected during the April DEPM cruises from 2004 to 2011. Otoliths were extracted either at sea or in the laboratory, dried and then stored in conical vials. Whole otoliths were immersed in distilled water and then read from the distal side, using a light microscope. Age determinations were done by Agers 1 and 2 from CDFG and Ager 12 from the SWFSC. Two data sets containing the age readings from the three readers, including frequency of observations, are presented in Table 6. All three agers assigned a final age to individual fish based on the capture date and an assumed July 1 birthdate.

2.3. Ageing Error Estimation
2.3.1. Traditional methods
Pairwise comparisons of age readings were performed using age bias plots between readers (Campana et al. 1995). These graphs consist in plotting the mean age estimated by an ager against the single predicted age for a group of fish reported by the most experienced ager (*i.e.*, assumed to be more likely unbiased). These plots may allow detecting both systematic and non-systematic bias between agers. These plots were also used as exploratory tools to determine a potential relationship between true age and age-reading precisions.
Further, from each dataset we computed the standard deviation of ages estimated for an individual fish j, following Equation 1:

$$(1) \qquad SD_j = \sqrt{\sum_{i=1}^{R} \frac{(a_{i,j} - a_j)^2}{R-1}},$$

where R is the number of readers, a_{ij} the age reported by reader i for fish j; and a_j is the mean age estimated for fish j. Similarly as in previous sardine stock assessment (i.e., Hill et al. 2007, 2009), the SD at age a (SD_a) reported in a given data set was estimated by Equation 2.

$$(2) \qquad SD_a = \frac{\sum_{j=1}^{n} SD_j}{n},$$

where n is the number of fish that was assigned an age a at least by one reader.

2.3.2. *Statistical Model*

We used the Agemat model developed by Punt et al. (2008) to estimate age-reading error matrices by reader. The model computed ageing error matrices based on otoliths that have been aged multiple times by one or more agers, while assuming that: (1) ageing bias depends on ager and the true age of a fish; (2) the age-reading error standard deviation depends on ager and true age; and (3) age-reading error is normally distributed around the expected age. Hence, the probability to assign an age a' to a fish of true age a is computed following Equation 3 (see also Punt: Agemat user manual):

$$(3) \qquad P^i(a'|a, \emptyset) = \int_{a'}^{a'+1} \frac{1}{\sqrt{2\pi\sigma_a^i(\emptyset)}} \exp[\frac{-\left(a'-b_a^i(\emptyset)\right)^2}{2\left(\sigma_a^i(\emptyset)\right)^2}]da',$$

where b_a^i is the expected age when ager i determines the age of a fish of true age a, σ_a^i is the standard deviation for ager i of the age reading error for fish whose true age is a, and ϕ is the vector of parameters that determines the age reading error matrices. The values for these parameters are estimated by maximizing the following likelihood function, assuming there was some set of J ageing structures that were read by all readers:

$$(4) \qquad L(A|\beta, \emptyset) = \prod_{j=i}^{J} \sum_{a=L}^{H} \beta_a \prod_{i=1}^{I} P^i(a_{i,j}|a, \emptyset)$$

where a_{ij} is the age assigned by ager i to the jth ageing structure; L and H are respectively the minimum and the maximum ages, and A is the entire data set of age-readings. The βs are nuisance parameters that can be interpreted as the relative frequency of fish of true age a in the sample.

For the purpose of this study we were mostly interested in estimating the SDs for the different fisheries and surveys. Agemat model typically estimates ageing errors by reader, however, age data input and precisions cannot be included in Stock Synthesis 3 by ager. As an alternative we defined various model scenarios, comparing models that assumed equal or unequal SDs among agers for each fishery and the survey. Then, we used AICc (Akaike Information Criterion with a correction for finite sample sizes) to select the best model, and determine whether there was enough evidence to support the assumption of equality of SDs among agers for the age-reading data sets considered in a given model.

We assumed that the functional form of random ageing error precisions followed either Equation 5 or 6 below.

$$(5) \qquad \sigma_a = \sigma_L + (\sigma_H - \sigma_L)\frac{1-\exp(-\delta(a-1))}{1-\exp(-\delta(a_{max}-1))}$$

where, σ_L and σ_H are respectively the standard deviation of the minimum and the maximum age in a given data set, and δ is a parameter that determines the extent of linearity between age and the age-reading standard deviation.

$$(6) \qquad CV_a = CV_L + (CV_H - CV_L)\frac{1-\exp(-\delta(a-1))}{1-\exp(-\delta(a_{max}-1))}$$

where CV_L and CV_H are respectively the coefficient of variation of the minimum and the maximum age in a given data set.

For the DEPM survey, the PNW and BC fisheries we also performed model runs where bias was estimated. In these cases, the most experienced agers were assumed to be unbiased, whereas the functional form for ageing bias for all other readers was assumed to follow Equation 7:

$$(7) \qquad E_a = E_L + (E_H - E_L)\frac{1-\exp(-\beta(a-1))}{1-\exp(-\beta(a_{max}-1))}$$

where E_a is the expected age of a fish of age a, E_L and E_H are respectively the minimum and the maximum ages in a given data set; a_{max} is a pre-specified maximum age; and β is a parameter that determines the extent of linearity between age and the expected age.

For all model runs the maximum expected age for sardine was set to be 15. Further, the maximum *SD* allowed in model runs was 100.

3. Results:

3.1. ENS Age-reading Errors

Pairwise comparison of age-reading 1 and 2 performed by Ager 13 for the ENS fishery, showed no bias in estimating age 0 through age 3. However, the second reading slightly underestimated age 4 compared to the first reading (Figure 1).

No bias was estimated from the Agemat model for the ENS fishery, but *SD* was estimated assuming that Ager 13 had equal *SD* in both readings. Estimates of *SD* from the ENS model are compared to traditional method's estimates in Table 7. Model fits to the ENS age-reading data set are presented in Figure 2.

3.2. CA Fishery Age-reading Errors

The CA fishery age-reading errors were estimated by date of sample collection. Both the number of readers involved in the age-reading process varied over time. In general there was little bias among readers from ages 0 to 2, except for Ager 5 for the 2007 and 2008-2009 data sets. Bias among readers was more significant for the age 3-6 group which occurs at a lower frequency in the CA data sets. Age bias plots and Agemat model fits to the CA age-reading data sets are presented in Figures 3 to 11.

No bias was estimated from the Agemat model for the CA fishery age-reading data sets. Model comparisons for the different time periods are presented in Table 8. In each of the time period considered, the models that assumed equal *SD* among agers had lower *AICc* than the models that assumed different *SD*s. In Table 7 we compare *SD*s estimated from the traditional method to estimates from the Agemat model that assumed equal *SD* among agers. Note that both model CA_0809 A and CA_0809_B did not fit well to the age-reading data set # 4, but changing the assumption on the functional form of the random ageing error precision could not improve these fits.

3.3. PNW Fishery Age-reading Errors

Pairwise comparison of age-reading showed that Ager 9 overestimated age 2, but underestimated age 7 compared to reader 8 (Figure 12). Agemat models with bias and no bias estimation are compared in Table 8. The model PNW_C that assumed no bias but equal *SD* between the two agers had the lowest *AICc* value. *SD*s estimated from model PNW_C are compared to traditional method estimates in Table 7. Model fits to the age-reading data set are presented in Figure 13.

3.4. BC Fishery Age-reading Errors

From age 2 to 5 Agers 10 and 11 showed no bias compared to the resolved age (RA) between these two readers. However, both readers underestimated age 6 to age 8 compared to the RA (Figure 8). Agemat model with bias and no bias estimation are compared in Table 8 for this fishery. The model BC_C that assumed no bias but equal *SD* had the lowest *AICc*. The *SD*s estimated from model BC_C are compared to *SD*s from the traditional method in Table 7. Model fits for the different data sets are presented in Figure 15.

3.5. DEPM Survey Age-reading Errors

Bias in the DEPM age-readings appeared to be non-systematic, *i.e.* Ager 12 over-estimated ages 0 to 3 but under-estimated ages 5 to 8 compared to Agers 1 and 2 (Figure 9). Agemat models with bias and no bias estimation are compared in Table 8. In Table 7, the *SD*s estimated from model DEPM_C are compared to estimates from the traditional method. Model fits to the two age-reading data sets are presented in Figure 17. Note that the model DEPM_C did not fit well to the the age-reading data sets, but changing the assumption on the functional form of the random ageing error precision could not improve these fits.

4. Discussion

4.1. Age-reading precision

Estimates of age-reading precision from the traditional method and the Agemat models were different. The traditional method estimation of standard deviation-at-age involved averaging across all fish that were assigned a given age *a* by one or more readers. Hence, this method assumed that all agers were unbiased, but without a mean to determine whether this assumption was appropriate. In contrast, with the Agemat model we assumed that all agers had equal standard deviation, but used an information criterion (*AICc*) to determine whether there was enough evidence in the age-reading data sets to support this assumption (i.e., when compared to alternative models). Although the Agemat model typically estimates age-reading precision by ager, the assumption of equality of standard deviation among agers was needed because ageing errors cannot be included by ager in the Stock Synthesis 3 model. The application of the Agemat model in this study provides a good example of the type of flexibility allowed by a statistical model compared to traditional method of estimating age-reading precision.

In general, estimates of standard deviation from the Agemat models that assumed equality of standard deviation among agers are within the range of expectation, and thus can be applied to the stock assessment model. Note that although we estimated ageing errors for the BC fishery, these estimates cannot be used in the 2011 stock assessment model because no age data were provided for the British Columbia fishery.

4.2. Age-reading accuracy

Although, the estimation of bias was not the primary focus of this study, we conducted Agemat model runs that estimated bias for the PNW and the BC fisheries and the DEPM survey. However, models that estimated bias were not selected because they had higher AICc values than those that assumed equal or unequal standard deviation among readers.

Most of the concerns regarding bias remain with ageing fish older than four years-old (i.e., the age 5^+- group). This age group is more frequent in the PNW and BC fisheries, and the DEPM survey. Interpreting increments at the edge of otoliths was challenging for all agers, because when ageing from whole otolith it is often difficult to differentiate a check mark from an annulus. For example, in the first year of life a wide opaque increment near the focus followed by a fine translucent ring can be interpreted as a check mark; whereas the same mark present in a more distal area of the otolith may be considered as an annulus (Yaremko 1996). The polished otolith method (McFarlane et al. 2010) may be an alternative method to reduce the level of bias currently observed among agers.

Regardless of the method used, a fundamental problem with ageing Pacific sardine is that there are no known-aged fish to determine age-reading accuracy. CDFG has established a Training Set of Otoliths (*TSO*) that has been used to train and certify new age readers. However, the *TSO* does not include any fish whose ages were validated, and thus cannot be used to directly address issues concerning ageing bias. The periodicity of sardine growth increments have been validated in juvenile fish (Butler 1987, Barnes and Foreman 1994), but to our knowledge validation of annulus in older mature fish has never been conducted. Validation of increments in young fish cannot be applied to older fish. In the absence of known age fish, the lack of verification of increment formation in each and every age group can lead to systematic bias in age determination (Campana 2011). Such systematic bias cannot be accounted by statistical models and need to be addressed via field/laboratory experiments.

5. Recommendations

- Final Stock Synthesis model runs for the 2011 Pacific sardine assessment can be based on estimates of standard deviation-at-age from the Agemat models that assumed equality of standard deviation among agers. These models had the lowest AICc values when compared to models that did not assumed equality of standard-deviation among agers, and thus were selected as the best models for the age-reading data sets considered in this study.

- Although estimates of standard deviation-at-age for the Ensenada and the PNW fishery were based on single year of collection, these errors can be applied to the entire time series of age data input for each fishery in the Stock Synthesis 3 model. These time series of age data were produced by the same agers in each fishery, and thus it can be assumed that ageing-errors did not vary over time for the Ensenada and the PNW fishery.

- Use time-varying estimates of standard deviation-at-age for the California fishery and the DEPM survey. These estimates account for turnover among readers and adjustments in age determination made by the CDFG and the SWFSC ageing laboratories.

6. Research needs

Several measures can be taken to improve both bias and precision of age determination of Pacific sardine:

- As ageing error can vary over time, and because of turnover among readers within laboratory, there is need for each ageing laboratory to conduct multiple readings of otolith samples on a yearly basis, similarly as being done by CDFG.

- Conduct growth experiment in the laboratory toward understanding the deposition of growth increment and check marks in both young and old Pacific sardines.

- Conduct a study to compare the surface and the polished otolith methods for Pacific sardine caught in Mexico and US waters.

- Develop an exchange program of otolith age-reading comparison between the different laboratories toward the standardization of the ageing method of Pacific sardine.

- Resolving the problem of bias in age determination of Pacific sardines would require mark-recapture data. In the last tagging experiment conducted by Clark and Jansen (1945) otoliths were not extracted or preserved. Any repeat of this experiment in the future can provide valuable data for the validation of sardine ages.

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Table 1. Summary of number of Pacific sardine otoliths (N) aged by reader and by year for each fishery or survey. **N** is the sample size, number of otoliths with age readings reported by all agers.

Ageing Laboratory	Fishery/Survey	Data set #	Collection Year	Number of Agers	Ager ID	Number of readings	N
CICIMAR-INP	ENS	1	2005	1	13	2	240
CDFG	CA	1	2005	3	1,2,3	3	219
		2	2007	4	2,4,5,6	4	148
		3	2008-2009	5	2,4,5,6,7	5	507
		4	2008-2009	4	2,5,6,7	4	145
		5	2010-2011	3	2,5,6	3	266
WDFG	PNW	1	2009	2	8,9	2	711
PBS	BC	1	2007	2	10,11	3	283
CDFG-SWFSC	DEPM	1	2004, 2006	2	1,12	2	360
		2	2006, 2008, 2009	2	2,12	2	360

Table 2. Age readings data reported by ager 13 for the Ensenada fishery. **n** is the frequency of observed otoliths for each unique age-reading combination.

Fishery	Data set	n	Age assigned from	
			Reading 1	Reading 2
ENS	1	19	0	0
		1	1	0
		150	1	1
		3	1	2
		4	2	1
		24	2	2
		5	3	2
		28	3	3
		3	4	3
		3	4	4

Table 3. Age readings data reported by agers and data set for Pacific sardines samples collected in the California fishery from 2005 to 2011. **n** is the frequency of observed otoliths for each unique age-reading combination.

Fishery	Collection Year	Data set #	n	Age assigned by						
				Ager 1	Ager 2	Ager 3	Ager 4	Ager 5	Ager 6	Ager 7
CA	2005	1	26	0	0	0				
			2	0	0	1				
			6	1	0	0				
			1	1	0	1				
			4	1	1	0				
			82	1	1	1				
			2	1	1	2				
			2	1	2	1				
			1	1	2	2				
			9	2	1	1				
			7	2	1	2				
			1	2	1	3				
			6	2	2	1				
			65	2	2	2				
			2	2	3	2				
			1	3	2	2				
			2	3	3	2				
	2007	2	1		1		1	1	0	
			57		1		1	1	1	
			8		1		1	1	2	
			4		1		1	2	1	
			1		1		1	2	2	
			2		1		1	3	1	
			1		2		1	1	2	
			3		2		1	2	1	
			1		2		2	1	2	
			8		2		2	2	1	
			48		2		2	2	2	
			6		2		2	2	3	
			1		2		2	3	1	
			2		2		2	3	2	
			1		2		2	4	2	
			1		3		2	2	1	
			1		3		2	3	1	
			1		3		2	3	2	
			1		3		2	3	3	

Table 3 Continued.

Fishery	Collection Year	Data set #	n	Age assigned by						
				Ager 1	Ager 2	Ager 3	Ager 4	Ager 5	Ager 6	Ager 7
			1		2		1	2	2	2
			1		2		2	0	1	1
			11		2		2	1	1	1
			3		2		2	1	2	1
			4		2		2	1	2	2
			1		2		2	1	4	1
			4		2		2	2	1	1
			2		2		2	2	1	2
			15		2		2	2	2	1
			33		2		2	2	2	2
			2		2		2	2	3	1
			7		2		2	2	3	2
			1		2		2	2	3	3
			1		2		2	2	4	2
			1		2		2	3	2	0
			5		2		2	3	2	1
			15		2		2	3	2	2
			2		2		2	3	2	3
			1		2		2	3	3	0
			9		2		2	3	3	1
			9		2		2	3	3	2
			1		2		2	4	3	1
			2		2		2	4	3	2
			1		2		2	4	3	3
			1		2		2	4	4	2
CA	2008-2009	3	1		2		3	1	1	1
			4		2		3	1	2	2
			5		2		3	1	3	2
			2		2		3	2	2	2
			1		2		3	2	3	2
			3		2		3	3	2	1
			3		2		3	3	2	2
			1		2		3	3	3	1
			1		2		3	3	3	2
			2		2		3	4	2	1
			2		2		3	4	3	1
			2		2		3	4	3	2
			1		2		3	4	4	1
			1		2		3	4	4	2
			1		2		3	4	5	2
			2		2		3	5	3	2
			1		2		3	5	4	2
			3		2		4	4	3	2
			1		2		4	5	3	2
			1		2		4	6	3	2
			1		3		2	2	3	2
			2		3		3	2	4	3
			1		3		3	3	2	2
			1		3		3	4	3	3
			2		3		4	4	3	2
			1	151	4		4	5	4	2

Table 3. Continued.

Fishery	Collection Year	Data set #	n	Ager 1	Ager 2	Ager 3	Ager 4	Ager 5	Ager 6	Ager 7
			29	0			0	0	0	0
			2	0			0	0	1	0
			28	0			0	1	0	0
			1	0			0	1	0	1
			20	0			0	1	1	0
			5	0			0	1	1	1
			4	0			0	1	2	0
			1	0			0	1	2	1
			6	0			0	2	0	0
			5	0			0	2	1	0
			1	0			0	2	1	1
			5	0			1	1	0	0
			1	0			1	1	1	0
			1	0			1	2	0	0
			2	0			1	2	1	0
			1	1			0	0	1	0
			9	1			0	1	0	0
			6	1			0	1	1	0
			1	1			0	1	1	1
			2	1			0	1	2	1
			2	1			0	2	1	0
			1	1			1	0	1	1
			5	1			1	1	0	0
			10	1			1	1	0	1
			18	1			1	1	1	0
CA	2008-2009	3	81	1			1	1	1	1
			2	1			1	1	1	2
			2	1			1	1	2	0
			10	1			1	1	2	1
			3	1			1	2	1	0
			8	1			1	2	1	1
			2	1			1	2	1	2
			4	1			1	2	2	1
			1	1			1	2	2	2
			13	1			2	1	1	1
			5	1			2	1	2	1
			3	1			2	2	1	1
			7	1			2	2	2	1
			2	1			2	2	3	1
			2	1			2	3	2	1
			1	1			2	3	3	2
			1	1			2	4	3	1
			1	1			3	3	1	0
			1	1			3	3	4	1
			1	1			3	4	4	1
			3	2			1	1	0	1
			1	2			1	1	1	0
			5	2			1	1	1	1
			1	2			1	1	2	2
			1	2			1	2	2	0
			1	2			1	2	2	1

Table 3. Continued.

Fishery	Collection Year	Data set #	n	Ager 1	Ager 2	Ager 3	Ager 4	Ager 5	Ager 6	Ager 7
								Age assigned by		
CA	2008-2009	4	17		1			1	1	1
			11		1			2	1	1
			4		1			2	2	1
			2		1			3	1	1
			3		2			1	1	1
			2		2			1	2	1
			1		2			1	2	2
			1		2			2	1	1
			4		2			2	1	2
			9		2			2	2	1
			43		2			2	2	2
			2		2			2	2	3
			2		2			2	3	2
			13		2			3	2	2
			4		2			3	3	3
			2		2			4	2	3
			1		3			1	2	1
			1		3			1	2	2
			1		3			2	2	1
			4		3			2	2	2
			1		3			2	2	3
			1		3			2	3	1
			1		3			2	3	2
			4		3			3	2	2
			2		3			3	2	3
			1		3			3	3	2
			3		3			3	3	3
			1		4			3	3	2
			1		4			3	3	4
			2		4			4	3	2
			1		4			4	3	3
	2010-2011	5	81		0			0	0	
			7		0			0	1	
			5		0			1	0	
			9		1			0	0	
			10		1			1	0	
			97		1			1	1	
			3		1			2	1	
			1		2			1	0	
			1		2			1	2	
			3		2			2	1	
			17		2			2	2	
			1		3			2	2	
			3		3			3	2	
			7		3			3	3	
			1		3			3	4	
			1		4			3	3	
			3		4			4	4	
			2		5			4	4	
			1		5			4	5	
			4		5			5	4	
			8		5			5	5	
			1		6			6	5	

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Table 4. Age readings data reported by agers 8 and 9 for the PNW fishery. Pacific sardines samples were collected in 2009 from port landings in Oregon. **n** is the frequency of observed otoliths for each unique age-reading combination.

			Age assigned by	
Fishery	**Data set #**	**n**	**Reader 8**	**Reader 9**
		3	2	3
		1	2	4
		16	3	3
		29	3	4
		1	3	5
		4	4	3
		178	4	4
		82	4	5
		2	4	6
		3	5	3
		33	5	4
PNW	1	199	5	5
		42	5	6
		1	5	7
		2	6	4
		31	6	5
		67	6	6
		4	6	7
		1	6	8
		8	7	6
		3	7	7
		1	7	8

Table 5. Age reading data reported by agers 10 and 11 for the BC fishery. Pacific sardines samples were collected off British Columbia in 2007. **n** is the frequency of observed otoliths for each unique age-reading combination. Resolved age (RA) was assigned after both agers re-read an otolith together and agreed on a final age.

| Fishery | Data set # | n | Age assigned by | | RA |
			Reader 10	Reader 11	
		10	3	3	3
		1	3	3	4
		1	3	3	5
		1	3	4	3
		12	3	4	4
		5	3	4	5
		1	3	5	3
		3	3	5	4
		4	3	5	5
		1	4	3	3
		2	4	3	4
		1	4	3	5
		87	4	4	4
		1	4	4	5
		1	4	4	6
		1	4	4	7
		1	4	4	8
		13	4	5	4
		19	4	5	5
		4	4	5	6
		2	4	6	4
		3	4	6	5
		1	4	6	6
		25	5	4	4
BC	1	2	5	4	6
		1	5	5	4
		34	5	5	5
		1	5	6	4
		7	5	6	5
		6	5	6	6
		1	5	6	7
		1	5	6	8
		1	5	7	5
		1	5	7	6
		2	5	7	7
		2	5	8	5
		1	5	8	7
		1	6	4	4
		1	6	4	5
		2	6	5	5
		5	6	5	6
		1	6	5	7
		6	6	6	6
		1	6	6	7
		1	6	7	7
		1	7	7	4
		1	7	7	7
		1	7	7	8
		2	8	8	8

Table 6. Age readings data reported by agers 1, 2, and 12 for the DEPM survey. Pacific sardines samples were collected in the April DEPM survey in 2004, 2006, 2008, 2009, and 2010. **n** is the frequency of observed otoliths for each unique age-reading combination.

Survey	Collection Year	Data set #	n	Age assigned by		
				Ager 1	Ager 2	Ager 12
DEPM	2004 ,2006	1	8	0		0
			7	0		1
			2	0		2
			2	0		3
			14	1		1
			20	1		2
			11	1		3
			4	1		4
			2	2		1
			63	2		2
			29	2		3
			8	2		4
			1	2		5
			2	3		2
			11	3		3
			3	3		4
			2	3		5
			12	4		3
			22	4		4
			11	4		5
			1	4		6
			2	5		2
			7	5		3
			24	5		4
			26	5		5
			6	5		6
			4	6		3
			9	6		4
			18	6		5
			8	6		6
			2	6		7
			4	7		3
			6	7		4
			2	7		5
			3	7		6
			2	7		7
			1	8		6
			1	8		7
	2006, 2008, 2009	2	3		0	0
			5		0	1
			2		0	2
			2		1	0
			27		1	1
			86		1	2
			26		1	3
			2		1	4
			1		2	1
			20		2	2
			28		2	3
			2		2	4
			5		3	2
			44		3	3
			21		3	4
			8		3	5
			1		3	6
			1		4	1
			3		4	2
			8		4	3
			11		4	4
			7		4	5
			2		4	6
			1		5	2
			7		5	3
			15		5	4
			9		5	5
			6		5	6
			3		5	7
			1		6	4
			1		6	5
			2		6	6

Table 7. Estimation of standard deviation- at-age by fishery / survey and dataset based on the traditional method and the Agemat model. Note that estimation of *SD* from Agemat was based on the assumptions that all agers had equal standard deviation.

Fishery / Survey	Collection Year	Data set #	Age	Estimation Traditonal method Mean SD	Agemat model SD
ENS		1	0	0.04	0.20
			1	0.04	0.20
			2	0.24	0.28
			3	0.16	0.31
			4	0.35	0.32
CA	2005	1	0	0.19	0.28
			1	0.23	0.28
			2	0.21	0.29
			3	0.65	0.80
	2007	2	0	0.50	0.25
			1	0.21	0.25
			2	0.25	0.34
			3	0.48	0.92
			4	1.00	4.64
	2008-2009	3	0	0.49	0.40
			1	0.47	0.40
			2	0.58	0.50
			3	0.76	0.58
			4	1.05	0.69
			5	1.24	0.82
			6	1.67	0.97
	2008-2009	4	1	0.42	0.40
			2	0.37	0.50
			3	0.54	0.58
			4	0.83	0.69
	2010-2011	5	0	0.17	0.28
			1	0.18	0.28
			2	0.84	0.30
			3	0.34	0.31
			4	0.43	0.33
			5	0.29	0.36
			6	0.58	0.40
PNW	2009	1	2	0.88	0.31
			3	0.55	0.36
			4	0.34	0.38
			5	0.36	0.40
			6	0.43	0.40
			7	0.59	0.40
			8	1.06	0.41
BC	2007	1	3	0.62	0.23
			4	0.42	0.37
			5	0.69	0.59
			6	0.74	0.94
			7	1.11	1.48
			8	1.26	2.32
DEPM	2004, 2006	1	0	0.63	0.50
			1	0.83	0.50
			2	0.57	0.73
			3	0.98	0.82
			4	1.36	0.86
			5	0.72	0.88
			6	0.86	0.88
			7	1.56	0.89
			8	1.06	0.89
	2006, 2008, 2009	2	0	0.65	0.50
			1	0.72	0.50
			2	0.65	0.73
			3	0.63	0.82
			4	0.74	0.86
			5	0.84	0.88
			6	0.84	0.88

Table 8. Summary of Agemat model assumption and comparison for each Pacific sardine fishery and survey.

| Fishery/Survey	Number of dataset	Dataset #	Model	Bias estimation	Ager SD assumption	N	Input EffN	Model EffN	EffN Ratio	Total likelihood	Number of parameters	AICc
ENS	1	1	ENS_1	No	Readings 1 = 2	240	240	1333.71	5.56	322.78		
	1	1	CA_05_A	No	Ager 1 ≠ 2 ≠ 3	219	219	299.156	1.37	416.504	13	15.71
	1	1	CA_05_B	No	Ager 1 = 2 = 3	219	219	253.677	1.16	423.874	7	2.43
	1	1	CA_07_A	No	Ager 1 ≠ 2 ≠ 3	148	148	235.321	1.59	315.986	17	27.20
	1	1	CA_07_B	No	Ager 1 = 2 = 3	148	148	76.786	0.52	337.979	8	5.39
CA	2	1	CA_0809_A	No	Ager 2 ≠ 4 ≠ 5 ≠ 6 ≠ 7	507	100	69.497	0.69	862.471	27	49.27
		2				145	100	22.108	0.22			
	2	1	CA_0809_B	No	Ager 2 = 4 = 5= 6=7	507	100	75.316	0.75	855.52	15	19.11
		2				145	100	25.02	0.25			
	1	1	CA_1110_A	No	Ager 2 ≠ 5 ≠ 6	266	160	159.21	1.00	342.139	15	21.66
	1	1	CA_1110_B	No	Ager 2 = 5 = 6	266	160	146.29	0.91	346.32	9	7.51
PNW	1	1	PNW_A	Ager 8 unbiased	Ager 8 ≠ 9	711	700	2992.13	4.27	1476.56	16	18.20
	1	1	PNW_B	No	Ager 8 ≠ 9	711	700	254.03	0.36	1494.12	13	11.91
	1	1	PNW_C	No	Ager 8 = 9	711	700	206.54	0.30	1502.38	10	5.69
BC	1	1	BC_A	RA unbiased	RA ≠ Ager 10 ≠ 11	283	260	221.32	0.85	798.38	21	32.52
	1	1	BC_B	No	RA ≠ Ager 10 ≠ 11	283	260	47.64	0.18	878.85	15	18.41
	1	1	BC_C	No	RA = Ager 10 = 11	283	260	69.21	0.27	839.69	9	5.25
DEPM	2	1	DEPM_A	Ager 1 unbiased	Ager 1≠ 2≠ 12	360	100	97.38	0.97	890.628	27	45.97
		2				360	200	186.65	0.93			
	2	1	DEPM_B	No	Ager 1≠ 2≠ 12	360	100	66.7	0.67	951.39	21	31.61
		2				360	200	23.67	0.12			
	2	1	DEPM_C	No	Ager 1= 2= 12	360	100	73.77	0.74	966.169	15	17.94
		2				360	200	18.7	0.09			

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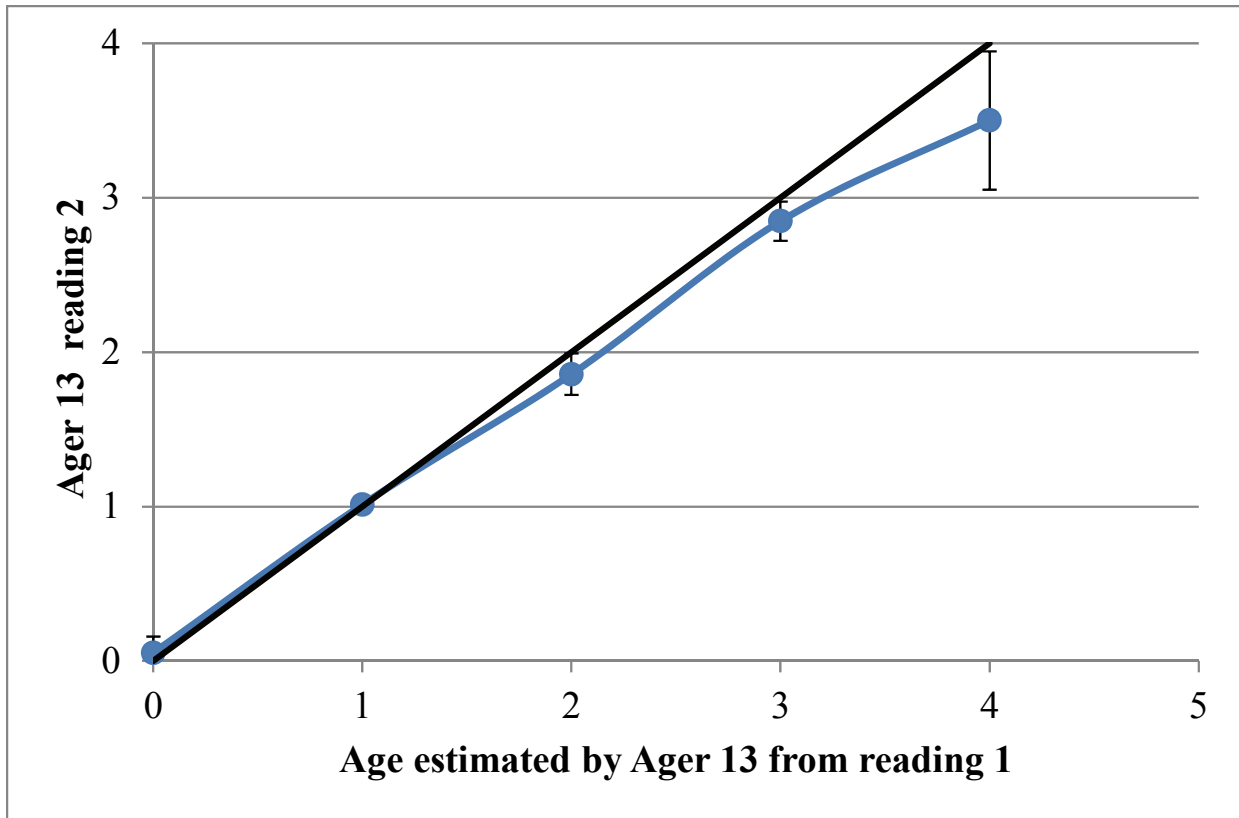
Figure 1. Age bias plot for the pairwise age comparison presented in Table 2 for the ENS fishery. Each error bar represents the 2*SE around the mean age assigned by ager 13 in the second reading for all fish assigned a given age in the first reading. The 1:1 equivalence (solid black line) is also shown on the plot.
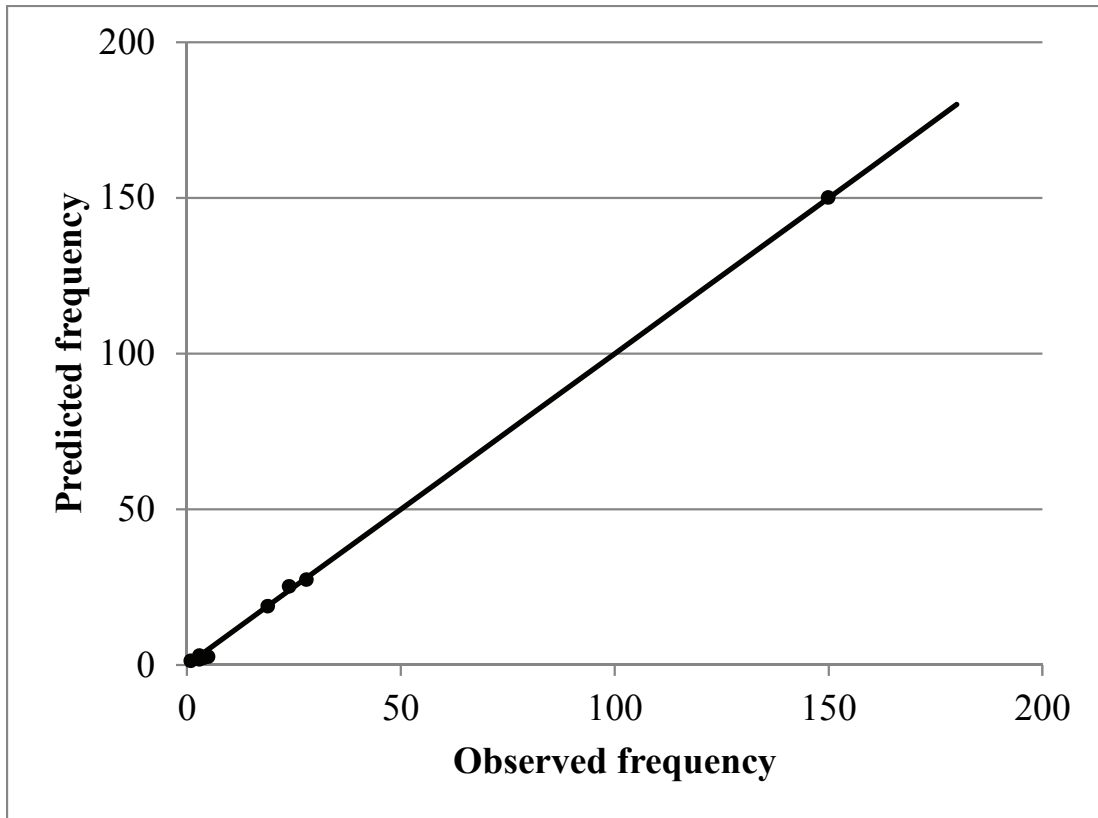
Figure 2. Predicted and observed frequency for the ENS fishey age-reading data. Predicted frequency was estimated from the ENS_1 Agemat model (see Table 8 for model assumptions). The 1:1 equivalence (solid black line) is also shown on each plot.
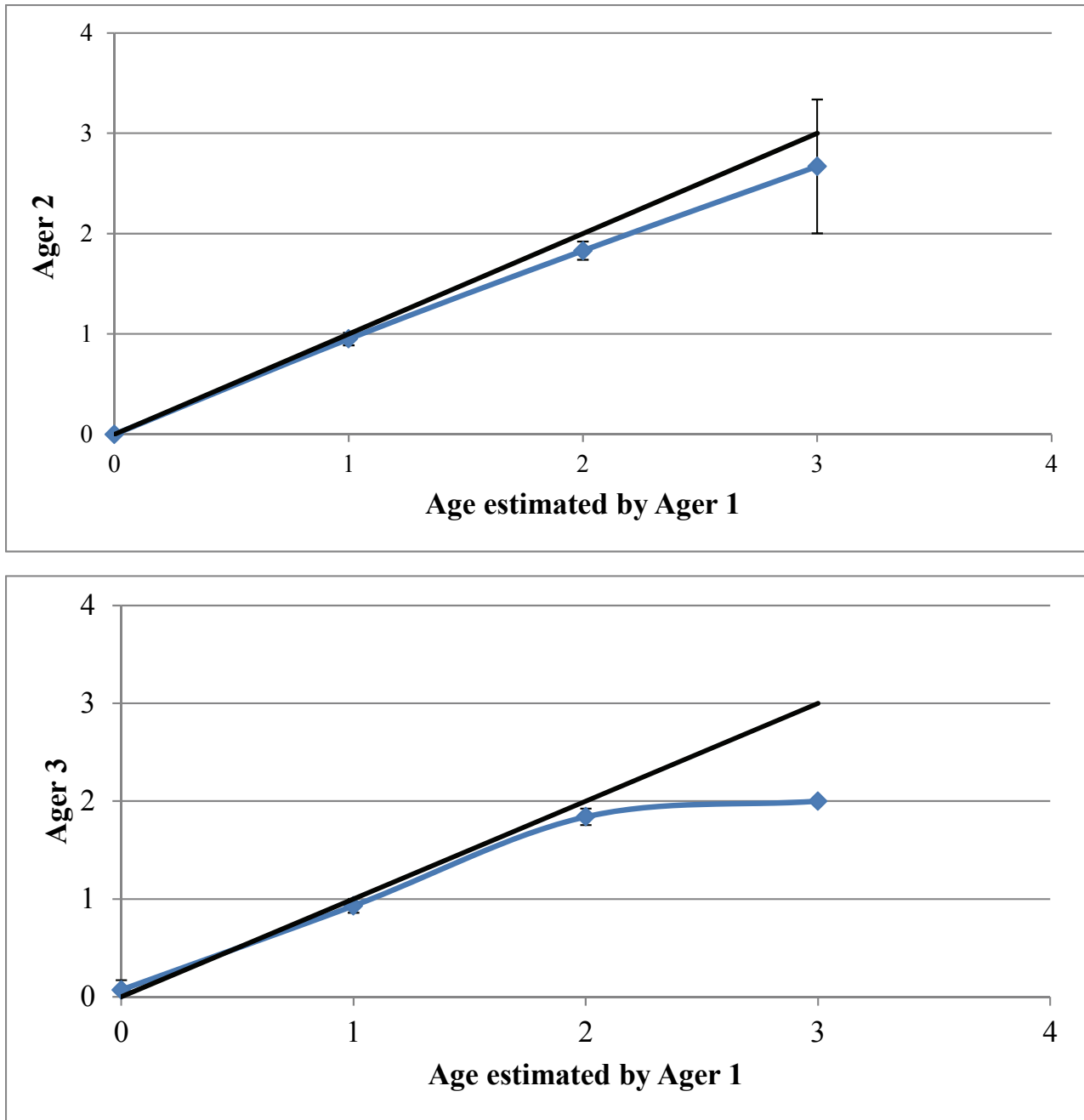
Figure 3. Age bias plots for each of the two pairwise age comparisons for fish collected in 2005 from landings of the CA fishery (Table 3, Data set # 1). Each error bar represents 2*SE around the mean age assigned by one ager for all fish assigned a given age by Ager 1. The 1:1 equivalence (solid black line) is also shown on each plot.
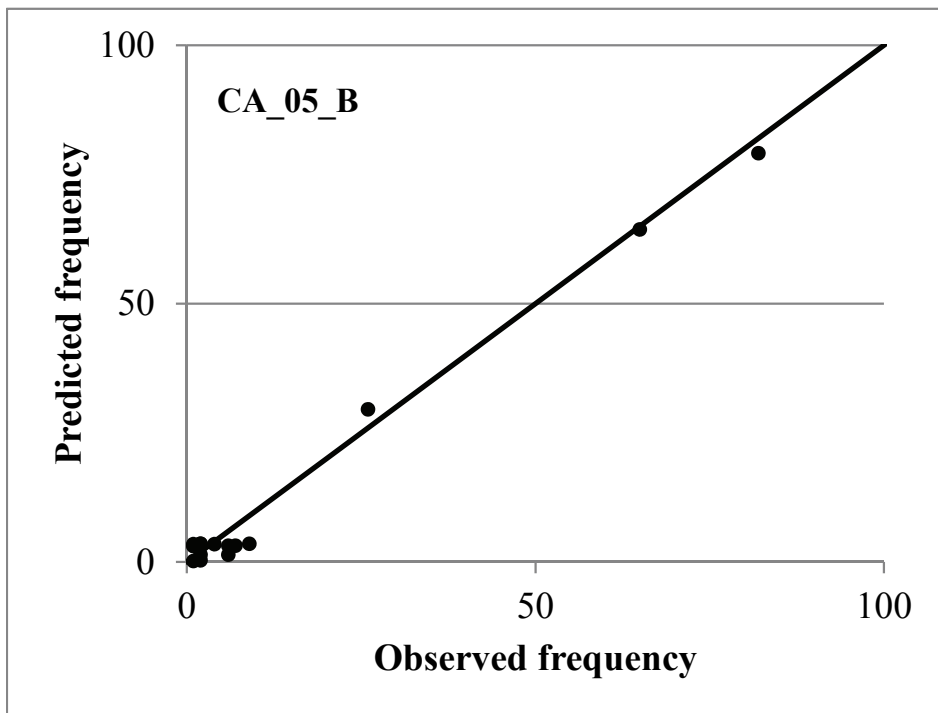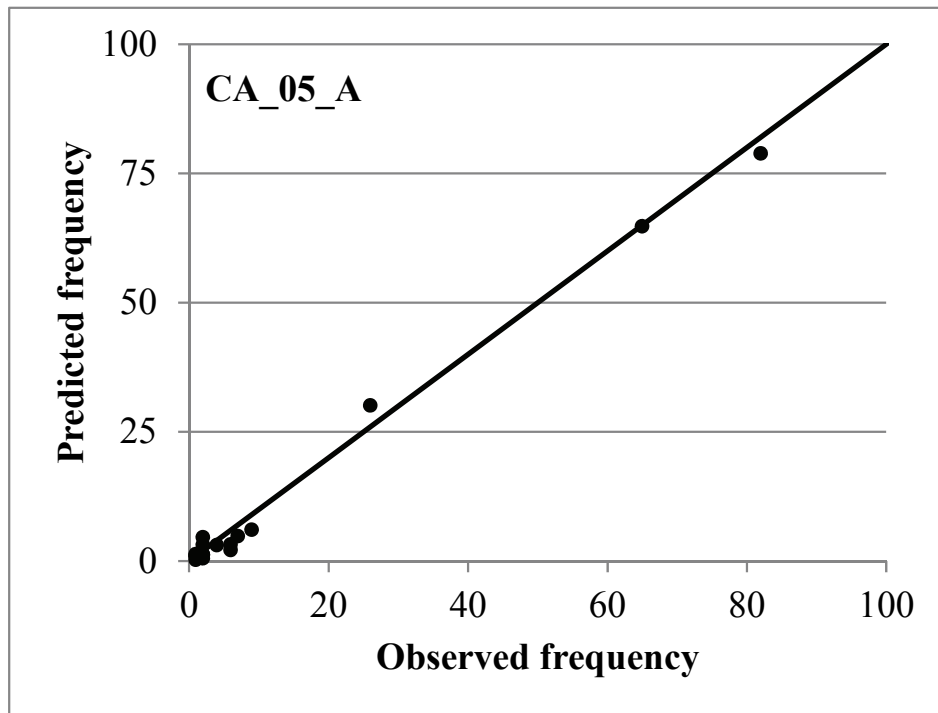
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Figure 4. Predicted and observed frequency for the 2005 CA fishery age-reading data set. Predicted frequency was computed from two different Agemat models, CA_05_A and CA_05_B (see Table 8 for model assumptions). The 1:1 equivalence (solid black line) is also shown on each plot.
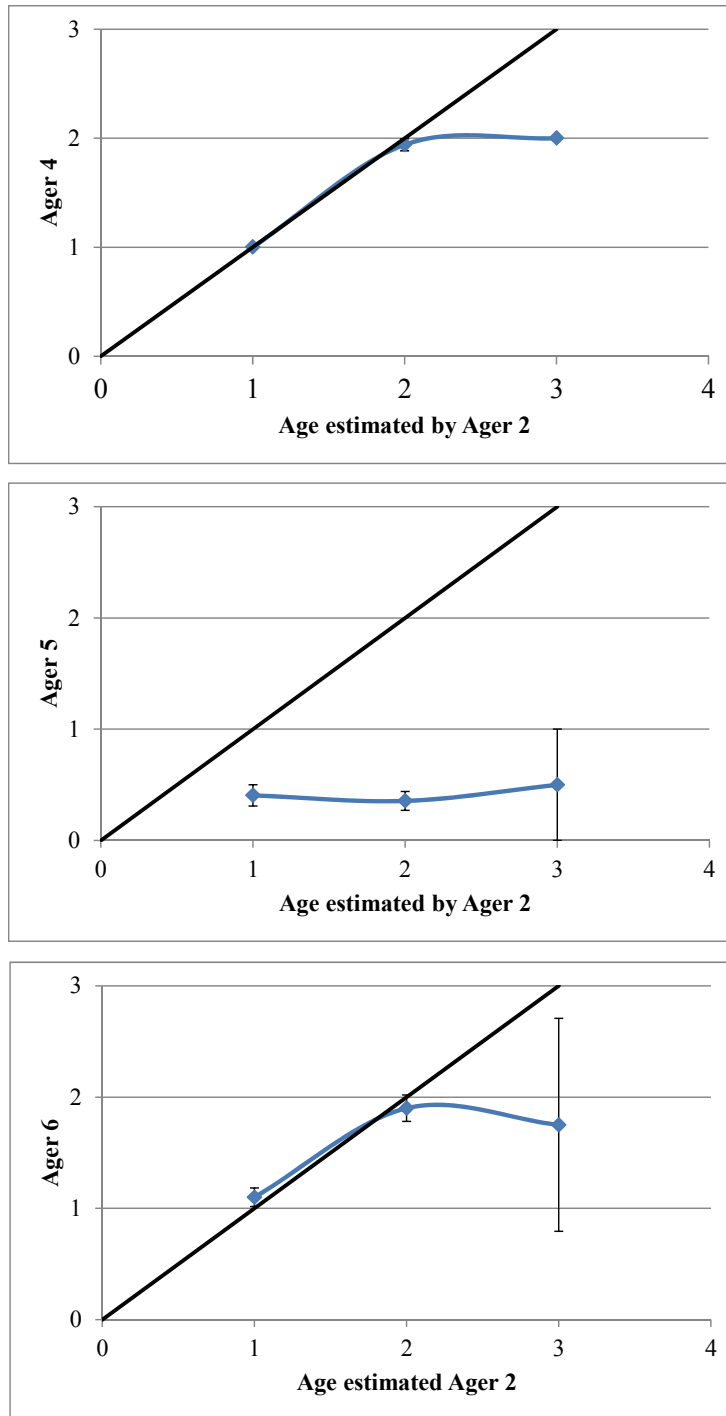
Figure 5. Age bias plots for each of the three pairwise age comparisons for fish collected in 2007 from landings of the CA fishery (Table 3, Data set # 2). Each error bar represents 2*SE around the mean age assigned by one ager for all fish assigned a given age by Ager 2. The 1:1 equivalence (solid black line) is also shown on each plot.
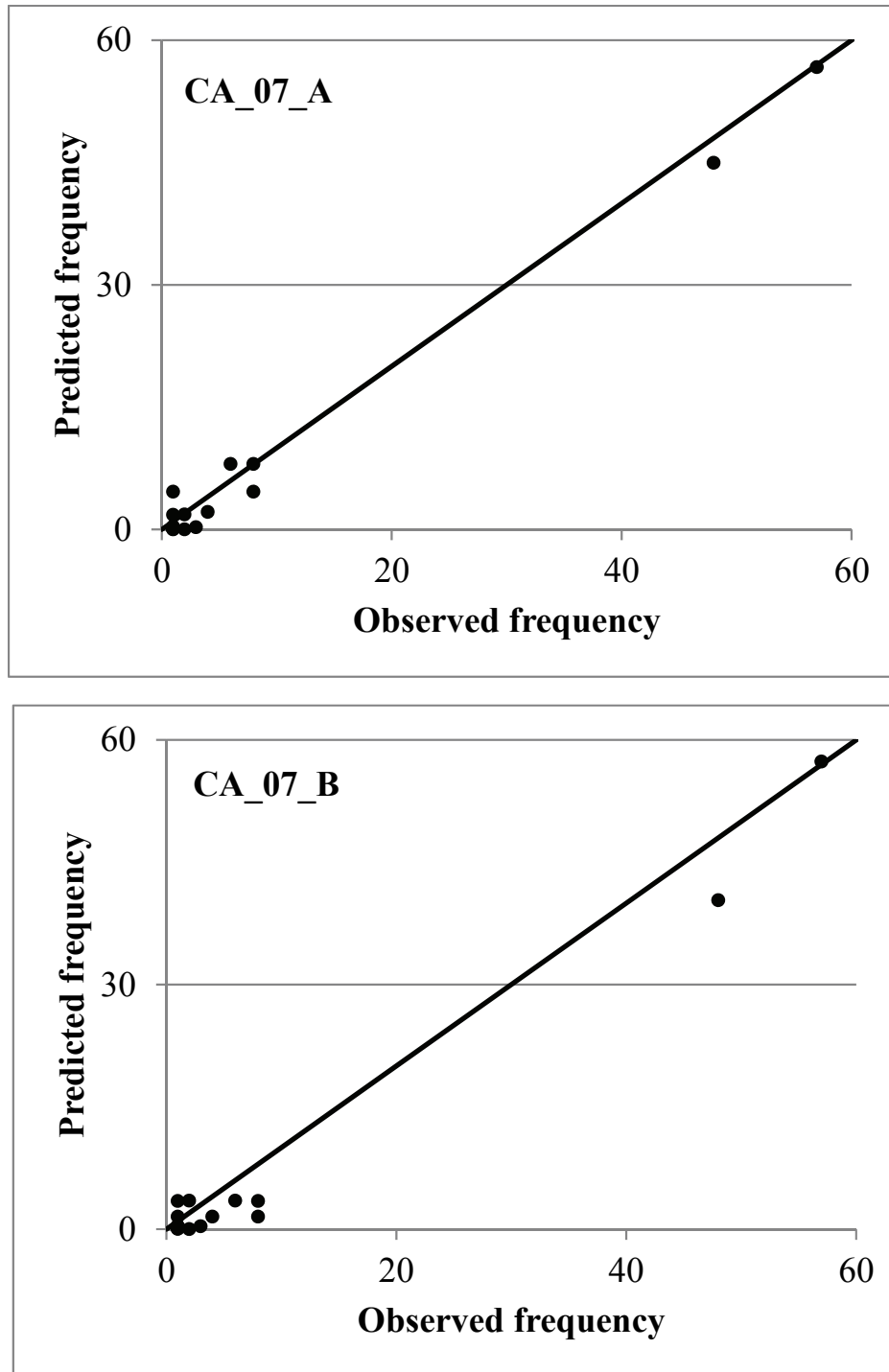
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Figure 6. Predicted and observed frequency for the 2007 CA fishery age-reading data set. Predicted frequency was computed from two different Agemat models, CA_07_A and CA_07_B (see Table 8 for model assumptions). The 1:1 equivalence (solid black line) is also shown on each plot.

Figure 7. Age bias plots for each of the four pairwise age comparisons for fish collected in 2008 and 2009 from landings of the CA fishery (Table 3, Data set # 3). Each error bar represents 2*SE around the mean age assigned by one ager for all fish assigned a given age by Ager 2. The 1:1 equivalence (solid black line) is also shown on each plot.
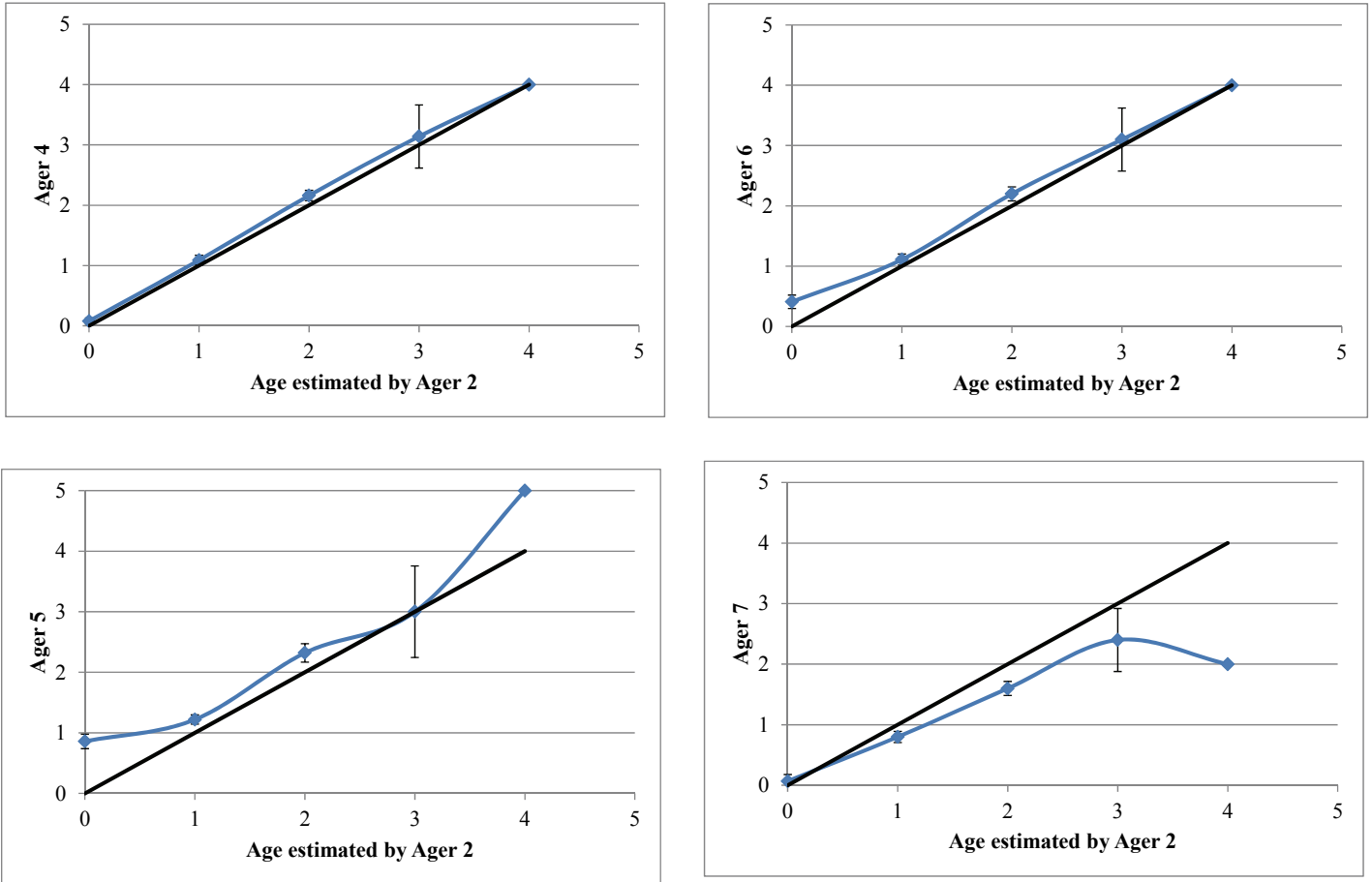
Figure 8. Age bias plots for each of the three pairwise age comparisons for fish collected in 2008 and 2009 from landings of the CA fishery (Table 3, Data set # 4). Each error bar represents 2*SE around the mean age assigned by one ager for all fish assigned a given age by Ager 2. The 1:1 equivalence (solid black line) is also shown on each plot.

Figure 9. Predicted and observed frequency for the 2008-2009 CA fishery age-reading data sets (#3 and 4). Predicted frequency was computed from two different Agemat models, CA_0809_A and CA_0809_B (see Table 8 for model assumptions). We refer the reader to Table 3 for a summary of data sets #3 and 4. The 1:1 equivalence (solid black line) is also shown on each plot.
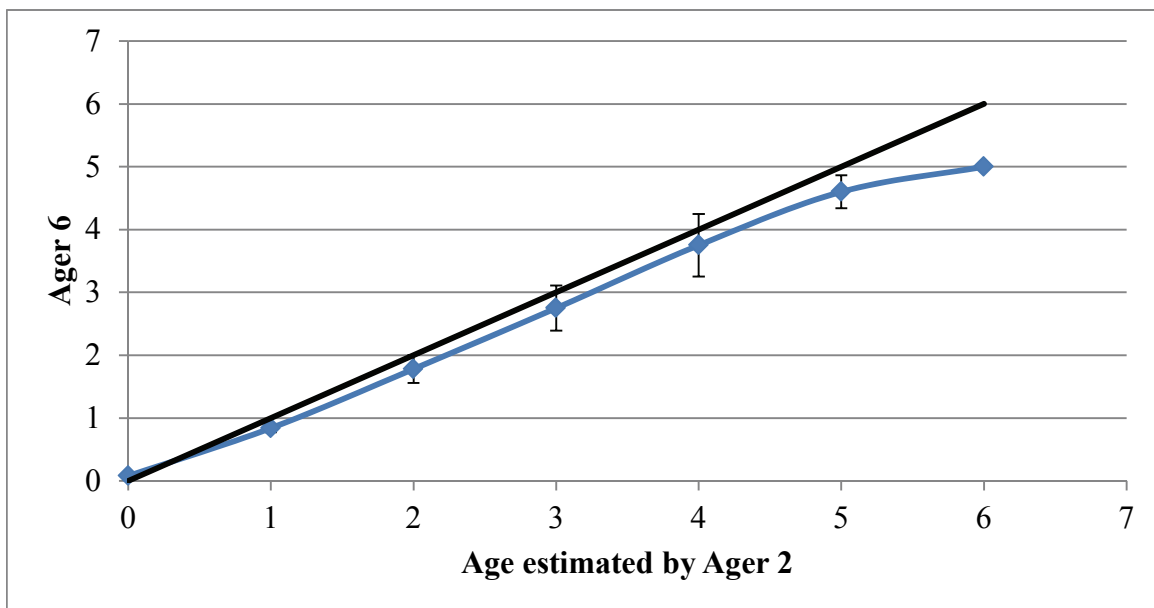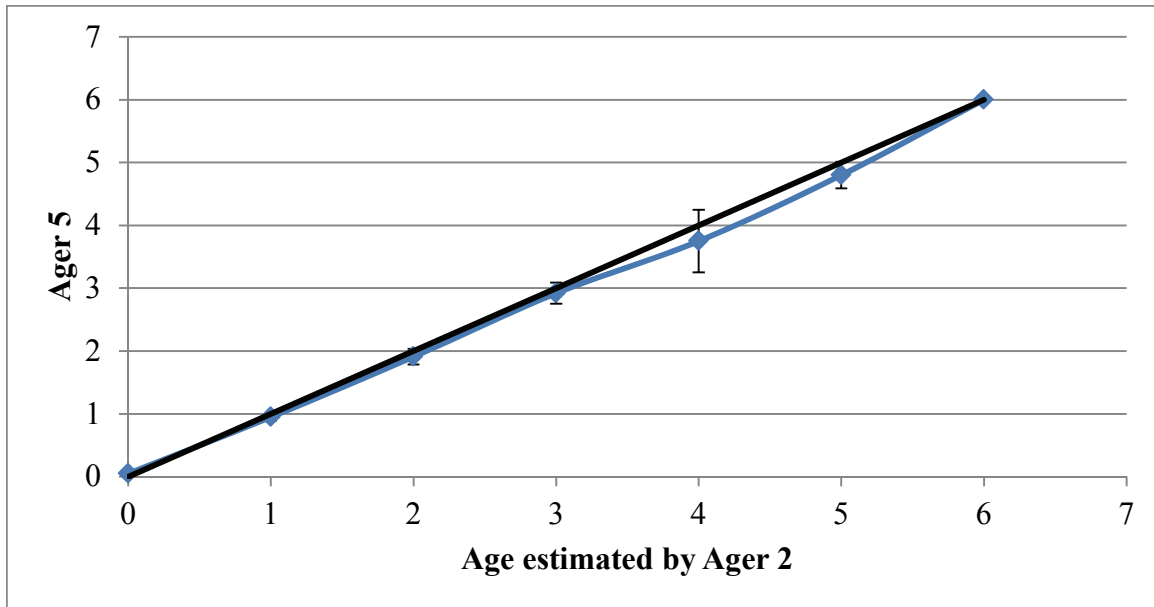
Figure 10.   Age bias plots for each of the two pairwise age comparisons for fish collected in 2010 and 2011 from landings of the CA fishery. Each error bar represents 2*SE around the mean age assigned by on ager for all fish assigned a given age by Ager 2. The 1:1 equivalence (solid black line) is also shown on each plot.
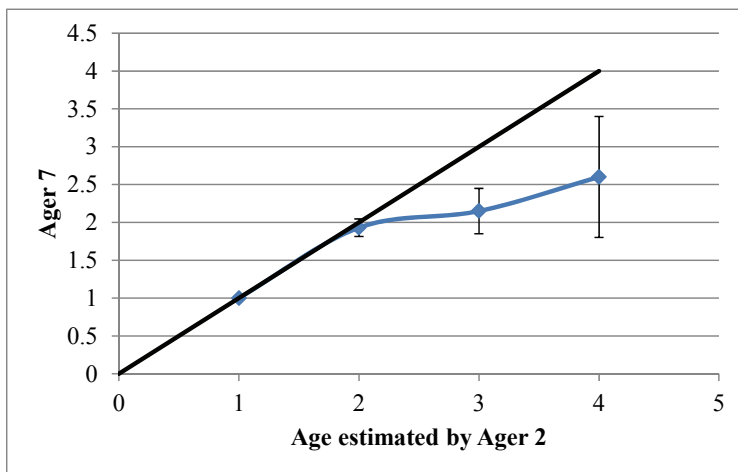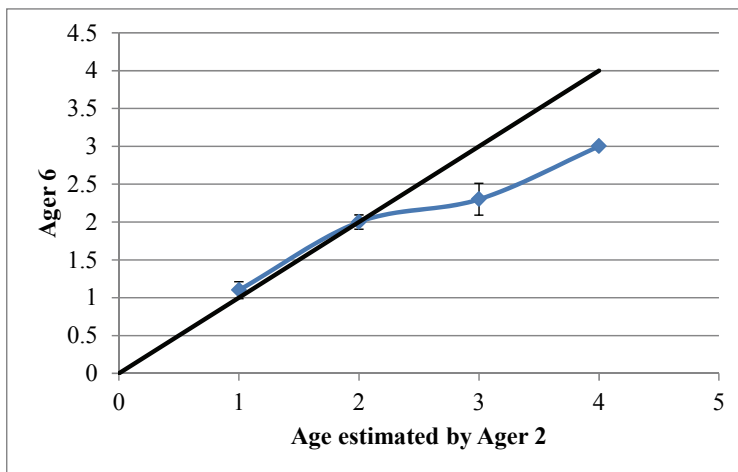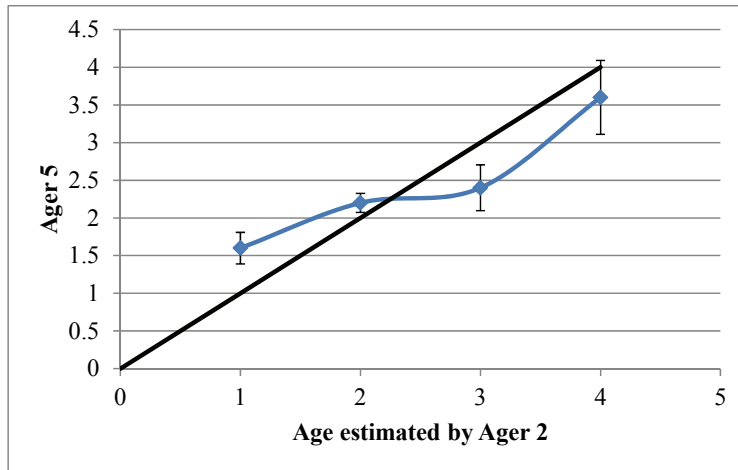
Figure 11. Predicted and observed frequency for the 2010-2011 CA fishery age-reading data set. Predicted frequency was computed from two different Agemat models, CA_1011_A andCA_1011_B (see Table 8 for model assumptions). The 1:1 equivalence (solid black line) is also shown on each plot.
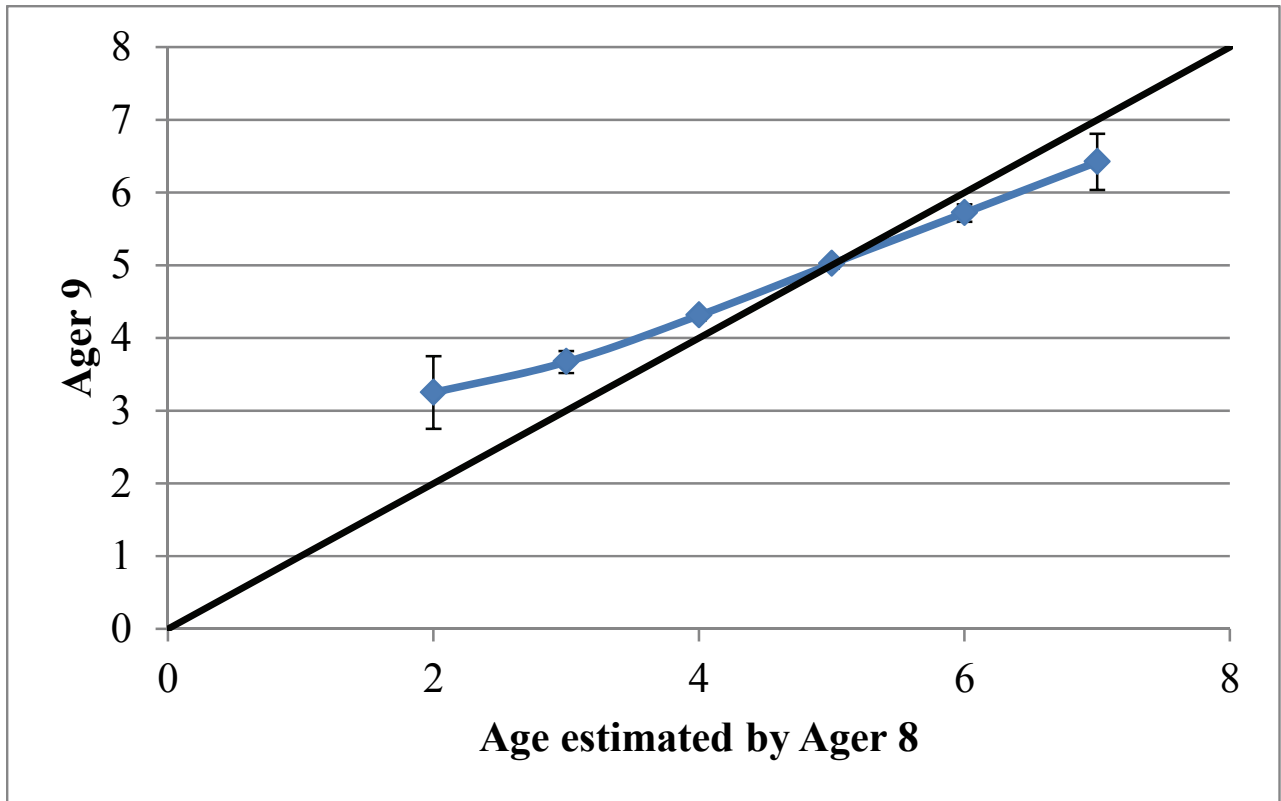
Figure 12. Age bias plot for the pairwise age comparison presented in Table 4 for the PNW
fishery. Each error bar represents the 2*SE around the mean age assigned by ager 9
for all fish assigned a given age by ager 8. The 1:1 equivalence (solid black line) is
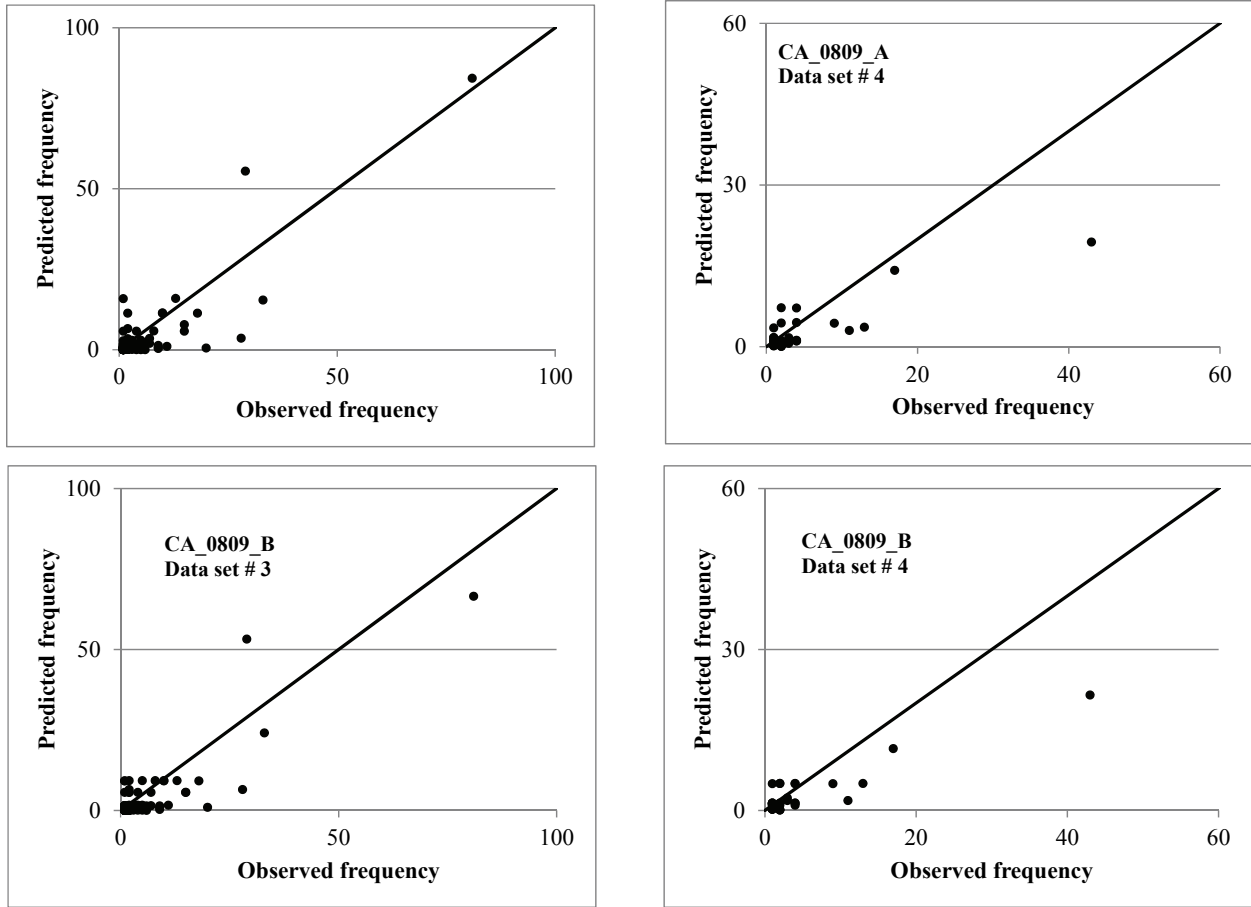also shown on the plot.
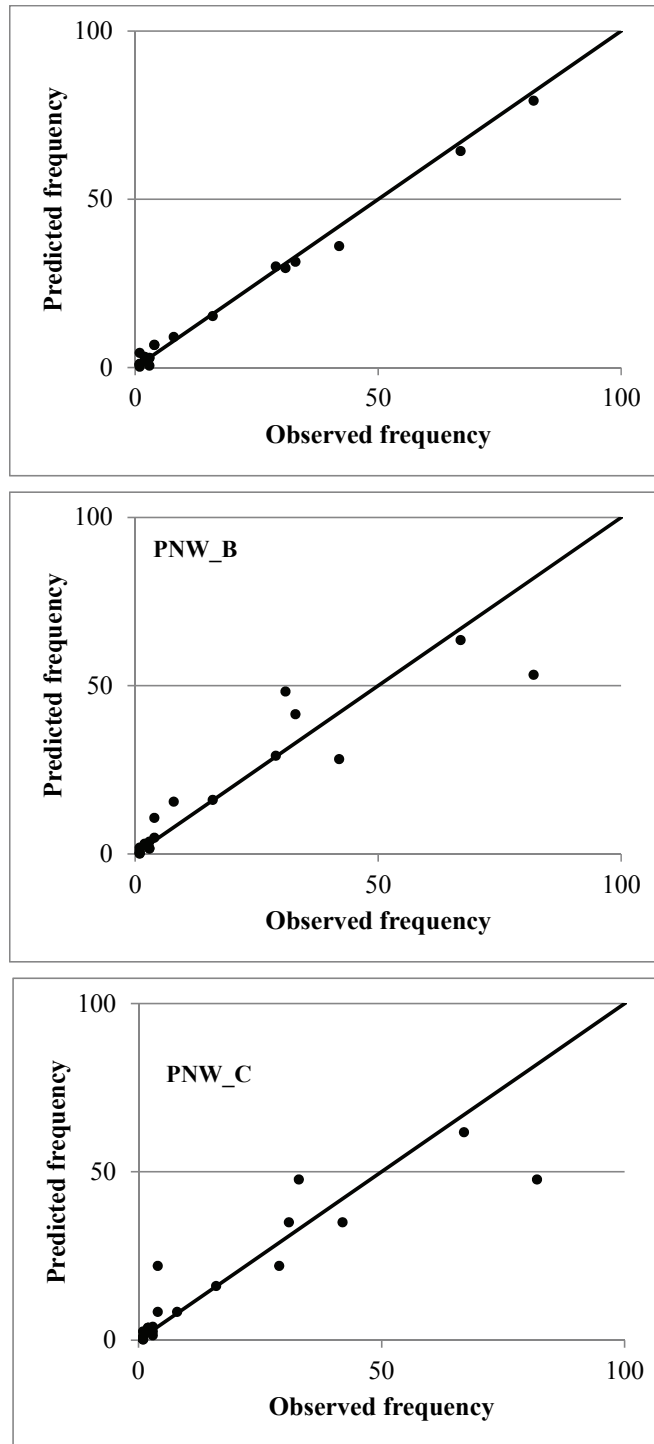
Figure 13. Predicted and observed frequency for the PNW fishery age-reading data set. Predicted frequency was computed from three different Agemat models, PNW_A, PNW_B and PNW_C (see Table 8 for model assumptions). The 1:1 equivalence (solid black line) is also shown on each plot.
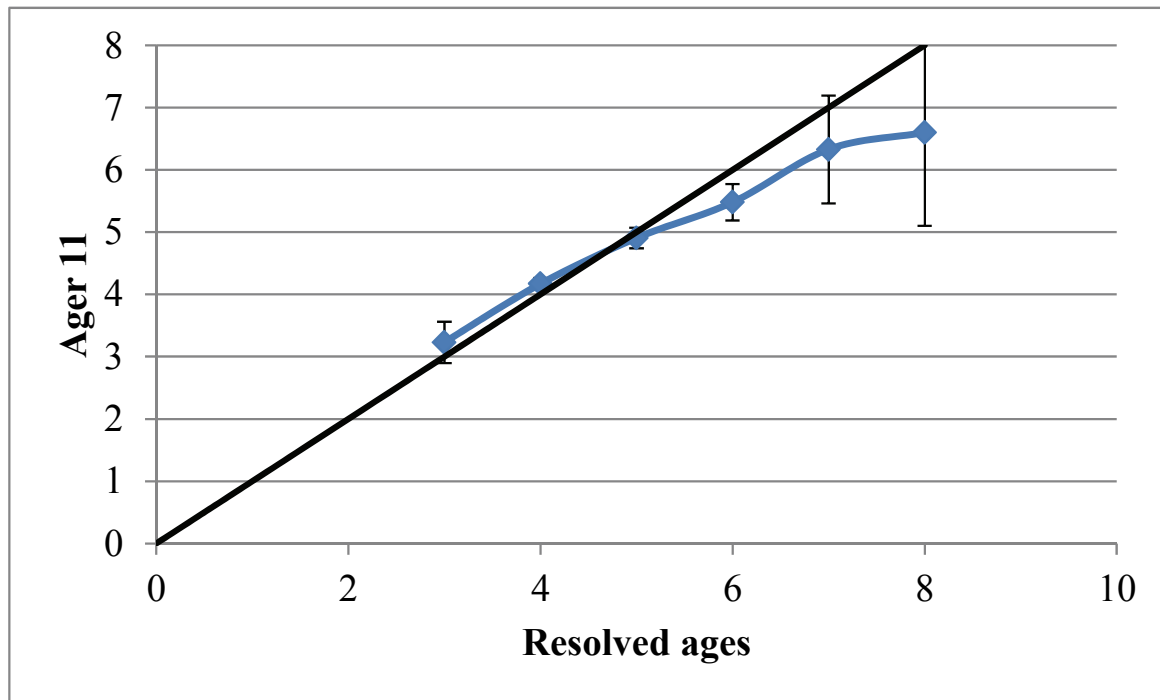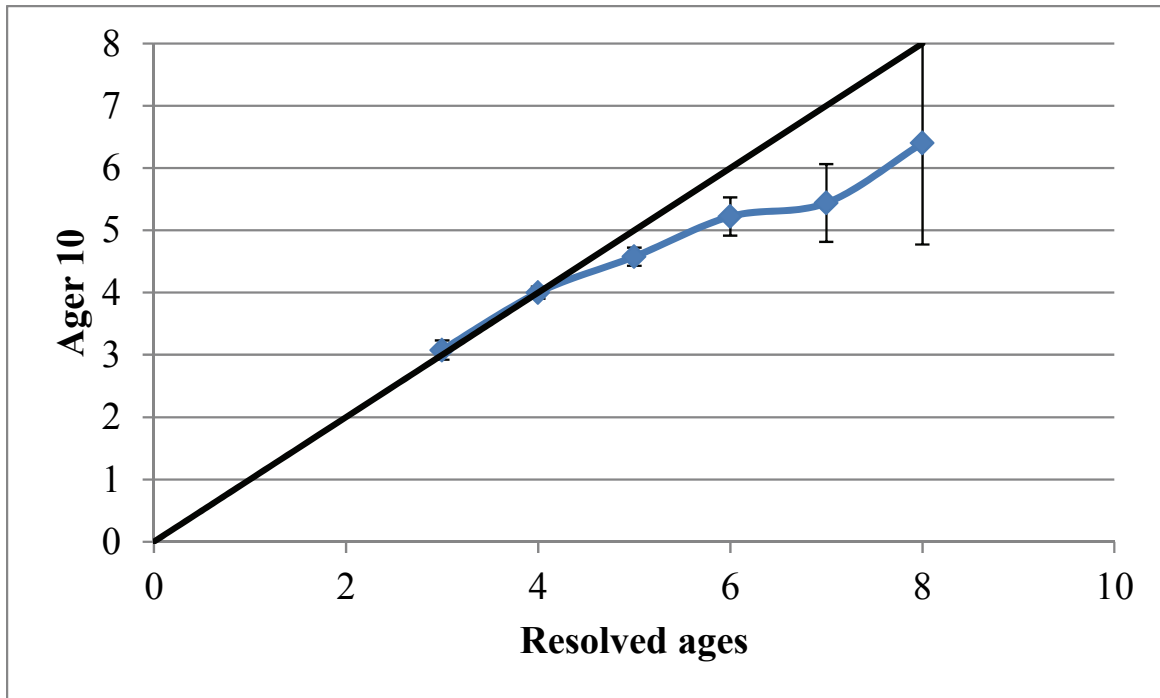
Figure 14. Age bias plot for the two pairwise age comparisons presented in Table 5 for the BC fishery. Each error bar represents the 2*SE around the mean age assigned by one ager for all fish assigned a given resolved age. The 1:1 equivalence (solid line) is also shown on the plot.
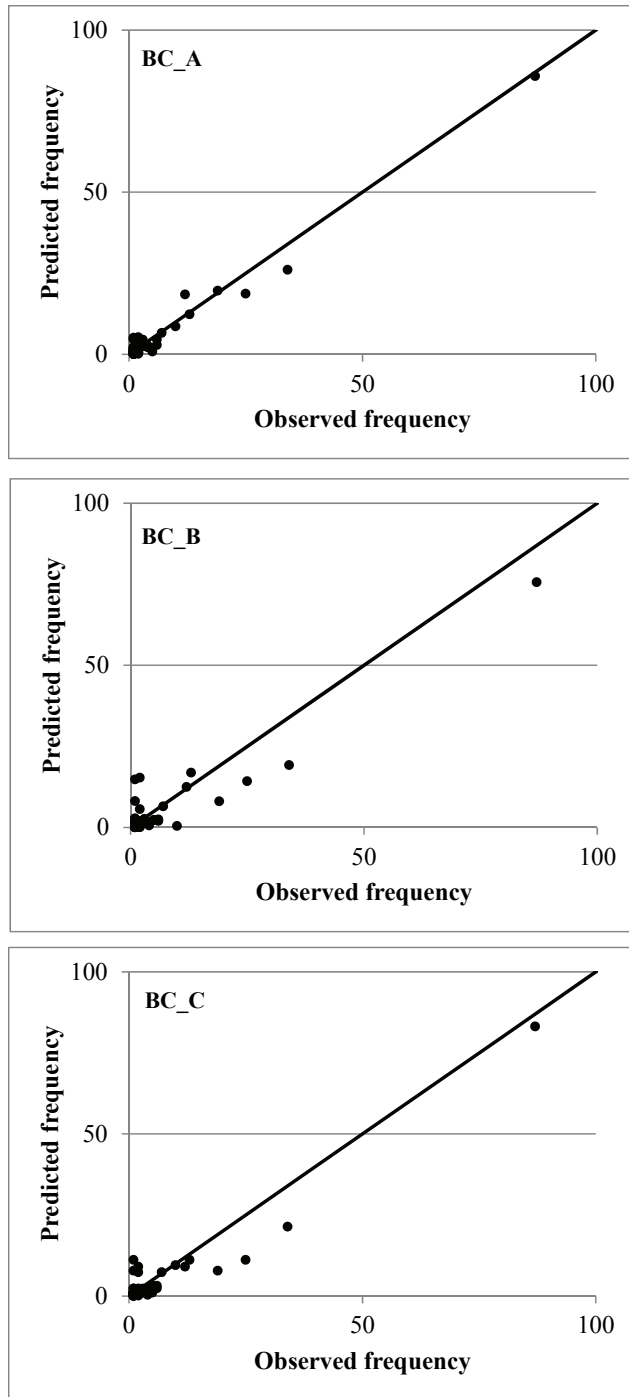
Figure 15. Predicted and observed frequency for the BC fishery age-reading data set. Predicted frequency was computed from three different Agemat models, BC_A, BC_B and BC_C (see Table 8 for model assumptions). The 1:1 equivalence (solid black line) is also shown on each plot.

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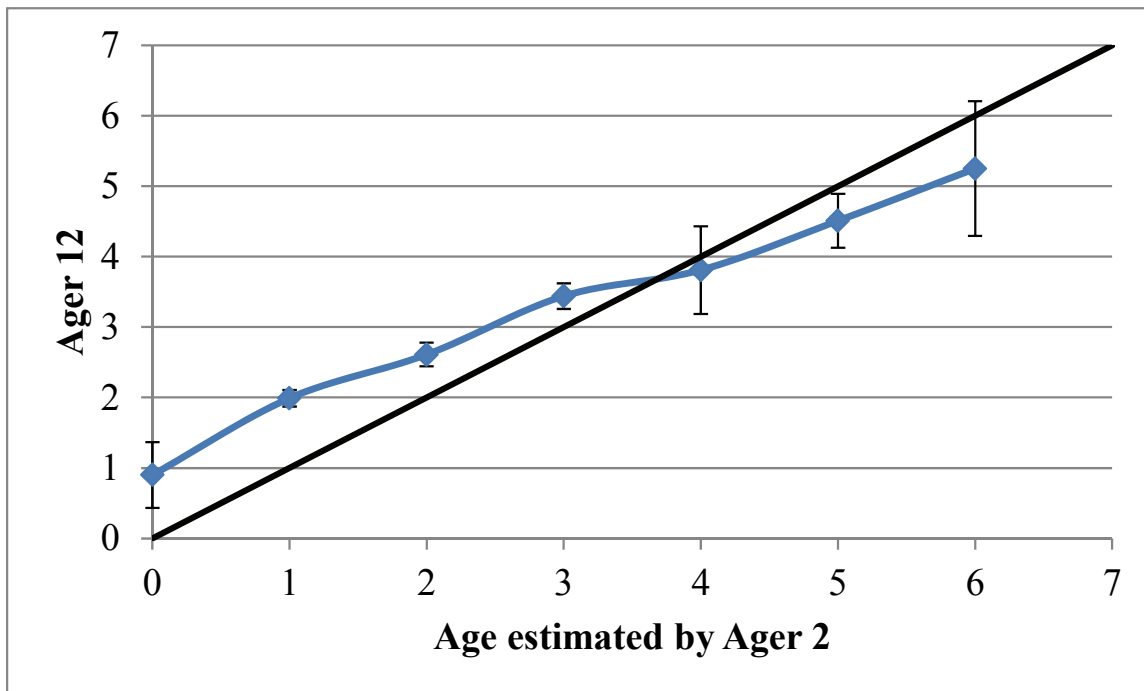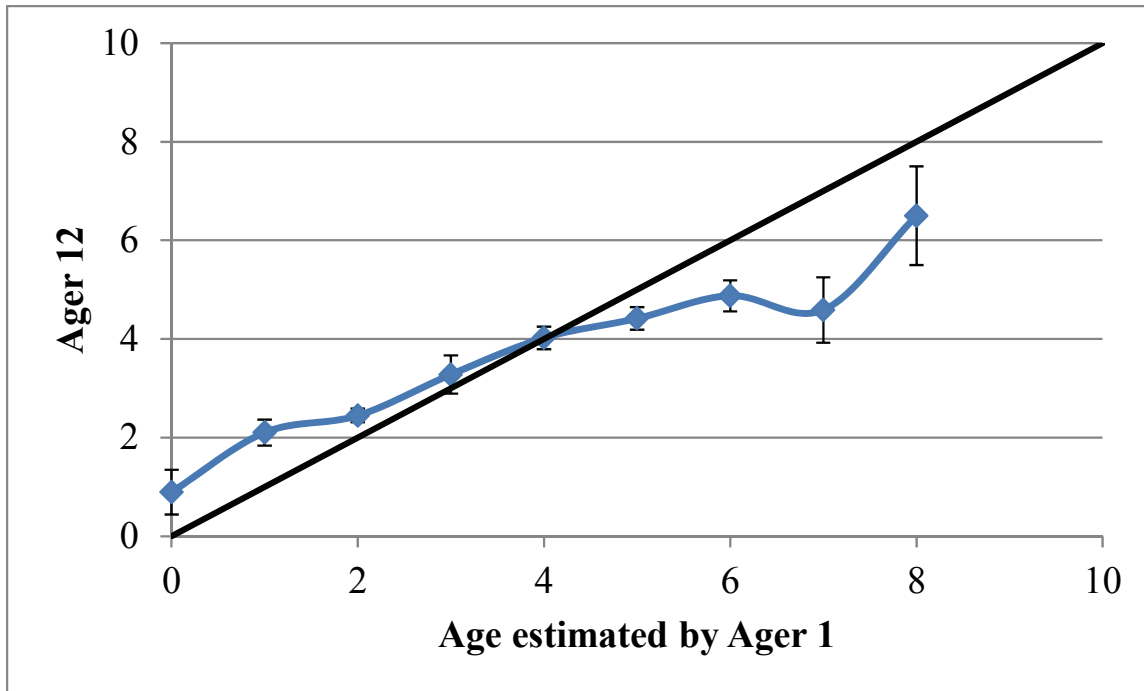
Figure 16. Age bias plot for the two pairwise age comparisons presented in Table 6 for the DEPM survey. Each error bar represents the 2*SE around the mean age assigned by ager 12 for all fish assigned a given by ager 1 or 2.The 1:1 equivalence (solid line) is also shown on the plot.
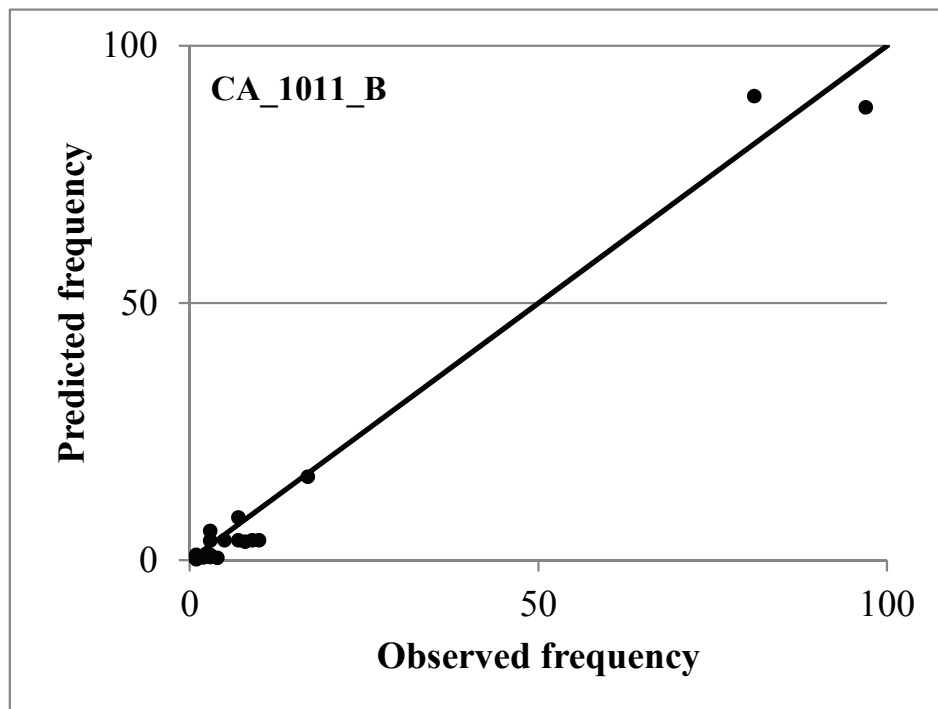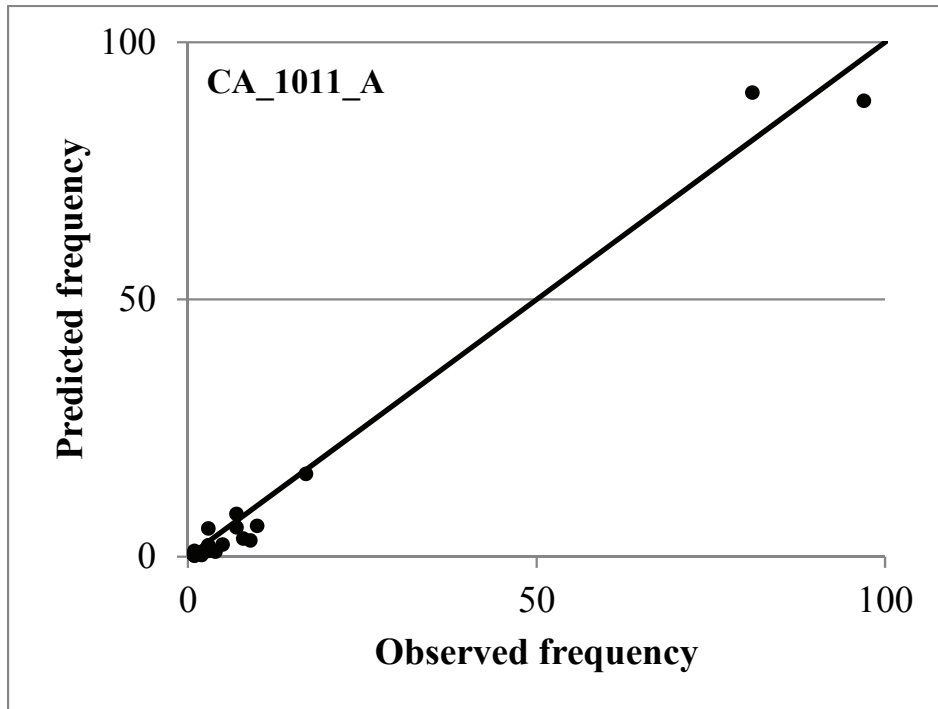
Figure 17. Predicted and observed frequency for the DEPM survey age-reading data sets (# 1 and 2).Predicted frequency was computed from three different Agemat models, DEPM _A, DEPM _B, and DEPM _C (see Table 8 for model assumptions). We refer the readers to Table 6 for a summary of DEPM data set # 1 and 2. The 1:1 equivalence (solid black line) is also shown on each plot.

APPENDIX 3

## SWFSC Juvenile Rockfish Survey (1983-11)
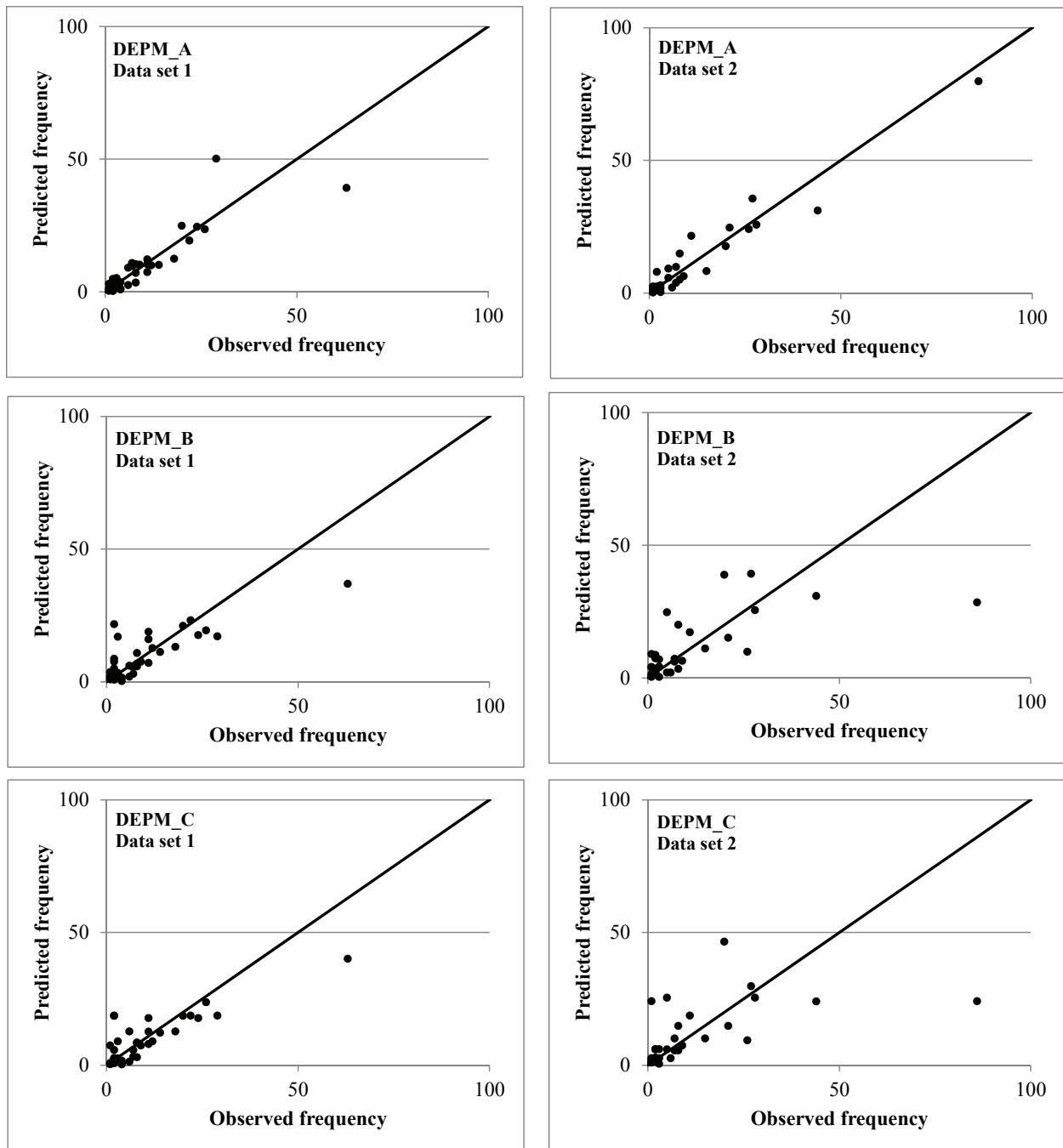
P. R. Crone
September 2011

<u>Overview</u>

Since 1983, NOAA Fisheries (Southwest Fisheries Science Center, Santa Cruz Laboratory) has conducted annual midwater trawl surveys designed to estimate the distribution and abundance of pelagic juvenile rockfishes (*Sebastes* spp.) along the central California coast (Ralston and Howard 1995; Sakuma et al. 2006; Field et al. 2010). Research cruises associated with the pelagic juvenile rockfish survey (JRS) were conducted onboard the *RV* David Starr Jordan and other cooperating vessels during May to June when the approximately 100-day old juveniles are most susceptible to capture by midwater trawling gear. The primary goal of the JRS is to collect density/abundance and biological data applicable to rockfish species inhabiting California waters. The JRS typically encounters other species in addition to rockfishes, including coastal pelagic species (CPS) such as Pacific sardine. Consequently, an index of relative abundance for sardines was developed from these survey data in efforts to evaluate the potential utility of these survey data to the ongoing stock assessment for this species.

Sampling stations for the JRS are at fixed locations, with typically five to six stations along a transect line that traverses the continental shelf break (although some stations are clustered); most stations are occupied two to three times per research cruise. From 1983 through 2003, a cruise included roughly 40 stations in central California, i.e., defined as the JRS 'core' area that spanned from southern Monterey Bay to just north of Point Reyes, i.e., about 2 degrees of latitude). Beginning in 2004, the survey grid was expanded to include a series of transects from the U.S./Mexico border to just south of Cape Mendocino (see Sakuma et al. 2006 for details). Comparable surveys have been conducted by the NWFSC and Pacific Whiting Conservation Cooperative (PWCC) since 2001. The cruises employ a modified Cobb midwater trawl, with a 26-m headrope and 9.5-mm codend liner. The research cruises employ a modified 26x26 m Cobb midwater trawl, with a cod-end liner of 1.27-cm stretched mesh. At each station, a 15-min nighttime trawl (tow) sample was taken at a standard depth (30 m where possible, 10 m at shallow stations), and catches were identified, enumerated, and (for most species) measured (standard length; Figure 1). Ageing structures are typically only collected for juvenile rockfish, although ad-hoc collections for other species have been conducted at times. Since 2004, the number of tows in the core area has averaged approximately 75, with as many typically conducted in the expanded survey area. On average, approximately 25% of the tows have one or more sardines, although this percentage varies substantially from year to year.

From 1983 through 2008, cruises took place on the *RV* David Starr, but since 2009, a series of cooperating vessels has been utilized. Specifically, in 2011, the cruise was conducted by the *FV* Excalibur Jordan (the ship used for the NWFSC/PWCC surveys) and had limited temporal and spatial coverage relative to the post-2003 period. Although the JRS has sampled a greater spatial area from 2004 onward, the time series of abundance presented here for Pacific sardine is based on the core survey and begins in 1990 (start of consistent sampling for non-rockfish species of

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interest), given this spatial/temporal combination represented the most informative index of relative abundance for this species.

It is important to note that at this time, the index of relative abundance for Pacific sardine estimated from data collected in the JRS is intended as a preliminary time series, requiring further evaluation before adopting as a final index to be included in the ongoing assessment for this species, given: (1) the survey (core area) design represents a limited spatial area in relation to this species' overall biology and movement dynamics; and (2) the survey was not designed to accurately sample coastal pelagic species in general, which exhibit highly variable depth distributions and overall availabilities to a survey/fishery due largely to prevailing oceanographic conditions (e.g., no sardines were observed in 2010 or 2011). Specifically, the prevailing interpretation of the survey data is that Pacific sardine (and other CPS) are typically more abundant in the core area during oceanographic regimes of low productivity and/or low upwelling (J. Field, personal communication, SWFSC (Santa Cruz Laboratory), September 2011).

Index of relative abundance

A delta general linear model (GLM) was used to develop a relative index of abundance for Pacific sardine, based on a binomial model (using a logit link) for tow-specific presence/absence information,

$$\log\left(\frac{\pi_i}{1-\pi_i}\right) = \mathbf{x}_i^{T}\beta, \tag{1}$$

where π_i is the predicted value of the binomial probability for ith observation, $\mathbf{x}_i$ is the vector specifying the explanatory variables for the ith value of the response variable, and β is the vector of the regression coefficients for the binomial model. The mean (μ) of positive tows was modeled with a normal linear model for the log-transformed data (y_i, in number of fish),

$$\mu_i = \log(y_i) - \varepsilon_i = \mathbf{x}_\mathbf{j}^{T}\gamma, where$$
$$\varepsilon \approx N(0,\sigma^2) \tag{2}$$

and γ is the vector of coefficients for the positive models. A gamma distribution was assumed for the positive observations in this standardization approach, which varied little from a model that used a lognormal distribution. The product of the year effects of the two models ($\pi\mu$) represented the final index of relative abundance for sardine (Figure 2), and a jackknife routine was utilized to provide an estimate of error (the average estimated CV for the data series in which year effects could be estimated was 0.80, ranging from 0.41 to 1.28). This delta-GLM approach for treating/standardizing the data is highly consistent with the approaches typically taken in stock assessments for developing fishery-independent indices of abundance for marine species (Dick 2004, Maunder and Punt 2004). Finally, a nominal index of relative abundance, based on the simple mean of log-transformed catch rates ($y_i+ 1$) resulted in a similar estimated time series of abundance as the delta-GLM above.

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Dick, E. J. 2004. Beyond 'lognormal versus gamma': discrimination among error distributions for generalized linear models. Fisheries Research 70:351–366.

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Ralston, S., and D. F. Howard. 1995. On the development of year-class strength and cohort variability in two northern California rockfishes. Fishery Bulletin 93:710-720.

Sakuma, K. M., S. Ralston, and V. G. Wespestad. 2006. Interannual and spatial variation in the distribution of young-of-the-year rockfish (*Sebastes* spp.): expanding and coordinating a survey sampling frame. CalCOFI Report 47:127-139.
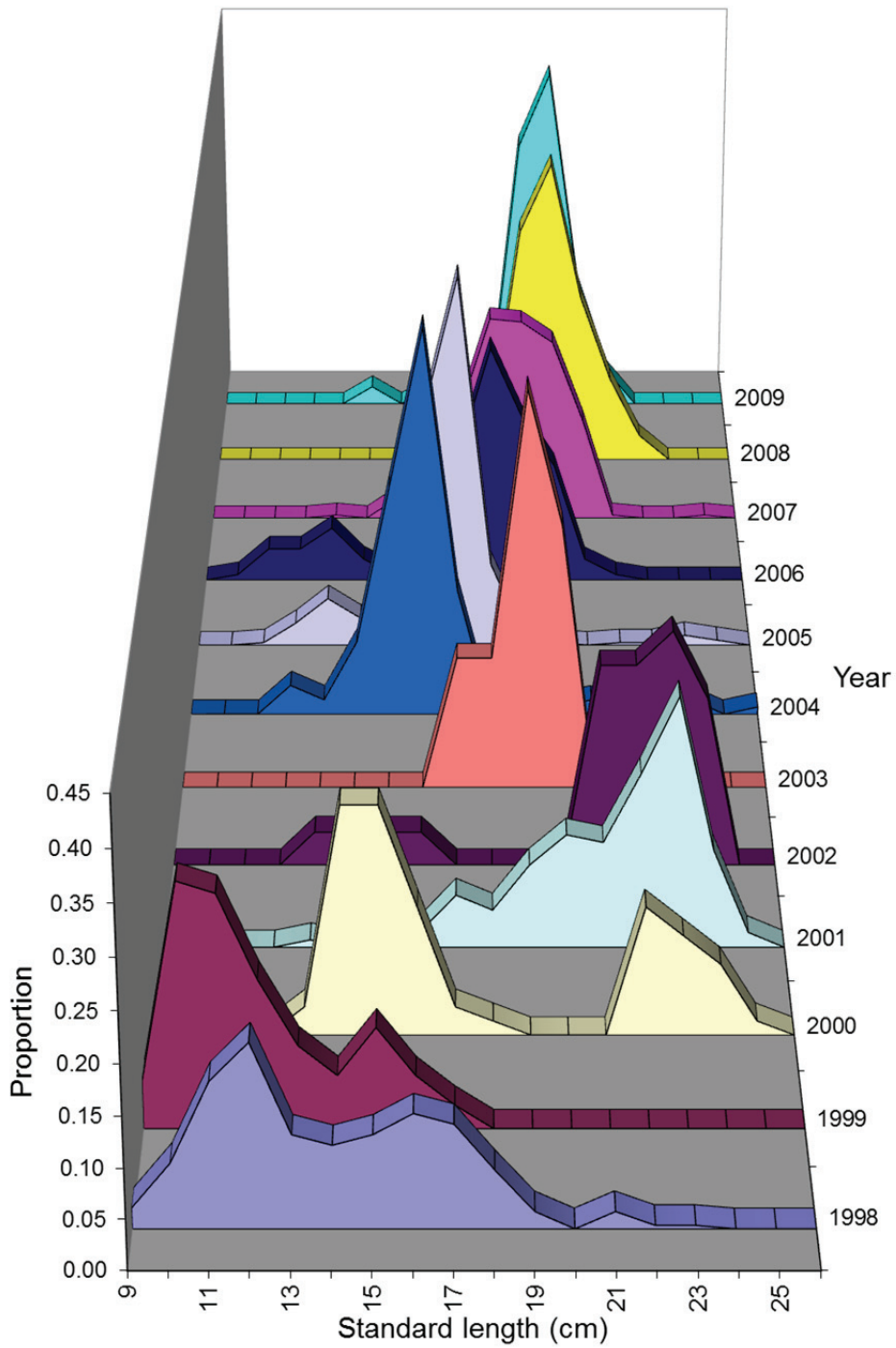
Figure 1. Pacific sardine length distributions (raw sample data, i.e. not catch-weighted) from the
   Juvenile Rockfish Survey, 1998-2009.
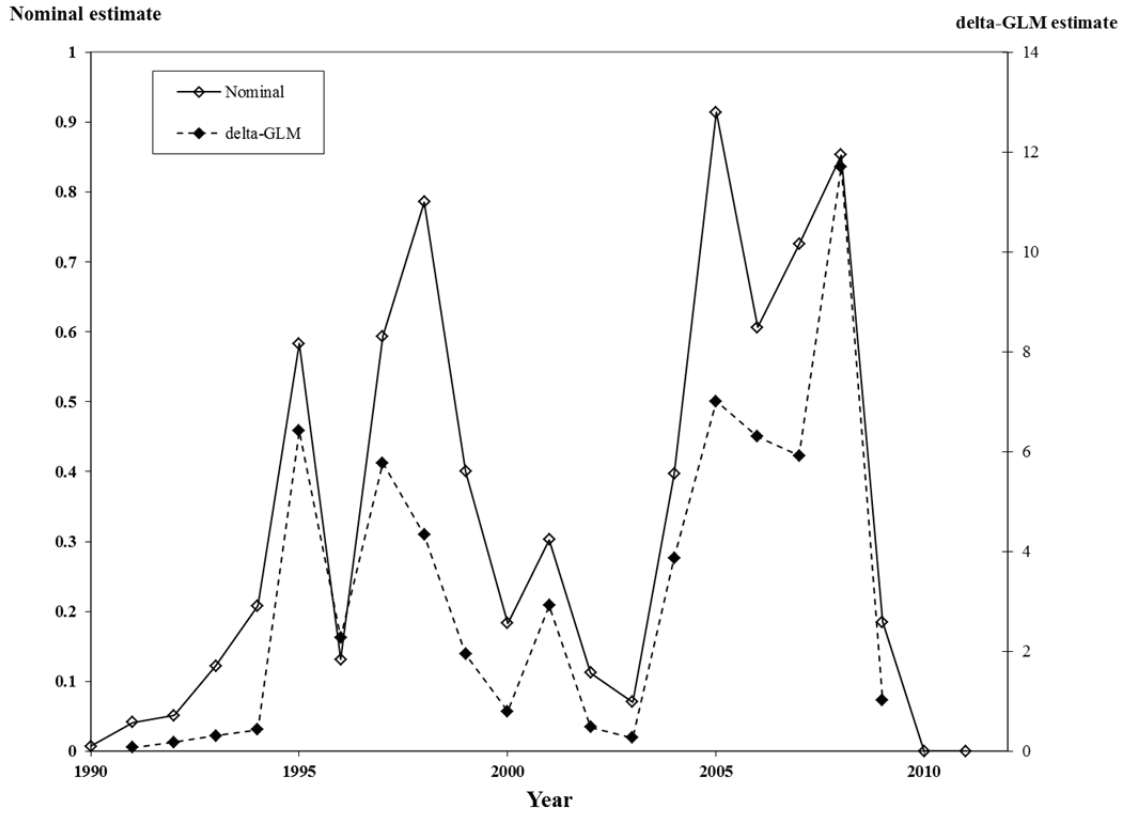
Figure 2. Pacific sardine relative abundance (nominal and delta-GLM estimates) from the Juvenile Rockfish Survey, 1990-2009.

APPENDIX 4

RE-EVALUATION OF F_{MSY} FOR PACIFIC SARDINE
IN THE ABSENCE OF AN ENVIRONMENTAL COVARIATE

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September 15, 2011

INTRODUCTION

The harvest control rule (HCR) implemented for U.S. management of Pacific sardine is unique in that it includes an environmentally-dependent harvest FRACTION based on the three-year running average of sea surface temperature (SST) at Scripps Institution of Oceanography (SIO) pier (PFMC 1998). This feature was based on the theory that: (1) sardine reproductive success was positively correlated with prevailing temperature in the California Current System (CCS); (2) temperature in the CCS could be indexed at SIO pier; and (3) a relationship between SST and F_{MSY} could be linked to surplus production and an appropriate removal rate (Jacobson & MacCall 1995, PFMC 1998). Under the current HCR, harvest FRACTION is bracketed between F_{MSY} values of 5% and 15%. The SST at SIO has been warmer than average for the past decade, so the FRACTION has remained at 15% since implementation of this rule in 2000. More recently, the temperature-F_{MSY} relationship was used to provide a potential range of overfishing limits (OFL) for the 2011 sardine management measures and during scoping for Amendment 13 to the CPS-FMP (PFMC 2010). For that analysis, F_{MSY} was limited to the lower and upper quartiles of SIO-SST observed since 1916, with F_{MSY} ranging 2.00% to 19.85%).

A recent study by McClatchie et al. (2010) re-assessed the relationship between SST and sardine recruitment success. Spawning biomass (S), recruitment (R), and sea-surface temperature (T) data used in Jacobson and MacCall (1995) and CPS Amendment 8 (PFMC 1998) were updated with more recent information, which resulted in a weaker relationship between SST and sardine productivity that was no longer statistically significant (McClatchie et al. 2010). The analysis also indicated that SST at SIO and SST off of southern-central California had diverged and therefore, SIO-SST was no longer representative of low-frequency SST variability in the sardine's core spawning habitat. McClatchie et al. (2010) did not infer that there was no relationship between sardine productivity and the environment, but their analysis does bring into question the current management approach (i.e. Harvest Control Rule 'FRACTION' based on SIO-SST) given the re-evaluation with updated time series. Finally, although research regarding sardine ecology is ongoing, a new environmental index has yet to be developed.

In light of McClatchie et al's. (2010) findings, there exists an interim need to estimate a static F_{MSY} value for sardine (i.e., one that is independent of environmental data) for the purpose of specifying OFL and ABC in the annual management process. Amendment 8 to the CPS-FMP analyzed a broad range of HCR options, including an estimate of 'Stochastic F_{MSY},' (where CUTOFF=0 and MAXCAT=infinite; PFMC 1998). Unfortunately, all of the simulations used to analyze HCRs in Amendment 8 also included the SIO temperature term in spawner-recruit (S-R) calculations, regardless of whether the harvest FRACTION was fixed or temperature-dependent:

[1] $\ln(R/S) = \alpha + \beta_1 T + \beta_2 S + \epsilon$

where R = recruits, S = spawning biomass, and T = SST at SIO (Jacobson and MacCall 1995). Therefore, in strict terms, 'Stochastic F_{MSY}' estimates from Amendment 8 should be considered outdated and potentially misleading. Moreover, S-R parameters from Jacobson and MacCall (1995) and PFMC (1998) were based on historic population estimates (Murphy 1966; MacCall 1979) and included only five years of data from the early stages of the population recovery (Barnes et al. 1992)and thus, were outdated by 23 years. Any new estimate of sardine F_{MSY} should include data from all available years, including the most recent stock assessment (Hill et

al. 2010). In the present work, biomass and recruitment time series are appended, spawner-recruit parameters are re-calculated, and the simulation model from Amendment 8 is used to estimate F_{MSY} in a stochastic model (independent of SST or other HCR parameters). The purpose of this study is to update parameters used for the current management model, which is intended to be used as an interim measure, and not to explore a full management strategy evaluation (MSE) for sardine.

MATERIALS AND METHODS

Data
Analyses conducted in Jacobson and MacCall (1995) and Amendment 8 (PFMC 1998) were based on biomass and recruitment estimates from Murphy (1996), MacCall (1979), and Barnes et al. (1992). Population biomass (1,000s mt) for ages two and older was assumed a close proxy for spawning stock biomass, and recruitment was taken as abundance of fish at age 2 (millions) (Table 1, Figure 1). The original analysis lagged biomass (ages 2+) and recruitment (age 2) by three years (Jacobson and MacCall 1995).

The most recent sardine stock assessment, spanning 1981-2010, was used to append the historic series (Table 1, Figures 1 & 2). The five years of data from Barnes et al. (1992), included in the original analysis, were replaced with data from the current assessment model (Hill et al. 2010). The assessment provided estimates of SSB and age 2+ biomass, so both series were used to examine recruitment success and estimate stochastic F_{MSY}. The sardine assessment uses a semester (6 month) time step and SSB is calculated in the middle of the biological year and thus, biomass and recruitment were lagged by 2.5 years. For example, the abundance of age-2 sardine in July 2010 were produced by SSB (or age 2+ biomass) in January 2007 (Table 1).

The updated series of biomass and recruits (Table 1) was used to estimate new intercept (α) and slope (β) parameters for the linearized Ricker (1975) S-R relationship originally applied by Jacobson and MacCall (1995) and PFMC (1998), with the temperature term removed:

$$[2] \qquad \ln(R/S) = \alpha + \beta S$$

Simulation model
The simulation model used for this analysis is generally described in Appendix B of Amendment 8 (PFMC 1998). The model was based on a simple, age-aggregated biomass dynamic model described in detail by Jacobson et al. (1994). The original simulation model, using the 'SAS' statistical platform, was provided by Drs. Larry Jacobson (NEFSC-Woods Hole) and Richard Parrish (SWFSC-retired) for this analysis. Prior to modification, the simulation was tested to confirm reproducibility of HCR outputs (performance measures) summarized in Tables 4.2.3.3-1 and 4.2.5-1 of Amendment 8 (see Tables 5 and 6 of this report).

The primary goal of the analysis was to estimate F_{MSY}, based on an updated time series of biomass and recruits and independent of the temperature covariate. While it would have been possible to update other model parameters (e.g., instantaneous growth rate 'G', recruitment and biomass variances), a decision was made to keep these parameters consistent with Amendment 8

analyses for ease of comparison. Future efforts for a full MSE should revisit all model parameters in addition to addressing the PMFC's management goals.

Following is a summary of some key model elements and constraints that remained unchanged from the original simulation (PFMC 1998):
- Begin with estimated stock biomass in 1996 (463,000 mt);
- Random numbers affecting errors in simulated biomass and recruitment were unchanged;
- Instantaneous natural mortality (M) was 0.4 yr^{-1} and instantaneous growth (G) was 0.1 yr^{-1};
- Recruitment variability was addressed by assuming log-normally distributed random errors in the S-R relationship, with a standard deviation = 0.91;
- Biomass estimates from stock assessments had CVs = 50%;
- 'Quota' = (BIOMASS - CUTOFF) * FRACTION;
- 'Quota' catch was assumed to be taken entirely, except when biomass fell to such a low level that a fishing mortality rate(F) >1.0 yr^{-1} would have been required;
- In addition to 'Quota' catch, 2,000 mt of sardine per year were assumed to be taken as live bait as long as the estimated stock biomass was >50,000 mt (overfished level); and
- Biomass was never allowed to fall below 5,000 mt, and recruitment was never allowed to exceed ~30 billion two-year old fish.

Current changes to the simulation model included:
- S-R intercept (α) and slope (β_2) parameters were set per models (3) and (4) in Table 3;
- Slope (β_1) for the temperature term was set to 0, disabling SST effects on S-R calculations;
- CUTOFF = 0;
- Maximum allowable catch (MAXCAT) was unlimited;
- Harvest FRACTION was varied to range from 0% to 60%, in 1% increments; and
- Number of simulation years (iterations) was increased in orders of magnitude from 1K to 10M years to examine stability of simulation results, with final results based on models simulated over 100K years.

In Amendment 8 and for purposes of this study, 'Stochastic F_{MSY}' was defined as the value of FRACTION that maximizes average catch (i.e., equilibrium yield) in a stochastic simulation model when CUTOFF is equal to zero and MAXCAT is unlimited. Stochastic MSY was calculated by determining the average catch over 100K years for a series of constant FRACTION values between 0% and 60%, in 1% increments. The FRACTION level with the highest average catch was the annual harvest rate (vs. instantaneous F) associated with F_{MSY}.

RESULTS & DISCUSSION
The relationship between recruitment success and biomass was modeled with linear regression for both the original (Jacobson & MacCall 1995) and updated time series (SSB and age 2+ biomass) in the absence of SST data. Regression statistics for the original management model (Jacobson & MacCall 1995, PFMC 1998) are displayed in the lower half of Table 2 and in Table 3 (model 1). Regression slopes for biomass (β_2) from the original data series were not significant for models that either included or excluded SST (models 1 & 2 in Table 3; Figure 3a). Addition of 23 years of data improved fit to the regression slope, with β_2 being significant for models using SSB (model 3; p=0.0024) or age 2+ biomass (model 4; p=0.0016). Both updated

regression models (3 & 4) had lower R^2 values and higher variances than the original management model, however, the intercept and slope parameters for the updated models were all significant (Table 3; Figures 3b,c).

The HCR analyses presented in Amendment 8 (PFMC 1998, Appendix B) were based on simulations iterated over 1,000 years. To examine the effect of simulation years on stability of model results, the update model based on SSB (model 3) was run for 1K, 10K, 100K, 1M, and 10M years. Average catch-at-fraction results are displayed in Figure 4. Stochastic F_{MSY} was equal to 18% in all simulation runs. Simulations run for 10K years or more had higher average biomasses and catches than the model run for 1K years. Simulations run for 100K years or more had similar scales of average biomass and catch, so are more appropriate when considering other biological reference points, such as B_{MSY} or B_0 (Figure 4).

Two 'stochastic F_{MSY}' estimates were presented in analyses for Amendment 8 -- one in Table 4.2.3.3-1 and the other in Table 4.2.5-1 (Appendix B; PFMC 1998). These Tables are reproduced in Tables 5 and 6 of this report and are also summarized in Table 4 (see columns 1 & 2). While the stochastic F_{MSY} estimates in Tables 4.2.3.3-1 and 4.2.5-1 were identical (12%), and both were supposedly based on the same model parameterization, the HCR performance measures (e.g., average catch and biomass) differed among the two tables. The stochastic F_{MSY} model based on the older data and parameters was re-run for this study (see Table 4, 'Amendment 8 Stochastic F_{MSY} Redux'). The model based on 1K year simulation had a F_{MSY} equal to 0.11 in addition to having different HCR performance measures (Table 4, column 4), however, the HCR measures associated with FRACTION=0.12 were identical to values presented in Table 4.2.3.3-1 of Amendment 8 (see Table 4, columns 2 & 3). Nonetheless, analysis of the same data and control rule over 100K years resulted in an F_{MSY} estimate of 12%, which is consistent with estimates from Amendment 8 (Table 4, column 5).

The sardine simulation model was revised using updated S-R parameters based on either SSB or age 2+ biomass (Table 3, models 3 & 4), and the model was run over 100K years for the range of FRACTION values. Both simulations resulted in stochastic F_{MSY} estimates of **18%**, with only minor differences in HCR performance measures (Table 4, columns 6 & 7; Figure 5). Average biomass for F_{MSY} (0.18) ranged from 980,000 to 1,005,000 mt.

For comparative purposes, the PFMC's current HCR (where CUTOFF=150,000, MAXCAT=200,000, and FRACTION is fixed at 15%; no SST) was simulated over 100K years using the updated S-R parameters. Average biomass was 50% higher than the updated stochastic F_{MSY} models, and the percent of years with biomass greater than 400,000 was 98% (Table 4, column 8).

The final goal of this analysis was to use the revised F_{MSY} estimate to calculate OFL and ABCs for a range of biomass levels and compare these to HGs from the current HCR. Uncertainty buffers for a range of overfishing probabilities (P^*) (for σ=0.36) are displayed in Figure 6. OFLs, buffered ABCs (for P^*=0.20-0.45), and HGs for a range of sardine biomass are presented in Figure 7. In most cases, HG from the current HCR is lower than buffered ABCs, with the only exception being ABC for P^*=0.20 when biomass ranges ~1.3 to 1.7 million mt (Figure 7).

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Table 1. Biomass (1,000 mt), recruits (millions), and ln(*R/S*) as published in Jacobson and MacCall (1995) and used in Amendment 8 analyses (left), and as appended from Hill et al. (2010)(right).

| Jacobson & MacCall (1995) and Amendment 8:					Appended 1983 onward from Hill et al. (2010):					
Year (y)	SSB(y-3)	R-age2(y)	ln(*R/SSB*)		Year (y)	SSB(y-3)	B-age2+(y-3)	R-age2(y)	ln(R/SSB)	ln(R/B2+)
1935	3,526	4,098	0.150		1935	3,526	3,526	4,098	0.150	0.150
1936	3,417	2,821	-0.192		1936	3,417	3,417	2,821	-0.192	-0.192
1937	3,628	5,383	0.395		1937	3,628	3,628	5,383	0.395	0.395
1938	2,847	6,940	0.891		1938	2,847	2,847	6,940	0.891	0.891
1939	1,689	6,763	1.387		1939	1,689	1,689	6,763	1.387	1.387
1940	1,207	11,808	2.281		1940	1,207	1,207	11,808	2.281	2.281
1941	1,202	14,442	2.486		1941	1,202	1,202	14,442	2.486	2.486
1942	1,609	6,152	1.341		1942	1,609	1,609	6,152	1.341	1.341
1943	1,761	3,268	0.618		1943	1,761	1,761	3,268	0.618	0.618
1944	2,459	3,720	0.414		1944	2,459	2,459	3,720	0.414	0.414
1945	2,066	2,385	0.144		1945	2,066	2,066	2,385	0.144	0.144
1946	1,679	1,625	-0.033		1946	1,679	1,679	1,625	-0.033	-0.033
1947	1,261	1,667	0.279		1947	1,261	1,261	1,667	0.279	0.279
1948	720	3,875	1.683		1948	720	720	3,875	1.683	1.683
1949	566	4,261	2.019		1949	566	566	4,261	2.019	2.019
1950	405	3,690	2.209		1950	405	405	3,690	2.209	2.209
1951	740	290	-0.937		1951	740	740	290	-0.937	-0.937
1952	793	397	-0.692		1952	793	793	397	-0.692	-0.692
1953	780	972	0.220		1953	780	780	972	0.220	0.220
1954	277	1,197	1.464		1954	277	277	1,197	1.464	1.464
1955	136	382	1.033		1955	136	136	382	1.033	1.033
1956	202	264	0.268		1956	202	202	264	0.268	0.268
1957	239	588	0.900		1957	239	239	588	0.900	0.900
1958	170	1,586	2.233		1958	170	170	1,586	2.233	2.233
1959	108	905	2.126		1959	108	108	905	2.126	2.126
1960	90	288	1.163		1960	90	90	288	1.163	1.163
1961	177	111	-0.467		1961	177	177	111	-0.467	-0.467
1962	122	74	-0.500		1962	122	122	74	-0.500	-0.500
1963	88	56	-0.452		1963	88	88	56	-0.452	-0.452
1986	5	88	2.868		1983	17	6	33	0.682	1.665
1987	18	57	1.153		1984	8	8	47	1.776	1.731
1988	24	212	2.179		1985	10	10	111	2.411	2.413
1989	33	161	1.585		1986	12	13	104	2.135	2.098
1990	56	238	1.447		1987	21	21	116	1.725	1.733
					1988	26	27	280	2.369	2.327
					1989	34	33	388	2.447	2.464
					1990	50	54	543	2.383	2.313
					1991	78	84	459	1.777	1.694
					1992	114	119	969	2.141	2.095
					1993	140	134	1,944	2.631	2.674
					1994	154	168	1,617	2.350	2.264
					1995	193	250	4,045	3.045	2.782
					1996	266	329	4,650	2.861	2.648
					1997	421	562	1,775	1.438	1.150
					1998	629	821	2,456	1.362	1.095
					1999	756	820	6,949	2.218	2.137
					2000	740	772	7,868	2.364	2.322
					2001	884	1,096	1,330	0.409	0.194
					2002	1,197	1,496	937	-0.245	-0.467
					2003	1,308	1,324	2,469	0.636	0.623
					2004	1,136	1,055	279	-1.405	-1.331
					2005	936	922	7,054	2.020	2.035
					2006	746	670	3,804	1.630	1.736
					2007	751	967	3,886	1.644	1.391
					2008	886	1,032	1,037	0.157	0.004
					2009	959	1,071	1,013	0.054	-0.056
					2010	880	848	684	-0.251	-0.215
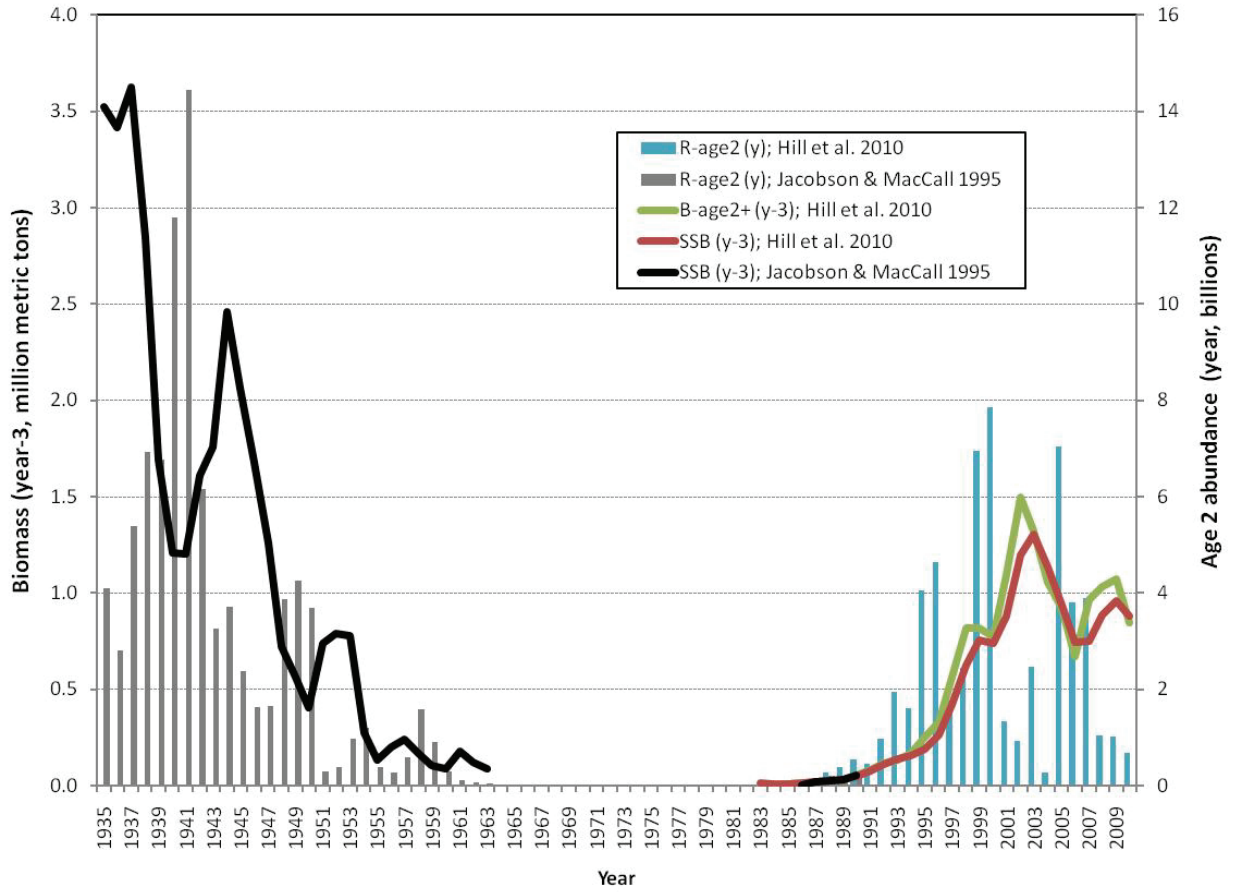
Figure 1. Biomass (yr-3) and recruits (age-2, yr) from Jacobson & MacCall (1995) and Hill et al. (2010).
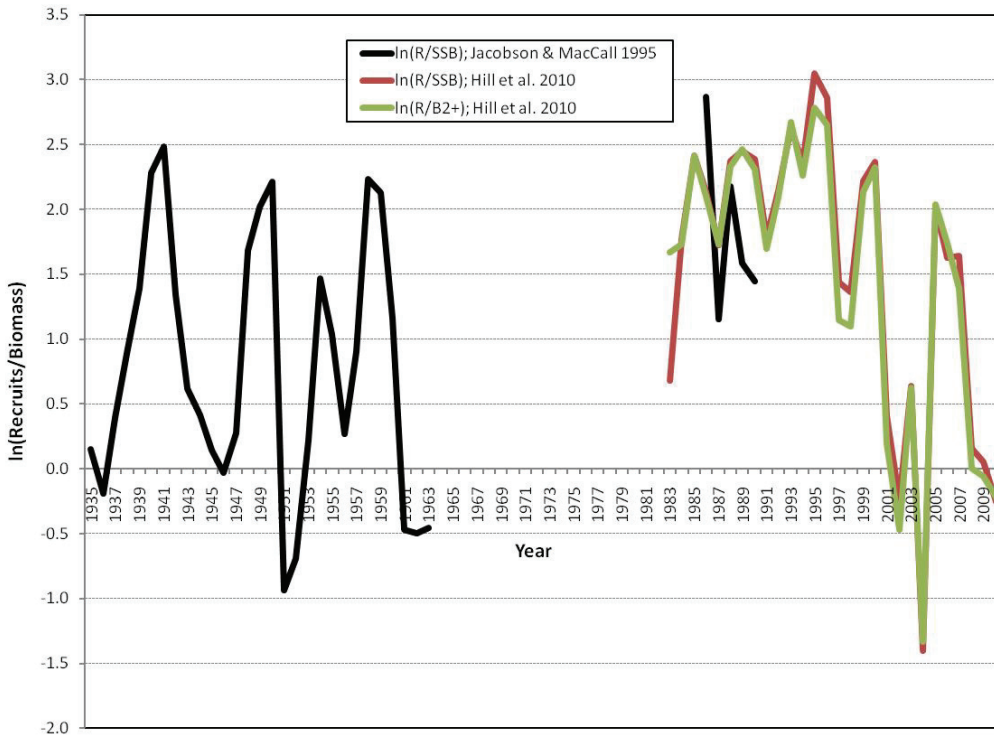

Figure 2. Recruitment success from Jacobson & MacCall (1995) and Hill et al. (2010).

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Table 2. Regression statistics published in Table 5 of Jacobson & MacCall (1995). The second model served as the basis for Amendment 8 simulations (PFMC 1998).

Table 5. Summary statistics for management models [2] fit to log reproductive success data for sardine.

Parameter	Estimate	Standard error	t value	p value
Management model with temperature only				
$\ln(R/S) = \alpha + \beta T$				
α	-16.45	6.077	-2.71	0.011
β_1 (temperature)	1.025	0.358	2.86	0.007
($R^2 = 20\%$, Var(ϵ) = 0.87)				
Management model with temperature and spawning biomass				
$\ln(R/S) = \alpha + \beta_1 T + \beta_2 S$				
α	-15.12	5.99	-2.53	0.017
β_1 (temperature)	0.961	0.352	2.73	0.010
β_2 (spawning biomass)	-0.0002331	0.0001441	-1.62	0.116
($R^2 = 27\%$, Var(ϵ) = 0.83)				

Table 3. Summary statistics for models fit to log reproductive success data for Pacific sardine. Regression model: $\ln(R/S) = \alpha + \beta_1 T + \beta_2 S$, where R is age-2 abundance in year y, S is spawning biomass in y-3, and T is sea surface temperature at SIO pier, included model (1) only. See Figure 3 for scatter plots and modeled regressions.

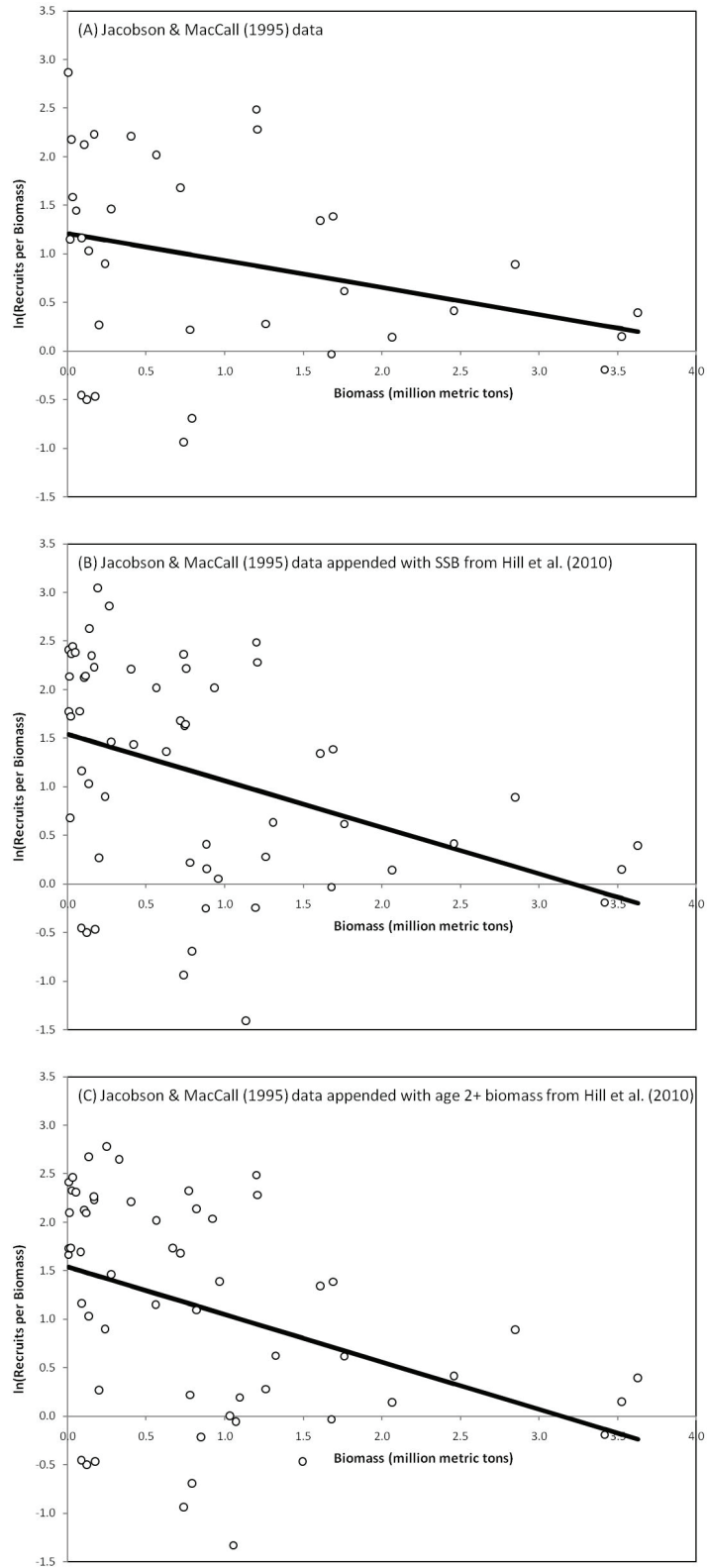| Model/Parameter	Estimate	Standard error	t value	p value
(1) Model in J&M 1995 and Amendment 8 (R^2 = 27%, Var(ϵ) = 0.83, n = 34)				
α	-15.1220	5.99000	-2.530	1.700E-02
β_1	0.9609	0.35200	2.730	1.000E-02
β_2	-0.00023310	0.00014	-1.620	1.160E-01
(2) J&M 1995 model without SST (R^2 = 9%, Var(ϵ) = 0.99, n = 34)				
α	1.2097	0.23258	5.201	1.107E-05
β_1	0	---	---	---
β_2	-0.00027762	0.00016	-1.768	8.652E-02
(3) Updated model using SSB and no SST (R^2 = 15%, Var(ϵ) = 1.07, n = 57)				
α	1.5414	0.18548	8.310	2.733E-11
β_1	0	---	---	---
β_2	-0.00047896	0.00015	-3.175	2.454E-03
(4) Updated model using Age 2+ Biomass and no SST (R^2 = 17%, Var(ϵ) = 1.03, n = 57)				
α	1.5405	0.18457	8.346	2.385E-11
β_1	0	---	---	---
β_2	-0.00049010	0.00015	-3.311	1.648E-03

Figure 3. Plot of regressions for old (minus SST) and new data. See Table 3 for all regression statistics.

Table 4. Simulation parameters and performance measures for HCR from Amendment 8 and the updated analyses.

	Amendment 8 Stochastic F_{MSY}		Amendment 8 Stochastic F_{MSY} Redux			Updated Stochastic F_{MSY}		Current HCR:
	A8 Table 4.2.5-1	A8 Table 4.2.3.3-1	Fraction=12%	Actual F_{MSY}	100K Years	Using SSB	Using 2+ Biomass	new SSB, 100K yrs
Data Source / S-R parameters:								
$\ln(R/S) = \alpha + \beta_1 T + \beta_2 S$	JM95 & A8	JM95 & A8	JM95 & A8	JM95 & A8	JM95 & A8	JM95+2010	JM95+2010	JM95+2010
α	-15.1220	-15.1220	-15.1220	-15.1220	-15.1220	1.5414	1.5405	1.5414
β_1 (temperature)	0.9609	0.9609	0.9609	0.9609	0.9609	0	0	0
β_2 (spawning biomass)	-0.00023310	-0.00023310	-0.00023310	-0.00023310	-0.00023310	-0.00047896	-0.00049010	-0.00047896
Control Rule Parameters:								
Number of Simulation Years	1,000	1,000	1,000	1,000	100,000	100,000	100,000	100,000
Range of FRACTION Simulated	0-60%	0-60%	12%	0-60%	0-60%	0-60%	0-60%	15%
F_{MSY}	12%	12%	---	11%	12%	18%	18%	---
CUTOFF	0	0	0	0	0	0	0	150
MAXCAT	infinite	infinite	infinite	infinite	infinite	infinite	infinite	200
HCR Performance Measures:								
Average Catch	180	176	176	178	209	201	196	152
Std. Dev. Catch	180	180	180	173	218	175	171	59
Average Biomass	1,408	1,332	1,332	1,468	1,544	1,005	980	1,530
Std. Dev. Biomass	39	38	38	40	7	3	3	2
Average Log Catch	4.72	4.66	4.66	4.74	4.84	4.99	4.96	4.90
Average Log Biomass	6.89	6.76	6.76	6.94	6.93	6.69	6.66	7.20
Percent Years Biomass>400	84%	80%	80%	85%	84%	84%	84%	98%
Percent Years No Catch	0%	0%	0%	0%	0%	0%	0%	0.2%
Median Catch	128	123	123	127	139	148	144	180
Median Biomass	1,500	1,049	1,049	1,199	1,199	849	848	1,398

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Table 5. Table 4.2.3.3-1 from Amendment 8 to the CPS-FMP. Stochastic F_{MSY} model is shown in the last column.

TABLE 4.2.3.3-1. Performance variables for various MSY control rules with constant FRACTION values. Biomass values are in thousand mt. All control rules except deterministic equilibrium F_{msy} were evaluated in a stochastic model (see Table 4.2.5-1).

	Maximum Average Catch Policy ("Pulse Fishery")	Maximum Average Log Catch Policy	Maximum Median Catch Policy	Minimum Percent Years With No Catch Policy	Status Quo Policy	Deterministic Equilibrium F_{msy} Policy in a Deterministic Model (Unrealistic)	Stochastic F_{msy} Policy
MSY Control Rule Parameter							
FRACTION	45%	10%	100%	many	20%	8.8%	12%
CUTOFF	1,000	0	975	many	50	0	0
MAXCAT	1,000	300	300	many	400	Infinite	Infinite
Performance Variable							
Average Catch	208	159	173	many	151	170	176
Standard Deviation Catch	306	98	142	many	137	153	180
Average Biomass	1,307	1,754	1,675	many	936	1,756	1,332
Std. Dev. Biomass	15	45	30	many	27	44	38
Average Log Catch	3.19	4.79	3.74	many	4.33	4.78	4.66
Average Log Biomass	6.97	7.17	7.16	many	6.24	7.21	6.76
Percent Years With Biomass >400K mt	94%	91%	94%	many	61%	93%	80%
Percent Years With No Catch	47%	0%	37%	0%	5%	0%	0%
Median Catch	16	142	298	many	103	127	123
Median Biomass	1,049	1,449	1,324	many	598	1,499	1,049

Table 6. Table 4.2.5-1 from Amendment 8 to the CPS-FMP. Stochastic F_{MSY} model is Option L.

TABLE 4.2.5-1. MSY control rule options for Pacific Sardine. All options evaluated in a stochastic model.

	Option A (Status Quo)	Option B	Option C	Option D	Option E	Option F	Option G	Option H	Option I	Option J	Option K	Option L (Stochastic F_{MSY})	Option M (Determ. Equil. F_{MSY} in a Stochastic Model)
Overfishing Definitions													
Overfishing Rate	Catch> ABC	F_{MSY} (10-30%)	Catch> ABC	F_{MSY} (10-30%)	F_{MSY} (10-30%)	F_{MSY} (5-25%)	F_{MSY} (5-15%)	F_{MSY} (5-15%)	F_{MSY} (5-25%)	Catch> ABC	F_{MSY} (10-30%)	F_{MSY}	Catch> ABC
Overfished Threshold (mt)	50	50	50	50	50	50	50	50	50	50	50	50	50
Control Rule Parameters													
FRACTION	20%	F_{MSY} (10-30%)	20%	F_{MSY} (10-30%)	F_{MSY} (10-30%)	F_{MSY} (5-25%)	F_{MSY} (5-15%)	F_{MSY} (5-15%)	F_{MSY} (5-25%)	F_{MSY} (5-15%)	F_{MSY} (10-30%)	12%	8.8%
CUTOFF	50	50	100	100	100	100	100	100	100	150	50	0	0
MAXCAT	400	400	400	300	300	400	300	300	300	200	200	Infinite	Infinite
Performance Measure													
Average Catch	151	159	165	171	165	177	179	169	169	145	141	180	170
Std. Dev. Catch	137	140	140	143	113	143	133	105	112	67	72	180	153
Mean Biomass	936	964	1,073	1,091	1,280	1,216	1,543	1,665	1,400	1,952	1,516	1,408	1,784
StdDev Biomass	27	27	29	28	34	32	39	42	37	49	43	39	43
Mean Log Catch	4.33	4.46	4.44	4.54	4.64	4.62	4.77	4.80	4.70	4.76	4.65	4.72	4.77
Mean Log Biom	6.24	6.37	6.50	6.59	6.75	6.74	7.06	7.15	6.89	7.34	6.87	6.89	7.24
Percent Years Biomass>400	61%	64%	70%	73%	79%	81%	90%	92%	84%	96%	79%	84%	93%
Percent Years No Catch	5%	2%	7%	4%	3%	2%	1%	0%	1%	0.5%	1%	0%	0%
Median Catch	103	104	119	121	148	131	140	156	158	182	188	128	127
Median Biomass	598	600	700	748	898	850	1,248	1,349	1,048	1,648	1,099	1,500	1,049
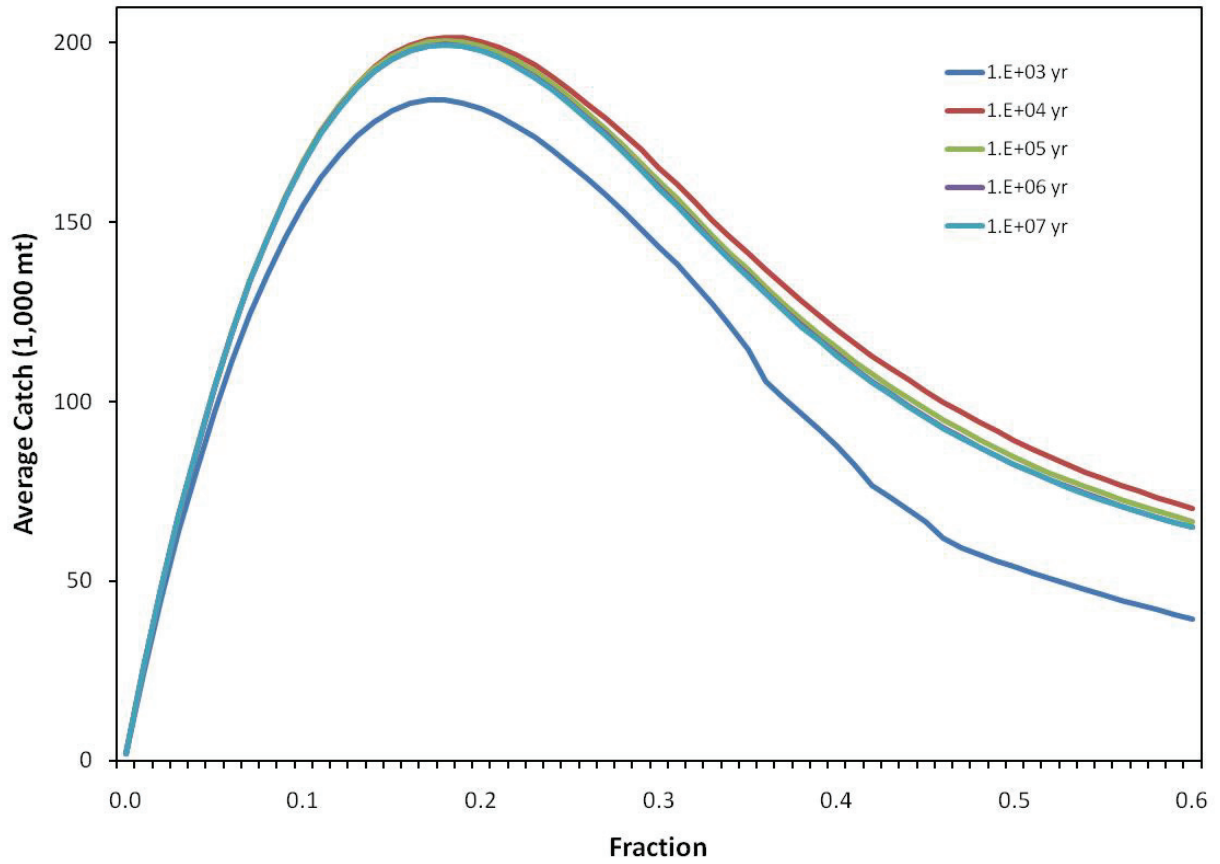
Figure 4. Average catch- at- fraction for the updated model and simulations ranging from 1,000 to 10 million iterations.
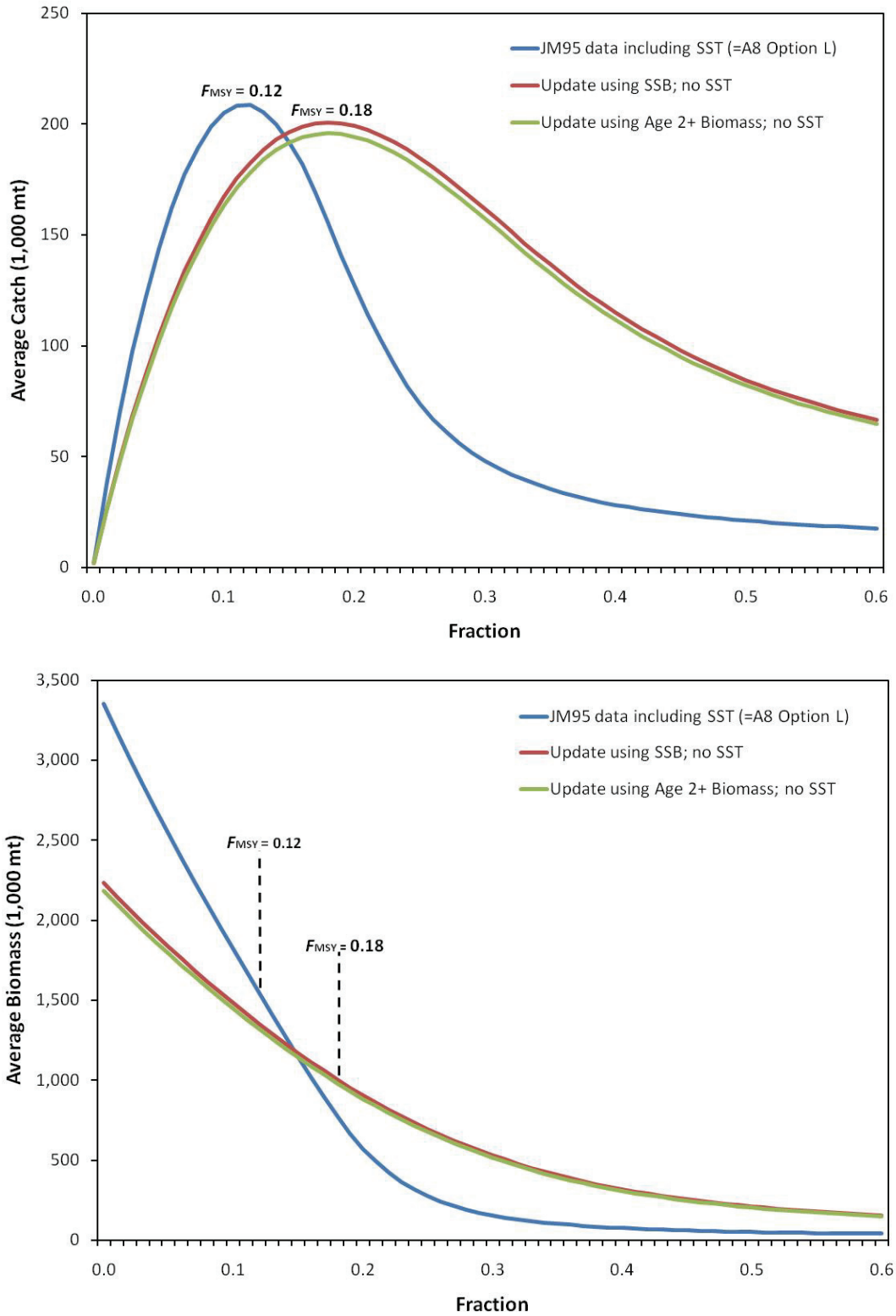
Figure 5. Average catch (upper panel) and average biomass (lower panel) for the updated 'Stochastic F_{MSY}' models for a range of harvest fraction values, each simulated over 100K iterations.
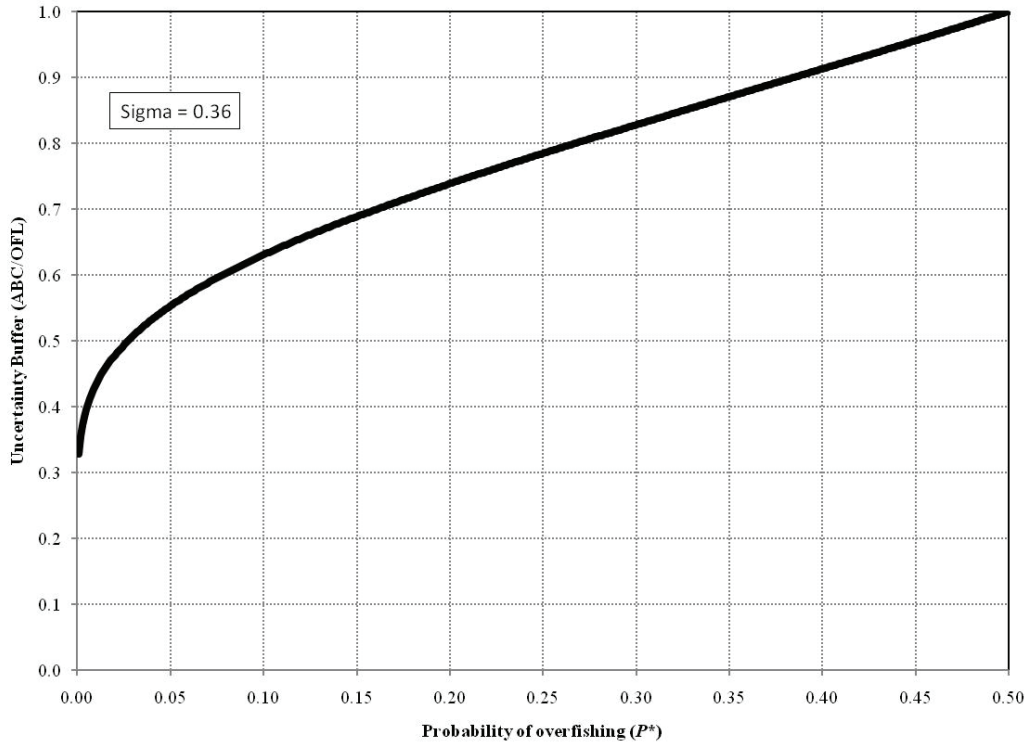
Figure 6. Uncertainty buffer for a range of *P** values where Sigma = 0.36.
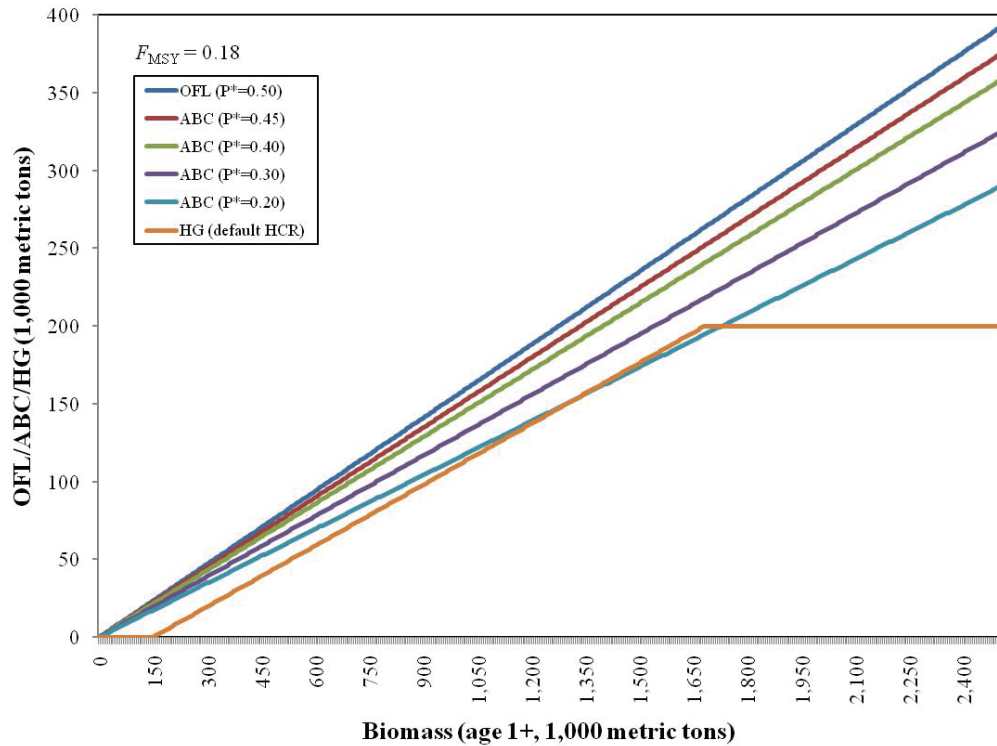
Figure 7. The OFL and ABC for a range of Pacific sardine biomasses, where F_{MSY} = 0.18 and Sigma = 0.36

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Spawning fraction using Baysian hierarchical (Random effect) model for years in 1986-2011

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Abstract

Spawning fraction (S), the proportion of mature female fish that spawn per day, is one of the adult reproductive parameters used in the daily egg production method to estimate the spawning biomass. This parameter is one of the most difficult parameters to estimate with relative large coefficient of variation (CV). Since 2004, number of trawls for Pacific sardine ichthyoplankton-trawl surveys has increased. To fully utilize trawl data from all years, a Bayesian hierarchical model (BHM) was investigated, as recommended by the May 2009 STAR panel[1]. The BHM was used for each of two regions (region1: high density area and region 2: low density area) when data of that region were available. For both regions, the point estimates from the original estimates and the BHM were similar. The CVs of the BHM estimates were lower than those from the original method in most years. In recent year, the CV of estimates from these two methods were similar for region 1, but the CV of BHM estimates were much lower than those of the original estimates for region 2. One of the reasons for the similarities of two estimators in recent years is due to the large sample sizes. We choose to continue using the original method for following reasons: 1). The shrinkage effect is small for future years when sample size is large, thus the gain from the BHM is minimum. 2). In many years (e.g. 1987, 1997, 2001, 2002 and 2004), when trawls were taken only in region 1 but not in region 2, the mean of the posterior predictive distribution for region 2 was used. The BHM is also needed for other adult parameters like fecundity, female weight and sex ratio Extensive computer programming is needed to incorporate the BHM estimates of adult samples and egg samples to compute the spawning biomass. 3). The current practice is for years when no adult samples were available in any one or both regions, the total egg production (TEP) time series was obtained and used in the stock assessment.

Introduction

The spawning biomass of Pacific sardine has been estimated using the daily egg production method (DEPM) (Piquelle and Stauffer 1985) since 1986 (Hill et al. 2009). Data were collected from ichthyoplankton-trawl surveys off California in most years and off the west coast of US in recent years (Lo et al. 2010). Although the icthyoplankton survey was conducted yearly, trawl samples were collected only in 1986-1988, 1994,

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[1] Star Panel Report 2009, Daily Egg Production Methods for Pacific Sardine
Report of STAR Panel Meeting. NOAA / Southwest Fisheries Science Center
La Jolla, California, May 4-8, 2009 Star Panel Agenda Item H.2.a Attachment 4
(http://www.pcouncil.org/bb/2009/0609/H2a_ATT4_0609.pdf)

1997, 2001, 2002, and 2004-present. Further, the number of trawls was small during 1997, 2001 and 2002 when all the trawls were opportunistic collections. To compute the spawning biomass prior to 2009, for years when trawls samples were lacking or small, (e.g. 1995–2001), an overall average of the spawning fraction during 1986–94 and estimates of other adult parameters in 1994 were once used to estimate daily specific fecundity (number of eggs/gram weight). In 2003, when no trawls were taken, the estimates of adult reproductive parameters from 2002 were also once used. Since 2004, a full-scale survey has been conducted to estimate the spawning biomass of Pacific sardine (Lo et al. 2005). Starting in 2009, a stratified sampling scheme was used where the spawning biomass was estimated for each of two regions for years when trawls were available for both regions. Otherwise, the total egg production (TEP) was computed to form another time series for the stock assessment.

The spawning fraction (S), the proportion of mature female fish that spawn per day, is one of the most difficult parameters to estimate and typically has relative large coefficient of variation (CV) (see below). In recent years, number of trawls has been increased while in most of early years, prior to 2004, number of trawls was low. To fully utilize trawl data from all years, a Bayesian hierarchical model (a.k.a. random effects model) was recommended by the May 2009 STAR panel for the sardine survey (STAR panel report 2009). In this report, we provide Bayesian estimates of spawning fraction for the years between 1986 and 2011 when adult samples were available in at least in one of the two regions.

Material and method

Spawning biomass for Pacific sardine off California was estimated using DEPM for the survey area south of CalCOFI line 60 (DEPM survey area) during the spring DEPM survey even during some years, e.g. 2006, 2008, 2010, and 2011 when the survey also covered area off the Washington and Oregon coast (Figure 1). The survey area was post stratified into two regions based on egg density from the continuous underway egg sampler (CUFES) (Checkley et al. 1977, Lo et al 2001): region 1 (high density area: eggs/minute >=1) and region 2 (low density area: eggs/minutes<1) (Figure 1). The spawning biomass was computed for each of the two areas in the DEPM area and the sum of the two estimates was used to estimate the total spawning biomass. For stock assessment, we have provided the female spawning biomass since 2009 (Hill et al. 2009).

The spawning biomass was computed as:

$$B_s = \frac{P_0 A C}{RSF / W_f} \qquad (1)$$

where P_0 is the daily egg production per 0.05m^2, A is the survey area in units of 0.05m^2, S is the fraction of mature females spawning per female per day, F is the batch fecundity (number of eggs per mature female released per spawning), R is the fraction of mature female fish by weight (sex ratio), W_f is the average weight of mature females (g), and C is

the conversion factor from grams (g) to metric tons (mt). P_0A is the total daily egg production in the survey area, and the denominator (RSF/W_f) is the daily specific fecundity (number of eggs/population weight (g)/day).

The variance of the spawning biomass estimate $(\hat{B}_s)$ was computed using Taylor expansion and in terms of the coefficient of variation (CV) for each parameter estimate and covariance for adult parameter estimates (Parker 1985):

$$VAR(\hat{B}_s) = \hat{B}_s^2 \left[CV(\hat{P}_0)^2 + CV(\hat{W}_f)^2 + CV(\hat{S})^2 + CV(\hat{R})^2 + CV(\hat{F})^2 + 2COVS \right] \quad (2)$$

The last term, involving the covariance term, on the right-hand side is

$$COVS = \sum_i \sum_{i<j} sign \frac{COV(x_i, x_j)}{x_i x_j}$$

where x's are the adult parameter estimates, and subscripts i and j represent different adult parameters; e.g., $x_i = F$ and $x_j = W_f$. The sign of any two terms is positive if they are both in the numerator of B_S or denominator of B_S (equation 1); otherwise, the sign is negative. The covariance term is

$$cov(x_{i,}x_j) = \frac{[n/(n-1)] \sum_k m_k(x_{i,k} - x_i) g_k(x_{j,k} - x_j)}{\left(\sum_k m_k \right) \left(\sum_k g_k \right)}$$

where k refers to k^{th} tow, and $k = 1,...,n$. The terms of m_k and g_k are sample sizes and $x_{i,k}$ and $x_{j,k}$ are sample means from the kth tow for x_i and x_j respectively.

For the female spawning biomass, the parameter, sex ratio (R), was excluded from equations 1 and 2.

DEPM trawl samples

Adult Pacific sardines were collected from the entire survey area, e.g. 2011 survey (Figure 1), onboard a NOAA research vessel using either a high-speed mid- water trawl or a Nordic 264 midwater trawl, or in recent years, onboard the chartered commercial vessel F/V *Frosti,* using a Nordic 264 midwater trawl. Allocation of trawls was based on evidence of schools on echo-sounder or sardine eggs in CUFES samples in the early years. From 2006 on, trawls have been taken either at the pre-determined stations or

randomly along survey transects. Collections of sardines were taken at night between 18:00 and 05:00 hours. Up to 50 randomly sampled fish from each collection were sexed and standard length was measured to the nearest millimeter. All females sampled were individually weighed to the nearest gram. After the random subsample, additional fish were processed following procedures used in 1994 (Macewicz et al. 1996) if necessary, to obtain 25 mature females per trawl to be used to calculate reproductive parameters. In the laboratory, each preserved ovary was processed (Hunter and Macewicz 1985). We analyzed oocyte development, atresia, and postovulatory follicle age to assign female maturity and reproductive state (Macewicz et al. 1996).

Annual number of mature female sardines analyzed ranged from 9 (2001) to 746 (1988) between 1986-2011 for the standard DEPM area (south of CalCOFI line 60, close to San Francisco, to CalCOFI line 95, close to San Diego), and was considered to be a random sample of the population in the area trawled. Histological criteria can be used to identify four different spawning nights: postovulatory follicles aged 44-54 hours old indicated spawning two nights before capture (day-2 female) postovulatory follicles aged about 20-30 hours old indicated spawning the night before capture (day-1 female); hydrated oocytes or new (without deterioration) postovulatory follicles indicated spawning the night of capture (day-0 female); and early stages of migratory-nucleus oocytes indicated that spawning would have occurred the night after capture (mn-female). The daily spawning fraction can be estimated using the number of females spawning on one night, an average of several nights, or average of all nights (Macewicz et al. 1996). Prior to 2009, number of day-1 females was used to replace day-0 females because of possible over representation of day-0 female during the spawning time (Picquelle and Stauffer 1985). Since 2009, we have used the average of number of day-1 female and number of day-2 female, and the adjusted number of mature females caught in each trawl to estimate the population spawning fraction (S_{12}) and its variance (Picquelle and Stauffer 1985, Hill et al. 2009). This pooled estimate of spawning fraction based on day-1 and day-2 females was used for Peruvian anchovy (Alheit et al. 1984), sardine off Spain (Garcia et al. 1992) and Portugal (Cunha et al. 1992). The spawning fraction was estimated for each region and the spawning biomass (and thus female spawning biomass) was the sum of the estimates, from both low and high density regions.

Bayesian hierarchical model (BHM)

The Bayesian hierarchical model (BHM) (Sahai 1975, Casella 1995, 2001, Clark 2007) has been used widely in ecological studies in recent years (Helser and Lai, 2004, Clark et al. 2005, Eguchi and Gerrodette 2009). Because the egg production method requires estimates of each parameter, for years when the sample size was small, the BHM can utilize data from other years to shrink the estimates, in particular for spawning fraction. The Bayesian estimates of the spawning fraction in each year were computed as follows.

The number of females spawned in the random sample of a maximum of 25 mature females (N_{ij}) from the jth trawl in the ith year (n_{ij}) follows the binomial distribution: $B(N_{ij}, S_{ij})$ where S_{ij} is the spawning fraction . The ratio of n_{ij} / N_{ij} is an estimate of S_{ij}. The prior distribution of logit (S_{ij}) was modeled by a logistic regression, and logit (S_{ij})

follows normal distribution: $\ln(\frac{S_{ij}}{(1-S_{ij})}) \sim N(\mu_{ij},1/\tau)$ where μ_{ij}, the mean, is a function of temperature, region, time block where the latter two independent variables are categorical variables and τ ($=1/\sigma^2$) is a measure of precision (equation 3). Before the implementation of the Bayesian hierarchical model (BHM), we conducted regression analyses to determine which independent variables to be included in the logistic equation. The independent variables considered were temperature, fish weight, region, season and time block where time block 1 included the years up to 2006, and time block 2 included years after 2006. Our regression analyses indicated that the effects of the fish weight and season were not significant, and thus were not included in the BHM.

$$\mu_{ij} = \alpha_i + \beta_{i1}(t_{ij} - \bar{t}_i) + \beta_{i2}x_{ij2} + \beta_{i3}x_{ij3} \quad (3)$$

where t_{ij} is the temperature of the jth tow in the year i
  x_{ij2} =1 for region 1 and =0 for region 2
  x_{ij3} =1 for time block 2: years >2006 and =0 for time block 1: for years<=2006.

Note that α_i is the mean of $\ln(\frac{S_{ij}}{(1-S_{ij})})$ for average temperature in year i in region 2 and year is 2006 or earlier (<=2006).

The spawning fraction for the year i (S_i) was computed as a ratio estimator (Picquelle and Stauffer 1985):

$$S_i = \frac{\sum_j S_{ij}N_{ij}}{\sum_j N_{ij}} \quad (4)$$

The priors for parameters: The random effect was assumed for each of the regression coefficients for the ith year:

$$\alpha_i \sim normal(\alpha_c,\tau_\alpha) \quad (5)$$

$$\beta_{ik} \sim normal(\beta_{ck},\tau_{\beta_{ck}}) \quad (6)$$

$$\tau \sim gamma(0.001,0.001) \quad (7)$$

where k = 1,2, and 3 for temperature, region and time block.

Using the vague non-informative hyper priors, we have

$\alpha_c \sim normal(0, 1.0E - 6)$

$\tau_\alpha \sim gamma(0.001, 0.001)$

Similarly, we have

$\beta_{ck} \sim normal(0, 1.0E - 6)$

$\tau_{\beta_{ck}} \sim gamma(0.001, 0.001)$

For k = 1, 2 and 3 for temperature, region and time block.

If the survey was not post stratified, the equation (3) would include temperature and time block as the independent variables. Estimates of S_i (equation 4) and other parameter were obtained using program WINBUGS [2].

In years, when no trawls were taken in region 2 (Table 1), we obtained an overall estimate of the spawning fraction $S_i = \dfrac{e^{\mu_i}}{1 + e^{\mu_i}}$ from its posterior predictive distribution where $\mu_i = \alpha_c + \beta_{c2}$ and $\mu_i = \alpha_c$ for region 1 and 2 respectively at the average temperature for years<= 2006 (equation 3) for example. The posterior distributions of BHM β_{c1} and β_{c2}, β_{c3}, and α_c (intercept) and thus μ_i plus the posterior predictive distribution of spawning fraction (S_i) for each of two regions and time blocks were obtained to estimate their mean(e.g. posterior.α_c and posterior.β_{ck}), standard deviation, and 95% confidence.

The posterior mean of spawning fraction in years<=2006 is

$posterior. S_1 = \exp(posterior.\alpha_c + posterior.\beta_{ck}) / (1 + \exp(posterior.\alpha_c + posterior.\beta_{ck}))$ for region 1

and

$posterior. S_2 = \exp(posterior.\alpha_c) / (1 + \exp(posterior.\alpha_c))$ for region 2

In practice, n_{ij} was replaced by n_{aij}, the adjusted total number of mature females by replacing number of day-0 (n_0) by either number of day-1 female ($n_{1,ij}$), or the average of number of day-1 and day-2 females ($n_{12,ij}$). For the latter, one would have the adjusted total number of mature females as $N_{aij} = n_{12,ij} + n_{1,ij} + n_{2,ij} + others$ and $S_{aij} = n_{12,ij} / N_{aij}$. For years 1987, 1994 and 2002, only the number of day-1 female was available, and thus day-1 females were used in the analysis. We used WINBUGS program (http://www.stat.uiowa.edu/~gwoodwor/ BBIText/AppendixBWinbugs.pdf) to obtain the

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[2] http://www.mrc-bsu.cam.ac.uk/bugs/winbugs/manual14.pdf

posterior distributions of all the parameters, because the Gibbs sampler usually produces chains with smaller autocorrelation than other MCMC samplers (Draper,1995, 2000[3] (http://www.bath.acx.uk/~masdd), Walsh 2004). To reduce possible autocorrelation,

we used 1000 burn-in samples, took every 10th output for a total of 30,000 iterations

Results

The summary statistics for the Bayesian estimates of parameters: α_c τ_α β_{ck} , τ and S for region 1 and region 2 are given in Table 2. The estimates of the spawning fractions and their coefficient of variation (CV) for each region in each year are given in Figures 2 and 3. The BHM point estimates and the original estimates were similar while the CV of the BHM estimates were lower than those of the traditional estimates for most years, except for 1986, 2005, 2008 and 2010 for region 1 estimates and 1986 and 1988 for region 2 estimate (Figures 2 and 3). For years when no trawls were taken in region 2, the estimates of spawning fraction were based on the mean of the posterior predictive distribution: 0.045 (Table 1 and 2, Figure 3). Note that the BHM estimate was close to the estimate using equation 3 with the Bayesian estimates of regression coefficients: 0.055.

Table 1. Number of positive trawls taken in years from 1986-2011 in the DEPM area

Year	86	87	88	94	97	01	02	04	05	06	07	08	09	10	11
Total	11	13	19	22[a]	4	2	6	16	13[b]	7	14	12	28[c]	17	28[d]
Region 1	5	13	14	18	4	2	6	16	5	2	8	4	14	3	14
Region 2	6	0	5	4	0	0	0	0	8	5	6	8	14	14	14

[a] total trawls was 24, a trawl from region 1 and region 2 lacked SST and was not used in analysis
[b] total trawls was 14, a trawl from region 1 had only day-0 female and was not used in analysis
[c] total trawls was 29, a trawl from region 1 had only day-0 female and was not used in analysis
[d] total trawls was 30, 2 trawls from region 2 had only day-0 female and was not used in analysis

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[3] Draper, David. 2000. *Bayesian Hierarchical Modeling*.

Table 2. Summary statistics of the Bayesian estimates of the parameters of the hyper priors of each regression coefficient: the intercept (α_c), coefficient for temperature (β_{c1}), and coefficient for region effect (β_{c2}), time block (β_{c3}) and the precision ($\tau=1/\sigma^2$) of the logit (S_{ij}) (equations 3-6)) and spawning fraction estimates from the posterior predictive distribution: S_1 and S_2 are for years<=2006 and S_3 and S_4 are for years in 2007-2011 in region 1 and 2 respectively.

Parameters	mean	sd	CV	2.50%	median	97.50%	start	sample
α_c (intercept)	-3.118	0.217	-0.070	-3.560	-3.115	-2.703	1001	3000
β_{c1}(temperature)	0.499	0.116	0.232	0.290	0.495	0.740	1001	3000
β_{c2} (region)	0.815	0.212	0.259	0.407	0.811	1.255	1001	3000
β_{c3} (timeblock)	0.436	0.225	0.516	-0.052	0.430	0.950	1001	3000
$\tau=1/\sigma^2$	0.847	0.090	0.107	0.682	0.841	1.039	1001	3000
S_1(spawning fraction in region 1 for years<=2006)	0.098	0.032	0.330	0.038	0.091	0.208	1001	3000
S_2(spawning fraction in region 2 for years<=2006)	0.045	0.017	0.371	0.022	0.043	0.084	1001	3000
S_3(spawning fraction in region 1 for years>2006)	0.202	0.094	0.466	0.053	0.185	0.480	1001	3000
S_4 (spawning fraction in region 2 for years>2006)	0.098	0.033	0.338	0.039	0.091	0.209	1001	3000

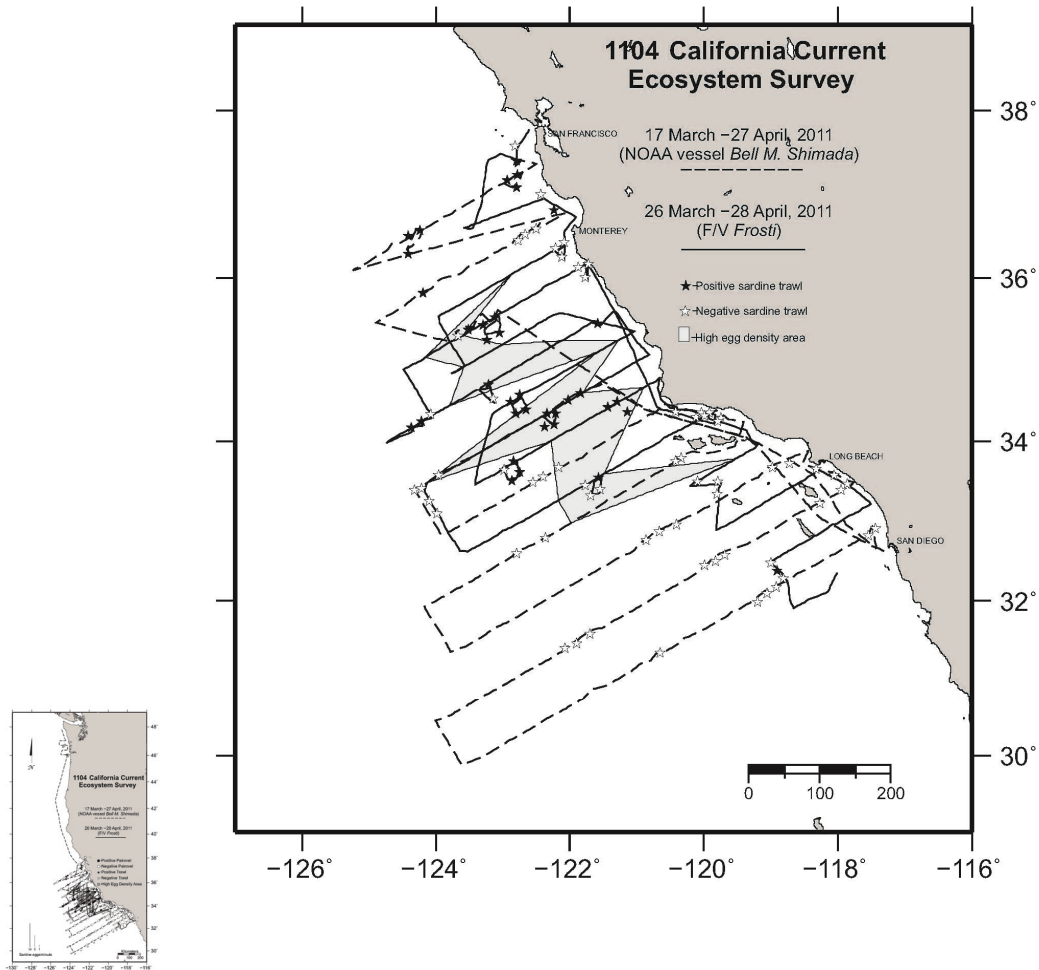Figure 1. Trawl locations (solid star is catch with sardine adults and open star is catch without sardines) during the 2011 survey aboard two vessels: F/V *Frosti* (solid line) and R/V *Shimada* (dash line). Shaded area is Region 1, the high egg-density area, and the rest of survey area is Region 2 in the DEPM survey area. Some of the positive trawls had only immature females. The whole survey area was shown in the small graph.

Region 1 Ratio Comparison

	1986	1987	1988	1994	1997	2001	2002	2004	2005	2006	2007	2008	2009	2010	2011
Dir Est	0.231	0.148	0.159	0.071	0.133	0.111	0.174	0.130	0.178	0.091	0.106	0.250	0.141	0.165	0.136
Bayes Est	0.226	0.148	0.156	0.080	0.144	0.116	0.151	0.127	0.171	0.107	0.111	0.252	0.144	0.156	0.138

Region 1 CV Comparison

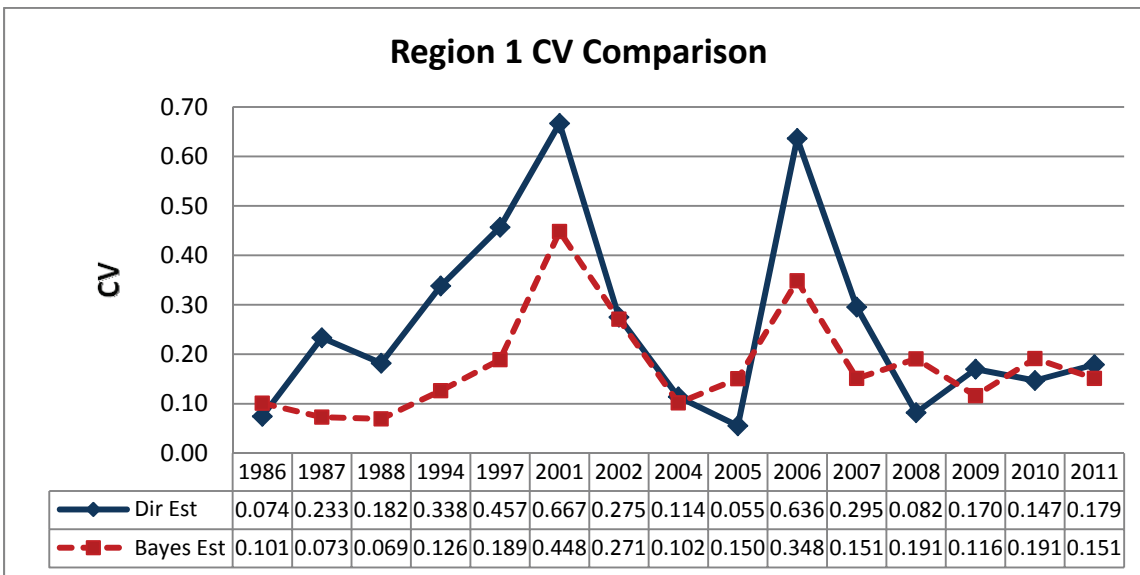|	1986	1987	1988	1994	1997	2001	2002	2004	2005	2006	2007	2008	2009	2010	2011
Dir Est	0.074	0.233	0.182	0.338	0.457	0.667	0.275	0.114	0.055	0.636	0.295	0.082	0.170	0.147	0.179
Bayes Est	0.101	0.073	0.069	0.126	0.189	0.448	0.271	0.102	0.150	0.348	0.151	0.191	0.116	0.191	0.151

Figure 2: Point estimates (above) and CV (below) of the spawning fraction (S_{12}) in region 1 based on the average of day-1 and day-2 female from original (diamond and solid line) and HM estimates (square and dash line) from 1986-2011.

	1986	1987	1988	1994	1997	2001	2002	2004	2005	2006	2007	2008	2009	2010	2011
Dir Est	0.068		0.000	0.041					0.027	0.060	0.146	0.079	0.085	0.088	0.084
Bayes Est	0.059	0.045	0.014	0.042	0.045	0.045	0.045	0.045	0.038	0.074	0.143	0.076	0.082	0.090	0.083

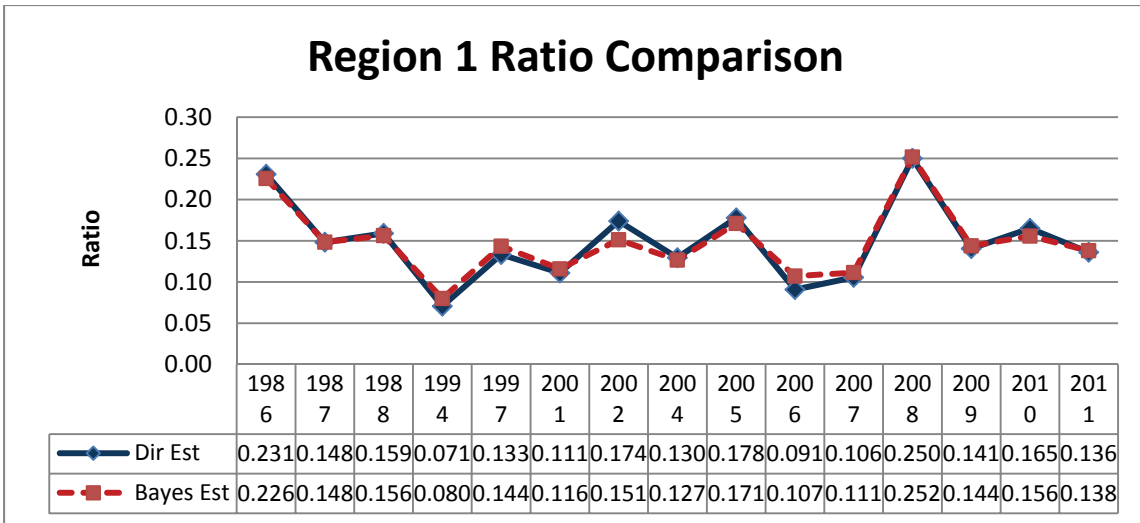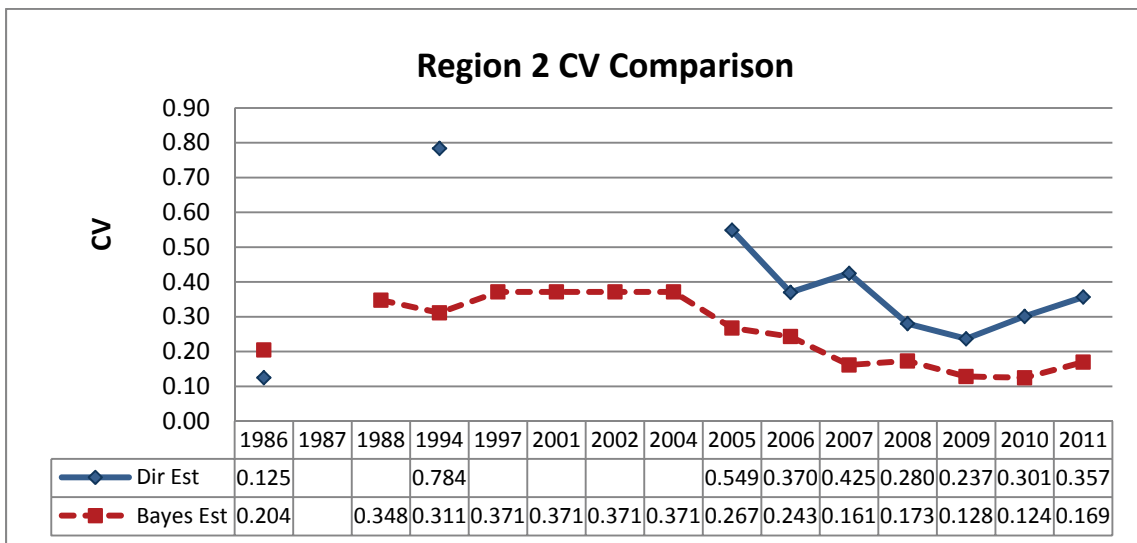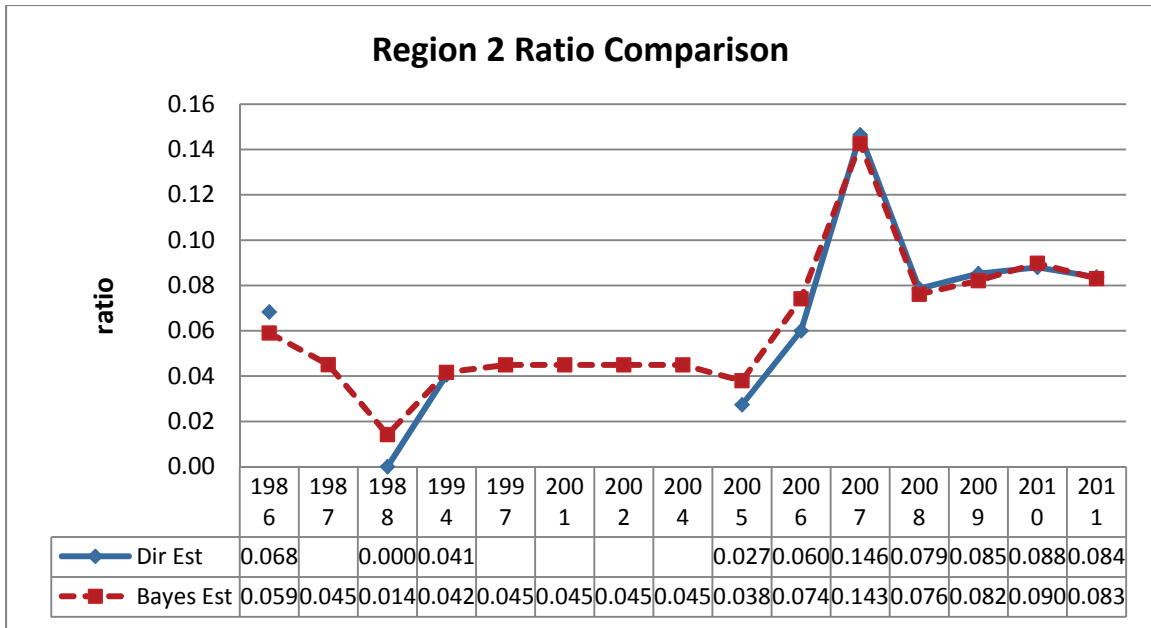|	1986	1987	1988	1994	1997	2001	2002	2004	2005	2006	2007	2008	2009	2010	2011
Dir Est	0.125			0.784					0.549	0.370	0.425	0.280	0.237	0.301	0.357
Bayes Est	0.204		0.348	0.311	0.371	0.371	0.371	0.371	0.267	0.243	0.161	0.173	0.128	0.124	0.169

Figure 3: Point estimates (above) and CV (below) of the spawning fraction (S_{12}) in region 2 based on the average of day-1 and day-2 female from original (diamond and solid line) and BHM estimates (square and dash line) from 1986-2011: point estimate (above) and CV (below). For years 1987,1997,2001,2002 and 2004, only Bayesian estimate was obtained.

Conclusions

For the Pacific sardine, improvements have been made for adult parameter estimates, primarily for the spawning fraction (S) and spawning biomass since 2009. The estimates of spawning fraction (S_{12}) based on the average numbers of day-1 and day-2 females to replace the number of day-0 female have lower CVs than those from the original ratio

estimate (Hill et al. 2010). The CV of spawning fraction from the Bayesian hierarchical model was further reduced from the CV of original estimates while the point estimates of BHM and the original method were similar for both regions. In many years, when no trawls were taken in region 2, (1987, 1997, 2001-2004) (Table 2), an overall estimate from the posterior predictive distribution for years <=2006 was used for all those years. The same estimate for many years may not be desirable for the stock assessment procedure, as experienced for years 1995-2001 and 2003. For years when no trawls were taken at all, (1996, 1998, 1999, 2000 and 2003), the estimates of total egg production (TEP) are used.

This BHM for the spawning fraction is a good exercise to seek alternative estimators for the spawning fraction. We chose not to use the BHM estimate after our analysis due to the following reasons:

1). The shrinkage effect from the Bayesian approach is small for future years when sample sizes are large, which we believe will continue. The reduction of CV of spawning biomass in region 2 does not have much effect on the CV of overall spawning biomass as the majority of spawning biomass was in region 1, in particular for recent years. Therefore the gain from the BHM is small and not be needed for the future years.

2). In many years, (1987, 1997, 2001, 2002 and 2004), no data were collected in region 2. All other adult parameters, (like fecundity, fish weight and sex ratios) were not available either and needed to be estimated by the HBM, which is not practical. If each of the other adult parameters was estimated by the mean of its posterior predictive distribution, the contribution of the change of the biomass in region 2 would be primarily due to the egg production and not the adult parameters as the estimates of adult parameters would be constant. Extensive computer programming is necessary to apply the BHM for all adult parameters in region 2 for years when no trawls were taken in region 2, which is not possible to implement right now.

and

3). The BHM requires the recalculation of estimates each year and the recalculation of yearly estimates are likely to be similar, which was demonstrated by the Bayesian estimates of spawning biomass up to 2010 and up to 2011(not shown in this report). Currently, for years when no adult samples were taken in both regions or in region 2, the total egg production (TEP) time series was obtained once for all and no recalculation is needed.

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APPENDIX 6

PFMC scientific peer reviews and advisory body reports

Pacific Sardine

STAR Panel Meeting Report

NOAA / Southwest Fisheries Science Center
La Jolla, California
October 4-7, 2011

STAR Panel Members:
André Punt (Chair), Scientific and Statistical Committee (SSC), Univ. of Washington
Ray Conser, SSC, Southwest Fisheries Science Center (SWFSC)
Larry Jacobson, External Reviewer, Northeast Fisheries Science Center
Chris Francis, Center for Independent Experts (CIE)

Pacific Fishery Management Council (Council) Representatives:
Lorna Wargo, Coastal Pelagic Species Management Team (CPSMT)
Mike Okoniewski, Coastal Pelagic Species Advisory Subpanel (CPSAS)
Kerry Griffin, Council Staff

Pacific Sardine Stock Assessment Team:
Kevin Hill, NOAA / SWFSC
Paul Crone, NOAA / SWFSC
Nancy Lo, NOAA / SWFSC
Beverly Macewicz, NOAA / SWFSC
Emmanis Dorval, NOAA / SWFSC
Jennifer McDaniel, NOAA / SWFSC
Yuhong Gu, NOAA / NWFSC

Acoustic- Trawl Survey Team
David Demer, NMFS, SWFSC
Juan Zwolinski, NMFS, SWFSC

Aerial Survey Team
Tom Jagielo, Tom Jagielo Consulting

1) Overview
The Pacific Sardine Stock Assessment and Review (STAR) Panel (Panel) met at the Southwest Fisheries Science Center, La Jolla, CA Laboratory from October 4-7, 2011 to review a draft assessment by the Stock Assessment Team (STAT) for Pacific Sardine. Introductions were made (see list of attendees, Appendix 1), the agenda was adopted, and Kerry Griffin reviewed the Terms of Reference (TOR) for CPS assessments with respect to how the Panel would be conducted. A draft assessment document and background materials were provided to the Panel in advance of the meeting on a SWFSC FTP site. The Chair, André Punt, noted that the assessment report included analyses related to estimating F_{MSY}, but that reviewing this analysis was beyond the scope of the TOR for the Panel.

Kevin Hill presented the assessment methodology and the results from a draft assessment utilizing the Stock Synthesis Assessment Tool, Version 3.21d (SS3) to the Panel. The model on which the draft assessment was based differed from that on which the 2009 assessment was based in several respects. The draft assessment included: (a) two rather than four fleets, (b) a later start-date for the assessment (1993 rather than 1981), (c) fewer time-blocks for selectivity, (d) no time-blocking for growth, (e) inclusion of the indices of abundance from the acoustic-trawl surveys, (f) revised age-reading error matrices, and (g) the aerial (and acoustic-trawl) surveys were assumed to be relative rather than absolute indices of abundance. The draft assessment benefited from a number of improvements to the abundance data and an improved understanding of the precision of the age data for sardine. The assessment was also based on other updated data streams, in particular additional age and length data for the Ensenada fishery.

David Demer, Nancy Lo, and Tom Jagielo respectively presented aspects of the methodology and results for the acoustic-trawl, Daily Egg Production Method (DEPM), and aerial surveys. The Panel agreed that the current approach of calculating spawning fraction for DEPM estimates should be continued and no futher work related to a Bayesian analysis of spawning fraction was required. The Panel noted, and was particularly appreciative of, the efforts made by the STAT to respond to the recommendations from past panels and the SSC.

The review and subsequent explorations of the assessment through sensitivity analyses were motivated primarily by the reasons for the changes from the last assessment, the poor residual patterns for some of the fits, understanding the best way to weight the various data sources, the considerable sensitivity of the estimate of current 1+ biomass to what would seem to be minor changes to the specifications of the assessment (see, for example request U below), and the assumptions related to catchability for the aerial and acoustic-trawl surveys. The Panel supported the effort by the STAT to simplify the assessment; with the aim of finding a more stable assessment (likelihood profiles presented to the Panel indicated that even though the assessment includes many data points, these are largely uninformative regarding current 1+ biomass).

The Panel noted that the approach to computing effective Ns in Appendix 2 differs from that used in most assessments of west coast coastal pelagic and groundfish species. This approach accounts for correlations among residuals within years, unlike the conventional

method of McAllister & Ianelli (1997), which is used in SS3 to calculate 'output' effective sample sizes. These correlations are often substantial (those shown in Figure 2 of Appendix 2 are typical). The SSC should consider whether the approach of Appendix 2 should be used regularly when conducting stock assessments for Council-managed stocks.

The STAR Panel thanked the STAT for their hard work and willingness to respond to Panel requests, and the staff at the SWFSC La Jolla laboratory for their exceptional support and provisioning during the STAR meeting.

2) Discussion and Requests Made to the STAT during the Meeting
Tuesday AM
A. Tabulate and plot the annual mean size-at-age in the catch by fishery (Mexico, California and Oregon/Washington) for semester 1; and superimpose the growth curve estimated in the model and, if possible, growth curves from the literature. ***Rationale***: To determine if there is evidence in the data for differences in growth by fishery and over time (mean size-at-age by fishery is not reported in the assessment document). These diagnostics may also provide some insight into possible model misspecification, and allow an evaluation of whether the estimated growth curve is biologically realistic. ***Response***: Mean size-at-age (averaged over years) was plotted for the various regions along the west coast. Mean size-at-age increased with latitude but decreased over time within region. The reduction in mean size-at-age over time was most apparent in the Pacific Northwest (PacNW) region, but most of the change occurred before 1991 (the assessment modeling begins in 1993).

B. Smooth the ageing error standard deviation (SD) relationship for California ages in 2007 (Figure 8 of the assessment report). ***Rationale***: Ageing error data are very noisy for fish older than 3.5 yr. The ageing error SD for age 4.5 is clearly an artifact. ***Response***: The spike in SD at age 4.5 was eliminated and linear extrapolation was used for all older ages. This change led to no changes in the 1+ biomass and became part of the base case for all subsequent model runs.

C. Conduct a run that does not use the ageing error matrix, or downweights the ageing error to near zero. ***Rationale***: To determine whether ageing error has an important effect on key assessment results. ***Response***: This change smoothed the recruitment estimates, but did not cause an appreciable change in the time-series of 1+ biomass.

D. Add the recommendations from the September 2010 SSC CPS Subcommittee review and the November 2010 SSC report to the recommendation list from the 2009 STAR Panel (see 2010 assessment document, p 135+). ***Rationale***: This will complete the assessment review history of requests and actions taken. ***Response***: This request could not be completed before the end of the Panel meeting and was added to the list of changes that need to be made to the final document.

Tuesday PM
E. Progressively estimate fewer recruitment deviations (2007-11) at the end of the time series. Carry out retrospective analyses (2007-11) to ascertain if estimating

fewer recruitment deviations improves the retrospective pattern. Determine the appropriate number of recruitment deviations to estimate using this analysis. Keep the number of recruitment deviations not estimated constant. **_Rationale_**: There are few data near the end of the time series to inform estimation of annual recruitment. **_Response_**: Changing the number of year classes forced to fall on the S/R curve near the end of the time series led to fairly large changes in 1+ biomass, especially near the end of the time series. The retrospective pattern seen in the base case generally persisted.

F. Check the estimate of biomass from the acoustic-trawl survey for summer 2008 and the CVs of these biomass estimates for all years. **_Rationale_**: Values in Table 5 of the assessment document appear to differ from those shown in the acoustic-trawl survey presentation. **_Response_**: The values were corrected. This change led to no difference in the estimates of 1+ biomass and the revised estimate of abundance became part of the base case for all subsequent runs.

G. Conduct a sensitivity run which replaces the CV for the spring 2008 acoustic-trawl survey with the average CV from the other acoustic-trawl surveys. **_Rationale_**: The CV for the spring 2008 acoustic-trawl survey (9.2%) appears to be too small given the CVs for the other acoustic-trawl surveys and the sampling issues experienced during the 2008 survey. **_Response_**: The CV was changed to the average value (CV=33%). This change led to no appreciable difference to the 1+ biomass.

H. Examine the effect on the biomass estimates from the aerial survey of using complete point sets observed from altitudes less than 4000 feet when fitting the density vs. school area relationship. **_Rationale_**: A considerable amount of potentially useful data are currently not being used in biomass estimation because of the operating constraint that requires the 4000 foot altitude. **_Response_**: The biomass estimate increased less than 10% and the CV decreased slightly. There was no appreciable change to the fitted curve to the density vs school size data.

I. Modify Table 7 (p.43) of the aerial survey report to include the sum of the biomass for each column, and do a paired t-test on the effect of different readers. **_Rationale_**: The Panel wanted to get a better understanding of the possible effects from the two independent readers. **_Response_**: While the paired t-test showed a difference at the α=0.05 level of significance, the biomass estimates from the two readers were quite similar. There appears to be no practical difference between the two readers.

J. Compute the autocorrelation function among positive transects from the 2011 aerial survey. **_Rationale_**: Strong autocorrelation will violate the assumption of independence among transects on which method used to calculate the CV for the 2011 aerial survey is based. **_Response_**: The correlation was 0.25 at lag 1; similar or smaller correlations were found for lags greater than 1. The transects appear to be sufficiently independent for application of the chosen method of variance estimation.

K. Compute the mean length of fish in each school from the point sets from the 2009, 2010 and 2011 aerial surveys, and plot by latitude. **_Rationale_**: To examine whether the size data from the point sets are representative of the sardine population in the Pacific Northwest; in particular, to determine whether the shift

(to the right) in length compositions over 2009-11 (Figure 11 of the aerial survey assessment report) are an artifact of the latitude at which the point sets were made. ***Response***: There are clearly year effects in mean length-at-age from the point sets, and some trend with latitude, but not enough to explain the misfitting of the length compositions in the assessment.

L. Plot catch weight vs. school area for the 2011 point sets and add a fitted line. ***Rationale***: This relationship may be an alternative to the density vs. school area relationship. ***Response***: The plot of catch weight vs. school area showed large variance and confirmed that density vs. school area is more likely to produce a useful predictive relationship.

M. Create a likelihood profile for q for the acoustic-trawl survey ($q = 0.25$ - 1.75). Tabulate the likelihood components for each discrete value of q used in the profile. ***Rationale***: To determine the key likelihood components over a range of biomass scalings. ***Response***: The total likelihood was flat across all values of acoustic-trawl q (less than 2 units difference over the entire range). The likelihood components for the indices of abundance and the age compositions favoured q at the high end of the range profiled (other than the PacNW age-at-length data), but the length compositions favored q at the low end of the range. However, the overall difference in likelihood units was small (~ 5 units) for all individual components over the full range of q ($0.25 \rightarrow 1.75$).

N. Conduct a run with initial F set to zero and continue to estimate the recruitment deviations starting in 1987. ***Rationale***: The initial F estimate in the base case model is not credible ($F=4$ yr^{-1}), and the estimated recruitment deviations are not significantly different from zero. Setting $F=0$ may result in better recruitment deviation estimates as a means of initializing the model, i.e. creating numbers-at-age at the start of 1993. ***Response***: This run led to a trend in 1+ biomass that was nearly identical to that for the base case, but overall 1+ biomass was approximately 50% greater than for the base case. The recruitment trend was also similar, but recruitment was ~30% larger than for the base case. Some of the later early deviations became significantly different from zero and R_0 increased approximately 35% compared to the base case. Early recruitment deviations were negative rather the zero as for the base case, indicating lower than average recruitment during late 1980s. The q estimates were more reasonable (all less than 1.0). The Panel and STAT agreed that this run (which also reflects the modifications from Requests B and F, above) was more plausible than the base case in the assessment document, and should serve as the base case for all subsequent runs.

O. Conduct a run with one vector of recruitment deviations, i.e. do not model early and main recruitment deviations separately. ***Rationale***: It was not clear to the Panel why the early and main recruitment deviations need to be modeled separately. ***Response***: This run was not carried out due to lack of time and the low priority given to it by the Panel.

P. Plot the sex ratio by length for each fishery. ***Rationale***: The model is not sex-specific. This plot will help to assess whether the data support a single-sex model. ***Response***: The sex ratios were plotted by length bin and region. The proportion of males decreases appreciably above the 21 cm size bin in all regions. It was also

noted that the sex ratio data by weight from the DEPM surveys also showed that the percentage of females in the spawning population is consistently greater than 50%. Future modeling may wish to consider sex explicitly (see research recommendations, below).

Q. Do a profile over S/R variability (σ_R) using the base case in the assessment document. Show the 1+ biomass trend for each σ_R. ***Rationale***: σ_R from the base case (σ_R=0.622) may be smaller than is typical for a small pelagics. ***Response***: As σ_R increases from σ_R=0.622, the 2011 1+ biomass increases considerably through σ_R=1.0, but 1+ biomass decreases markedly when σ_R>1.

R. Do a sensitivity run dropping the TEP index. ***Rationale***: The DEPM time series is now much longer that when the TEP index was first introduced. It may not be necessary to continue to use the TEP index which ignores variation among years in biological parameters. ***Response***: Removing the TEP index had little effect on the time series of 1+ biomasses.

Based on the requests, above, the Panel and STAT considered the run from Request N to be the candidate base case subject to the additional requests, below.

Wednesday

S. Create a separate Canadian fishery with selectivity mirrored to the USA portion of the PacNW fishery. Present length and conditional age-at-length residuals by fishery. If possible, keep the annual effective sample sizes the same as in the base case model. ***Rationale***: While this change should not affect model fitting and results greatly, it will provide additional diagnostics for understanding the poor fits to the length compositions from the PacNW fishery and to assess whether it is justified to pool data for Oregon, Washington and Canada. ***Response***: The residual pattern for the Canadian fishery is quite different than that for the USA PacNW fishery (the former has many more positive residuals at the larger sizes). The next stock assessment should consider establishing a separate Canadian fishery.

T. Create a separate Mexican fishery with selectivity mirrored to the USA portion of the MexCal fishery. Present length and conditional age-at-length residuals by fishery. If possible, keep the annual effective sample sizes the same as in the base case model. ***Rationale***: While this change should not affect model fitting and results greatly, it will assist the Panel examine whether it is justified to pool data across Mexico and California. ***Response***: The residual pattern for the Mexican fishery is somewhat different than that for the USA portion of the MexCal fishery (the former has more positive residuals at the larger sizes, particularly during semester 2). The next stock assessment should consider re-establishing a separate Mexican fishery.

U. Drop the 2008-10 conditional age-at-length data for the PacNW fishery. ***Rationale***: The age readings from these years appear to be quite different from all other years. ***Response***: The trend in 1+ biomass is similar to the base case (run N), but the average biomass is much reduced - current 1+ biomass is ~20% less that for run N.

V. Reduce the multipliers for the effective sample sizes for the length composition data using the Francis vector (Appendix 2 of this report) and reduce the multipliers for the effective sample sizes for the conditional age-length data by 90%. ***Rationale***: Considerable among-length / -age correlation is evident in both the length composition and conditional age-at-length residuals, but the method used to infer effective sample sizes in SS3 assumes independence among residuals. Hence, the presence of strong correlation, combined with the method used in SS3 to compute downweighting factors, effectively over-weights the age and length data. ***Response***: The trend in 1+ biomass differed from that for the base case (run N) and all other runs examined to date. The average 1+ biomass was lower than for run N, but closer to that run than to the average biomass from run U. The fit to the indices were similar to those seen in all earlier runs.

W. Apply a model that fits predominately to age-based data. Use the age composition data rather than the combination of length and conditional age-at-length data, whenever available; do not use length data whenever acceptable age data are available; fix growth using the base case (run N) parameter estimates; continue using length-based selectivity for the fisheries (as in the base case); and use the effective sample sizes and lambda multipliers for the length data from the base case for the age data. ***Rationale***: The sardine assessment is unusual in that a large proportion of the sampled fish are aged. The additional information from length compositions may be marginal, and the model has difficulty fitting the length compositions. This should be considered an exploratory model, i.e. not one that is likely to be used as a base case for this year's assessment. ***Response***: Selectivity at length did not differ greatly from for the base case run (some selectivity curves were steeper at small sizes, but had similar points of inflection). The recruitment deviations for recent years differed markedly from those for run N (all were highly positive). Fits to indices of abundance were generally similar; as were fits to the age compositions. The trend in 1+ biomass differed from that for run N (two roughly equally high peaks) and the average 1+ biomass was slightly lower than for run N. The next stock assessment should consider an approach similar to the one explored here.

Thursday

X. Conduct six additional model runs based on the current base-case model (run N):
1. fix DEPM survey $q=0.5$ and retain length and conditional age-at-length composition weighting as in run N;
2. fix DEPM survey $q=0.5$ and weight the length and conditional age-at-length composition data as in run V;
3. fix aerial survey $q=1$ and retain length and conditional age-at-length composition weighting as in run N;
4. fix aerial survey $q=1$ and weight the length and conditional age-at-length composition data as in run V;
5. fix acoustic-trawl survey $q=1$ and retain length and conditional age-at-length composition weighting as in run N;
6. fix acoustic-trawl survey $q=1$ and weight the length and conditional age-at-length composition data as in run V.

Rationale: The results of these runs are needed to address two issues: (i) the scale of biomass in the assessment is not well determined; fixing $q=1$, one survey at a time, should better inform the scale issue; and (ii) the length and conditional age-at-length data appear to be over-weighted relative to the indices of abundance (see Request V, above), but the full impact of alternative weighting needs to be more fully examined. *Response*: The estimate of 2011 1+ biomass (used in the PFMC control rule) was greater in run N than in any of runs X.1 through X.6. The trend in 1+ biomass was similar in runs X.1, X.3 and X.5 to that for run N, but those for runs X.2, X.4, X.6 (when the age and length data were further down-weighted relative to the indices) differed from that for run N. The fits to the indices of abundance were similar across all runs. Biomass scaling differed most from run N for runs X.1, X.2, and X.6. The realized S/R variability was noticeable smaller for run X.6 ($\sigma_R=0.39$). The estimated q's for the aerial and acoustic-trawl surveys were most plausible for runs X.3 through X.6 (i.e., except when the DEPM indices were assumed to be absolute).

Y. Use run X.5 (above) as the reference run (i.e. a candidate for a new base case) and conduct six additional runs:
   1. drop the conditional age-at-length data from the PacNW fishery for 2008-10 (analogous to run V);
   2. constrain only the last recruitment such that it falls on the S/R curve;
   3. constrain the last three recruitments such that they fall on the S/R curve;
   4. fix $\sigma_R = 0.4$;
   5. fix $\sigma_R = 0.8$; and
   6. fix $\sigma_R = 1.0$.

Rationale: Run N has been the candidate base case, but it exhibited some instabilities – particularly in biomass scale (see Requests E, Q, and U, above). The q for the acoustic-trawl survey was fixed ($q=1$) in run X.5 in an effort to provide more stability. This set of runs was designed to examine the stability of run X.5 relative to the stability of run N. *Response*: Run Y.1 showed the largest effect on biomass scaling (relative to run X.5), but the amount of change in biomass scaling was much less than was seen for the comparable sensitivity run based on run N (*cf.* Request U). The biomass scaling effect was not greatly different for Run Y.2 than that for the comparable runs based on the base case in the assessment document (*cf.* Request E). However, runs Y.5 and Y.6 did show improved stability in biomass scale relative to the comparable sensitivity runs based on run N (*cf.* Request Q). The biomass series for runs Y.3 and Y.4 differed from that for run X.5, but SS3 failed to converge for these runs so the Panel could not draw conclusions regarding stability.

Z. Consider run X.5 to be the new base case and make a final set of sensitivity runs:
   1. jitter to the 10% level; for each jitter, present total likelihood, q for all surveys, terminal year 1+ biomass and exploitation rate;
   2. create a likelihood profile on M [0.25-0.75yr^{-1}; step size 0.125yr^{-1}]; for each M, present total likelihood, q for all surveys, terminal year 1+ biomass and exploitation rate;

3. create a likelihood profile on the q for the acoustic-trawl survey [0.25-2.00; step size 0.25]; for each q, present total likelihood, q for all surveys, terminal year 1+ biomass and exploitation rate;
4. conduct a retrospective analysis over the last 5 years (2007-11); for each terminal year, present time-series of 1+ biomass and recruitment;
5. conduct a prospective analysis over the first 5 years (1993-97); for each initial year, present time series of 1+ biomass and recruitment.

Rationale: Additional runs are needed for the candidate base case (run X.5) to check for local minima; to identify the major axis of uncertainty and to quantify same; and to check for retrospective and prospective patterns. ***Response***:

1. **Run Z.1** (test for local minima). The full jitter was not completed, but will be included in the final assessment document. A few runs with R_0 changed converged to the same minimum as run X.5.

2. **Run Z.2** (*M* profile) showed that the total likelihood and the conditional age-at-length likelihood tend to strongly favor higher natural mortality rates than assumed in the base case; the length compositions favored a somewhat higher *M*. Increasing *M* reduces 2011 1+ biomass and increases the exploitation rate. The *M* profile is quite similar to the corresponding profile from the 2010 assessment.

3. **Run Z.3** (*q* profile) indicated that the length compositions do not inform the choice of acoustic-trawl q, but the conditional age-at-length data do have some influence. Overall, however, the likelihood surface is quite flat (even after fixing the acoustic-trawl q) – the profile showed a difference of only 2 units over the entire range of q (0.25 - 1.75). As expected, terminal year biomass and *F* were greatly affected by q.

4. **Run X.4** (retrospective analysis) showed an appreciable retrospective variability (up to 400,000 t changes among years in terminal biomass), but no systematic effect (i.e. the pattern is mixed - some high some low).

5. **Run X.5** (prospective analysis) showed modest changes in early year biomass estimates (and no systematic pattern), but virtually no change in 2011 biomass.

3) Technical Merits and/or Deficiencies of the Assessment
During its deliberations (see Section 2 of this report) the Panel identified a number of issues which should be explored for the assessment of Pacific sardine (see Section 6) including (a) further downweighting of the age and length data; (b) use of age-compositions rather than the combination of length-compositions and conditional age-at-length data, given within-year growth and among-region variation in growth; (c) additional fleets; and (d) inclusion of spatial- and sex-structure. Several analyses were conducted by the STAT to examine whether such changes warrant consideration in future. However, the STAT stated that major changes to the structure of the assessment should not be made without full and careful analyses of model structure and weights. The Panel agreed with the STAT that making these types of changes was not feasible in the time available and therefore focused on model configurations with two fleets and no spatial- or sex-structure. Some of these suggested changes may lead to more complicated models that cannot be supported by available, largely uninformative, data, and which may exhibit the types of undesirable behaviours seen in previous assessments. These

changes should therefore only be implemented if there are clear benefits to the assessment and management of the stock.

Although trends in 1+ biomass do not change much given changes to the specifications to the assessment (although not necessarily to marked changes in data weighting), absolute biomass is poorly determined. The STAT and Panel therefore agreed that an appropriate way to increase stability in the assessment was to fix the q for one of the surveys. This is not an ideal approach, and the Panel recommends that the next full assessment include the development of informative priors for the q parameters for the DEPM, aerial and acoustic-trawl surveys. Development of informative priors is a non-trivial task and should involve people in addition to the STAT, in particular the surveys teams; therefore this task should start before the analytical work on the assessment itself, perhaps in the form of a workshop. The STAT and Panel agreed to impose the assumption $q=1$ for the acoustic-trawl survey because (a) there are more estimates of abundance for this series than for the aerial survey, (b) the acoustic-trawl survey is more synoptic than the aerial survey, (c) the estimates are generally more precise than those for the aerial survey, and (d) the assumption $q=1$ for the DEPM survey leads to unrealistic values of q for the aerial and acoustic-trawl surveys (>1.8). While the SSC recommended that strong evidence is needed to assume $q=1$ for any survey, the STAT and Panel agree that in this instance it is best available science to make this assumption. The use of $q=1$ for this assessment is, however, _not_ an endorsement of this assumption for future assessments. Rather it is preference of the STAT and Panel to use informative q priors in future. However, this is not feasible at present.

The STAT and Panel strongly agreed that it would be better in principle to downweight the age and length data using an approach such as that of Appendix 2 of this report. However, runs with the downweighted data led to lower than expected values for the root mean square error of the recruitment deviations (0.391 for the acoustic-trawl $q=1$ run), and to a growth curve which did not match the size-at-age data well. Further work on models with downweighted age and length data should form part of the next full assessment, but there was insufficient time during the Panel to find a model configuration which downweighted the data and did not exhibit poor behaviour in other respects.

The final base model incorporates the following specifications:
- two seasons (Jul-Dec and Jan-Jun) (assessment years 1993 to 2011);
- sex is ignored;
- two fleets (MexCal, PacNW), with an annual selectivity pattern for the PacNW fleet, and seasonal selectivity patterns for the MexCal fleet;
- length-based, double-normal selectivity with time-blocking (1993-1998, 1999-2011) for the MexCal fleet; asymptotic length-selectivity for the PacNW fleet;
- Ricker stock-recruitment relationship with estimated "steepness";
- $M = 0.4$ yr^{-1}; $\sigma_R = 0.622$ (tuned value);
- initial recruitment estimated; recruitment residuals estimated for 1987-2009;
- length-frequency and conditional age-at-length data for all fisheries;
- virgin (R_0) and initial recruitment offset (R_1) were estimated;
- initial Fs set to 0 for all fleets;

- DEPM and TEP measures of spawning biomass; q estimated;
- aerial survey biomass, 2009-2011, q estimated, domed selectivity; and
- acoustic-trawl survey biomass, 2006-2011, $q=1$, asymptotic selectivity.

The Panel agrees that the final base model represents the best available science regarding the status of the northern subpopulation of Pacific sardine.

It is difficult to fully characterize uncertainty in the assessment. However, estimates of 1+ biomass from sensitivity analyses about run N, including runs with $q=1$ for each survey (Figure 1 of this report), are a crude depiction of the underlying uncertainties.

An important uncertainty not addressed elsewhere stems from the differences in biomass scale and trend indicated by the acoustic, DEPM and aerial surveys (see Figure 15 in the assessment report). In trying to fit all of the surveys, the final base case model estimates an average trend that does not match the trends in any of the individual surveys. In particular, the final model does not match or explain the relatively substantial and consistent decline in the acoustic-trawl survey during 2007-2011. In future assessments, it would be advisable to examine models that may better fit the trend in each of the individual surveys.

4) Areas of Disagreement
There were no major areas of disagreement between the STAT and Panel, nor among members of the Panel.

5) Unresolved Problems and Major Uncertainties
1. The ongoing uncertainties, in particular regarding absolute biomass, are likely to persist until the information content of the data increases substantially.
2. The Panel wishes to highlight that the level of variation in terminal biomass evident from the retrospective pattern (on the order of 100,000s of tons from one year to the next; Figure 2 of this report) is not unexpected, and changes in terminal 1+ biomass estimates of this extent may occur when the 2012 assessment update occur.
3. The indices of abundance do not exhibit consistent trends even after allowing for the differences in their respective selectivities, and remain in conflict even when the age and length data are greatly down-weighted.
4. The data set is able to estimate general trends in abundance fairly robustly, but the likelihood is flat over a wide range of current biomass levels, which means that relatively small changes to the data set or assumptions can lead to marked changes in current abundance. The current assessment has somewhat reduced the influence of this lack of information by fixing survey catchability. Ultimately, it is only through further data collection (or the development of informative priors for survey catchability) that these uncertainties may be overcome.
5. The STAT evaluated a large number of model configurations to identify a more stable model that fits the data better. However, the residual patterns for the composition data and indices remain unsatisfactory. Furthermore, attempts to split the data by fleet to reduce some of these patterns led to unrealistic results (e.g. Fs > $2yr^{-1}$ in recent years for the MexCal fishery). The Panel identified the need to consider models with sex-

and spatial-structure, but there was insufficient time to develop, test, and evaluate such models during the Panel meeting.

6. Further downweighting the age and length data is warranted given the analyses in Appendix 2 of this report. However, time is needed to find a model configuration that does not lead to undesirable diagnostics (such as a low value for the root mean square error for the recruitment deviations, or a poor fit to the size-at-age data, as found in initial models examined during the meeting).

7. The period covered by the current assessment starts in 1993 (rather than in 1981 as in past assessments). This change was necessary because of a variety of factors, including lack of precise abundance estimates for the years 1981-92, lack of age and length data for the Ensenada fishery (only three years of data), and the fact that the age and length data for southern California were collected from an incidental fishery for sardine for much of this period. In addition, the growth data for these years is inconsistent with the later growth data and was one reason for the previous assessment invoking the assumption of time-varying growth. While the Panel supports the change in start year, dropping the early data means that it is no longer possible to assess the state of the stock prior to 1993, which adds to uncertainty about the dynamics of this population and current biomass levels.

8. The scarcity of old and large sardines in the data relative to model estimates is a fundamental tension in the assessment that may be due to assumptions about, for example, growth, selectivity, natural mortality, and data weighting.

6) Issues raised by the CPSMT and CPSAS representatives during the meeting
a) CPSMT issues
The CPSMT representative commends the Panel and STAT for the significant amount of work accomplished prior to and during the meeting, and for a conducting a well-run review. The CPSMT representative notes that poor fitting of age data from fisheries in the Pacific Northwest by the model was identified as potentially an age reading issue and encourages efforts to evaluate whether or not this is the case, or if there is another reason. The upcoming ageing workshop in December 2011 offers an excellent opportunity to pursue future exchanges of otoliths for comparison among readers in the various laboratories. Previous recommendations have called for new indices to be incorporated into the sardine stock assessment. The CPSMT representative is encouraged to see the acoustic-trawl survey and aerial survey as recent additions, and notes that another survey (Canadian trawl survey) may be under consideration as well. The CPSMT representative suggests that in addition to considering new surveys in the next assessment, that a comparable effort to further refine and improve all data sources should be made to ensure these data are as informative as possible.

The Panel's consensus is that the model is very sensitive to relatively minor changes in parameters and data, and thus the biomass estimate is subject to significant variations of several hundred thousand metric tons. Given this uncertainty inherit in the model, the CPSMT representative suggests careful consideration of this fact when establishing sardine harvest management measures.

b) CPSAS issues

The CPSAS representative commends the Panel and STAT for integrating a new acoustic-trawl survey into the SS3 model. Previous Panels, the CPS Advisory Bodies, and the SSC have remarked that additional work was needed in the areas of surveys to enrich the data sources that are use when fitting the model.

Industry wants to see a sustainable resource that is not in danger of being overfished. Overfishing makes a poor platform for economic investment. That said, the CPSAS representative does not believe there is any immediate danger that overfishing is taking place at present. Anecdotal reports from Ensenada to the Queen Charlottes suggest that the sardine biomass is larger at this point in the expansion cycle than at any time since the last expansion. Boats in Westport Washington and Monterey California were often able to do "daily doubles" when there was sufficient processing capacity during the brief fishing periods this summer. Canadian vessels now report a "solid wall" of fish in October the entire length of West Vancouver Island.

The CPSAS representative does not have concerns about the model work, but it is very complex. The model demands data to function rationally. Slight tweaks to data and assumptions can lead to huge swings in outputs, particularly for the original base model. The model cannot operate effectively without robust data. The acoustic-trawl survey is a welcome tool, but when strictly coupled with the habitat model, migration theory, and certain assumptions on vessel avoidance we believe that this survey capacity is not fully utilized. The 2011 Sardine Workshop recommended utilization of the acoustic-trawl survey with application of a powerful sonar during the height of the summer feeding season, when the sardines are in peak abundance simultaneously in the Northwest and Canada. These stocks should be surveyed in Canada to the northern end of their range.

It is now known that the Canadian swept-trawl survey CV reported previously was an over-estimate. A recommendation of the 2009 STAR Panel was to consider possible use of the Canadian data in the stock assessment. One reason for not doing so in the current assessment was the high CV. The CPSAS representative recommends that this important data source be utilized as soon as feasible, and believes that there well may be, an older, and as large a biomass in Canada at peak season as inhabits the Northwest at the same time. None of this information is presently available for the modeling platform. To advance use of the Canadian survey data will require a methodology review for the swept trawl survey. This should be undertaken in 2012.

The CPSAS representative would like to thank the STAT, the SWFSC, the survey teams, and the Panel, along with the public for their hard work, dedication, and time.

7) Research Recommendations (not in priority order)
A. Continue to explore possible additional fishery-independent data sources. As noted by previous Panels, there would be value in attempting to include the data from the mid-water trawl surveys off the west coast of Vancouver Island (see Appendix 3 of this report for an overview) in the assessment. However, inclusion of a substantial new data source would likely require review which would not be easily accomplished during a standard STAR Panel meeting so would likely need to be reviewed during a

Council-sponsored Methodology Panel. Similarly, the information provided on presence of sardine in the SWFSC juvenile rockfish survey should be explored further for possible inclusion in the future assessment.

B. The Panel continues to support expansion of coast-wide sampling of adult fish for use when estimating parameters in the DEPM method (and when computing biomass from the acoustic-trawl surveys). It also encourages sampling in Mexican and Canadian waters (aerial and acoustic-trawl surveys).

C. Temperature at catch could provide insight into stock structure and the appropriate catch stream to use for assessments, because the southern subpopulation is thought to prefer warmer water. Conduct sensitivity tests to alternative assumptions regarding the fraction of the MexCal catch that comes from the northern subpopulation

D. The assessment would benefit not only from data from Mexico and Canada, but also from joint assessment, which includes assessment team members from these countries.

E. Conduct additional studies on stock structure - otolith and microchemistry studies are useful tools for this purpose.

F. The relationship between environmental correlates and abundance should be examined. In particular, the relationship between environmental covariates and overall recruitment levels as well as recruitment deviations should be explored further.

G. Consider spatial models for Pacific sardine, which can be used to explore the implications of regional recruitment patterns and region-specific biological parameters. These models could be used to identify critical biological data gaps as well as better represent the latitudinal variation in size-at-age.

H. Explore models which consider a much longer time-period (e.g. 1931 onwards) to determine whether it is possible to model the entire period and determine whether this leads to a more informative assessment and to provide a broader context for evaluating changes in productivity.

I. Modify Stock Synthesis so that the standard errors of the logarithms of 1+ biomass can be reported. These biomasses are used when computing the Overfishing Level, the Acceptable Biological catch, and the Harvest Level, but the CV used when applying the ABC control rule is currently that associated with spawning biomass and not 1+ biomass.

J. In relation to the aerial survey: (a) provide the otoliths collected from the point sets to the SWFSC for possible ageing, (b) explore different functional forms for the mean relationship between school density and area (e.g. splines) as well as the variation about the mean curve (e.g. gamma), and (c) consider possible covariates (e.g. average fish size) in the relationship between catch weight and area.

K. Modify the r4ss package to include a plot of correlations among the residuals for the length and data data, as well as the fit of the model to the mean length or age in each composition (see Appendix 2 of this report).

L. Consider a model which explicitly models the sex-structure of the population and the catch.

M. Consider a model which has separate fleets for Mexico, California, Oregon-Washington and Canada.

N. Develop a relationship between egg production and age which accounts for the duration of spawning, batch fecundity, etc. by age.
O. Consider model configurations which use age-composition rather than length-composition and conditional age-at-length data given evidence for time- and spatially-varying growth.
P. Further explore methods to reduce between-reader ageing bias. In particular, consider comparisons among laboratories and assess whether the age-reading protocol can be improved to reduce among-ager variation.
Q. The reasons for the discrepancy between the observed and expected proportions of old animals in the length and age compositions should be explored further. Possible factors to consider in this investigation include ageing error / ageing bias and the way dome-shaped selectivity has been modeled.
R. Any future management strategy evaluation work to compare control rules should focus on alternatives which are as robust as possible to uncertainty regarding absolute abundance.
S. Profiles on key parameters should be included in future draft assessment to facilitate initial review.

Suggestions for modifications to the assessment report
A. Add a section on 'data sources considered but not used.'
B. Add a description of the derivation of the acoustic-trawl estimates in an appendix to the assessment report.
C. Add text to the report to explain why selectivity blocking was changed. Discuss whether the resulting selectivity patterns are consistent with auxiliary information on the behaviour of sardine and the fishery.
D. Add an update to Table 5a from the previous aerial survey report to the current report, and add the intended and achieved distribution of point sets by weight.
E. Document how the reweighting of the model was done (including changes in effective Ns for the age and length data and extra CVs for the abundance indices)
F. Add the recommendations from the September 2010 SSC CPS Subcommittee review and the November 2010 SSC review to the recommendation list from the 2009 STAR Panel (see 2010 assessment document, p 135+).
G. Include profiles and prospective and retrospective analyses for the final base model and the full range of sensitivity tests, including those in which the age and length data are downweighted, and each survey is assumed to be an absolute index of abundance, in the final report.

Reference
McAllister, M.K., and Ianelli, J.N. 1997. Bayesian stock assessment using catch-age data and the sampling-importance resampling algorithm. *Can. J. Fish. Aquat. Sci.* 54: 284‑300.
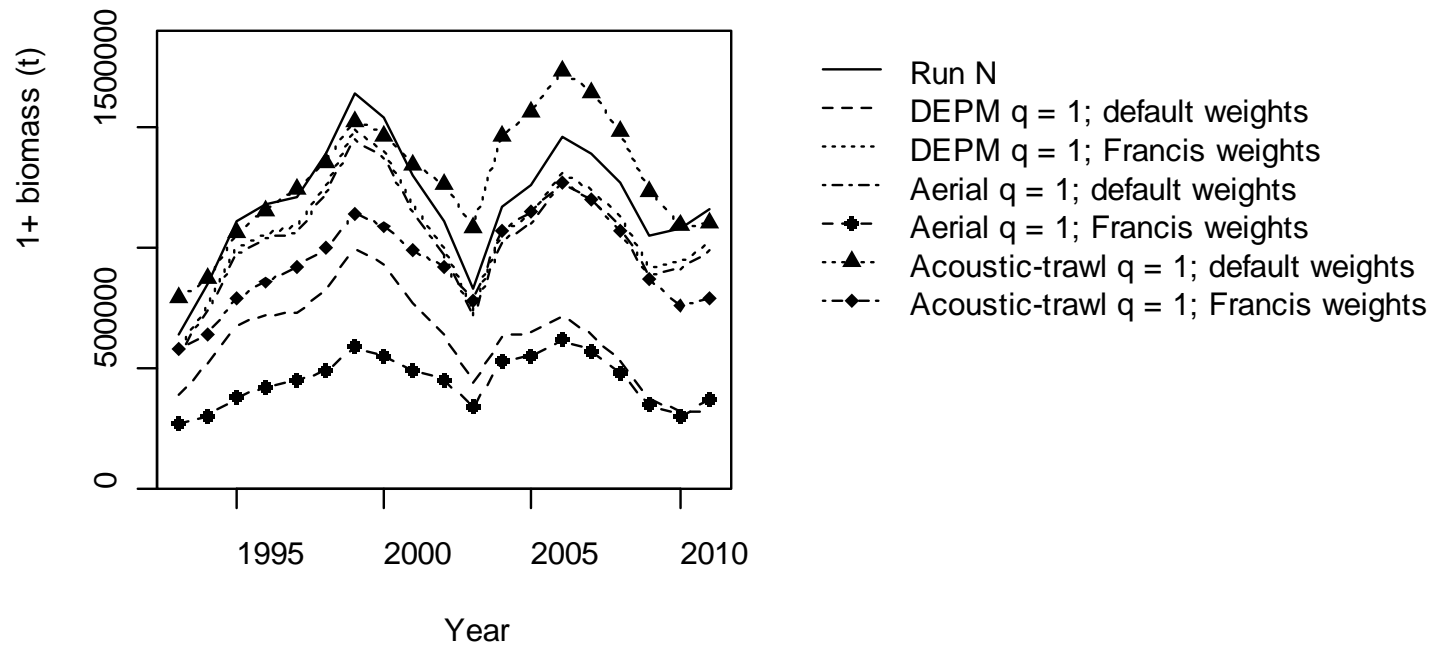
Figure 1. Time-trajectories of 1+ biomass from run N and six variants of this run in which each of three survey series are assumed to be absolute indices of abundance and the weights assigned to the age and length data are set to the default values and reduced as in run X.
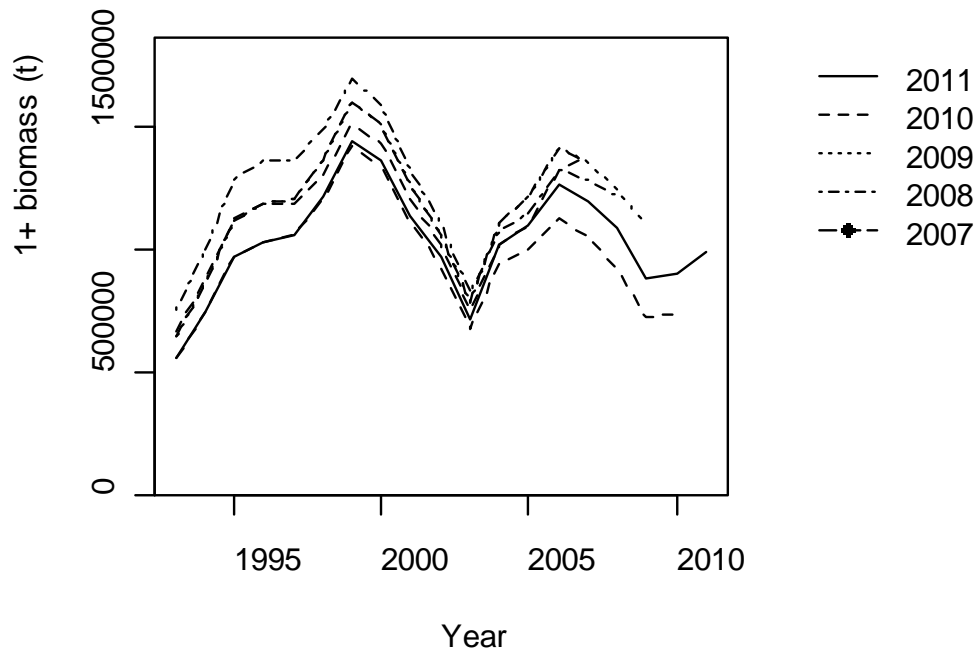
Figure 2. Results of the retrospective analysis based on the final base model.

Appendix 1
2011 Pacific Sardine STAR Panel Meeting Attendees

STAR Panel Members
André Punt (Chair), University of Washington
Ray Conser, NOAA Southwest Fisheries Science Center
Chris Francis, New Zealand National Institute of Water & Atmospheric Research
Larry Jacobson, NOAA Northeast Fisheries Science Center

Other Attendees
Mike Okoniewski, CPSAS Rep to STAR Panel
Lorna Wargo, CPSMT Rep to STAR Panel
Kevin Hill, NOAA Southwest Fisheries Science Center (SWFSC)
Kerry Griffin, Council Staff
Jenny McDaniel, SWFSC
Nancy Lo, SWFSC
Beverly Macewicz, SWFSC
Paul Crone, SWFSC
David Demer, SWFSC
Greg Krutzikowsky, ODFW
Steve Marx, Pew Charitable Trusts
Piera Carpi, UMass, Dartmouth
Sandy McFarlane, Canadian DFO & Canadian Pacific Sardine Association
Linnea Flostrand, Canadian DFO
Bob Seidel, Commercial fishing
Kirk Lynn, CDFG
Jerry Thon, Northwest Aerial Sardine Survey (NWSS)
Tom Jagielo, NWSS
Dale Sweetnam, SWFSC
Erin Reed, SWFSC
Sam Herrick, SWFSC
Diane Pleschner-Steele, CA Wetfish Producers Association
Ryan Howe, NWSS
Richard Carroll, Ocean Gold Seafood
Ed Weber, SWFSC
David Haworth, Commercial fishing
Fabio Campanella, SWFSC
Josh Lindsay, NMFS SWR
Christina Show, SWFSC
Russ Vetter, SWFSC
Emmanis Dorval, SWFSC
Kristen Koch, SWFSC
Briana Brady, CPSMT

Appendix 2
Comments on Weighting of Composition Data
Chris Francis

The composition data in many stock assessment models are given too much weight because most approaches to assigning weight to this type of data ignore the strong correlations in these data (and also in the associated residuals). A useful way to highlight this problem is to plot observed and expected mean lengths (or ages), as in done in Figure 1 for the base model length comps. The fact that the expected mean lengths in this plot are often outside the confidence intervals for the observations indicates that the data are over-weighted. Down-weighting these data (by decreasing the multinomial sample sizes) would increase the width of the plotted confidence intervals.
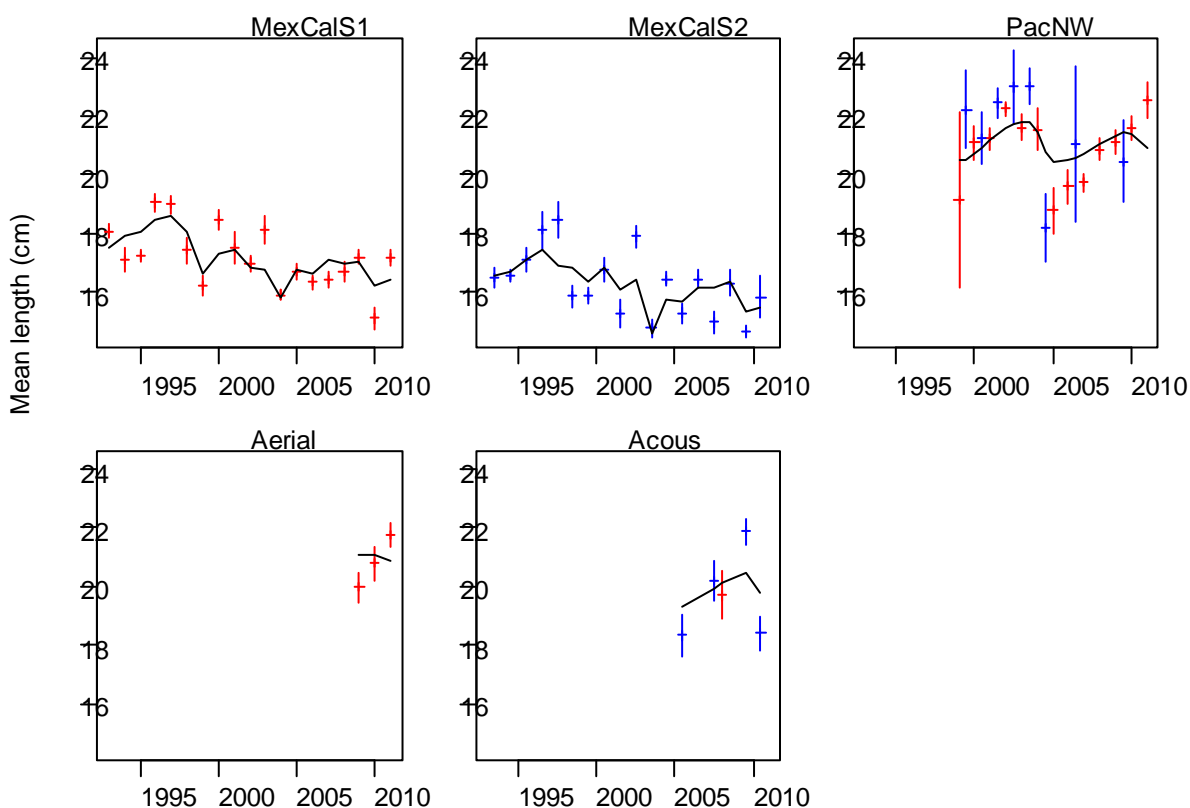

Figure 1: Observed ('+', with 95% confidence intervals shown as vertical lines) and expected (lines) mean lengths for all length composition data in the base model. The plotting colour of the observed values indicates the semester (red for semester 1, blue for semester 2). The confidence intervals were calculated using the multinomial sample sizes assumed for the base model (i.e., the products of the initial sample sizes and effN_mult_Lencomp values in Tables 4 and 9 of the assessment report).

The method of iteratively reweighting composition data in Stock Synthesis implicitly assumes that the residuals associated with one length (or age) bin are uncorrelated with those in another bin. In fact, correlations between composition residuals are often strong, and show a characteristic pattern like that in Figure 2.

One way of avoiding over-weighting composition data (by ignoring these correlations) is to base the re-weighting calculations on the residuals of mean length (or age), rather than on residuals of individual proportions. When this was done for the length composition data in the base model it suggested that the multinomial sample sizes for these data should be smaller by a factor of 0.06 – 0.1 (Table 1).

Full details about this method of re-weighting composition data are given in Francis (2011) [see method TA1.8 in Table A1; the w_j in that table is the same as the N_multipler in Table 1 below].
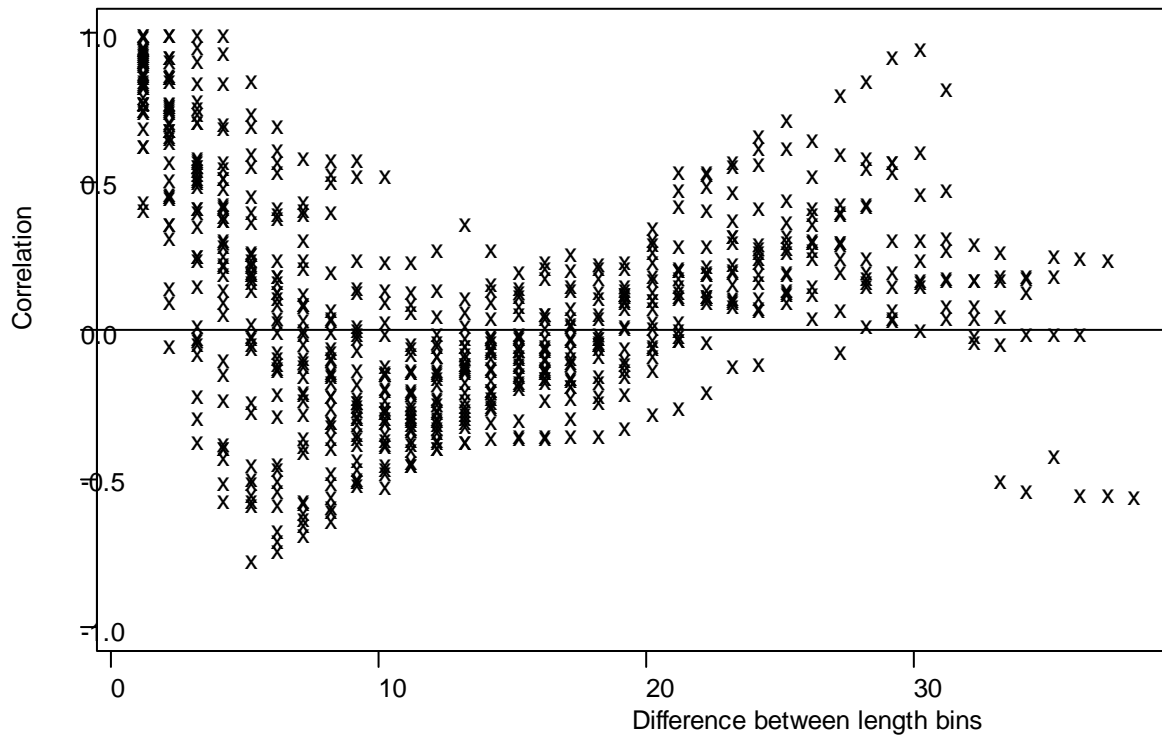

Figure 2: Correlations amongst the residuals from the MexCal_S1 length comps in the base model. Each plotted point represents a correlation between the vector of residuals for one length bin and that for a different length bin; the x-axis shows the difference (number of bins) between the two length bins.

Table 1: Suggested reweighting of the length composition data from the base model, showing the median sample sizes assumed for each data set in the base model (N_base), an N multiplier calculated from the mean length residuals, and the suggested median sample sizes (N_new), which are the product of N_base and the multiplier. Because of small sample sizes (i.e., few years of observations), the N_multiplier for the aerial and acoustic-trawl surveys was calculated by combing these two series.

Data set	Median N_base	N_multiplier	Median N_new
MexCalS1	135.9	0.058	7.9
MexCalS2	117.7	0.061	7.2
PacNW	40.9	0.104	4.3
Aerial	14.8	0.067	1.0
Acous	43.5	0.067	2.9

Reference

Francis, R.I.C.C. (2011). Data weighting in statistical fisheries stock assessment models. *Canadian Journal of Fisheries and Aquatic Sciences* **68**: 1124–1138.

Appendix 3
West coast of Vancouver Island sardine trawl survey

Provided by L. Flostrand and J. Schweigert
Department of Fisheries & Oceans Canada
Pacific Biological Station, 3190 Hammond Bay Rd. Nanaimo, BC V9T 6N7

Summer surveys directed at collecting information on sardines off the West coast of Vancouver Island (WCVI) started in 1997. Fishing is conducted in surface waters (≤ 30 m) using a mid water trawl towed at average speeds approximating 4-5 knots. Since 2006, sampling has been conducted at night. Biomass estimates are based on extrapolating the average sardine catch density (metric ton /km^3) by stratum over an estimate of the stratum's spatial size (km^3) and then summing across strata. The core area of the survey region is approximately 16,740 km^2 and catch densities are assumed to represent sardine distributions in the top 30m of the region, therefore the region's surface volume is estimated at ~ 502.2 km^3 (see Figure below). Recent regional estimates of sardine catch density and seasonal biomass in the WCVI core survey region from night sampling in 2006 and 2008 to 2010 (no survey was conducted in 2007) show a declining trend, whereas the 2011 estimates are approximately double the 2010 estimates (see Table below).

The current Canadian harvest control rule is based on the U.S. assessment of coastwide adult biomass and the migration rate of sardines into Canadian waters (Ware 1999, Schweigert et al 2009, DFO 2009), upon which a harvest rate equivalent to the U.S. rate is established (a 15% harvest rate has been in place since 2002; DFO 2010). More information on the provision of science advice and the harvest control rule is reported in the 2011 Science Advisory Report on the *Evaluation of Pacific sardine stock assessment and harvest guidelines in British Columbia* (http://www.dfo-mpo.gc.ca/csas-sccs/Publications/SAR-AS/2011/2011_016-eng.pdf, DFO 2011)

Table. Summary information and statistics associated with West Coast Vancouver Island (WCVI) trawl survey sardine catch densities and biomass estimates. For 95% confidence interval, LL= lower limit and UL= upper limit.

YEAR	2006	2008	2009	2010	2011 [*]
WCVI SAMPLING					
Tows with sardines / total number of tows	42/45	44/71	53/109	40/72	41/68
Core survey region					
Tows with sardines/ total number of tows	41/44	40/60	47/95	37/57	41/68
SARDINE DENSITY (mt/km^3)					
Mean	759.9	420	378.3	163.2	~300.0
95% LL	461.6	196.5	220.2	57.6	Not available
95% UL	1,105.60	736.4	557.8	309.7	Not available
CV **	0.23	0.33	0.23	0.39	~0.28
BIOMASS (mt)					
Mean	381,617	210,924	189,977	81,964	~150,000
95% LL	231,816	98,682	110,589	28,927	Not available
95% UL	555,232	369,820	280,127	155,541	Not available

* 2011 estimates are preliminary and have not been reviewed

** CVs presented above have been corrected from previously reported estimates (reported to have ranged from ~ 1-3).
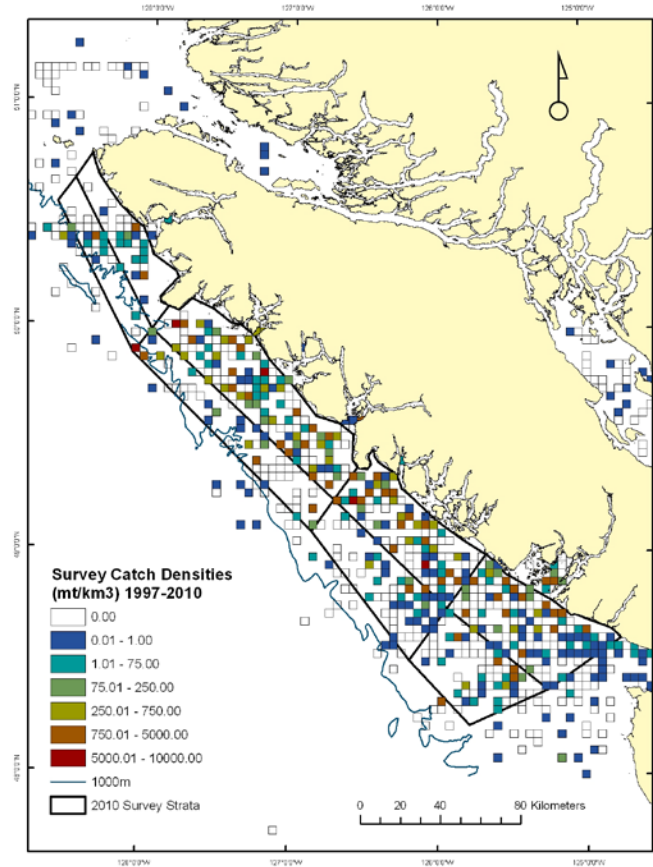
Figure. Mean sardine densities for all 1997-2010 sardine survey trawl tows based on 4x4 km sized grid cells. Outer boundaries define the core WCVI survey region. Also shown are sub-regional boundaries as they pertain to future work interests for stratification schemes.

REFERENCES

DFO. 2009. Proceedings of the Pacific Scientific Advice Review Committee (PSARC) meeting for the assessment of scientific information to estimate Pacific sardine seasonal migration into Canadian waters. DFO Can.Sci. Advis.Sec. Proceed. Ser. 2009/034.

DFO. 2010. Pacific Sardine Integrated Fisheries Management Plan 2010/2011. Government of Canada.

DFO. 2011. Evaluation of Pacific sardine (*Sardinops sagax*) stock assessment and harvest guidelines in British Columbia. DFO Can. Sci. Advis. Sec. Science Advisory Report. 2011/016.

Schweigert, J., McFarlane, G.A., and Hodes, V. 2009. Pacific sardine (*Sardinops sagax*) biomass and migration rates in British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/088. 14p.

Ware, D.M. 1999. Life history of Pacific sardine and a suggested framework for determining a B.C. catch quota. DFO Can. Sci. Advis. Sec. Res. Doc. 1999/204.

SCIENTIFIC AND STATISTICAL COMMITTEE REPORT ON PACIFIC SARDINE
ASSESSMENT AND COASTAL PELAGIC SPECIES MANAGEMENT MEASURES
FOR 2012

Dr. Kevin Hill presented the 2011 assessment of the northern subpopulation of Pacific sardine and Dr. André Punt reported on the Stock Assessment Review (STAR) Panel that convened on October 4-7, 2011.

The 2011 assessment uses four survey indices: two egg production indices and an aerial index, which have been the primary abundance data series in previous assessments, and an acoustic survey, which had not been previously used. The acoustic survey was reviewed by a methodology review panel earlier this year and endorsed by the Scientific and Statistical Committee (SSC) for use in the assessment model. Additional length data from the Mexican fishery were also included. The current assessment model has many fewer parameters than the 2009 assessment (61 vs. 132). This was accomplished by reducing the number of fisheries modeled, reducing time blocking of fisheries selectivity, and shortening the assessment time period. In addition, during the STAR Panel the initial fishing mortality (F) was set to zero and catchability (q) in the acoustic trawl survey was set to one.

The SSC notes that there are contradictory trends in the three recent survey indices, which introduce substantial uncertainty into sardine biomass estimates. The new model estimated a higher sardine biomass than previous assessments for recent years, and the SSC was advised that this was likely due to increases of varying magnitude in all of the survey indices and recent data suggesting strong recruitment.

The SSC endorses the 2011 assessment as the best available science for management of the northern subpopulation of Pacific sardine in 2012.

Dr. Hill also briefed the SSC on a re-estimation of F_{MSY} in which the Amendment 8 analysis was duplicated with two differences: the Scripps Institute of Oceanography (SIO) Pier temperature index was removed from the stock-recruit relationship, and recent stock and recruitment information was used. The F_{MSY} harvest rate of 0.18 is very similar, but slightly lower than the previous F_{MSY} estimate of 0.1985. The SSC notes that temperature, or another correlated environmental variable, may be important in sardine recruitment, but that the SIO index is not reflective of the temperature in the area of greatest sardine spawning activity and is no longer correlated with sardine productivity.

The SSC recommends that the updated F_{MSY} be used for management in 2012, but that this should be considered strictly an interim measure. The SSC further endorses an overfishing limit (OFL) of 154,781 that arises from this updated F_{MSY}. To set acceptable biological catch (ABC) for sardine, SSC again recommends use of the P* approach, in which the buffer between OFL and ABC is determined by the value of sigma, representing scientific uncertainty and established by the SSC, and the Council's choice of a P* to express its policy decision on acceptable risk. The default value of sigma (0.36) for category 1 stocks was considered appropriate for Pacific sardine.

The SSC further recommends that a workshop be convened within the next year to design a simulation analysis similar to Amendment 8 analysis but employs current modeling approaches provide estimates of F_{MSY} and updated parameters for the harvest control rule. The SSC further recommends that a full management strategy evaluation be performed for the northern subpopulation of Pacific sardine as soon as time and resources permit.

PFMC
11/04/11

COASTAL PELAGIC SPECIES MANAGEMENT TEAM REPORT ON
PACIFIC SARDINE STOCK ASSESSMENT AND COASTAL PELAGIC SPECIES (CPS)
MANAGEMENT MEASURES FOR 2012

The Coastal Pelagic Species Management Team (CPSMT) received a presentation from Dr. Kevin Hill concerning the Pacific sardine stock assessment conducted in 2011. The CPSMT recommends that the Pacific Fishery Management Council (Council) adopt the full assessment (model X5) for management of the 2012 sardine fishery. Based upon the 988,385 mt age 1+ biomass estimate from this assessment, the harvest control rule produces a harvest guideline (HG) of 109,409 mt (Table 1 below). The 2011 biomass estimate represents an 84 percent increase from the update stock assessment previously adopted by the Council in November, 2010. The CPSMT notes a number of factors including new data and new sources of data that influence the increase in the biomass estimate, including a relatively large 2009 year class is now evident in the fishery and survey data, the daily egg production method exhibited an increase, and the addition of the Southwest Fisheries Science Center (SWFSC) Acoustic Survey as another index of abundance. The final model has less than half of the number of estimated parameters compared to the previous assessment.

Dr. Kevin Hill undertook a re-evaluation of F_{msy} for Pacific sardine in the absence of an environmental covariate for use in the overfishing limit (OFL) and acceptable biological catch (ABC) calculations (see Appendix 4 of Stock Assessment, Agenda Item F.2.b Supplemental Attachment 8). An updated value of F_{msy} estimated independently of temperature was presented to the Scientific and Statistical Committee (SSC). The SSC endorsed the use of the temperature-independent F_{msy} as an interim measure, and the CPSMT agrees.

The CPSMT acknowledges that the temperature relationship underlying FRACTION in the harvest control rule needs to be revised. For 2012, the CPSMT is confident that FRACTION of 15 percent adequately protects the stock and points out that it is less than the F_{msy} of 18 percent. It is clear that sardine reproductive success is related to environmental conditions. The CPSMT anticipates research relative to environmental covariates may take time to provide conclusive information.

Harvest Specifications for 2012
Table 1 (below) contains harvest formula parameters and a range of ABC values based on various P* (probability of overfishing) values. The CPSMT recognizes that the Council will select a P*. The CPSMT recommends that the annual catch limit (ACL) equal the ABC resulting from the Council's P* choice, and that the HG/ACT be set equal to 109,409 mt.

The CPSMT discussed the Quinault Indian Nation request for an allocation of Pacific sardine. Acknowledging that the final allocation is yet to be determined, Table 2 incorporates the requested allocation of 9,000 mt. In addition, the CPSMT recommends that the incidental catch for CPS fisheries in each of the three allocation periods should be set to 1,000 mt (Table 2). The CPSMT recommends setting aside 3,000 mt for potential sardine Exempted Fishing Permits (EFP). Any EFP set aside not included in an EFP, as well as any EFP fish allocated but not utilized in research, should be re-allocated to the third period directed fishery. The CPSMT

recommends that the incidental landing allowance for CPS fisheries be no more than 30 percent Pacific sardine by weight.

Table 1. Pacific sardine Amendment 13 Harvest Formulas Parameters

Harvest Formula Parameters	Value			
BIOMASS (ages 1+, mt)	988,385			
Pstar (probability of overfishing)	0.45	0.40	0.30	0.20
BUFFER$_{Pstar}$ (Sigma=0.36)	0.95577	0.91283	0.82797	0.73861
F_{MSY}	0.18			
FRACTION	0.15			
CUTOFF (mt)	150,000			
DISTRIBUTION (U.S.)	0.87			

Amendment 13 Harvest Formulas	MT
OFL = BIOMASS * F_{MSY} * DISTRIBUTION	154,781
ABC$_{0.45}$ = BIOMASS * BUFFER$_{0.45}$ * F_{MSY} * DISTRIBUTION	147,935
ABC$_{0.40}$ = BIOMASS * BUFFER$_{0.40}$ * F_{MSY} * DISTRIBUTION	141,289
ABC$_{0.30}$ = BIOMASS * BUFFER$_{0.30}$ * F_{MSY} * DISTRIBUTION	128,153
ABC$_{0.20}$ = BIOMASS * BUFFER$_{0.20}$ * F_{MSY} * DISTRIBUTION	114,323
ACL = EQUAL TO ABC	
ACT=HG=(BIOMASS-CUTOFF)*FRACTION*DISTRIBUTION	109,409

Table 2. Preliminary Allocation scheme for 2011 Pacific Sardine ACT

HG = 109,409 mt; Tribal Allocation = 9,000 mt; Potential EFP set aside = 3,000 mt Adjusted HG = 97,409 mt				
	Jan 1- Jun 30	Jul 1- Sep 14	Sep 15 – Dec 31	Total
Seasonal Allocation (mt)	34,093 (35%)	38,964 (40%)	24,352 (25%)	97,409
Incidental Set Aside (mt)	1,000	1,000	1,000	3,000
Adjusted Allocation (mt)	33,093	37,964	23,352	94,409

Finally, the CPSMT supports a methodology review of the Canadian West Coast Vancouver Island Swept Area Trawl Survey as a potential new source of abundance data to inform the next full sardine stock assessment.

PFMC
11/4/11

COASTAL PELAGIC SPECIES ADVISORY SUBPANEL REPORT ON PACIFIC
SARDINE STOCK ASSESSMENT AND COASTAL PELAGIC SPECIES
MANAGEMENT MEASURES

The Coastal Pelagic Species Advisory Subpanel (CPSAS), along with the Coastal Pelagic
Species Management Team (CPSMT), received a presentation on the Pacific Sardine stock
assessment from Dr. Kevin Hill. The CPSAS commends Dr. Hill and the Stock Assessment
Team for its significant body of work and effort to address Stock Assessment Review (STAR)
Panel requests. The CPSAS concurs with the STAR Panel and Scientific and Statistical
Committee (SSC) that the 2011 sardine stock assessment represents the best available science.
The CPAS points out that the harvest guideline (HG) produced by the Harvest Control Rule is
significantly more precautionary than all potential P* policy figures included in the stock
assessment document.

Management Measures
The CPSAS recognizes the tribal right to harvest sardine, and we welcome cooperation in areas
of research and data sharing. We would appreciate National Marine Fisheries Service (NMFS)
working with the Quinault Indian Nation to consider developing a mechanism to allow any
unharvested portion of the tribal allocation to be rolled into the directed fishery for the third and
final harvest period. This would ensure full utilization of the harvest guideline. We also suggest
that the CPSAS be expanded to include tribal representation.

A majority of the CPSAS recommends the following management measures for the 2012 sardine
fishery:

(1) An HG/annual catch target (ACT) of 109,409 mt should be approved as derived from Dr.
Hill's model run X5, based on an age 1+ biomass estimate of 988,385 mt.
(2) Harvest parameters for the 2012 fishery:

Biomass	988,385 mt
Overfishing Limit (OFL)	154,781 mt
Acceptable Biological Catch (ABC)$_{0.45}$	147,935 mt
ABC$_{0.40}$	141,289 mt
ABC$_{0.30}$	128,153 mt
ABC$_{0.20}$	114,323 mt
Annual Catch Limit (ACL)	Equal to ABC
HG/ACT	109,409 mt

The conservation representative of the CPSAS has serious concerns with the application of
the Pacific sardine harvest control rule (HCR) given that, while potentially innovative, the
HCR has serious flaws (see Agenda Item F.2.d, Public Comment).

Incidental Set Aside
The CPSAS supports an aggregate total of 3,000 mt to be set aside for incidental catch in non-sardine fisheries (1,000 mt of incidental allowance would be set aside for each of the three fishing periods. For the first two periods, any of the 1,000 mt not utilized would roll into the next period's directed fishing. Any incidental set aside not utilized in the third period would be foregone.)

The CPSAS recommends that the non-sardine incidental landing allowance in 2012 be no more than 30 percent Pacific sardine by weight, as adopted in 2011. The CPSAS recommends that if the directed seasonal allocation and set-asides are reached in any fishing period, the retention of Pacific sardine be prohibited for the remainder of that period.

The CPSAS commends the effective in-season actions taken by the NMFS to deal with surpluses or shortages in the directed and incidental seasonal allocations.

Season Start Date
The CPSAS discussed the letter submitted by Mr. Ryan Kapp about season start date (Agenda Item F.2.d, Supplemental Public Comment). CPSAS members and members of the public representing industry also gave various opinions in support and in opposition to changing the start date. After further discussion among CPSAS members, no consensus was achieved. A majority of the CPSAS would like to discuss this issue further with industry participants to gauge support for a change of start dates in the future.

Exempted Fishing Permits
The CPSAS unanimously supports an Exempted Fishing Permit (EFP) set aside of 3,000 mt to be approved for Pacific Northwest industry-supported research, to be deducted from the HG before it is allocated to fishing periods. Any EFP set aside not included in an EFP, as well as any EFP fish allocated but not utilized in research, should be re-allocated to the third period directed fishery.

Members of the public representing industry also expressed support for the continuation of the aerial survey to be conducted under an EFP. A detailed EFP application encompassing the aerial survey project, including methodology and operational plans, will be submitted to the Council prior to the March 2012 meeting. The CPSAS thanks the Council for its support of EFP research.

Coastwide Research
The CPSAS continues to voice strong support for the recommendations produced in the sardine survey methods workshop that took place in June 2011 (see June 2011 Agenda Item G.1.b, Supplemental Sardine Workshop Report), and further thanks the Council for its letter of support. We encourage the NMFS to fully fund the "Cadillac" version of the synoptic survey in 2012, and to cooperate with Canadian and Mexican participants to ensure full coverage of the coast-wide population. This is necessary to improve understanding of the spawning biomass and migration patterns.

Methodology Review
The CPSAS strongly supports a methods review of the Canadian swept trawl survey for inclusion into the Sardine Stock Assessment. The CPSAS believes this will be a valuable source of data and will provide access to information about sardine biomass and habitat that is not available in the USA surveys.

International Research and Management
The CPSAS reiterates that coordinated international management of CPS fisheries is essential to safeguard against the potential for coast-wide overfishing. The CPSAS again strongly urges the Council, NMFS and the State Department to continue their work to promote international management of CPS stocks and to achieve the timely receipt of research and catch data from Mexico and Canada.

CPSAS Minority Statement
The conservation rep supports a full management strategy evaluation that includes the objective of providing sufficient forage for dependent marine predators in the California Current ecosystem, and economic considerations that account for the needs of other businesses, and fisheries where the target fish (e.g. salmon and tuna) depend on Pacific sardine as prey (see Hannesson and Herrick 2010).

> Hannesson, R. and S.F. Herrick. 2010. *The value of Pacific sardine as forage fish. Marine Policy. 34: 935-942*

PFMC
11/04/11

Report on the 2011 assessment of Pacific sardine

Prepared for The Center for Independent Experts
Northern Taiga Ventures, Inc.

October 2011

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Contents

Reviewed by

Approved for release by

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Dr Julie Hall

Executive summary

A STAR Panel met 4-7 October 2011 at the Southwest Fisheries Science Center in La Jolla, California to review the 2011 draft assessment of Pacific sardine. The assessment, and some additional analyses, were presented and discussed. Some modifications to the assessment were agreed to, and the Panel wrote its report.

I conclude that the modified assessment, though characterised by a high degree of uncertainty, constitutes the best available science. The analytic methodology used was generally sound but methods of data weighting could be improved. The review process was excellently run.

With regard to data weighting I recommend consideration be given to

- adopting the approach proposed by Francis (2011) in future assessments, and

- improving the Stock Synthesis documentation related to this topic.

To reduce uncertainty in future assessments I recommend particular attention be paid to

- reducing relative bias in age estimates,

- producing priors on survey catchabilities, and

- resolving uncertainty about survey selectivities.

For future assessments I also recommend that

- age compositions be used, rather than the combination of length compositions and conditional age-at-length data,

- the methodology of the Canadian trawl survey be reviewed so that these data might be used if found suitable,

- an attempt be made to reduce the lack of model fit for older fish, and

- in considering whether to change model structural assumptions concerning sex and the number of fisheries, the STAT be cautious about unnecessarily complicating the model structure.

For future CIE reviews I recommend that attention be given to the way that Statements of Work specify the structure of the reviewer's report.

1   Background

This report reviews, at the request of the Center for Independent Experts (see Appendix 2), the 2011 assessment of the stock of Pacific sardine (*Sardinops sagax*) which is fished off the west coast of North America, from northern Mexico to Canada. The author was provided with various documents (Appendix 1), and participated both in the meeting which considered the assessment, and in the writing of the Panel Report from that meeting.

2   Review activities

The stock assessment review (STAR) Panel met 4-7 October 2011 at the Southwest Fisheries Science Center of NOAA/NMFS in La Jolla, California. Those attending the meeting included four Panel members, three representatives of the Pacific Fishery Management Council (PFMC), the teams responsible for the stock assessment and associated surveys, and other interested parties from both the fishing industry and the research community (Appendix 3). The assessment and related material were presented to the Panel, and numerous additional analyses requested by the Panel were carried out and discussed. The Panel, in consultation with the STAT (the stock assessment team), agreed on some modifications to the assessment, and further analyses were carried out to evaluate the modified assessment. The Panel drafted their report.

3   Summary of findings

For reasons given below (in Section 3.6), neither this section nor the next is structured according to the Terms of Reference for the review, as was required by my Statement of Work (Appendix 1). Instead, I have grouped my findings in a way that seemed natural.

3.1   Best available science

I believe that the Pacific sardine assessment, as produced by the STAT, with some modifications developed during the STAR Panel meeting, constitutes the best available science, and does a reasonable job of estimating the status of the stock and quantifying the considerable uncertainty about that status. The assessment used state of the art software (Stock Synthesis), which was applied professionally and diligently by the STAT.

Much of the uncertainty in this assessment stems from the fact that, although it is relatively data-rich, it is still information-poor. In particular, although four separate time series of abundance were available (Total Egg Production [TEP], Daily Egg Production Method [DEPM], trawl-acoustic, and aerial) these were not in agreement about biomass trends.

One consequence of this uncertainty was that the assessment model was quite unstable. That is, small changes in the data or model assumptions sometimes produced large changes in estimated stock status. This instability imposed a considerable constraint on both the STAT and the STAR Panel by making the process of evaluating alternative model assumptions very time-consuming. Thus some possible model improvements could not be evaluated in the time available. In particular it was not possible to seek model configurations that better fitted the abundance time series.

3.2   Analytic methodology

The analytic methodology used in this assessment – implemented in Stock Synthesis (Methot 2005, 2011) – followed standards that have been established in other assessments within the PFMC jurisdiction. I believe Stock Synthesis to be excellent software, which has been thoroughly tested and is widely used – both within and outside the PFMC jurisdiction.

In general I approve of the standard methodology, but I think there is one aspect that could be improved in the next assessment: data weighting.

3.2.1   Data weighting

Stock assessment results are often sensitive to the weight (or emphasis) given to different data sets. A data set can be given more weight by decreasing coefficients of variation (c.v.s) (in the case of abundance data) or increasing effective sample sizes (in the case of age or length composition data). The approach I suggest considering for the next assessment is that proposed by Francis (2011). I will not repeat the arguments advanced in that paper, but will discuss two components of the proposed approach in the context of the sardine assessment, and then make some comments about data weighting in Stock Synthesis.

The first component is the need to down-weight length and/or age composition data to account for correlations. A useful way to illustrate this need is to plot observed and expected mean lengths (or ages), as is done in Figure 1 for the length composition data in the draft base model. The fact that the expected mean lengths in this plot are often outside the confidence intervals for the observations indicates that the length composition data were over-weighted. Down-weighting these data (by decreasing the multinomial sample sizes) would increase the width of the plotted confidence intervals.

Most methods of iteratively reweighting composition data (including that used in Stock Synthesis) implicitly assume that the residuals associated with one length (or age) bin are uncorrelated with those from another bin. In fact, correlations between composition residuals are often strong, and show a characteristic pattern like that in Figure 2.

Francis (2011) suggested that one way to avoid over-weighting composition data is to base the re-weighting calculation on the residuals of mean length (or age), rather than on residuals of individual proportions. Application of this approach to the length composition data in the base model suggested that the multinomial sample sizes for these data should be smaller by a factor of 0.06 – 0.1 (Table 1).
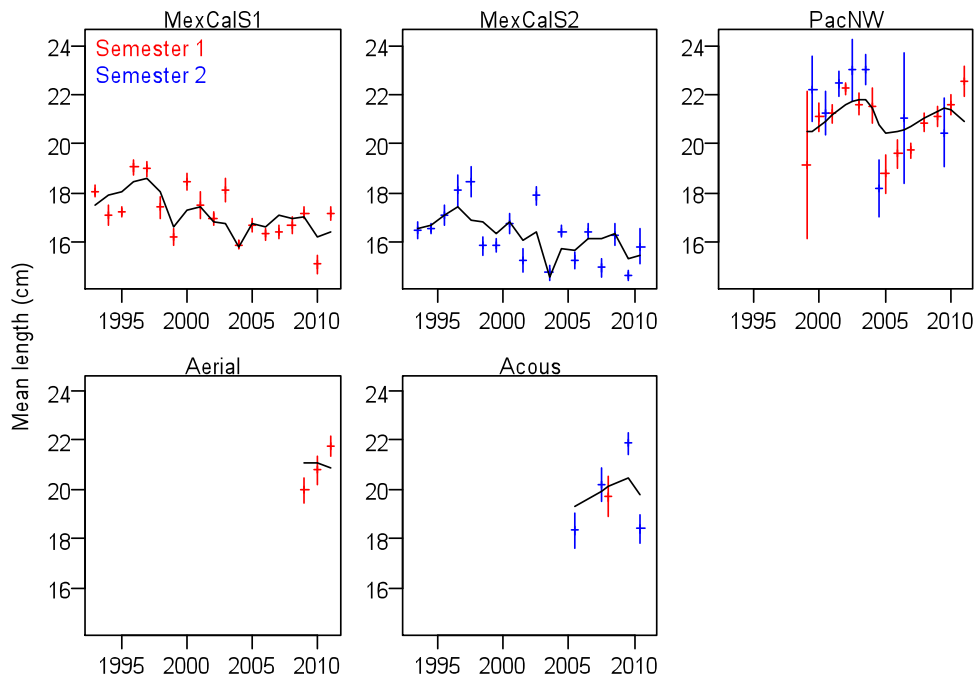
Figure 1: **Observed ('+') and expected (lines) mean lengths for all length composition data in the base model.** Confidence intervals (shown as vertical lines) were calculated using the multinomial sample sizes assumed for the base model (i.e., the products of the initial sample sizes and effN_mult_Lencomp values in tables 4 and 9 of Hill et al. 2011).
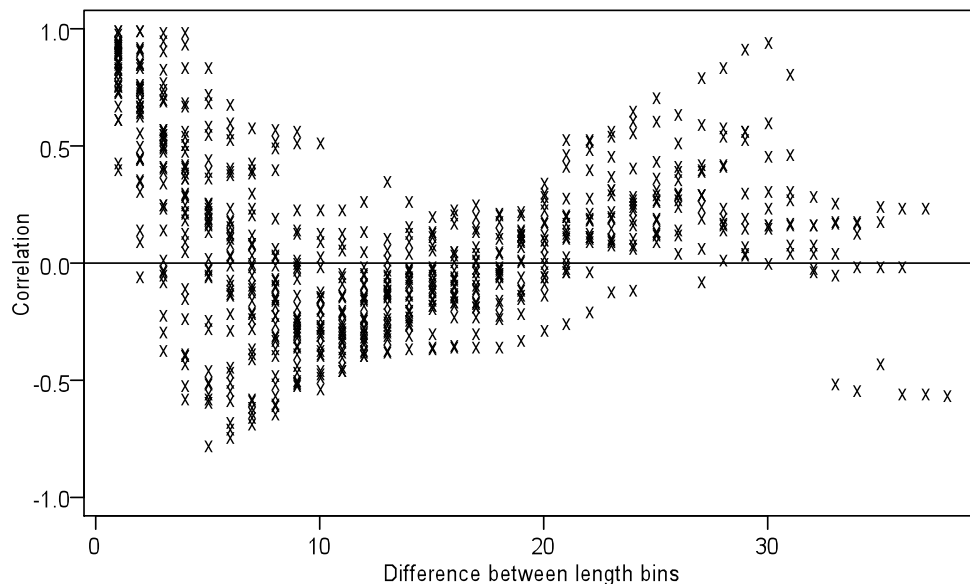

Figure 2: **Correlations amongst residuals from the MexCal_S1 length composition data in the base model.** Each plotted point represents a correlation between the vectors of residuals for two length bins; the x-axis shows the distance (number of bins) between the two length bins.

Table 1: Suggested reweighting of the length composition data from the base model in the draft assessment report (Hill et al. 2011). The suggested sample sizes, N_new, are the product of the sample sizes assumed in the base model, N_base, and a multiplier, N multiplier.

Data set	Median N_base	N_multiplier[1]	Median N_new
MexCalS1	135.9	0.058	7.9
MexCalS2	117.7	0.061	7.2
PacNW	40.9	0.104	4.3
Aerial	14.8	0.067[2]	1.0
Acous	43.5	0.067[2]	2.9

[1]Calculated using method TA1.8 of Francis (2011, Appendix A, in which N_multiplier is denoted w_j)
[2] Because of small sample sizes (i.e., few years of observations), the N_multiplier for the aerial and acoustic-trawl surveys was calculated by combing these two series

Another component of the data weighting approach proposed by Francis (2011) is the importance of fitting abundance indices well. A striking feature of both the draft and final assessments was that none of the four abundance indices was well fitted. One possible reason for this is that the three indices that overlap (DEPM, trawl-acoustic, and aerial) show quite different trends. All indicate that the biomass dropped substantially, but they disagree about the years over which this occurred (2004-2007 for DEPM; 2005-2009 for trawl-acoustic; and 2009-2010 for aerial). Schnute & Hilborn (1993) pointed out that when two data sets are contradictory it is a mistake to include both in an assessment model. It is better to consider two alternative assessments: one without the first data set, and one without the second. If there are no grounds for preferring one data set over the other then the difference between the two alternative assessments serves as a measure of the uncertainty about stock status. In jurisdictions in which a STAT is required to provide only one assessment they will be forced to choose which of two contradictory data sets is more plausible. One fact in support of choosing the trawl-acoustic survey is its similarity in trend to the Canadian trawl survey (see Section 3.4.2 below).

Sometimes the year-to-year changes in an abundance index are so large that the index cannot be well fitted by any plausible model. In this case, the appropriate response is to discard the index, on the grounds that it cannot be representative of the population. This might be the case with the TEP index, which jumped up by a factor of almost 4 in 1999, and then dropped by a factor of more than 5 over the next 2 years. I wonder if the spawning biomass of sardines can change so rapidly.

Finally, I offer some comments on the iterative reweighting of abundance indices as is commonly done (including in this assessment) with Stock Synthesis. This involves adding to the initial survey standard errors (labelled 'S.E. ln(index)' in table 5 of Hill et al. 2011), variance adjustment terms (labelled 'index_extra_cv' in table 9 of Hill et al. 2011) which have been calculated from an earlier model run without any variance adjustment. This approach has the apparent merit of being objective, but Francis (2011) argued that full objectivity is not possible in data weighting. A perverse consequence of this approach in the sardine assessment was that it assigned slightly more weight to TEP than to DEPM (the median final standard errors for the two series were 0.62 and 0.66, respectively), even though the consensus of attendees at the STAR Panel seemed to be that DEPM was likely to be superior to TEP as an index of spawning biomass (that consensus opinion – partly subjective – was not used in the stock assessment). I note also that I could not find in the Stock

Synthesis documentation provided (Methot 2005,2011) either a description of how these variance adjustments were calculated, or a justification for simply adding them to the initial standard errors (the conventional approach is to sum standard errors as squares: s.e.[final]^2 = s.e.[initial]^2 + s.e.[extra]^2). My attempts to replicate the calculation of the variance adjustments, using what seemed to me to be the appropriate approach, were not successful. Whatever the method of calculation, it cannot be considered very reliable because it is analogous to estimating a variance from a very small sample (sample sizes [i.e., numbers of years] were 8, 9, 3, and 5 for the DEPM, TEP, aerial, and trawl-acoustic surveys, respectively).

3.3   Sources of uncertainty

Two types of factor contributed to the uncertainty in this assessment: those that were largely unavoidable; and those that are potentially reducible.

Some important unavoidable factors are the wide area traversed by this stock (from northern Mexico to Canada); the substantial movements (both ontogenetic and annual) that it undertakes; and the fact that the nature and extent of these movements (primarily north-south, but also inshore-offshore) will vary from year to year in a way that is inherently difficult to measure. A consequence of these factors is that there may be substantial variation in the portion of the stock that is vulnerable to capture or sampling (either by the fishery or by surveys) at a given place and time. This variation is likely to be responsible for much of the year-to-year changes in mean lengths (and ages) in the fishery catches, and possibly also in the survey samples (see Figure 1). It also leads to uncertainty about the extent to which we can be sure that each survey is indexing the same portion of the population in each year.

Potentially reducible sources of uncertainty include sampling error (e.g., survey c.v.s), stock structure, ageing error, and survey catchabilities (*q*s) and selectivities. It is obviously sensible to try to reduce uncertainty from all these sources, but I think special emphasis should be given to the last three, which I now discuss in turn.

3.3.1 Ageing error

In my view ageing error could well be a serious problem for this assessment, and my concern is more with (relative) bias, than with precision. Between-reader bias was sometimes very substantial (see plots labelled 'Age bias plot' in Dorval et al. 2011), to the point that I wondered how bad such bias would need to be before the age estimates were deemed unusable in the stock assessment. I don't mean to imply incompetence on the part of age readers. Some species' otoliths are inherently very difficult to read, and Pacific sardine appears to be one such species. However, I am aware that the consistency of ageing has been significantly improved for *some* species by the development of strict ageing protocols and regular inter-agency comparisons. This is not a simple task, and it will not be achieved quickly.

3.3.2 Survey catchabilities

There are three approaches to dealing with survey catchabilities (commonly referred to as *q*s) in stock assessment models. First, we can tell the model we know nothing about the catchabilities, as was done for all surveys in the draft assessment. Because the survey biomass indices showed no consistent trends, this approach made the model unstable in terms of absolute biomass. That is, slightly different model configurations sometimes

estimated biomass trajectories that were similar in trend, but greatly different in level. In order to reduce this type of instability the STAR Panel meeting decided to adopt a second approach – for the trawl-acoustic survey alone – which was to tell the model that catchability was known exactly (it was fixed to 1). I approve of this decision as a short-term measure, because it will tend to reduce year-to-year changes in stock status (and in particular, in the estimate of current 1+ biomass, which is important for management purposes). However, I recommend that the third approach, which is intermediate between the first two, be adopted for future assessments if possible. This is to provide the model with a summary of what is known about each survey catchability in the form of a prior distribution for this parameter.

I note that the task of generating survey catchability priors should not be the responsibility of the STAT. This task is often addressed by the combination of a Bayesian statistician (whose expertise relates to the function of a prior distribution in a model) and subject experts (the survey teams, whose expertise is in understanding all the factors that contribute to catchability for their type of survey [e.g., target strength for acoustic surveys, proportion spawning for egg surveys, etc]). In Bayesian parlance the statistician is said to 'elicit' the prior from the experts.

3.3.3 Survey selectivities

The assessment model was unable to fit the considerable year-to-year changes in length compositions for both the trawl-acoustic and aerial surveys. There was a similar problem with age compositions for the acoustic survey.

There are three alternative explanations for this lack of fit. One possibility is that the survey selectivity is changing substantially from year to year. This would be of concern because it would undermine the value of these surveys, since they would be surveying a substantially different portion of the population each year.

In both of the other two explanations the survey selectivity does not vary significantly from year to year, but there are different reasons for the lack of fit. One reason would be that the composition data from these surveys were not representative of the portion of the population being surveyed. This would be of concern because it would mean that the survey selectivity was poorly estimated in the assessment. Thus, in fitting the survey biomass index the observed biomass would be compared by the model to the wrong expected biomass. Alternatively, it could be that the composition data *are* representative, but the model has estimated the wrong parameters (particularly those for growth and recruitment). It may be that with different parameter values the model would achieve a much better fit to the survey composition data.

This last explanation may be correct for the aerial surveys, where an upward trend in mean length is consistent with a similar trend from the catches in the PacNW fishery (in a similar area), and neither trend was fitted by the model (see Figure 1). An upward trend in mean length suggests the population in that area is dominated by one or more year classes. This could be checked if the otoliths from the aerial survey were aged.

3.4   Model data and structure

3.4.1   Use of age and length data

Both age and length composition data were available for most years for the three fisheries (MexCal in semesters 1 and 2, and PacNW), and for three of the five years for the trawl-acoustic survey. I suggest that it is a mistake in this situation to include both the length composition (LC) and the conditional age-at-length data (CA@L) in the model. It is better to include just the age compositions (ACs), omitting the other data types.

I acknowledge that this suggestion is counter-intuitive. It seems obvious that there is more information in the combination of LC and CA@L, than there is in AC alone. While this is true in general, it is *not* true for the type of model used in this assessment, because this model is age-structured. That is to say, the model's accounting system is age-based: it reconstructs the history of the sardine population by keeping track of the number of fish of each age in each time step in each year. The model deals with length data (and with selectivities that are functions of length) only by converting back and forth between length and age, using its growth parameters. In particular, to calculate a likelihood for an observed LC the model converts its expected AC to an expected LC using information about the relationship between length and age that is contained in its growth parameters. The problem is that these growth parameters are the same for all years and all areas, whereas we know, from the CA@L data that the relationship between length and age varies, both from year to year, and from south to north. Thus, it is better to use the time and area-varying information we have in the CA@L data to convert our LCs to ACs outside the model, and then to include only these ACs in the model.

3.4.2   Canadian survey

The 2009 STAR Panel recommended that the fishery-independent mid-water trawl survey series off the west coast of Vancouver Island should be considered for inclusion in the current assessment. The STAT rightly argued that this series would be of limited utility because of (*inter alia*) very high c.v.s (1.5 – 3.0). During the STAR Panel meeting a Canadian representative reported that there had been an error in the calculation of these c.v.s, and the correct values were much smaller (0.23 – 0.39 [see Appendix 3 of the STAR Panel report]).

Another important characteristic of this survey, not noticed during the STAR Panel meeting (at least by me), is that it estimates a biomass trend very similar to that from the U.S. trawl-acoustic survey (Figure 3). Since these surveys were carried out independently, and in different areas, this similarity in trend provides strong support to both surveys as being representative of actual changes in the sardine population.
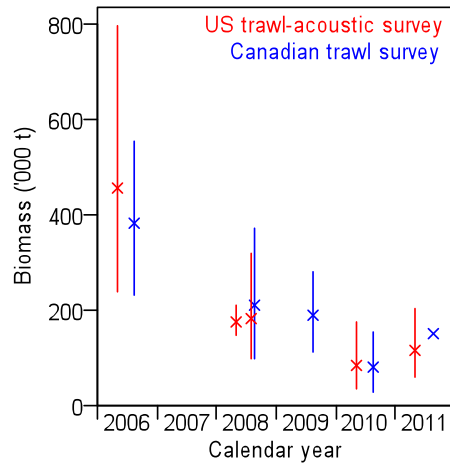
Figure 3: **Comparison of biomass estimates from Canadian trawl surveys and US trawl-acoustic surveys.** To aid comparison the US estimates have been scaled to have the same mean as the Canadian ones. Vertical bars are 95% confidence intervals.

3.4.3 Lack of fit to old fish

A systematic lack of fit to the conditional age-at-length data indicated that fewer old fish were observed – in surveys and catches – than was expected by the model. This lack of fit is most easily seen in the plots of residuals to the implied age frequencies: most of the residuals for the older age classes were negative. As a consequence, a profile on natural mortality, M, had its minimum at $M = 0.625$ y^{-1}: higher than was considered plausible, and much higher than the value assumed in the assessment ($M = 0.4$ y^{-1}).

It would be good to try to remove this systematic lack of fit in future assessments. This might be done by introducing age-dependent natural mortality, or changing the form of the selectivities. The danger is that the model might compromise the fit to the abundance indices in an attempt to find combinations of parameters that slightly reduce the lack of fit at older ages.

3.4.4 Sex and fishery structure

During the STAR Panel meeting, evidence emerged that suggested that two of the STAT's decisions on model structure – to ignore sex, and to have only two fisheries – may need to be reconsidered. Proportion female in fishery catches was shown to exceed 0.5 in bigger fish, and female spawning biomass was estimated to be more than half of total spawning biomass in 7 of the 8 DEPM surveys. Also, splitting the length composition data from the two model fisheries showed that Canadian fish tended to be larger than those from Oregon and Washington, and Mexican fish were larger than those from California.

I support the suggestion that these structural decisions be reconsidered, but urge caution. Changes to these structures will increase model complexity (and parameter numbers), and increased complexity makes it harder for the modeller to understand what is driving the model. I point out that the aim of stock assessment modelling is to inform fishery management, not to build the most realistic model possible.

For example, consider the decision as to whether to include sex in the model. The evidence cited above makes it clear that including sex would make the model more realistic. But realism isn't the point. I suggest the questions to ask are (a) does including sex materially change the estimated stock status? and (b) if so, is the change in estimated status plausible? Sex should be included in the model only if the answers to both questions are 'yes'. If in doubt, err on the side of simplicity.

3.5   Review process

The review process was excellently run by PFMC, with support from SWFSC staff. Before the meeting I was particularly aware of contributions from Kerry Griffin, Nancy Lo, and Jennifer McDaniell, and of course Kevin Hill, who lead the considerable effort required to get the draft assessment report ready in time. I was especially pleased to see the Stock Synthesis input files included in this report because that allowed me to check on some of the technical details that can be important. During the meeting, both the STAT and survey teams went out of their way to respond to queries and requests from the Panel. The Panel was very ably chaired, and all participants showed a constructive approach to the review.

3.6   Terms of Reference

The present review raised a problem that I think needs to be considered when Statements of Work (SOWs) are prepared for future reviews. The problem concerns the Terms of Reference (ToRs) within the SOW (Appendix 1).

These ToRs were used in two distinct ways within the SOW.   The first way, which posed no problems for me, was to direct the activities of the CIE reviewer before (ToR 1) and during (ToRs 2-6) the review meeting (e.g., on p. 3 of the SOW: "The CIE reviewer shall … participate in … the meeting review panel, and … shall be focused on the ToRs …"). The second way was to structure the CIE reviewer's report (e.g., Annex 1 of the SOW says the report shall include "Summary of Findings for each ToR", and this is underlined under **Acceptable Performance Standards** where it says "the CIE report shall address each ToR").

This latter use of the ToRs has not been a problem for me in previous reviews because the ToRs for those reviews have referred to aspects of the assessment being reviewed (e.g., "Comment on quality of data used in the assessment" and "Evaluate and comment on analytic methodologies"). However, the ToRs in the present SOW refer to activities of the panel members, rather than aspects of the assessment. It would not make sense for me to include in my report findings for each of these ToRs. For example, ToR 2 is "Working with STAT Teams to ensure assessments are reviewed as needed", and ToR 3 is "Documenting meeting discussions". If I were to present findings related to these ToRs I would be reviewing the panel activities rather than the sardine assessment.

I discussed this problem with Manoj Shivlani (CIE) before the review meeting and he agreed that, for this review, I need not take literally the requirement to structure my report around the ToRs.

4   Conclusions and recommendations

4.1   Best available science

I conclude that the assessment, as modified during the STAR Panel meeting, constitutes the best available science.

4.2   Analytic methodology

The analytic methodology used in this assessment was generally sound but methods of data weighting could be improved.

I recommend consideration be given to

- adopting the data-weighting approach proposed by Francis (2011), and

- improving the Stock Synthesis documentation relating to data weighting.

4.3　Sources of uncertainty

This assessment was characterised by a high degree of uncertainty.

To reduce uncertainty in future assessments I recommend particular attention be paid to

- reducing relative bias in age estimates,

- producing priors on survey catchabilities, and

- resolving uncertainty about survey selectivities.

4.4　Model data and structure

For future assessments I recommend that

- age compositions be used, rather than the combination of length compositions and conditional age-at-length data,

- the methodology of the Canadian trawl survey be reviewed so that these data might be used if found suitable,

- an attempt be made to reduce the lack of model fit for older fish, and

- in considering whether to change assumptions concerning sex and the number of fisheries, the STAT be cautious about unnecessarily complicating the model structure.

4.5　Review process

The review process was excellently run, with great support from PFMC and SWFSC staff, and enthusiastic cooperation from both STAT and survey teams.

4.6　Terms of Reference

The STAR Panel's Terms of Reference were suitable for guiding the reviewer's activities during the Panel meeting, but not for structuring this report.

For future CIE reviews I recommend that attention be given to the way that Statements of Work specify the structure of the reviewer's report.

5 References

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RECENT TECHNICAL MEMORANDUMS

NOAA-TM-NMFS-SWFSC-477 Osteological specimens of tropical dolphins *(Delphinus, Grampus, Lagenodelphis, Stenella, Steno and Tursiops)* killed in the tuna fishery in the tuna fishery in the eastern tropical Pacific (1966-1992) and placed in museums by the Southwest Fisheries Science Center.
W.F. PERRIN and S.J. CHIVERS
(May 2011)

478 Ichthyoplankton and station data for surface (Manta) and oblique (Bongo) plankton tows for California Cooperative Oceanic Fisheries Investigations Survey cruises in 2007.
S.R. CHARTER, W. WATSON, and S.M. MANION
(May 2011)

479 Passive acoustic beaked whale monitoring survey of the Channel Islands, CA.
T.M. YACK, J. BARLOW, J. CALAMBOKIDIS, L. BALLANCE, R. PITMAN, and M. McKENNA
(May 2011)

480 Determining transmitter drag and best-practice attachment procedures for sea turtle biotelemetry studies.
T.T. JONES, B. BOSTROM, M. CAREY, B. IMLACH, J. MIKKELSEN, P. OSTAFICHUK, S. ECKERT, P. OPAY, Y. SWIMMER, J.A. SEMINOFF, and D.R. JONES
(November 2011)

481 Ichthyoplankton, paralarval cephalopod, and station data for surface (Manta) and oblique (Bongo) plankton tows for California Cooperative Oceanic Fisheries Investigations Survey and California Current Ecosystem Survey cruises in 2008.
W. WATSON and S.M. MANION
(May 2011)

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