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RE-EVALUATION OF THE RECRUITS-PER-SPAWNER AND CALCOFI SST RELATIONSHIP IN PACIFIC SARDINE

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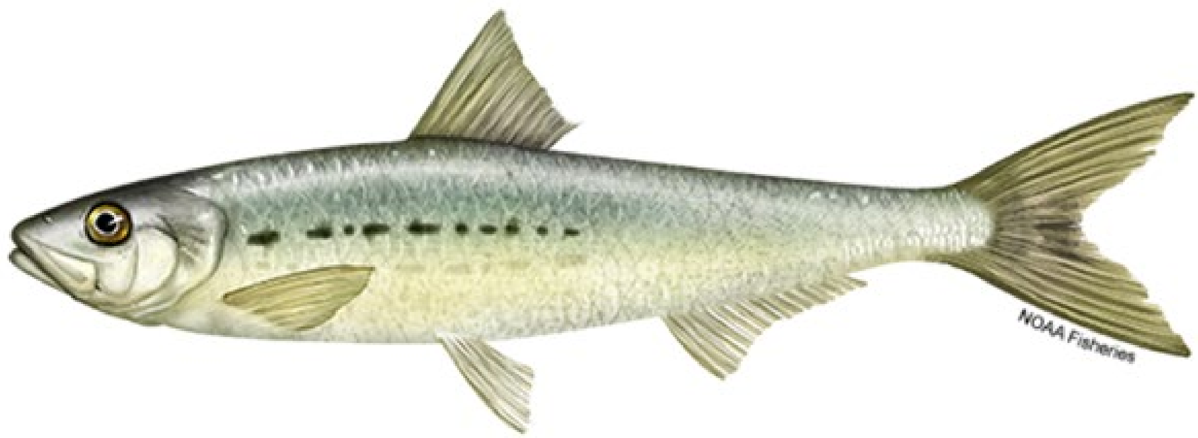

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1. Purpose

The purpose of this document is to re-calculate the correlation between the CalCOFI SST index and the indices of biomass and recruits with updated time series data, and to re-examine model selection results and model fit. This analysis follows the documented methods from the Pacific Fishery Management Council's 2013 sardine harvest parameters workshop (PFMC and SWFSC 2013).

2. Background

2.1. 2013 Workshop

The 2013 Pacific sardine harvest parameters workshop selected a general additive model (GAM) to assess the relationship between Pacific sardine recruits/spawner, age 2+ biomass, and the smoothed (non-linear) average sea surface temperatures (SST) measured by the CalCOFI survey. This workshop used a time series of sardine age 2+ biomass (spawners) and recruits that were assembled from previous stock assessments, from 1984-2008 (Table 1; Hill et al., 2010). The results are reported in PFMC and SWFSC (2013). In particular, Appendix Table E.6. of the 2013 Workshop report includes the model results. In re-creating these models, we found the values reported as R-squared in the Appendix E.6. table are squared Pearson correlations and the reported deviance explained values are adjusted R-squared values. We have renamed those values in this report for consistency and clarity (Table 2).

3. Data

3.1. Biomass and Recruitment Time Series

This relationship was re-evaluated by updating the recruits/spawner, age 2+ biomass, and CalCOFI SST time series. Recruits/spawner data for 1984-2004 were appended with the most recent stock assessment estimates of age 2+ biomass and recruits from 2005-2023 (Kuriyama et al, 2024). The decision to supplant 2005-2008 workshop values of recruits/spawner data with more recent data produced by stock assessments is based on the rationale that the most recent stock assessment values represent the best available science.

It is worth noting that the recruits/spawner time series spans changes in stock assessment model structure, assumptions, and an update to the habitat model.

3.2. CalCOFI SST

Values for the average annual CalCOFI SST reported in the workshop and published stock assessment reports also vary slightly. The time series of annual SST values are published stock assessments (2014 – 2023, Table 1). Earlier SST calculations (1984 – 2013) were conducted in a consistent manner with those generated for stock assessment by SWFSC scientists (documented in Kuriyama et al., 2024, section 5.3), and were used in this re-analysis, replacing SST values from the 2013 workshop (Table 1).

4. Methods: 2024 Model Update

Model Configurations:

1. Recruits/spawner time series:
    a. One time series patching together the 1984-2023 data.
    b. One time series with only the most recent stock assessment data (2005-2023).

2. Indicator: fitting to a log(recruits/spawner) relationship, which is consistent with the model chosen in the 2013 workshop.
3. GAM type:
    a. Configuration L model: SST (T_y) as a linear covariate: $\alpha + s(S_y, k = 3) + \beta T_y + \varepsilon_y$ where "α is an intercept parameter, $s(x, k = 3)$ is a nonlinear smooth function of x, and k controls smoothness by limiting the number of parameters in $s(x, k = 3)$, S_y is [age 2+] spawning biomass in year y, β is a slope parameter, T_y is SST, and ε_y is a normally distributed statistical error" (PFMC and SWFSC, 2013).
    b. Configuration G (consistent with the model chosen in the 2013 workshop): the same as L, but includes a smoother on SST (non-linear covariate), i.e.: $\alpha + s(S_y, k = 3) + s(T_y, k{=}3) + \varepsilon_y$.
    c. Configuration B is presented for comparison and does not include the SST covariate, i.e.: $\alpha + s(S_y, k = 3) + \varepsilon_y$.

5. Comparison of 2024 Update Results to 2013 Workshop Results

In comparing the updated time series models to the previous workshop results, we find that the best fitting model is still the GAM with CalCOFI SST as a smoothed covariate (model G) using the extended time series (1984-2023) across metrics for AIC, adjusted-R^2, squared Pearson correlation (R^2), and deviance explained (Table 2). While the adjusted R^2 in the best-fitting model has decreased to 0.44 from 0.74 with the addition of new data, it remains higher than the analysis based on same time series but with no SST covariate in model B at 0.11 (Table 2). The squared Pearson correlation of the best-fitting model for the extended time series (0.49) is similarly lower than the previously estimated value of 0.76, but is still much higher than the squared correlation of 0.13 for the baseline extended time series model with no SST covariate. In addition, the likelihood ratio tests (LRT) show similar results to the 2013 workshop in rejecting model B in favor of one with temperature as a covariate and indicating that the smoothed covariate term provides improved fit relative to the linear term (Table 3).

6. Additional Discussion

We agree with the workshop evaluation that fitting to the log(recruits/spawner) is a better choice than log(recruits) since log(recruits) will always be greater than 0 as long as temperature is greater than zero, irrespective of spawning abundance (Hurtado-Ferro and Punt, 2013). In addition, the smoothed GAM model fit to the extended time series now exhibits a dome-shaped response to SST, which is representative of a typical biological response to an optimal range of temperatures (e.g., Brewer, 1976; Figure 1).

Table 1. Data available for this reanalysis. Bolded data represent the data used in the full time series reanalysis, and bolded data after 2004 represent data used in the recent time series reanalysis. *Methods for SST estimation are documented in Kuriyama et al. (2024), section 5.3.

Year	BIOMASS (AGES 2+; 10^3 mt)		RECRUITS (AGE-0; millions)		Workshop Report	Annual SST from Stock Assessment Reports	
	Hill et al. 2010	Kuriyama et al. 2024	Hill et al. 2010	Kuriyama et al. 2024	SST_CC_ann	T_DegC	Source
1984	**13**		**239**		15.99	**16.35**	*E. Weber, *pers. comm.*
1985	**21**		**268**		15.67	**15.76**	E. Weber, *pers. comm.*
1986	**27**		**654**		15.73	**15.98**	E. Weber, *pers. comm.*
1987	**33**		**885**		16.19	**16.3**	E. Weber, *pers. comm.*
1988	**54**		**1270**		15.71	**15.79**	E. Weber, *pers. comm.*
1989	**84**		**1084**		15.65	**15.46**	E. Weber, *pers. comm.*
1990	**119**		**2261**		15.94	**15.99**	E. Weber, *pers. comm.*
1991	**134**		**5354**		15.71	**15.8**	E. Weber, *pers. comm.*
1992	**168**		**3910**		16.63	**16.7**	E. Weber, *pers. comm.*
1993	**250**		**10078**		16.33	**16.42**	E. Weber, *pers. comm.*
1994	**329**		**11130**		16.45	**16.48**	E. Weber, *pers. comm.*
1995	**562**		**4223**		15.79	**15.92**	E. Weber, *pers. comm.*
1996	**821**		**6252**		16.22	**16.33**	E. Weber, *pers. comm.*
1997	**820**		**17156**		16.8	**16.69**	E. Weber, *pers. comm.*
1998	**772**		**19743**		16.55	**16.77**	E. Weber, *pers. comm.*
1999	**1096**		**3624**		15.19	**15.28**	E. Weber, *pers. comm.*
2000	**1496**		**2928**		15.73	**15.79**	E. Weber, *pers. comm.*
2001	**1324**		**7959**		15.5	**15.55**	E. Weber, *pers. comm.*
2002	**1055**		**804**		14.91	**14.94**	E. Weber, *pers. comm.*
2003	**922**		**18578**		15.98	**16.03**	E. Weber, *pers. comm.*
2004	**670**		**9617**		15.78	**15.88**	E. Weber, *pers. comm.*
2005	967	**457**	10448	**26832**	15.36	**15.46**	E. Weber, *pers. comm.*

2006	1032	**582**	3277	**10311**	15.72	**15.92**	E. Weber, *pers. comm.*
2007	1071	**748**	3596	**5104**	15.06	**15.15**	E. Weber, *pers. comm.*
2008	848	**792**	2674	**3242**	15.13	**15.27**	E. Weber, *pers. comm.*
2009		**483**		**5072**		**15.36**	E. Weber, *pers. comm.*
2010		**313**		**6955**		**15.55**	E. Weber, *pers. comm.*
2011		**267**		**458**		**15.56**	E. Weber, *pers. comm.*
2012		**278**		**124**		**15.29**	E. Weber, *pers. comm.*
2013		**147**		**156**		**14.91**	E. Weber, *pers. comm.*
2014		**64**		**558**		**16.77**	Hill et al. 2014
2015		**32**		**608**		**17.47**	Hill et al. 2015
2016		**35**		**197**		**16.33**	Hill et al. 2016
2017		**39**		**349**		**16.12**	Hill et al. 2017
2018		**40**		**677**		**15.89**	Hill et al. 2018
2019		**28**		**548**		**15.98**	Hill et al. 2019
2020		**31**		**1589**		**16.41**	Kuriyama et al. 2020
2021		**52**		**559**		**15.48**	Kuriyama et al. 2021
2022		**42**		**571**		**15.69**	Kuriyama et al. 2022
2023		**41**		**728**		**15.62**	Kuriyama et al. 2024

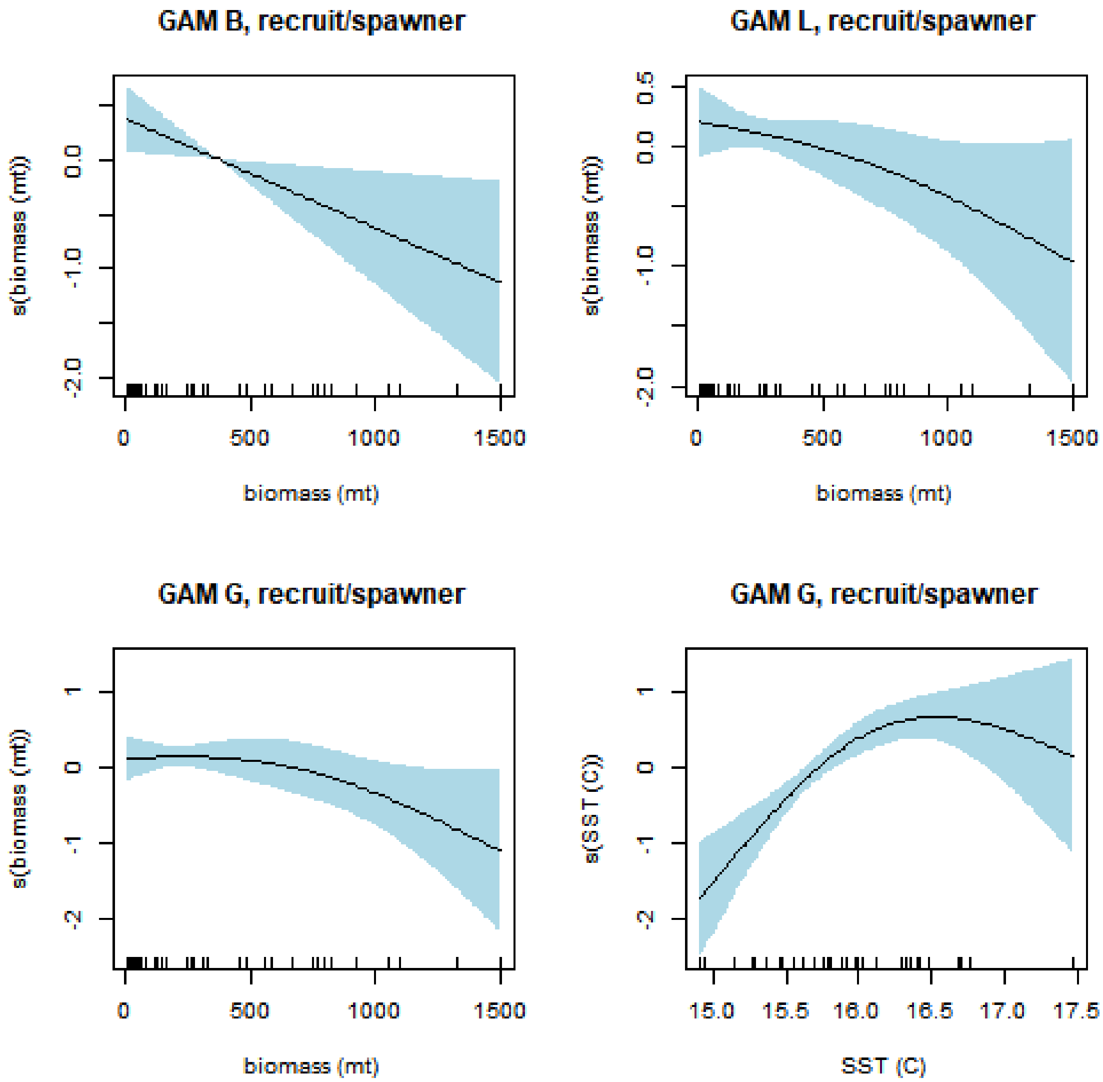
Table 2. Output of the updated model results, with the 2013 workshop model results included in the bottom two rows of the table for comparison. [1]The workshop reported deviance explained values that are actually adjusted R-squared values, and [2]the workshop values reported as R-squared in the Appendix E.6. table are squared Pearson correlations; both have been renamed for consistency and comparability with our analysis.

Time series	GAM type	GAM	N	Resid. DF	EDF of SST	AIC	R^2 adjusted	Squared Pearson corr. (R^2)
1984-2023	B	no SST covariate	40	38.00	0.00	122.23	0.11	0.13
1984-2023	**G**	**smooth SST covariate**	**40**	**35.50**	**1.89**	**106.04**	**0.44**	**0.49**
1984-2023	L	linear SST covariate	40	36.69	0.00	112.66	0.32	0.36
2005-2023	B	no SST covariate	19	17.00	0.00	66.49	-0.04	0.02
2005-2023	G	smooth SST covariate	19	15.33	1.67	63.42	0.18	0.30
2005-2023	L	linear SST covariate	19	16.00	0.00	65.18	0.07	0.17
1984-2008	**G**	**smooth SST covariate**	**25**	**21.73**	**1.27**	**44.49**	**0.74**[1]	**0.76**[2]
1984-2008	L	linear SST covariate	25	22.00	0.00	44.68	0.73[1]	0.76[2]

Table 3. Results of likelihood ratio tests between the different model configurations.

Model	Time series	pBG	pBL	pGL
Full timeseries	1984-2023	0	0.0007	0.0046
Short timeseries	2005-2023	0.0414	0.0806	0.0855
2013 workshop	1984-2008	0	0	0.12

A.


GAM B, recruit/spawner
s(biomass (mt))
biomass (mt)
GAM L, recruit/spawner
s(biomass (mt))
biomass (mt)
GAM G, recruit/spawner
s(biomass (mt))
biomass (mt)
GAM G, recruit/spawner
s(SST (C))
SST (C)

B.

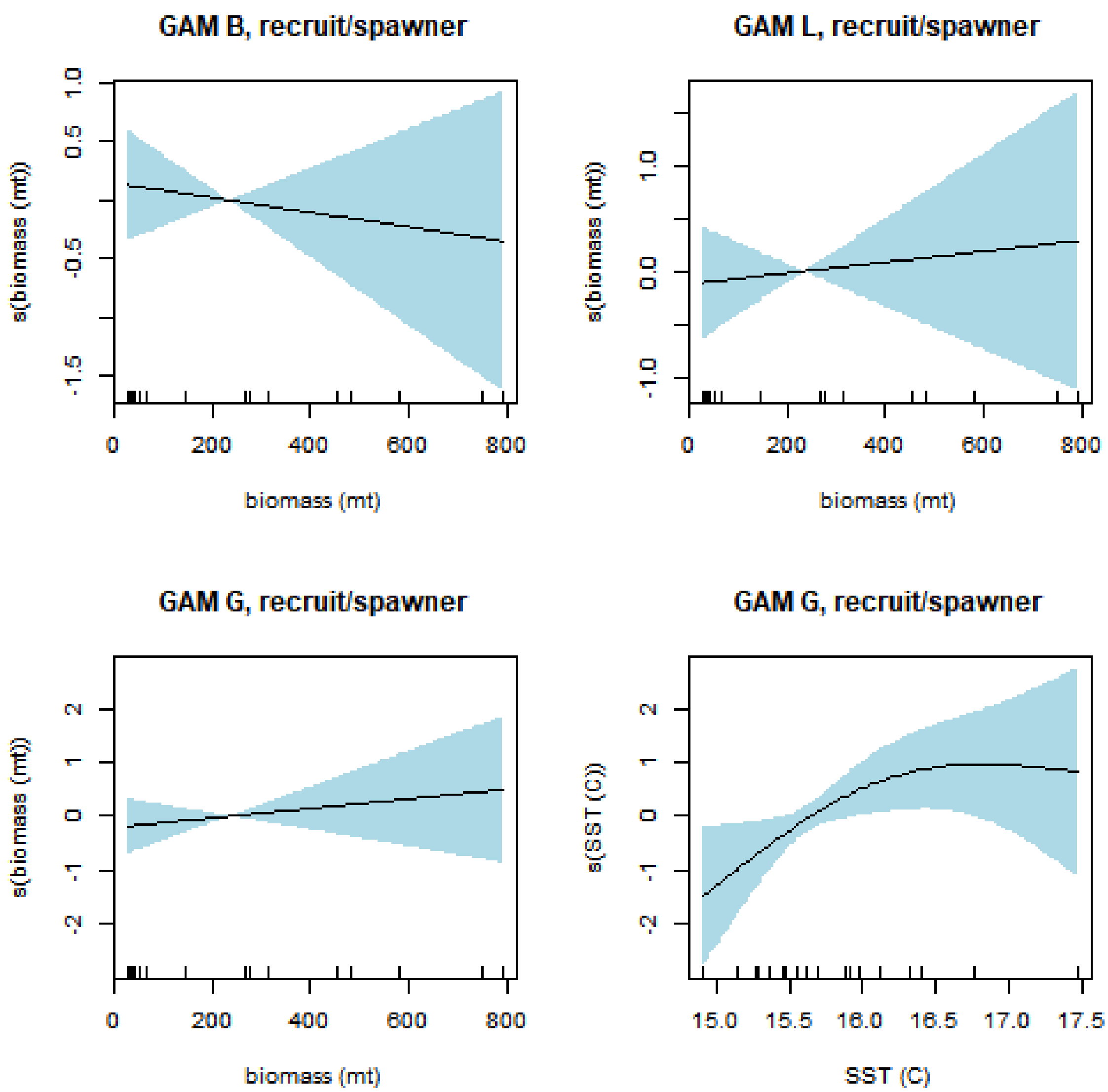


Figure 1. Plots of GAM results for each smoothed term (s(biomass (mt)) for spawning biomass or s(SST (C)) for temperature). The top figure (A) shows GAM results using the extended time series (1984-2023), and the bottom figure (B) shows GAM results using only the current assessment time series (2005-2023).

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