Review and Re-evaluation of Minimum Stock Size Thresholds for Finfish in the Coastal Pelagic Species Fishery Management Plan for the U.S. West Coast

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August 22, 2016

Introduction

Background

The following review and analysis were conducted by the National Marine Fisheries Service's Southwest Fisheries Science Center (NMFS-SWFSC) to meet terms of a settlement agreement specified in Oceana, Inc. v. Penny Pritzker, et al. (Ninth Circuit No. 13-16183; District Court No. C-11-6527 EMC (N.D. Cal.)). Specifically, paragraphs 7-8 of that agreement state:

> *7. NMFS shall consider revising or establishing, as appropriate, minimum stock size threshold ("MSSTs") for Pacific sardine, as it is managed under the Coastal Pelagic Species Fishery Management Plan; Pacific mackerel; the central subpopulation of northern anchovy; the northern subpopulation of northern anchovy; and jack mackerel.*
>
> *8. NMFS shall compile and examine scientific information available at the time of NMFS's analysis pertaining to MSSTs for the stocks listed in paragraph 7; develop recommendations based on that evaluation, which might or might not include recommendations to revise or establish MSSTs; and present a report of the results to the Council at or before the September 2016 Council meeting.*

It is important to preface this report by clarifying that it strictly pertains to minimum stock size thresholds (MSSTs) for stocks in the Coastal Pelagic Species Fishery Management Plan(CPS-FMP), not the CUTOFF parameters used in the harvest control rules (HCRs) used for setting acceptable catch limits (ACLs). CUTOFF can be the same as the MSST (e.g. 18,200 mt for Pacific mackerel), but the Council has also set CUTOFF higher than MSST, e.g. for Pacific sardine (CUTOFF=150,000 mt v. MSST=50,000 mt; PFMC 1998) and northern anchovy central subpopulation (CUTOFF=300,000 mt v. MSST=50,000 mt; PFMC 1990).

The NMFS guidelines for National Standard 1 (NS1) of the Magnuson-Stevens Fishery Conservation and Management Act states the following regarding MSSTs (50 CFR 600.310(e)(2)(i)-(ii)):

> <u>Minimum stock size threshold (MSST).</u> *The level of biomass below which the stock or stock complex is considered to be overfished.*
>
> <u>Overfished</u>. *A stock or stock complex is considered ''overfished'' when its biomass has declined below a level that jeopardizes the capacity of the stock or stock complex to produce MSY on a continuing basis.*
>
> <u>SDC to determine overfished status.</u> *The MSST or reasonable proxy must be expressed in terms of spawning biomass or other measure of reproductive potential. To the extent possible, the MSST should equal whichever of the following is greater: One-half the MSY stock size, or the minimum stock size at which rebuilding to the MSY level would be expected to occur within 10 years, if the stock or stock complex were exploited at the MFMT specified under paragraph (e)(2)(ii)(A)(1) of this section. Should the estimated size of the*

stock or stock complex in a given year fall below this threshold, the stock or stock complex is considered overfished.

The NS1 guidance regarding MSSTs has been applied across many federally managed stocks, however, variations and proxies have been implemented regionally. The New England Fishery Management Council uses the default of $0.5*SSB_{\mathrm{MSY}}$ (spawning stock biomass associated with maximum sustainable yield) as the overfished threshold. Following Restrepo et al. (1998), the South Atlantic Fishery Management Council defines MSST as $(1\text{-}M)*SSB_{\mathrm{MSY}}$ when $M<0.5$ (but $0.5SSB_{\mathrm{MSY}}$ when $M>=0.5$). The Pacific Fishery Management Council (Council) uses a depletion-based approach for groundfish, defining MSST as $0.25*SSB_0$ for most species and $0.125*SSB_0$ (spawning stock biomass associated with virgin, unfished conditions) for flatfish species. The above approaches have been implemented such that the biomass basis for MSST (SSB_{MSY}, SSB_0) is updated with each new stock assessment. In contrast, MSSTs in the CPS-FMP (where available) have been specified as biomass metrics for each species (e.g. 50,000 mt for Pacific sardine, 18,200 mt for Pacific mackerel) which are 'hard-wired' in the CPS FMP. Additionally, many domestic stocks have MSSTs that are either not estimated or are undefined similar to jack mackerel and northern anchovy as a result of not enough information. Modifying MSSTs for CPS finfish would thus require an amendment to the FMP.

The most appropriate method for defining MSST depends, in part, on life history characteristics of the managed species/stock complex. The underlying stock-recruitment relationship, S-R, (steepness, form, variability, random v. serial correlation), as well as assumptions regarding potential environmental covariates that may influence recruitment success will largely determine a stock's ability to rebuild from a depleted condition to SSB_{MSY}. It is important to note that long-term equilibrium metrics (e.g., SSB_{MSY} and SSB_0) are often unrealistic (i.e., not constant) for many fish stocks, particularly, short-lived productive species, which are characterized by highly variable recruitment that is strongly influenced by oceanographic conditions. For example, Pacific sardine and northern anchovy abundance can fluctuate widely on annual, decadal, and longer periods, even in the absence of fishing mortality (Figure 1, Baumgartner et al. 1992). A recent management strategy evaluation (MSE) for Pacific sardine demonstrated how average B_0 (stock biomass associated with unfished conditions) corresponds directly to the average sea surface temperature (SST) in the California Current (Figure 2, Hurtado & Punt 2013).

This report: 1) summarizes existing MSST definitions for finfish in the CPS-FMP; 2) describes default and potential alternative MSST approaches; 3) reviews existing sources of data for each stock; 4) applies a range of approaches to each stock, depending upon the type of data available; and 5) concludes with discussion questions on potential future work and analysis.

<u>Current MSST definitions in the CPS-FMP</u>

The CPS-FMP (PFMC 1998) provides the following guidance regarding overfished stocks:

By definition, an overfished stock in the CPS fishery is a stock at a biomass level low enough to jeopardize the capacity of the stock to produce MSY on a continuing basis. An overfished condition is approached when projections indicate that stock biomass will fall below the overfished level within two years. The Council must take action to rebuild *overfished stocks and to avoid overfished conditions in stocks with biomass levels approaching an overfished condition.*

Since adoption of the original Anchovy Plan, stock-specific MSSTs have been adopted or developed for Pacific sardine, Pacific mackerel, and the central subpopulation of northern anchovy. The following is a summary of these definitions and where applicable, the technical basis is described.

Pacific sardine

The CPS FMP (PFMC 1998, 2016) defines an overfished sardine population as one with an age 1+ stock biomass on July 1 of 50,000 mt or less. In CPS FMP Amendment 8, Appendix B - Options and Analyses for the Coastal Pelagic Species Fishery Management Plan (PFMC 1998), 50,000 mt was the minimum stock required to rebuild to 1.5 million metric tons (Mmt) in less than 10 years. This simple analysis assumed a population growth rate of 40% per year, reflecting a population under highly productive conditions. The 1.5 Mmt rebuilding 'target' was the average B_{MSY} (age 1+ stock biomass associated with MSY) in Amendment 8 simulations (options G through L). This was included in the CPS-FMP as an illustrative example for the minimum stock biomass required to rebuild to B_{MSY} in less than 10 years, based on NS1.

Prior to CPS FMP Amendment 8, the State of California had already adopted an overfished definition of 50,000 mt, because this was near the minimum biomass level that could be objectively measured in the absence of fishery data, i.e., via DEPM surveys (Wolf & Smith 1986; Barnes et al. 1992). Hence, California's 50,000 mt policy was carried-over in the development of Amendment 8 to the CPS FMP. It is important to note that the MSST in the CPS-FMP refers to age 1+ biomass and not SSB, although the two can be similar quantities when recruitment levels are poor. While the 50,000 mt definition does address the 'rebuild in less than 10 years' guidance, it was based on a high productivity scenario (increase of 40% per year) and not on some fraction of SSB_{MSY} or SSB_0. In addition, the sardine population metrics (SSB_{MSY}, SSB_0) scale up and down with productivity of the stock, as is the case for the E_{MSY} parameter that is directly linked to prevailing environmental conditions in the current harvest control rule. For example, the relationship between SST and B_0 was recently evaluated in re-analysis of sardine HCRs by Hurtado & Punt (2013) (Figure 2).

Pacific mackerel

The CPS-FMP defines an overfished Pacific mackerel stock as one with 18,200 mt or less of age 1+ biomass (PFMC 1998, 2016). Like sardine, the overfished criterion for Pacific mackerel was adopted as status quo from State of California regulations. California statutes imposed a moratorium on directed mackerel fishing when the spawning stock dropped below 20,000 short tons (18,200 mt) of age 1+ biomass, but did allow for incidental catches (Klingbeil 1983). MacCall et al. (1985) analyzed this MSST in the context of the State's harvest control rule and found it to be a reasonable proxy. California's control rule was adopted for management in CPS FMP Amendment 8 (PFMC 1998), with the addition of a 70% U.S. Distribution term. As is the case for Pacific sardine, the MSST metric for Pacific mackerel refers to age 1+ biomass and not SSB. For Pacific mackerel, SSB can represent a considerably smaller fraction of the age 1+ biomass (50% or less). Likewise, the current definition of MSST is not based on a fraction of SSB_{MSY} or SSB_0.

Northern anchovy (central subpopulation)
The MSST for the northern anchovy central subpopulation is not currently specified in the CPS-FMP, given the monitored classification for this species (PFMC 1998, 2016). However, the sixth amendment to the northern anchovy FMP implemented an 'overfishing' definition for the stock (PFMC 1990). In Amendment 6, 'overfishing' was defined as fishing when the stock drops below 50,000 mt of spawning biomass, so this was a *de facto* biomass-based 'overfished' criterion, which was previously reviewed by the SSC and adopted by the Council. Harvest control rule simulations by Jacobson & Thomson (1989) served as the basis for this recommendation in Amendment 6. Including a CUTOFF value of 50,000 mt in the simulations allowed the spawning stock to rebuild to 300,000 mt in less than 10 years in the presence of a modest 7,000 mt non-reduction (bait) fishery. The 300,000 mt limit was the rebuilding target above which directed harvest for reduction processing was allowed. However, the 300,000 mt rebuilding 'target' was not explicitly defined as 'B_{MSY}'.

Jack mackerel
A MSST has not yet been specified for jack mackerel.

Northern anchovy (northern subpopulation)
A MSST has not yet been specified the northern subpopulation of northern anchovy.

Methods

<u>Alternative MSSTs examined</u>

The harvest control rules currently defined for the actively managed CPS stocks (i.e., Pacific sardine and Pacific mackerel) function by ending fishing mortality when the stock drops below CUTOFF. In the case of Pacific sardine, the CUTOFF parameter is three-fold higher than the currently defined MSST. For Pacific mackerel, the CUTOFF is equal to the MSST. However, the MSST definitions currently in place for CPS do not necessarily represent a fixed fraction of SSB_{MSY} or SSB_0 as described in NS1 guidelines (Restrepo et al. 1998, Federal Register 2009). This report examines several possible metrics for defining or redefining MSST for CPS finfish, drawing from current practice for other FMP stocks. The three options considered include:

1) MSST = 0.5*SSB_{MSY} (for M=>0.5); *or* MSST = (1-M)*SSB_{MSY} (for M<0.5)

2) MSST = 0.2*SSB_0

3) MSST = 0.2*$SSB_{0\mathrm{current},F=0}$

Options 1 and 2 represent standard practices for many domestic FMP stocks and are based on estimates of SSB_{MSY} and SSB_0 under longer-term 'equilibrium' conditions. Option 2 is a depletion-based method applied in the PFMC's groundfish FMP, with the exception that MSST for most groundfish stocks is defined as 25% of SSB_0 (higher due to lower resilience) and MSST for flatfish species is 12.5% of SSB_0. For purposes of this report, the depletion criterion of 20%

of SSB_0 is applied, which is considered an appropriate lower-limit for stocks with average or better resilience (Beddington & Cooke 1983, Mace & Sissenwine 1993, Mace 1994, Myers et al. 1994).

Option 3 is based on an estimate of recent (or 'current') dynamic SSB_0. While this approach has not yet been applied to any domestically managed stocks, it was recently adopted by the Western and Central Pacific Fisheries Commission (WCPFC) to define limit reference points (termed '20%$SB_{\text{current},F=0}$') for some highly migratory stocks (Harley et al. 2012, Berger et al. 2013). The rationale for this approach is that equilibrium conditions are not as applicable to stocks with high recruitment variability and for which productivity is strongly affected by the environment. The WCPFC examined a range of methods for defining 'current' time-windows for $SSB_{\text{current},F=0}$, including environmental trends (El Nino-Southern Oscillation, ENSO and Pacific Decadal Oscillation, PDO), mean generation time (one and two generations), and recruitment trend (Berger et al. 2013). The WCPFC's approach has not yet been applied in U.S. fisheries management, but it is consistent with the NS1 guidelines with regards to reference points representing prevailing environmental conditions. A number of options are available for defining the time window for calculating 'current' (Berger et al. 2013). For purposes of this report, we only examine the metric $SSB_{0\text{current},F=0}$ with respect to one and two generation times to define SSB_0 'current'. Additional time-window alternatives could be explored in the future.

Data for defining CPS-finfish MSSTs

Pacific sardine

Pacific sardine (northern subpopulation, NSP) has been assessed annually since the mid-1990s. Stock assessments have been based on fully-integrated, age-structured population models (e.g., CANSAR, ASAP, and Stock Synthesis). Stock Synthesis (SS) model outputs include maximum likelihood-based estimates (MLE) of SSB_{MSY}, SSB_0, and dynamic SSB_0. Time series and MLEs of these parameters derived from the latest stock assessment update (Hill et al. 2016) were used for purposes of calculating MSSTs (Table 1). Mean generation time (gen) from the sardine stock assessment was four years, so $SSB_{0\text{current}}$ was based on an average of dynamic SSB_0 estimates from 2013-2016 (1-gen) and 2009-2016 (2-gen).

Pacific mackerel

Like Pacific sardine, Pacific mackerel has been assessed with high frequency since the 1990s using age-structured population models. The latest stock assessments have also been conducted using SS. For this analysis, we use MLEs of equilibrium SSB_{MSY} and SSB_0, and dynamic SSB_0 derived from the latest stock assessment adopted for management (Table 2) (Crone and Hill 2015). Mean generation time from the Pacific mackerel stock assessment was five years, so $SSB_{0\text{current}}$ was based on an average of dynamic SSB_0 estimates from 2012-2016 (1-gen) and 2007-2016 (2-gen).

Northern anchovy (central subpopulation)

Northern anchovy (central subpopulation) was last assessed for formal management purposes in 1995 (Jacobson et al. 1995). The assessment used the age-structured production model SMPAR (Jacobson et al. 1994). The assessment model produces estimated time series of *SSB* and recruitment, but not estimates of SSB_{MSY}, SSB_0, or dynamic SSB_0. For the present analysis, estimates of SSB_{MSY} and SSB_0 were derived using SRFIT, an age-structured production model with an S-R curve (Brodziak & Legault 2010). The SRFIT model produces MSY-based reference points using time series of stock-recruitment data, age-specific life history vectors (e.g., weight, maturity, natural mortality, and fishery selectivity). The *SSB* and recruitment time series were obtained from Jacobson et al. (1995) (Table 3), and age-specific life history and selectivity vectors were taken from Methot (1989), based on a SS model for northern anchovy (Table 4). Reference points were calculated for models based on eight spawner-recruit relationship scenarios: Beverton-Holt vs. Ricker functions, lognormal vs. normal error, and random vs. autoregressive recruitment predictions. Results from the eight model variants were averaged to calculate MSSTs based on equilibrium SSB_{MSY} and SSB_0.

Jack mackerel

Jack mackerel off the U.S. west coast have never been formally assessed for management. However, MacCall and Stauffer (1983) developed a dynamic pool model for the population. The model was a simple data-limited, life-history table approach to estimate fishery potential of the stock (Table 6). The model produced an estimate of equilibrium SSB_0 that was used here to calculate a MSST.

Northern anchovy (northern subpopulation)

Northern anchovy (northern subpopulation) have never been assessed and therefore, no data are available to estimate MSST for this stock.

Results

Pacific sardine

The MLE estimates of $SSB_{MSY,}$ $SSB_{0,}$ and $SSB_{0current}$ from Hill et al. (2016) are provided in Tables 1 and 7, and MSST metrics associated with those estimates are provided in Table 7. The MSST estimates ranged from 61,074 to 121,697 mt -- the lowest value based on (1-M)*SSB_{MSY} and the highest being based on 0.2*$SSB_{0current\ (2\text{-}gen)}$. All MSST values were slightly higher than the 50,000 mt MSST that is currently in place for this stock.

For comparison, Myers et al. (1994) calculated a suite of MSSTs for Pacific sardine using *SSB* and recruitment data from the historic population (Murphy 1966). Results from that study are collated in Table 8. The MSST estimates ranged from 20,000 to 295,000 mt, depending on the type of *S-R* relationship assumed in the model, with an average of 87,250 mt and a median value of 62,000 mt (Myers et al. 1994); the MSST estimates from the current study are, on average, of similar magnitude.

Pacific mackerel

The $SSB_{MSY,}$ $SSB_{0,}$ and dynamic SSB_0 estimates are presented in Tables 1 and 7. Associated MSST metrics are provided at the bottom of Table 7. The MSSTs for Pacific mackerel were all of similar magnitude, ranging from 24,599 mt for 0.2*$SSB_{0current\ (1\text{-}gen)}$ to 31,370 mt for 0.2*SSB_0. All estimates were slightly higher than the MSST currently specified in the CPS-FMP (18,200 mt). However, the 18,200 mt in the FMP is based on age 1+ biomass, not SSB, so any differences between *status quo* policy and the present results are likely greater.

The MSST study by Myers et al. (1994) also included estimates for Pacific mackerel based on analysis of *SSB* and recruitment of the historic population (Parrish & MacCall 1978). Estimates from this evaluation ranged from 0 to 47,000 mt, with an average of 22,375 mt and a median of 25,500 mt (Table 8); the MSST estimates from the current study were generally similar.

Northern anchovy (central subpopulation)
The SSB_{MSY} and SSB_0 derived from SRFIT analysis for models based on eight S-R relationship scenarios are provided in Table 6. Estimates of SSB_{MSY} ranged from 94,846 to 172,036 mt, with an average value of 139,561 mt (Table 6). The MSST corresponding to $0.5*SSB_{\mathrm{MSY}}$ is 69,781 mt (Table 7). The SRFIT estimates of SSB_0 ranged from 308,532 to 381,284 mt, with an average across models of 345,246 mt (Table 6). The MSST based on $0.2*SSB_0$ was 69,049 mt (Table 7).

Myers et al. (1994) also included MSST estimates for northern anchovy (Table 8). The MSST estimates ranged from 15,000 to 59,000 mt, with an average of 21,875 mt and median of 20,500 mt. Their estimates were all lower than those from the current study and lower, on average, than that associated with the MSST definition adopted in Amendment 6 to the FMP (50,000 mt).

Jack mackerel
Based on the MacCall & Stauffer (1983) study using a simple dynamic pool model, equilibrium SSB_0 for jack mackerel was approximately 1.36 million metric tons (Table 6). The only MSST metric available for jack mackerel is that based on $0.2*SSB_0$ or 272,160 mt (Table 7). There are no past studies for comparison to this estimate.

Northern anchovy (northern subpopulation)
Data are not available regarding abundance and productivity for the northern subpopulation of northern anchovy that resides off Oregon and Washington and thus, MSST for this stock was unable to be investigated at this time.

Discussion

This report includes reviews of MSSTs as currently defined in the CPS-FMP, re-evaluated MSSTs for CPS-finfish based on available data and a range of methods, and results from applying the respective methods for purposes of showing the range of quantities that can be calculated. A number of issues and questions remain with the values and methods presented in this report. .

The MSSTs in the CPS-FMP are currently defined as fixed quantities (e.g., 50,000 mt for Pacific sardine and 18,200 mt for Pacific mackerel), which are not re-evaluated when new stock assessments are conducted. For some domestic stocks, current status is evaluated relative to a limit-reference point derived from the same stock assessment model. Given the dynamics of CPS stocks and the substantial variability in assessment results that can occur among subsequent assessments of the same stock, an important question to consider is whether the *status quo* (fixed values) MSSTs should be replaced by one based on changing management metrics using recently conducted assessments?

The MSSTs in the CPS-FMP are based on age 1+ biomass and not SSB. Differences between age 1+ biomass and SSB can be trivial for species with early age-at-maturity (e.g., sardine or anchovy), but more substantial for other species like Pacific and jack mackerels.

Should MSSTs for CPS-finfish be based on SSB_{MSY} or should some proxy, such as percent depletion, be used (i.e., $\%SSB_0$ or $\%SSB_{0\mathrm{current}}$)? The SSB_{MSY} is the average spawning biomass resulting from fishing at F_{MSY} under equilibrium conditions. Estimates of SSB_{MSY} from age-structured stock assessments are dependent on the shape of the stock-recruit relationship and variability of recruitment around this relationship (σ_R). If the parent-offspring relationship is not well defined, then SSB_{MSY} proxies (% depletion) are sometimes used (e.g., groundfish FMP). If a depletion-based proxy is to be adopted, further work may be required to define the most appropriate depletion level for CPS based on their life history characteristics (Clark 1991, 1993). For example, a depletion level of $20\%SSB_0$ is considered adequate for most stocks with average or above average resilience, however, flatfish in the Council's groundfish FMP have a MSST based on $12.5\%SSB_0$.

If a depletion-based method is to be used, should SSB_0 be based on longer-term 'equilibrium' conditions or 'current' unfished conditions (i.e., recent estimates of dynamic SSB_0)? Given the highly dynamic, environment-driven nature of CPS reproductive success, the approach adopted by the WCPFC for tuna stocks ($\%SSB_{0\mathrm{current},\ F=0}$) may be the best criterion for CPS. The $\%SSB_{0\mathrm{current}}$ method is consistent with NS1 guidance to base biological reference points on prevailing environmental conditions, but this approach has yet to be applied to management of any domestic fish stocks. If MSST is based on $\%SSB_{0\mathrm{current}}$, what is the most appropriate window of time for defining 'current', as a range of methods could be explored (e.g., Berger et al. 2013), depending on our knowledge of stock dynamics and how recruitment success relates to the environment.

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Table 1. Pacific sardine *SSB* and dynamic SSB_0 time series from the 2016 update stock assessment using the Stock Synthesis model (Hill et al. 2016). MLEs of equilibrium SSB_{MSY} and SSB_0, derived from Stock Synthesis, are provided in the bottom row.

Year	*SSB*	SSB_0	
1993	389,395	390,023	
1994	533,450	551,596	
1995	630,040	690,263	
1996	630,932	722,587	
1997	596,042	703,283	
1998	681,023	804,259	
1999	766,577	941,772	
2000	681,193	929,073	
2001	534,937	806,431	
2002	395,682	690,848	
2003	280,332	590,202	
2004	406,208	717,054	
2005	583,424	922,644	
2006	757,295	1,119,970	
2007	763,427	1,186,750	
2008	699,527	1,144,270	
2009	586,470	1,032,440	
2010	507,364	936,388	
2011	415,388	828,149	
2012	249,089	671,991	
2013	131,188	509,106	
2014	79,391	371,589	
2015	65,118	274,735	
2016	87,961	243,472	
		349,726	**← $SSB_{0current\ (2013\text{-}2016)}$**
		608,484	**← $SSB_{0current\ (2009\text{-}2016)}$**
SSB_{MSY} →	**101,790**	**421,572**	**← SSB_0**

Table 2. Pacific mackerel *SSB* and dynamic SSB_0 time series from the 2015 stock assessment using the Stock Synthesis model (Crone & Hill 2015). MLEs of equilibrium SSB_{MSY} and $SSB_{0,}$ derived from Stock Synthesis, are provided in the bottom row.

Year	*SSB*	SSB_0	
1983	509,274	509,274	
1984	597,460	618,743	
1985	563,560	613,557	
1986	479,463	556,094	
1987	338,693	425,074	
1988	259,474	350,600	
1989	221,688	318,079	
1990	226,256	330,083	
1991	210,684	337,191	
1992	184,380	330,322	
1993	169,913	316,671	
1994	147,946	272,408	
1995	141,839	251,727	
1996	149,443	244,510	
1997	156,141	246,966	
1998	139,079	246,185	
1999	92,679	221,396	
2000	70,473	185,406	
2001	38,347	140,029	
2002	24,465	104,757	
2003	16,237	84,528	
2004	12,948	74,061	
2005	13,108	74,478	
2006	16,139	87,314	
2007	21,364	112,166	
2008	26,957	139,188	
2009	31,632	154,458	
2010	33,506	152,743	
2011	31,247	134,101	
2012	29,970	115,961	
2013	28,474	107,664	
2014	30,807	112,079	
2015	40,777	132,848	
2016	47,178	146,426	
		122,996	**← $SSB_{0current\ (2012\text{-}2016)}$**
		130,763	**← $SSB_{0current\ (2007\text{-}2016)}$**
SSB_{MSY} →	**55,297**	**156,849**	**← SSB_0**

Table 3. Northern anchovy SSB and recruitment time series from Jacobson et al. (1995) as modeled in the age-structured production model SRFIT.

Year	SSB (10^3 mt)	Age-0 Fish (10^6 indiv.)
1963	612	12,769
1964	356	15,923
1965	236	35,692
1966	230	19,077
1967	206	18,538
1968	173	63,846
1969	198	19,846
1970	172	66,769
1971	138	52,308
1972	383	334,462
1973	474	115,000
1974	932	204,000
1975	1,069	76,154
1976	901	38,154
1977	520	50,308
1978	337	136,154
1979	654	73,923
1980	490	48,538
1981	320	157,692
1982	711	17,077
1983	395	148,846
1984	555	85,769
1985	715	23,385
1986	409	16,692
1987	227	98,846
1988	167	14,308
1989	239	10,462
1990	152	20,769
1991	171	13,385
1992	145	18,077
1993	154	72,154
1994	388	43,154

Table 4. Northern anchovy life history and selectivity vectors as modeled in the age-structured production model SRFIT.

Age	Natural mortality	Fishery selectivity	Proportion mature	Average catch weight (kg)	Average stock weight (kg)
0	0.8	0.161	0	0.0130	0.0000
1	0.8	0.666	0.55	0.0165	0.0096
2	0.8	0.993	1	0.0196	0.0150
3	0.8	1.000	1	0.0221	0.0190
4	0.8	0.668	1	0.0253	0.0217
5	0.8	0.300	1	0.0284	0.0243
6	0.8	0.000	1	0.0311	0.0311

Table 5a. Dynamic pool model of jack mackerel population and estimates of potential yield, using assumed natural mortality rates (taken from MacCall & Stauffer 1983, Table 1).

Age	Assumed natural mortality rate	Fishing mortality rate	Relative number	Length (mm-FL)	Mean weight[\1] (g)	Initial biomass (10^3 MT)	Mean catch[\2] (10^3 MT)	Potential Yield (10^3 MT) Low X=0.3	High X=0.5
0	(0.5)	---	1,000	---	---	---	---	---	---
0.5[\3]	(0.5)	0.018	779	---	60	(123.3)	2.360	9.3[\4]	15.4[\4]
1	0.5	0.043	602	198	85	135.0	5.728	20.2	33.7
2	0.45	0.046	350	234	140	129.3	5.664	17.4	29.1
3	0.4	0.058	213	267	207	116.5	6.340	14	23.3
4	0.35	0.032	135	297	285	101.2	3.024	10.6	17.7
5	0.3	0.012	92	324	370	89.7	1.048	8.1	13.4
6	0.25	0.004	67	349	461	81.8	0.337	6.2	10.3
7	0.2	0.002	52	372	556	76.6	0.124	4.6	7.6
8	0.2	0.001	43	392	653	73.5	0.025	4.4	7.3
0-8	---	---	---	---	---	926.8	24.649	94.8	157.9
9-15	0.2	---	145	411-493	959	367.0	---	22	36.7
16-30	0.2	---	45	503-576	1598	190.3	---	11.4	19.1
0-30						1360.8 (spawning)		128.3	213.7
						1484.1 (total)			

[\1]Weight is based on length-weight relationship with correction for σ_L = 21.5 mm (Pienaar and Ricker 1968).
[\2]Catch includes only San Pedro landings.
[\3]Age 0 fish are assumed to be unavailable for the first half year; mean weight is approximate: and biomass does not spawn.
[\4]Potential yield reduced by ½ because fish are only available for ½ year.

Table 5b. Dynamic pool model of jack mackerel population and potential yield estimates, using assumed natural mortality rates and partial fecundity of young fish (taken from MacCall & Stauffer 1983, Table 2).

Age	Assumed fecundity	Assumed natural mortality rate	Fishing mortality rate	Initial biomass (10^3 MT)	Potential Yield (10^3 MT) Low X=0.3	High X=0.5
0.5[\1]	0.0	0.50	0.032	(148.2)	11.2[\2]	18.5[\2]
1	0.2	0.50	0.036	161.0	24.1	40.3
2	0.4	0.45	0.038	155.1	21.0	34.9
3	0.6	0.40	0.048	140.9	16.9	28.2
4	0.8	0.35	0.026	123.6	13.0	21.6
5	1.0	0.30	0.010	110.3	9.9	16.5
6	1.0	0.25	0.003	100.8	7.5	12.6
7	1.0	0.20	0.001	94.3	5.6	9.4
8	1.0	0.20	0.001	90.6	5.4	9.1
0-8	---	---	---	1124.9	114.6	191.1
9-15	1.0	0.2	---	452.5	27.1	45.3
16-30	1.0	0.2	---	234.6	14.1	23.5
0-30				1360.8 (spawning)	155.8	259.9
				1812.0 (total)		

[\1]Age 0 fish are assumed to be unavailable for the first half year: weight is approximate; and biomass does not spawn.
[\2]Potential yield reduced by because fish are only available for ½ year.

Table 6. Northern anchovy (central subpopulation) biological reference points derived from SRFIT for models based on eight stock-recruitment relationship scenarios: Beverton-Holt vs. Ricker, lognormal vs. normal error, and random vs. autoregressive term in recruitment prediction.

SR Model	Error type	Autoregression	R_0 (10^9 fish)	Steepness	Alpha	Beta	Sigma-R	F_{MSY}	SSB_{MSY}	SSB_0	-log(L)
B-H	lognormal	yes	63.0	0.515	na	na	0.893	0.455	94,846	308,532	161.436
B-H	lognormal	no	65.4	0.372	na	na	0.885	0.250	123,535	320,346	161.919
B-H	normal	yes	67.8	0.428	na	na	66.380	0.330	116,138	331,798	179.556
B-H	normal	no	67.8	0.400	na	na	66.361	0.290	122,076	332,105	179.649
Ricker	lognormal	yes	na	na	423.8	2.055	0.898	0.230	157,446	355,077	161.435
Ricker	lognormal	no	na	na	345.8	1.476	0.886	0.160	161,370	356,668	161.956
Ricker	normal	yes	na	na	417.5	1.875	66.137	0.225	169,044	381,284	194.796
Ricker	normal	no	na	na	381.8	1.663	66.059	0.190	172,036	376,155	194.646
							Average	**0.266**	**139,561**	**345,246**	

Table 7. Estimates of equilibrium SSB_{MSY}, SSB_0, and dynamic $SSB_{0,}$ with associated MSST calculations. Calculated MSSTs are provided in the lower half of the table.

	Pacific Sardine	Pacific Mackerel	No. Anchovy CSP	Jack Mackerel	No. Anchovy NSP
Metric \ Source	Hill et al. 2016	Crone & Hill 2015	Jacobson et al. 1995 & SRFIT	MacCall & Stauffer 1983	none available
Natural Mortality (M)	0.4	0.5	0.8	0.46	nd
Equilibrium SSB_{MSY}	101,790	55,297	139,561	nd	nd
Equilibrium SSB_0	421,572	156,849	345,246	1,360,800	nd
Dynamic $SSB_{0current\ (1\ gen)}$	349,726	122,996	nd	nd	nd
Dynamic $SSB_{0current\ (2\ gen)}$	608,484	130,763	nd	nd	nd
Current MSST Definition	50,000	18,200	50,000	nd	nd
0.5*SSB_{MSY} (for M>=0.5)	na	27,649	69,781	nd	nd
(1-M)*SSB_{MSY} (for M<=0.5)	61,074	na	na	nd	nd
0.2*SSB_0	84,314	31,370	69,049	272,160	nd
0.2*$SSB_{0current\ (1\ gen)}$	69,945	24,599	nd	nd	nd
0.2*$SSB_{0current\ (2\ gen)}$	121,697	26,153	nd	nd	nd

Table 8. Minimum stock size thresholds for Pacific sardine, Pacific mackerel, and northern anchovy (central subpopulation) as estimated by Myers et al. (1994) using a range of stock-recruitment relationships and methods. Pacific sardine fit to data from Murphy (1966), Pacific mackerel fit to data from Parrish & MacCall (1978), and northern anchovy were fit using assessment data from either Methot or Jacobson.

Metric \ Species	Pacific Sardine	Pacific Mackerel	No. Anchovy CSP
SSB at 50% R_{max} - BH50\1	295,000	0	0
SSB at 50% R_{max} - RK50\2	77,000	30,000	17,000
SSB at 50% R_{max} - SH50\3	42,000	3,000	15,000
SSBb\4	57,000	26,000	59,000
20%SSB_0 - BHv\5	103,000	25,000	21,000
20%SSB_0 - RKv\6	67,000	47,000	22,000
20%SSB_0 - SHv\7	37,000	28,000	21,000
20%SSB_0 - Rmnv\8	20,000	20,000	20,000
Average	87,250	22,375	21,875
Median	62,000	25,500	20,500

\1 BH50 = SSB at 50% of maximum predicted recruitment (50% R_{max}) from fitted Beverton-Holt curve.
\2 RK50 = SSB at 50% of maximum predicted recruitment (50% R_{max}) from fitted Ricker curve.
\3 SH50 = SSB at 50% of maximum predicted recruitment (50% R_{max}) from fitted Shepherd curve.
\4 SSBb = Intersection of 90th percentile of survival rate and 90th percentile of recruitment observations.
\5 BHv = 20% virgin biomass from fitted Beverton-Holt curve and F=0 replacement line.
\6 RKv = 20% virgin biomass from fitted Ricker curve and F=0 replacement line.
\7 SHv = 20% virgin biomass from fitted Shepherd curve and F=0 replacement line.
\8 Rmnv = 20% virgin biomass from mean recruitment and F=0 replacement line.

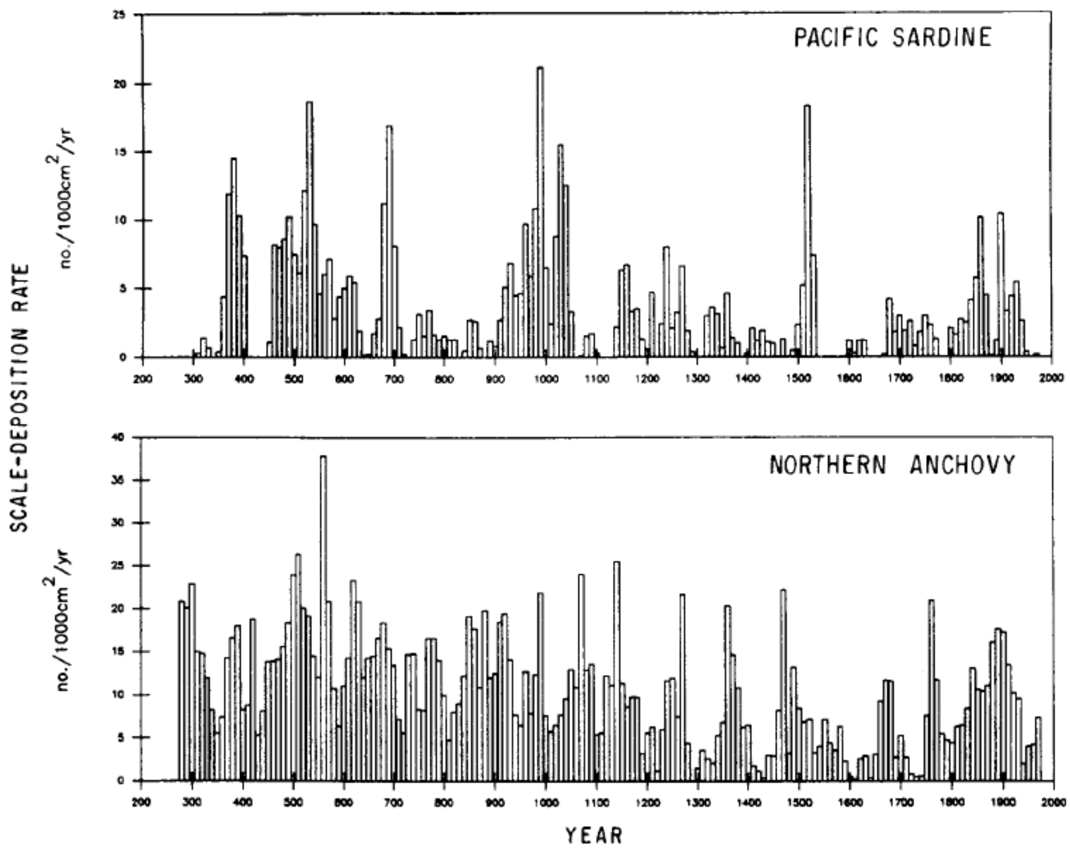

Figure 1. Composite time series of the Pacific sardine and northern anchovy scale-deposition rates in Santa Barbara Basin sediments (from Baumgartner et al. 1992).

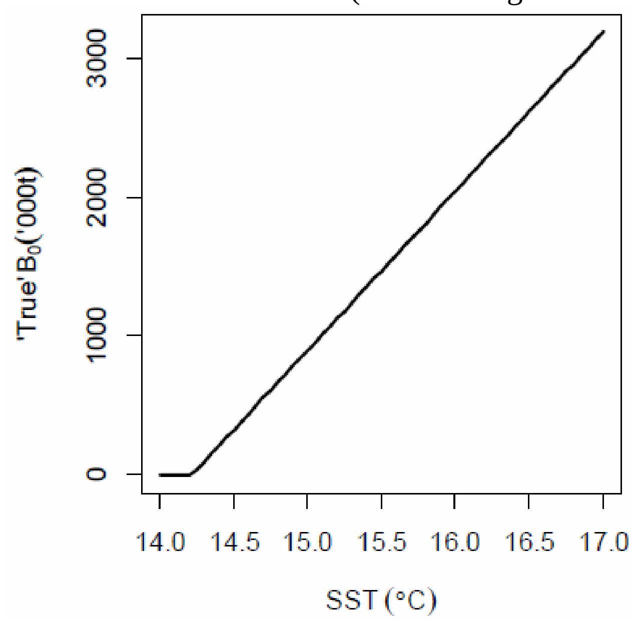

Figure 2. Relationship between SST and unfished equilibrium population size, B_0 (from Hurtado & Punt 2013). Scale of biomass estimates in this display are based on the MSE's operating model and should not interpreted as absolute.