Stock Assessment of Pacific Sardine with Management Recommendations for 2003

Executive Summary

by

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Introduction

The following summary presents pertinent results and harvest recommendations from a stock assessment conducted on Pacific sardine (*Sardinops sagax*). It is an update to the stock assessment carried out last year (Conser et al. 2001), and is intended for use by the Pacific Fishery Management Council (PFMC) when developing management goals for the upcoming fishing season for sardine beginning January 2003.

The assessment results presented here are applicable to the sardine population off the North America Pacific coast from Baja California, Mexico to British Columbia, Canada. Research surveys (fishery-independent) have been conducted on an annual basis in the spawning areas off central and southern California. For most of the contemporary time series (1983-98), significant fishing for sardine occurred only off northern Mexico and California (Area 1 or *Inside* Area). As the sardine population rebuilt and expanded its range through the mid-1990's, sardine became more available seasonally off Oregon, Washington, and British Columbia. Subsequently, fisheries in these more northerly areas expanded with significant landings beginning in 2000. As in past assessments, research survey data (fishery-independent) are used to index the size of the sardine spawning biomass; and when coupled in a modelling framework with fishery-dependent data and structural information on sardine biology and migration, provide the stock size estimates and demographics needed by the PFMC to establish harvest guidelines for the USA fisheries.

Methods

An age-structured stock assessment model (CANSAR-TAM, **C**atch-at-age **AN**alysis for **SAR**dine - **T**wo **A**rea **M**odel, see Hill et al.1999) was applied to fishery-dependent and fishery-independent data to derive estimates of population abundance and age-specific fishing mortality rates. In 1998, the original CANSAR model (Deriso et al. 1996) was modified to account for the expansion of the population northward to waters off the Pacific northwest. The models are based on a 'forward-simulation' approach, whereby parameters (e.g., population sizes, recruitments, fishing mortality rates, gear selectivities, and catchability coefficients) are estimated after log transformation using the method of nonlinear least squares. The terms in the objective function (to be minimized) included the sum of squared differences in ($\log_e$) observed and ($\log_e$) predicted estimates from the catch-at-age and various sources of auxiliary data used for 'tuning' the model, e.g., indices of abundance from research survey data. Bootstrap procedures were used to calculate variance and bias (95% confidence intervals) of sardine biomass and recruitment estimates generated from the assessment model. The CANSAR-TAM model was based on two fisheries (California, U.S. and Ensenada, Mexico) and semesters within a year were used as time steps, with ages being incremented between semesters on July 1 and spawning that was assumed to occur on April 1 (middle of the first semester).

Fishery-dependent data from the California and Ensenada fisheries (1983 to first semester 2002) were used to develop the following time series: (1) catch (in mt)-Table 1 and Figure-1; (2) catch-at-age in numbers of fish; and (3) estimates of weight-at-age. Fishery-independent data (time series) from research surveys included the following indices, which were developed from data collected from Area 1 (*Inside Area*, primarily waters off central and southern California) and used as relative abundance measures (Table 2): (1) index (proportion-positive stations) of sardine egg abundance from California Cooperative Oceanic and Fisheries Investigations (CalCOFI) survey data (*CalCOFI Index*)-Figure 2; (2) index of spawning biomass (mt) based on the Daily Egg Production Method (DEPM) survey data (*DEPM Index*)-Figure 3, see Lo et al. (1996); (3) index of spawning area (Nmi^2) from CalCOFI and DEPM survey data (*Spawning Area Index*)-Figure 4, see Barnes et al. (1997); and (4) index of pre-adult biomass (mt) from aerial spotter plane survey data (*Aerial Spotter Index*)-Figure 5, see Lo et al. (1992). Time series of sea-surface temperatures (Figure 6) recorded at Scripps Pier, La Jolla, California were used to determine appropriate harvest guidelines (*Sea-*

surface Temperature Index), see Amendment 8 of the Coastal Pelagic Species Fishery Management Plan, Option J, Table 4.2.5-1, PFMC (1998).

Survey indices of relative abundance were re-estimated using generally similar techniques as was done in previous assessments (Hill et al. 1999; Conser et al. 2000; and Conser et al. 2001). The final model configuration was based on equally 'weighted' indices except for the CalCOFI index, which was downweighted to 0.7 (relative to 1.0 for the other indices). The relative weight used for the CalCOFI index (0.7) was consistent with previous assessments in which the proportion of the total spawning area covered by the CalCOFI surveys (~70%) was used to determine its relative weighting in the model. Further the CalCOFI Index has undergone considerable saturation in recent years due to the higher frequency of positive stations as the sardine stock expanded throughout and beyond the southern California Bight. As in the previous assessment, the CalCOFI index was fit with a non-unity exponent (0.3547) to allow for a nonlinear relationship between the index and sardine spawning biomass. This procedure produced a better fit to these data and a more acceptable residual pattern than assuming the classical linear relationship between the index of abundance and population size. As in the two previous assessments, the Aerial Spotter Index was assumed to primarily track pre-adult fish (ages 0 and 1 plus a portion of age 2 fish). All of the other fishery-independent indices were used as indices of the spawning stock biomass, which can be approximated by the biomass of ages 1+ sardine.

Recognizing that the geographical extent of the sardine population tends to increase as population size increases (inferred largely from tagging data and the expansion of the fishery in the 1930's), the CANSAR-TAM model uses explicit time-varying migration rates to `move' sardine from the well-sampled Area 1 (roughly Baja California through central California) to the larger, coastwide stock area. Internal consistency checks are done to ensure that reasonable numbers of sardine are present outside Area 1 to account for the catches of the developing fisheries in the Pacific Northwest. In conjunction with this assessment, a sensitivity run was carried out in which (i) the available catch-at-age from Oregon and Washington fisheries (mostly 2000 and 2001) were formally incorporated into the model and (ii) no structural assumptions regarding migration rates were imposed. As the time series of catch-at-age data from the Pacific Northwest fisheries accumulates and fishery-independent data become available from northern areas, the structure of this sensitivity run is likely to become the template for future sardine stock assessments.

Results

Pacific sardine landings for the directed fisheries off California, USA and Ensenada, Mexico decreased from the high levels that were reached during 2000 (109,000 mt), with a total 2002 harvest of roughly 81,000 mt (Table 1, Figure 1); however, note that semester 2 landings in 2002 reflect projected estimates based on landing patterns observed in the fisheries during the mid to late 1990s (Table 1). Both California and Ensenada landings in 2002 are expected to decrease from the 2000 level, with a more notable decrease in the projected Ensenada landings (51,000 mt in 2000, decreasing to 27,000 mt in 2002). Currently, the USA fishery is regulated using a quota (harvest guideline) management scheme and the Mexico fishery (Ensenada landings) is essentially unregulated.

As has been the case in recent years, landings from the USA Pacific sardine fishery (California, Oregon, and Washington) are below the harvest guideline recommended for 2002 (118,000 mt), with roughly 79,000 mt landed through September 2002 and 87,000 mt projected landings for the entire year (the fishing year ends December 31, 2002).

Estimated stock biomass ($\geq$1-year old fish on July 1, 2002) from the assessment conducted this year indicated the sardine population has remained at a relatively high abundance level, with a bias-corrected estimate of nearly 1.0 million mt (Table 3 and Figure 7). Estimated recruitment (age-0 fish on July 1) during the past four years has declined considerably from that estimated for the strong 1998 year-class (Table 3 and Figure 8). However, it should be noted that recent recruitment (4-22 billion recruits) is not estimated precisely (Figure 8), and another 2-3 years of data may be needed to ascertain whether the sardine population biomass has reached a plateau at the 1.0 million mt level (Figure 7).

Estimates of Pacific sardine biomass from the 1930's (Murphy 1966 and MacCall 1979) indicate that the sardine population may have been more than three times its current size prior to the population decline and eventual collapse in the 1960's (Figure 9). Considering the historical perspective, it would appear that the sardine population, under the right conditions, may still have growth potential beyond its present size. However, per capita recruitment estimates show a downward trend in recruits per spawner in recent years that may be indicative of a stock that has reached a plateau under current environmental conditions (Conser et al. 2001).

The estimate of 2002 stock biomass from the sensitivity run (in which available catch-at-age from Oregon and Washington fisheries were formally incorporated into the model and no structural assumptions regarding migration rates were imposed) was virtually identical to the corresponding estimate from the baseline assessment model, described above (Figure 10). Most annual biomass estimates from the sensitivity run fell within the 95% confidence interval from the baseline assessment (with notable exceptions in 1998 and 1999). However, biomass estimates from the sensitivity run were systematically smaller than those from the baseline during the (recent) years of rapid stock size increase. This may be indicative of a rapidly growing and expanding stock coupled with a lag in the development of fisheries in the northern area to `sample' the sardine in that area. Overall, confidence intervals on stock biomass from the sensitivity run were much broader than those from the baseline and some parameters were poorly estimated (e.g. selectivity for the northern fishery). It is reasonable to expect the performance of this model configuration to improve as the time series of catch-at-age data from the Pacific Northwest fisheries accumulates and fishery-independent data become available for northern areas.

Harvest Guideline for 2003

The harvest guideline recommended for the U.S. (California, Oregon, and Washington) Pacific sardine fishery for 2003 is 110,908 mt. Statistics used to determine this harvest guideline are discussed below and presented in Table 4. To calculate the proposed harvest guideline for 2003, 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:

$$HG_{2003} = (\text{TOTAL STOCK BIOMASS}_{2002} - \text{CUTOFF}) \bullet \text{FRACTION} \bullet \text{U.S. DISTRIBUTION},$$

where HG_{2003} is the total U.S. (California, Oregon, and Washington) harvest guideline recommended for 2003, TOTAL STOCK $BIOMASS_{2002}$ is the estimated stock biomass (ages 1+) from the current assessment conducted in 2002 (see above), CUTOFF is the lowest level of estimated biomass at which harvest is allowed, FRACTION is an environment-based percentage of biomass above the CUTOFF that can be harvested by the fisheries (see below), and U.S. DISTRIBUTION is the percentage of TOTAL STOCK $BIOMASS_{2002}$ 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-water ocean conditions persist, the following formula has been used to determine an appropriate (sustainable) FRACTION value:

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

where T is the running average sea-surface temperature at Scripps Pier, La Jolla, California during the three preceding years. Ultimately, under Option J (PFMC 1998), F_{msy} is constrained and ranges between 5% and 15% (Figure 11).

Based on the T values observed throughout the period covered by this stock assessment (1983-2002), the appropriate F_{msy} exploitation fraction has consistently been 15% (see Figures 6 and 11); and this remains the case under current oceanic conditions (T_{2002} = 17.3 °C). However, it should be noted that the decline in sea-surface temperature observed in recent years (1998-2002) may invoke environmentally-based reductions in the exploitation fraction as early as next year (i.e. in setting the harvest guideline for the 2004 fishing season) – see Figure 11.

Although the 2003 USA harvest guideline (110,908 mt) is less than the 2002 level (118,442 mt), recent fishery practices indicate that it may not be constraining with regard to USA fishery landings in 2003 (Figure 12). However, should the recent declining recruitment trend estimated in this assessment be confirmed with future work, and should the sea-surface temperature decline, it is likely that harvest guidelines in the out years will constrain USA fishery practices and removals.

Further when viewed on a stock-wide basis and considering the landings of Mexico and Canada as well as the USA, adherence to an implied 'stock-wide harvest guideline' may constrain fisheries even without sea-surface temperature declines. Figure 13 compares recent international landings with the annual harvest guidelines that would have resulted from applying the PFMC CPS FMP harvest formula (above) absent the "U.S. Distribution" term. Should Oregon and Washington landings continue to increase (at rates comparable to the past few years) and/or Mexican landings return to their 1999-2000 levels, the implied stock-wide harvest guideline may be exceeded as early as next year (2003).

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Table 1. Pacific sardine time series of landings (mt) by semester (1 is January-June and 2 is July-December) in California and Baja California (Ensenada), 1983-2002. Semester 2 (2002) estimates are projections.

	CALIFORNIA			ENSENADA			
Year	**Semester 1**	**Semester 2**	**Total**	**Semester 1**	**Semester 2**	**Total**	**Grand Total**
83	245	244	489	150	124	274	762
84	188	187	375	<1	<1	0	375
85	330	335	665	3,174	548	3,722	4,388
86	804	483	1,287	99	143	243	1,529
87	1,625	1,296	2,921	975	1,457	2,432	5,352
88	2,516	1,611	4,128	620	1,415	2,035	6,163
89	2,161	1,561	3,722	461	5,763	6,224	9,947
90	2,272	1,033	3,305	5,900	5,475	11,375	14,681
91	5,680	3,354	9,034	9,271	22,121	31,392	40,426
92	8,021	13,216	21,238	3,327	31,242	34,568	55,806
93	12,953	4,889	17,842	18,649	13,396	32,045	49,887
94	9,040	5,010	14,050	5,712	15,165	20,877	34,927
95	29,565	13,925	43,490	18,227	17,169	35,396	78,886
96	17,896	18,161	36,057	15,666	23,399	39,065	75,121
97	11,865	34,331	46,196	13,499	54,941	68,439	114,636
98	21,841	19,215	41,055	20,239	27,573	47,812	88,868
99	31,791	24,956	56,747	34,760	23,810	58,569	115,316
00	35,174	22,761	57,935	25,800	25,373	51,173	109,108
01	30,118	24,785	54,903	9,307	12,939	22,246	77,149
02	28,079	25,624	53,703	14,453	12,969	27,422	81,125

Table 2. Pacific sardine time series of survey indices of relative abundance and sea-surface temperature, 1983-02.

Year	CalCOFI (% positive)	DEPM (mt)	Spawning area (Nmi^2)	Spotter plane (mt)	Sea-surface temperature (C)
83	na	na	40	na	17.25
84	4.9	na	480	na	17.58
85	3.8	na	760	na	17.80
86	1.9	7,659	1,260	22,049	17.87
87	4.0	15,704	2,120	11,498	17.71
88	7.9	13,526	3,120	55,882	17.55
89	7.2	na	3,720	32,929	17.24
90	3.7	na	1,760	21,144	17.19
91	16.7	na	5,550	40,571	17.35
92	8.8	na	9,697	49,065	17.61
93	6.1	na	7,685	84,070	17.84
94	17.8	127,096	24,539	211,293	17.97
95	13.4	na	23,816	188,924	18.04
96	28.0	83,175	25,890	119,731	18.06
97	27.3	409,585	40,591	66,943	18.06
98	24.3	313,985	33,446	118,492	18.44
99	16.7	282,236	55,171	40,506	18.04
00	7.8	1,063,845	32,784	48,373	17.73
01	12.5	790,958	31,663	na	17.24
02	7.1	206,323	61,753	na	17.31

Table 3. Pacific sardine time series of stock biomass (age 1+ fish in mt) and recruitment (age 0 fish in 1,000s) estimated at the beginning of semester 2 of each year. Stock biomass estimates are presented for Area 1 (Inside) and the Total Area of the stock. The 95% CIs for Total Area biomass and recruitment estimates are also presented.

		Stock biomass			Recruitment		
Year	**Area 1**	**Total Area**	**Lower CI**	**Upper CI**	**Total Area**	**Lower CI**	**Upper CI**
83	5,145	5,145	2,988	10,237	149,689	89,658	270,675
84	13,409	13,473	9,132	23,233	224,302	147,543	392,307
85	21,173	21,675	15,754	36,295	217,919	147,483	370,813
86	29,917	31,546	24,369	49,475	866,710	623,621	1,366,185
87	73,715	77,313	60,204	115,178	839,143	605,890	1,256,424
88	107,013	116,721	95,152	162,348	1,465,991	1,032,887	2,389,804
89	162,381	181,604	148,898	254,547	1,157,082	791,458	1,975,840
90	176,794	210,440	173,500	301,142	4,792,851	3,130,855	8,333,861
91	226,334	263,632	203,648	413,259	5,889,816	3,719,993	10,548,967
92	353,005	421,519	323,045	659,025	4,170,058	2,597,005	7,521,409
93	335,486	447,224	344,253	681,348	9,244,272	6,537,849	15,455,594
94	494,524	654,337	535,996	955,097	10,755,601	7,664,169	17,160,261
95	508,294	726,690	598,227	1,029,945	6,607,815	4,604,385	10,396,623
96	531,651	791,496	667,663	1,094,850	5,550,420	4,069,965	8,823,371
97	482,595	770,613	659,886	1,030,390	9,424,984	6,870,295	14,799,898
98	457,126	775,882	668,011	1,056,753	15,082,296	10,943,898	23,682,041
99	610,828	992,323	833,745	1,384,818	8,217,217	5,254,279	14,563,581
00	586,710	1,000,871	827,203	1,404,431	9,386,310	5,567,436	17,800,084
01	510,877	928,578	728,391	1,405,681	10,773,256	5,945,732	22,997,633
02	570,306	999,871	704,161	1,668,985	8,362,928	3,677,163	21,765,966

Table 4. Proposed harvest guideline for Pacific sardine for the 2003 fishing season. See Harvest Guideline for 2003 section for methods used to derive harvest guideline.

Total stock biomass (mt)	**Cutoff (mt)**	**Fraction (%)**	**U.S. Distribution (%)**	**Harvest guideline (mt)**
999,871	150,000	15%	87%	**110,908**

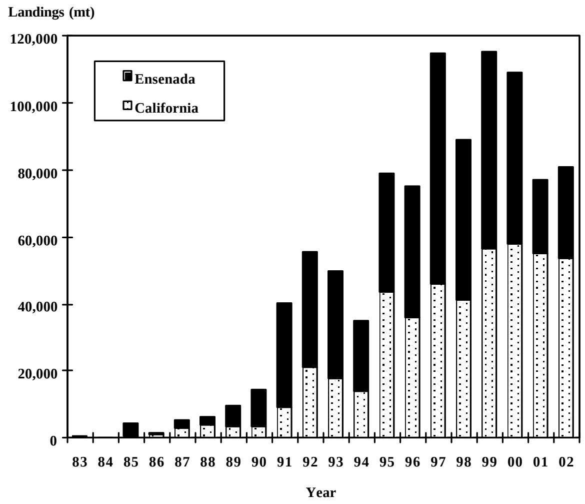

Figure 1. Pacific sardine landings (mt) in California and Baja California (Ensenada), 1983-02.

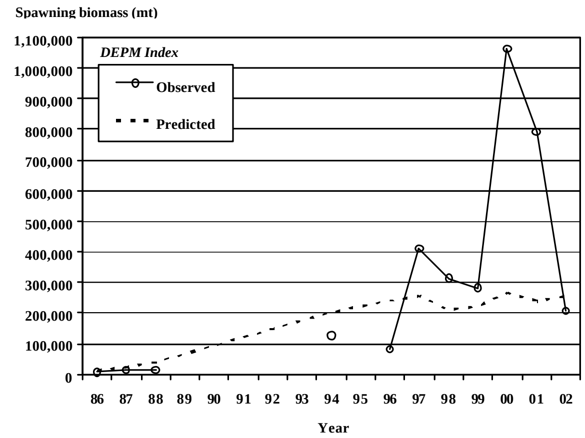

Figure 3. Index of relative abundance of Pacific sardine spawning biomass (mt) off California based on daily egg production method (DEPM) estimates from ichthyoplankton survey data (1986-02). Note that no sample data (Observed estimates) were available for years 1989-93 and 1995.

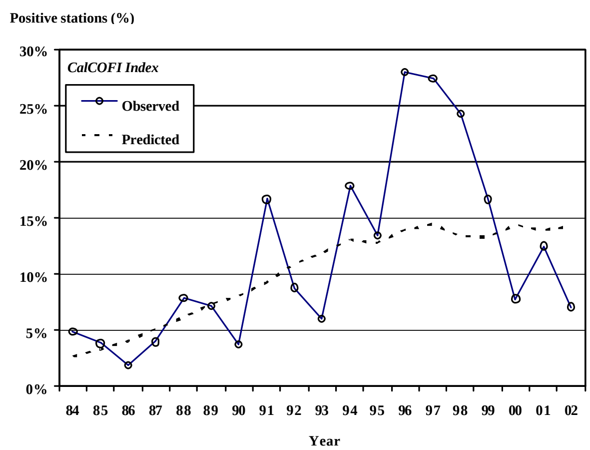

Figure 2. Index of relative abundance of Pacific sardine eggs (proportion-positive stations) off California based on CalCOFI bongo-net survey (1984-02).

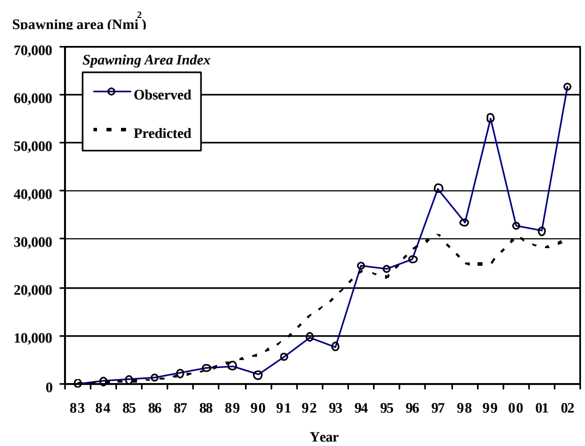

Figure 4. Index of relative abundance of Pacific sardine spawning stock size based on estimates of spawning area (Nmi^2) calculated from CalCOFI and DEPM survey data (1983-02).

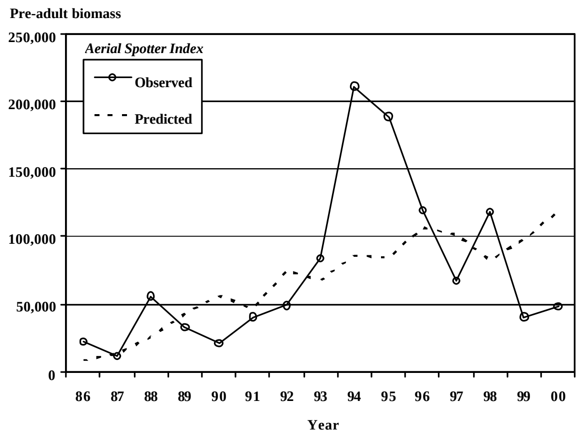

Figure 5. Index of relative abundance of Pacific sardine pre-adult biomass (primarily age 0-2 fish in mt) off California based on aerial spotter plane survey data (1986-00). Note that no sample data were available for 2001-02.

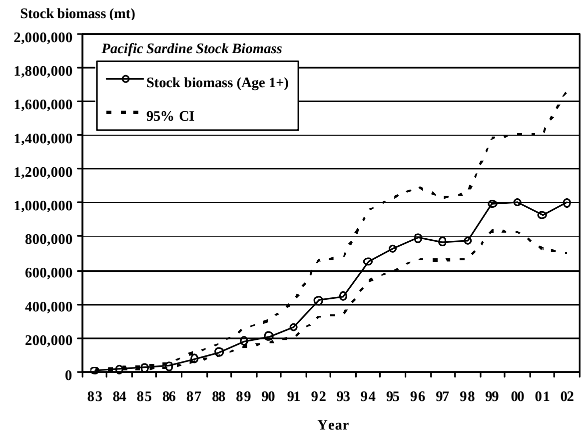

Figure 7. Time series (1983-02) of Pacific sardine stock biomass (age 1+ fish on July 1 of each year in mt) estimated from an age-structured stock assessment model (CANSAR-TAM, see Hill et al. 1999).

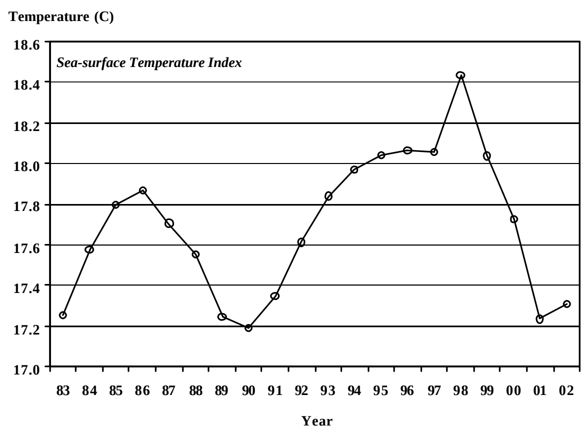

Figure 6. Time series of sea-surface temperature (C) recorded at Scripps Pier, La Jolla, CA (1983-02). Annual estimates reflect 3-year 'running' averages, see Jacobson and MacCall (1995).

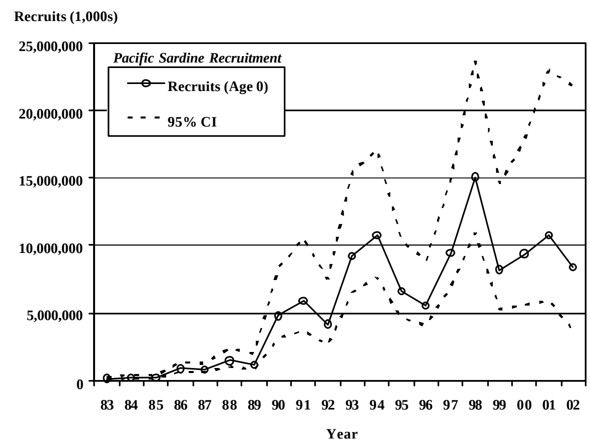

Figure 8. Time series (1983-02) of Pacific sardine recruitment (0-yr old fish on July 1 of each year in 1,000s) estimated from an age-structured stock assessment model (CANSAR-TAM, see Hill et al. 1999).

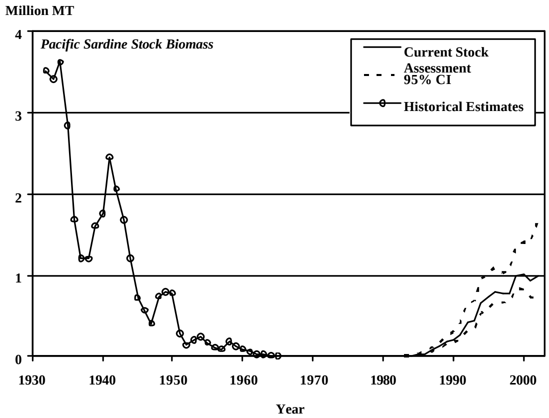

Figure 9. Time series (1983-2002) of Pacific sardine stock biomass (age 1+ fish on July 1 of each year in million mt) and associated 95% confidence intervals estimated in the current stock assessment (cf. Figure 7); and historical stock biomass estimates (1932-65) from Murphy (1966). Confidence intervals or other measures of precision are not available for the historical estimates. No stock assessment-based estimates are available for the period 1966-82. The sardine fishery was closed during much of this period and biomass was at very low levels.

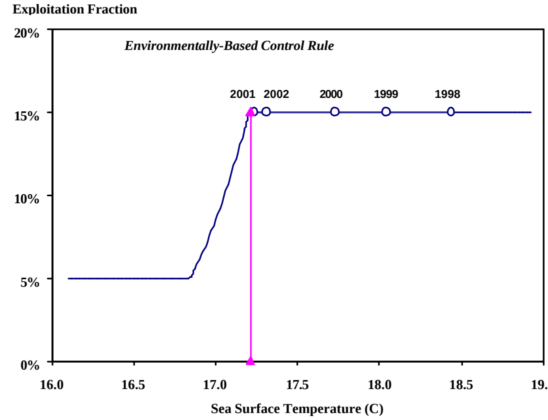

Figure 11. Environmentally-based harvest rate control rule for Pacific sardine as specified in the Coastal Pelagic Species Fishery Management Plan (PFMC 1998). For any given year, sea surface temperature (X-axis) is the running average sea surface temperature at Scripps Pier (La Jolla, CA) during the three preceding years. The exploitation fraction (Y-axis), which can range between 5-15%, is an explicit part of the algorithm used to determine the annual harvest guideline (quota) for the coastwide U.S. fishery – see Table 4. Open circles illustrate the sea surface temperature and exploitation fraction for recent years (1998-2002).

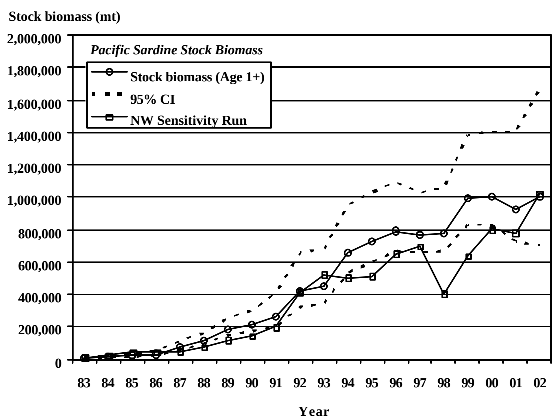

Figure 10. Time series (1983-02) of Pacific sardine stock biomass (age 1+ fish on July 1 of each year in mt) and 95% confidence intervals from this stock assessment (cf. Figure 7); and the stock biomass estimates from a sensitivity run using the NW fisheries data (Oregon and Washington) during 1999-2002. See text for details regarding the sensitivity run.

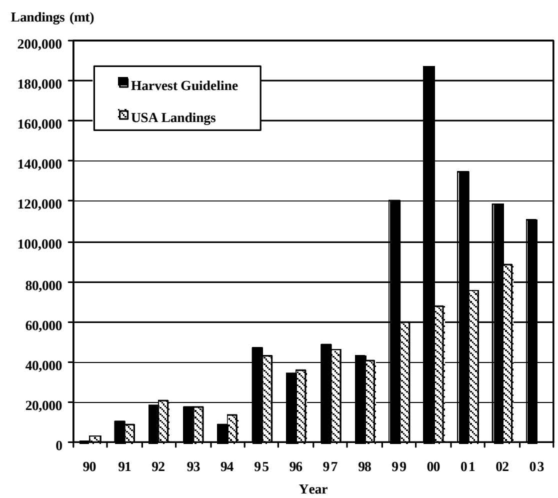

Figure 12. Time series (1990-03) of Pacific sardine harvest guidelines ('quotas') and actual USA landings (mt). State-based (California) regulations were in place for 1990-99, with federal-based (California, Oregon, and Washington) regulations beginning in 2000. Note that landings in 2002 represent an estimate projected through the end of the year. The 2003 harvest guideline is based on the 2002 stock biomass estimated in this assessment (Figure 7).

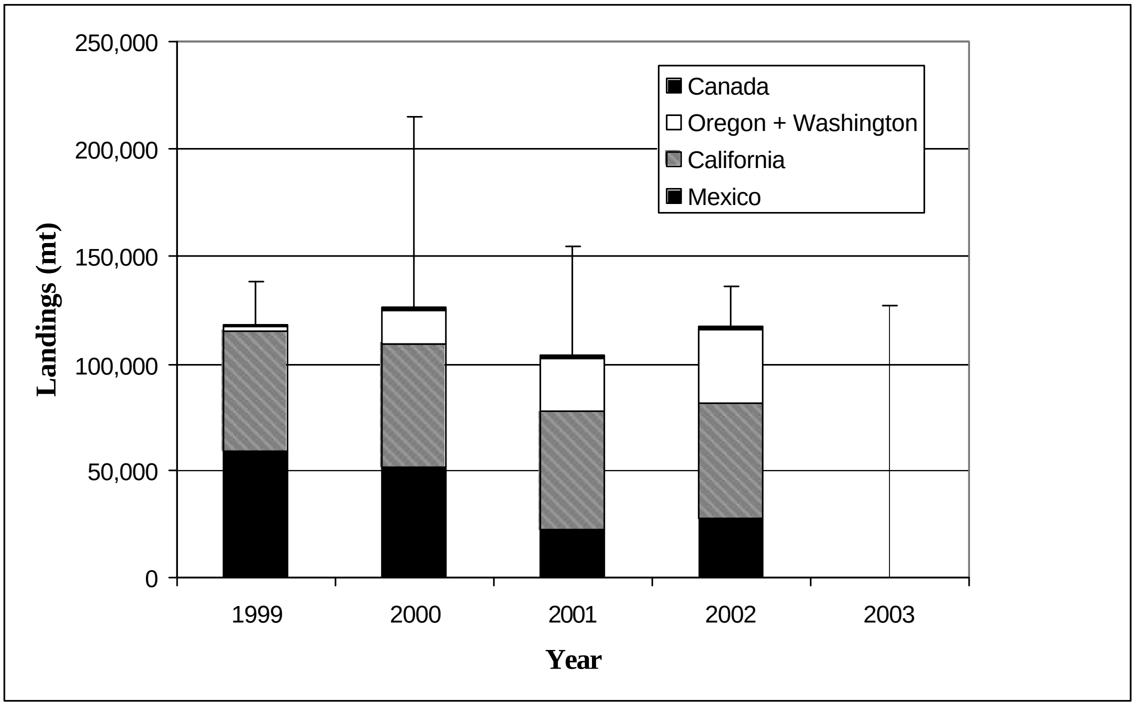

Figure 13. Pacific sardine landings (mt) from Mexico (Ensenada); California; Oregon and Washington; and Canada during 1999-2002. Landings shown for 2002 are estimates projected through the end of the calendar year. The thin bars illustrate the annual harvest guidelines that would have resulted from applying the PFMC CPS FMP harvest formula (see Table 4 and related text) on a stock-wide basis, i.e. applying the harvest guideline formula absent the "U.S. Distribution" term.