APPENDIX 1

2007 PACIFIC SARDINE STOCK ASSESSMENT, NOVEMBER 2006 SCIENTIFIC AND STATISTICAL COMMITTEE STATEMENT, AND 2004 STOCK ASSESSMENT REVIEW PANEL REPORT

www.pcouncil.org

NOAA Technical Memorandum NMFS

NOVEMBER 2006

ASSESSMENT OF THE PACIFIC SARDINE (*Sardinops sagax caerulea*) POPULATION FOR U.S. MANAGEMENT IN 2007

Kevin T. Hill
Nancy C.H. Lo
Beverly J. Macewicz
Roberto Felix-Uraga

NOAA-TM-NMFS-SWFSC-396

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Southwest Fisheries Science Center

The National Oceanic and Atmospheric Administration (NOAA), organized in 1970, has evolved into an agency which establishes national policies and manages and conserves our oceanic, coastal, and atmospheric resources. An organizational element within NOAA, the Office of Fisheries is responsible for fisheries policy and the direction of the National Marine Fisheries Service (NMFS).

In addition to its formal publications, the NMFS uses the NOAA Technical Memorandum series to issue informal scientific and technical publications when complete formal review and editorial processing are not appropriate or feasible. Documents within this series, however, reflect sound professional work and may be referenced in the formal scientific and technical literature.

NOAA Technical Memorandum NMFS
This TM series is used for documentation and timely communication of preliminary results, interim reports, or special purpose information. The TMs have not received complete formal review, editorial control, or detailed editing.

NOVEMBER 2006

ASSESSMENT OF THE PACIFIC SARDINE (*Sardinops sagax caerulea*) POPULATION FOR U.S. MANAGEMENT IN 2007

Kevin T. Hill[1], Nancy C.H. Lo[1], Beverly J. Macewicz[1], and Roberto Felix-Uraga[2]

[1]NOAA National Marine Fisheries Service
Southwest Fisheries Science Center
8604 La Jolla Shores Drive
La Jolla, California, USA 92037

[2]CICIMAR-IPN
Ave. IPN s/n A.P. 592
Col. Playa Paso Sta. Rita C.P. 230096
La Paz, Baja California Sur, México

NOAA-TM-NMFS-SWFSC-396

U.S. DEPARTMENT OF COMMERCE
Carlos M. Gutierrez, Secretary
National Oceanic and Atmospheric Administration
VADM Conrad C. Lautenbacher, Jr., Undersecretary for Oceans and Atmosphere
National Marine Fisheries Service
William T. Hogarth, Assistant Administrator for Fisheries

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

ADMB	automatic differentiation model builder (a programming language)
ASAP	age structured assessment program
BC	British Columbia, Canada
CA	State of California
CANSAR-TAM	catch-at-age analysis for sardine – two area model
CalCOFI	California Cooperative Oceanic Fisheries Investigations
CDFG	California Department of Fish and Game
CDFO	Canada Department of Fisheries and Oceans
CICIMAR-IPN	Centro Interdisciplinario de Ciencias Marinas - Instituto Politécnico Nacional
CONAPESCA	Comisión Nacional de Acuacultura y Pesca
CPS	Coastal Pelagic Species
CPSMT	Coastal Pelagic Species Management Team
CPSAS	Coastal Pelagic Species Advisory Subpanel
CV	coefficient of variation
FMP	fishery management plan
HG	harvest guideline
INP-CRIP	Instituto Nacional de la Pesca - Centro Regional de Investigación Pesquera
MSY	maximum sustainable yield
MX	Mexico
MX-Ensenada	Mexican fishery that lands its product in Ensenada, Baja California
NMFS	National Marine Fisheries Service
NOAA Fisheries	National Oceanic and Atmospheric Administration, National Marine Fisheries Service
OR	State of Oregon
PFMC	Pacific Fishery Management Council
SAFE	stock assessment and fishery evaluation
SEMARNAP	Secretaria del Medio Ambiente, Recursos Naturales y Pesca
SSB	spawning stock biomass
SSC	Scientific and Statistical Committee
SST	sea surface temperature
STAR	Stock Assessment Review (Panel)
STAT	Stock Assessment Team
VPA	virtual population analysis
WA	State of Washington

ACKNOWLEDGMENTS

This annual stock assessment depends in large part on the diligent efforts of many colleagues and the timely receipt of their data products. Landings data from the Ensenada fishery were kindly provided by Celia Eva-Cotero of INP-CRIP, Ensenada, Mexico. Port samples for the Ensenada, Mexico, fishery were collected by Walterio Garcia-Franco and Alfredo Cota (INP-CRIP in Ensenada) and were aged by Roberto Felix-Uraga and Casimiro Quiñonez of CICIMAR-IPN, La Paz. Tim Baumgartner (CICESE) transmitted updated landings information from the Ensenada fishery as compiled by Jesús Garcia Esquivel (SEMARNAP-Ensenada). Ed Pederson (IATTC-Ensenada) provided additional information about tuna net pen operations in northern Baja California. Port samples and age data for the California fishery were provided by CDFG Marine Region personnel in Los Alamitos, Santa Barbara and Monterey, with special thanks to Leeanne Laughlin, Valerie Taylor, Kelly O'Reilly, Travis Tanaka, Dianna Porzio, Kim Penttila, Brianna Brady, Alia Al-Humaidhi, and Sonia Torres for long dockside and laboratory hours. Thanks also go to the dedicated staff that collected and processed biological samples from the fisheries off Oregon, Washington, and British Columbia, including Jill Smith, Keith Matteson, and Sheryl Manley of ODFW, and Carol Henry of WDFW. Sandra Rosenfield and Jennifer Topping (WDFW) aged all of the Oregon and Washington otoliths. Monthly landings for the British Columbia fishery were provided by Christa Hrabok of DFO-Canada. Ron Dotson, Amy Hays, and Sue Manion (NMFS, La Jolla) provided aerial spotter logbook data. Numerous staff from SIO and NMFS assisted in the ongoing collection and identification of CalCOFI ichthyoplankton samples. We thank Melissa Carter (SIO) for providing Scripps Pier sea surface temperature data. We are grateful to Christopher Legault and Alan Seaver (NMFS, Woods Hole) for providing and maintaining the ASAP model.

EXECUTIVE SUMMARY

A Pacific sardine stock assessment is conducted annually in support of the Pacific Fishery Management Council (PFMC) process that, in part, establishes an annual harvest guideline (quota) for the U.S. fishery. In June 2004, the PFMC, in conjunction with NOAA Fisheries, organized a Stock Assessment Review (STAR) Panel in La Jolla, California, to provide peer review of the methods used for assessment of Pacific sardine and Pacific mackerel. The following report was initially prepared in draft form for the STAR panel's consideration, and was updated for the 2005 and 2006 management cycles (Conser et al. 2004; Hill et al. 2005, 2006). Many of the STAR panel review recommendations as well as considerable new data were incorporated into the stock assessment updates. The assessment is once again updated here for 2007 management; as such, it will be reviewed by the Pacific Fishery Management Council (PFMC) CPSMT, CPSAS, and SSC-CPS subcommittee in October 2006 (Portland, OR), and by the PFMC at it's November meeting in San Diego.

This assessment was conducted using 'ASAP', a forward simulation, likelihood-based, age-structured model developed in AD Model Builder. New information has been incorporated into the update, including: (1) Ensenada landings through December 2005; (2) an additional year of landings and sample data from the California and Pacific Northwest fisheries; and (3) DEPM-based estimates of SSB (San Diego to San Francisco portion) based on the coast-wide survey conducted in April 2006. Model structure is described in Hill et al. (2005), and has not been altered in this assessment update.

Results from the final base model indicate a general decline in stock productivity (recruits per spawning biomass) which began in the mid-1990s. Recruit (age-0) abundance increased rapidly from low levels in 1982-83, peaking at 9.79 billion fish in 1994-95. Recruitment has subsequently declined, with the exception of a strong 2003 year class (YC) estimated at 14.37 billion fish. There was a large proportion of 2003 YC in the catch, as well as relatively high abundance in fishery-independent trawl surveys off California and the Pacific northwest. Stock biomass (ages 1+) peaked at 1.56 million metric tons (mmt) in 1996-97, declining to 0.97 mmt in 2003-04. Stock biomass was estimated to be 1.32 mmt as of July 2006.

The primary motivation for conducting this annual assessment is to provide the scientific basis for the Pacific Fishery Management Council's (PFMC) sardine management process. This process -- centered on an environmentally-based control rule -- establishes U.S. coast-wide harvest guidelines (HG) for sardine for the fishing year beginning on January 1st of each year. Based on the sardine biomass estimate from this assessment (1,319,072 mt) and current environmental conditions, the PFMC control rule suggests a 2007 HG of 152,564 mt for the U.S. fisheries. This HG recommendation is 28% higher than the HG adopted for calendar year 2006, and 51,197 mt higher than the largest recent harvest by the U.S. fisheries.

INTRODUCTION

For stock assessment purposes, many of the world's fisheries may be considered data-limited. However, when a data-limited fishery is economically important, data availability generally improves over time as additional resources are allocated to better assess and manage the stock(s). With sufficient time and resources, these data-limited fisheries tend to become data-rich.

In the case of Pacific sardine off the west coast of North America, the fishery has been economically important since the early part of the 20th century. As large scale fishing operations developed, fisheries data collection programs were established along with biological studies and eventually fisheries independent surveys. The fishery collapsed in the 1950's following dramatic declines in stock biomass and remained at low levels for nearly forty years. Sampling programs remained in place, however, and when the stock began to recover in the late 1980's, an apparent data-rich assessment environment appeared to be in place. But sardine biology and ecology, along with oceanographic changes in the Pacific Ocean, conspired to prove this wrong.

For nearly half a century (mid-1940's through mid-1990's), the sardine population was distributed only from Baja California, Mexico northward to Monterey, California USA. This area represented a substantial contraction of the range occupied by sardine when the stock was at high biomass levels (1930's). Fisheries sampling programs were in place over this reduced geographic range; and annual egg production surveys were established in the early 1980's (Wolf 1988a,b), covering sardine spawning areas in southern and central California. Periodic stock assessments took advantage of this data-rich environment. In the mid-1990's, however, the population began a rapid recovery with concomitant expansion of its range northward through British Columbia, Canada. With some lag, fisheries sampling programs were established in the Pacific Northwest but due to budgetary constraints and logistical difficulties, systematic surveys were only recently launched in this area. Consequently, stock assessments are now much more difficult to carry out due to what has become a data-limited situation.

Recently-used Pacific sardine stock assessment models were designed for the data-rich environment and subsequently, had been modified in order to function in the new data-limited environment (Hill et al. 1999). The primary thrust of this report is go back to basics by utilizing stock assessment methods better suited from the ground up for contemporary sardine stock assessment and management; and for serving as a flexible framework to take advantage of new data sources as they become available. With regard to the latter, there is a reasonable expectation that over the course of the next few years, there will be significant improvements in the fisheries database, new fisheries-independent surveys, and better understanding of stock structure and the oceanographic constraints that govern suitable sardine habitat and productivity.

BACKGROUND

Scientific Name, Distribution, Stock Structure, Management Units

Biological information about Pacific sardine (*Sardinops sagax caerulea*) is available in Clark and Marr (1955), Ahlstrom (1960), Murphy (1966), MacCall (1979), Leet et al. (2001) and in the references cited below. Other common names for Pacific sardine include 'California pilchard',

‘pilchard’ (in Canada), and ‘sardina monterrey’ (in Mexico).

Sardines, as a group of species, are small pelagic schooling fish that inhabit coastal subtropical and temperate waters. The genus *Sardinops* is found in eastern boundary currents of the Atlantic and Pacific, and in western boundary currents of the Indo-Pacific oceans. Recent studies indicate that sardines in the Alguhas, Benguela, California, Kuroshio, and Peru currents, and off New Zealand and Australia are a single species (*Sardinops sagax*, Parrish et al. 1989), but stocks in different areas of the globe may be different at the subspecies level (Bowen and Grant 1997).

Pacific sardine have 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^{o} N latitude) to southeastern Alaska (57^{o} N latitude), and throughout the Gulf of California. In the northern portion of the range, occurrence tends to be seasonal. When sardine abundance is low, as during the 1960s and 1970s, sardine do not occur in commercial quantities north of Point Conception.

It is generally accepted that sardine off the West Coast of North America consists of three subpopulations or stocks. A northern subpopulation (northern Baja California to Alaska), a southern subpopulation (off coastal Baja California to southern California), and a Gulf of California subpopulation were distinguished on the basis of serological techniques (Vrooman 1964) and, more recently, a study of temperature-at capture (Felix-Uraga et al., 2004; 2005). A recent electrophoretic study (Hedgecock et al. 1989) showed, however, no genetic variation among sardine from central and southern California, the Pacific coast of Baja California, or the Gulf of California. A fourth, far northern subpopulation, has also been postulated (Radovich 1982). Although the ranges of the northern and southern subpopulations overlap, the stocks may move north and south at similar times and not overlap significantly. The northern stock 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 sardine 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 (Clark and Janssen 1945) indicate that the older and larger fish moved farther north. 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. At present, the combination of increased stock size and warmer sea surface temperatures have resulted in the stock reoccupying areas off northern California, Oregon, Washington, and British Columbia, as well as habitat far offshore from California. During a cooperative U.S.-U.S.S.R. research cruise for jack mackerel in 1991, several tons of sardine were collected 300 nm west of the Southern California Bight (Macewicz and Abramenkoff 1993). Abandonment and re-colonization of the higher latitude portion of their range has been associated with changes in abundance of sardine populations around the world (Parrish et al. 1989).

Important Features of Life History that Affect Management

Life History

Pacific sardine may reach 41 cm, but are seldom longer than 30 cm. They may live as long as 14 years, but individuals in historical and current California commercial catches are usually younger than five years. In contrast, the most common ages in the historical Canadian sardine fishery were six years to eight years. There is a good deal of 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 likely also important (Butler 1987). At relatively low biomass levels, sardine 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).

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 rates 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 sardine stock would die each year of natural causes if there were no fishery.

Pacific sardine spawn in loosely aggregated schools in the upper 50 meters of the water column. Spawning occurs year-round in the southern stock and peaks April through August between San Francisco and Magdalena Bay, and January through April in the Gulf of California (Allen et al. 1990). Off California, 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. Temperature requirements are apparently flexible, however, because eggs are most common at 22^{o}C to 25^{o} C in the Gulf of California and at 17^{o}C to 21^{o}C off Central and Southern Baja (Lluch-Belda et al. 1991).

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). Historically, spawning may also have been fairly regular off central California. Spawning was observed off Oregon (Bentley et al. 1996), and young fish were seen in waters off British Columbia in the early fishery (Ahlstrom 1960) and during recent years (Hargreaves et al. 1994). The main spawning area for the historical population off the U.S. was between Point Conception and San Diego, California, out to about 100 miles offshore, with evidence of spawning as far as 250 miles offshore.

Sardine are oviparous multiple-batch spawners with annual fecundity that is indeterminate and highly age- or size-dependent (Macewicz et al. 1996). Butler et al. (1993) estimated that two-year-old sardine spawn on average six times per year whereas the oldest sardine spawn up to 40 times per year. Both eggs and larvae are found near the surface. Sardine eggs are spheroid, have a large perivitelline space, and require about three days to hatching at 15^{o}C.

Sardine are planktivores that consume both phytoplankton and zooplankton. When biomass is high, Pacific sardine may consume a significant proportion of total organic production in the

California Current system.

Pacific sardine are taken by a variety of predators throughout all life stages. Sardine eggs and larvae are consumed by an assortment of invertebrate and vertebrate planktivores. Although it has not been demonstrated in the field, anchovy predation on sardine eggs and larvae was postulated as a possible mechanism for increased larval sardine mortality from 1951 through 1967 (Butler 1987). There have been few studies about sardine as forage, but juvenile and adult sardine are consumed by a variety of predators, including commercially important fish (e.g., yellowtail, barracuda, bonito, tuna, marlin, mackerel, hake, salmon, and sharks), seabirds (pelicans, gulls, and cormorants), and marine mammals (sea lions, seals, porpoises, and whales). In all probability, sardine are consumed by the same predators (including endangered species) that utilize anchovy. It is also likely that sardine will become more important as prey as their numbers increase. For example, while sardine were abundant during the 1930s, they were a major forage species for both coho and chinook salmon off Washington (Chapman 1936).

Abundance, Recruitment, and Population Dynamics

Extreme natural variability and susceptibility to recruitment overfishing are characteristic of clupeoid stocks like Pacific sardine (Cushing 1971). Estimates of the abundance of sardine from 1780 through 1970 have been derived 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 sardine have varied more than anchovy. Sardine population declines were characterized as lasting an average of 36 years; recoveries lasted an average of 30 years. Biomass estimates of the sardine population inferred from scale-deposition rates in the 19th and 20th centuries (Soutar and Isaacs 1969; Smith 1978) indicate that the biomass peaked in 1925 at about six million mt.

Sardine age-three and older were fully recruited to the historical fishery until 1953 (MacCall 1979). Recent fishery data indicate that sardine 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 unlikely to be fully available to fisheries south of Point Conception.

Sardine spawning biomass estimated from catch-at-age analysis averaged 3.5 million mt from 1932 through 1934, fluctuated between 1.2 million mt to 2.8 million mt over the next ten years, then declined steeply during 1945 through 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% annually in the early 1980s (Barnes et al. 1992). Recent estimates (Hill et al. 2005, 2006) indicate that the total biomass of sardine age one or older is greater than one million metric tons.

Recruitment success in sardine is generally autocorrelated and affected by environmental processes occurring on long (decadal) time scales. Lluch-Belda et al. (1991) and Jacobson and

MacCall (1995) demonstrated relationships between recruitment success in Pacific sardine and sea surface temperatures measured over relatively long periods (i.e., three years to five years). Their results suggest that equilibrium spawning biomass and potential sustained yield is highly dependent upon environmental conditions associated with elevated sea surface temperature conditions.

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

MacCall (1979) estimated that the average potential population growth rate of sardine was 8.5% during the historical fishery while the population was declining. He concluded that, even with no fishing mortality, the population on average was capable of little more than replacement. Jacobson and MacCall (1995) obtained similar results for cold, unproductive regimes, but also found that the stock was very productive during warmer regimes.

MSY for the historical Pacific sardine population was estimated to be 250,000 mt annually (MacCall 1979; Clark 1939), which is far below the catch of sardine during the peak of the historical fishery. Jacobson and MacCall (1995) found that MSY for sardine depends on environmental conditions, and developed a stock-recruitment model that incorporates a running average of sea-surface temperature measured off La Jolla, California. This stock-recruitment model has been used in recent assessments.

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, and peaked at over 700,000 mt. Pacific sardine supported the largest fishery in the western hemisphere during the 1930s and 1940s, with landings along the coast in British Columbia, Washington, Oregon, California, and Mexico. The 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 the catch as the fishery decreased, with landings ceasing in the northwest in 1947 through 1948, and in San Francisco in 1951 through 1952. Sardine were primarily used for reduction to fish meal, oil, and as canned food, with small quantities taken for live bait. An extremely lucrative dead bait market developed in central California in the 1960s.

In the early 1980s, sardine fishers began to take sardine incidentally with Pacific (chub) mackerel and jack mackerel in the southern California mackerel fishery. Sardine were primarily canned for pet food, although some were canned for human consumption. As sardine continued to increase in abundance, a directed purse-seine fishery was reestablished. Sardine landed in the directed sardine U.S. fisheries are mostly frozen and sold overseas as bait and aquaculture feed, with minor amounts canned or sold fresh for human consumption and animal food. Small quantities are harvested live bait.

Besides San Pedro and Monterey, California, significant Pacific sardine landings are now made in the Pacific northwest and in Baja California, Mexico. Sardine landed in Mexico are used for reduction, canning, and frozen bait. Total annual harvest of Pacific sardine by the Mexican fishery is not regulated by quotas, but there is a minimum legal size limit of 165 mm. To date, no international management agreements between the U.S. and Mexico have been developed.

Management History

The sardine fishery developed in response to an increased demand for protein products that arose during World War I. The fishery developed rapidly and became so large that by the 1930s sardines accounted for almost 25% of all fish landed in the U.S. (Leet et al. 2001). Coast wide landings exceeded 350,000 mt each season from 1933 through 1934 to 1945 through 1946; 83% to 99% of these landings were made in California, the remainder in British Columbia, Washington, and Oregon. Sardine landings peaked at over 700,000 tons in 1936. In the early 1930s, the State of California implemented management measures including control of tonnage for reduction, case pack requirements, and season restrictions.

In the late 1940s, sardine abundance and landings declined dramatically (MacCall 1979; Radovich 1982). The decline has been attributed to a combination of overfishing and environmental conditions, although the relative importance of the two factors is still open to debate (Clark and Marr 1955; Jacobson and MacCall 1995). Reduced abundance was accompanied by a southward shift in the range of the resource and landings (Radovich 1982). As a result, harvests ceased completely in British Columbia, Washington, and Oregon in the late 1940s, but significant amounts continued to be landed in California through the 1950s.

During 1967, in response to low sardine biomass, the California legislature imposed a two-year moratorium that eliminated directed fishing for sardine, and limited the take to 15% by weight in mixed loads (primarily jack mackerel, Pacific [chub] mackerel and sardines); incidentally-taken sardines could be used for dead bait. In 1969, the legislature modified the moratorium by limiting dead bait usage to 227 mt (250 short tons). From 1967 to 1974, a lucrative fishery developed that supplied dead bait to striped bass anglers in the San Francisco Bay-Delta area. Sardine biomass remained at low levels and, in 1974, legislation was passed to permit incidentally-taken sardines to be used only for canning or reduction. The law also included a recovery plan for the sardine population, allowing a 907 mt (1,000-short ton) directed quota only when the spawning population reached 18,144 mt (20,000 short tons), with increases as the spawning stock increased further.

Management Since Onset of the Recovery

In the late 1970s and early 1980s, CDFG began receiving anecdotal reports about the sighting, setting, and dumping of "pure" schools of juvenile sardines, and the incidental occurrence of sardines in other fisheries, suggesting increased abundance. In 1986, the state lifted its 18-year moratorium on sardine harvest on the basis of sea-survey and other data indicating that the spawning biomass had exceeded 18,144 mt (20,000 short tons). CDFG Code allowed for a directed fishery of at least 907 mt once the spawning population had returned to this level.

California's annual directed quota was set at 907 mt (1,000 short tons) during 1986 to 1990; increased to 10,886 mt in 1991, 18,597 mt in 1992, 18,144 mt in 1993, 9,072 mt in 1994, 47,305 mt in 1995, 34,791 mt in 1996, 48,988 mt in 1997, 43,545 mt in 1998, and 120,474 mt in 1999.

Management Under the PFMC CPS Fishery Management Plan (2000 to Present)

In January 2000, management authority for the U.S. Pacific sardine fishery was transferred to the Pacific Fishery Management Council. 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 sardine from being overfished and maintain relatively high and consistent catch levels over a long-term horizon. The harvest formula for sardine is provided at the end of this report (see '**Harvest Guideline for 2007'** below**)**. A thorough description of PFMC management actions for sardine, including harvest guidelines, may be found in the most recent CPS SAFE document (PFMC 2006). U.S. harvest guidelines and resultant landings since calendar year 2000 are displayed in Figure 1.

ASSESSMENT DATA

Biological Parameters

Stock Structure

For purposes of this assessment, we assume a single Pacific sardine stock that extends from northern Baja California, Mexico to British Columbia, Canada and extends well offshore, perhaps 300 nm or more (Macewicz and Abramenkoff 1993; Hill et al. 1999). More specifically, all U.S. and Canadian landings are assumed to be taken from the single stock being accessed. Similarly, all sardine landed in Ensenada, Baja California, Mexico are also assumed to be taken from the single stock being accessed and sardine landed in Mexican ports south of Ensenada are considered to be part of another stock that may extend from southern Baja California into the Gulf of California. In the near future, alternative stock structure scenarios will be explored, including one that separates the catches in Ensenada and San Pedro into the respective 'cold' and 'temperate' stocks proposed by Felix-Uraga et al. (2004, 2005) and takes into account subpopulation differences in growth and natural mortality.

Length-weight Relationship

The length-weight relationship for Pacific sardine was modeled using fish measured from survey and port samples collected from 1982 to 2004. The following power function was used to determine the relationship between weight (g) and standard length (mm) for both sexes combined:

$$W_L = a\,(L^b),$$

where W_L is weight-at-length L, and a and b are the estimated regression coefficients. The estimated coefficients were a = 0.000001 and b = 3.113 (corrected R^2 = 0.928; n = 86,606).

Length-at-age Relationship

The von Bertalanffy growth equation was used to derive the relationship between standard length (mm) and age (yr) for Pacific sardine:

$$L_A = L_\infty\,(1 - e^{-K(A-to)}),$$

where L_A is the length-at-age A, L_∞ ('L infinity') is the theoretical maximum size (length) of the fish, K is the growth coefficient, and t_o ('t zero') is the theoretical age at which the fish would have been zero length. The best estimate of von Bertalanffy parameters for Pacific sardine was: L_∞ = 244 mm, K = 0.319, and t_o = -2.503 (corrected R^2 = 0.561; n = 86,606).

Maximum Age and Size

The largest recorded Pacific sardine was 410 mm long (Eschmeyer et al. 1983), but the largest Pacific sardine taken by commercial fishing since 1983 was 288 mm and 323 g. The oldest recorded age for a Pacific sardine was 14 years, but most commercially-caught sardine are typically less than four years old.

Maturity Schedule

The maturity schedule provided in Table 1 was used for all model runs (Hill et al. 1999). The "Coded Age" appears in all model input and output files. The correspondence between "Coded Age" and "True Age" is also provided in the table.

Natural Mortality

Adult natural mortality rates have 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 sardine stock would die each year of natural causes if there were no fishery. Consistent with previous assessments, 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

Fishery data for assessing Pacific sardine include commercial landings and port sample (biological) data for three regional fisheries: California (San Pedro and Monterey), northern Baja California (Ensenada), and the Pacific northwest (Oregon, Washington, and British Columbia). Biological data includes individual weight (g), standard length (mm), sex, maturity, and otoliths for age determination. CDFG currently collects 12 random port samples (25 fish per sample) per month to determine age composition and weights-at-age for the directed fishery. Mexican port samples, collected by INP-Ensenada 1989-2002, were aged and made available for this assessment by coauthor Felix-Uraga. ODFW and WDFW have collected port samples since 1999. A listing of sample sizes relative to fishery landings, 1982-83 to present, is provided in Table 2.

Following recommendations of the CPS STAR Panel (PFMC 2004), all fishery inputs were compiled based on a 'biological year' as opposed to a calendar year time step, with the biological year being based on the birthdates used to assigned age. Therefore, data were aggregated from

July 1 ($year_x$) through June 30 ($year_{x+1}$). In the input and output files, the sardine fisheries (or 'Fleets') are assigned numbers as follows:

ASAP Fleet Number	*Corresponding Sardine Fishery*
1	California (San Pedro and Monterey)
2	Ensenada (northern Baja California, México)
3	Pacific Northwest (Oregon, Washington, British Columbia)

Landings

The ASAP model includes commercial landings in California, northern Baja California and the Pacific Northwest from 1982-83 through 2006-07. Landings were aggregated by biological year and are presented in Table 2 and Figure 2.

California commercial landings were obtained from a variety of sources based on dealer landing receipts (CDFG), which in some cases augmented with special sampling for mixed load portions. During California's incidental sardine fishery (1982-83 through 1990-91), many processors reported sardine as mixed with jack or Pacific mackerel, but in some cases sardine were not accurately reported on landing receipts. For these years, sardine landings data were augmented with shore-side 'bucket' sampling of mixed loads to estimate portions of each species. CDFG reports these data in monthly 'Wetfish Tables', which are still distributed by the Department. These tables are considered more accurate than PacFIN or other landing receipt-based statistics for California CPS, so were used for this assessment. Projected landings for the final time step (2006-07) were based on 2005-06 landings.

Ensenada (northern Baja California) landings from July 1982 through December 1999 were compiled using monthly landings from the 'Boletín Anual' series published by the Instituto Nacional de la Pesca's (INP) Ensenada office (e.g. see Garcia and Sánchez, 2003). Monthly catch data from January 2000 through June 2005 were provided by Dr. Tim Baumgartner (CICESE-Ensenada, Pers. Comm.), who obtained the data electronically from Sr. Jesús Garcia Esquivel (Department of Fisheries Promotion and Statistics, SEMARNAP-Ensenada). These new catch data for 2000 to mid-2005 incorporate estimates of sardine delivered directly to tuna rearing pens off northern Baja California, and are overall 37% higher than statistics used in the previous assessment. Ensenada landings for calendar year 2005 were reported to be 56,684 mt (Cota-V. et al. 2006). Projected landings for 2005-06 were based on the 2004-05 value.

For the Pacific Northwest fishery, we included sardine landed in Oregon, Washington, and British Columbia. Monthly landing statistics were provided by ODFW (McCrae 2001-2004, McCrae and Smith 2005), WDFW (WDFW 2001, 2002 and 2005; Robinson 2003, Culver and Henry 2004), and CDFO (Christa Hrabok, pers. comm.). The Pacific Northwest fishery has progressed more slowly in the summer of 2006. Based on landings-to-date the 2006-07 projection is assumed to be about two-thirds of the 2005-06 landings.

Catch-at-age

Descriptions of sardine otolith ageing techniques can be found in Walford and Mosher (1943) and Yaremko (1996). Pacific sardine are aged by fishery biologists in Mexico, California, and the Pacific Northwest, using annuli in sagittal otoliths. A birth date of July 1 was assumed when assigning ages to California, Oregon, and Washington samples. Ensenada age assignments were adjusted to match this assumption *post-hoc* by subtracting one year of age from fish caught during the first semester of the calendar year. Sample sizes by fishery and biological year are provided in Table 2. In summary, port sample data for the three fisheries were available for the following seasons: California, 1982-82 to 2005-06; Ensenada, 1988-89 to 2002-03; and Pacific northwest, 1998-99 to 2005-06.

Catch-at-age matrices were developed for each fishery using port sample and landings data aggregated by month. Estimates of catch-at-age were weighted to take into account variation in sample size relative to total landings. Sample percent-by-weight for each age class was calculated by dividing the total weight of fish-at-age by the total weight of fish sampled in each month. Landed weight of fish in each age class was estimated as the product of metric tons landed and the percent-by-weight in the fishery sample. Numbers-at-age in the monthly landings were then calculated by dividing the landed weight-at-age by the average individual weight-at-age for the month. For months with landings but no fishery sample taken, data were substituted by summing sample information (i.e., fish numbers, weights, and sample weights) from the two adjacent (previous and following) months. Finally, numbers-at-age were summed across months to provide the catch-at-age (thousands of fish) for each biological year. Individuals five years of age and older were pooled into a ‘plus’ group, and sexes were pooled for the assessment. Catch-at-age data compiled for ASAP input are provided in Tables 3-5, and proportions-at-age are displayed in Figures 3-5. Based on estimates from preliminary model runs, effective sample sizes for the California and Ensenada fisheries were set to λ=50. Effective sample size for the Pacific Northwest fishery data was estimated to be lower, and was set to λ=12 for the final base run. In years with landings but no samples, effective sample size was set to zero.

<u>Fishery weight at age</u>

Mean weights-at-age were calculated for each fishery and biological year by dividing total sampled weight of fish-at-age by the total number of fish-at-age. The current version of ASAP is only configured to accommodate one weight-at-age matrix, so a pooled weight-at-age was calculated by taking a weighted weight-at-age for the three fisheries, using respective landings in each year as a basis for the weighting. Pooled fishery weights-at-age applied in ASAP are provided in Table 6 and Figure 6.

<u>Population weight at age</u>

Because the sardine fisheries do not cover the stocks’ full geographic range (i.e., fishery coverage is generally inshore, whereas the spawning stock extends 200 miles offshore), fishery weight-at-age estimates are often smaller than those of the population as a whole. For the purposes of converting model-based number-at-age estimates into stock biomass (Ages 1+) for management, biological samples from fishery-independent sources that span the geographical range of the stock were used to calculate population weights-at-age (Table 7) outside of the ASAP model. Data included survey samples from summer 1998 and spring 2004.

Fishery-Independent Data

Overview
In the input and output files, the fisheries-independent indices of abundance are assigned numbers are follows:

Index Number	*Corresponding Data*	*Represents*
1	DEPM	SSB
2	Aerial Spotter	Biomass of pre-adults (ages 0-2)

Daily Egg Production Method (DEPM) Spawning Biomass Index (Index 1)
Daily egg production method (DEPM) spawning biomass estimates were available for 1986-1988 and 1994-2006 (Table 8, Figure 7). Methods employed for the DEPM-SSB point estimates are published in Wolf and Smith (1986), Wolf et al. (1987), Wolf (1988a,b), Lo et al. (1996 & 2005), and Lo and Macewicz (2006). Adult samples were not taken on a consistent basis and, consequently, it was necessary to use averaged values for adult reproductive parameters (egg production, daily specific fecundity, etc.) in some years.

A coast-wide sardine survey (Baja California, Mexico to British Columbia, Canada) was conducted April 1-May 8, 2006 (Figure 8). Three U.S. vessels were deployed to sample the area from California to British Columbia, including the FRVs *David Starr Jordan* and *Oscar Dyson*, and the SIO's *New Horizon* which covered the standard CalCOFI stations. The Mexican research vessels *El Puma* and *BIP XI* were used off outer Baja California -- results from this portion of the coast-wide survey are not yet available for an assessment. The original survey design for U.S.-Canada portion included both the *Oscar Dyson* and *David Starr Jordan* in ichthyoplankton and adult sampling (trawl and acoustic), with the *Dyson* sampling from British Columbia to San Francisco and the *David Starr Jordan* from San Diego to San Francisco. Due to trawl equipment failures on the *David Starr Jordan*, the *Oscar Dyson*'s survey tracks were revised to enable trawl sampling off California. Thus, the final survey was not synchronized (egg v. adult samples) as originally planned and had lower spatial resolution.

The *David Starr Jordan* took CalVET and CUFES samples during the entire cruise from April 6-28, and bongo tows in the area north of CalCOFI line 76.7. The *Oscar Dyson* collected trawl, CalVET, and bongo samples in the area from Vancouver Island to north of San Francisco from April 12-May 8 and trawl and CUFES samples during the entire cruise. The *New Horizon* took CalVET and Bongo samples at regular CalCOFI stations from San Diego to north of Point Conception during April 1-17.

The total DEPM-based spawning biomass during April-May 2006 was estimated to be 1,304,806 mt (CV = 0.47) within a 885,523 km^2 spawning area from San Diego to British Columbia. This estimate was based on a daily egg production estimate of $0.75/0.05m^2$ (CV = 0.23) and a daily specific fecundity of 10.18 (number of eggs/population weight (g)/day) for the entire survey area. Sardine eggs and adults were not found north of Coos Bay, Oregon. The standard DEPM sampling region off California (San Diego to San Francisco) had a spawning area of 336,774 km^2. For this region, egg production was estimated to be $1.37/0.05m^2$ (CV = 0.26), daily specific fecundity was 8.47 (number of eggs/population weight (g)/day), and the resulting spawning biomass was 1,081,612 mt (CV=0.47). Thus, the portion spawning biomass from San Francisco to British Columbia was approximately 223,194mt.

In ASAP, the DEPM index was taken to represent sardine SSB in April (month 10) of each biological year. CVs for DEPM estimates are also presented in Table 8. The 2005-06 DEPM estimate, based on eggs and adults collected from the standard survey area (San Diego to San Francisco) during the April 2006, was 1,081,612 mt of SSB (Table 8). The selectivity pattern for this survey was fixed, based on maturity-at-age proportions (Table 9, Figure 9). Within ASAP, a CV of 0.30 was applied to all DEPM observations.

Aerial Spotter Survey (Index 2)

Pilots employed by the fishing fleet to locate pelagic fish schools, including sardine, report data for each flight on standardized logbooks and provide them to NOAA Fisheries for a fee per flying hour ($1-$5). Spotter indices for sardine were calculated as year effects estimated using delta log-normal linear models (LLM; Lo et al. 1992). The spotter index covers the period 1985 through 2005, with a July-June time step Table 8, Figure 7). After the year 2000, there was rapid decline in both the number of active pilots and total logbooks returned (Tables 10 and 11), as well as a southward shift in effort to offshore areas off of Baja California (Figure 10). To remedy this problem, NOAA Fisheries started to contract professional spotter pilots to survey the Southern California Bight region in 2004 and 2005. Newly available data from this enhanced survey were incorporated into the index, and a new time series was calculated using a delta Generalized Linear Model (GLM). CVs of delta GLM estimates from 2000-01 onward were higher than the earlier portion of the time series partially due to reduced sample size (Table 8, Figures 11 & 12). To account for this uncertainty, we applied higher CVs to observed values within the ASAP model (increasing from 0.3 to 0.7 in the final year; Figure 12), in effect lowering the influence of the 2000-01 to 2004-05 spotter data in the overall likelihood. We applied a CV of 0.30 to all observations prior to 2000-01. The aerial survey index was taken to represent the inshore, younger sardine (primarily ages 0-2; Table 9, Figure 9).

The old time series based on logbook data had an informal design. Pilots flew year-round at night and in the day, and in areas and seasons frequented by the fishery. The pilot's searching behavior, like most fishermen, might be characterized as “adaptive”, that is, searches for target species may be concentrated in areas where schools were previously sighted. No doubt exists that a formal fishery-independent survey design would be more precise and less biased than the present indices. However, by altering the design one loses the old aerial surveys most valuable property, i.e., a time series that extends back 38 years. Regardless of its merit, a new index will have little value in stock assessment until it extends over at least 5-10 years. Clearly, the time series that ended in 2000 needed to be extended, but was also valuable to develop a new, more precise index with less potential bias.

The new data collected in 2004 and 2005 were based on a line-transect design with regular occupation of fixed grid lines spaced at regular intervals with random starting points, while the simulated old survey employed a adaptive design to simulate fishing conditions where, having found one school the fishermen will search the vicinity to find others. After searching, the pilot returns to the transect line and continues along the line. In this way, we gathered information appropriate to both old and new survey designs. The month, area, and daylight of new surveys are close to those standardized conditions used in the spotter index model developed by Lo et al (1992): experienced pilots, under contract, flew along the predetermined track lines in March and April from San Diego to San Francisco, at a maximum of 100 nm offshore (Figure 13). In reality, pilots were unable to all assigned surveys in March and April due to weather conditions and their flying schedules. In addition, they only fly in the day time and not in the night alone. As a result, flights in 2004 took place throughout the entire year.

Two analyses were conducted. The first, based on Delta GLM, included new datasets together with the historical aerial survey data, and the second was stand-alone estimates from the strip transect method. For the strip transect method, we grouped flights by month into individual surveys and density of sardine was computed for each survey. In 2004, a total of 5 surveys by month (3, 4, 5, 7, and 9) were accomplished from March-November, including two single-pilot flights in September and November. In 2005, we had two 3-pilot complete surveys, three 2-pilot surveys and one 1-pilot survey during March and April. A set of these two estimates for 5-10 years datasets can be used to calibrate these two estimates and to link the data from the past to the future. The goal of contracted pilots is for the future to use strip transect method on data collect from the predetermine track lines, area and time of the year. In the following sections, we will describe the first analysis: delta linear models: delta lognormal linear model and delta GLM.

Delta Linear Models

The relative abundance of pelagic species (e.g. anchovy or sardine) can be expressed as the product of density and a measure of area:

$$I = DA$$

where *I* is the index of relative abundance for a given year (tons), *D* is density of sardine (tons per block) and *A* is the area (blocks) covered by fish spotters. In the original data analysis of the relative abundance of anchovy (Lo et al. 1992), it was reasonable to assume that fish spotters flew over an area that was at least as large as the area occupied by the anchovy stock in each year. This is not so for the entire sardine population but may apply to young sardines (<=2 year old). In the current analysis for sardine, units for the index *(I)* are tons of young sardine, sighted by fish spotters.

Density of sardine *(D)* for each year can be expressed as the product of *d* and *P:*

$$D = dP$$

where *d* is a standardized measure of sardine density (tons per block) for positive flights (flights during which young sardine were seen) and P is a standardized measure of the proportion of blocks covered by positive flights (referred to as 'proportion positive') (Table 10). We used the product in order to avoid problems that arise from including a large number of zeros, therefore the distribution of D is Delta distribution.

Delta Lognormal Linear Model

In the original lognormal linear model, we assumed that data tons/block (y) or proportion positive (p) follows a lognormal distribution and varies with some covariates, i.e. log(y) or log(p+1) was a function of many covariates: year, region, season, pilot, night/day flights plus some interaction terms: log(y) or log(p+1) =x'B. The final estimates of standardized *d* and *P* were obtained by taking anti log of the linear equations (x'B) plus correction terms. The relative abundance for each year is:

$$\hat{I} = \hat{d}\hat{P}A$$

Delta GLM model

To continue including spotter pilot data for the stock assessment from the new datasets, we decided to switch from Delta lognormal linear model to a more flexible model, like GLM using S+, to allow us to incorporate other possible distribution of tonnages/block (y) of sardine sighted by the pilots for the positive flights and the proportion of positive flights (p) with appropriate link functions for the expected values (d and P) respectively. As stated in Lo et al. (1992), "…Although we used lognormal linear models for components of the delta distribution, other linear or nonlinear models based on other statistical distributions could be used instead."

For the delta GLM, we chose family of Poisson and used log as the link function for the tons/block of positive flights (d), e.g. log (the expected tonnage/block) = x'B and family of Binomial and the link function of the logistic, for the proportion of positive flight (P), e.g. log(P/(1-P)) = x'B. The estimate of density of sardine is $\hat{D} = \hat{d}\hat{P}$ with variance:

$$\mathrm{var}(\hat{D}) = \mathrm{var}(\hat{d}\hat{P}) = \hat{P}^2\,\mathrm{var}(\hat{d}) + \hat{d}^2\,\mathrm{var}(\hat{P}) - \mathrm{var}(\hat{d})\,\mathrm{var}(\hat{P})$$

where the estimated variance of estimates of d and P came directly from S+. No correction of *d* and *P* was included in the variance of *D* because the correlation from the data was not significant. The final estimate of the relative abundance (*I*) and its CV are simply as follows.

$$\hat{I} = \hat{D}A$$
$$CV(\hat{I}) = CV(\hat{D})$$

where *A* is total number of blocks within the tradition area covered by spotter pilots prior to 2004.

The time series of the relative abundance of sardines from spotter data set are given in Figure 14 based on the original delta-lognormal distribution and the delta-GLM.

The Delta distribution (Aitchison and Brown 1957; Pennington 1983) was used because of low proportion of positive flights in most years. As the current survey designs continue for long period of time, the Delta distribution may not be needed. The current procedure includes the standardization of region to region 2, which was originally designed for anchovy. For sardine, it may be more proper to use region 3. The current flights all take place in the day time.

Comparisons between Delta lognormal linear model and Delta GLM

Data from 1985-2004 (calendar year) were analyzed using both models. Two time series have similar shape except that the time series from lognormal linear model fluctuated a little less than that from Delta GLM even though the peak from the former is higher than the latter (Figure 14). The CVs from LLM (Bradu and Munklak 1970) are higher than those from GLM because the variances of the estimates from LLM included those of bias-correlation terms for the parameter estimates of lognormal distribution and the delta-methods for variance of estimates were used in GLM (Chambers and Hastie 1992).

ASSESSMENT MODEL

ASAP Model Description

Overview

The Age-structured Assessment Program (ASAP) model (Legault and Restrepo 1999; see Appendix I) is based on the AD Model Builder (ADMB) software environment, a high-level programming language that utilizes C++ libraries for nonlinear optimization (Otter Research 2001). Further, the ASAP model is maintained through the NOAA Fisheries Toolbox Project (NFT), which includes various fishery-related models that have been customized with graphical user interfaces (GUIs) to enable users to conduct modeling exercises and evaluate results more readily.

The general estimation approach used in the ASAP is that of a flexible forward-simulation that allows for the efficient and reliable estimation of a large number of parameters. The population dynamics and statistical principles of ASAP are well established and date back to Fournier and Archibald (1982), and Deriso et al. (1985). However, reliable implementation of such large scale models for fisheries stock assessment has only become practical during the past decade as microprocessors have become powerful enough to handle the computational demands and professional quality optimization software (ADMB) has been developed.

The following is a brief description of estimation methods employed in the ASAP model. Readers interested in further details and model equations should refer to Legault and Restrepo (1999; see Appendix I).

- Model estimation begins in the first year of available data with an estimate of the population abundance-at-age.
- The spawning stock for that year is calculated and the associated recruitment for the next year is determined via the stock-recruitment relationship (in this case, based on a Beverton-Holt model). Recruitment variability is accommodated by accounting for divergence from the estimated central tendency (expected value).
- Each cohort estimated in the initial population abundance at age is then reduced by the total mortality rate and subsequently, projected into the next year/age combination. This process of estimating recruitment and projecting the population 'forward' continues until the final year of data is reached.
- Total mortality rates (Z) used to decrease cohort abundances over time represent the sum of natural mortality (M) and the fishing mortalities (F) from all fisheries.
- The Fs for each fishery are assumed to be 'separable' into age (commonly referred to as selectivity) and year (commonly referred to as F-multipliers). The product of selectivity-at-age and the year specific F-multiplier equals the F for each fishery/year/age combination.
- The added structure of time-varying selectivity and/or catchability can be incorporated via the estimation of random walks.
- Predicted catch in weight and catch-at-age are estimated using Baronov's catch equation and user-provided mean weights at age and natural mortality.
- The method of maximum likelihood serves as the foundation of the overall numerical estimation. Sources of data are compartmentalized into various likelihood components,

depending on the level of structure of the overall, fully-integrated population model. Generally, the ASAP model includes nine likelihood components and a few penalties, given a baseline population model (see Table 12).

- The tuning indices are assumed to represent changes in the population over time for specific age ranges and can be measured in numbers or weight.
- Given the large number of parameters, it is possible to fit both the catch-at-age and the abundance indices relatively well, but often at the expense of producing somewhat unrealistic trends in other stock parameters of interest (e.g., recruitment, selectivity, and catchability). Constraints and penalty functions can be employed to the constrain estimation to more feasible regions of parameter space.
- Because the number of parameters can be large and highly nonlinear, it is often difficult to estimate all parameters simultaneously in one run of the model. In practice, the minimization usually proceeds in phases, where groups of parameters are estimated simultaneously, while the remaining parameters are maintained at their initially assigned ('starting') values. Once the objective function is minimized for a particular phase, more parameters are evaluated in a step-wise fashion. Estimation within additional phases continues until all parameters are estimated. For this assessment, parameters were estimated in the following order: Phase (1): Selectivity in 1st Year, Fmult in 1st Year, Catchability in 1st Year, Stock-Recruitment Relationship, and Steepness; Phase (2): Fmult Deviations, Recruitment Deviations; Phase (3): Selectivity Deviations.
- While ASAP has the ability to estimate population numbers at age in the first year, attempts to do so with sardine resulted in unrealistically high numbers in the initial population which carried through the entire time series. For this reason, we fixed numbers-at-age for the initial population to a biomass equivalent of 5,000 mt. Specifically, numbers-at-age (1,000s) for ages 0 to 5+ were set to the following starting values, respectively: 25,000, 15,000, 9,000, 5,400, 3,240, and 1,944.

<u>Assessment Program with Last Revision Date</u>
ASAP version 1.3.2 (compiled 14 Sept. 2004) was used for all runs presented in this paper. ASAP was implemented using NFT GUI version 2.7 (compiled 4 Mar. 2005).

<u>Likelihood Components and Model Parameters</u>
Likelihood components in the final ASAP base model ('Base-D5') are listed in Table 12. Parameterization summaries for the baseline ASAP model are provided in Table 13.

<u>Convergence Criteria</u>
The iterative process for determining numerical solutions in the model was continued until the difference between successive likelihood estimates was <0.0001. The number of function evaluations ranged from 800 to 10,000, depending on the model configuration and initial values. Fidelity of model convergence was explored by modifying selected initial values (stock size at the beginning of the time series, catchability coefficients associated with indices of abundance, etc.) and then comparing the likelihoods and estimates of key management parameters.

MODEL RESULTS

Overview

An ASAP model was developed initially by mimicking (to the extent possible) the structure employed in the last CANSAR-TAM stock assessment (Conser et al 2003). However, as noted above, recent assessments have not used the fisheries data from the northern area (OR+WA+BC) – instead fish were moved from the modeled southern area at fixed transfer rates. In this implementation of ASAP, fisheries data from the northern area were fully incorporated and no assumptions were made regarding sardine migration rates. The initial model configuration was then modified following recommendations of the June 2004 STAR Panel and further examination of model diagnostics (Conser et al. 2004; Hill et al. 2005). The assessment model '06_Base-A1' constructed for this update is parameterized as described by Hill et al. (2005) – only the fishery and survey data have been updated for the final two time steps (2005-06 and 2006-07).

In the ASAP baseline model, most parameters were freely estimated without strong constraints or penalties. The likelihood components at the optimal solution are provided in Table 12. A total of 140 parameters were estimated (Table 13). Model run times were usually only a few minutes and converged without problem, and with a positive-definite Hessian matrix. Limited exploration of the response surface via adjustments to the starting values did not uncover additional local minima. Standard deviations were reasonable for most of the key model parameters including the derived parameters such as SSB (Table 13).

Catch

Model fit to catch data for each fishery is displayed in Figure 15. The observed and predicted time series essentially overlay each other, indicating precise fit to this data source.

Catch-at-age

Effective sample sizes for the California and Ensenada fisheries were set to λ=50. Effective sample size for the Pacific Northwest fishery data was set to λ=12 (Figure 16). Model residuals for catch-at-age data are displayed in Figure 17. Residuals for the three fisheries were random, with no obvious trends over age or time.

Indices of Abundance

Model fits to DEPM and Aerial Spotter series are displayed in Figure 18. Comparisons of observed data for the two indices may be found in Figure 19. Note the inverse relation between the two indices for the year-year comparison (Figure 19A), and relative lack of correlation when DEPM is lagged by two years (Figure 19B) to account for differences in selectivity.

Selectivity Estimates

Estimated selectivities (S_{age}) for the three respective fisheries are displayed in Figure 20.

Selectivity for the California fishery was estimated for two periods: 1982-1990 (biological years) when the population was smaller, quotas were lower, and a large portion of sardine was captured mixed with schools of jack and Pacific mackerel; and 1991-2006, when the population was larger, quotas were higher, and pure schools of sardine were targeted. Selectivity patterns for the California and Ensenada fisheries were dome-shaped (Figure 20), with 2 year old fish being fully selected. Relative paucity of older ages in these two fisheries is likely an artifact of availability (larger, older fish offshore or north of the fishing areas) as opposed to gear- or market-related causes. Estimated selectivity for the Pacific Northwest fishery is asymptotic (Figure 20), with the oldest two ages being more or less fully selected. Again, this likely reflects the coast-wide distribution of sardine population.

Fishing Mortality Rate

Fishing mortality estimates for the three respective fisheries are displayed in Figure 21. Combined fishing mortality-at-age is displayed in Figure 22 and Table 14.

Spawning Stock Biomass

Population SSB from ASAP is provided in Table 15. Population SSB was estimated to be 1.16 mmt as of July 2006. This is well within the range of DEPM-based SSBs estimated from the April 2006 survey: 1.08 mmt from San Diego to San Francisco; 1.30 mmt from San Diego to British Columbia.

Recruitment

Recruitment estimates (age-0 abundance) are presented in Tables 13 and 15 and displayed in Figure 23. The recruitment trend is similar to that of Hill et al. (2005), with peaks in 1994-95 (9.79 billion) and 2003-04 (14.37 billion).

Stock-recruitment Relationship

Recruitment CVs were set at 0.5 for most years in ASAP. Recruits are poorly estimated in the final years of any age-structured model. To obtain more reasonable estimates of recruitment and biomass in the last several years, we increased weights on spawner-recruit predictions in ASAP by applying gradually smaller CVs (0.4, 0.3, 0.2, 0.1, 0.05) from 2002 to 2006. A similar *S-R* constraint has been applied in previous sardine assessments (Deriso et al. 1996, Hill et al. 1999, Conser et al. 2003, Hill et al. 2005). The relationship between SSB and recruitment is displayed in Figure 24. Beverton-Holt model parameters were estimated as follows: α = 6.1599e+06; β = 221,233; Virgin = 1.465e+06; and Steepness (h) = 0.66 (Table 13).

Relative spawning success, calculated as anomalies from average $ln(R/SSB)$, is displayed in Figure 25. Spawning success was highest during the onset of the recovery, with a trend toward negative anomalies in more recent years. Positive anomalies in 1993-94 and 2002-03 are attributed to peak year classes in 1994 and 2003.

The strong year class estimated for 2003 was driven, in part, by large portions of this year class in the California fishery samples collected 2003-04 through 2005-06 (Table 3, Figure 3), as well as relatively large proportions of this year class in the Pacific Northwest fishery in 2004-05 and 2005-06 (Table 5, Figure 5). Trawl surveys conducted off California in 2004 and 2005 and the Pacific Northwest from 2003 to 2005 provide fishery-independent evidence for a strong 2003 year class. Length composition data from these surveys are displayed in Figure 26. Off the Pacific Northwest the 2003 year class first appeared in March 2004 as the length mode ranging 100-130 mm SL. This mode progressively appeared in subsequent surveys in July 2004 and March 2005 (Figure 26, top panel). Off California, the presumed 2003 year class appeared as the 140-180 mm SL mode in April 2005. Age determinations for the survey samples are pending.

Biomass of Stock for PFMC Management (Ages 1+)

Stock biomass (ages 1+) estimates are presented in Table 15 and displayed in Figure 27. Stock biomass increased from low levels in the early 1980s to a peak of 1.56 mmt in 1996-97. The stock has subsequently declined to lower levels and was estimated to be approximately 1.32 million mt as of July 1, 2006. Stock biomass from the current assessment is similar in trend but slightly higher in magnitude compared to Hill et al. (2005) (Figure 27). This increase is attributed to the 2006 DEPM estimate, which is the highest in the time series (Figure 18A).

Model Diagnostic Examinations and Uncertainty

The specifications of the 2006 base model were identical to those of the 2005 assessment – only new fishery and survey data were added in 2006: Ensenada landings (2005); landings and catch-at-age data for California and Pacific Northwest (2005-06); and a DEPM-based SSB estimate from the April 2006 survey. The 2006 base model estimates of biomass and recruitment are considerably higher compared to the 2005 final model. For example, this year's estimate of stock biomass (age 1+) in July 2005 was 42% greater than the final model from 2005, and the 2006 estimate of the 2003 recruitment was 43% higher. During a meeting with the SSC's CPS Subcommittee (17 October, 2006), the following sensitivity tests were completed to more fully understand differences between the 2005 and 2006 assessments:

1. Starting with the 2005 model configuration, the impact of each new data source on assessment outcome was examined: a) adding the landings data; b) adding the 2005-06 catch-at-age data (California and the Pacific Northwest); c) adding the core-area DEPM index for 2006. These tests were performed using the 2005 σ_R settings, and shifting σ_R for the terminal year-classes (2006 base configuration) and hence imposing less constraint on the size of the 2003 year-class.
2. Examine the relative influence of the two contradictory indices by ignoring the DEPM and Aerial Spotter series in turn.
3. Reduce the emphasis factor placed on the F_{mult} penalty from 1 to 0.1.
4. Conduct a sensitivity run in which the DEPM index for 2006 is set to the estimate for the entire survey area rather than just for the core sampling area.

Results from the sensitivity runs are summarized in Table 16 and Figure 28. Shifting and increasing σ_R for the recent year-classes and including the 2006 DEPM estimate resulted in higher estimates of 2003 recruitment and 2006-07 stock biomass (age 1+). Conversely, adding in the 2005-06 catches-at-age resulted in the opposite effect. Excluding the aerial spotter index led to more optimistic results while excluding the DEPM index resulted in much lower recruitment and biomass (Table 16, Figure 28). Survey-based DEPM estimates should provide results that are, in theory, close to absolute estimates of abundance, which suggests that the sensitivity test based on ignoring the DEPM data is less plausible than that in which the spotter index is ignored. The results were fairly insensitive to down-weighting the F_{mult} penalty, and this component will be down-weighted in future assessments. Using the 2006 coast-wide survey DEPM estimate (20% greater than the 'core area' estimate) in the time series only increased model age 1+ biomass by 3.7%.

Assessment Plans for the Pacific Sardine STAR Panel in 2007

A full assessment of Pacific sardine is scheduled for STAR Panel review during 19-21 September, 2007. During the assessment update review of 17 October, 2006, the SSC's CPS Subcommittee recommended the following items be examined as part of the 2007 assessment:

1. The selectivity pattern for the aerial spotter index is pre-specified based on the selectivity pattern of the California fishery, adding the assumption that schools of age-zero fish would be visible to the pilots. However, the two California selectivity patterns are not identical, and the selectivity pattern for the spotter planes may have changed in response to changes in the distribution of the resource and fishery targets;
2. The reliability of DEPM estimates depends on representative sampling of eggs and adult reproductive parameters to adequately characterize the spawning season. Analyses should be conducted to assess whether the ability to use the DEPM estimates as indices of abundance (or as estimates of absolute abundance) is compromised due to, for example, spatial-temporal variability in spawning activity. The impact of changes in the spatial distribution of the population on whether DEPM estimates from the core region provide an index that is linearly related to spawning biomass should be examined;
3. The historical CALCOFI data should be examined to explore seasonal patterns in spawning and decadal scale variability in egg production;
4. The available survey data should be assessed to determine whether they support time-varying weight- and maturity-at-age;
5. The possibility of including sea surface temperature as a covariate when fitting the stock-recruitment relationship should be explored;
6. Given the contradictory nature of the two indices of relative abundance, there needs to be a clear rationale for the inclusion of each index in the assessment. Specifically, inclusion and weighting of indices of abundance should be based on consideration of experimental design.
7. The CVs assigned to abundance indices appear to be too small because too few of the 95% confidence intervals are intersected by the population trajectory;
8. The acoustic data collected during the 2006 survey should be analyzed with a view towards the development of an alternative index of abundance.

In addition to items requested above, the sardine STAT plans to explore the following areas for consideration at the 2007 STAR:

1. develop an assessment model using Stock Synthesis 2 (SS2), and compare results to the ASAP update;
2. transition from an annual to a semester or quarterly time step to resolve issues related to

seasonal movement and selectivity;

3. extend time series to include previous era; incorporate historical catch, length/age compositions to as early as 1919;
4. explore sensitivity to stock structure hypotheses; expand/contract geographic extent of data;
5. more fully utilize data collected from coast-wide and NW surveys;
6. develop indices of abundance from historical surveys, e.g. CalCOFI ichthyoplankton & CDFG pelagic 'sea surveys';
7. explore re-incorporating environmental covariate in S-R model (also recommended by SSC-CPS Subcommittee).

HARVEST GUIDELINE FOR 2007

The Pacific sardine harvest guideline recommended for the U.S. fishery in calendar year 2007 is 152,564 mt. Statistics used to determine this harvest guideline are discussed below and presented in Table 17. To calculate the proposed harvest guideline for 2007, we used the maximum sustainable yield (MSY) control rule defined in Amendment 8 of the Coastal Pelagic Species-Fishery Management Plan, Option J, Table 4.2.5-1, PFMC (1998). This formula is intended to prevent Pacific sardine from being overfished and maintain relatively high and consistent catch levels over a long-term horizon. The Amendment 8 harvest formula for sardine is:

HG_{2007} = ($BIOMASS_{2006}$ - CUTOFF) • FRACTION • DISTRIBUTION;

where HG_{2007} is the total USA (California, Oregon, and Washington) harvest guideline in 2007, $BIOMASS_{2006}$ is the estimated July 1, 2006 stock biomass (ages 1+) from the current assessment (1,319,072 mt), CUTOFF is the lowest level of estimated biomass at which harvest is allowed (150,000 mt), FRACTION is an environment-based percentage of biomass above the CUTOFF that can be harvested by the fisheries (see below), and DISTRIBUTION (87%) is the percentage of $BIOMASS_{2006}$ assumed in U.S. waters. The value for FRACTION in the MSY control rule for Pacific sardine is a proxy for F_{msy} (i.e., the fishing mortality rate that achieves equilibrium MSY). Given F_{msy} and the productivity of the sardine stock have been shown to increase when relatively warm-ocean conditions persist, the following formula has been used to determine an appropriate (sustainable) FRACTION value:

FRACTION or $F_{msy} = 0.248649805(T^2) - 8.190043975(T) + 67.4558326$,

where T is the running average sea-surface temperature at Scripps Pier, La Jolla, California during the three preceding seasons (July-June). Ultimately, under Option J (PFMC 1998), F_{msy} is constrained and ranges between 5% and 15%. Based on the T values observed throughout the period covered by this stock assessment (1982-2006; Table 8, Figure 29), the appropriate F_{msy} exploitation fraction has consistently been 15%; and this remains the case under current oceanic conditions (T_{2006} = 18.11 °C). The 2007 USA harvest guideline (152,564 mt) is 28% higher than the 2006 harvest guideline (118,937 mt), and 51,197 mt greater than the largest recent harvest by the U.S. fisheries (101,367 mt in 2002; Table 18).

For a broader perspective on coast-wide sardine harvest relative to MSY, we applied the U.S. harvest control rule to the current stock biomass time series, ignoring the 87% pro-ration for assumed U.S. distribution. Theoretical coast-wide HGs and recent harvests are displayed in Figure 30. Based on our current estimate of stock biomass, and ignoring various assumptions regarding stock distribution, the current coast-wide sardine harvest can be viewed as being at or below MSY in recent years.

LITERATURE CITED

Ahlstrom, E. H. 1960. Synopsis on the biology of the Pacific sardine (*Sardinops caerulea*). Proc. World Sci. Meet. Biol. Sardines and Related Species, FAO, Rome, 2: 415-451

Aitchison, J. and J. A. C. Brown. 1957. The Lognormal Distribution. Cambridge University Press, Cambridge. MA. 387 p.

Allen, M. J., R. J. Wolotira, Jr., T. M. Sample, S. F. Noel, and C. R. Iten. 1990. West coast of North America coastal and oceanic zones strategic assessment: Data Atlas. N.O.A.A. Seattle, WA. Invertebrate and fish 145.

Barnes, J. T., L. D. Jacobson, A. D. MacCall, and P. Wolf. 1992. Recent population trends and abundance estimates of the Pacific sardine (*Sardinops sagax*). CalCOFI Rep. 33: 60-75.

Baumgartner, T., A. Soutar, and V. Ferriera-Bartrina. 1992. Reconstruction of the history of pacific sardine and northern anchovy populations over the past two millenia from sediments of the Santa Barbara Basin, California. CalCOFI Rep. 33: 24-40.

Bentley, P. J., R. L. Emmett, N. C. H. Lo and G. Moser. 1996. Egg production of Pacific sardine (*Sardinops sagax*) off Oregon in 1994. CalCOFI Rep. 37:193-200.

Bowen, B. W., and W.S. Grant. 1997. Phylogeography of the sardines (*Sardinops* spp.): Assessing biogeographic models and population histories in temperate upwelling zones. Evolution 51, 1601-1610.

Bradu, D. and Y. Munklak. 1970. Estimation in lognormal linear models J. Am. Stat. Assoc. 65: 198-211.

Butler, J. L. 1987. Comparisons of the larval and juvenile growth and larval mortality rates of Pacific sardine and northern anchovy and implications for species interactions. Ph. D. Thesis, Univ. Calif., San Diego, 240 pp.

Butler, J.L., P.E. Smith, and N.C.H. Lo. 1993. The effect of natural variability of life-history parameters on anchovy and sardine population growth. CalCOFI Rep. 34: 104-111.

Chambers, J. M. and T. J. Hastie 1992. Statistical models in S. Wadsworth & Brooks/Cole Advanced Books & Software, Pacific Grove, Ca. 608p.

Chapman W.M. 1936. The pilchard fishery of the state of Washington in 1936 with notes on the food of the silver and chinook salmon off the Washington coast. Dept. of Fisheries, State of Washington, Biological Rept. 36. 30p.

Clark, F. N. 1939. Can the supply of sardines be maintained in California waters? Calif. Fish and Game 25: 172-176.

Clark, F. N., and J. F. Janssen. Jr. 1945. Movements and abundance of the sardine as measured by tag returns. Calif. Div. Fish Game Fish. Bull. 61: 7-42.

Clark, F. N., and J. C. Marr. 1955. Population dynamics of the Pacific sardine. CalCOFI Prog. Rep. 1 July 1953-31 March 1955: 11-48.

Conser, R. J., K. T. Hill, P. R. Crone, N. C. H. Lo, and D. Bergen. 2003. Stock assessment of Pacific sardine with management recommendations for 2004: Executive Summary. Pacific Fishery Management Council, November 2003. 15 p.

Conser, R., K. Hill, P. Crone, N. Lo, and R. Felix-Uraga. 2004. Assessment of the Pacific sardine stock for U.S. management in 2005: Pacific Fishery Management Council, November 2004. 135 p.

Cota-V., A., R. Troncoso-G., and F. Javier-Sanchez. 2006. Análisis de la pesqueria de pelágicos menores para la costa occidental de Baja California durante la temporada del 2005. (Abstract) *In:* Memorias del XIV Taller de Pelágicos Menores, La Paz, Baja California Sur, 21-23 Junio de 2006.

Culver, M. and C. Henry. 2004. Summary Report of the 2004 Experimental Purse Seine Fishery for Pacific Sardine (*Sardinops sagax*). Washington Department of Fish and Wildlife, Montesano, WA. 12 p. http://wdfw.wa.gov/fish/commercial/sardine/04sardine_summary.pdf

Cushing, D. H. 1971. The dependence of recruitment of parent stock on different groups of fishes. J. Cons. Int. Explor. Mer. 33: 340-362.

Deriso, R., T. J. Quinn and P. R. Neal. 1985. Catch-age analysis with auxiliary information. Can. J. Fish. Aquat. Sci. 42:4.

Deriso, R. B., J. T. Barnes, L. D. Jacobson, and P. J. Arenas. 1996. Catch-at-age analysis for Pacific sardine (*Sardinops sagax*), 1983-1995. CalCOFI Rep. 37:175-187.

Eschmeyer, W. N., E. S. Herald, and H. Hammann. 1983. A Field Guide to Pacific Coast Fishes of North America. Houghton Mifflin Company, Boston, MA. 336 p.

Félix-Uraga, R., V. M. Gómez-Muñoz, C. Quiñónez-Velázquez, F. Neri Melo-Barrera, and W. García-Franco. 2004. On the existence of Pacific sardine groups off the west coast of Baja California and Southern California. CalCOFI Rep. 45: 146-151.

Felix-Uraga, R., V. M. Gómez-Muñoz, C. Quiñónez-Velázquez, F. Neri Melo-Barrera, K. T. Hill and W. García-Franco. 2005. Pacific sardine stock discrimination off the west coast of Baja California and southern California using otolith morphometry. CalCOFI Rep. 46: 113-121.

Fournier, D. A. and C. P. Archibald. 1982. A general theory for analyzing catch at age data. Can. J. Fish. Aquat. Sci. 39: 1195-1207.

García F. W. and Sánchez R. F. J. 2003. Análisis de la pesquería de pelágicos menores de la costa occidental de Baja California durante la temporada del 2002. Boletín Anual 2003. Secretaria de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación. Instituto Nacional de la Pesca. Centro Regional de Investigación Pesquera de Ensenada, Cámara Nacional de la Industria Pesquera y Acuícola, Delegación Baja California. 15 p.

Hargreaves, N.B., D.M. Ware, and G.A. McFarlane. 1994. Return of the Pacific sardine (*Sardinops sagax*) to the British Columbia coast in 1992. Can. J. Fish. Aquat. Sci. 51: 460-463.

Hart, J. L. 1973. Pacific fishes of Canada. Fish. Res. Board Can., Bull. 180. 740 p.

Hedgecock, D., E. S. Hutchinson, G. Li, F. L. Sly, and K. Nelson. 1989. Genetic and morphometric variation in the Pacific sardine, *Sardinops sagax caerulea*: comparisons and contrasts with historical data and with variability in the northern anchovy, *Engraulis mordax*. Fish. Bull. 87: 653-671.

Hill, K. T. 1999. Determining age composition of coastal pelagic species in northern California, Oregon, and Washington coastal waters. Pacific States Marine Fisheries Commission. Gladstone, Oregon. Project #1-IJ-9 Final Report. 47 p.

Hill, K.T., L.D. Jacobson, N.C.H. Lo, M. Yaremko, and M. Dege. 1999. Stock assessment of Pacific sardine for 1998 with management recommendations for 1999. Calif. Dept. Fish. Game. Marine Region Admin. Rep. 99-4. 92 pp.

Hill, K. T. and P. R. Crone. 2004. Stock assessment of Pacific mackerel (*Scomber japonicus*) in 2004. Pacific Fishery Management Council. Portland, Oregon.

Hill, K. T., N. C. H. Lo, B. J. Macewicz, and R. Felix-Uraga. 2005. Assessment of the Pacific sardine (Sardinops sagax caerulea) population for U.S. management in 2006. Pacific Fishery Management Council, Agenda Item D.1.a, Supplemental Attachment 1. 141 p.

Hill, K. T., N. C. H. Lo, B. J. Macewicz, and R. Felix-Uraga. 2006. Assessment of the Pacific sardine (*Sardinops sagax caerulea*) population for U.S. management in 2006. NOAA Tech. Memo. NOAA-TM-NMFS-SWFSC-386. 75 p.

Jacobson, L. J. and A. D. MacCall. 1995. Stock-recruitment models for Pacific sardine (*Sardinops sagax*). Can. J. Fish. Aquat. Sci. 52:566-577.

Lasker R. 1970. Utilization of zooplankton energy by a Pacific sardine population in the California Current, p. 265-284. *In*: J.H. Steele (ed.). Marine Food Chains. Oliver and Boyd Ltd., Edinburgh.

Leet, W. S., C. M. Dewees, R. Klingbeil, and E. J. Larson (Eds.). 2001. California's Living Marine Resources: A Status Report. Calif. Dep. Fish and Game. ANR Publication #SG01-11.

Legault, C. M., and V. R. Restrepo. 1999. A flexible forward age-structured assessment program. ICCAT Coll. Vol. Sci. Pap. 49(2): 246-253.

Lluch-Belda, D., D.B. Lluch-Cota, S. Hernandez-Vazquea, C.A. Salina-Zavala. 1991. Sardine and anchovy spawning as related to temperature and upwelling in the California Current system. CalCOFI Rep. 32: 105-111.

Lo, N. C. H., L. D. Jacobson and J. L. Squire. 1992. Indices of relative abundance from fish spotter data based on delta-lognormal models. Can. J. Fish. Aquat. Sci. 49:2515-2526. http://lajolla.noaa.gov/om/library/publications/CR/1992/9264.pdf

Lo, N. C. H., Y. A. Green Ruiz, Merecedes J. Cervantes, H. G. Moser, R. J. Lynn. 1996. Egg production and spawning biomass of Pacific sardine *(Sardinops sagax*) in 1994, determined by the daily egg production method. CalCOFI Rep. 37:160-174.

Lo, N. C. H., B. J. Macewicz, and D. A. Griffith. 2005. Spawning biomass of Pacific sardine (*Sardinops sagax*) from 1994-2004 off California. CalCOFI Rep. 46: 93-112.

Lo, N. C. H. and B. J. Macewicz. 2006. Spawning biomass of Pacific sardine (*Sardinops sagax*) off California in 2005. NOAA Tech. Memo. NOAA-TM-NMFS-SWFSC-387. 29 p.

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

MacCall, A. D. 1990. Dynamic Geography of Marine Fish Populations. University of Washington Press. 153 p.

Macewicz, B. J. and D. N. Abramenkoff. 1993. Collection of jack mackerel, *Trachurus symmetricus*, off southern California during 1991 cooperative U.S.-U.S.S.R. cruise. Southwest Fisheries Science Center, National Marine Fisheries Service, Admin. Rep. LJ-93-07. 13 p.

Macewicz B. J, J. J. Castro-Gonzalez, C. E. Cotero Altamirano, and J. R. Hunter. 1996. Adult reproductive parameters of Pacific Sardine (*Sardinops sagax*) during 1994 CalCOFI Rep 37:140-151.

Mangel, M., and P. E. Smith. 1990. Presence-absence sampling for fisheries management. Can. J. Fisheries Aquat. Sci. 47(10):1875-1887.

McCrae, J. 2001. Oregon's Sardine Fishery, 2000. Newport, OR: Oregon Department of Fish and Wildlife. 12pp. http://www.dfw.state.or.us/MRP/publications/sardine_1.pdf

McCrae, J. 2002. Oregon's Sardine Fishery, 2001. Newport, OR: Oregon Department of Fish and Wildlife. 15pp. http://www.dfw.state.or.us/MRP/publications/sardine_2.pdf

McCrae, J. 2003. Oregon's Sardine Fishery, 2002. Newport, OR: Oregon Department of Fish and Wildlife. 13pp. http://www.dfw.state.or.us/MRP/publications/sardine_3.pdf

McCrae, J. 2004. Oregon's Sardine Fishery, 2003. Newport, OR: Oregon Department of Fish and Wildlife. 12pp. http://www.dfw.state.or.us/MRP/publications/sardine_4.pdf

McCrae, J. and J. Smith. 2005. Oregon's Sardine Fishery, 2004. Newport, OR: Oregon Department of Fish and Wildlife. 14pp. http://www.dfw.state.or.us/MRP/publications/sardine_5.pdf

Murphy, G. I. 1966. Population biology of the Pacific sardine (*Sardinops caerulea*). Proc. Calif. Acad. Sci. Vol. 34 (1): 1-84.

Otter Research Ltd. 2001. An introduction to AD Model Builder (Version 6.0.2) for use in nonlinear modeling and statistics. Otter Research Ltd., Sidney, B.C., Canada. 202 p.

Parrish, R. H., R. Serra, and W. S. Grant. 1989. The monotypic sardines, *Sardina* and *Sardinops*: their taxonomy, distribution, stock structure and zoogeography. Can. J. Fish. Aquat. Sci. 46: 2019-2036.

Pennington, M. 1983. Efficient estimators of abundance for fish and plankton surveys. Biometrics 39: 281-286.

PFMC 1998. Amendment 8 (to the northern anchovy fishery management plan) incorporating a name change to: the coastal pelagic species fishery management plan. Pacific Fishery Management Council, Portland, OR.

PFMC 2004. Pacific sardine STAR panel meeting report. Pacific Fishery Management Council Briefing Book, Agendum I.2.b, September 2004. 12 p.

PFMC 2006. Status of the Pacific Coast Coastal Pelagic Species Fishery and Recommended Acceptable Biological Catches. Stock Assessment and Fishery Evaluation – 2006. Pacific Fishery Management Council, Portland, OR. http://www.pcouncil.org/cps/cpssafe/0606safe.html

Phillips, J. B. 1948. Growth of the sardine, *Sardinops caerulea*, 1941-42 through 1946-47. Calif. Div. Fish Game Fish Bull. 71: 33 p.

Radovich, J. 1982. The collapse of the California sardine fishery: what have we learned? CalCOFI Rep. 23: 56-78.

Robinson, M. 2003. Summary Report of the 2003 Trial Purse Seine Fishery for Pacific Sardine (*Sardinops sagax*). Washington Department of Fish and Wildlife, Montesano, WA. http://wdfw.wa.gov/fish/commercial/sardine/03sardine_summary.pdf

Smith, P. E. 1978. Biological effects of ocean variability: time inferred from fish scales in anaerobic sediments off California. CalCOFI Rep. 13: 63-70.

Soutar, A. and J. D. Isaacs. 1969. History of fish populations inferred from fish scales in anaerobic sediments off California. CalCOFI Rep. 13: 63-70.

Soutar, A., and J. D. Isaacs. 1974. Abundance of pelagic fish during the 19th and 20th centuries as recorded in anaerobic sediment off the Californias. Fish. Bull. 72: 257-273.

Vrooman, A. M. 1964. Serologically differentiated subpopulations of the Pacific sardine, *Sardinops caerulea*. J. Fish. Res. Bd. Canada, 21: 691-701.

Walford, L. A. and K. H. Mosher. 1943. Studies on the Pacific pilchard or sardine (*Sardinops caerulea*). U.S. Dep. of Interior, Fish and Wildlife Service, Special Sci. Rep. No. 20. 33 p.

WDFW. 2001. Summary Report of the 2001 Trial Purse Seine Fishery for Pacific Sardine (*Sardinops sagax*). Washington Department of Fish and Wildlife, Montesano, WA. http://wdfw.wa.gov/fish/commercial/sardine/01sardine_summary.pdf.

WDFW. 2002. Summary Report of the 2002 Trial Purse Seine Fishery for Pacific Sardine (*Sardinops sagax*). Washington Department of Fish and Wildlife, Montesano, WA. http://wdfw.wa.gov/fish/commercial/sardine/02sardine_summary.pdf

WDFW. 2005. 2005 Washington Experimental Sardine Fishery Summary. http://wdfw.wa.gov/fish/commercial/sardine/sardine_creel05.htm

Wolf, P. and P. E. Smith. 1986. The relative magnitude of the 1985 Pacific sardine spawning biomass off southern California. CalCOFI Rep. 27: 25-31.

Wolf. P., P. E. Smith, and C. L. Scannell. 1987. The relative magnitude of the 1986 Pacific sardine spawning biomass off California. CalCOFI Rep. 28: 21-26.

Wolf, P. 1988a. Status of the spawning biomass of Pacific sardine, 1987-1988. Calif. Dep. Fish Game, Mar. Res. Div., Rep. to the Legislature, 9 p.

Wolf, P. 1988b. Status of the spawning biomass of Pacific sardine, 1988-1989. Calif. Dep. Fish Game, Mar. Res. Div., Rep. to the Legislature, 8 p.

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

Table 1. Maturity schedule applied in the baseline model to calculate spawning stock biomass.

Coded Age (ASAP)	True Age	% Mature
1	0	30
2	1	53
3	2	91
4	3	97
5	4	99
6	5+	100

Table 2. Pacific sardine landings (mt) and sample sizes (number of fish) for production of fishery catch-at-age.

	------- CALIFORNIA -------			------- ENSENADA -------			-- PACIFIC NORTHWEST --		
Biological Year	Landings (mt)	# Fish Sampled	Fish per 1,000 mt	Landings (mt)	# Fish Sampled	Fish per 1,000 mt	Landings (mt)	# Fish Sampled	Fish per 1,000 mt
1982-83	337	941	2,791	150	0	0	0	---	---
1983-84	248	599	2,413	124	0	0	0	---	---
1984-85	397	214	539	3,174	0	0	0	---	---
1985-86	1,191	1,150	965	647	0	0	0	---	---
1986-87	1,548	1,517	980	1,118	0	0	0	---	---
1987-88	3,810	2,855	749	2,077	0	0	0	---	---
1988-89	2,919	1,634	560	1,876	34	18	0	---	---
1989-90	3,659	1,486	406	11,663	170	15	0	---	---
1990-91	5,856	2,344	400	14,746	901	61	0	---	---
1991-92	9,574	2,040	213	25,447	2,179	86	0	---	---
1992-93	24,320	3,683	151	49,890	719	14	4	0	0
1993-94	12,431	1,148	92	19,108	346	18	0	---	---
1994-95	32,902	3,668	111	33,393	494	15	0	---	---
1995-96	29,820	2,626	88	32,835	500	15	23	0	0
1996-97	29,027	4,509	155	36,897	478	13	44	0	0
1997-98	56,172	4,305	77	75,179	485	6	28	0	0
1998-99	51,005	4,463	88	62,333	537	9	563	31	55
1999-00	60,360	2,672	44	57,743	553	10	1,155	178	154
2000-01	52,916	3,196	60	50,457	512	10	17,923	2,006	112
2001-02	52,981	4,283	81	46,948	362	8	25,683	2,581	100
2002-03	60,714	3,216	53	44,938	55	1	36,123	2,834	78
2003-04	29,650	3,572	120	37,040	0	0	39,860	2,488	62
2004-05	45,858	4,057	88	47,379	0	0	47,747	1,870	39
2005-06	41,812	4,823	115	56,684	0	0	54,356	1,151	21

Table 3. Pacific sardine catch-at-age (thousands of fish) and landings (metric tons) for the California fishery (Fishery 1), 1982-83 to 2006-07 seasons (July-June). Landings were projected for 2006-07.

Biological	--------------- Catch-at-age (thousands)				----------------	Landings
Year	0	1	2	3	4	5+	(mt)
1982-83	0	880	1,261	261	56	8	337.2
1983-84	398	740	1,135	78	3	0	248.2
1984-85	17	804	1,611	282	0	0	397.0
1985-86	19	2,273	4,907	715	40	0	1,191.1
1986-87	185	1,167	5,924	2,305	175	26	1,548.2
1987-88	38	14,431	9,912	3,757	676	58	3,810.3
1988-89	356	4,999	11,193	2,602	786	109	2,919.0
1989-90	188	15,741	9,135	1,533	91	0	3,658.8
1990-91	1,350	9,506	14,557	10,456	5,050	2,919	5,855.6
1991-92	7,452	21,252	28,460	12,301	5,303	5,714	9,574.2
1992-93	33,463	147,999	98,106	22,749	5,997	3,354	24,319.9
1993-94	26,760	41,603	50,290	30,094	5,058	2,043	12,431.2
1994-95	206,712	236,588	64,598	29,723	4,091	868	32,902.4
1995-96	84,888	240,038	132,467	12,176	1,793	122	29,819.7
1996-97	89,636	96,347	136,744	57,311	7,157	2,119	29,026.8
1997-98	49,163	325,948	218,952	97,980	31,395	5,755	56,172.3
1998-99	219,059	601,996	183,576	25,483	14,214	1,990	51,005.2
1999-00	209,576	729,802	252,953	13,953	5,931	1,325	60,360.5
2000-01	173,501	260,540	283,685	157,218	12,562	1,851	52,915.6
2001-02	525,651	184,094	148,101	105,555	20,576	6,988	52,980.7
2002-03	126,574	568,045	156,788	31,379	10,102	2,505	60,713.6
2003-04	403,850	79,132	93,183	20,685	8,140	4,558	29,649.7
2004-05	28,510	733,750	88,935	12,513	2,853	893	45,858.4
2005-06	322,969	345,966	244,257	14,913	2,013	2,214	41,811.6
2006-07	0	0	0	0	0	0	*41,811.6*

Table 4. Pacific sardine catch-at-age (thousands of fish) and landings (metric tons) for the segment of the Mexican fishery that lands its product in Ensenada, Baja California (Fishery 2), 1982-83 to 2006-07 seasons (July-June). Landings were projected for 2006-07.

Biological	------------------- Catch-at-age (thousands) ---------------------						Landings
Year	0	1	2	3	4	5+	(mt)
1982-83	0	0	0	0	0	0	149.5
1983-84	0	0	0	0	0	0	124.1
1984-85	0	0	0	0	0	0	3,174.2
1985-86	0	0	0	0	0	0	647.3
1986-87	0	0	0	0	0	0	1,118.4
1987-88	0	0	0	0	0	0	2,076.8
1988-89	0	0	0	0	0	0	1,875.7
1989-90	30,029	35,488	15,431	4,272	1,887	66	11,663.2
1990-91	26,364	41,035	34,641	8,016	1,643	1,440	14,746.3
1991-92	20,559	68,135	50,263	41,932	18,599	8,898	25,447.3
1992-93	236,304	512,739	53,762	395	263	0	49,889.8
1993-94	103,939	69,104	120,215	8,697	0	0	19,108.4
1994-95	262,031	174,392	55,347	42,693	5,253	0	33,392.7
1995-96	191,289	144,459	85,039	17,658	5,799	0	32,834.8
1996-97	39,883	112,217	132,568	46,846	23,194	2,034	36,897.2
1997-98	44,799	157,950	266,468	184,200	79,962	23,397	75,179.4
1998-99	267,923	285,025	154,083	102,702	64,506	13,703	62,333.2
1999-00	393,256	288,886	164,243	81,932	31,978	13,576	57,743.0
2000-01	143,737	290,687	88,381	33,814	8,185	1,593	50,456.8
2001-02	221,428	236,772	145,254	14,659	1,715	0	46,948.1
2002-03	0	0	0	0	0	0	44,937.9
2003-04	0	0	0	0	0	0	37,040.3
2004-05	0	0	0	0	0	0	47,379.4
2005-06	0	0	0	0	0	0	56,684.0
2006-07	0	0	0	0	0	0	*56,684.0*

Table 5. Pacific sardine catch-at-age (thousands of fish) and landings (metric tons) for the fisheries off Oregon, Washington, and British Columbia, Canada (Fishery 3), 1982-83 to 2006-07 seasons (July-June). Landings for 2006-07 were projected to be two-thirds of the 2005-06 value.

Biological	-------------- Catch-at-age (thousands) ---------------						Landings
Year	0	1	2	3	4	5+	(mt)
1982-83	0	0	0	0	0	0	0.0
1983-84	0	0	0	0	0	0	0.0
1984-85	0	0	0	0	0	0	0.0
1985-86	0	0	0	0	0	0	0.0
1986-87	0	0	0	0	0	0	0.0
1987-88	0	0	0	0	0	0	0.0
1988-89	0	0	0	0	0	0	0.0
1989-90	0	0	0	0	0	0	0.0
1990-91	0	0	0	0	0	0	0.0
1991-92	0	0	0	0	0	0	0.0
1992-93	0	0	0	0	0	0	4.1
1993-94	0	0	0	0	0	0	0.0
1994-95	0	0	0	0	0	0	0.0
1995-96	0	0	0	0	0	0	22.7
1996-97	0	0	0	0	0	0	43.5
1997-98	0	0	0	0	0	0	28.0
1998-99	0	0	0	0	0	0	562.8
1999-00	0	0	3,791	1,937	1,040	2,262	1,154.6
2000-01	0	1,814	45,205	48,656	19,198	13,823	17,923.0
2001-02	178	3,499	21,320	70,724	44,439	26,569	25,682.9
2002-03	0	1,726	6,647	28,202	73,487	87,564	36,123.0
2003-04	0	4,538	38,538	37,039	25,874	129,242	39,860.2
2004-05	0	141,327	58,285	45,783	26,510	93,795	47,747.1
2005-06	0	8,925	230,672	69,493	33,543	116,754	54,356.1
2006-07	0	0	0	0	0	0	*35,331.0*

Table 6. Pacific sardine fishery weight-at-age (kg) for the 1982-83 to 2006-07 seasons (July-June). Values are weighted averages based on landings of the three respective fisheries.

Biological	--------- Fishery Weight-at-age (kg) -----------					
Year	0	1	2	3	4	5+
1982-83	0.069	0.118	0.128	0.155	0.184	0.187
1983-84	0.069	0.087	0.138	0.154	0.167	0.187
1984-85	0.083	0.108	0.135	0.148	0.164	0.160
1985-86	0.074	0.117	0.148	0.170	0.185	0.186
1986-87	0.054	0.111	0.150	0.164	0.184	0.172
1987-88	0.087	0.107	0.142	0.169	0.183	0.187
1988-89	0.069	0.101	0.148	0.169	0.185	0.195
1989-90	0.109	0.130	0.153	0.161	0.170	0.165
1990-91	0.082	0.122	0.143	0.152	0.155	0.159
1991-92	0.059	0.097	0.132	0.146	0.157	0.169
1992-93	0.054	0.062	0.095	0.123	0.161	0.146
1993-94	0.047	0.070	0.079	0.082	0.131	0.146
1994-95	0.050	0.062	0.087	0.095	0.102	0.115
1995-96	0.057	0.069	0.079	0.096	0.111	0.116
1996-97	0.063	0.077	0.107	0.114	0.121	0.122
1997-98	0.049	0.073	0.094	0.114	0.118	0.118
1998-99	0.042	0.056	0.078	0.103	0.104	0.115
1999-00	0.051	0.056	0.063	0.065	0.071	0.093
2000-01	0.057	0.078	0.089	0.096	0.106	0.126
2001-02	0.042	0.070	0.101	0.114	0.132	0.145
2002-03	0.054	0.084	0.100	0.113	0.128	0.145
2003-04	0.046	0.088	0.101	0.113	0.136	0.150
2004-05	0.048	0.065	0.089	0.114	0.130	0.155
2005-06	0.046	0.067	0.080	0.088	0.110	0.150
2006-07	0.046	0.067	0.080	0.088	0.110	0.150

Table 7. Pacific sardine population weight-at-age (kg) used to calculate the total stock biomass (Ages 1+) for management, and population SSB as presented in Table 15.

Biological	--- Population Weight-at-age (kg) ---				
Year	1	2	3	4	5+
1982-83	0.103	0.147	0.168	0.172	0.179
1983-84	0.103	0.147	0.168	0.172	0.179
1984-85	0.103	0.147	0.168	0.172	0.179
1985-86	0.103	0.147	0.168	0.172	0.179
1986-87	0.103	0.147	0.168	0.172	0.179
1987-88	0.103	0.147	0.168	0.172	0.179
1988-89	0.103	0.147	0.168	0.172	0.179
1989-90	0.103	0.147	0.168	0.172	0.179
1990-91	0.103	0.147	0.168	0.172	0.179
1991-92	0.103	0.147	0.168	0.172	0.179
1992-93	0.103	0.147	0.168	0.172	0.179
1993-94	0.103	0.147	0.168	0.172	0.179
1994-95	0.103	0.147	0.168	0.172	0.179
1995-96	0.103	0.147	0.168	0.172	0.179
1996-97	0.103	0.147	0.168	0.172	0.179
1997-98	0.103	0.147	0.168	0.172	0.179
1998-99	0.103	0.147	0.168	0.172	0.179
1999-00	0.103	0.147	0.168	0.172	0.179
2000-01	0.103	0.147	0.168	0.172	0.179
2001-02	0.103	0.147	0.168	0.172	0.179
2002-03	0.103	0.147	0.168	0.172	0.179
2003-04	0.103	0.147	0.168	0.172	0.179
2004-05	0.103	0.147	0.168	0.172	0.179
2005-06	0.103	0.147	0.168	0.172	0.179
2006-07	0.103	0.147	0.168	0.172	0.179

Table 8. Pacific sardine time series of survey indices of relative abundance and sea-surface temperature, 1982-2006. The SST is a moving average of monthly SST observations for the three-year period prior to July 1st of the given year.

Biological	DEPM (SSB)		Aerial Spotter (pre-adult)		SST at SIO Pier
Year	Estimate (mt)	CV	Estimate (mt)	CV	(°C)
1982-83	---		---	---	17.05
1983-84	---		---	---	17.25
1984-85	---		---	---	17.58
1985-86	7,659	---	19,301	0.34	17.80
1986-87	15,704	---	10,177	0.32	17.87
1987-88	13,526	---	16,807	0.22	17.71
1988-89	---		9,880	0.27	17.55
1989-90	---		3,999	0.23	17.24
1990-91	---		19,781	0.15	17.19
1991-92	---		20,384	0.14	17.35
1992-93	---		107,743	0.14	17.61
1993-94	127,102	0.32	150,630	0.10	17.84
1994-95	79,997	0.60	70,240	0.12	17.97
1995-96	83,176	0.48	23,079	0.12	18.04
1996-97	409,579	0.31	30,414	0.18	18.07
1997-98	313,986	0.41	59,407	0.15	18.08
1998-99	282,248	0.42	22,651	0.15	18.47
1999-00	1,063,837	0.67	7,454	0.17	18.08
2000-01	790,925	0.45	739	0.44	17.75
2001-02	206,333	0.35	43,543	0.38	17.24
2002-03	485,121	0.36	12,082	0.42	17.31
2003-04	281,639	0.30	17,959	0.75	17.46
2004-05	619,320	0.54	2,005	1.03	17.60
2005-06	1,081,612	0.47	---	---	18.03
2006-07	---		---	---	18.11

Table 9. Selectivities applied to survey data in the ASAP model.

	Age					
Survey	0	1	2	3	4	5+
DEPM						
1982-2006	0.30	0.53	0.91	0.97	0.99	1.00
Aerial Spotter						
1982-2005	1.00	1.00	0.59	0.18	0.03	0.00

Table 10. Total number of flights by year, flights with sightings by year, and proportion of positive flights by year, for calendar years 1985 to 2005. A = Flights, B = Flights with Sightings, C = Proportion of Positive Flights.

Year	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05
A	783	692	591	595	599	849	541	432	586	609	692	513	553	514	429	340	31	107	13	44	22
B	115	123	206	239	165	261	294	228	306	339	312	166	187	174	151	72	9	21	3	39	20
C	0.17	0.22	0.31	0.31	0.22	0.36	0.54	0.43	0.5	0.6	0.55	0.45	0.41	0.45	0.45	0.3	0.35	0.23	0.23	0.85	0.92

Table 11. Number of positive flights, day versus night, for calendar years 1985 to 2005.

Year	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05
Day	20	64	64	85	107	62	140	136	152	203	125	141	54	105	86	96	1	54	9	21	3
Night	0	51	59	121	132	103	121	158	76	103	214	171	112	82	88	55	2	18	0	0	0
Unkwn	0	3	4	1	3	4	8	6	6	4	4	4	0	3	3	4	3	0	0	0	0

Table 12. Likelihood components for the baseline model in which 140 parameters were estimated. See text for definitions of fleet (fishery) numbers and index numbers.

Component	**RSS**	**nobs**	**Lambda**	**Likelihood**	**% of Total**
Catch_Fleet_1	0.0020	25	100	0.1995	
Catch_Fleet_2	0.0054	25	100	0.5390	
Catch_Fleet_3	0.1224	25	100	12.2400	
Catch_Fleet_Total	**0.1298**	75	100	**12.9784**	**2%**
Discard_Fleet_1	0.0000	25	0	0.0000	
Discard_Fleet_2	0.0000	25	0	0.0000	
Discard_Fleet_3	0.0000	25	0	0.0000	
Discard_Fleet_Total	0.0000	75	0	0.0000	
CAA_proportions	---	450	---	**215.2380**	**39%**
Discard_proportions	---	450	---	0.0000	
Index_Fit_1	13.2986	16	1	67.3526	
Index_Fit_2	37.7115	20	1	132.6520	
Index_Fit_Total	**51.0101**	36	2	**200.0050**	**37%**
Selectivity_devs_fleet_1	15.5946	1	0	0.0000	
Selectivity_devs_fleet_2	0.0000	1	0	0.0000	
Selectivity_devs_fleet_3	0.0000	1	0	0.0000	
Selectivity_devs_Total	**15.5946**	3	0	**0.0000**	**0%**
Catchability_devs_index_1	0.0000	16	10	0.0000	
Catchability_devs_index_2	0.0000	20	10	0.0000	
Catchability_devs_Total	**0.0000**	36	20	**0.0000**	**0%**
Fmult_fleet_1	6.6400	24	1	6.6400	
Fmult_fleet_2	15.3860	24	1	15.3860	
Fmult_fleet_3	53.9198	24	1	53.9198	
Fmult_fleet_Total	**75.9458**	72	3	**75.9458**	**14%**
N_year_1	0.0000	5	0	0.0000	
Stock-Recruit_Fit	**15.3656**	25	1	**27.5839**	**5%**
Recruit_devs	**15.3656**	25	1	**15.3656**	**3%**
SRR_steepness	0.0001	1	0	0.0000	
SRR_virgin_stock	0.1580	1	0	0.0000	
Curvature_over_age	19.7258	12	0	0.0000	
Curvature_over_time	31.1892	414	0	0.0000	
F_penalty	2.1666	150	0.001	0.0022	
Mean_Sel_year1_pen	0.0000	18	1000	0.0000	
Max_Sel_penalty	2.3543	1	100	0.0000	
Fmult_Max_penalty	0.0000	--	100	0.0000	
TOTAL	**229.0055**	**1849**		**547.1189**	**100%**

Table 13. ASAP parameter estimates and standard deviations for the baseline model. The first 140 parameters are formal model parameters. The remaining are state variables derived from the formal model parameters. See text for definition of coded ages, fisheries, and indices.

Coded Age	Biol. Year	Fishery	Param #	Parameter	Estimate	Std. Dev.
1	1982	1	1	log_sel_year1	-5.301E+00	1.426E+02
2	1982	1	2	log_sel_year1	-1.781E+00	1.426E+02
3	1982	1	3	log_sel_year1	-3.682E-01	1.426E+02
4	1982	1	4	log_sel_year1	-7.867E-01	1.426E+02
5	1982	1	5	log_sel_year1	-1.551E+00	1.426E+02
6	1982	1	6	log_sel_year1	-2.154E+00	1.426E+02
1	1982	2	7	log_sel_year1	-2.644E+00	2.444E+02
2	1982	2	8	log_sel_year1	-1.846E+00	2.444E+02
3	1982	2	9	log_sel_year1	-1.710E+00	2.444E+02
4	1982	2	10	log_sel_year1	-2.078E+00	2.444E+02
5	1982	2	11	log_sel_year1	-2.429E+00	2.444E+02
6	1982	2	12	log_sel_year1	-4.031E+00	2.444E+02
1	1982	3	13	log_sel_year1	-6.000E+00	2.008E-02
2	1982	3	14	log_sel_year1	-2.032E+00	1.482E+00
3	1982	3	15	log_sel_year1	-9.006E-02	1.437E+00
4	1982	3	16	log_sel_year1	4.889E-01	1.442E+00
5	1982	3	17	log_sel_year1	8.563E-01	1.454E+00
6	1982	3	18	log_sel_year1	5.431E-01	1.454E+00
1	1982	1	19	log_sel_devs_vector	3.619E+00	7.829E-01
2	1982	1	20	log_sel_devs_vector	1.250E+00	7.278E-01
3	1982	1	21	log_sel_devs_vector	-1.527E-01	7.235E-01
4	1982	1	22	log_sel_devs_vector	-1.528E-01	7.392E-01
5	1982	1	23	log_sel_devs_vector	-3.406E-01	8.236E-01
6	1982	1	24	log_sel_devs_vector	-8.764E-01	9.683E-01
1	1982	2	25	log_sel_devs_vector	0.000E+00	5.810E+03
2	1982	2	26	log_sel_devs_vector	0.000E+00	5.810E+03
3	1982	2	27	log_sel_devs_vector	0.000E+00	5.810E+03
4	1982	2	28	log_sel_devs_vector	0.000E+00	5.810E+03
5	1982	2	29	log_sel_devs_vector	0.000E+00	5.810E+03
6	1982	2	30	log_sel_devs_vector	0.000E+00	5.810E+03
1	1982	3	31	log_sel_devs_vector	0.000E+00	5.810E+03
2	1982	3	32	log_sel_devs_vector	0.000E+00	5.810E+03
3	1982	3	33	log_sel_devs_vector	0.000E+00	5.810E+03
4	1982	3	34	log_sel_devs_vector	0.000E+00	5.810E+03
5	1982	3	35	log_sel_devs_vector	0.000E+00	5.810E+03
6	1982	3	36	log_sel_devs_vector	0.000E+00	5.810E+03
---	1982	1	37	log_Fmult_year1	-1.376E+00	1.426E+02
---	1982	2	38	log_Fmult_year1	-2.108E+00	2.444E+02
---	1982	3	39	log_Fmult_year1	-1.500E+01	9.710E-03
---	1983	1	40	log_Fmult_devs	-9.874E-01	1.433E-01
---	1984	1	41	log_Fmult_devs	-7.882E-01	1.314E-01
---	1985	1	42	log_Fmult_devs	3.626E-01	1.312E-01

cont'd next page…

Table 13 (cont'd). ASAP parameter estimates and standard deviations for the baseline model.

Coded Age	Biol. Year	Fishery	Param #	Parameter	Estimate	Std. Dev.
---	1986	1	43	log_Fmult_devs	-1.151E-01	1.309E-01
---	1987	1	44	log_Fmult_devs	5.253E-01	1.352E-01
---	1988	1	45	log_Fmult_devs	-8.129E-01	1.255E-01
---	1989	1	46	log_Fmult_devs	-1.897E-01	1.271E-01
---	1990	1	47	log_Fmult_devs	1.803E-01	1.180E-01
---	1991	1	48	log_Fmult_devs	5.150E-08	7.071E-01
---	1992	1	49	log_Fmult_devs	1.039E+00	1.091E-01
---	1993	1	50	log_Fmult_devs	-7.139E-01	1.097E-01
---	1994	1	51	log_Fmult_devs	6.319E-01	1.107E-01
---	1995	1	52	log_Fmult_devs	-3.576E-01	1.074E-01
---	1996	1	53	log_Fmult_devs	-1.974E-01	1.053E-01
---	1997	1	54	log_Fmult_devs	8.613E-01	1.072E-01
---	1998	1	55	log_Fmult_devs	2.006E-01	1.074E-01
---	1999	1	56	log_Fmult_devs	3.434E-01	1.109E-01
---	2000	1	57	log_Fmult_devs	-2.504E-01	1.059E-01
---	2001	1	58	log_Fmult_devs	8.888E-02	1.078E-01
---	2002	1	59	log_Fmult_devs	-4.093E-02	1.194E-01
---	2003	1	60	log_Fmult_devs	-8.180E-01	1.191E-01
---	2004	1	61	log_Fmult_devs	2.013E-01	1.242E-01
---	2005	1	62	log_Fmult_devs	6.727E-02	1.148E-01
---	2006	1	63	log_Fmult_devs	2.296E-01	1.134E-01
---	1983	2	64	log_Fmult_devs	-1.024E+00	1.292E-01
---	1984	2	65	log_Fmult_devs	2.327E+00	1.195E-01
---	1985	2	66	log_Fmult_devs	-1.969E+00	1.115E-01
---	1986	2	67	log_Fmult_devs	1.682E-01	1.161E-01
---	1987	2	68	log_Fmult_devs	6.449E-02	1.195E-01
---	1988	2	69	log_Fmult_devs	-4.435E-01	1.085E-01
---	1989	2	70	log_Fmult_devs	1.265E+00	1.119E-01
---	1990	2	71	log_Fmult_devs	1.473E-01	1.067E-01
---	1991	2	72	log_Fmult_devs	4.978E-01	1.077E-01
---	1992	2	73	log_Fmult_devs	7.833E-01	1.070E-01
---	1993	2	74	log_Fmult_devs	-1.013E+00	1.075E-01
---	1994	2	75	log_Fmult_devs	2.359E-01	1.087E-01
---	1995	2	76	log_Fmult_devs	-2.528E-01	1.053E-01
---	1996	2	77	log_Fmult_devs	-6.571E-02	1.044E-01
---	1997	2	78	log_Fmult_devs	8.811E-01	1.060E-01
---	1998	2	79	log_Fmult_devs	9.348E-02	1.053E-01
---	1999	2	80	log_Fmult_devs	1.385E-01	1.084E-01
---	2000	2	81	log_Fmult_devs	-2.529E-01	1.046E-01
---	2001	2	82	log_Fmult_devs	-2.223E-02	1.062E-01
---	2002	2	83	log_Fmult_devs	-1.496E-01	1.152E-01
---	2003	2	84	log_Fmult_devs	-3.803E-01	1.199E-01
---	2004	2	85	log_Fmult_devs	1.247E-01	1.178E-01
---	2005	2	86	log_Fmult_devs	2.747E-01	1.123E-01

cont'd next page…

Table 13 (cont'd). ASAP parameter estimates and standard deviations for the baseline model.

Coded Age	Biol. Year	Fishery	Param #	Parameter	Estimate	Std. Dev.
---	2006	2	87	log_Fmult_devs	2.372E-01	1.127E-01
---	1983	3	88	log_Fmult_devs	-9.389E-02	6.856E-01
---	1984	3	89	log_Fmult_devs	-9.370E-02	6.856E-01
---	1985	3	90	log_Fmult_devs	-9.261E-02	6.852E-01
---	1986	3	91	log_Fmult_devs	-8.736E-02	6.833E-01
---	1987	3	92	log_Fmult_devs	-7.315E-02	6.778E-01
---	1988	3	93	log_Fmult_devs	-4.447E-02	6.667E-01
---	1989	3	94	log_Fmult_devs	2.727E-02	6.419E-01
---	1990	3	95	log_Fmult_devs	1.947E-01	5.955E-01
---	1991	3	96	log_Fmult_devs	6.631E-01	5.007E-01
---	1992	3	97	log_Fmult_devs	3.027E+00	3.073E-01
---	1993	3	98	log_Fmult_devs	-2.909E+00	2.801E-01
---	1994	3	99	log_Fmult_devs	7.466E-02	3.358E-01
---	1995	3	100	log_Fmult_devs	4.238E+00	2.491E-01
---	1996	3	101	log_Fmult_devs	2.590E-01	1.178E-01
---	1997	3	102	log_Fmult_devs	-4.759E-01	1.147E-01
---	1998	3	103	log_Fmult_devs	3.097E+00	1.126E-01
---	1999	3	104	log_Fmult_devs	1.148E+00	1.175E-01
---	2000	3	105	log_Fmult_devs	2.459E+00	1.056E-01
---	2001	3	106	log_Fmult_devs	3.478E-01	1.049E-01
---	2002	3	107	log_Fmult_devs	4.764E-01	1.081E-01
---	2003	3	108	log_Fmult_devs	1.182E-01	1.159E-01
---	2004	3	109	log_Fmult_devs	2.005E-01	1.239E-01
---	2005	3	110	log_Fmult_devs	1.366E-02	1.499E-01
---	2006	3	111	log_Fmult_devs	-4.019E-01	1.530E-01
1	1982	---	112	log_recruit_devs	-3.415E+00	1.766E-01
1	1983	---	113	log_recruit_devs	4.976E-01	2.129E-01
1	1984	---	114	log_recruit_devs	1.622E-01	2.035E-01
1	1985	---	115	log_recruit_devs	-4.973E-01	1.996E-01
1	1986	---	116	log_recruit_devs	-1.077E-02	1.733E-01
1	1987	---	117	log_recruit_devs	-2.311E-01	1.602E-01
1	1988	---	118	log_recruit_devs	7.926E-03	1.326E-01
1	1989	---	119	log_recruit_devs	-2.206E-01	1.235E-01
1	1990	---	120	log_recruit_devs	-2.457E-01	1.239E-01
1	1991	---	121	log_recruit_devs	1.959E-01	1.097E-01
1	1992	---	122	log_recruit_devs	-7.404E-02	1.286E-01
1	1993	---	123	log_recruit_devs	5.363E-01	1.106E-01
1	1994	---	124	log_recruit_devs	8.343E-01	1.036E-01
1	1995	---	125	log_recruit_devs	4.006E-01	1.160E-01
1	1996	---	126	log_recruit_devs	1.621E-01	1.263E-01
1	1997	---	127	log_recruit_devs	2.852E-01	1.252E-01
1	1998	---	128	log_recruit_devs	3.397E-01	1.193E-01
1	1999	---	129	log_recruit_devs	5.421E-02	1.229E-01
1	2000	---	130	log_recruit_devs	-1.677E-01	1.336E-01

cont'd next page…

Table 13 (cont'd). ASAP parameter estimates and standard deviations for the baseline model.

Coded Age	Biol. Year	Fishery	Param #	Parameter	Estimate	Std. Dev.
1	2001	---	131	log_recruit_devs	4.529E-01	1.262E-01
1	2002	---	132	log_recruit_devs	-3.448E-01	1.749E-01
1	2003	---	133	log_recruit_devs	1.112E+00	1.329E-01
1	2004	---	134	log_recruit_devs	4.905E-02	1.550E-01
1	2005	---	135	log_recruit_devs	1.156E-01	9.654E-02
1	2006	---	136	log_recruit_devs	1.961E-03	5.033E-02
---	1982	---	137	log_q_year1	-1.346E+01	2.040E-01
---	1982	---	138	log_q_year1	-1.334E+01	1.736E-01
---	---	---	139	log_SRR_virgin	1.420E+01	1.448E-01
---	---	---	140	SRR_steepness	6.559E-01	4.164E-02
---	1982	---	141	SSB	7.393E+03	6.801E+02
---	1983	---	142	SSB	1.524E+04	2.112E+03
---	1984	---	143	SSB	3.559E+04	5.769E+03
---	1985	---	144	SSB	5.774E+04	1.031E+04
---	1986	---	145	SSB	8.807E+04	1.651E+04
---	1987	---	146	SSB	1.486E+05	2.918E+04
---	1988	---	147	SSB	2.231E+05	4.527E+04
---	1989	---	148	SSB	3.665E+05	7.409E+04
---	1990	---	149	SSB	4.317E+05	8.615E+04
---	1991	---	150	SSB	4.899E+05	9.468E+04
---	1992	---	151	SSB	4.674E+05	8.952E+04
---	1993	---	152	SSB	4.918E+05	9.691E+04
---	1994	---	153	SSB	6.293E+05	1.171E+05
---	1995	---	154	SSB	7.786E+05	1.437E+05
---	1996	---	155	SSB	1.024E+06	1.858E+05
---	1997	---	156	SSB	9.769E+05	1.705E+05
---	1998	---	157	SSB	8.040E+05	1.411E+05
---	1999	---	158	SSB	6.286E+05	1.064E+05
---	2000	---	159	SSB	7.524E+05	1.360E+05
---	2001	---	160	SSB	7.514E+05	1.430E+05
---	2002	---	161	SSB	7.298E+05	1.425E+05
---	2003	---	162	SSB	8.237E+05	1.613E+05
---	2004	---	163	SSB	8.365E+05	1.643E+05
---	2005	---	164	SSB	8.335E+05	1.703E+05
---	2006	---	165	SSB	7.312E+05	1.634E+05
1	1982	---	166	recruits	1.759E+05	3.286E+04
1	1983	---	167	recruits	3.277E+05	6.536E+04
1	1984	---	168	recruits	4.668E+05	1.024E+05
1	1985	---	169	recruits	5.191E+05	1.231E+05
1	1986	---	170	recruits	1.261E+06	2.886E+05
1	1987	---	171	recruits	1.392E+06	3.235E+05
1	1988	---	172	recruits	2.495E+06	5.542E+05
1	1989	---	173	recruits	2.481E+06	5.310E+05
1	1990	---	174	recruits	3.004E+06	6.006E+05

cont'd next page…

Table 13 (cont'd). ASAP parameter estimates and standard deviations for the baseline model.

Coded Age	Biol. Year	Fishery	Param #	Parameter	Estimate	Std. Dev.
1	1991	---	175	recruits	4.954E+06	9.053E+05
1	1992	---	176	recruits	3.941E+06	7.644E+05
1	1993	---	177	recruits	7.148E+06	1.314E+06
1	1994	---	178	recruits	9.785E+06	1.711E+06
1	1995	---	179	recruits	6.803E+06	1.170E+06
1	1996	---	180	recruits	5.641E+06	9.205E+05
1	1997	---	181	recruits	6.737E+06	9.810E+05
1	1998	---	182	recruits	7.054E+06	9.766E+05
1	1999	---	183	recruits	5.100E+06	7.763E+05
1	2000	---	184	recruits	3.853E+06	6.682E+05
1	2001	---	185	recruits	7.487E+06	1.257E+06
1	2002	---	186	recruits	3.371E+06	7.291E+05
1	2003	---	187	recruits	1.437E+07	2.578E+06
1	2004	---	188	recruits	5.100E+06	1.057E+06
1	2005	---	189	recruits	5.468E+06	9.519E+05
1	2006	---	190	recruits	4.877E+06	7.563E+05
6	1982	---	191	plus_group	1.944E+03	0.000E+00
6	1983	---	192	plus_group	3.299E+03	3.712E+01
6	1984	---	193	plus_group	4.266E+03	5.359E+01
6	1985	---	194	plus_group	4.844E+03	8.269E+01
6	1986	---	195	plus_group	5.629E+03	1.254E+02
6	1987	---	196	plus_group	2.329E+04	4.267E+03
6	1988	---	197	plus_group	5.187E+04	1.059E+04
6	1989	---	198	plus_group	8.793E+04	1.888E+04
6	1990	---	199	plus_group	1.189E+05	2.626E+04
6	1991	---	200	plus_group	2.280E+05	5.289E+04
6	1992	---	201	plus_group	3.125E+05	7.413E+04
6	1993	---	202	plus_group	4.697E+05	1.179E+05
6	1994	---	203	plus_group	5.588E+05	1.422E+05
6	1995	---	204	plus_group	6.432E+05	1.638E+05
6	1996	---	205	plus_group	8.682E+05	2.168E+05
6	1997	---	206	plus_group	9.462E+05	2.302E+05
6	1998	---	207	plus_group	1.292E+06	3.098E+05
6	1999	---	208	plus_group	1.709E+06	4.118E+05
6	2000	---	209	plus_group	1.636E+06	4.034E+05
6	2001	---	210	plus_group	1.383E+06	3.608E+05
6	2002	---	211	plus_group	1.217E+06	3.373E+05
6	2003	---	212	plus_group	1.072E+06	3.240E+05
6	2004	---	213	plus_group	8.892E+05	2.920E+05
6	2005	---	214	plus_group	7.097E+05	2.543E+05
6	2006	---	215	plus_group	8.084E+05	2.973E+05

Table 14. Pacific sardine instantaneous rates of fishing mortality at age (yr^{-1}) for biological years 1982-83 to 2006-07 (July-June).

Biological	----- Instantaneous Fishing Mortality Rate at Age (yr^{-1}) -----					
Year	0	1	2	3	4	5+
1982-83	0.010	0.062	0.197	0.130	0.064	0.031
1983-84	0.004	0.023	0.073	0.048	0.024	0.012
1984-85	0.032	0.078	0.111	0.075	0.049	0.013
1985-86	0.005	0.020	0.054	0.036	0.019	0.008
1986-87	0.006	0.021	0.051	0.034	0.018	0.008
1987-88	0.006	0.028	0.078	0.052	0.027	0.012
1988-89	0.004	0.015	0.038	0.025	0.013	0.006
1989-90	0.013	0.034	0.056	0.038	0.023	0.007
1990-91	0.015	0.040	0.066	0.045	0.027	0.008
1991-92	0.032	0.078	0.086	0.059	0.036	0.008
1992-93	0.075	0.186	0.204	0.139	0.083	0.019
1993-94	0.030	0.076	0.083	0.056	0.032	0.008
1994-95	0.044	0.117	0.125	0.084	0.046	0.011
1995-96	0.033	0.086	0.092	0.062	0.035	0.008
1996-97	0.029	0.075	0.081	0.055	0.031	0.007
1997-98	0.070	0.180	0.195	0.132	0.075	0.018
1998-99	0.080	0.208	0.225	0.153	0.087	0.021
1999-00	0.100	0.266	0.287	0.196	0.110	0.029
2000-01	0.078	0.210	0.245	0.191	0.141	0.063
2001-02	0.080	0.220	0.263	0.213	0.167	0.082
2002-03	0.073	0.205	0.263	0.235	0.210	0.117
2003-04	0.041	0.115	0.174	0.183	0.195	0.121
2004-05	0.048	0.136	0.207	0.220	0.236	0.148
2005-06	0.058	0.159	0.234	0.240	0.251	0.152
2006-07	0.073	0.195	0.253	0.225	0.205	0.111

Table 15. Pacific sardine population numbers at age (millions), spawning stock biomass (SSB, mt), and age 1+ biomass (mt) at the beginning of each biological year, 1982-83 to 2006-07 (July-June). 'Model SSB' is based on maturity-at-age (Table 1) and fishery weights-at-age (Table 6) and is used in ASAP to estimate stock-recruitment. 'Population SSB' and 'Age 1+ biomass' were calculated using assumed population weights-at-age (Table 7). Total landings by biological year are also provided. Recruitment is shown as population numbers at age-0. Age 1+ biomass as of July 2006 (bold) serves as the basis for setting a harvest guideline for the U.S. fishery in calendar year 2007 (calculated in Table 17).

Biological	--- Population Numbers-at-age (millions) ---						Model	Population	Age 1+	Total
Year	0	1	2	3	4	5+	SSB	SSB	Biomass	Landings
1982-83	176	15	9	5	3	2	7,393	5,543	4,680	487
1983-84	328	117	9	5	3	3	15,236	12,826	15,395	372
1984-85	467	219	77	6	3	4	35,590	29,056	36,085	3,571
1985-86	519	303	136	46	4	5	57,736	48,793	60,367	1,838
1986-87	1,261	346	199	86	30	6	88,068	78,108	85,518	2,667
1987-88	1,392	841	227	127	56	23	148,640	124,428	155,124	5,887
1988-89	2,495	927	548	141	81	52	223,080	194,543	222,866	4,795
1989-90	2,481	1,666	612	354	92	88	366,450	286,496	352,707	15,322
1990-91	3,004	1,641	1,080	388	228	119	431,690	387,036	453,436	20,602
1991-92	4,954	1,984	1,058	678	249	228	489,870	492,340	557,239	35,022
1992-93	3,941	3,217	1,230	650	428	312	467,370	613,992	751,102	74,214
1993-94	7,148	2,452	1,791	673	380	470	491,760	702,226	777,950	31,540
1994-95	9,785	4,651	1,523	1,105	426	559	629,310	907,218	1,062,119	66,295
1995-96	6,803	6,276	2,774	901	681	643	778,570	1,158,675	1,437,764	62,677
1996-97	5,641	4,413	3,861	1,695	567	868	1,024,000	1,341,011	1,559,516	65,968
1997-98	6,737	3,673	2,744	2,386	1,075	946	976,910	1,375,343	1,536,719	131,380
1998-99	7,054	4,212	2,056	1,514	1,401	1,292	803,950	1,291,477	1,462,943	113,901
1999-00	5,100	4,366	2,293	1,101	871	1,709	628,580	1,229,013	1,427,391	119,258
2000-01	3,853	3,092	2,242	1,153	607	1,636	752,430	1,090,755	1,238,913	121,295
2001-02	7,487	2,389	1,680	1,177	639	1,383	751,430	977,236	1,048,074	125,612
2002-03	3,371	4,631	1,285	866	637	1,217	729,770	925,604	1,139,043	141,774
2003-04	14,370	2,100	2,528	662	459	1,072	823,690	972,553	969,557	106,550
2004-05	5,100	9,245	1,255	1,424	370	889	836,480	1,177,696	1,599,603	140,985
2005-06	5,468	3,258	5,412	684	766	710	833,470	1,323,892	1,503,871	152,852
2006-07	4,877	3,459	1,862	2,870	361	808	731,210	1,160,075	**1,319,072**	133,827

Table 16. Estimates of 2003 recruitment, the age 1+ biomass in 2005-06 and 2006-07, and the 2006 and 2007 harvest guidelines for a) the 2005 final model, b) the 2006 base model, and c) the sensitivity tests based on modifying the assumptions regarding the data inputs and assumptions of the assessment model.

Assessment Run:	2003 Recruitment (Billions)	2006-07 Age 1+ biomass (mt)	2007 HG (mt)	2005-06 Age 1+ biomass (mt)	2006 HG (mt)
2005 final model	10.04	-	-	1,061,391	118,937
2005 σ_R values					
+ Landings	10.14	886,888	96,164	1,068,636	119,882
+ catch-at-age	8.30	743,976	77,514	895,365	97,270
+ DEPM	12.01	1,198,244	136,796	1,377,556	160,196
2006 σ_R values					
+ Landings	13.24	1,010,210	112,257	1,236,957	141,848
+ catch-at-age	9.70	817,036	87,048	970,195	107,036
+ DEPM (base model)	14.37	1,319,072	152,564	1,503,871	176,680
Ignore DEPM	5.60	246,595	12,606	361,455	27,595
Ignore Aerial Spotter	17.12	1,625,193	192,513	1,844,860	221,179
F_{mult} pen = 0.1	14.82	1,361,620	158,116	1,550,159	182,721
DEPM – coast-wide SSB	14.87	1,368,373	158,998	1,556,995	183,613

Table 17. Proposed harvest guideline for Pacific sardine for the 2007 management year. See 'Harvest Guideline' section for methods used to derive harvest guideline.

Stock biomass (age 1+, mt)	Cutoff (mt)	Fraction	Distribution	Harvest guideline (mt)
1,319,072	150,000	15%	87%	**152,564**

Table 18. Coast-wide harvest (mt) of Pacific sardine for calendar years 1983 through 2005.

Calendar	México	United States				Canada	Total
Year	Ensenada	So. Cal.	No. Cal.	Oregon	Wash.	B.C.	Landings
1983	274	352	0	0	0	0	626
1984	0	171	64	0	0	0	235
1985	3,722	559	34	0	0	0	4,315
1986	243	1,051	113	0	0	0	1,407
1987	2,432	2,056	39	0	0	0	4,526
1988	2,035	3,775	10	0	0	0	5,820
1989	6,224	3,443	238	0	0	0	9,905
1990	11,375	2,508	307	0	0	0	14,190
1991	31,392	6,774	976	0	0	0	39,142
1992	34,568	16,061	3,128	4	0	0	53,761
1993	32,045	15,488	705	0	0	0	48,237
1994	20,877	10,346	2,359	0	0	0	33,582
1995	35,396	36,561	4,928	0	0	23	76,908
1996	39,065	25,171	8,885	0	0	0	73,121
1997	68,439	32,837	13,361	0	0	71	114,707
1998	47,812	31,975	9,081	1	0	488	89,357
1999	58,569	42,863	13,884	775	0	24	116,116
2000	67,845	46,835	11,367	9,529	4,765	1,722	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	148,951
2003	41,342	30,289	7,448	25,258	11,604	977	116,918
2004	41,897	32,393	15,308	36,112	8,799	4,438	138,948
2005	56,684	30,253	7,940	45,110	6,929	3,232	150,147

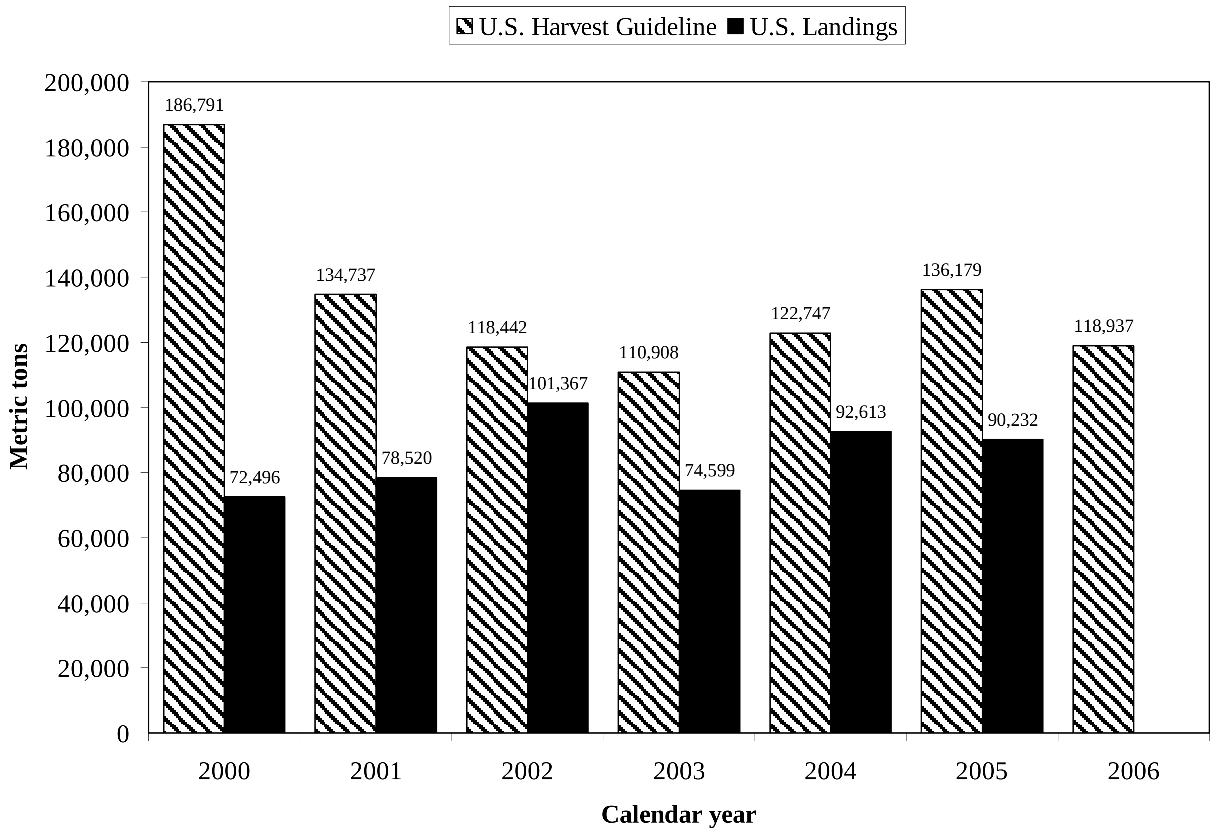


Figure 1. U.S. Pacific sardine harvest guidelines and resultant landings (mt) since the onset of PFMC management in calendar year 2000.

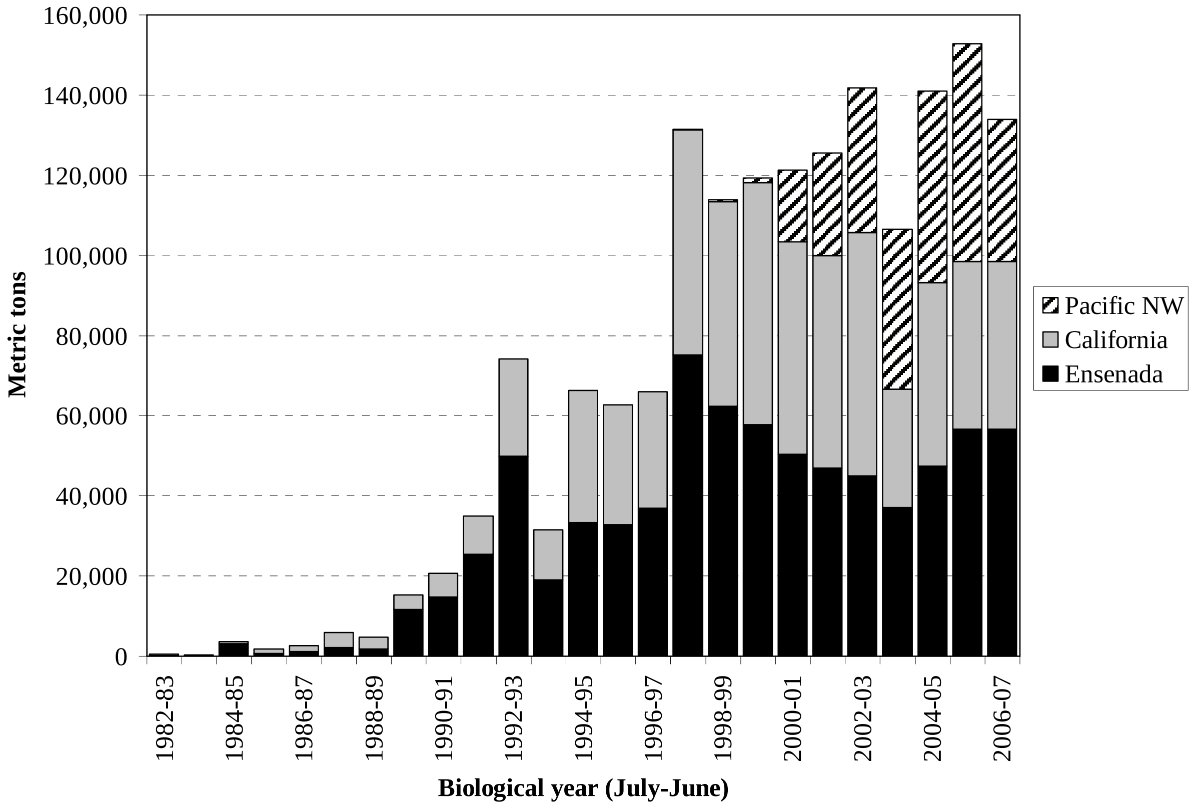


Figure 2. Pacific sardine landings (mt) by fishery for biological years 1982-83 to 2006-07 (July-June). Landings were projected for 2006-07.

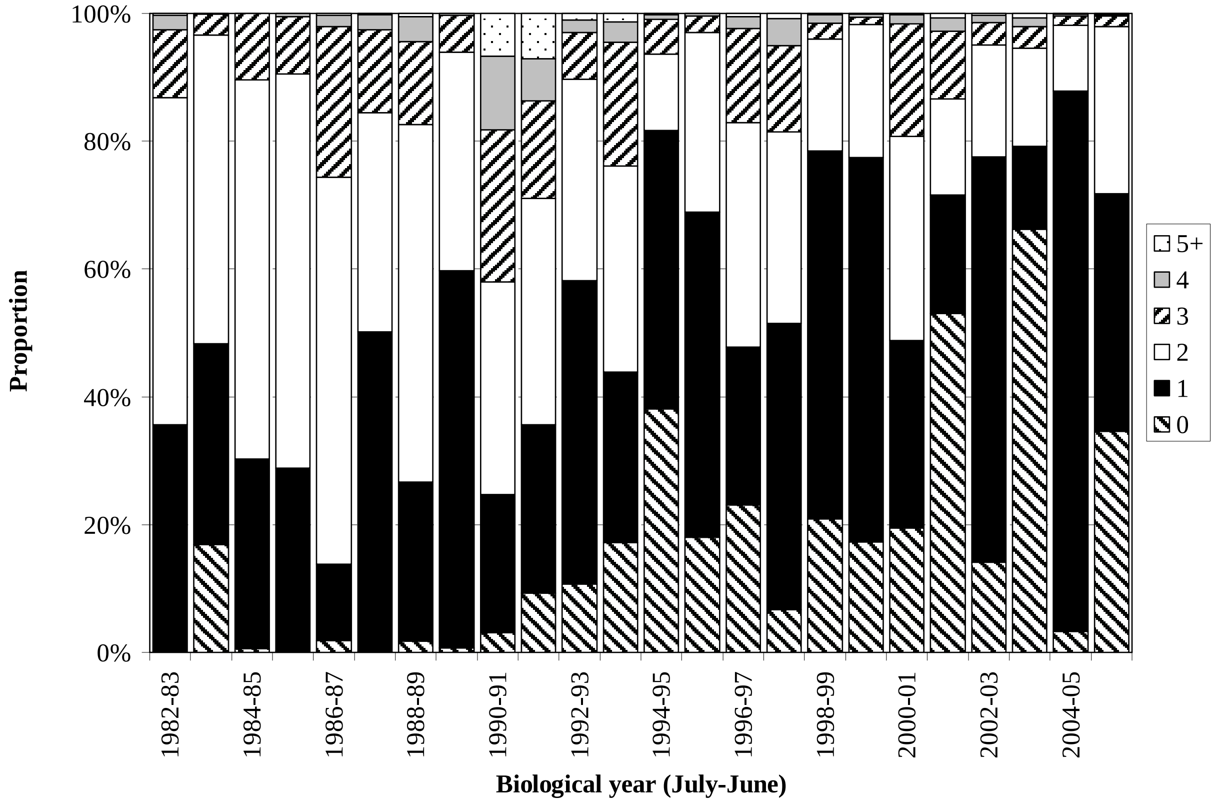


Figure 3. Catch-at-age proportions for the Pacific sardine fishery in California (San Pedro and Monterey) for biological years 1982-83 to 2005-06 (July-June).

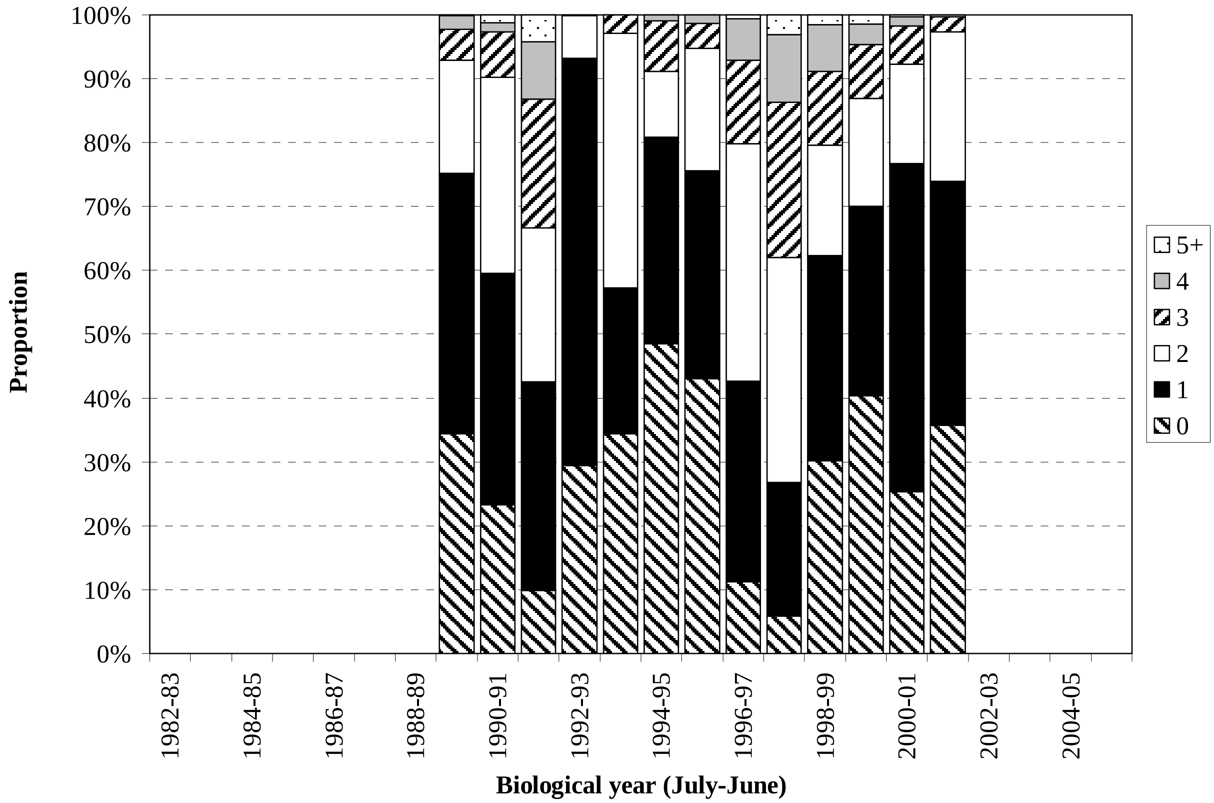


Figure 4. Catch-at-age proportions for the Pacific sardine fishery in Ensenada (Baja California, Mexico) for biological years 1989-90 to 2001-02 (July-June).

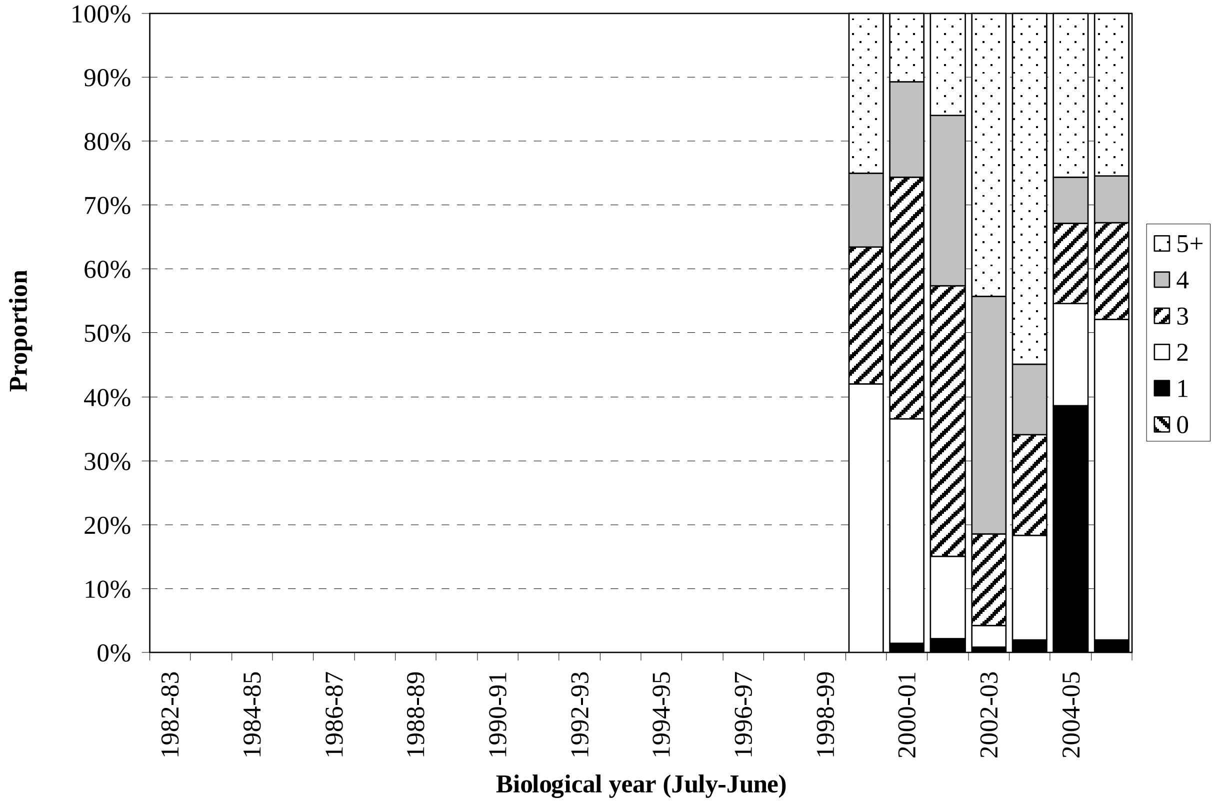


Figure 5. Catch-at-age proportions for the Pacific sardine fishery in the Pacific Northwest for biological years 1999-00 to 2005-06 (July-June).

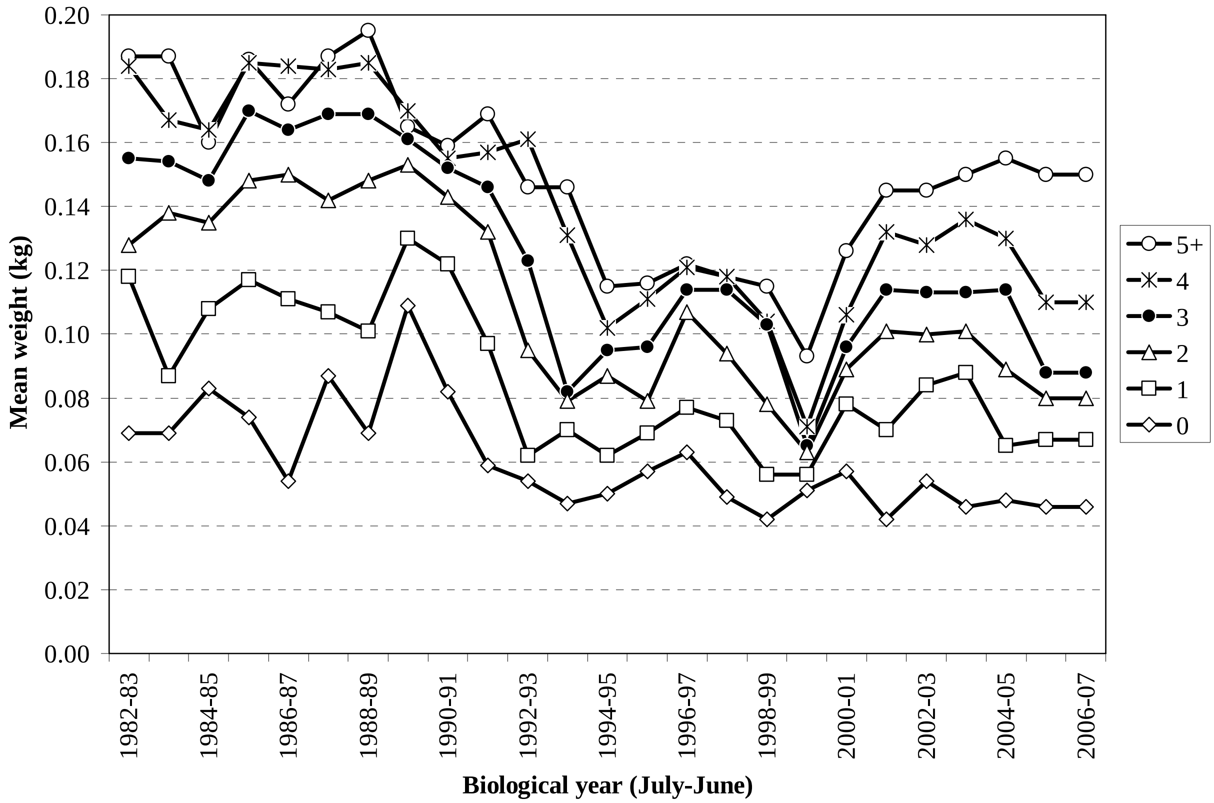


Figure 6. Pooled fishery weight-at-age (kg) for Pacific sardine as applied in the ASAP base model. Whole body weights were averaged across the three fisheries using respective landings to weight the data.

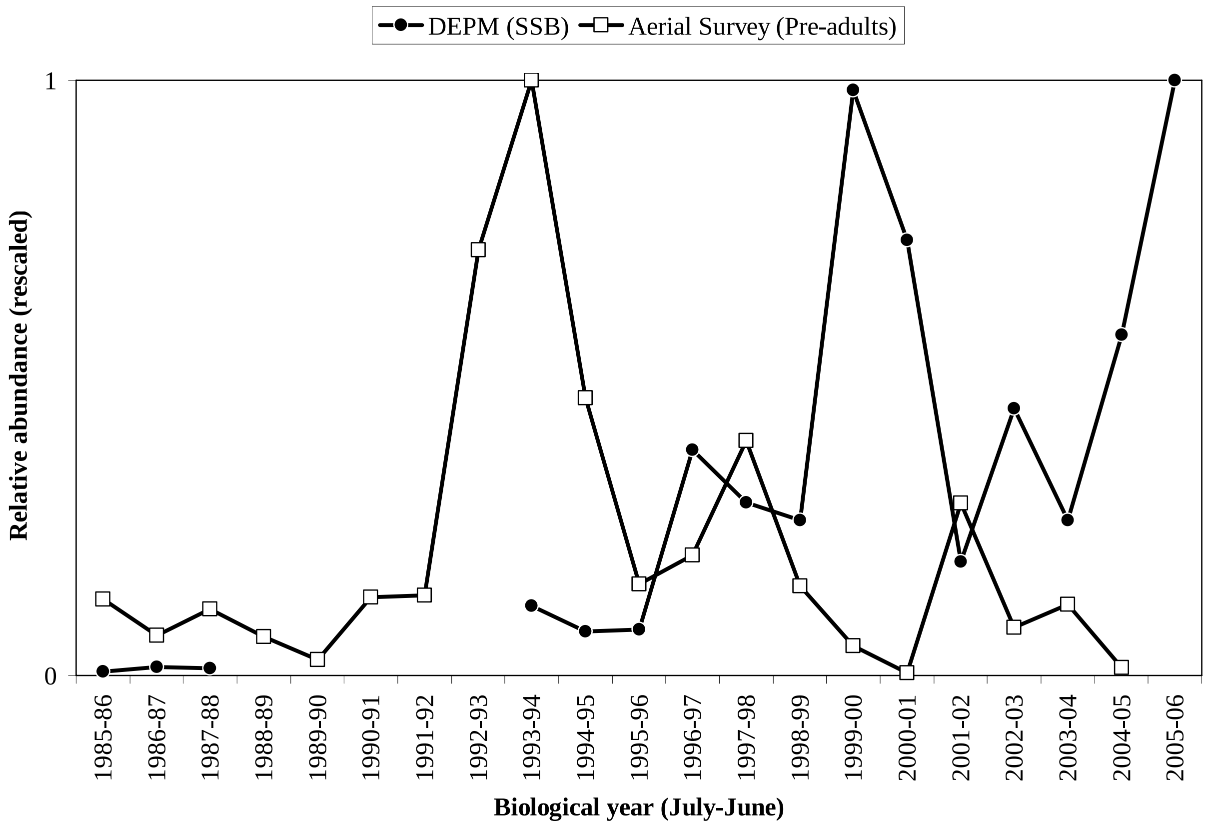


Figure 7. Rescaled indices of relative abundance for Pacific sardine applied in ASAP.

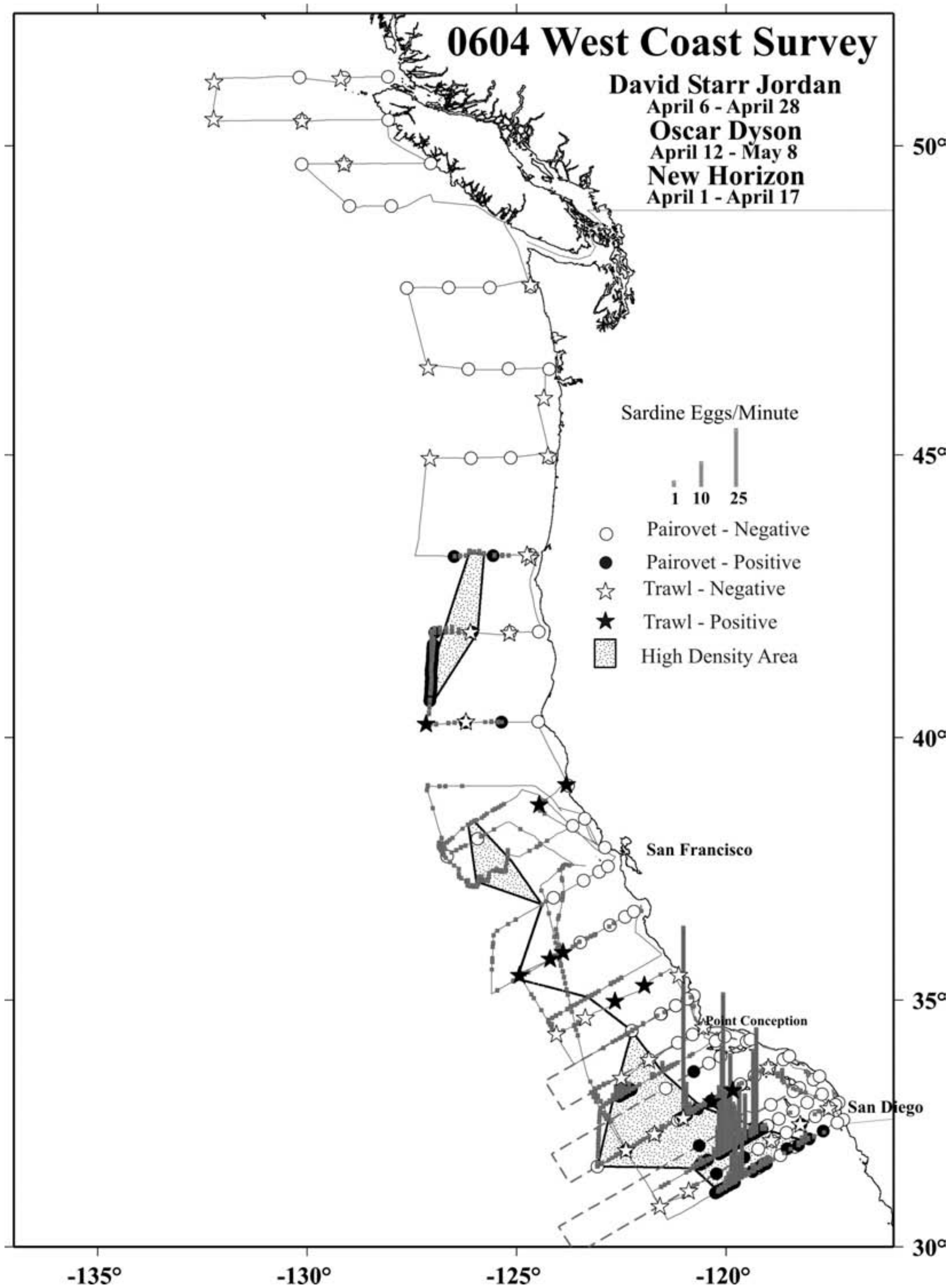


Figure 8. Track lines occupied by three research vessels from April 1 to May 8, 2006, for the coast-wide sardine survey. Shaded area was the high density area for sardine eggs.

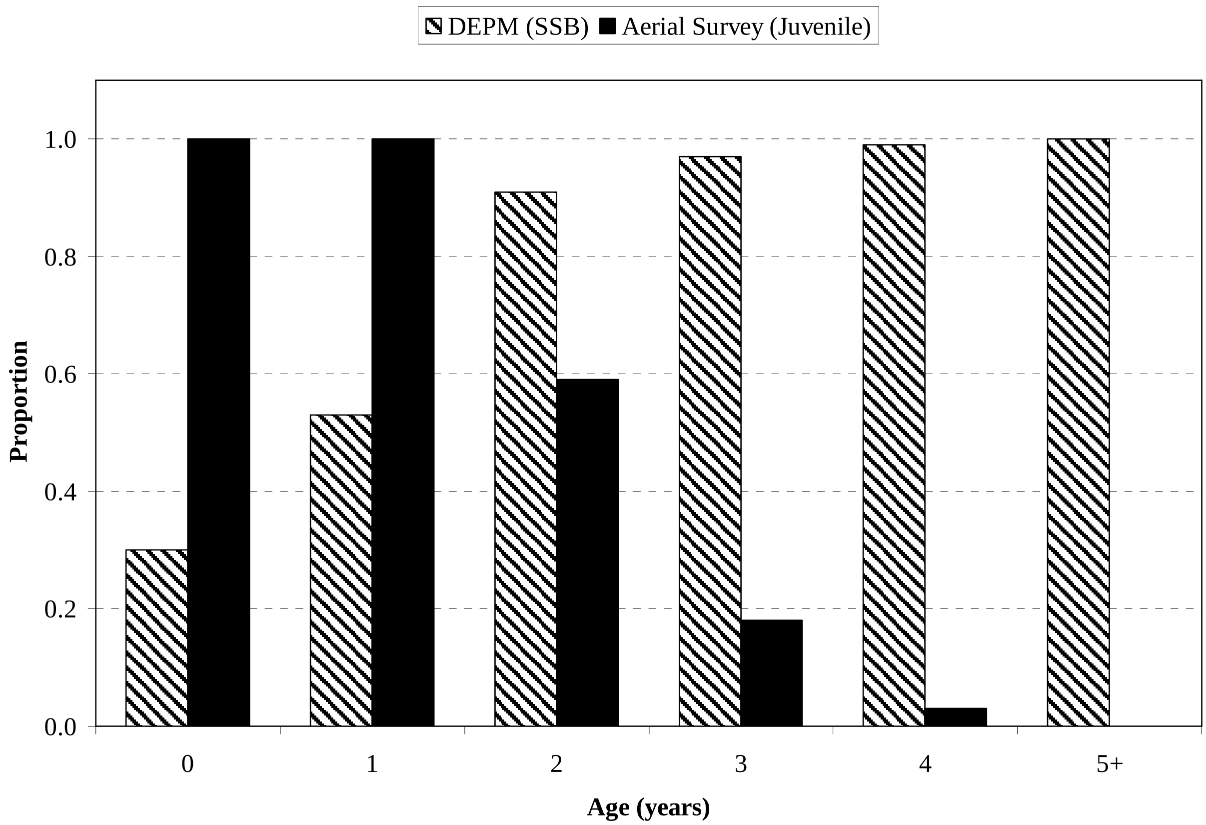


Figure 9. Selectivity patterns applied to Pacific sardine survey data in ASAP.

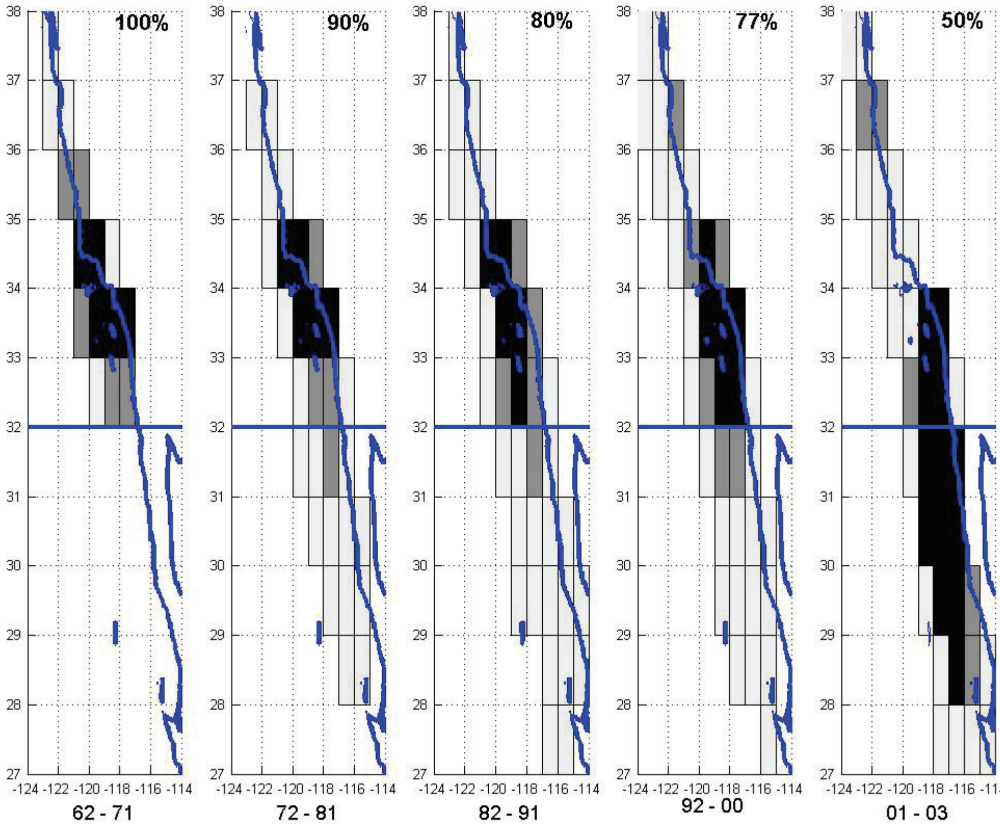


Figure 10. Distribution and southward shift of aerial spotter effort, Monterey Bay (California) to Cedros Island (Baja California), 1962 to 2003.

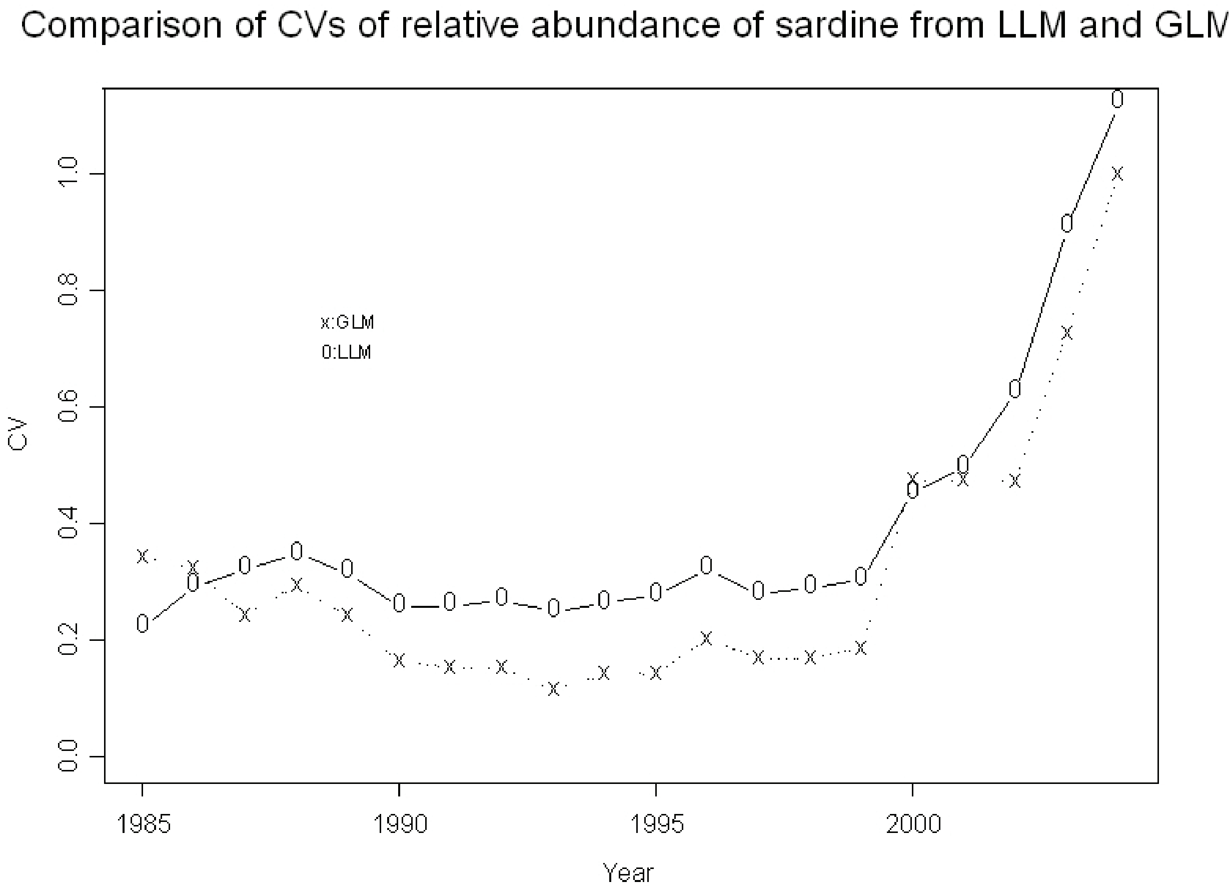


Figure 11. Coefficient of variation (CV) of the estimates of the relative abundance of young sardine based on GLM (x) and LLM (0).

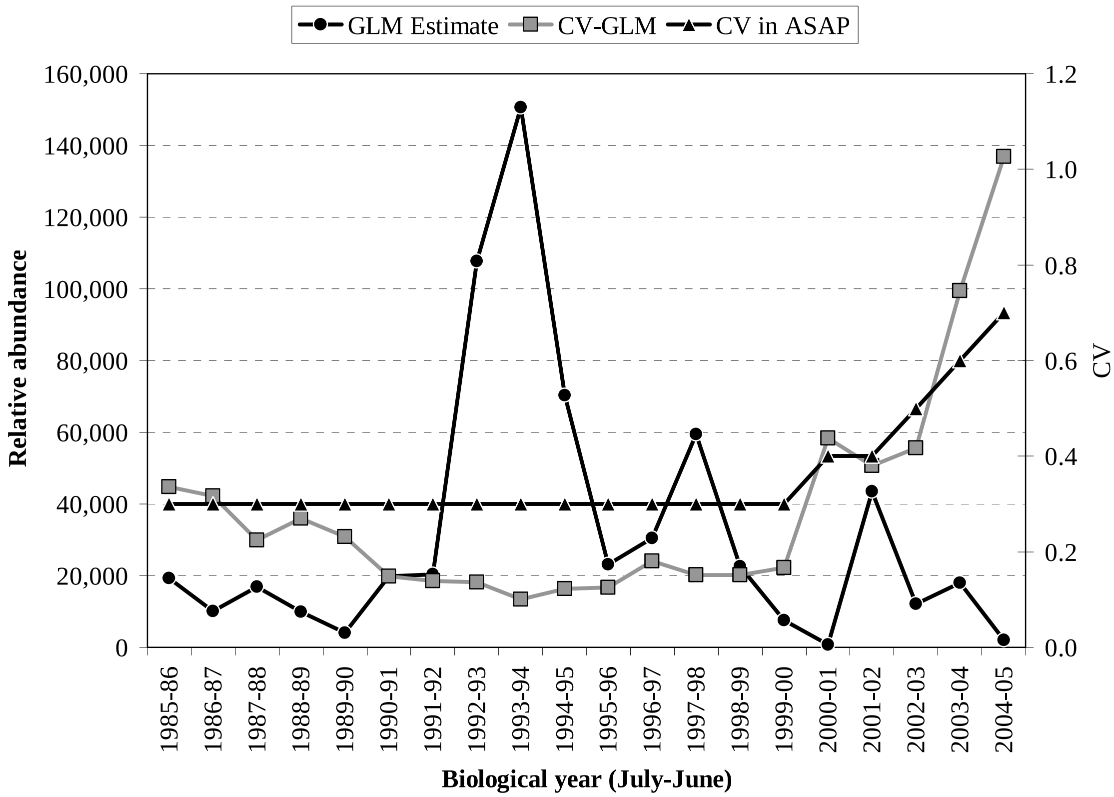


Figure 12. Aerial spotter survey index of relative abundance and coefficients of variation (CVs) from the GLM. CVs applied in the ASAP model are also displayed.

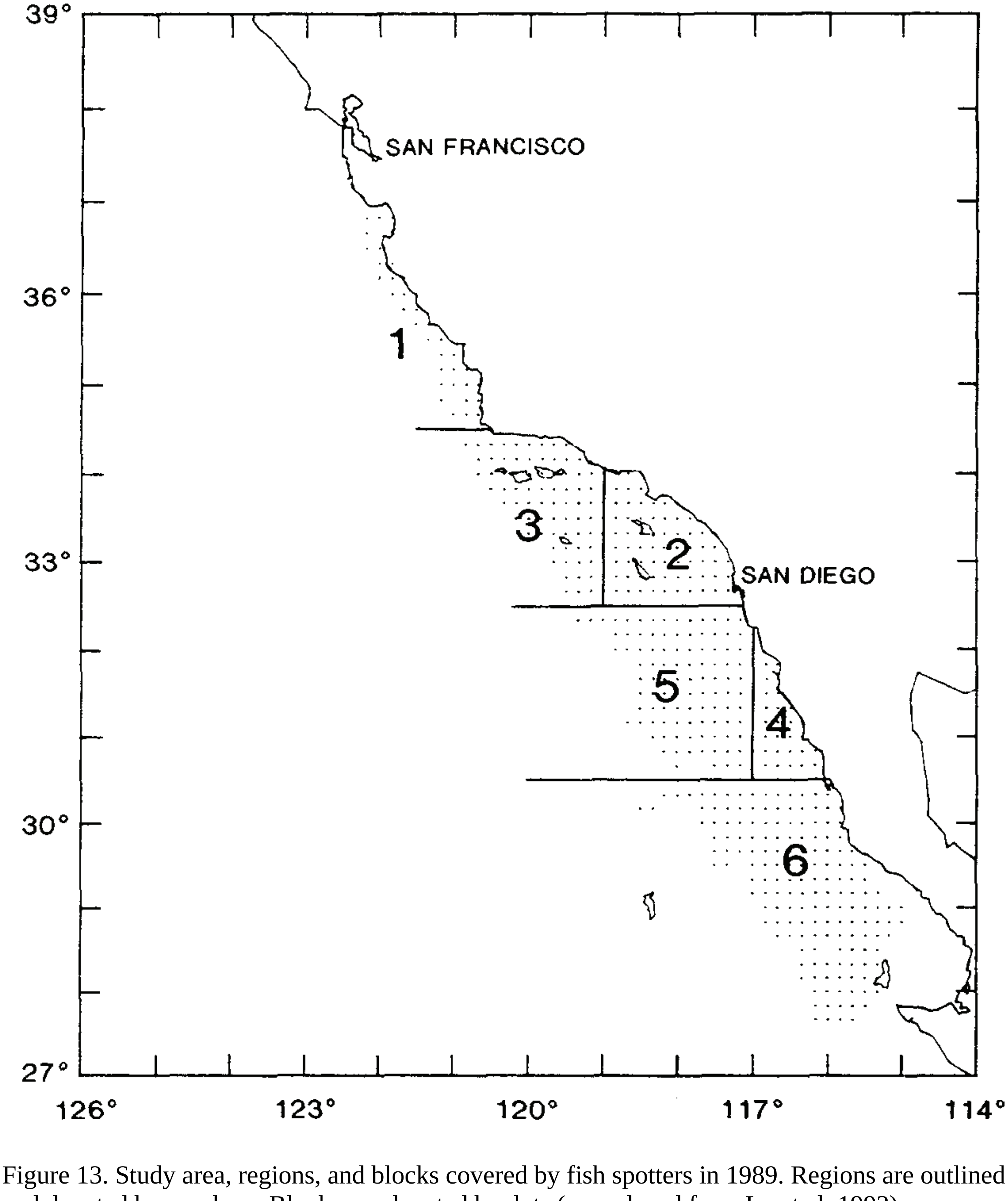


Figure 13. Study area, regions, and blocks covered by fish spotters in 1989. Regions are outlined and denoted by numbers. Blocks are denoted by dots (reproduced from Lo et al. 1992)

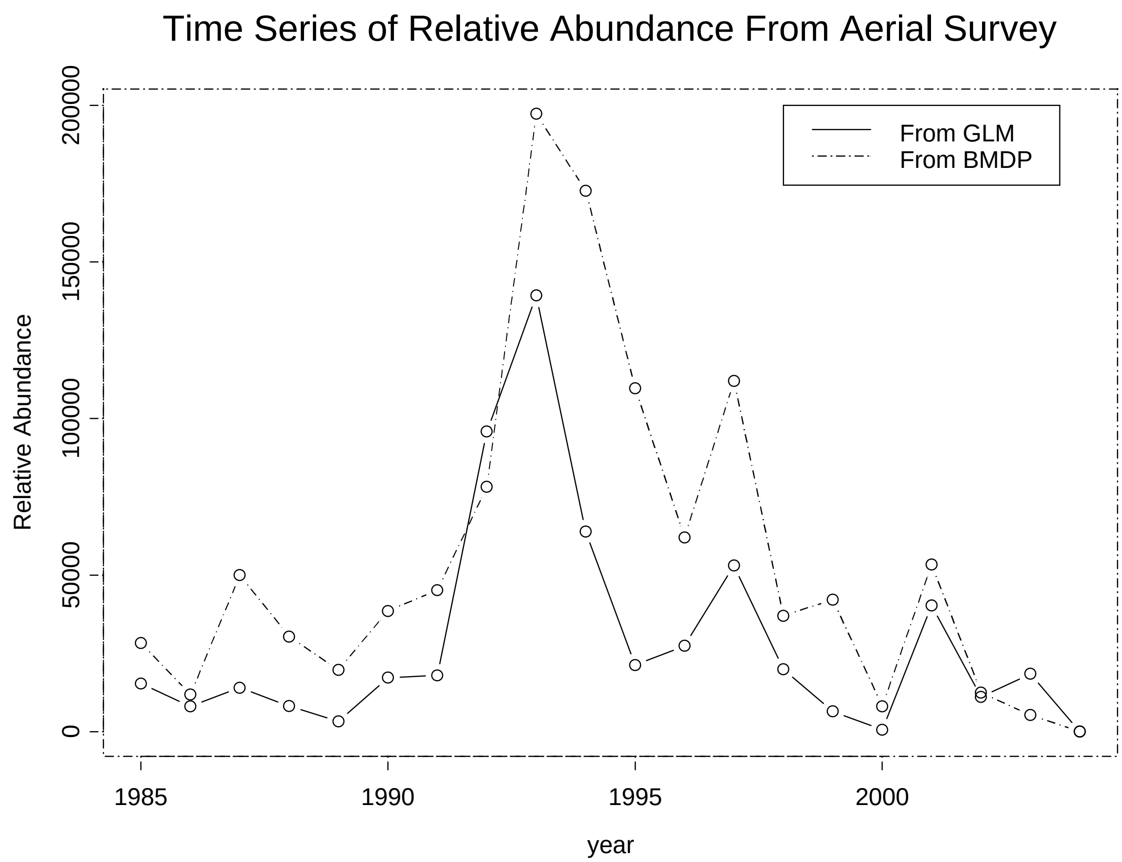


Figure 14. Time series of relative abundance of young sardine from 1985-86 to 2004-05 (July-June).

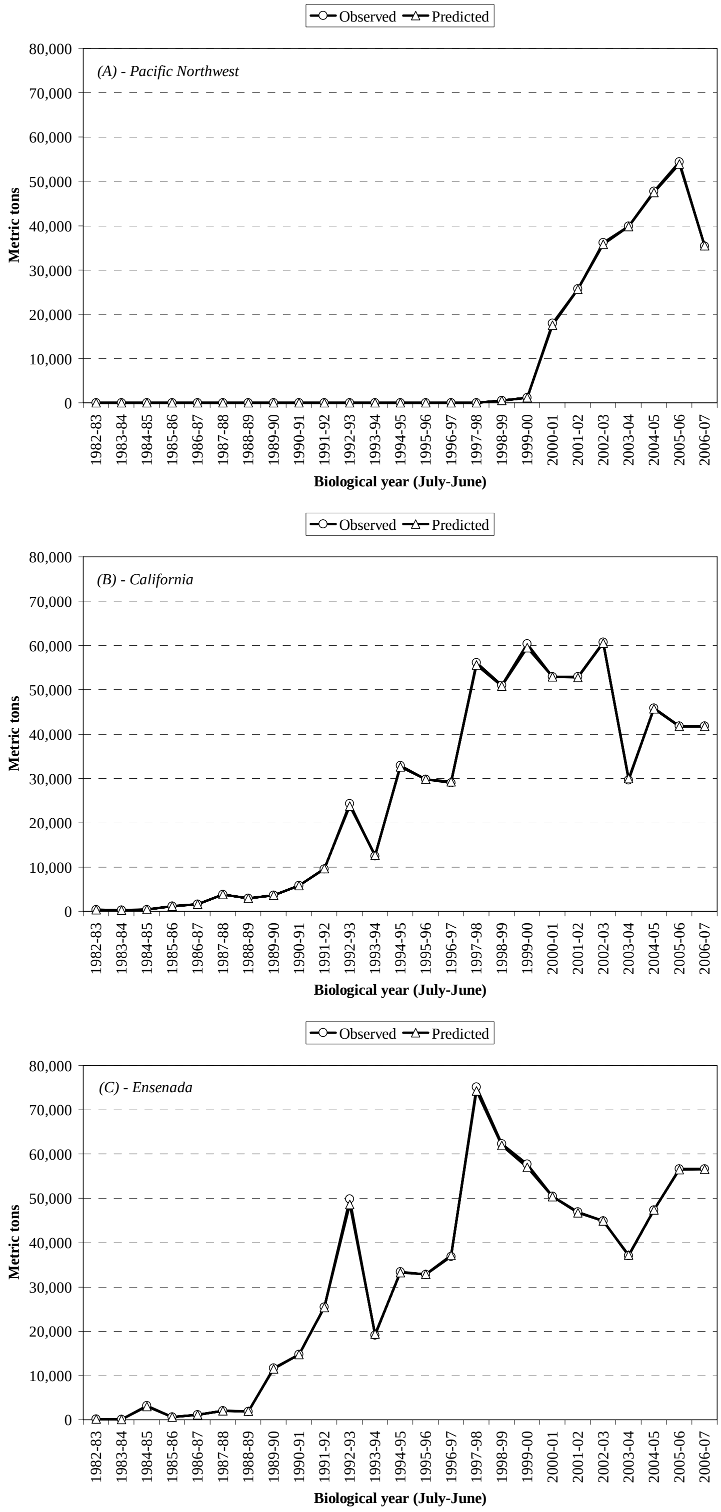


Figure 15. Observed and predicted estimates of total catch (mt) from the ASAP model (1982-83 to 2006-07): (A) Pacific northwest, (B) California, and (C) Ensenada.

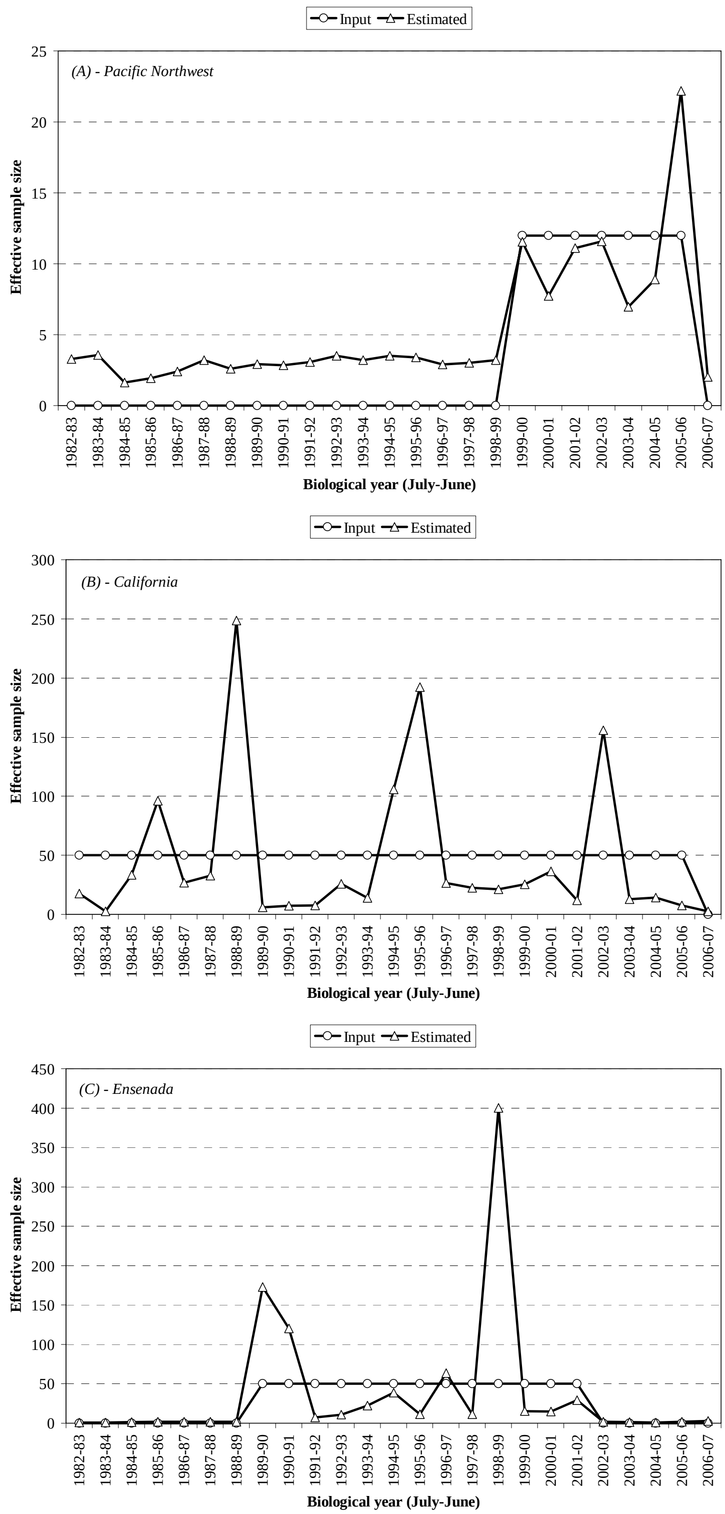


Figure 16. Effective sample sizes estimated for catch-at-age data from the (A) Pacific northwest, (B) California, and (C) Ensenada fisheries.

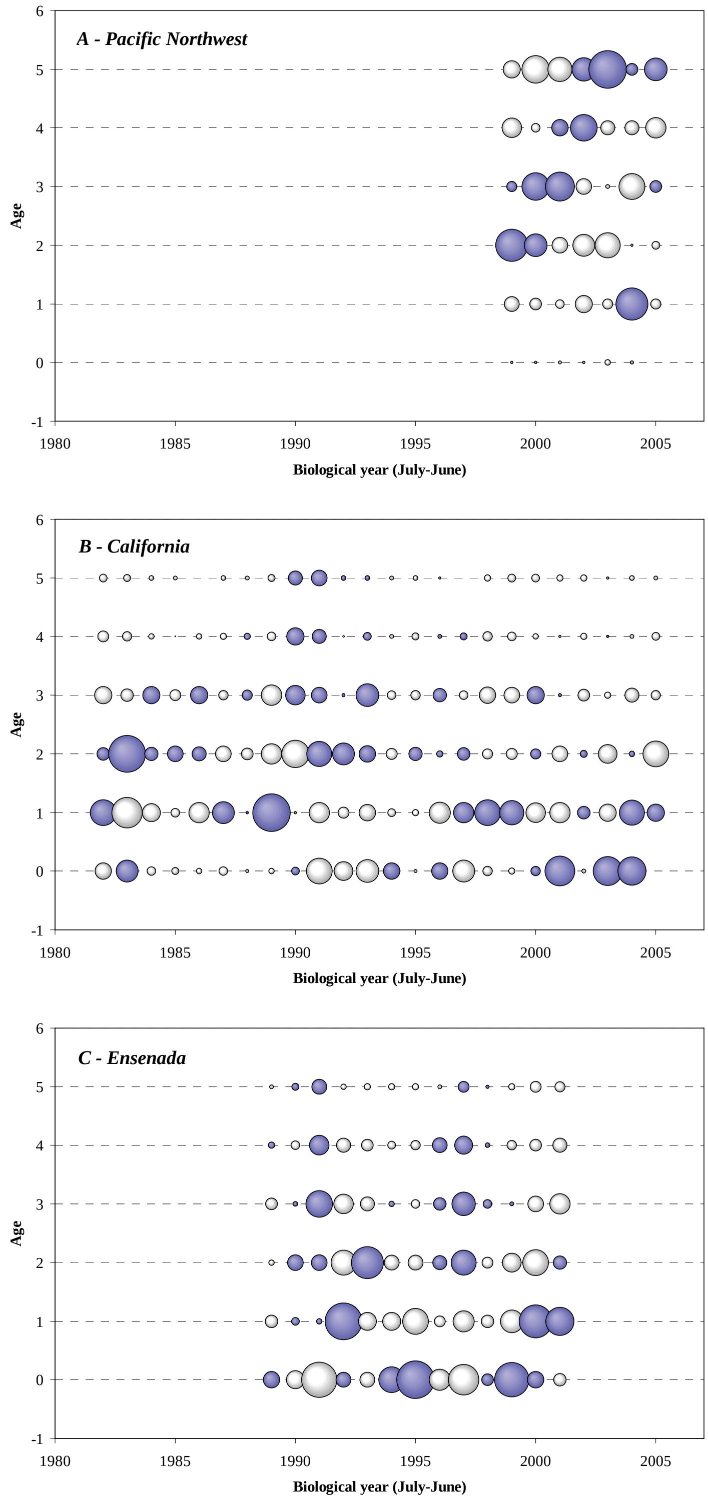


Figure 17. Standardized residuals from ASAP model fit to catch-at-age data for the three sardine fisheries. Dark bubbles are positive residuals, light bubbles are negative.

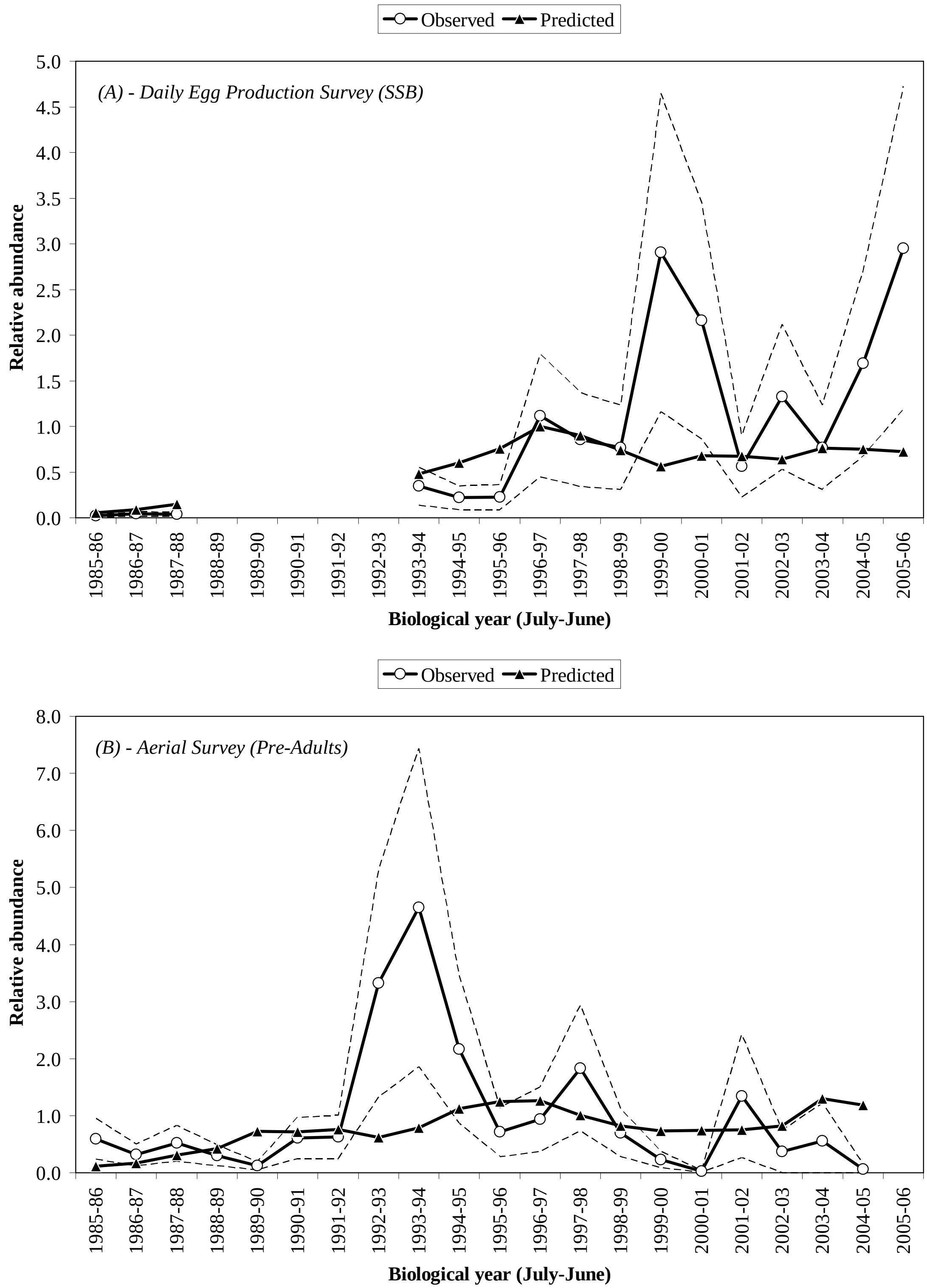


Figure 18. ASAP model fits to survey data: (A) Index of relative abundance of sardine spawning stock biomass (mt) based on daily egg production method (DEPM) estimates from ichthyoplankton survey data, 1985-86 to 1987-88, and 1993-94 to 2006-06; (B) Index of relative abundance of sardine pre-adult biomass (primarily age 0-2 fish) based on aerial spotter plane survey, 1985-86 to 2004-05.

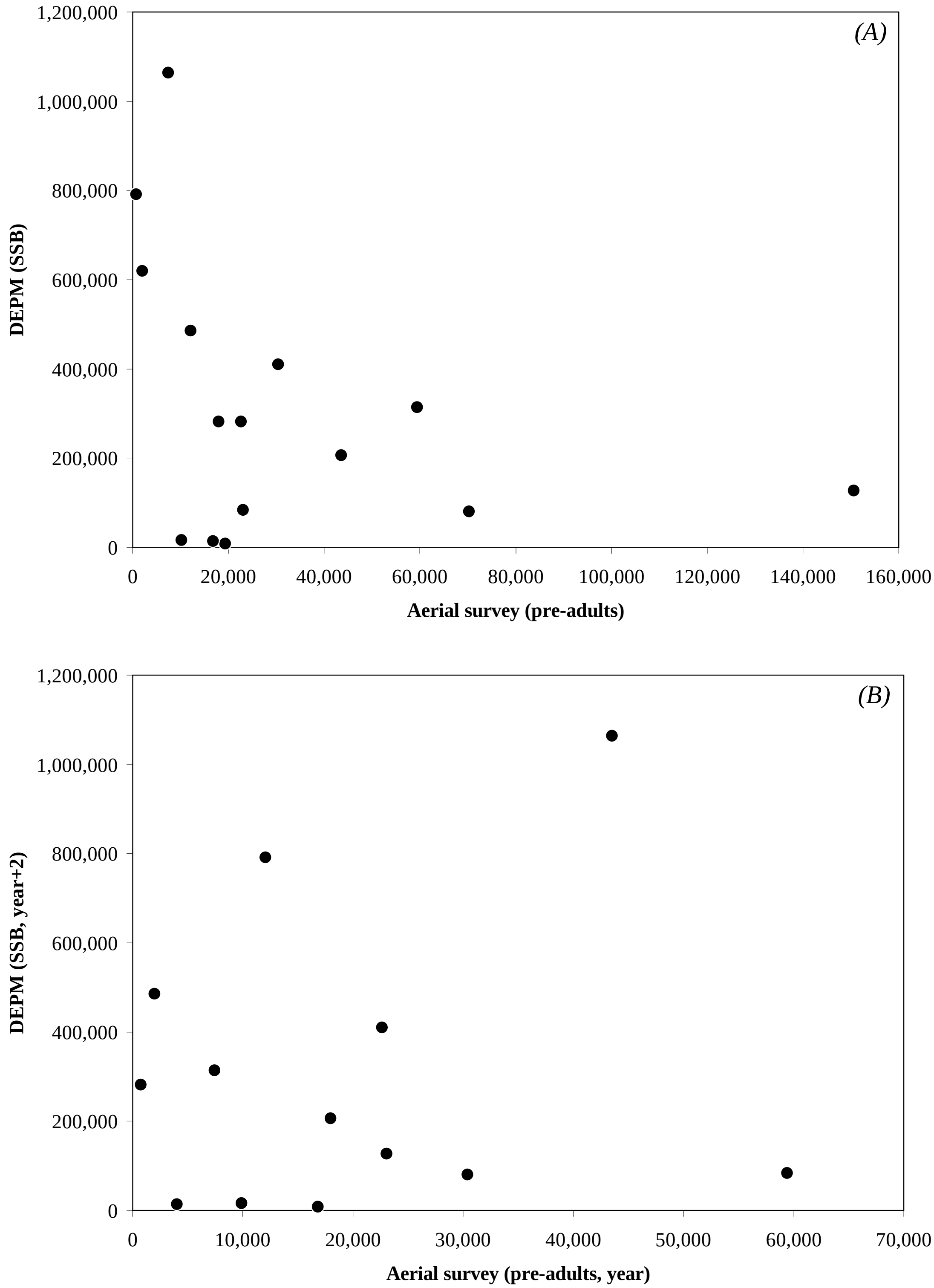


Figure 19. Comparisons of observed values for the DEPM survey (index of spawning stock biomass) and Aerial Spotter survey (index of young sardine): (A) year by year comparisons, and (B) surveys lagged two years, i.e. the aerial spotter index values were plotted against the DEPM index two years later.

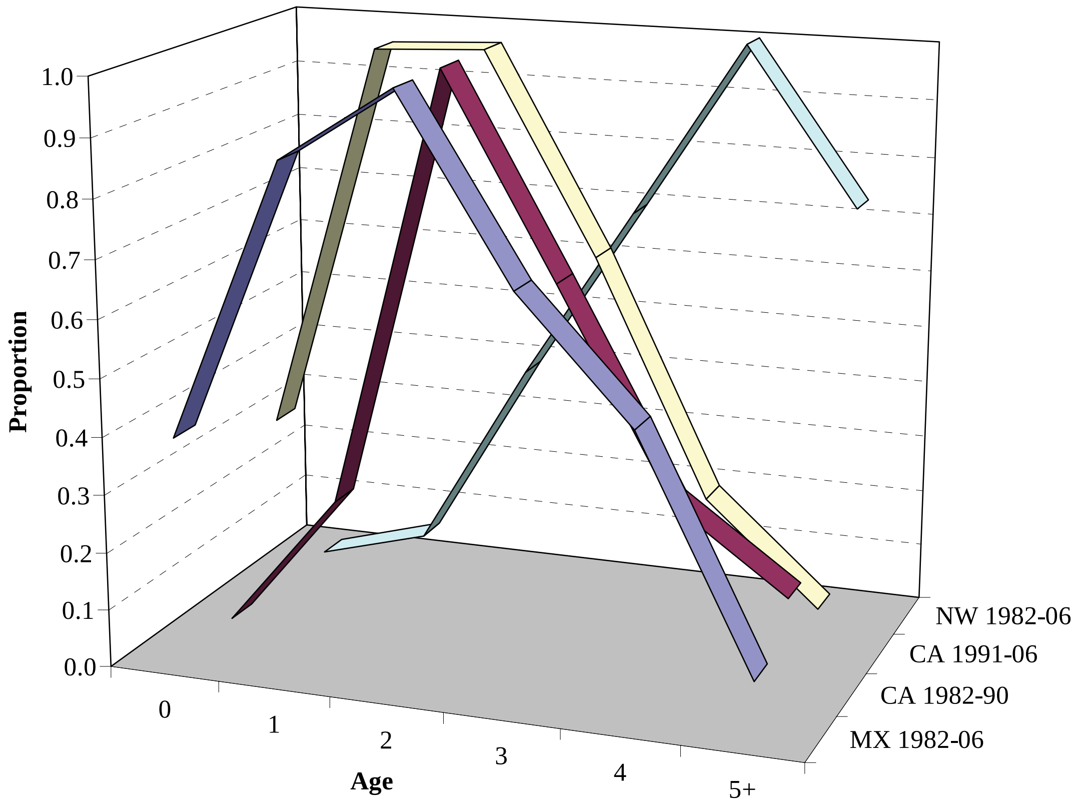


Figure 20. Fishery selectivities estimated in the ASAP baseline model. Selectivities for the California fishery were estimated in two time blocks: 1982-83 to 1990-91 (incidental fishery) and 1991-92 to 2006-07 (directed fishery).

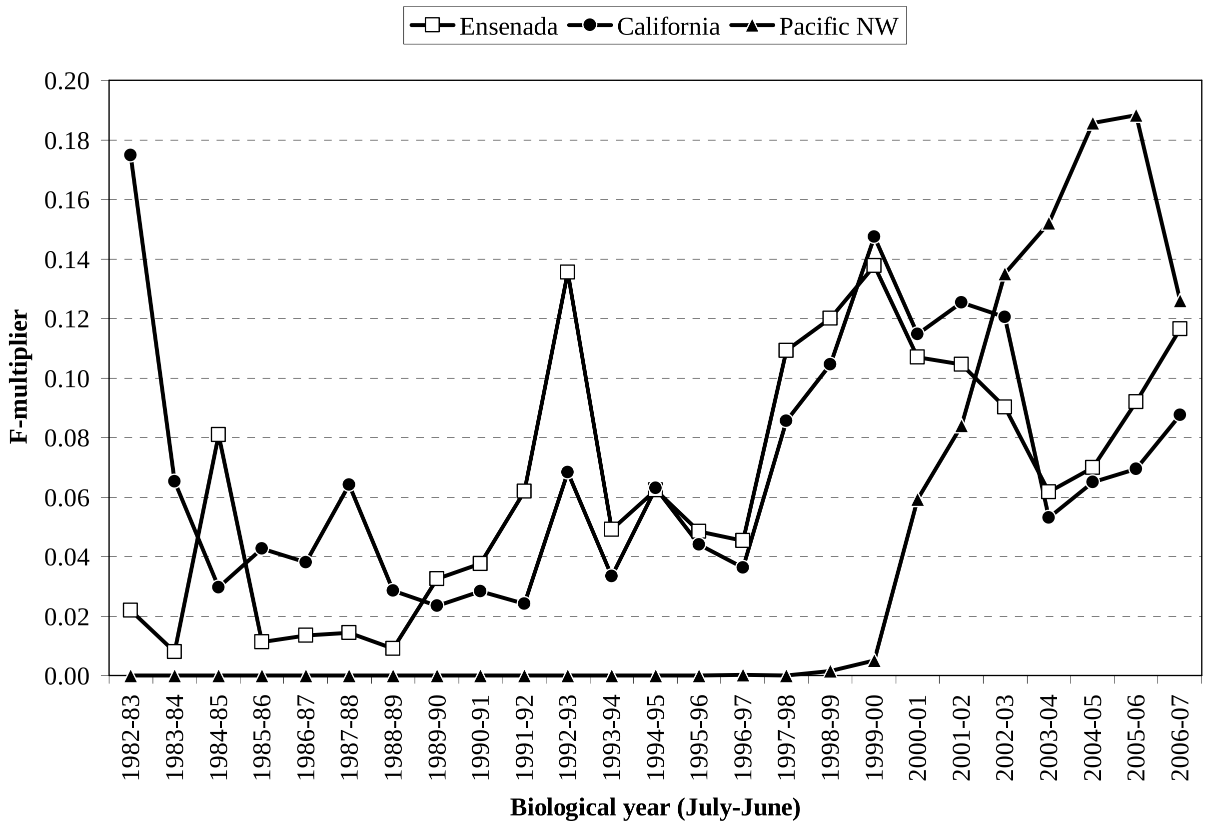


Figure 21. ASAP baseline model estimates of instantaneous rate of fishing mortality (yr^{-1}) for fully-selected age(s) in the three modeled fisheries.

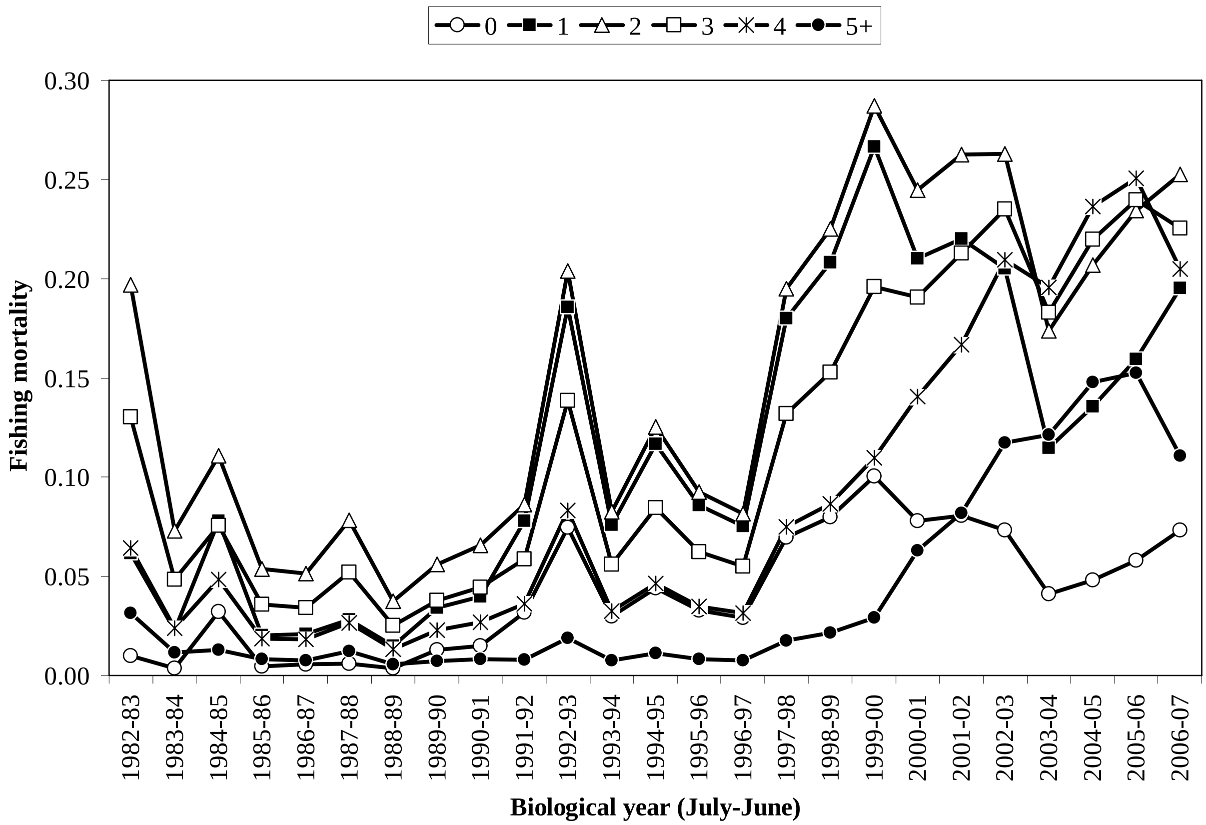


Figure 22. Estimated instantaneous rates of fishing mortality (yr^{-1}) by age and year for the combined fisheries in the ASAP baseline model.

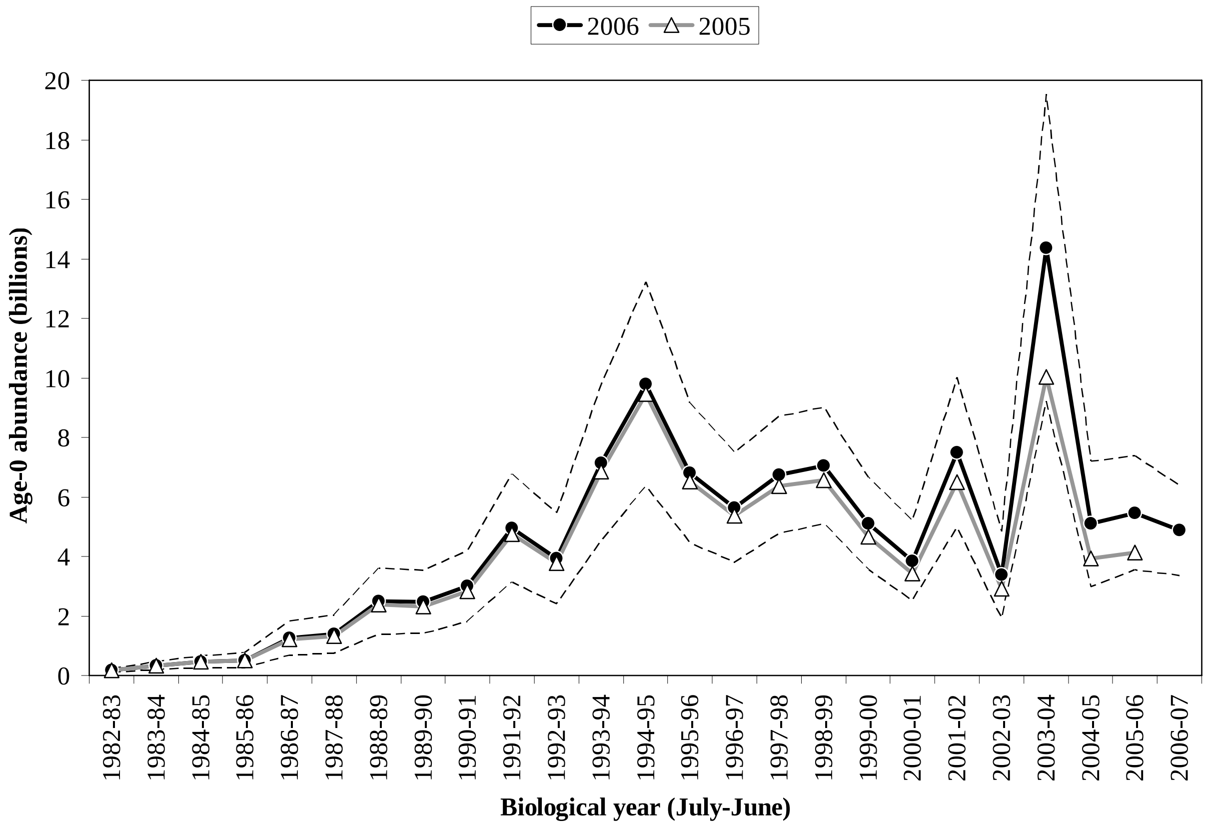


Figure 23. Pacific sardine recruitment estimates (age 0 abundance in billions) from the ASAP baseline model (solid circles) along with a 2-standard deviation uncertainty envelope (dashed lines). Corresponding estimates from Hill et al. (2005) are shown for comparison (triangles).

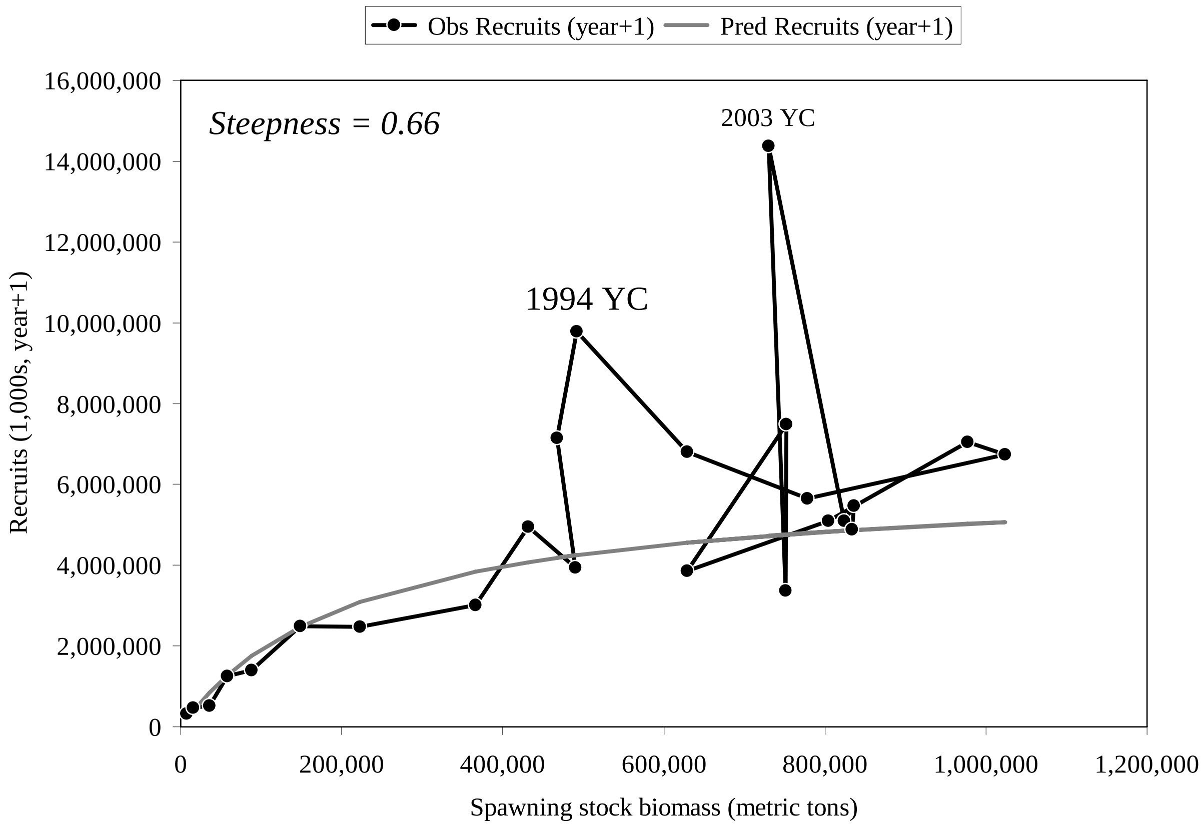


Figure 24. Sardine spawning stock biomass and recruitment estimates from the baseline model. Estimated recruitments from the Beverton-Holt stock-recruitment relationship are also shown. Year labels indicate the biological year associated with the spawning stock biomass.

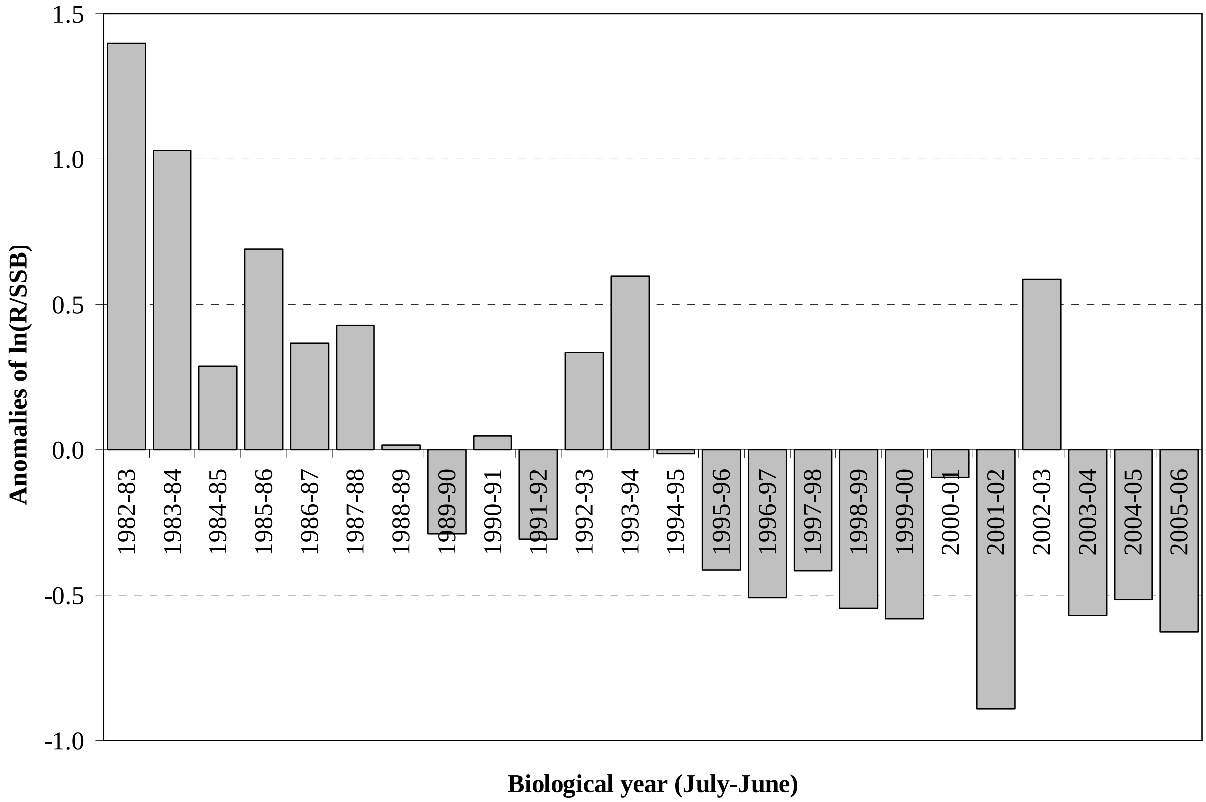


Figure 25. Relative reproductive success of Pacific sardine, 1982-83 to 2005-06.

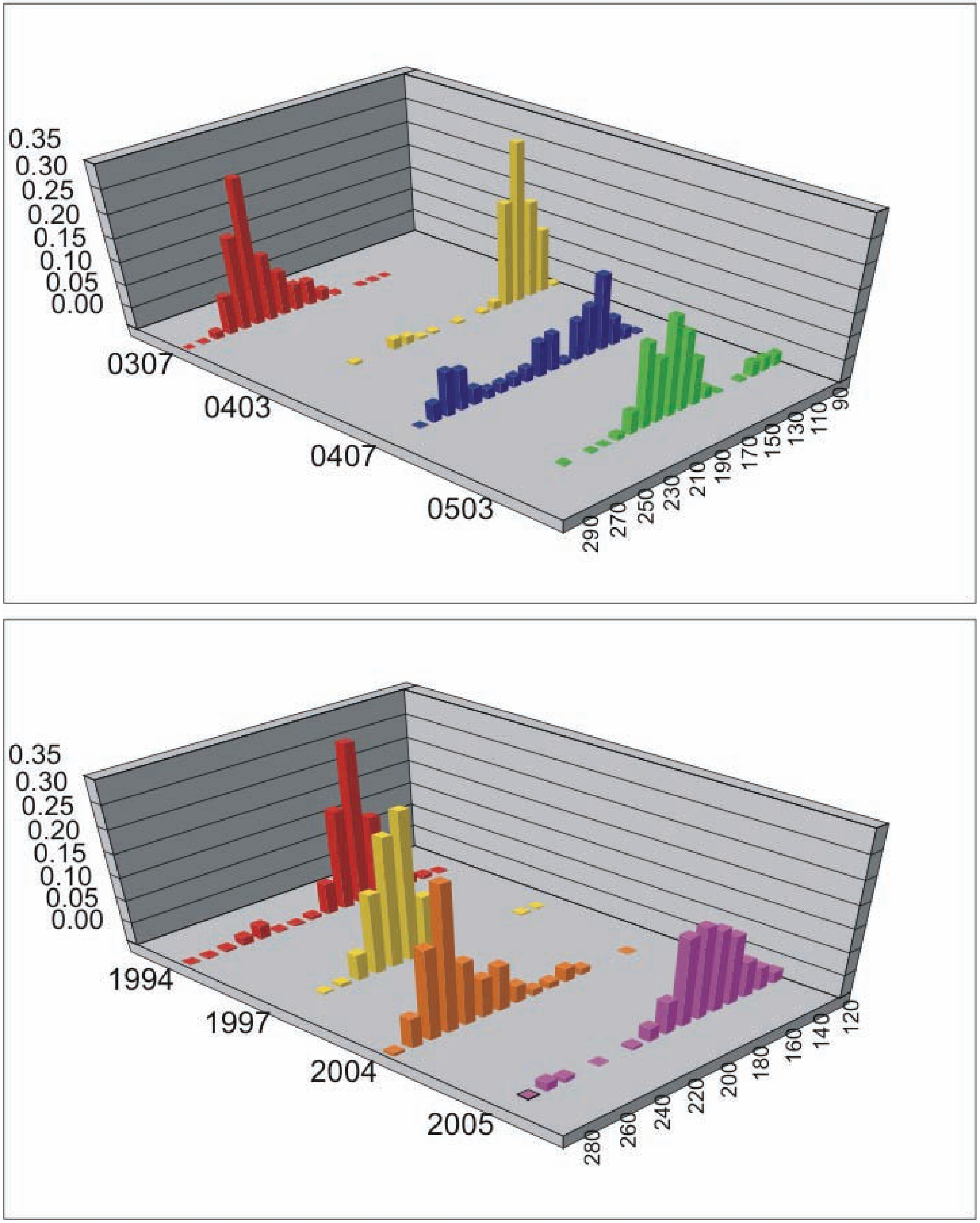


Figure 26. Length compositions of Pacific sardine collected during fishery-independent surveys, with evidence for a relatively strong 2003 year class in both areas: (top) Pacific northwest surveys in July 2003, March 2004, July 2004, and March 2005; (bottom) April surveys conducted in California offshore waters in 1994, 1997, 2004, and 2005.

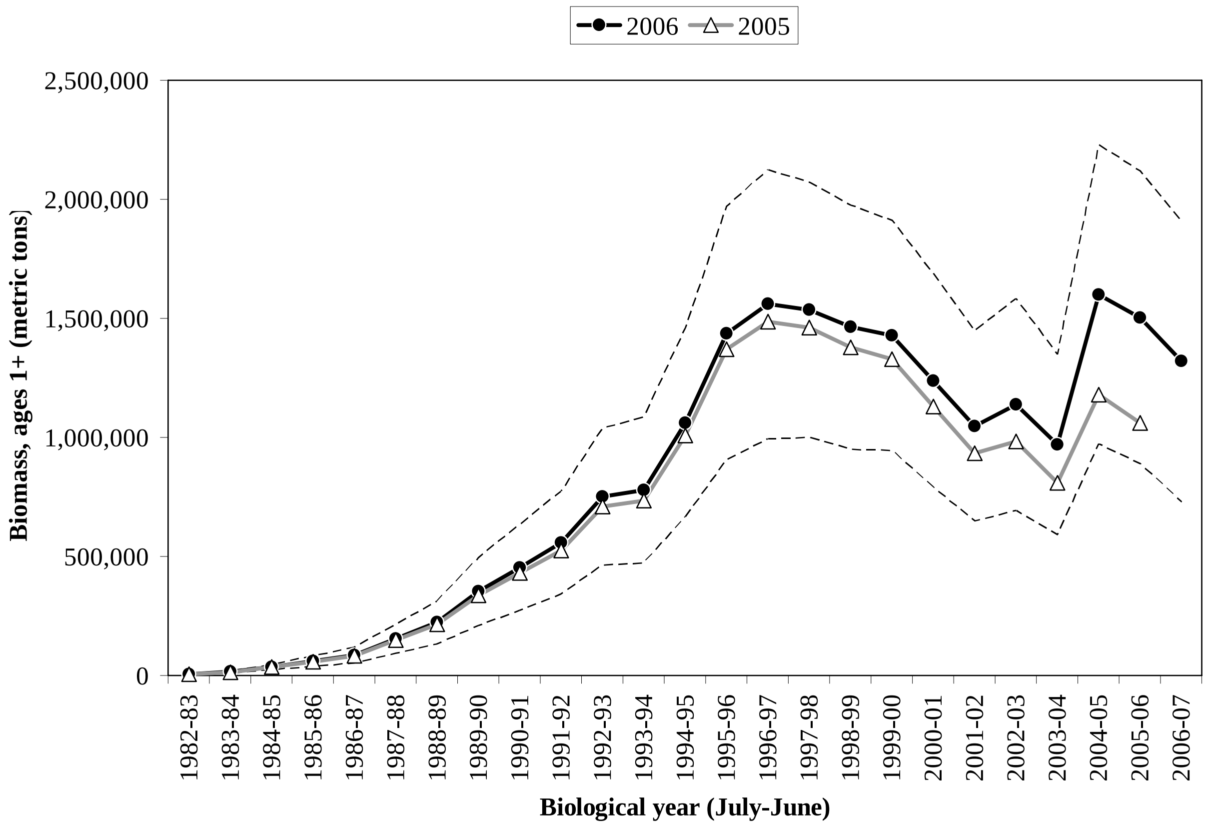
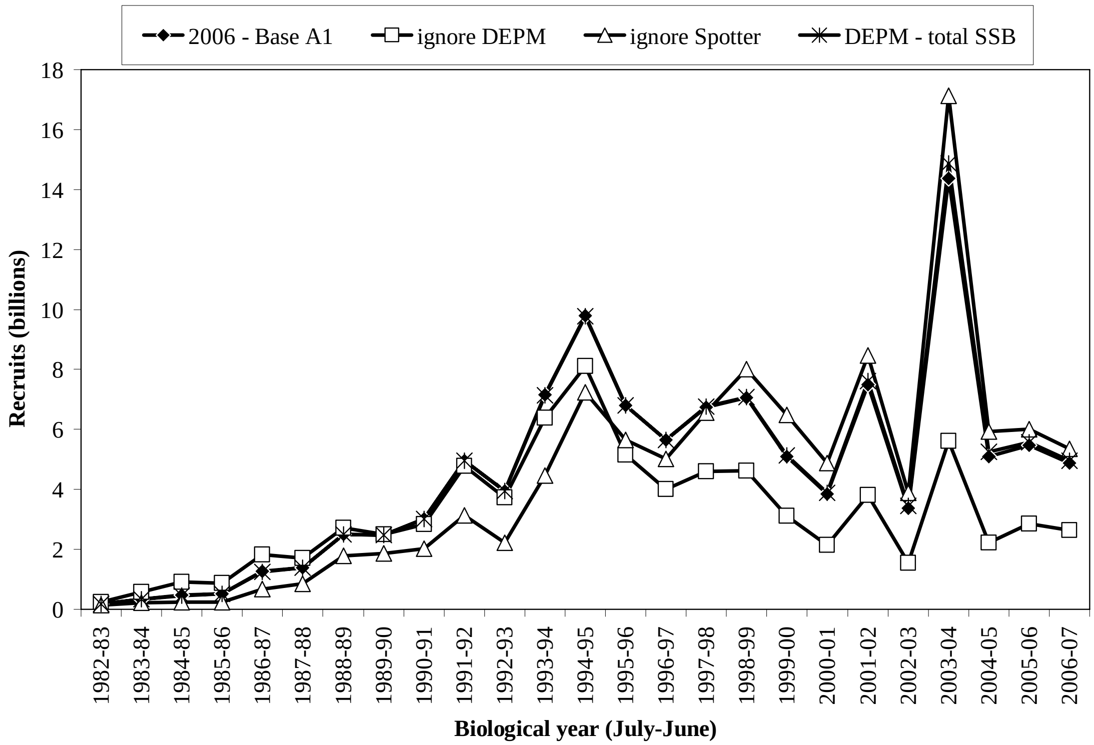


Figure 27. Pacific sardine stock biomass (ages 1+) estimates from the ASAP baseline model (solid circles) along with a 2-standard deviation uncertainty envelope (dashed lines). Corresponding estimates from Hill et al. (2005) are shown for comparison (triangles).



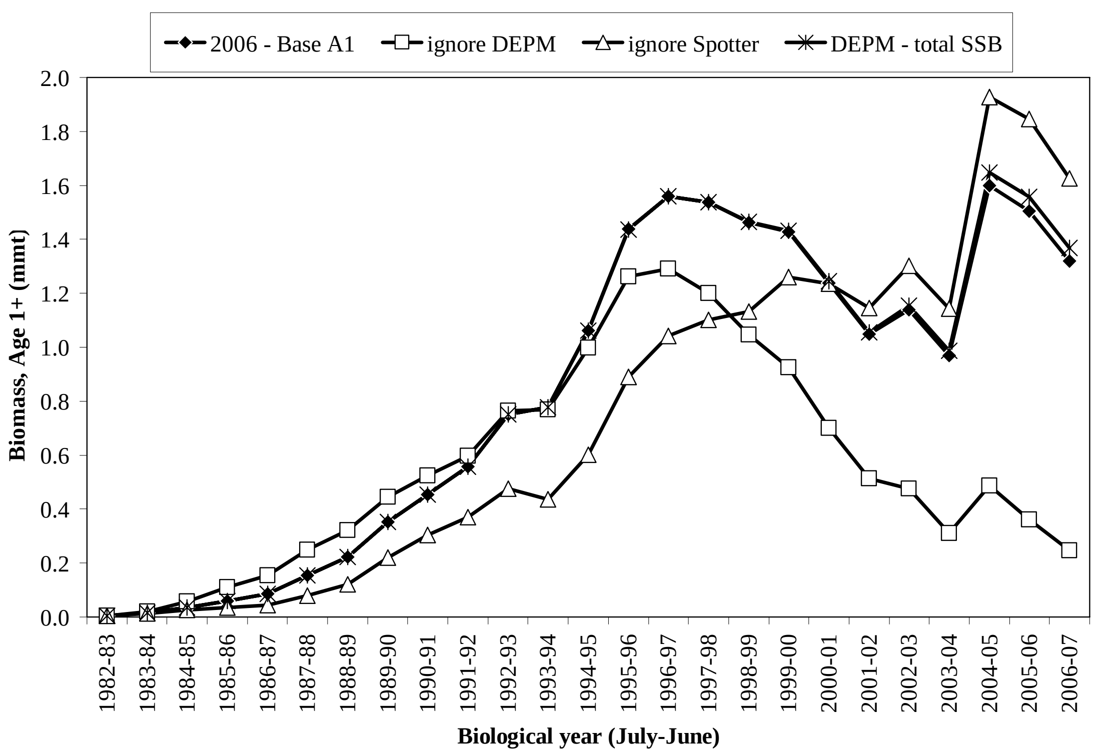


Figure 28. Sensitivity of recruitment and stock biomass estimates to the DEPM and Aerial Spotter indices.

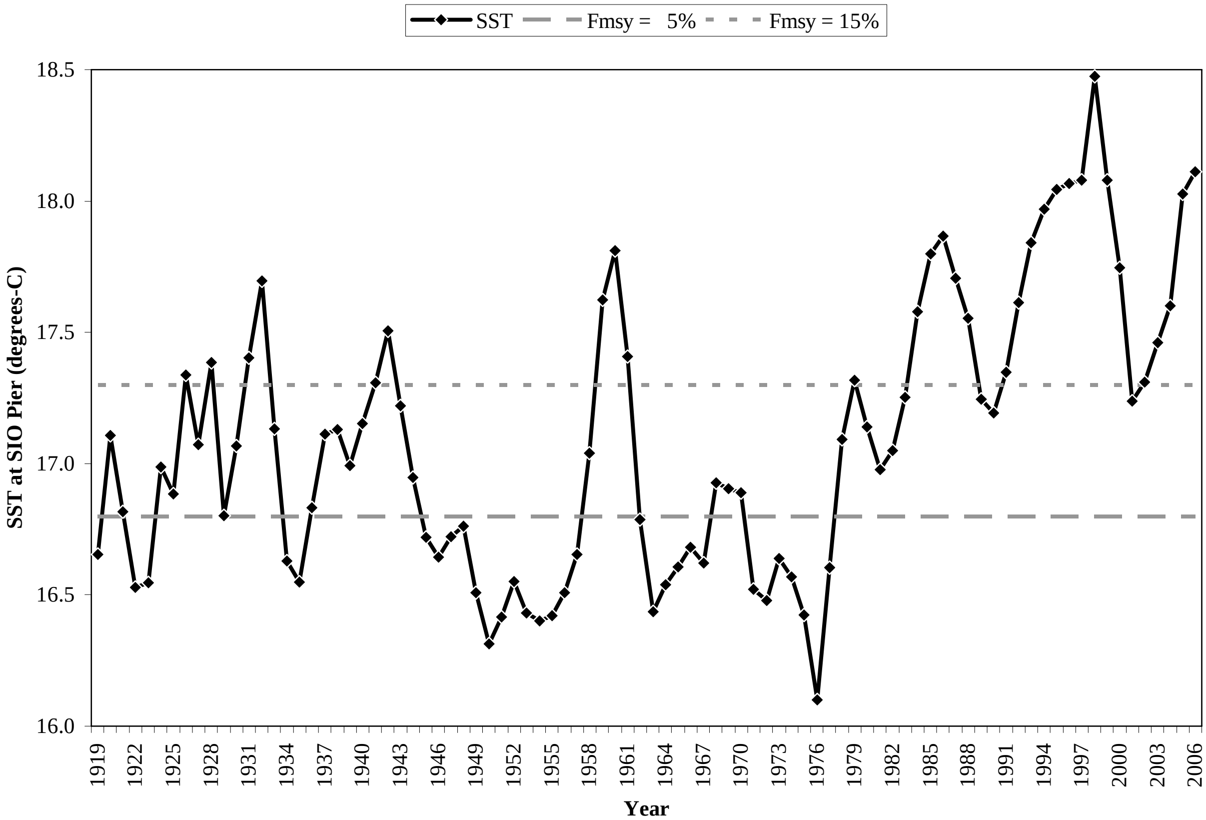


Figure 29. Three-season (July-June) running average of sea surface temperature (SST) data collected daily at Scripps Institution of Oceanography pier since 1916. For any given year, SST is the running average temperature during the three preceding years, e.g. the 2006 estimate is the average from July 1, 2003 through June 30, 2006. The 2006 value used for management in 2007 is 18.11 °C, so a 15% exploitation fraction (F_{msy}) should be applied in the harvest control rule.

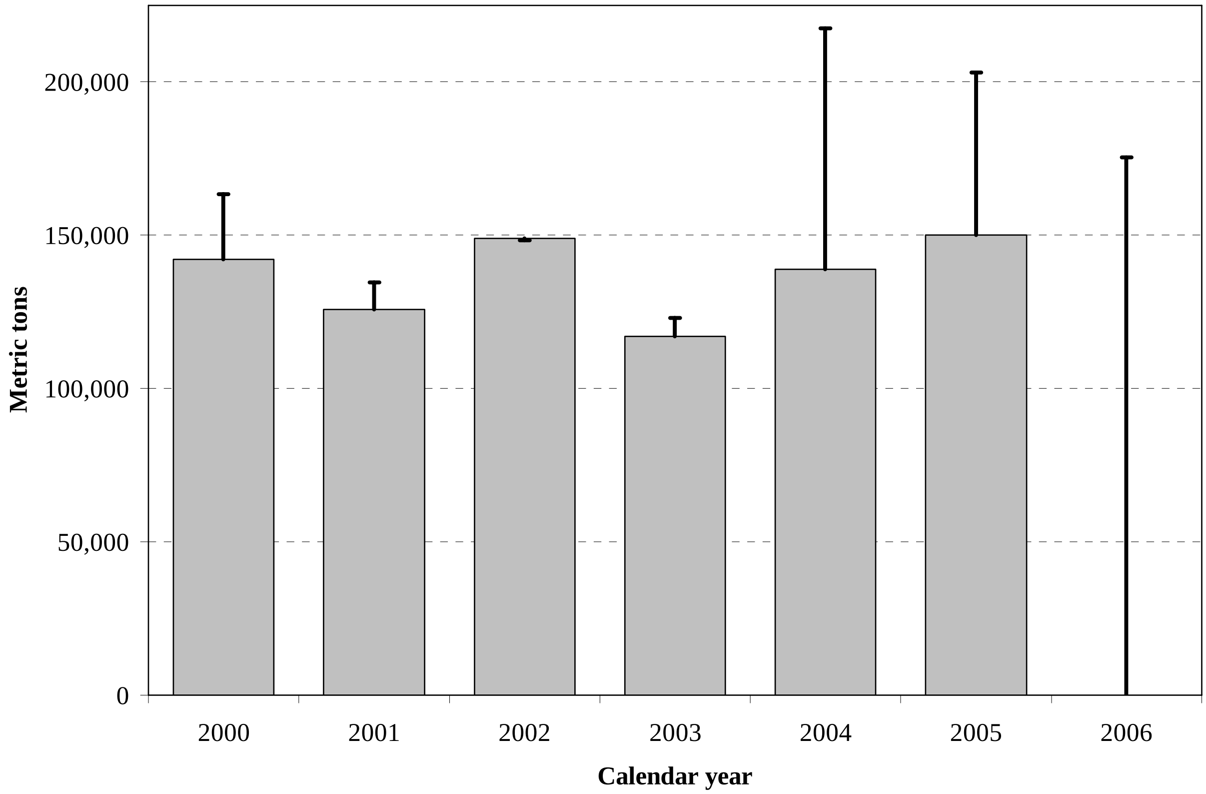


Figure 30. Coast-wide harvest (gray bars) of Pacific sardine relative to retrospective (theoretical) harvest guidelines (black lines) based on the biomass time series from the current assessment. Total HGs are based on the formula presented in 'HARVEST GUIDELINE FOR 2007' but are not prorated for assumed U.S. Distribution and therefore represent the sustainable harvest for the west coast of North America.

APPENDIX I – ASAP Model Description (reprint of Legault and Restrepo, 1999)

SCRS/1998/058 Col.Vol.Sci.Pap. ICCAT, 49 (2) : 246-253 (1999)

A FLEXIBLE FORWARD AGE-STRUCTURED ASSESSMENT PROGRAM

Christopher M. Legault[1], *Victor R. Restrepo*[2]

SUMMARY

This paper documents an age-structured assessment program (ASAP) which incorporates various modeling features that have been discussed by the SCRS in recent years, particularly during meetings of the bluefin tuna species group. The software was developed using the commercial package of AD Model Builder, an efficient too for optimization that uses an automatic differentiation algorithm in order to find a solution quickly using derivatives calculated to within machine precision, even when the number of parameters being estimated is rather large. The model is based on forward computations assuming separability of fishing mortality into year and age components. This assumption is relaxed by allowing for fleet-specific computations and by allowing the selectivity at age to change smoothly over time. The software can also allow the catchability associated with each abundance index to vary smoothly with time. The problem's dimensions (number of ages, years, fleets and abundance indices) are defined at input and limited by hardware only. We illustrate an application of ASAP using data for western Atlantic bluefin tuna.

RÉSUMÉ

Le présent travail documente un programme d'évaluation structuré par âge (ASAP) qui comprend plusieurs facettes de modélisation qui ont été abordées par le SCRS ces dernières années, notamment pendant les sessions du groupe d'espèce thon rouge. Le logiciel a été élaboré au moyen du programme commercial AD Model Builder, qui est un outil efficace d'optimisation utilisant un algorithme différentiel automatique pour arriver rapidement à une solution au moyen de dérivatifs calculés avec une précision quasi-mécanique, même lorsque le nombre de paramètres à estimer est assez important. Le modèle se base sur des calculs forward postulant que la mortalité par pêche peut être ventilée par année et par âge. Ce postulat est rendu plus flexible par le fait qu'il prévoit la réalisation de calculs en fonction de la flottille, ainsi que l'évolution progressive dans le temps de la sélectivité par âge. Le logiciel peut aussi tenir compte de la variation graduelle dans le temps de la capturabilité associée à chaque indice de l'abondance. Les dimensions du problème (nombre d'âges, d'années, de flottilles et d'indices d'abondance) sont définies en tant que données d'entrée et ne sont limitées que par le matériel. Une application de l'ASAP à des données sur le thon rouge de l'Atlantique ouest est présentée à titre d'illustration.

RESUMEN

Este papel documenta un programa de evaluación estructurado por edad (ASAP), que incorpora varias características de modelización discutidas por el SCRS en años recientes, particularmente durante las reuniones del Grupo de especies del atún rojo. Se desarrolló el programa utilizando el paquete comercial AD Model Builder, una eficaz herramienta para la optimización, que utiliza un algoritmo de diferenciación automática para hallar una rápida solución empleando derivados calculados con precisión, incluso cuando el número de parámetros que se estima es amplio. El modelo se basa en cálculos "forward" que asumen la capacidad de separación de la mortalidad por pesca en componentes anuales y por edad. Este supuesto se suaviza permitiendo a lo largo del tiempo el cambio progresivo de los cálculos específicos de la flota y la de la selectividad por clases de edad. El programa también permite que la capturabilidad asociada a cada índice de abundancia varíe gradualmente a lo largo del tiempo. Las dimensiones del problema (números de edades, años, flotas e índices de abundancia) se definen en los datos de entrada y sólo están limitados por el hardware. Se ilustra una aplicación de ASAP que utiliza datos para el atún rojo del Atlántico oeste.

[1] U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, 75 Virginia Beach Dr., Miami, Florida 33149, USA.

[2] University of Miami, Rosenstiel School of Marine and Atmospheric Science, Cooperative Unit for Fisheries Education and Research, 4600 Rickenbacker Causeway, Miami, Florida 33149, USA.

Introduction

Stock assessment algorithms explain observed data through a statistical estimation procedure based on a number of assumptions. The number and severity of these assumptions are determined by the algorithm and reflect not only the user's paradigms but also the amount and quality of the available data. We present an age-structured assessment program (ASAP) which allows easy comparison of results when certain assumptions are made or relaxed. Specifically, ASAP is a flexible forward program that allows the assumption of separability of gear specific fishing mortality into year and age components to be relaxed and change over time. The assumption of constant catchability coefficients for scaling observed indices of abundance can also be relaxed to change over time. The advantage of this flexibility is an increased ability to fit models and less reliance on assumptions that are thought to be too strict. The disadvantage of such an approach is exactly this ability to explain the data in more (and possibly contradictory) ways through different choices in the amount of variability in the changing parameters. Explicit choices for relative weightings amongst the different parts of the objective function must be made. Slight changes in these parameter weightings in a complex model can produce vastly different results, while a simpler model will be more consistent (not necessarily more accurate) relative to changes in the parameter weightings.

Allowing flexibility in selectivity and catchability greatly increases the number of parameters to be estimated. We use the commercial software package AD Model Builder to estimate the relatively large number of parameters. The software package is based on a C++ library of automatic differentiation code (see Greiwank and Corliss 1991) which allows relatively fast convergence by calculating derivatives to machine precision accuracy. These derivatives are used in a quasi-Newton search routine to minimize the objective function. The array sizes for parameters are defined on input and limited only by hardware. Currently, ASAP is compiled to estimate a maximum of 5,000 parameters, but this can be increased by changing one line of code.

The AD Model Builder software package allows many matrix operations to be programmed easily in its template language and allows for the estimation of parameters to occur in phases. The phases work by estimating only some parameters initially and adding more parameters in a stepwise fashion until all parameters are estimated. When new parameters are added by incrementing the phase, the previously estimated parameters are still estimated, not fixed at the previous values. These phases also allow easy switching between simple and complex models by simply turning on or off phases through the input file. For example, index specific catchability coefficients can be allowed to change or have a constant value over time. An additional feature of the AD Model Builder software is easy likelihood profiling of specified variables, although this can be time consuming for models with large numbers of parameters. We first describe ASAP with all the features and then compare two analyses for bluefin tuna using different levels of complexity in the program.

The Model

Population dynamics

The model's population dynamics follow a standard form common to forward-projection methods such as those of Fournier and Archibald (1982), Deriso et al. (1985), Methot (1998), Ianelli and Fornier (1998), and Porch and Turner (In Press). Catches and fishing mortalities can be modeled as being fleet-specific.

Let a = age, 1...A,
y = year, 1...Y
g = fleet 1....G
u = abundance index series, 1....U

Selectivity (S) at age within a year by a fleet can be limited to a range of ages and averages one, as opposed to having a maximum of one,

$$\frac{\sum_{a(g_{start})}^{a(g_{end})} S_{a,y,g}}{a(g_{end})-a(g_{start})+1}=1.0 \tag{1}$$

where $a(g_{start})$ and $a(g_{end})$ denote the starting and ending ages for the gear's selectivity. The output of the program makes the simple conversion from averaging one to having a maximum of one in order to simplify comparisons with other models.
Fishing mortality is modeled as the product of the selectivity at age within a year by a fleet and a year and fleet specific fishing mortality multiplier ($Fmult_{y,g}$)

$$F_{a,y,g}=S_{a,y,g}Fmult_{y,g}\,. \tag{2}$$

Total fishing mortality at age and year is the sum of the fleet specific fishing mortality rates

$$Ftot_{a,y}=\sum_{g}F_{a,y,g} \tag{3}$$

and adding the natural mortality rate (M) produces the total mortality rate

$$Z_{a,y}=Ftot_{a,y}+M_{a,y}\,. \tag{4}$$

The catch by age, year and fleet is

$$C_{a,y,g}=\frac{N_{a,y}F_{a,y,g}(1-e^{-Z_{a,y}})}{Z_{a,y}} \tag{5}$$

where N denotes population abundance at the start of the year.
The yield by age, year and fleet is

$$Y_{a,y,g}=C_{a,y,g}W_{a,y} \tag{6}$$

where $W_{a,y}$ denotes weight of an individual fish of age a in year y.
The proportion of catch at age within a year for a fleet is

$$P_{a,y,g} = \frac{C_{a,y,g}}{\sum_a C_{a,y,g}}. \tag{7}$$

The forward projections begin by computing recruitment as deviations from an average value

$$N_{1,y} = \bar{N}_1 e^{\upsilon_y} \tag{8}$$

where υ_y~N(0,σ_{Ny}^2) and the other numbers at age in the first year as deviations from equilibrium

$$N_{a,1} = N_{1,1} e^{-\sum_{i=1}^{a-1} Z_{i,1}} e^{\psi_a} \quad for\ a < A$$

$$N_{a,1} = \frac{N_{1,1} e^{-\sum_{i=1}^{a-1} Z_{i,1}}}{1 - e^{-Z_{A,1}}} e^{\psi_a} \quad for\ a = A \tag{9}$$

where ψ_a~N(0,σ_{Na}^2). The remaining population abundance at age and year is then computed

$$N_{a,y} = N_{a-1,y-1} e^{-Z_{a-1,y-1}} \quad for\ a < A$$

$$N_{a,y} = N_{a-1,y-1} e^{-Z_{a-1,y-1}} + N_{a,y-1} e^{-Z_{a,y-1}} \quad for\ a = A. \tag{10}$$

Predicted indices of abundance ($\hat{I}$) are a measure of the population scaled by catchability coefficients (q) and selectivity at age (S)

$$\hat{I}_{u,y} = q_{u,y} \sum_{a(u_{start})}^{a(u_{end})} S_{u,a,y} N^*_{a,y} \tag{11}$$

where $a(u_{start})$ and $a(u_{end})$ are the index specific starting and ending ages, respectively, and N^* corresponds to the population abundance in either numbers or weight at a specific time during the year. The abundance index selectivity at age can either be input or linked to a specific fleet. If the latter is chosen, the age range can be smaller than that of the fleet and the annual selectivity patterns are rescaled to equal 1.0 for a specified age (a_{ref})such that the catchability coefficient is linked to this age

$$S_{u,a,y} = \frac{S_{a,y,g}}{S_{a_{ref},y,g}}. \tag{12}$$

Time-varying parameters

Fleet specific selectivity and catchability patterns are allowed to vary over time in the model. Changes in selectivity occur each τ_g years through a random walk for every age in a given fleet

$$S_{a,y+\tau,g} = S_{a,y,g} e^{\varepsilon_{a,y,g}} \tag{13}$$

where $\varepsilon_{a,y,g}$~N(0,$\sigma_{S_g}^2$) and are then rescaled to average one following equation (1). If τ_g is greater than one, then the selectivity at age for the fleet is the same as previous values until τ_g years elapse. The catchability coefficients also follow a random walk

$$q_{u,y+1} = q_{u,y} e^{\omega_{u,y}} \tag{14}$$

as do the fleet specific fishing mortality rate multipliers

$$Fmult_{y+1,g} = Fmult_{y,g} e^{\eta_{y,g}} \tag{15}$$

where $\omega_{u,y}$~N(0,$\sigma_{q_u}^2$) and $\eta_{y,g}$~N(0,$\sigma_{F_g}^2$).

Parameter estimation

The number of parameters estimated depends upon the values of τ_g and whether or not changes in selectivity or catchability are considered. When time varying selectivity and catchability are not considered the following parameters are estimated: Y recruits, A-1 population abundance in first year, YG fishing mortality rate multipliers, AG selectivities (if all ages selected by all gears), U catchabilities, and 2 stock recruitment parameters. Inclusion of time varying selectivity and catchability can increase the number of parameters to be estimated by a maximum of $(Y\text{-}1)AG$ + $(Y\text{-}1)U$. Sensitivity analyses can be conducted to determine the tradeoffs between number of parameters estimated and goodness of fit caused by changes in the τ_g values.

The likelihood function to be minimized includes the following components (ignoring constants): total catch in weight by fleet (lognormally distributed)

$$L_1 = \lambda_1 [\ln(\sum_a Y_{a,y,g}) - \ln(\sum_a \hat{Y}_{a,y,g})]^2 ; \tag{16}$$

catch proportions in numbers of fish by fleet (multinomially distributed)

$$L_2 = -\sum_y \sum_g \lambda_{2,y,g} \sum_a P_{a,y,g} \ln(\hat{P}_{a,y,g}) - P_{a,y,g} \ln(P_{a,y,g}) ; \tag{17}$$

and indices of abundance (lognormally distributed)

$$L_3 = \sum_g \lambda_{3,g} \sum_y [\ln(I_{y,g}) - \ln(\hat{I}_{y,g})]^2 / 2\sigma^2_{y,g} + \ln(\sigma_{y,g}), \tag{18}$$

where variables with a hat are estimated by the model and variables without a hat are input as observations. The second term in the catch proportion summation causes the likelihood to equal zero for a perfect fit. The sigmas in equation 18 are input by the user and can optionally be set to all equal 1.0 for equal weighting of all index points. The weights (λ) assigned to each component of the likelihood function correspond to the inverse of the variance assumed to be associated with that component. Note that the year and fleet subscripts for the catch proportion lambdas allow zero weights to be assigned to specific year and fleet combinations such that only the total catch in weight by that fleet and year would be incorporated in the objective function. Priors for the variances of the time varying parameters are also included in the likelihood by setting λ equal to the inverse of the assumed variance for each component

$$L_4 = \sum_g \lambda_{4,g} \sum_a \sum_y \varepsilon_{a,y,g}^2 \quad (selectivity) \tag{19}$$

$$L_5 = \sum_u \lambda_{5,u} \sum_y \omega_{u,y}^2 \quad (catchability) \tag{20}$$

$$L_6 = \sum_g \lambda_{6,g} \sum_y \eta_{y,g}^2 \quad (F\ multipliers) \tag{21}$$

$$L_7 = \lambda_7 \sum_y \upsilon_y^2 \quad (recruitment) \tag{22}$$

$$L_8 = \lambda_8 \sum_y \psi_y^2 \quad (N\ year1). \tag{23}$$

Additionally, there is a prior for fitting a Beverton and Holt type stock-recruitment relationship

$$L_9 = \lambda_9 \sum_y [\ln(N_{1,y}) - \ln\left(\frac{\alpha\, SSB_{y-1}}{\beta + SSB_{y-1}}\right)]^2 \tag{24}$$

where SSB denotes the spawning stock biomass and α and β are parameters to be estimated. Penalties are used to determine the amount of curvature allowed in the fleet selectivity patterns, both at age

$$P_1 = \lambda_{p1} \sum_y \sum_g \sum_{a(g_{start})}^{a(g_{end})-2} (S_{a,y,g} - 2S_{a+1,y,g} + S_{a+2,y,g})^2 \tag{25}$$

and over time

$$P_2 = \lambda_{p2} \sum_a \sum_g \sum_{y=1}^{Y-2} (S_{a,y,g} - 2S_{a,y+1,g} + S_{a,y+2,g})^2 . \tag{26}$$

The function to be minimized is then the sum of the likelihoods and penalties

$$L = L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + L_7 + L_8 + L_9 + P_1 + P_2 . \tag{27}$$

An additional penalty is utilized in early phases of the minimization to keep the average total fishing mortality rate close to the natural morality rate. This penalty ensures the population abundance estimates do not get exceedingly large during early phases of the minimization. The final penalty added to the objective function forces the parameters for fleet selectivities in the first year to average 1.0. This penalty prevents multiple parameter sets from having the same objective function value, which would cause difficulty for the minimization routine. Each component of the objective function is reported in the output file along with the corresponding number of observations, weight assigned to that component, and residual sum of squared deviations (if appropriate).

Additional Features

The model optionally does some additional computations once the likelihood function has been minimized. These "extras" do not impact the solution, they are merely provided for reference. Each fleet can be designated as either directed or nondirected for the projections and F reference point calculations, with the option to modify the nondirected F in the future. The directed fleets are combined to form an overall selectivity pattern that is used to solve for common fishing mortality rate reference points ($F_{0.1}$, F_{max}, $F_{30\%SPR}$, $F_{40\%SPR}$ and F_{msy}) and compared to the terminal year F estimate. The inverse of the SPR for each of these points is also given so replacement lines corresponding to these reference values can be plotted on the spawner-recruit relationship. Projections are computed using either the stock-recruitment relationship or input values to generate future recruitment. The projections for each successive year can be made using either a total catch in weight or the application of a static $F_{X\%SPR}$, where X is input. A reference year is also input that allows comparison of the spawning stock biomass (SSB) in the terminal year and that in the final projection year as SSB_t/SSB_{ref}. Likelihood profiles for these SSB ratios can optionally be generated.

Example: Western Atlantic Bluefin Tuna

Two analyses of western Atlantic bluefin tuna data using ASAP are presented here. The first analysis (simple) did not allow selectivity and catchability to change over time (225 parameters estimated). The second analysis (complex) used the full complexity allowed by the model, with fleet selectivities allowed to change every two years and index catchabilities allowed to change every year (914 parameters estimated). In both analyses the model was structured for years 1970-1995, ages 1-10+, five fleets, and seven tuning indices (each point input with a variance) with all likelihood component weightings equal between the analyses. The natural mortality rate was set at 0.14 for all ages (for data details see Restrepo and Legault In Press). The number of observations associated with, and the weights given to, each part of the likelihood function are shown in Table 1. In this example, the weights assigned to each component were chosen arbitrarily. In an actual assessment, these weights will need to be selected by the assessment working group.

The overall fit of the complex analysis was better than the simple analysis (lower objective function value) as expected due to the greater number of parameters (Table 1). The complex analysis fits the indices better than the simple analysis, especially the US Rod and Reel Large, US Longline Gulf of Mexico, and the Japan Longline Gulf of Mexico indices. (Figure 1). Recruitment estimates from the two analyses are similar to the estimates from the 1996 SCRS assessment, which used virtual population analysis (VPA) with the main differences occurring in the early years of the time series (Figure 2). The estimates of spawning stock biomass (SSB) differ between the analyses, the complex one is similar in magnitude to the SCRS96 results, while the simple analysis estimates larger values (Figure 3). However, standardizing the SSB trends (dividing by the SSB in 1975) produces similar trends for all three analyses (Figure 3). The resulting stock-recruitment relationship is shown in figure 4. The total fishing mortality rates by year and age differ in both magnitude and pattern, with the complex analysis more closely matching the 1996 SCRS assessment (Figure 5). These differences in F are due to the assumptions about selectivity, fixed for the simple analysis and allowed to vary for the complex one (Figure 6). Note in particular the large change in selectivity of the purse seine fleet, mainly young fish in the early years and old fish in recent years. The catchability values also reflect the difference in assumptions, constant for the simple analysis and allowed to vary in the complex analysis (Figure 7). Note the large lambda given to the larval index causes the catchability coefficients to vary only slightly in the complex analysis. The catch at age proportions are fit relatively well in both analyses, the input and effective sample sizes are similar, even though this is the largest part of the total likelihood. The estimated effective sample size can be computed as

$$\textit{Effective}\ N_g = \frac{\sum_a \sum_y \hat{p}_{a,y,g}(1-\hat{p}_{a,y,g})}{\sum_a \sum_y (p_{a,y,g}-\hat{p}_{a,y,g})^2} \qquad (28)$$

(for details see McAllister and Ianelli, 1997 Appendix 2).

Discussion

The flexibility afforded by ASAP is a continuation of the trend in stock assessment programs from the relatively simple structure of Fournier and Archibald (1982) to the more flexible structure found in Methot (1998), Ianelli and Fournier (1998), and Porch and Turner (In Press). In fact, ASAP is based on the same logic as these more flexible programs, but combines the advantages of the AD Model Builder software with the more general input flexibility of stock synthesis and CATCHEM. J. Ianelli (NMFS, Seattle, pers. comm.) also provided guidance in the formulation of certain model components, specifically the logic of linking fleet specific indices with a specific age in the tuning process (see equation 12). The distinguishing feature between this approach and that found in virtual population analysis (VPA) (Gavaris 1988, Powers and Restrepo 1992) is that VPA assumes the catch at age is measured without error, while ASAP assumes the observed catch at age varies about its true value.

The flexibility of ASAP can also cause problems however. Slight changes in the weights assigned to each likelihood component can produce different results, both in magnitude and trend. The large number of parameters, in the complex model especially, required the solutions in each phase to progress towards a satisfactory region in the solution space. If any phase led the solution away from this region, the final result will not be believable (e.g. total F<1e-5). This problem was not found in multiple tests using simulated data that did not contain errors or only small observation errors. Thus, the ability to fit highly complex models depends upon the quality of the data available, especially the consistency between the catch at age and the tuning indices. Nevertheless, the flexible nature of ASAP allows for easy exploration of the data to determine what level of complexity can appropriately be modeled.

Acknowledgments

The conclusions presented here are entirely the authors' and are not necessarily endorsed by NMFS or UM. We are grateful to Jim Ianelli, Clay Porch, Joe Powers, Gerry Scott and Steve Turner for helpful discussions.

References

Deriso, R.B., T.J. Quinn II and P.R. Neal. 1985. Catch-age analysis with auxiliary information. Can. J. Fish. Aquat. Sci. 42:815-824.

Fournier, D. and C.P. Archibald. 1982. A general theory for analyzing catch at age data. Can. J. Fish. Aquat. Sci. 39:1195-1207.

Greiwank, A. and G.F. Corliss (eds). 1991. Automatic differentiation of algorithms: theory, implementation and application. Proceedings of the SIAM Workshop on the Automatic Differentiation of Algorithms, held Jan. 6-8, Breckenridge, CO. Soc. Indust. and Applied Mathematics, Philadelphia.

ICCAT. 1997. Report for biennial period 1996-1997- Part I (1996), Vol. 2. Int. Comm. Cons. Atl. Tunas. 204 pp.

Ianelli, J.N. and D.A. Fournier. 1998. Alternative age-structured analyses of the NRC simulated stock assessment data. NOAA Tech. Memo. NMFS-F/SPO-30. pp. 81-96.

McAllister, M.K. and J.N. Ianelli. 1997. Bayesian stock assessment using catch-age data and the sampling-importance resampling algorithm. Can. J. Fish. Aquat. Sci. 54:284-300.

Methot, R. 1998. Application of stock synthesis to NRC test data sets. NOAA Tech. Memo. NMFS-F/SPO-30. pp. 59-80.

Porch, C.E. and S.C. Turner. In Press. Catch-at-age analyses of west Atlantic bluefin tuna incorporating data from 1960 to 1994 (preliminary results). Int. Comm. Cons. Atl. Tunas, Coll. Vol. Sci. Pap. (Working Document SCRS/96/119).

Powers, J.E. and V.R. Restrepo. 1992. Additional options for age-sequenced analysis. Int. Comm. Cons. Atl. Tunas, Coll. Vol. Sci. Pap. 39:346-354.

Restrepo, V.R. and C.M. Legault. In Press. A stochastic implementation of an age-structured production model. Int. Comm. Cons. Atl. Tunas, Coll. Vol. Sci. Pap. (Working Document SCRS/97/59).

Table 1. Likelihood function components for two ASAP analyses. nobs=number of observations in that component, λ=weight given to that component, RSS=residual sum of squared deviations, L=likelihood value

			Simple		Complex	
Component	nobs	λ	RSS	L	RSS	L
Total Catch in Weight						
Rod and Reel	26	100.5	0.0005	0.0479	0.0001	0.0147
Japan Longline	26	100.5	0.0015	0.1558	0.0003	0.0322
Other Longline	26	100.5	0.0001	0.0069	0.0001	0.0070
Purse Seine	26	100.5	0.0002	0.0183	0.0039	0.3913
Other	26	100.5	0.0001	0.0065	0.0000	0.0026
Total	130	100.5	0.0023	0.2353	0.0045	0.4477
Catch at Age Proportions	1300	N/A	N/A	874.40	N/A	396.47
Index Fits						
Larval Index	16	1	5.26	11.95	5.29	11.61
US Rod and Reel Small	15	1	3.95	9.33	2.02	-1.02
Canadian Tended Line	15	1	2.08	3.05	0.64	-5.95
US Rod and Reel Large	13	1	1.76	1.22	0.39	-5.74
US Longline Gulf of Mexico	9	1	6.13	15.26	0.31	-3.79
Japan Longline Gulf of Mexico	8	1	0.74	1.10	0.58	1.05
Japan Longline NW Atlantic	20	1	3.22	9.51	0.58	-9.19
Total	96	7	23.15	51.43	9.80	-13.02
Selectivity Deviations						
Rod and Reel	12	0.1	0	0	2.52	0.25
Japan Longline	12	0.1	0	0	4.42	0.44
Other Longline	12	0.1	0	0	3.56	0.36
Purse Seine	12	0.1	0	0	8.74	0.87
Other	12	0.1	0	0	3.00	0.30
Total	60	0.5	0	0	22.25	2.22
Catchability Deviations						
Larval Index	16	1000	0	0	0.00	0.29
US Rod and Reel Small	15	6.7	0	0	0.51	3.43
Canadian Tended Line	15	6.7	0	0	0.37	2.45
US Rod and Reel Large	13	6.7	0	0	0.18	1.20
US Longline Gulf of Mexico	9	6.7	0	0	0.21	1.39
Japan Longline Gulf of Mexico	8	6.7	0	0	0.00	0.03
Japan Longline NW Atlantic	20	6.7	0	0	0.35	2.35
Total	96	1040.2	0	0	1.62	11.14
Fmult Deviations						
Rod and Reel	25	0.1	5.26	0.53	5.01	0.50
Japan Longline	25	0.1	21.44	2.14	19.67	1.97
Other Longline	25	0.1	24.30	2.43	23.97	2.40
Purse Seine	25	0.1	5.24	0.52	8.07	0.81
Other	25	0.1	5.60	0.56	6.84	0.68
Total	125	0.1	61.84	6.18	63.56	6.36
Recruitment	26	0.01	10.14	0.10	14.51	0.15
N in Year 1	9	1.44	3.34	4.82	3.08	4.43
Stock-Recruit Fit	25	0.001	9.47	0.01	3.94	0.00
Selectivity Curvature over Age	40	1.44	12.03	17.32	17.19	24.76
Selectivity Curvature over Time	1200	1.44	0	0	52.03	74.92
F penalty	260	0.001	3.0E-01	3.0E-4	2.3E-02	2.3E-02
Mean Sel Year 1 Penalty	50	1	4.5E-12	4.5E-12	4.7E-12	4.7E-12
Objective Function Value				954.50		507.87

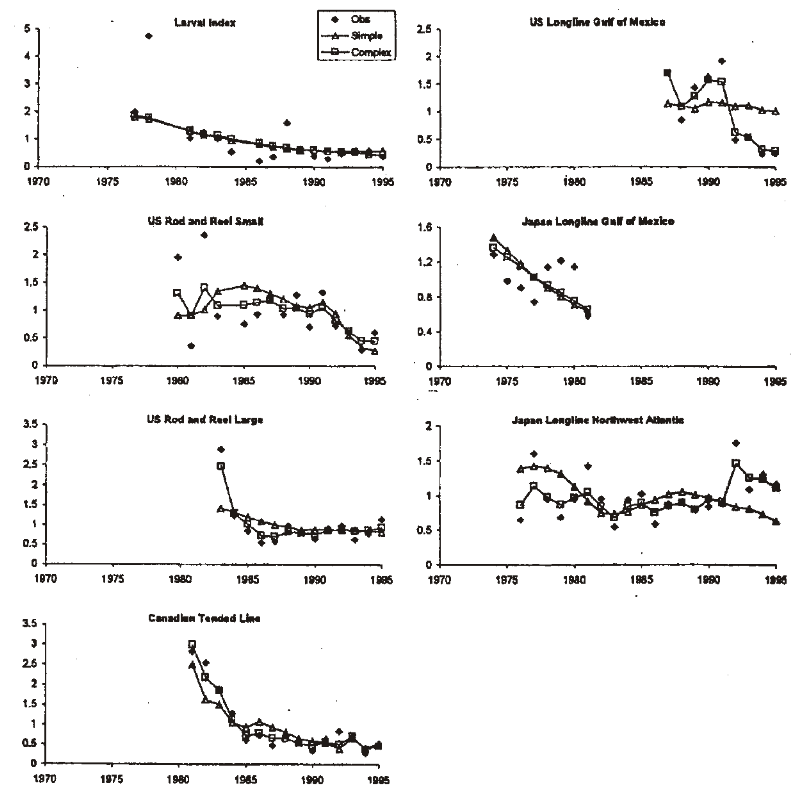


Figure 1. Observed and predicted indices for the simple and complex ASAP analyses.

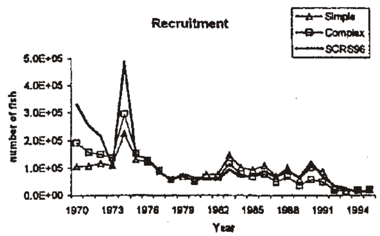


Figure 2. Estimated recruitment from two ASAP analyses and the SCRS 1996 assessment.

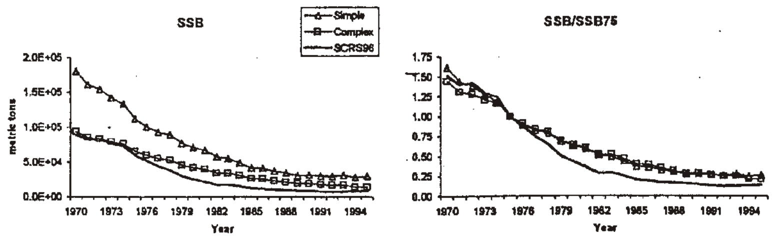


Figure 3. Spawning stock biomass (SSB) from two ASAP analyses and SCRS 1996.

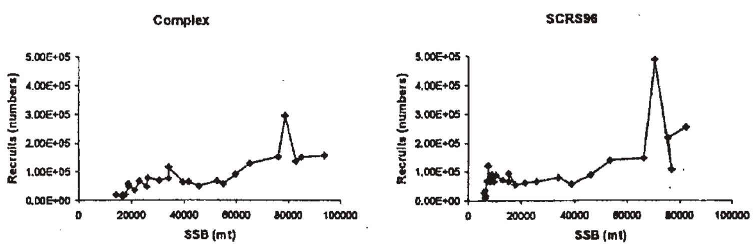


Figure 4. Complex ASAP analysis and SCRS 1996 stock-recruitment relationships.

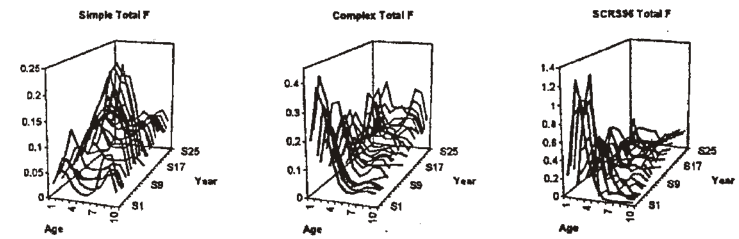


Figure 5. Estimated fishing mortality rates by age and year for two ASAP analyses and SCRS 1996.

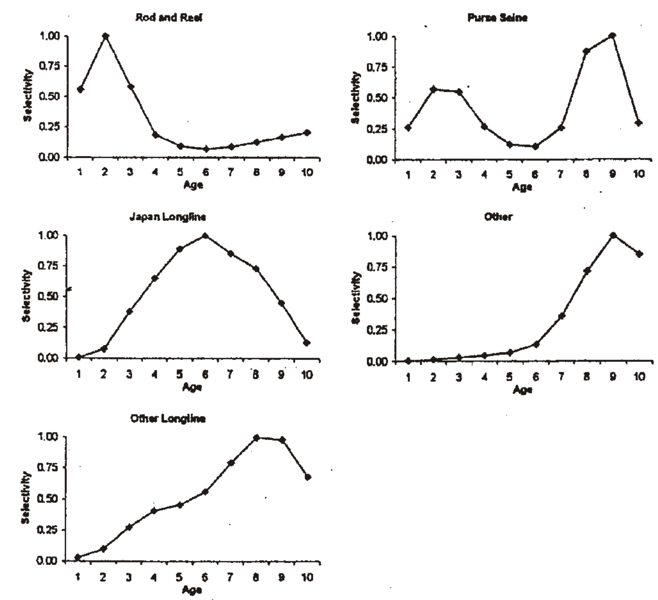


Figure 6a. Selectivity at age for the simple ASAP analysis, constant over all years for each fleet.

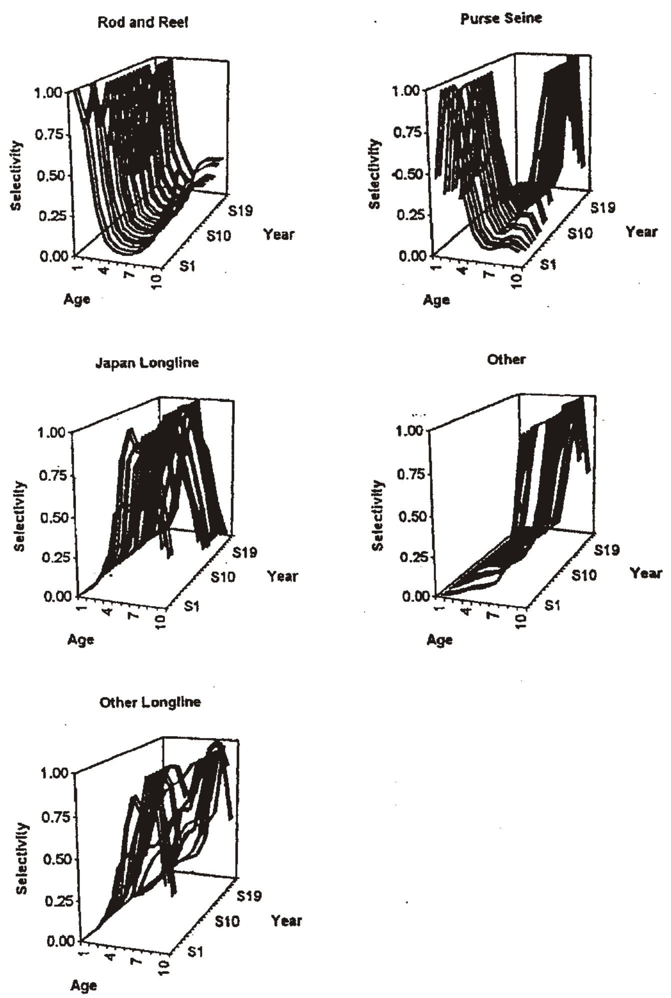


Figure 6b. Selectivity at age for the complex ASAP analysis.

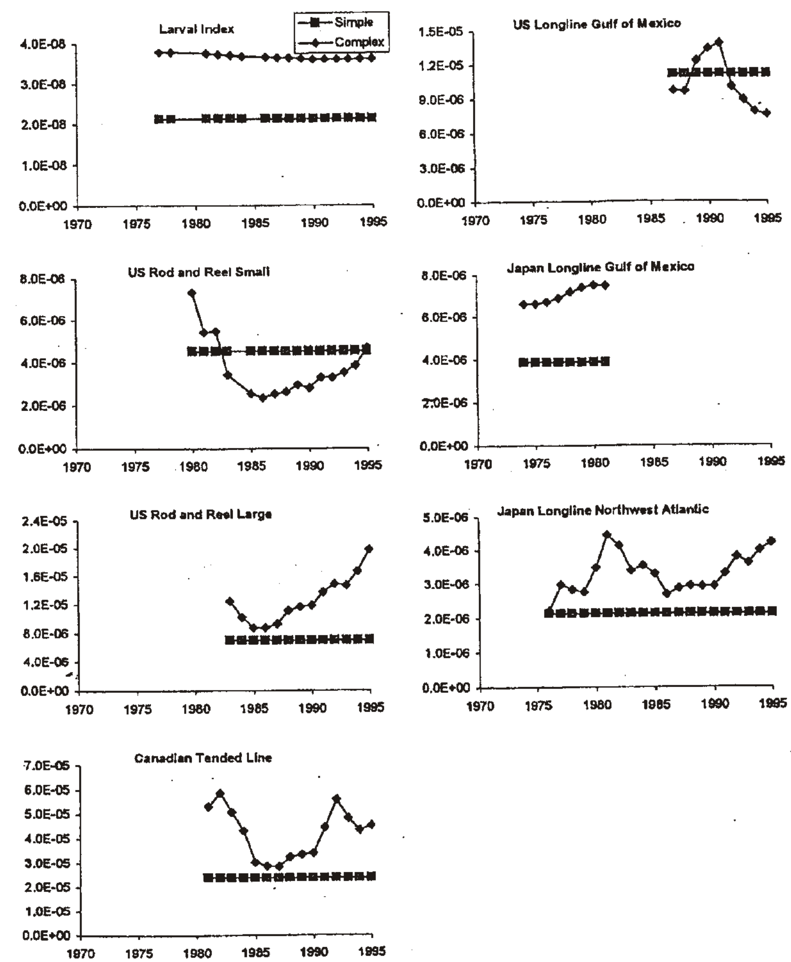


Figure 7. Catchability for each tuning index from the two ASAP analyses.

RECENT TECHNICAL MEMORANDUMS

Copies of this and other NOAA Technical Memorandums are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22167. Paper copies vary in price. Microfiche copies cost $9.00. Recent issues of NOAA Technical Memorandums from the NMFS Southwest Fisheries Science Center are listed below:

NOAA-TM-NMFS-SWFSC-385 AMLR 2004/2005 field season report: Objectives, Accomplishments, and Tentative Conclusions.
J.D. LIPSKY, Editor
(December 2005)

386 Assessment of the Pacific sardine (Sardinops sagax caerulea) population for U.S. Management in 2006.
K.T. HILL, N.C.H. LO, B.J. MACEWICZ, and R. FELIX URAGA
(March 2006

387 Spawning biomass of Pacific sardine (Sardinops sagax) off California in 2005.
N.C.H. LO and B.J. MACEWICZ
(March 2006)

388 U.S. Pacific marine mammal stock assessments: 2005.
J.V. CARRETTA, K.A. FORNEY, M.M. MUTO, J. BARLOW, J. BAKER, B. HANSON, and M.S. LOWRY
(March 2006)

389 An iterative finite difference approach to option and project valuation.
D. TOMBERLIN and V. BOSETTI
(March 2006)

390 Historical population structure of coho salmon in the Southern Oregon/Northern California coasts evolutionarily significant unit.
T.H. WILLIAMS, E.P. BJORKSTEDT, W.G. DUFFY, E. HILLEMEIER, G. KAUTSKY, T.E. LISLE, M. McCAIN, M. RODE, R.G. SZERLONG, R.S. SCHICK, M.N. GOSLIN, and A. AGRAWAL
(June 2006)

391 Potential steelhead oversummering habitat in the south-central/southern California coast recovery domain: maps based on the envelope method.
D.B. BOUGHTON and M. GOSLIN
(July 2006)

392 Ichthyoplankton and station data for surface (manta) and oblique (bongo) plankton tows for California Cooperative Oceanic Fisheries Investigations survey cruises in 2005.
D.A. AMBROSE, R.L. CHARTER, and S.M. MANION

393 Ichthyoplankton, paralarval cephalopod, and station data for oblique (bongo) plankton tows from the Oregon, California, and Washington line-transect expedition (ORCAWALE) in 2001.
S.R. CHARTER, B.S. MacCALL, R.L. CHARTER, S.M. MANION, W. WATSON, and L.T. BALLANCE

394 Steelhead of the South-Central/Southern California Coast: Population characterization for recovery planning.
D.A. BOUGHTON, P.B. ADAMS, E. ANDERSON, C. FUSARO, E. KELLER, E. KELLEY, L. LENTSCH, J. NIELSEN, K. PERRY, H. REGAN, J. SMITH, C. SWIFT, L. THOMPSON, and F. WATSON
(September 2006)

395 The physical oceanography off the central California coast during May-June 2001: A summary of CTD and other hydrographic data from young of the year juvenile rockfish surveys.

Agenda Item F.1.d
Supplemental SSC Report
November 2006

SCIENTIFIC AND STATISTICAL COMMITTEE REPORT ON PACIFIC SARDINE STOCK ASSESSMENT AND HARVEST GUIDELINE

Dr. Kevin Hill (Southwest Fisheries Science Center) discussed the stock assessment of Pacific sardine with the Scientific and Statistical Committee (SSC). The SSC Coastal Pelagic Species (CPS) subcommittee reviewed the Pacific sardine assessment during a joint meeting with the Coastal Pelagic Species Management Team (CPSMT) and Coastal Pelagic Species Advisory Subpanel (CPSAS) on October 17, 2006, based on the draft terms of reference for CPS assessments (see Agenda Item F.2). The assessment of Pacific sardine is based on the same modelling software (Age-Structured Assessment Program (ASAP)), specifications, and data sources as the 2005 assessment, except that the landings data for Ensenada, the landings and catch-at-age data for California and the Pacific Northwest, and an additional estimate of spawning biomass based on the April 2006 survey were included in the assessment.

The assessment has followed the draft terms of reference for CPS stock assessment updates because the assessment carried forward the previously reviewed structure and the model results are consistent with previous data and results. The SSC therefore supports the continued use of the base model in the development of management advice. The SSC highlights that the two main indices of abundance remain inconsistent. In particular, the SSC is concerned that two indices appear to give contradictory signals, and not having 2006 data for the spotter index may have influenced the results towards the signal from the egg production indices, which was at an all time high in 2006. This issue needs to be addressed for the next assessment.

The assessment update led to an increase in both the estimate of the 2003 recruitment and 2005 age 1+ biomass. The SSC endorses the use of the harvest guideline (152,564mt) estimated using the fishery management plan control rule and the biomass estimate of 1.32 million mt for the management of the Pacific sardine fishery for 2007. This harvest guideline is 28% larger than the 2006 harvest guideline of 118,937 mt.

A Stock Assessment Review Panel is scheduled for September 19-21, 2007, to review the Pacific sardine assessment. Dr. Hill informed the SSC that he planned to move the model software for the assessment from ASAP to Stock Synthesis 2, to explore starting the model prior to 1983, and to examine the implications of alternative assumptions about stock structure. Dr. Hill is also planning to continue to collaborate with Mexican scientists to obtain catch data, catch-at-age data, and indices of larval abundance for Baja California.

PFMC
11/14/06

Pacific Sardine

STAR Panel Meeting Report

NOAA / Southwest Fisheries Science Center
La Jolla, California
June 21-24, 2004

STAR Panel
Tom Barnes, California Department of Fish and Game (Chair)
André Punt, University of Washington (SSC Representative, Rapporteur)
Rodolfo Serra, IFOP, Valparaiso, Chile
John Wheeler, Department of Fisheries and Oceans, Canada (CIE)

PFMC
Brian Culver, Washington Department of Fish and Wildlife, CPSMT
Diane Pleschner-Steele CPSAS

STAT
Ray Conser, NOAA / Southwest Fisheries Science Center
Kevin Hill, NOAA / Southwest Fisheries Science Center
Suzanne Kohin, NOAA / Southwest Fisheries Science Center
Nancy Lo, NOAA / Southwest Fisheries Science Center

1. **Overview**

The STAR Panel (hereafter the Panel) reviewed the assessment documents prepared by the STAT for Pacific sardine. The entire STAT was available to present and discuss aspects of the report.

The Panel focused exclusively on assessment models for Pacific sardine. The Terms of Reference for CPS STAR panels includes consideration of management recommendations. The Harvest Guideline for Pacific sardine is currently based on the catch control rule specified in the CPS Fishery Management Plan. The STAR Panel did not review the basis for this catch control rule but noted that the SSC has identified that a future STAR Panel could evaluate the catch control rule for Pacific sardine (and Pacific mackerel). Public comment on the issue on the control rule (verbal and written) was presented to the Panel. The written public comment will be forwarded to the Council.

The "wetfish" purse-seine fleet in California historically has taken CPS (market squid, Pacific sardine, northern anchovy, Pacific mackerel, jack mackerel, bonito), and tunas on an opportunistic basis. The fishery has progressed from one focused primarily on squid and Pacific mackerel in the early 1980s to one that focuses substantially on squid and sardine, although the fishery still relies to some degree on all target species. A CPS purse-seine fishery focused primarily on sardine has developed in the Pacific northwest in recent years.

The results from the assessment models presented to the Panel were preliminary and based on data through 2003. The Panel did not focus on the consequences of the results, and instead focused on the most appropriate framework for conducting future assessments of Pacific sardine. The first occasion that any new assessment for Pacific sardine could be used to provide management advice will be November 2004.

The STAT provided results for two assessment frameworks: CANSAR-TAM (catch-at-age analysis for sardine – two area model) and ASAP (age structured assessment program). CANSAR-TAM has provided the basis for the assessment of Pacific sardine since 1998. CANSAR-TAM is an extension to the CAGEAN approach to fisheries stock assessment that explicitly allows for migration of the northern component of the Pacific sardine population from southern California to the Pacific northwest. The assessment relies on indices of abundance for southern California to infer the status of the total population size.

The migration model underlying CANSAR-TAM is simple, and the values for the parameters related to migration are largely arbitrary. The treatment of the fisheries in Pacific northwest in CANSAR-TAM is also *ad hoc*. In contrast, ASAP is a multi-fleet model that can deal relatively straightforwardly with the component of the population in the Pacific northwest, both in terms of its contribution to the spawning biomass and to the catches. Both the STAT and Panel agreed that ASAP provides a more defensible basis for conducting assessments of Pacific sardine.

The Panel commended the STAT for their excellent presentations, well-written and complete documentation, and their willingness to respond to the Panel's requests for additional analyses.

2. Requests made and comments to the STAT during the meeting (Table 1 provides a summary of the alternative models considered during the workshop).

a) **Assemble a table of the sample sizes on which the catch-at-age matrix is based**.
The sample sizes for the USA-California fishery range from 432 (1984) to 3887 (1995). The Panel agreed that, given that the sample sizes are all fairly large, and the fact that there are several sources of uncertainty associated with the catch-at-age data other than sampling error, there is no need to assign year-specific weights to the catch age-composition data when fitting the population dynamics model.

b) **Examine the implications of different assumptions about selectivity in the USA-California using "bubble plots" of residuals.**
The residual patterns for the baseline case in the assessment document provide no evidence for trends in residuals within cohorts but several "runs" of residuals within age-classes are evident. The Panel highlighted the continuing importance of reviewing the residuals about the fits to the catch age-composition data, particularly once these data have been revised.

c) **Examine the trends in *q* for the CalCOFI percent positive index and the spawning area index.**
There are noteworthy trends in *q* (increasing for the percent positive index / decreasing for the spawning area index). These trends were expected given percent positive indices will saturate at high population size while square miles of spawning area would under-estimate spawning stock size if there is a "basin effect". See Section 3.2 for further discussion in terms of the utility of these indices for tuning purposes.

d) **Examine the sensitivity of the results to setting the population weights-at-age from 1990 equal to the weights-at-age in the catch.**
The results of this sensitivity test were broadly similar to those for the baseline case. The most notable difference between the results of this sensitivity test and those from the baseline case were that the estimates of recruitment for 1990-99 were greater for baseline case. The Panel and the STAT agreed that this was expected given that the fishery weights-at-age are higher than the population weights-at-age for these years. The value of a sensitivity test along these lines will be enhanced once the assessment software can include separate fishery and population weight-at-age matrices.

e) **Plot indices against each other in the form of an X-Y plot.**
These plots suggest that the relationships among the DEPM (Daily Egg Production Method), CalCOFI percent positive and spawning area indices are, in general, not linear. There does appear, however, to be a linear relationship between the DEPM and spotter plane indices, even though these indices relate to different components of the population.

f) **Conduct a sensitivity test in which the only abundance indices are the DEPM estimates and the spotter plane index.**
The results of this sensitivity test were not statistically different to those for the baseline case, although the variances were slightly larger owing to the reduction in

the number of data points. The Panel agreed that this sensitivity analysis should form the baseline case for the November 2004 assessment.

g) Conduct a preliminary evaluation of estimation uncertainty using the Markov chain Monte Carlo (MCMC) module.

The results of a preliminary application of the MCMC algorithm (1,000,000 cycles) indicated evidence for lack of convergence (see Fig. 1). The Panel advised the STAT to examine the .COR matrix from ADMB and to use this to guide how the model should be re-parameterized in future to reduce the correlations among the model parameters. It is likely that modifying the parameterization of selectivity in the first year should lead to reduced correlation among the selectivity parameters.

h). **Examine the sensitivity of the results of the assessment to having a single selectivity pattern for entire 1983-2003 period and to there being three periods of selectivity (1983-91, 1992-97, and 1998-2003).**

The fit to the data deteriorates markedly if selectivity for the southern California fishery is assumed to be time-invariant, providing support for having at least two periods of fishery selectivity. There is little improvement in fit if three periods of fishery selectivity are assumed for the southern California fishery. The Panel agreed that the baseline case for the November 2004 assessment should include two selectivity periods for the southern California fishery.

3. Technical merits and/or deficiencies of the assessment

The STAT identified three areas of considerable (but largely unquantifiable) uncertainty in its initial presentation to the Panel:

- Stock structure and migration are not well understood
- Fishery-independent data are limited to central and southern California, even though spawning occurs off Mexico and limited spawning has been reported to the north.
- The biological data for the Mexican, Canadian and Pacific northwest fisheries are limited.

3.1 Stock structure

There are several hypotheses regarding the stock structure of Pacific sardine. The current stock assessment is based on the working hypothesis that Pacific sardine off northern Mexico, southern California, northern California and the Pacific northwest constitute a single biological stock with substantial mixing / migration. However, there is considerable uncertainty regarding this hypothesis. Evidence that may support an alternative stock structure hypothesis includes:

- The presence in the Pacific northwest of some spawning and some zero-year-old fish.
- The marked differences in mean weight-at-age among fish in the Pacific northwest and those off southern California (the fish tend to be much larger and have higher weight-at-age off the Pacific northwest).

There is also uncertainty regarding the relationship between the fish found offshore of where the fishery off California is prosecuted and those elsewhere, and between the Mexican fish and those elsewhere. The Panel emphasized the considerable importance of research to resolve issues related to stock structure, and to develop abundance indices for areas in addition to southern California. The latter aspect is as important as the former because, if data are collected which provide support for an alternative stock structure hypothesis (e.g. separate California and Pacific northwest stocks), abundance data for the Pacific northwest will be required to conduct an assessment for the population in this area. Even if additional data confirm the present working hypothesis, there is still considerable value in obtaining abundance information for regions other than for which the DEPM and spotter plane indices are available.

The importance of resolving stock structure uncertainty was also emphasized during the period of public comment.

The Panel, the STAT and members of the public identified several areas of research which might shed light on the issue of stock structure (see Section 6.1). It was agreed that for the present time, the assessment should be based on a single coastwide assessment.

3.2 Input data

The variant of the assessment presented initially to the Panel included four indices of abundance: a) the CalCOFI percent positive index, b) the DEPM index, c) the spawning area index, and d) the spotter plane index (see Table 1 for the basic data for the first three indices). The STAR panel noted that the three fishery-independent indices are correlated with each other because they are based on the some of the same underlying data and that the DEPM estimates of abundance are correlated among years because of the way the biological information for 1994 is used to construct the DEPM estimates for several years.

The Panel noted that the DEPM estimates used in the assessment are based on biological data (from which the estimates of daily fecundity per gram are computed) from 1994 and 2002[1]. Although the estimates of fecundity per gram are fairly similar for 1994 and 2002, the values for the biological parameters that are used to estimate fecundity per gram differ markedly between 1994 and 2002. For example, percentage spawning was 7% for 1994 and 17% for 2002. The Panel agreed that biological data for use in the DEPM should be collected more routinely in the future than has been the case in the past.

There is an overlap between the data on which the DEPM estimates are based and the data on which the spawning area and CalCOFI percent positive indices are based. Furthermore, unless allowance is made for time-varying catchability, the fit of the model to the latter two indices is very poor. The Panel and STAT considered three ways to resolve this problem:

- Ignore the CalCOFI percent positive and the spawning area indices and base the assessment solely on the DEPM and spotter plane indices.
- Include the CalCOFI percent positive and the spawning area indices in the assessment but restrict them to years for which the assumption that these indices

[1] Data for 2004 are still being processed so were not available to the Panel.

are linearly proportional to abundance appears to be most valid (e.g. prior to 1998 for the CalCOFI index and after 1998 for the spawning area index).

- Use a mixed effects model to fill in years with no DEPM data.

The Panel and STAT agreed that the assessment to be presented to the Council in November 2004 should be based on ignoring the CalCOFI percent positive and the spawning area indices.

The Panel and STAT were concerned about relying substantially on the DEPM estimates when it is known that these can vary markedly from one year to the next. The Panel agreed that an attempt should be made to extend the DEPM method so that constraints are placed on the extent to which the estimate of P_0 (the number of eggs spawned) can vary over time to avoid biologically unrealistic changes in this quantity. One approach that could be investigated is to force a time-series structure on the values for P_0 over time.

3.3 Biological data

The model makes use of the weight-at-age data for the population (in addition to that for the fishery). Weight-at-age in the catches off southern California are lower than weight-at-age in the population because the larger individuals appear to be located outside the areas that are fished primarily. Survey data are used to infer post-1990 population weight-at-age. However, this is a crude approach and efforts should be made to include data on weight-at-age from the fisheries in the Pacific northwest when constructing population weight-at-age. This problem can not, however, be resolved easily without sampling of offshore and northern areas to determine the relative proportion of the population in different areas, such as through the use of a synoptic survey of the entire west coast.

3.4 Other

The catch control rule relies on the estimate of 1+ biomass for the start of the last year of the assessment period. The STAT currently bases this estimate on population weight-at-age. However, the alternative of basing it on the fishery weight-at-age may be more appropriate. This issue should be considered when the catch control rule is reviewed at a future STAR Panel.

The weightings given to the various data sources and penalties (the lambdas) impact the sizes of the variances calculated using asymptotic (Hessian and delta method) and Bayesian approaches. The Panel noted that it would be desirable to develop an overall scaling parameter so that the residuals about the data are not over-dispersed relative to the variances implied by the lambda values.

4. Areas of disagreement

There were no areas of major disagreement between the STAT and the Panel[2].

[3] The Panel was unable to reach agreement on the correct way to pronounce certain letters of the Latin and Greek alphabets. The Panel therefore recommends that future Panels include not only LANs but also translators who can translate from American “English” into English as it is used elsewhere.

5. Unresolved problems and major uncertainties

Problems unresolved at the end of the meeting form the basis for the recommendations in Sections 6.0 - 6.3.

6. Recommendations

The following recommendations are not given in priority order.

6.0 General

The Tri-national Sardine Forum should be utilized to share fishery, survey and biological information among researchers in Mexico, Canada, and the U.S. The long-term benefits of this forum will be greatly enhanced if it can be formalized through international arrangements.

6.1 Stock structure

a) Growth data for Mexico, southern California, northern California, the Pacific northwest and the offshore areas should be collected and analyzed to quantitatively evaluate differences in growth among areas. This evaluation would need to account for differences between Mexico and the U.S. on how birthdates are assigned, and the impact of spawning on growth.
b) The timing and magnitude of spawning off California and the Pacific northwest should be examined.
c) The likelihood of various stock structure hypotheses should be examined using existing tagging data and additional tagging experiments or (preferably) techniques such as analyses of trace element composition.
d) Information which could be used in an assessment of the Pacific northwest component of a single coastwide population or of a separate Pacific northwest stock should be obtained. Synoptic surveys of Pacific sardine on the entire west coast have the potential to provide such information as well as the basic data needed to address research questions 1) and 2) above.

6.2 Data and monitoring needs

a) The Panel endorsed the aerial survey which started during 2004 and emphasized the value and importance of a rigorous survey protocol. It suggested that the surveys be augmented to estimate schooling areas and distinguish schools. It also supported the collection of data (e.g. bearing and distance to schools) which could be used in line transect-type estimation methods. 'Sea-truthing' of the species identification of the aerial surveys will enhance the value of any resulting index of abundance.
b) An aerial survey program should be started in the Pacific northwest. Such a survey program would provide data for a component of the population currently not surveyed. However, it would take several years before any index based on such a survey could be included in the assessments.
c) The current abundance indices provide data which can be used to fit a population dynamics model. However, alternative methods for indexing the population (e.g. acoustics) should continue to be evaluated. Acoustic methods are a qualitatively different approach to indexing relative abundance and are the primary fishery-independent method for obtaining abundance indices for many of the world's major

pelagic fish stocks. Acoustic methods have been applied to northern anchovy off California. Acoustic data have the potential to provide information on the relative abundance of the populations off southern California and the Pacific northwest.

d) The catch-at-age data should be updated so that ages are defined in terms of a calendar year lifecycle (if the model continues to be based on a calendar year). At present the catch-at-age matrix combines animals from different cohorts into the same age-class because no account is taken of the assumed 1 July birthdate.
e) Biological data for use in the DEPM must be collected and analyzed more routinely in the future than has been the case in the past.
f) The DEPM method should be extended so that constraints are placed on the extent to which the estimates of P_0 vary over time.
g) The impact of environmental variability on the CalCOFI percent positive data should be examined.
h) The data on maturity-at-age should be reviewed to assess whether there have been changes over time in maturity-at-age, specifically whether maturity may be density-dependent.
i) The algorithm used to determine the catch proportion-at-age data from the raw data collected from the fishery should be documented and included in the assessment report.

6.3 Modeling and assessment issues

a) The November 2004 assessment for Pacific sardine should be based on an extension of ASAP in which:
    - allowance is made for fleet-specific weights-at-age (specifically the fishery weights-at-age for the fishery in the Pacific northwest);
    - spawning biomass is defined in terms of the numbers at the end of the year;
    - explicitly include a zero age-class;
    - a log-normal bias-correction factor is included in the component of the objective function related to deviations about the stock-recruitment relationship; and
    - parameter uncertainty is quantified using the MCMC algorithm.
b) The data on which the November 2004 assessment will be based will differ from those on which the analyses reviewed during the Panel meeting:
    - only the DEPM and spotter plane indices will be used as abundance indices when fitting the model;
    - the latest fishery and abundance index data will be included in the assessment;
    - substantial additional catch-at-age data for the Mexican fisheries for 1983-2002 will be included in the assessment;
    - additional catch-at-age data for the fisheries in the northwest will be included in the assessment; and
    - the DEPM estimate will be enhanced using new biological data.
c) An attempt should be made move from a model that is based on a calendar year to one based on a biological year. This may improve the fits of the model to catch-at-age data but may lead to the catch-at-age data being overweighted relative to the abundance indices.
d) The extent of ageing error should be quantified and included in future assessments.

e) The sensitivity of the results of the assessment to the assumption that recruitment is related to spawning biomass by a Ricker stock-recruitment relationship should be examined.
f) The sensitivity of the results of the assessment to the weight assigned to each data point / abundance index (e.g. equal weight, weight based on the sampling standard error) should be explored.
g) Environmental covariates should be considered when fitting the stock-recruitment relationship.
h) Confidence intervals for the data should be added to the time-series plots which compare observed *versus* model-predicted values.
i) The values for the lambdas should be chosen so that these are consistent with variances of the residuals.
j) Data that may be included in assessments for years beyond November 2004:
   - additional indices of abundance for Oregon / British Columbia / Mexico.
   - the results of the new spotter plane index (if the new index can be related to the historical index).
   - an index based on the spawning volume for Pacific sardine (if such an index can be developed).
k) Sensitivity should be examined to different southern boundaries for the "stock" (i.e. if there is a separate stock off northern Mexico, how does it mix with the stock(s) exploited in the U.S.).

Table 1. Sardine models considered during the STAR Panel

Run	Description	Number of Parameters	Total Likelihood	SSB Virgin (1000 MT)	SSB 2003 (1000 MT)	Recruits 2003 (Billions)
R06-9	Baseline in paper	131	381	2,038	1,490	9.4
R08-0	Remove 2 indices: CalCOFI and Spawn Area. New Baseline	129	281	2,100	1,609	9.9
R08-1	Use USA-CA fishery WAA as population WAA. R08-0 is still new baseline	129	268	1,628	1,836	8.2
R08-2	No time varying selex R08-0 is still new baseline	111	359	1,676	1,365	13.7
R08-3	3 selex blocks for USA-CA 1983-92 / 1993-97 / 1998-2003 R08-0 is still new baseline ???	135	276	2,086	1,510	7.8

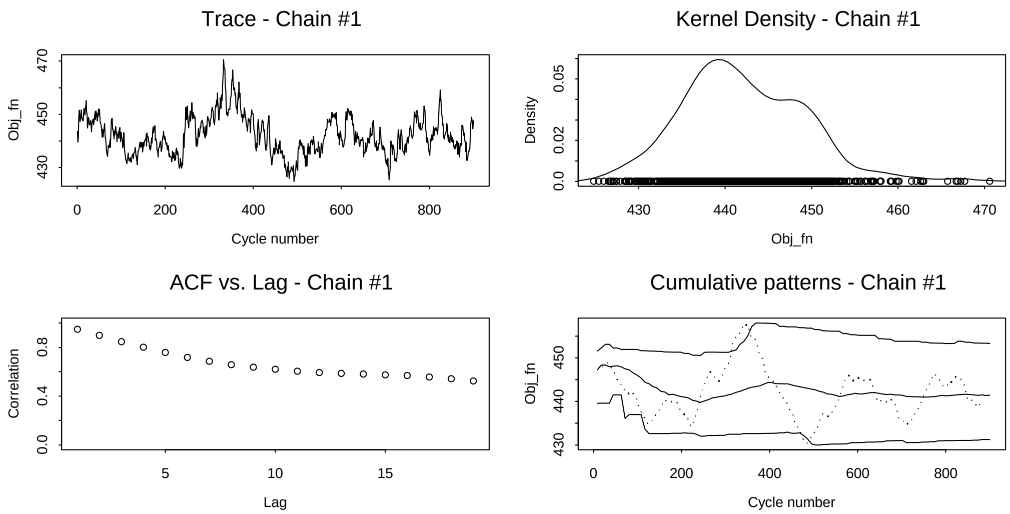
Table 2. Raw data used to construct the DEPM estimates and the indices of abundance based on the positive stations in the CalCOFI surveys and the spawning area.

Year	$\boldsymbol{P_0}$	$\boldsymbol{Z}$	**Area (km²)**	**SSB (CV)**	**Positive Stations**	**Spawning Area index**	**Spotter Plane**
1983					-	40	-
1984					4.9	480	-
1985					3.8	760	-
1986				7,659	1.9	1,260	22,049
1987				15,704	4.0	2,120	11,498
1988				13,526	7.9	3,120	55,882
1989					7.2	3,720	32,929
1990					3.7	1,760	21,144
1991					16.7	5,550	40,571
1992					8.8	9,697	49,065
1993					6.1	7,685	84,070
1994	0.193 (0.21)	0.12 (0.91)	380,175	127,102 (0.32)	17.8	24,539	211,293
1995	-	-	-	-	13.4	23,816	188,924
1996	0.415 (0.42)	0.105 (4.15)	235,960	83,176 (0.48)*	28.0	25,890	119,731
1997	2.77 (0.21)	0.35 (0.14)	174,096	409,579 (0.31)*	27.3	40,591	66,943
1998	2.279 (0.34)	0.255 (0.37)	162,253	313,986 (0.41)*	24.3	33,446	118,492
1999	1.092 (0.35)	0.10 (0.6)	304,191	282,248 (0.42)*	16.7	55,171	50,506
2000	4.235 (0.4)	0.42 (0.73)	295,759	1,063,837 (0.67)*	7.8	32,784	48,373
2001	2.898 (0.39)	0.37 (0.21)	321,386	790,925 (0.45)*	12.5	31,663	-
2002	0.728 (0.17)	0.4 (0.15)	325,082	206,333 (0.35)	7.1	61,753	-
2003	1.52 (0.18)	0.48 (0.08)	365,906	485,121 (0.36)	14.2	41,702	-

* $CV = (CV^2(P_0) + 0.054 CV_{1994}^2)^{1/2}$

Figure 1. Example MCMC diagnostics for two model outputs. The panels for each quantity show the trace, the posterior density function (estimated using a normal kernel density), the correlation at different lags, the 50-point moving average against cycle number (dotted line in the rightmost panels), and the running mean and running 95% probability intervals (solid lines in the rightmost panels).

(a) The objective function



(b) The second selectivity parameter