

# New Estimates of Monthly Biomass, Recruitment and Related Statistics of Anchoveta (*Engraulis ringens*) off Peru (4-14°S), 1953-1985\*

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## Abstract

A length-structured version of Virtual Population Analysis, implemented through the ELEFAN III computer program, was used to estimate, on a monthly basis, anchoveta (*Engraulis ringens*) biomass, recruitment, as well as fishing and natural mortalities off Peru for the period 1953 to 1985. This analysis, pertaining to the northern/central stock of anchoveta, took into account the predation effects of mackerel, horse mackerel, hake, bonito, guano birds (three species) and pinnipeds (two species), and was calibrated using acoustic estimates of anchoveta biomass.

The resulting time series demonstrate the impact of El Niño events on anchoveta population dynamics, and allow separation of the effects of various anchoveta predators from that of the fishery.

## Resumen

Se estimaron, en una base mensual, la biomasa, reclutamiento y la mortalidad natural y por pesca de la anchoveta peruana para el período 1953 a 1985, mediante el análisis de Población Virtual con estructuras por longitudes implementado en el programa ELEFAN III. Este análisis, llevado a cabo para el stock norte/central, consideró los efectos de predación de la caballa, jurel, merluza, bonito, aves guaneras (3 especies) y pinnípedos (2 especies) y fué calibrado usando estimaciones de biomasa obtenidas por medio de evaluaciones acústicas.

La serie de tiempo resultante demuestran el impacto de los eventos El Niño sobre la dinámica de la población de anchoveta y permite visualizar por separado el efecto de los predadores y de la pesquería.

## Introduction

This contribution presents time series of anchoveta (*Engraulis ringens*) biomass recruitment and mortality on a time scale (one month) that is sufficiently small for capturing the rapid changes that characterize this resource. Monthly time series of various aspects of the population dynamics of anchoveta have been presented earlier (Palomares et al. 1987; Pauly et al. 1987a). This contribution aims to:

- i) extend (to 1985) the previous time series, which covered the years 1953 to 1982;
- ii) include in the analysis the predatory effects of horse mackerel (*Trachurus murphyi*), mackerel (*Scomber japonicus*) and hake (*Merluccius gayi*), which were not explicitly considered earlier; and thus,

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- iii) reduce the uncertainty associated with the input values of baseline natural mortality ( $M_0$ ), an important parameter of Virtual Population Analysis (VPA), when this is implemented such as to explicitly account for predation.

This contribution represents, as far as the estimation of anchoveta biomass (and related statistics) is concerned, the "third iteration" mentioned by Pauly and Tsukayama (1987). As was also the case with the previous iterations, the biomass estimates presented here do not question the validity of the available independent estimate of anchoveta biomass off Peru obtained through acoustics and other methods. Rather, these were used to calibrate our VPA's, i.e., to estimate values of baseline natural mortality ( $M_0$ ) which made the VPA results compatible with the independent biomass estimates.

## Materials

The data used for this analysis largely overlap with those used in Pauly et al. (1987a). However, more information was available at the time this analysis was performed. Among other things, we used Tables 1 to 5, covering the period 1983 to 1987, in addition to the catch and catch composition data from Tables 1 to 30 of Tsukayama and Palomares (1987), covering the period 1953 to 1982. As in the previous analysis, all monthly nominal catches were multiplied with a factor of 1.2 to account for unrecorded catches (Castillo and Mendo 1987).

Total monthly withdrawals from the anchoveta population were computed as the sum of anchoveta consumption by the predators explicitly accounted for, plus the catch taken by the fishery (Table 6). In addition to the predator groups considered in Pauly et al. (1987a), i.e., cormorants, boobies and pelicans (from Muck and Pauly 1987); bonito (from Pauly et al. 1987b); sea lions and fur seals (from Muck and Fuentes 1987), the anchoveta consumption estimates of mackerel and horse mackerel (from Muck and Sanchez 1987), and hake (from Muck et al., this

Table 1. Monthly catch (in  $t \times 10^3$ ), per cent catch composition and condition factor (c.f.) of Peruvian anchoveta (*E. ringens*, northern/central stock, 4-14°S) based on data collected by IMARPE staff in 1983.

Tabla 1. Capturas mensuales (en  $t \times 1,000$ ), composición en porcentaje y factor de condición (c.f.) de la anchoveta peruana (*E. ringens*, stock norte/central, 4-14°S) basado en datos colectados por personal de IMARPE en 1983.

Midlength (TL; cm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
5.25												
6.25												
7.25												
8.25												
9.25												
10.25		0.06										
11.25		0.42										
12.25	7.24	1.59	4.5									
13.25	14.04	13.01	15.02									
14.25	18.81	21.36	17.32									
15.25	27.33	27.98	27.75									
16.25	18.00	23.04	19.62									
17.25	10.90	9.96	11.58									
18.25	3.71	2.4	4.02									
19.25		0.19	0.19									
20.25												
Catch	87,692	19,991	693	0	0	0	0	0	0	0	0	0
c.f. <sup>a</sup>	1.029	0.690	0.690	(0.598)	(0.633)	(0.642)	(0.666)	(0.673)	(0.665)	(0.652)	(0.714)	(0.635)

<sup>a</sup>Values in parentheses estimated from SST data in Table 6 of Brainard and McLain (1987) and SST vs. c.f. relationship in Palomares et al. (1987).

Table 2. Monthly catch (in  $t \times 10^3$ ), per cent catch composition and condition factor (c.f.) of Peruvian anchoveta (*E. ringens*, northern/central stock, 4-14°S) based on data collected by IMARPE staff in 1984.

Tabla 2. Capturas mensuales (en  $t \times 1,000$ ), composición en porcentaje y factor de condición (c.f.) de la anchoveta peruana (*E. ringens*, stock norte/central, 4-14°S) basado en datos colectados por personal de IMARPE en 1984.

Midlength (TL; cm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
5.25												
6.25					0.26							
7.25					7.96							
8.25					22.98					0.03		
9.25					11.67	2.39				0.03		
10.25					9.55	16.10	3.88			0.05		5.13
11.25	5.17				1.62	40.84	3.88		0.06	0.30		59.93
12.25	6.68				0.88	31.31	19.27		1.45	0.80	0.03	31.95
13.25	8.45				7.35	6.56	46.83		6.94	2.61	0.43	1.19
14.25	10.51		83.34		21.59	0.54	26.14		30.66	23.00	5.29	0.76
15.25	12.88		16.67		12.21	1.03			48.54	46.88	45.03	0.54
16.25	15.58				36.68	1.12			11.72	24.83	44.47	0.51
17.25	18.65				0.27	0.13			0.61	1.35	4.52	
18.25	22.08								0.06	0.13	0.33	
19.25												
Catch c.f. <sup>a</sup>	0 (0.616)	0 (0.605)	11 0.758	0 (0.620)	1,265 1.079	907 0.719	26 0.618	0 (0.674)	6,911 0.849	9,069 0.827	4,339 0.841	836 0.723

<sup>a</sup>Values in parentheses estimated from SST data in Table 6 of Brainard and McLain (1987) and SST vs. c.f. relationship in Palomares et al. (1987).

Table 3. Monthly catch (in  $t \times 10^3$ ), per cent catch composition and condition factor (c.f.) of Peruvian anchoveta (*E. ringens*, northern/central stock, 4-14°S) based on data collected by IMARPE staff in 1985.

Tabla 3. Capturas mensuales (en  $t \times 1,000$ ), composición en porcentaje y factor de condición (c.f.) de la anchoveta peruana (*E. ringens*, stock norte/central, 4-14°S) basado en datos colectados por personal de IMARPE en 1985.

Midlength (TL; cm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
8.25	0.06	0.01	0.03									
9.25	0.40	0.06	0.91	0.07	0.07	0.01						
10.25	0.93	0.24	3.39	1.35	1.35	0.79	0.20					
11.25	4.30	4.76	3.91	10.77	10.77	9.91	4.24					
12.25	21.42	22.17	8.14	13.01	13.01	28.92	18.96	0.51	0.06	0.05	0.02	0.08
13.25	38.47	33.00	38.21	20.29	20.29	34.23	29.75	9.98	3.29	3.86	2.80	2.58
14.25	20.29	23.03	39.21	26.62	26.62	20.31	25.39	37.33	24.86	36.21	25.63	29.76
15.25	6.10	9.37	4.43	20.40	20.40	4.47	14.23	38.29	40.16	42.11	44.51	41.71
16.25	6.59	6.16	1.13	4.39	4.39	0.83	5.34	11.63	23.31	14.34	22.74	21.40
17.25	1.44	1.19	0.60	2.81	2.81	0.51	1.77	2.07	6.73	2.94	3.93	4.20
18.25			0.03	0.27	0.27	0.04	0.13	0.19	1.52	0.51	0.37	0.26
19.25								0.01	0.05	0.02		
Catch c.f.	14,894 0.716	63,875 0.708	20,329 0.746	0 (0.718) <sup>a</sup>	0 (0.790) <sup>a</sup>	78,959 0.662	114,067 0.475	90,042 0.713	13,666 0.713	176,416 0.703	154,852 0.714	98,657 0.669

<sup>a</sup>Interpolated values.

Table 4. Monthly catch (in  $t \times 10^3$ ), per cent catch composition and condition factor (c.f.) of Peruvian anchoveta (*E. ringens*, northern/central stock, 4-14°S) based on data collected by IMARPE staff in 1986.

Tabla 4. Capturas mensuales (en  $t \times 1000$ ), composición en porcentaje y factor de condición (c.f.) de la anchoveta peruana (*E. ringens*, stock norte/central, 4-14°S) basado en datos colectados por personal de IMARPE en 1986.

Midlength (TL; cm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
7.25											0.05	
8.25											0.07	0.11
9.25											0.03	1.41
10.25											0.04	3.10
11.25											0.03	3.36
12.25			0.05								0.01	1.01
13.25	0.54	0.56	0.60	0.06	0.03	0.01	0.04			0.01		0.06
14.25	18.05	16.96	10.56	4.23	2.33	2.29	3.17	1.29	0.17	0.08		0.10
15.25	52.05	50.13	46.25	35.16	31.29	29.54	34.25	27.33	8.39	7.67	3.94	3.70
16.25	25.78	28.96	37.78	47.84	51.68	47.58	47.51	52.16	44.63	46.1	40.64	38.67
17.25	3.26	3.32	4.73	12.07	14.09	17.41	14.16	18.07	40.65	40.27	47.55	42.08
18.25	0.31	0.10	0.05	0.63	0.56	3.19	0.88	1.14	6.13	5.81	7.56	6.30
19.25				0.03	0.01		0.01		0.03	0.08	0.09	0.11
Catch	181,025	167,004	138,447	275,645	350,026	221,780	388,388	181,822	95,443 <sup>a</sup>	346,733 <sup>a</sup>	429,086	285,046
c.f.	0.706	0.317	0.764	0.731	0.745	0.683	0.706	0.686	0.680	0.688	0.705	0.669

<sup>a</sup>Northern subarea only.

Table 5. Monthly catch (in  $t \times 10^3$ ), per cent catch composition and condition factor (c.f.) of Peruvian anchoveta (*E. ringens*, northern/central stock, 4-14°S) based on data collected by IMARPE staff in 1987.

Tabla 5. Capturas mensuales (en  $t \times 1,000$ ), composición en porcentaje y factor de condición (c.f.) de la anchoveta peruana (*E. ringens*, stock norte/central, 4-14°S) basado en datos colectados por personal de IMARPE en 1987.

Midlength (TL; cm)	Jan	Feb	Mar	Apr	May	Jun	Jul
7.25		0.06	0.03				
8.25	0.10	0.34	0.20	0.01			
9.25	1.21	0.37	0.55	0.19	0.03	0.03	0.01
10.25	4.31	0.91	1.27	0.94	0.95	0.35	0.85
11.25	4.05	4.72	1.38	0.82	0.80	1.14	6.78
12.25	2.98	11.64	2.17	0.96	0.59	1.08	3.81
13.25	0.65	6.46	2.76	1.72	0.88	0.73	1.79
14.25	0.25	1.36	1.45	1.05	1.07	0.88	4.79
15.25	3.12	3.28	5.26	4.34	15.69	2.55	4.20
16.25	32.41	30.89	40.06	40.13	56.00	29.88	20.66
17.25	42.92	34.86	39.33	43.39	22.89	52.67	46.63
18.25	7.86	5.03	5.50	6.32	1.10	10.51	10.35
19.25	0.14	0.06	0.06	0.09		0.18	0.13
Catch	297,252	227,712	206,730	179,324	162,123	128,912	68,380
c.f.	0.956	0.618	0.583	0.625	0.689	0.616	0.632

Table 6. Total monthly withdrawals (in tonnes) of anchoveta (*Engraulis ringens*) off Peru (4-14°S), 1953-1982. The fishery catches are nominal catch x 1.2; the anchoveta predators considered are horse mackerels, bonitos, mackerels, hakes, cormorants, boobies, pelicans, fur seals and sea lions.

Tabla 6. Remoción total mensual (en toneladas) de anchoveta (*Engraulis ringens*) frente al Perú (4-14°S), 1953-1982. Las capturas de la pesquería son capturas nominales x 1.2; los predadores de anchoveta considerados son jurel, bonito, caballa, merluza, guanay, piquero, pelicano, lobo fino y lobo chusco.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1953	825,792	1,072,915	1,186,318	1,067,930	836,488	709,967	650,404	570,244	615,045	654,029	713,487	707,991
1954	736,209	821,801	746,619	694,627	668,921	645,430	601,546	477,193	530,968	539,766	649,731	731,855
1955	988,469	890,593	690,993	776,348	688,842	715,316	649,647	587,985	623,807	556,878	630,384	566,006
1956	711,910	882,715	951,986	839,926	768,389	765,215	718,719	613,748	591,626	601,781	629,876	544,707
1957	704,513	1,145,595	1,121,876	1,087,444	1,128,893	1,025,455	865,765	668,789	624,876	715,647	750,074	926,959
1958	1,118,527	1,161,427	1,135,944	922,152	783,434	703,347	620,305	575,577	595,014	646,443	694,920	579,613
1959	885,506	1,095,688	1,081,000	1,001,509	872,124	768,844	680,423	597,914	632,035	748,284	943,484	931,112
1960	1,057,142	1,073,039	1,030,897	817,823	707,982	845,860	665,600	639,292	664,652	717,887	884,518	1,004,675
1961	1,168,485	1,286,119	1,027,421	1,048,639	1,090,453	931,878	766,058	628,438	715,093	900,597	1,111,755	1,079,428
1962	1,142,568	1,136,605	1,084,660	1,124,940	1,267,573	1,020,028	882,416	784,018	842,735	982,643	1,311,027	1,304,075
1963	1,345,736	917,011	1,371,533	1,335,938	1,320,676	944,821	768,580	725,337	772,972	924,277	1,160,852	1,313,983
1964	1,736,191	1,451,241	1,722,931	1,453,814	1,147,499	873,492	824,960	788,922	671,556	1,121,027	1,360,506	1,403,321
1965	1,634,799	1,406,029	1,889,431	1,738,490	1,526,724	1,239,930	705,963	619,880	619,062	739,460	1,217,483	1,724,949
1966	2,108,870	1,820,584	1,803,065	1,566,259	1,445,641	500,575	467,057	457,040	977,800	1,317,426	465,949	1,393,149
1967	2,132,128	1,319,437	1,578,827	1,774,488	1,593,738	585,881	446,846	411,721	646,675	1,487,237	1,610,151	1,782,979
1968	2,014,350	1,443,427	1,356,605	1,534,794	1,395,790	381,045	400,837	422,222	1,686,059	1,659,054	1,386,920	1,291,634
1969	1,842,948	658,394	2,565,124	2,073,777	1,683,409	706,069	501,760	500,734	973,974	971,377	874,870	2,331,660
1970	2,671,681	1,735,979	1,774,977	2,574,871	1,452,261	589,097	484,631	472,545	1,649,159	1,769,176	1,475,093	1,150,553
1971	592,382	681,036	3,107,920	2,213,205	1,272,190	663,789	569,688	566,269	1,627,966	1,704,829	1,557,603	1,643,667
1972	635,019	835,215	2,569,167	2,138,103	1,024,547	815,770	539,086	437,416	327,779	378,466	419,146	552,076
1973	807,698	1,030,097	1,554,825	717,164	315,292	262,364	239,135	208,637	245,256	247,312	321,169	259,926
1974	303,602	369,590	895,124	1,295,566	895,902	461,777	369,151	335,729	337,252	935,602	905,044	395,543
1975	586,136	802,060	1,587,162	1,409,670	1,033,478	387,792	353,905	311,313	364,466	405,657	380,340	414,789
1976	769,163	960,260	1,279,830	1,297,294	1,024,264	1,173,557	694,150	482,145	340,740	397,048	717,567	724,577
1977	541,429	270,448	301,930	587,632	403,019	263,517	253,406	243,993	247,148	261,224	295,894	298,250
1978	338,841	481,089	411,555	411,391	334,055	293,744	230,341	148,032	144,757	161,731	198,212	345,996
1979	229,936	242,076	497,954	822,228	177,902	147,158	126,104	125,559	105,885	172,324	113,345	37,194
1980	108,740	109,587	129,529	129,600	241,712	144,648	107,183	96,116	105,984	115,985	146,397	182,580
1981	154,775	175,154	134,644	141,936	157,429	124,706	52,880	52,566	42,307	87,563	81,968	141,819
1982	104,597	164,257	251,417	270,384	293,452	261,435	343,821	44,199	57,276	11,224	240,192	331,198

vol.) were also included. These contributions contain anchoveta length-frequency data from stomach contents showing that the predators in question consume anchoveta of roughly the same size composition as is taken by the fishery, thus allowing pooling of catch and consumption data. Tables 1 to 5 (and Tables 1 to 30 of Tsukayama and Palomares 1987) were raised to total withdrawals as follows:

$$RF_{(i)} = \text{withdrawals}/W_{s(i)} \quad \dots 1)$$

where RF is the raising factor for each month (i) and  $W_{s(i)}$  is the weight of the % catch composition data in month (i). The values of  $W_{s(i)}$  were computed as

$$W_{s(i)} = \sum_{j=1}^n f_{ij} W_{ij} \quad \dots 2)$$

where  $W_{ij}$  is the mean weight of fish in class j of sample i, n the total number of length classes in that sample, and  $f_{ij}$  the % frequency of class j in sample i. The mean weight of the fish in each length class interval was obtained via length-weight relationships of the form:

$$W = a_i L^b \quad \dots 3)$$

from

$$W = 1/(L_{j2}-L_{j1}) a_i/(b+1) [L_{j2}^{b+1} - L_{j1}^{b+1}] \quad \dots 4)$$

where  $L_{j1}$  and  $L_{j2}$  are the lower and upper limits of class (j), and which provides an unbiased estimate of the mean weight of fish in a given length class (Beyer 1987). The value of b used in equation (4) was set equal to 3 and the appropriate values of a = c.f./100 (see Tables 1-5 for c.f. values for 1983-1987. Equations (1) to (4) were applied 403 times, for every month from January 1953 to July 1987, i.e., to the data in Tables 1 to 30 of Tsukayama and Palomares (1987), to the data in Tables 1 to 5, and to the samples interpolated to fill in gaps.

Missing % length-composition data were linearly interpolated between adjacent months for all years with data gaps except for 1953 and 1983 for which data for the corresponding months of 1955 and 1984, respectively, were inserted. In a few cases, minimum catch estimates, set at 1 tonne, were inserted in the catch-at-length matrix to prevent underflow and/or division by zero errors. We expect these manipulations to have little impact on final results - at least when compared with the large impact of the parameter  $M_0$ , of which only approximate values could be obtained (see below).

## Methods

(adapted from Pauly et al. 1987a)

### *Brief Description of Length-Structured VPA*

Beverton and Holt (1957) showed that the catch ( $C_i$ ) from a population during a unit time period (i) is equal to the product of the population size at the beginning of the time period ( $N_i$ ) times the fraction of the deaths caused by fishing, times the fraction of total deaths, or:

$$C_i = \frac{F_i}{Z_i} (1 - e^{-Z_i}) N_i \quad \dots 5)$$

where  $F_i$  is the fishing mortality in the ith period, M is the natural mortality, generally assumed constant for all period, and  $Z_i = F_i + M$ .

The version of Beverton and Holt's catch equation which has become most widely used for stock assessment purposes, however, is:

$$\frac{N_{i+1}}{C_i} = \frac{Z_i \cdot e^{-Z_i}}{F_i (1 - e^{-Z_i})} \quad \dots 6)$$

also written

$$\frac{C_i}{N_{i+1}} = \frac{F_i}{Z_i} (e^{-Z_i} - 1) \quad \dots 7)$$

which is the equation in Gulland's (1965) VPA and which can be derived from equation (5) by substituting for  $N_i$  the relationship:

$$N_i = N_{i+1} e^{Z_i} \quad \dots 8)$$

Given values of  $C_i$  and an estimate of  $M$  (here: " $M_0$ "), equation (7) can be used to estimate (retroactively) the size of past cohorts (i.e., of groups of fish born at the same time and exposed to the same mortalities throughout their lives), given an estimate of  $N_{i+1}$  from which to start the computation. Such estimate of  $N_{i+1}$  (expressing the last population size a cohort had before it went extinct) are usually called "terminal populations" ( $N_t$ ). Values of  $N_t$  can be obtained from:

$$N_t = C_t / F_t \quad \dots 9)$$

where  $C_t$  is the terminal catch (i.e., the last catch taken from a cohort before it went extinct) and  $F_t$  is the terminal fishing mortality, i.e., the fishing pressure (here inclusive of predation) that generated  $C_t$  (Mesnil 1980; Pauly 1984).

The feature of VPA that is most important in the context of this contribution is that, given high withdrawal estimates of population size obtained by repeated application of equations (6) or (7) tend to rapidly converge toward their true value, and hence, usually provide, given reasonable estimates of  $M$ , very reliable estimates of recruitment (Pope 1972; Pauly 1984). Moreover, the speed of convergence from the guessed values of  $N_t$  (i.e., values of  $N_t$  based on guessed values of  $F_t$ ) toward accurate values of  $N_i$  is a function of the ratio of  $F$  to  $M$ . That is, the higher the proportion of the cohort is which ends up being withdrawn by the fishery and eaten by horse mackerel, mackerel, hake, bonito, birds and seals, the more reliable the population estimates will be. This is the reason why we have accounted explicitly here for the anchoveta consumed by these predators, and thus left  $M_0$  low, rather than replace predation by a higher, constant estimate of  $M$ .

Three forms of VPA, all included in the ELEFAN III program, may be distinguished (Pauly and Tsukayama 1983; Gayanilo et al. 1988):

- i) VPA I, which is the version originally proposed by Gulland (1965) and which Pope (1972) reformulated as "Cohort Analysis";
- ii) VPA II, the VPA equivalent of Jones' (1981) "Length Cohort Analysis" (see also Jones and van Zalinge 1981; Pauly 1984; Pauly and Morgan 1987); and
- iii) VPA III, which combines features of (i) and (ii) and which is documented in Pauly and Tsukayama (1983), in Pope et al. (p. 386-390) in Morgan and Pauly (1987) and in Gayanilo et al. (1988).

VPA III is a version of VPA I performed on "cohorts" obtained by superimposing growth curves, drawn at monthly intervals, onto a set of catch-at-length data, the catch pertaining to each "cohort" and month being simply that part of the monthly catches contained between two adjacent growth curves (see Fig. 1).

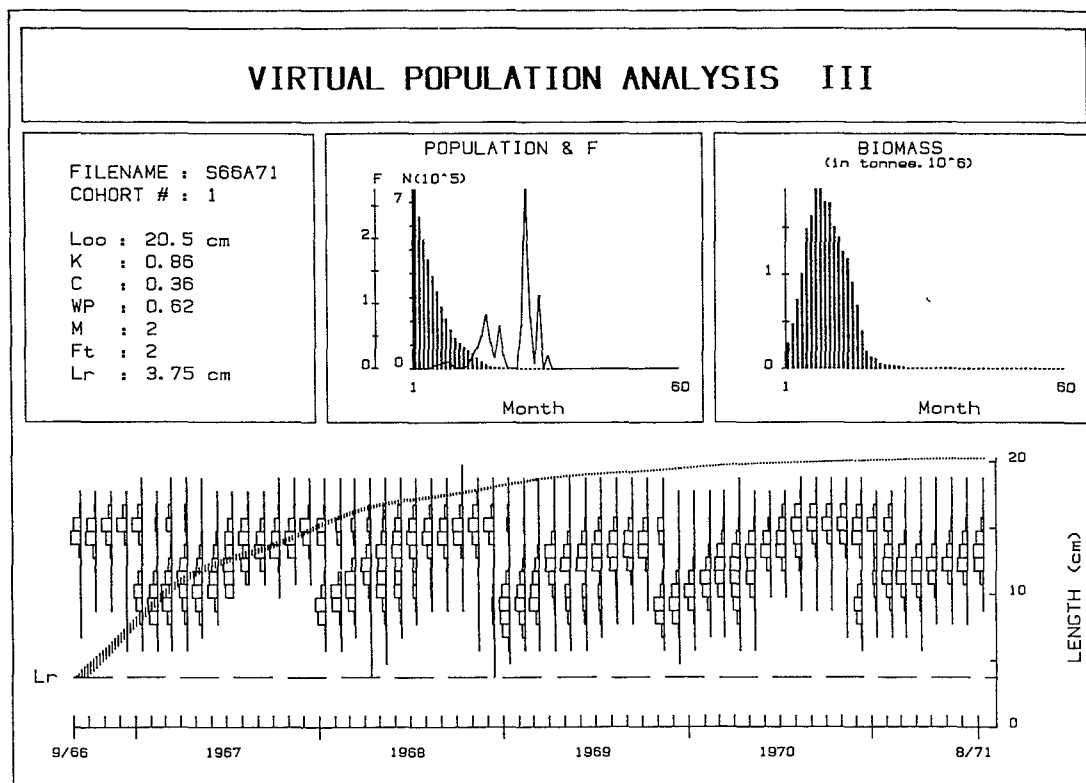


Fig. 1. Facsimile of an ELEFAN III output (via plotter) showing monthly catch-at-length data (not to scale) and one of the many monthly cohorts which can be superimposed on these data. The upper two panels show the population and fishing mortality estimate pertaining to this cohort, along with its biomass (rightmost panel). The population estimate pertaining to month 1 is an expression of recruitment of anchoveta of length  $L_r = 3.75-4.75$  cm (from Pauly et al. 1987a).

Fig. 1. Ejemplo de los resultados obtenidos con el ELEFAN III (via plotter) que muestra datos mensuales de la composición de la captura por longitudes (sin escala) y uno de los tantos cohortes que pueden ser sobrepuestos en esos datos. Los dos paneles de arriba muestran las estimaciones de la población y la mortalidad por pesca de esta cohorte junto a su biomasa (panel de la derecha). La población estimada correspondiente al mes 1 es una expresión del reclutamiento de la anchoveta de longitud  $L_r = 3.75-4.75$  cm (de Pauly et al. 1987a).

For such cohorts to really consist of fish recruited at the same time, the growth curves used for "slicing up" a cohort must be obviously as close to the true growth curve of that cohort as possible. This, among other things, makes it imperative that a seasonally oscillating growth curve be used, since, as shown in Pauly and Ingles (1981), Pauly (1982) and Longhurst and Pauly (1987), virtually all natural fish stocks, including those occurring in tropical waters, display seasonally oscillating growth (see also Palomares et al. 1987).

In reality, not all fish of a given cohort have the same growth parameters, however, and it can be expected that some fish will "leave their cohort" because they grow either faster or slower than predicted by the mean cohort growth curve. Such differences in growth rate should here have the effect of artificially increasing the autocorrelation between estimates of recruitment (see Mendelssohn and Mendo 1987).

The growth curves used here to "slice cohorts" were based on the seasonally oscillating version of the von Bertalanffy Growth Function (VBGF) developed by Pauly and Gaschütz (1979), i.e.,

$$L_t = L_\infty(1 - \exp(-[K(t-t_0)] = [KC/2\pi \sin 2\pi(t-t_s)]]) \quad \dots 10)$$

where  $L_t$  is the length at age  $t$ ,  $L_\infty$  the asymptotic length,  $K$  a growth constant,  $t_0$  the "age" at which length is zero if the fish always grew according to the equation,  $C$  is a dimensionless constant expressing the amplitude of the growth oscillations and  $t_s$  is the time (with respect to  $t = 0$ ) at the beginning of a sinusoidal growth oscillation of a one-year period.

For practical purposes, the estimation of  $t_s$  was replaced by the estimation of a Winter Point (WP), defined as:

$$t_s + 0.5 = \text{WP} \quad \dots 11)$$

which expresses (as a fraction of the year) the time during which growth is slowest. It should be mentioned here that the ELEFAN programs, being based on length-frequency data (rather than length-at-age data) do not allow for the estimation, nor require estimates of  $t_0$ , hence of *absolute* ages; all "ages" used internally by the programs are *relative* ages, expressed in relation to an arbitrary birthdate that is set internally and not output by the program.

For this reason, our estimates of growth parameters, biomass, recruitment, etc. are not affected by Somers' (1988) observation that equation (10) produces slightly biased estimates of  $t_0$  (when applied to *age-at-length* data).

The VPA III routines of ELEFAN III were applied to the available catch-at-length data, using for 1953 to 1982 the growth parameters in Table 3 of Palomares et al. (1987), new growth parameter estimates based on Tables 1 to 5 and on the ELEFAN I program (Pauly and David 1981; Gayanilo et al. 1988) for the years 1983 to 1987. The year-to-year differences in the values of these growth parameters caused a slight overlap of some "cohorts" (i.e., some of the catch data were used twice), and small gaps (i.e., some of the catch data were not included in any cohort). This source of error could have been avoided by using the same growth parameters throughout. This, however, would have caused a large bias, given the strong positive trend in anchoveta growth performance documented in Palomares et al. (1987).

### *Estimation of Monthly Recruitment and Biomass*

Monthly population estimates per length class were obtained by regrouping monthly values of  $N_i$  obtained on a cohort basis into regular class intervals (the same intervals as those in which the catch data were originally grouped). The population estimates (in numbers) of the smallest class considered here (3.75 to 4.75 cm) are here defined as "recruitment" (of fish with mean length 4.25 cm).

The population estimates (in numbers), by length class, were then multiplied, for each month and length class separately by the appropriate mean weight values (see equation 4) to obtain monthly population biomass by length class (Fig. 2).

The analyses for 1953 to 1982 were run with " $F_t$ " = 5 year<sup>-1</sup>, while those for 1983-1987 were run with " $F_t$ " = 2 year<sup>-1</sup>, because predation was not included as part of fishing "mortality" for the latter period. It is recalled that these values (a) pertain to  $Z-M_0$  (i.e., to the sum of true fishing mortality plus all sources of natural mortality represented by distinct predators and (b) that values of  $F_t$  have little impact on final results, especially on recruitment estimates.

### *Estimation of Natural and Fishing Mortalities*

The natural mortality ( $M_p$ ) exerted by any given predator (p) with anchoveta consumption  $C_{p(i)}$  was estimated, for each month (i) from

$$M_{p(i)} = \text{anchoveta consumption } (C_{p(i)}) / \text{anchoveta biomass } (i) \quad \dots 12)$$

Similarly, fishing mortality (F) was estimated from

$$F_i = \text{anchoveta fishery catch } (i) / \text{anchoveta biomass } (i) \quad \dots 13)$$

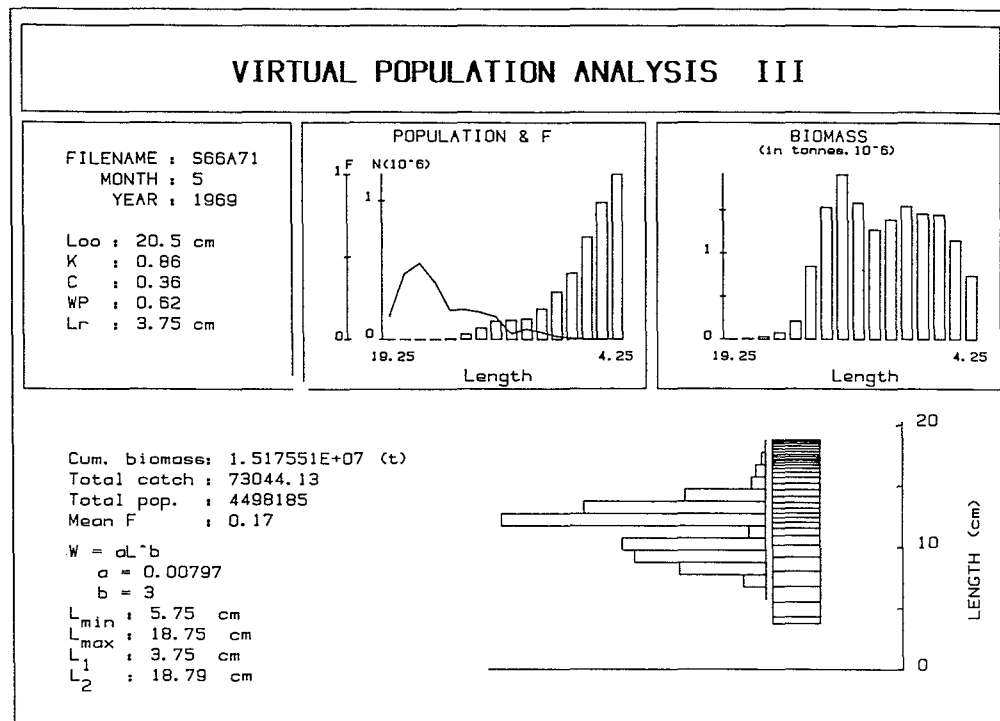


Fig. 2. Facsimile of an ELEFAN III output (via plotter) showing summary of result of a VPA III pertaining to a given month (here May 1969), and showing the catch data (lower panel, right, histograms) the cohorts "passing through" that month (box with narrowing lines), the size structure of the population (upper boxes, center and right), as well as summary statistics (lower panel, left) (from Pauly et al. 1987a).

Fig. 2. Ejemplo de los resultados obtenidos con el ELEFAN III (via plotter) mostrando un resumen de los resultados del VPA III correspondientes a un mes dado (aquí Mayo 1969), y los datos de captura (panel inferior de la derecha, histogramas) del cohorte que está "pasando a través" de ese mes (cuadro con líneas que se juntan), la estructura por tamaños de la población (cuadros de arriba, centro y derecha), así como un resumen estadístico (panel de abajo, izquierda) (de Pauly et al. 1987a).

Thus, all estimates of mortality presented here pertain to weights, not numbers. From these data, total mortality ( $Z$ ) can be estimated from:

$$Z_i = F_i + M_o + \sum_{m=1}^5 p_i \quad \dots 14)$$

where  $m$  is the number of predator groups considered here, i.e., horse mackerel and mackerel, hake, bonito, birds and seals.

## Results and Discussion

### *Estimate of Growth Parameters for the Years 1983 to 1987*

The length-frequency data in Tables 1 to 5 had too many gaps to allow estimation of growth parameters for different cohorts or years. Therefore, we applied the ELEFAN I program to all data in Tables 1 to 5. This resulted in the following estimates: asymptotic length  $L_{\infty} = 20.3$  cm (TL); growth constant  $K = 0.8$  year<sup>-1</sup>; amplitude of seasonal growth oscillation  $C = 0.27$  and Winter Point (i.e., time of the year with lowest growth rate)  $WP = 0.62$ .

These values resemble those estimated by Palomares et al (1987). However, the growth performance index  $\phi' = \log_{10} K + 2\log_{10}L_{\infty}$  (Pauly 1979; Pauly and Munro 1984) for this period was 2.518, i.e., lower than estimated for the late 1970s and early 1980s. The new estimate of  $\phi'$  is still higher, however, than the values estimated for the 1950s, thus confirming, overall, the trend expressed by Fig. 3.

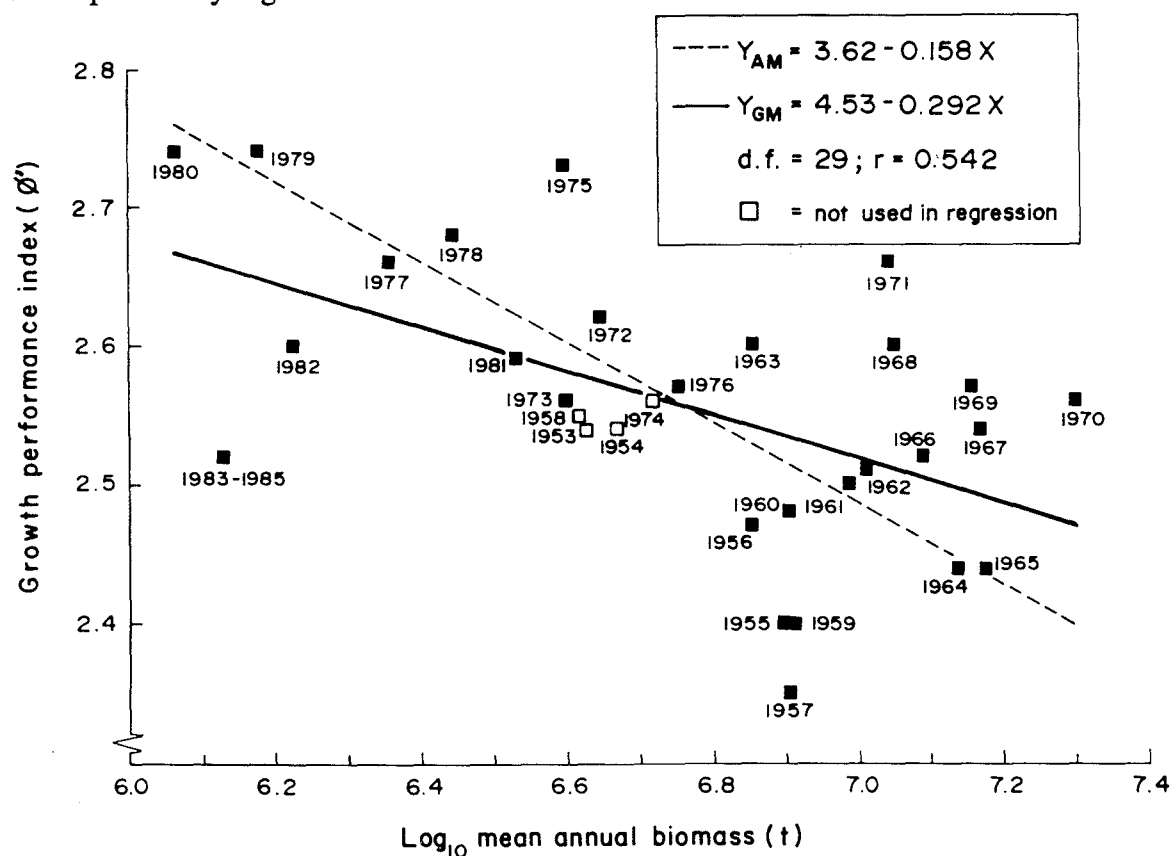


Fig. 3. Relationship between the growth performance index of anchoveta ( $\phi' = \log_{10}K + 2\log_{10}L_{\infty}$ ; K in year<sup>-1</sup>; L<sub>∞</sub> in cm T.L.) and mean anchoveta biomass off Peru (4-14°S), 1953 to 1985 (this contribution). The  $\phi'$  values are from Palomares et al. (1987) and the present contribution. Note clear evidence of density-dependent growth of anchoveta.

Fig. 3. Relación entre el índice de eficacia en crecimiento de la anchoveta ( $\phi' = \log_{10} K + 2 \log_{10} L_{\infty}$ ; K año<sup>-1</sup>; L<sub>∞</sub> en cm L.T.) y la biomasa promedio de anchoveta (4-14°S) 1953 a 1985 (ésta contribución). Los valores de  $\phi'$  son de Palomares et al. (1987) y de la presente contribución. Nótese la clara evidencia de la densodependencia del crecimiento de la anchoveta.

### Estimates of $M_0$ and Their Implication

Table 7 and Fig. 4 document the values of  $M_0$  obtained iteratively, i.e., by changing the input value of  $M_0$  for a given month until the biomass estimated by VPA matched the independent biomass estimates in Table 7.

As might be seen, the estimated values of  $M_0$  are extremely variable. Thus, our extrapolation of  $M_0 = 0.6$  year<sup>-1</sup> for the period 1953 to 1963 is tentative. On the other hand, the overall level of  $M_0$  is lower, by a factor of about three, than the level of  $M_0$  in Pauly et al. (1987a). This is due to the explicit consideration of the predation effect of horse mackerel, mackerel and hake, whose anchoveta consumption is now included in the total withdrawals (Table 6).

Indeed, if one assumes that the independent biomass estimates are accurate, then the drop to zero of the  $M_0$  values in the early 1970s suggests that total withdrawals were overestimated for that period.

A similar decline was demonstrated by Pauly et al. (1987a) for the early 1970s, and shown to parallel independent (tagging) estimates of natural mortality. The explicit consideration here

the effect of new predators - especially horse mackerel - has now further reduced our  $M_0$  estimates. Our VPA biomass estimates are, for the early 1970s, lower than the independent estimate (see Fig. 4) suggesting that, for that period,  $M_0$  should have been negative, or more reasonably, that the withdrawals and the observed biomasses are mutually incompatible. One way to correct for this would be to identify (in a fourth iteration) a mechanism leading to reduced estimates of consumption by the various anchoveta predators during the period in question.

Table 7. Independent estimates of anchoveta biomass off Peru (4-14°S) and estimated values of baseline natural mortality ( $M_0$ ) using VPA III (see also Fig. 4).

*Tabla 7. Estimaciones independientes de biomasa de anchoveta (4-14°S) y valores estimados de la línea base de mortalidad ( $M_0$ ) usando el VPA III (ver también Fig. 4).*

Month/ year	Independent biomass estimate (t x 10 <sup>6</sup> ) <sup>a</sup>	Source of biomass estimates	VPA III estimates of $M_0$ (year <sup>-1</sup> )	
Jan '64	14.20	Fig. 1 and text IMARPE (1974a)	0.84	
Jan '65	11.20		0.25	
Jan '66	13.30		1.04	
Jan '67	13.80		1.08	
Jan '68	13.30		1.41	
Jan '69	12.50		1.67	
Jan '70	18.30		1.59	
Jan '71	15.40		2.19	
Mar '72	3.00		<0.01	
Sep '72	2.00		<0.01	
Jan '73	3.16	<0.01		
Feb '73	3.30 <sup>b</sup>	<0.01		
Sep '73	3.09	<0.01		
Nov '73	4.48	IMARPE (1974b)	0.11	
Feb '74	3.39		<0.01	
May '74	2.19		<0.01	
Aug '74	3.92		<0.01	
Sep '74	3.09		<0.01	
Nov '74	3.25		<0.01	
Feb '75	4.32		<0.01	
Aug '75	3.39		0.66	
Sep '75	4.27		1.35	
Jan '76	7.41		0.89	
Aug '76	4.62	Johannesson and Vilchez (1981)	1.20	
Feb '77	1.89		0.08	
Jul '77	1.39		0.93	
Jun '78	3.78		2.59	
Nov '78	2.02		1.00	
Apr '79	2.15		2.25	
JI/A '84	0.83		Vilchez et al. (1988)	0.99
Apr '85	4.94			1.12
May '86	3.18			0.14
Nov '86	1.80			<0.01
Au/S '87	0.70	-		
Jun '88	3.77	IMARPE (1988)		-

<sup>a</sup>All values were adjusted through linear inter- and extrapolations to pertain only to the region between 4 and 14°S.

<sup>b</sup>See also Johannesson and Robles (1977).

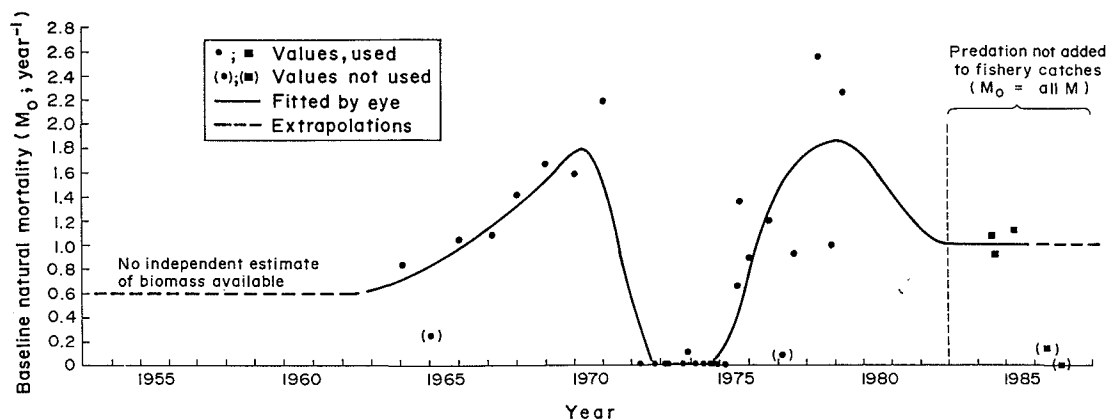


Fig. 4. Estimates of baseline natural mortality ( $M_0$ ), as required to reproduce independent estimates of anchoveta biomass in Table 7, using the VPA III routine of the ELEFAN III program. Note forward and backward extrapolations, and that high withdrawals, from 1972 to early 1975, precluded reproduction of independent biomass estimates using positive values of  $M_0$  (see text).

Fig. 4. Estimaciones de la línea base de mortalidad natural ( $M_0$ ) requeridas para reproducir estimaciones independientes de biomasa de anchoveta en la Tabla 7, usando la rutina del VPA del programa ELEFAN III. Nótese las extrapolaciones hacia adelante y hacia atrás y que las altas remociones, de 1972 y comienzos de 1975, imposibilitan la reproducción de estimaciones independientes de biomasa usando valores positivos de  $M_0$  (ver texto).

### Estimates of Anchoveta Biomass and Recruitment, 1953 to 1985

Table 8 and Fig. 5 present our biomass estimates. Table 8 presents the data on a monthly basis, while Fig. 5, recalls them as smoothed series, emphasizing the interannual changes.

As might be seen, this time series quite faithfully reflects the known dynamics of the stock, inclusive of rapid decreases associated with El Niño events. This also applies to the early period for which no independent biomass estimates are available (1953 to 1963) and whose overall level of biomass may be higher (or lower, depending on  $M_0$ ) than indicated. The biomass estimates for the early 1970s are, as discussed above, slightly too high. This improves, however, in the late 1970s and early 1980s, and indeed the near total collapse following the strong 1982-1983 El Niño event is rather well reproduced.

We have abstained from presenting in table form the length composition of the biomass estimates summarized in Table 8 and Fig. 5, but these are available on 5-1/4' MSDOS diskettes, along with our inputs and other data (see Appendix I).

Fig. 6 presents our estimates of anchoveta recruitment<sup>a</sup> for the period 1953 to 1985. As might be seen, these time series resemble those of biomass, which is not surprising for a resource in which 0.5 to 1.5 year old fish constitute the bulk of the biomass.

Two important features of this time series match those reported earlier by Pauly et al. (1987a), i.e.,

- i) the increased within-year variability of recruitment from the late 1950s to the late 1960s, probably an effect of the increasing fishing pressure; and
- ii) the fact that the recruitment collapse of 1971 appears to have occurred *before* the onset of the 1972-1973 El Niño event, as also observed by Mendelssohn and Mendo (1987).

Item (ii) implies that the El Niño event of 1972-1973 (at least as conventionally defined, i.e., as temperature anomaly) cannot have been the cause for the collapse of the fishery.

### Natural and Fishing Mortality of Anchoveta, 1953 to 1985

Fig. 7 presents our estimates of predator-specific  $M$  values, our estimates of total  $M$ , of  $F$  and of  $Z = M + F$ . As might be seen, horse mackerel is by far the most important predator of anchoveta, followed (in the 1950s at least) by cormorants, bonito, mackerel and hake.

<sup>a</sup>Editors' note: These estimates are also documented in Table 2 of Appendix I.

Table 8. VPA III estimates of anchoveta biomass off Peru (4-14°S), January 1953 to August 1985 (in tonnes).  
 Tabla 8. Estimaciones de biomasa de anchoveta frente al Perú (4-14°S) mediante el VPA III, Enero 1953 a Agosto 1985 (en toneladas).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1953	5,273,333	5,332,432	5,068,356	4,732,896	4,437,194	4,229,566	4,032,404	3,893,989	3,301,880	3,343,782	3,449,599	3,615,853
1954	4,515,320	4,719,681	4,823,731	4,924,143	4,917,512	4,810,300	4,544,498	4,440,413	4,508,864	4,559,097	4,698,249	4,752,512
1955	7,795,231	8,059,812	8,342,795	8,335,965	8,263,994	7,965,718	7,562,810	7,332,870	7,365,702	7,495,989	7,805,237	8,151,112
1956	7,089,264	7,206,608	7,265,571	7,439,651	7,366,700	7,343,874	7,149,830	6,966,351	6,753,963	6,744,946	6,901,314	7,147,365
1957	9,252,552	9,125,360	9,092,212	8,957,621	8,412,497	7,953,915	7,478,838	7,209,598	7,224,006	7,205,715	7,293,950	7,149,962
1958	5,070,142	4,892,199	4,795,686	4,573,515	4,491,117	4,312,200	4,083,549	3,727,062	3,565,956	3,475,082	3,452,610	3,526,188
1959	5,961,980	6,306,387	6,831,662	7,427,582	8,011,048	8,429,620	8,734,230	8,882,412	8,999,017	9,175,769	9,423,735	9,640,071
1960	6,666,056	7,142,783	7,597,619	7,980,020	8,314,255	8,398,191	8,184,005	8,040,322	8,024,638	8,206,459	8,576,082	8,903,001
1961	9,507,219	9,583,872	10,075,863	10,404,831	10,132,890	9,434,414	8,733,692	8,902,026	9,543,712	9,906,323	9,947,812	9,883,355
1962	10,051,414	10,061,623	10,941,309	11,120,378	10,850,292	10,083,781	9,818,269	9,871,519	10,105,850	10,094,572	10,213,415	9,812,666
1963	7,832,765	7,535,953	7,800,681	7,921,076	7,518,253	4,736,437	6,058,325	5,847,840	6,112,957	7,335,947	8,159,838	9,065,109
1964	13,229,833	13,210,993	14,062,682	14,369,568	15,096,616	14,771,587	14,739,721	14,836,930	14,104,511	14,171,854	10,639,644	11,377,494
1965	14,812,507	12,377,234	14,127,285	13,874,998	13,475,350	13,215,424	14,284,232	14,656,564	14,935,035	17,025,442	18,297,366	19,025,254
1966	12,916,518	13,208,795	12,438,383	12,738,976	12,721,971	10,925,868	11,152,847	11,480,069	11,690,221	12,324,594	12,327,534	13,329,965
1967	14,243,137	12,827,012	14,276,425	14,109,462	13,741,492	14,664,788	14,069,646	14,739,803	14,932,144	16,447,987	16,260,340	16,667,207
1968	12,766,037	12,198,458	12,320,137	12,846,767	11,453,907	10,709,782	10,719,875	10,830,087	10,363,791	9,642,320	10,201,184	10,735,116
1969	11,821,083	11,931,786	12,462,217	12,268,131	13,959,746	11,824,101	13,257,479	14,557,659	15,752,115	16,166,783	18,724,670	20,030,972
1970	20,388,480	21,218,716	22,783,714	21,079,576	20,434,284	19,123,574	19,074,822	18,536,920	18,815,296	18,833,030	18,920,386	20,664,156
1971	10,922,469	13,043,405	14,308,998	12,028,685	10,836,496	10,231,702	11,013,697	10,907,770	10,469,347	10,087,245	9,691,741	8,683,223
1972	8,043,960	7,969,600	8,068,886	5,313,904	3,753,378	3,146,167	2,626,106	2,442,102	2,418,136	2,597,167	2,889,928	3,915,887
1973	4,170,048	4,153,528	4,489,177	3,354,402	2,985,354	3,210,263	5,288,675	3,530,712	3,754,857	3,981,788	4,252,518	4,607,763
1974	4,936,110	5,270,781	6,035,931	5,502,677	4,800,321	4,449,409	4,640,200	4,879,067	5,126,927	5,774,150	5,789,662	5,429,115
1975	4,650,409	5,455,392	5,511,036	4,803,395	3,903,044	3,228,646	3,163,909	3,138,126	3,127,783	3,332,876	3,355,898	3,775,461
1976	7,092,915	7,415,232	8,020,737	6,544,905	6,096,795	5,131,526	4,315,163	4,693,030	4,681,332	4,519,576	4,932,656	4,560,410
1977	2,760,918	3,025,668	2,949,233	2,736,841	2,229,920	1,879,846	1,698,077	1,604,278	1,640,095	1,854,590	2,265,478	2,624,053
1978	2,674,240	2,374,089	3,060,656	2,928,502	2,890,239	2,489,025	2,636,846	3,074,006	2,751,110	2,709,076	2,769,031	2,883,141
1979	2,220,062	2,345,230	2,279,710	1,921,915	1,424,376	1,403,859	1,341,497	1,261,441	1,167,837	933,541	834,357	940,000
1980	1,078,731	1,195,093	1,337,266	1,023,803	1,366,529	1,146,462	1,307,882	1,262,657	1,084,800	1,021,143	970,076	1,040,570
1981	3,406,370	3,527,701	3,676,925	3,671,599	3,707,965	3,375,280	3,588,441	3,421,931	3,263,902	3,096,604	2,964,266	3,182,371
1982	2,820,826	2,695,177	2,761,440	2,399,998	2,328,817	1,626,237	1,651,296	1,004,998	929,512	828,566	673,280	412,053
1983	120,765	24,151	6,279	7,145	17,543	21,935	26,560	32,402	39,541	47,995	59,746	77,152
1984	106,408	151,009	269,524	304,091	868,126	721,067	742,965	949,138	1,052,128	1,546,609	1,959,610	2,134,431
1985	2,632,144	3,198,372	3,939,355	4,152,693	4,574,965	4,632,388	3,384,967	5,035,334	-	-	-	-

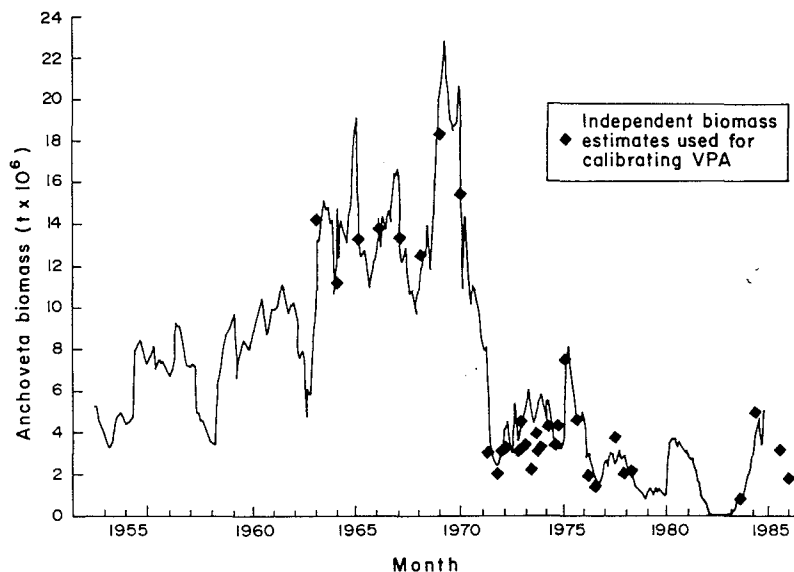
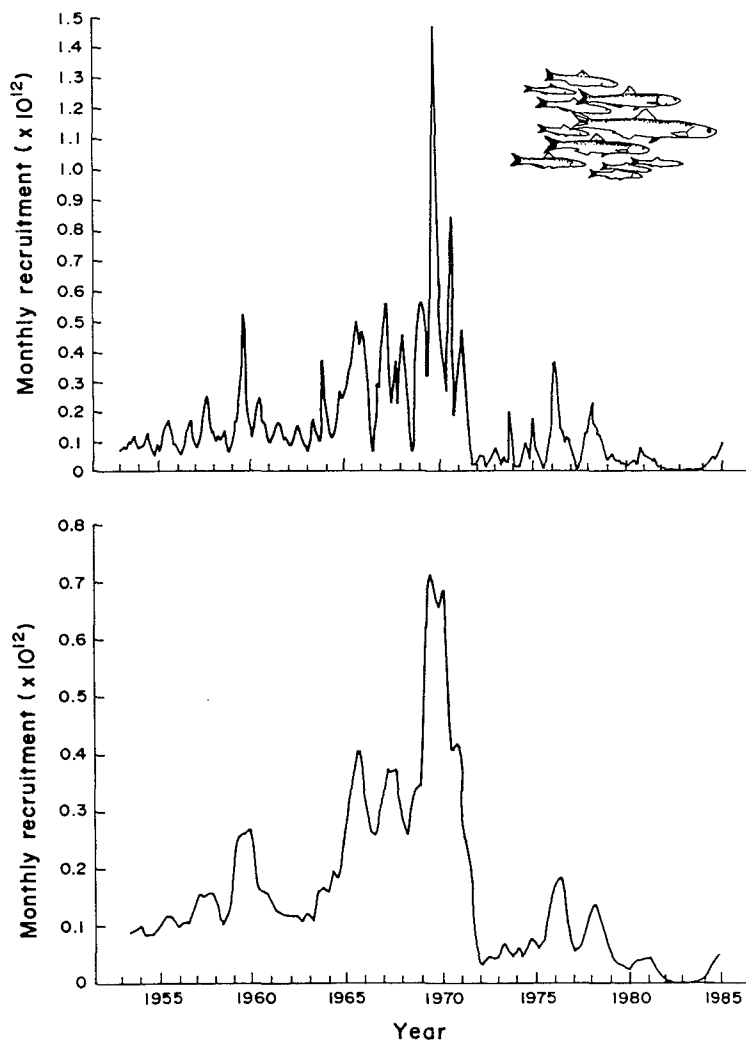


Fig. 5. Biomass estimates of Peruvian anchoveta, 4-14°S, 1953-1985 (obtained through the VPA III routine of the ELEFAN III program, see text) and showing independent biomass estimates used to calibrate VPA.

Fig. 5. Estimaciones de biomasa de la anchoveta peruana 4-14°S, 1953-1985 (obtenida mediante la rutina del VPA III del programa ELEFAN III, ver texto) y estimaciones de biomasa independientes usadas para calibrar el VPA.

Fig. 6. Time series of recruitment (of fish ranging from 3.75 to 4.75 cm, slightly less than 3 months old) into the anchoveta stock, January 1953 to December 1985. Above: monthly recruitment showing increasing variability, from the late 1950s to 1970, probably due to increasing fishing pressure and leading to recruitment collapse in early 1971, prior to the onset of the 1972-1973 El Niño. Below: smoothed data (using a 12-month running average), showing that the 1960s, which saw the buildup of the fishery, may have been a period of exceptionally and steadily high recruitment.

Fig. 6. Serie temporal de reclutamiento (de peces en un rango de 3.75-4.75 cm, algo menos de tres meses de edad) al stock de anchoveta, Enero 1953 a Diciembre 1985. Arriba: reclutamiento mensual mostrando un incremento en la variabilidad, de fines de la década del 1950 a 1970, probablemente debido al incremento de la presión pesquera y que condujo al colapso del reclutamiento a comienzos de 1971, antes de la aparición del fenómeno de El Niño 1972-1973. Abajo: datos suavizados (usando promedio corrido de 12 meses), mostrando que la década del 1960, que marcó el surgimiento de la pesquería, puede haber sido un período de reclutamiento excepcionalmente alto y constante.



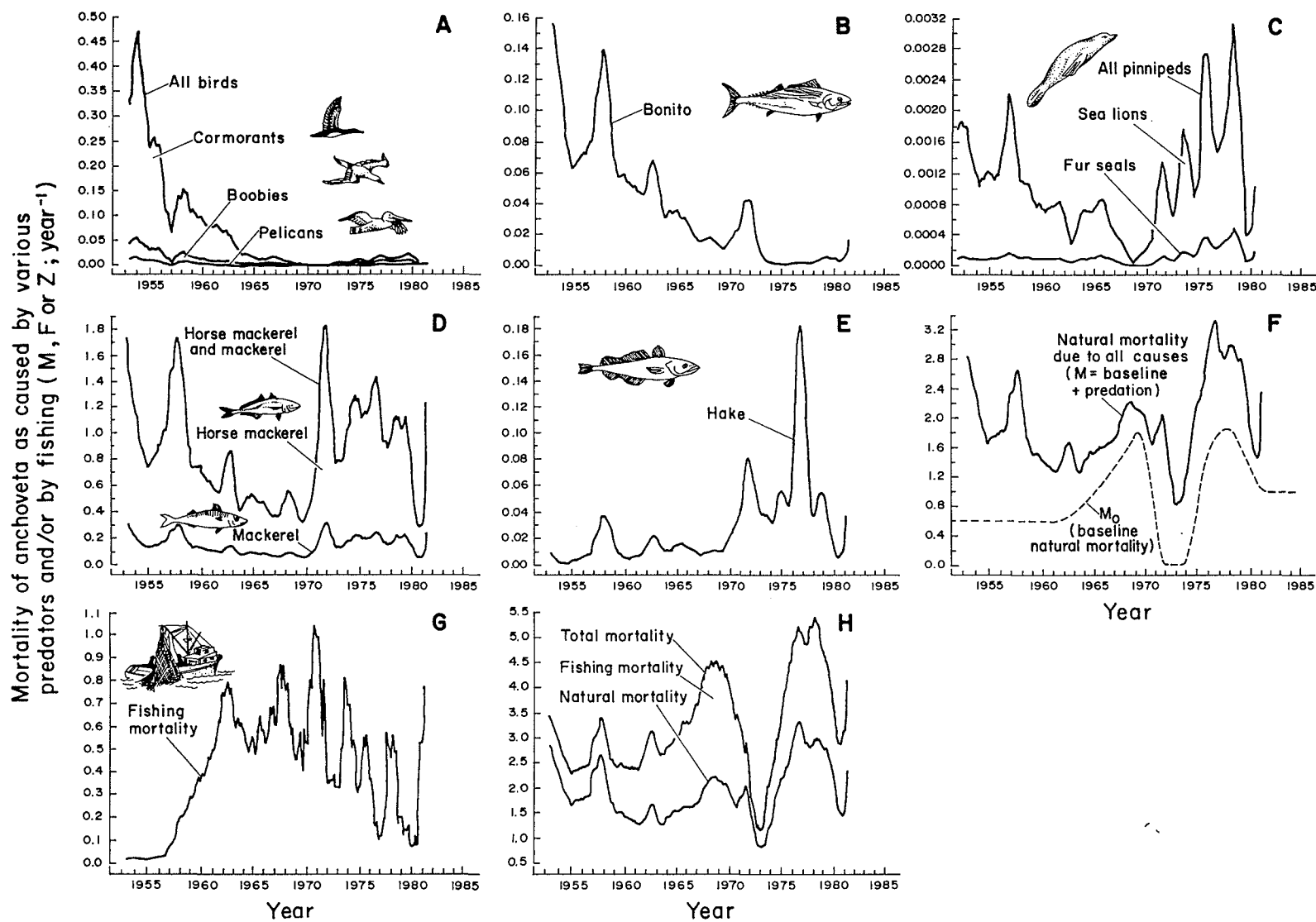


Fig. 7. Estimates of natural mortality due to various predators (A-E), all causes (F), and estimates of fishing (G) and total mortality (H) of Peruvian anchoveta. Data values smoothed over 13 months to emphasize interannual variations. Note different scales, and comparatively large impact of horse mackerel.

Fig. 7. Estimaciones de la mortalidad natural debido a varios predadores (A-E), a todas las causas (F) y estimaciones de mortalidad por pesca (G) y mortalidad total (H) de la anchoveta peruana. Los datos han sido suavizados con promedios corridos de 13 meses para enfatizar las variaciones interanuales. Nótese las escalas diferentes y comparativamente, el gran impacto del jurel.

The least important predators were, on the other hand, hake and pinnipeds (at least as far as the stretch of Peruvian coast comprised between 4 and 14°S is concerned). This is not surprising, as the bulk of Peruvian hake and pinnipeds are generally concentrated north and south of 4 - 14°S, respectively.

Overall, natural mortality (baseline + predator-induced) shows no long-term trend, averaging 1.9 year<sup>-1</sup> from 1953 to 1985, i.e., about two times the value of the growth parameter K, which was estimated by Palomares et al. (1987) to range from 0.6 to 1.3 year<sup>-1</sup>, with a mean of 0.9. Thus, M/K is in anchoveta of the order of 2 as is often the case in small fishes (Beverton and Holt 1959; Pauly 1980). The overall consistency of M, and its relationship with K, suggest that our values of M<sub>0</sub> are probably not too far off the mark.

Obviously, one could also emphasize the *variability* of M, which ranged from 0.8 year<sup>-1</sup> in the mid 1970s to about 3 year<sup>-1</sup> in the late 1970s. We cannot at present explain these changes; they may be real, or they may have to do with erroneous withdrawal estimates (especially with regard to the predation estimates by horse mackerel) or with biases in the acoustic estimate, due e.g. to post-collapse changes in the schooling patterns of anchoveta.

Overall, we feel we have achieved the aims of the third iteration, i.e., to derive new estimates of anchoveta biomass and recruitment while simultaneously accounting for all of its important predators. We leave the refinement of our analyses to a "fourth iteration", which would have to address the problems alluded to above, pertaining to the dip of natural mortality in the early 1970s.

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