

# Incorporating cannibalism into an age-structured model for the Chilean hake

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## Abstract

We incorporated predation equations from the multispecies virtual population analysis model MSVPA into an age-structured model for the Chilean hake (*Merluccius gayi gayi*) to estimate cannibalism. Two models, model I with constant natural mortality and the MSM, were fitted to the total annual catch, spawning biomass from acoustic surveys and length composition data from fishery and acoustic surveys. Model I fitted the data better than MSM. The majority of the MSM estimates of adult population and spawning biomass were larger than the model I estimates; probably due to the choice of residual mortality M1. High estimates of predation mortality were observed for age-0 hake. In spite of a decreasing fishing mortality, the spawning biomass decreased in the last years. Preliminary MSM results suggest that this might be due to an increase in cannibalism. A sensitivity analysis suggested all response variables were not sensible to the “other food” parameter but sensible to M1 and the predator annual ration. MSM is a promising approach that introduces the predation mortality equations into a statistical framework, allowing the incorporation of the uncertainty in the estimation of the parameters and the use of standard statistical tools in a multispecies context. This approach will contribute to provide useful information on the indirect effects of fishing on non-target species to fisheries managers.

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**Keywords:** Cannibalism; Hake; Multispecies models; MSM; Predation mortality

## 1. Introduction

The Chilean hake fishery catches around 100,000 t annually. It is managed by a system of quotas established by the Subsecretaría de Pesca (Subpesca), a federal office in charge of the management of the fishing resources in Chile. The quota system is based on the results of statistical age-structured stock assessment models (Gatica and Cubillos, 2004). Hake is the main groundfish resource in central Chile and the main predator in the system (Meléndez, 1984) presenting high cannibalism on juveniles (Arancibia et al., 1998). Thus, it is important to explore the potential effects of cannibalism in the hake population dynamics.

Most of the stock assessment models assume that the instantaneous rate of natural mortality is constant across all age classes (Schnute, 1987; Megrey and Wespestad, 1988), an assumption

that might not hold in the dynamics of some species and that biases the estimations of age-structured populations (Sims, 1984; Mertz and Myers, 1997). Trophic interactions between species have been incorporated in some age-structured models. In particular, the MSVPA, a deterministic model, is based on the seminal work of Anderson and Ursin (1977) on the predator–prey preferences and the estimates of suitability coefficients. It has been applied in the North Sea (Gislason, 1991; Sparre, 1991; Magnusson, 1995), the Georges Bank (Tsou and Collie, 2001), and the Bering Sea (Livingston and Jurado-Molina, 2000; Jurado-Molina and Livingston, 2002). Since this model lacks statistical assumptions about the error structure of the quantities concerned, it does not provide a measure of the uncertainty of the estimated parameters. A different approach, the statistical assessment model SAM in which predators are added to a single-species stock assessment model, was applied to the Bering Sea (Livingston and Methot, 1998) and the Gulf of Alaska (Hollowed et al., 2000); however, these models lack a predator–prey feedback that could be important in analyzing the indirect effects of fishing on non-target species.

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In this paper, we show how to incorporate cannibalism, using MSVPA predation equations, into an age-structured model for the Chilean hake (multispecies statistical model MSM) fitted to the acoustic survey spawning biomass, the total annual catch, and the length composition data (from the fishery and the acoustic survey), using the separable fishing mortality assumption (Doubleday, 1976; Pope, 1977). The multispecies statistical model has the advantage of incorporating the standard tools used in statistical single-species stock assessment models allowing the estimation of the instantaneous rate of predation mortality.

**2. Methods**

*2.1. Models*

We fit two age-structured models to the length composition data from the fishery and acoustic surveys, the total annual catch, and the acoustic survey spawning biomass. One model (MSM) estimates the instantaneous rate of predation mortality from cannibalism, while the other (model I) assumed constant natural mortality. Contrary to the standard hake stock assessment (Gatica and Cubillos, 2004), in our case, both models (MSM and model I) combined sexes due to the difficulty in sexing juvenile hake in the stomach contents. In the model without cannibalism (model I), we assumed a constant instantaneous rate of natural mortality  $M=0.35 \text{ year}^{-1}$  for ages 0 to 13+. In the MSM, we incorporated cannibalism through the predation Eqs. (15)–(17).

In model I, we assumed constant natural mortality for all age classes:

$$Z_{a,t} = M + F_{a,t} \tag{1}$$

In MSM, the instantaneous rate of natural mortality was time and age-dependent:

$$Z_{a,t} = M_{a,t} + F_{a,t} \tag{2}$$

Common equations to both hake models are:

$$N_{a+1,t+1} = N_{a,t} e^{-Z_{a,t}} \tag{3}$$

$$N_{A^*,t+1} = N_{A^*-1,t} e^{-Z_{A^*-1,t}} + N_{A^*,t} e^{-Z_{A^*,t}} \tag{4}$$

$$C_{a,t} = \frac{F_{a,t} N_{a,t} (1 - e^{-Z_{a,t}})}{Z_{a,t}} = F_{a,t} \bar{N}_{a,t} \tag{5}$$

$$F_{a,t} = S_a F_t, \quad S_a = \frac{1}{1 + e^{(\alpha + \beta a)}} \tag{6}$$

$$\psi_{a,l} = \frac{1}{\sqrt{2\pi\sigma_a^2}} e^{[-(1/2\sigma_a^2)(L_l - L_a)^2]} \tag{7}$$

$$\hat{p}_{t,l} = \sum_{a=1}^m \psi_{a,l} \hat{p}_{t,a}, \quad m = 13 \text{ (plus group)} \tag{8}$$

$$\hat{p}_{a,t} = \frac{\hat{C}_{a,t}}{\hat{C}_t}, \quad \hat{C}_t = \sum_{a=1}^m \hat{C}_{a,t} \tag{9}$$

where  $Z_{t,a}$  is the total mortality,  $F_{t,a}$  the fishing mortality of fish of age  $a$  in year  $t$ ,  $N_{t,a}$  the number of individuals of age  $a$  in the year  $t$ ,  $N_{t,A^*}$  the plus group,  $C_{t,a}$  the catch-at-age data,  $\bar{N}_{t,a}$  the

average population,  $S_a$  the selectivity at age  $a$ ,  $F_t$  the full fishing mortality,  $\alpha$  and  $\beta$  the selectivity parameters,  $\psi_{a,l}$  is length-at-age distribution,  $L_l$  the central value of bin  $l$ ,  $L_a$  the mean length-at-age,  $\sigma_a$  the length-at-age standard deviation,  $\hat{p}_{t,l}$  the estimated proportion of fish of length bin  $l$  in year  $t$ ,  $\hat{p}_{t,a}$  the estimated proportion of fish of age  $a$  in year  $t$  and  $\hat{C}_t$  is the estimated total catch-at-age.

In addition to Eqs. (2)–(9), we introduced into MSM the predation interactions based on the MSVPA assumptions, including the separation of the instantaneous rate of natural mortality of the juvenile age classes:

$$M_{a,t} = M1 + M2_{a,t} \tag{10}$$

where  $M1$  is the instantaneous rate of residual mortality, and  $M2_{a,t}$  is the instantaneous rate of predation mortality of the age class  $a$  in the year  $t$ . We also assumed that  $M1=0.35 \text{ year}^{-1}$ . Because cannibalism was assumed as the only trophic interaction in MSM, the estimation of the predation mortality required a simplified version of the predation equations (Sparre, 1991):

$$M2_a = \sum_j \frac{\bar{N}_j R_j S_{a,j}^*}{B_{\text{of}} S_{j,\text{of}}^* + \sum_a \bar{N}_a W_a S_{a,j}^*} \tag{11}$$

where  $\bar{N}_j$  represents the average predator (hake) abundance at age  $j$ ,  $R_j$  the predator annual ration. The denominator (Eq. (11)) represents the total suitable biomass available to the predator. In the denominator,  $\bar{N}_a$  represents the average prey (hake) abundance at age  $a$ ,  $W_a$  the prey weight (hake) at age  $a$ ,  $B_{\text{of}}$  the “other food” and  $S_{a,j}^*$  the suitability coefficient for each predator–prey combination. The “other food” parameter accounts for the food observed in predator’s stomach, which does not originate from hake. The estimation of  $M2_a$  requires estimates of the suitability coefficients, a weighting factor in determining the availability of the prey as food for the predator (Gislason and Sparre, 1987). The estimation of  $S_{a,j}^*$  is given by the following simplified equation:

$$S_{a,j}^* = \frac{U_{a,j} / \bar{N}_a W_a}{\sum_a U_{a,j} / \bar{N}_a W_a} \tag{12}$$

where  $U_{a,j}$  is the relative stomach content or the fraction of predator (adult hake) food obtained from the prey (juvenile hake) and  $\bar{N}_a$  is the average prey population. In this version of the model we assumed the stomach contents are measured without error. The estimation of the predation mortality used the average of the estimates of suitability from years 1992 and 1993. Eqs. (2)–(12) are solved iteratively using the Newton-Raphson method and three algorithms, the first for  $M2$ , the second for the stock size and the last one for the suitability coefficients (Sparre, 1991). For more details about the predation equations and the MSVPA model see Sparre (1991) and Magnusson (1995).

We assumed a multinomial distribution for the size composition fit to fishery data; therefore its negative log-likelihood  $LL_1$  is given by (Haddon, 2001):

$$LL_1 = - \sum_{t=1}^T \sum_{l=1}^L p_{t,l} \ln \hat{p}_{t,l} \tag{13}$$

where  $p_{t,l}$  corresponds to the observed proportion and  $\hat{p}_{t,l}$  is the estimated proportion,  $T$  is the last year of data available and  $L$  is the last length class.

For the acoustic survey, equations similar to (7)–(9) were used and the negative log-likelihood  $LL_2$  was estimated as

$$LL_2 = -\sum_{t=1}^T \sum_{l=1}^L d_{t,l} \ln \hat{d}_{t,l},$$

$$\hat{d}_{t,l} = \frac{\sum_{a=3}^m \psi_{a,l} S_a^{\text{surv}} \hat{N}_{a,t} e^{-(7/12)Z_{a,t}}}{\sum_{l=1}^L \sum_{a=3}^m \psi_{a,l} S_a^{\text{surv}} \hat{N}_{a,t} e^{-(7/12)Z_{a,t}}} \quad (14)$$

where  $d_{t,l}$  corresponds to the observed proportion of the length class  $l$ ,  $\hat{d}_{t,l}$  the estimated proportion for the acoustic survey and  $S_a^{\text{surv}}$  is the survey selectivity. There were a total of 42 two cm size-classes in the fishery and the acoustic survey, corresponding the first bin to 10 cm.

The total annual catch  $C_t^w(t)$  was assumed to be log-normal distributed with a negative log-likelihood  $LL_3$  for each period

of time as follows (Hilborn and Mangel, 1997):

$$LL_3 = n \ln(\hat{\sigma}) + \frac{n}{2} \ln(2\pi) + \frac{1}{2\hat{\sigma}^2} \sum_{t=1}^n \ln \left( \frac{C_t^w}{\hat{C}_t^w} \right)^2 \quad (15)$$

where  $n$  is the numbers of years with available data, and  $\hat{C}_t^w$  is the estimated total catch. The standard deviation  $\hat{\sigma}$  of the total catch was analytically estimated as follows:

$$\hat{\sigma} = \sqrt{\frac{1}{n} \sum_{t=1}^n \ln \left( \frac{C_t^w}{\hat{C}_t^w} \right)^2} \quad (16)$$

Similarly, we assumed a negative log-normal likelihood for the spawning biomass SSB from the acoustic survey:

$$-LL_4 = n \ln \sigma - \frac{n}{2} \ln(2\pi) + \frac{1}{2\sigma^2} \sum_{t=1}^n \ln \left( \frac{SSB_t}{\hat{SSB}_t} \right)^2 \quad (17)$$

The standard deviation  $\sigma$  was estimated with an equation similar to Eq. (16) and the estimated spawning biomass  $\hat{SSB}_t$

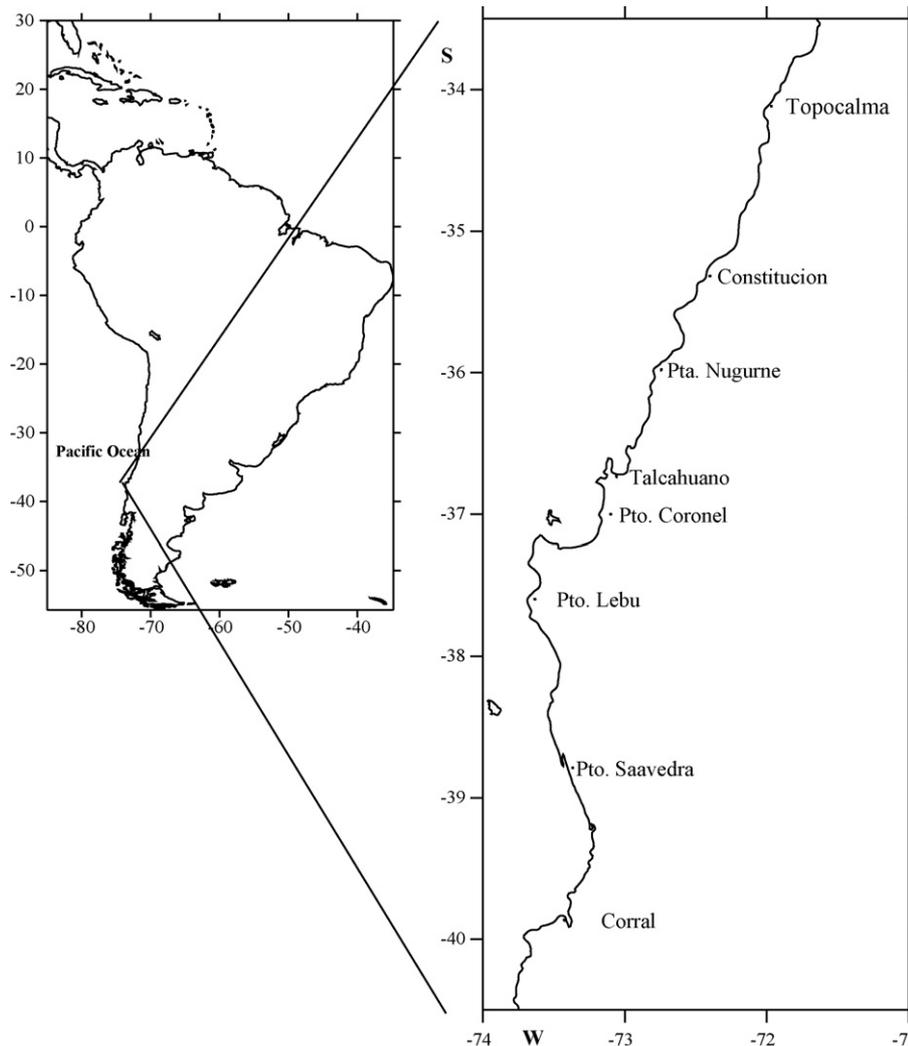


Fig. 1. Area of study in the south-central zone off Chile.

for the survey was given by:

$$\hat{S}SB_t = \sum_{a=3}^m S_a^{surv} \hat{N}_{t,a} w_a \mu_a e^{-(7/12)Z_{t,a}},$$

$$S_a^{surv} = \frac{1}{1 + e^{-P_1(a-P_2)}} \quad (18)$$

where  $w_a$  is the weight-at-age,  $\mu_a$  is the maturity-at-age,  $S_a^{surv}$  is the survey selectivity and  $P_1$  and  $P_2$  its parameters. The total negative log-likelihood is given by the sum of all terms (Eqs. (13), (14), (15) and (17)) for all years.

We estimated the same parameters in both models: the initial age-structure  $N_{1992,a}$ , the fully selected fishing mortality (1992–2003), age-0 recruitment (1992–2003) and the selectivity parameters ( $\alpha$ ,  $\beta$ ,  $P_1$  and  $P_2$ ). We took the length–age probability matrix from a previous hake stock assessment (Gatica and Cubillos, 2004). The MLE parameters were found using Excel’s premium solver platform (Frontline Systems, Inc.).

The estimation of the posterior distributions to assess the uncertainty of the instantaneous rate of predation mortality and the suitability coefficients was carried out using the sample-importance-resample (SIR) algorithm (McAllister and Ianelli, 1997) implemented in Visual Basic and Excel. We used uniform priors for all parameters in the SIR algorithm and a total of 100,000 iterations were made.

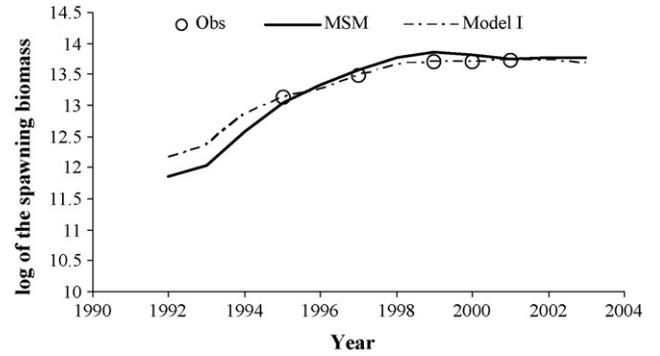


Fig. 2. MSM fit to hake spawning biomass acoustic survey data (1992–2003).

2.2. Data

The area of study is located between 34°00’S and 41°00’S in the south-central zone off Chile where the main hake catch occurs (Fig. 1). The information used in the models corresponds to the period 1992–2003 and includes total annual catch, estimates of spawning biomass from acoustic surveys (Fig. 2) and length composition data from the fishery (Fig. 3) and the acoustic survey (Fig. 4). More details can be found in Lillo et al. (2003), available on line ([www.fip.cl](http://www.fip.cl)).

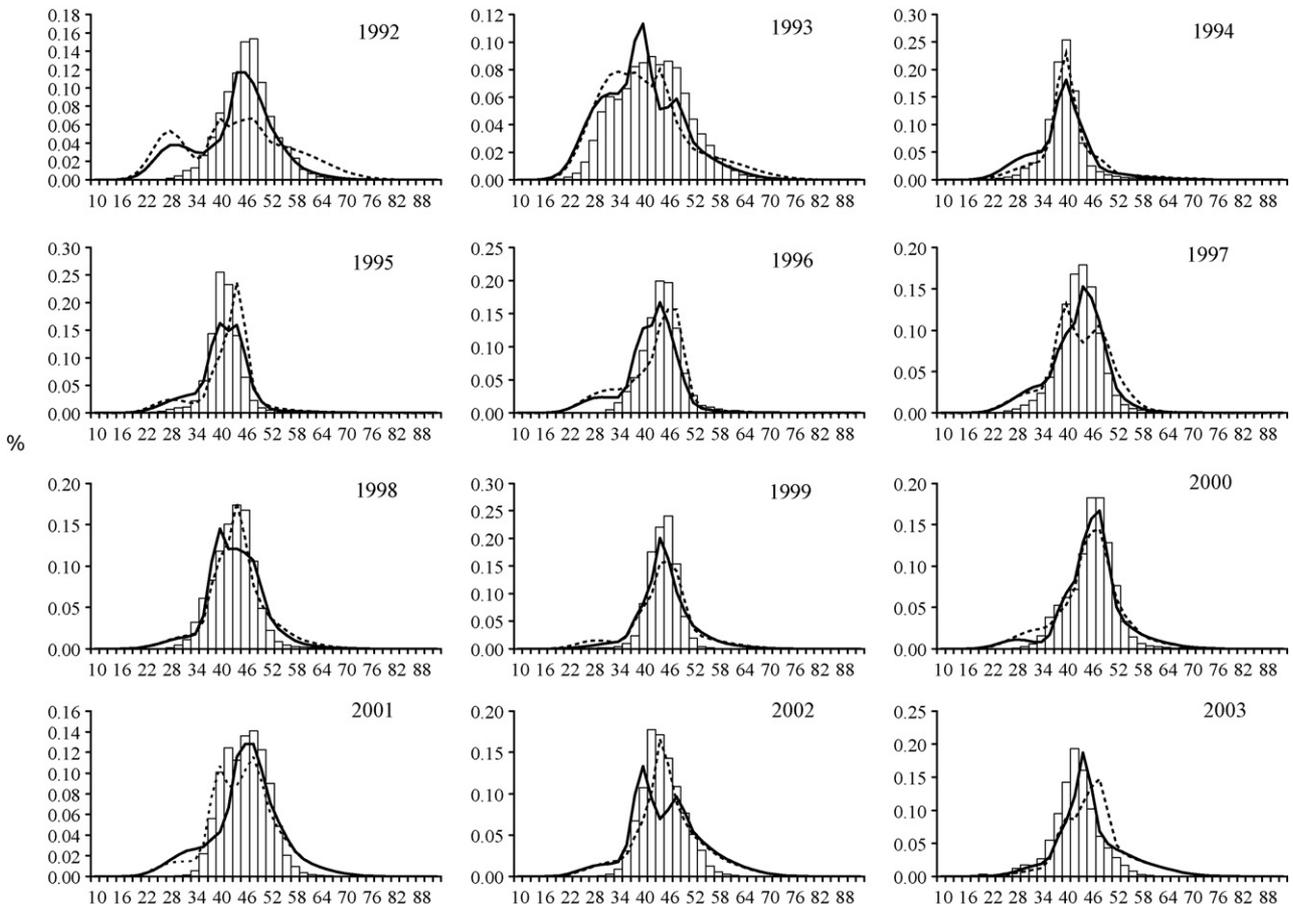


Fig. 3. MSM fit to Chilean hake fishery length composition data (1992–2003), ---, model I; —, MSM.

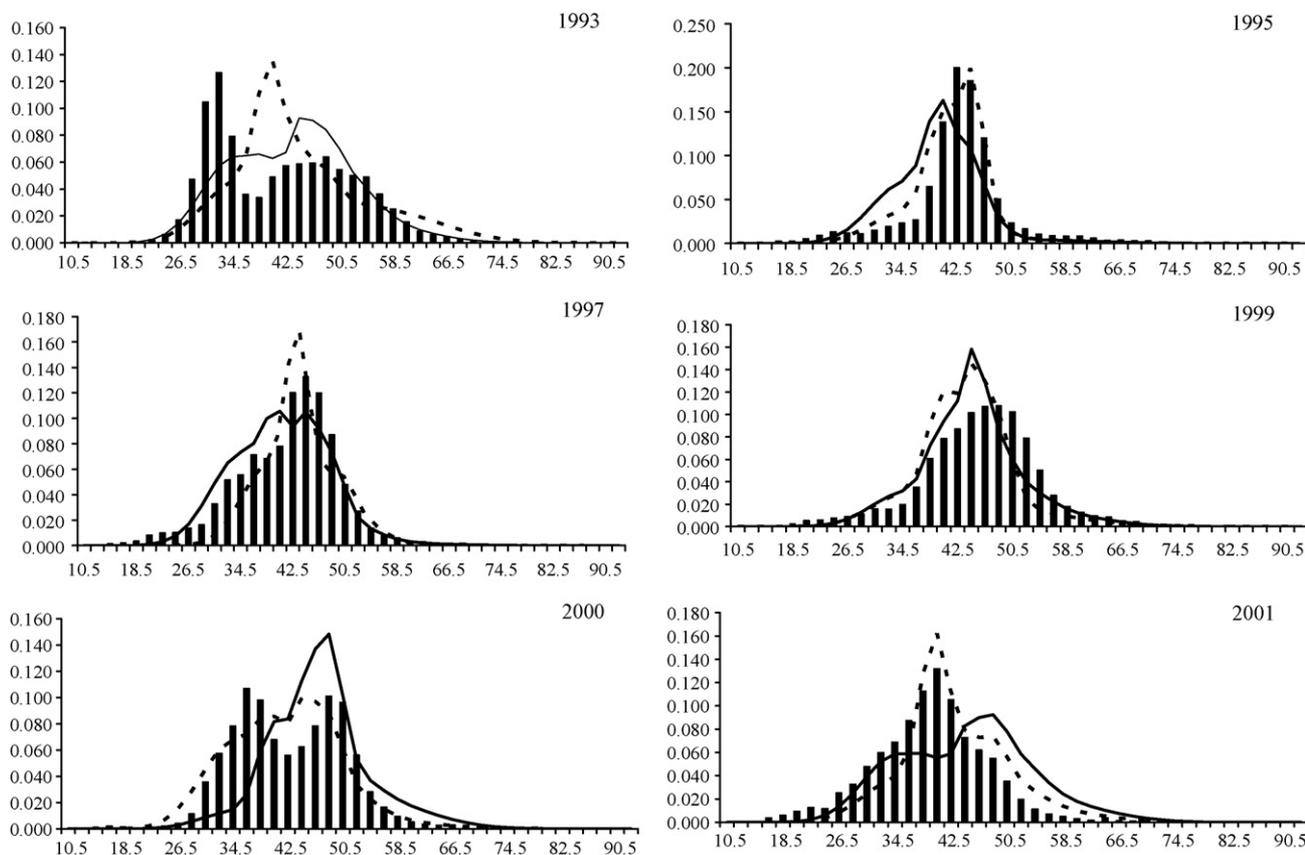


Fig. 4. MSM fit to Chilean hake survey length composition data (1993–2001), ---, model I; —, MSM.

The estimation of cannibalism was based on the analysis of 11,062 stomachs sampled in 1992 and 1993 in Talcahuano, Chile. The stomachs were preserved frozen. All prey items in the stomach were identified, if possible to species, counted and weighted. Aging was back calculated with the von Bertalanffy equation. The food composition used in MSM is shown below (Table 1). For further details for prey composition of Chilean hake see Cubillos et al. (2003).

The model with cannibalism required an estimate of the hake annual ration, which was estimated dividing the annual growth increment by an age dependent gross conversion efficiency rate calculated using the methods suggested by Brett and Groves (1979). The estimates of the hake annual ration included in the model were 0.89 kg/year for age-3 hake, 1.09 kg/year for age-4 and 1.04 for older age classes. The “other food” parameter was assumed constant with a value of 42 millions of tons. This value was estimated based on the jurel’s (*Trachurus symmetricus*) consumption of euphasids in the South Pacific (Cerde et al., 1997) and the jurel landings in the area of study. This parameter is underestimated, thus required a sensitivity analysis.

Due to the uncertainty of the “other food” parameter, the hake annual ration and the instantaneous rate of residual mortality, we did a sensitivity analysis to examine the effects on the response variables due to perturbations of these parameters. The percentage change in the response variable due to a perturbation was estimated as

$$\% \text{ change} = \left( \frac{x_i - x_0}{x_0} \right) \times 100 \quad (19)$$

where  $x_0$  is the value of the response variable without perturbation and  $x_i$  corresponds to the perturbed response variable.

The magnitudes of the perturbations of the “other food”, ration and “M1” parameters were: 25%, 50%, 75%, 100%, 125%, 175%, and 200% of the value without perturbation. The response variables selected were: the average predation mortality (ages 0 and 1), the average spawning biomass and the spawning biomass in 1996 and 2001 (years selected randomly).

### 3. Results

The MSM and model I fit to the total annual catch, the acoustic biomass survey, the fishery length composition data and the survey fishery length composition data are shown below (Figs. 2–4). Both models fitted the total catch almost exactly. Model I (negative log-likelihood = −367.8) fit the observed data better than MSM (negative log-likelihood = −126.5) did. Age-3 recruitment estimates from both models are shown below (Fig. 5). Out of 12, seven MSM age-3 recruitment estimates were larger than the estimates from model I. Overall, MSM provided the largest age-3 recruitment estimate in 1997 (2,007,838 individuals). The smallest age-3 recruitment estimate was calculated with model I (100,252 individuals) in 2004. The temporal trend of adult population (N3+) from both models was

Table 1  
Chilean hake food composition (proportion of the prey in the stomach of the predator) in 1992 and 1993

Predator age	Prey age			Other food	Sample size
	0	1	2		
Year 1992					
0				1	
1				1	
2				1	
3	0.05			0.95	642
4	0.34			0.66	3133
5	0.20			0.80	2202
6	0.05	0.04		0.92	1516
7	0.04	0.23		0.72	851
8		0.30		0.70	499
9		0.28		0.72	233
10		0.36	0.02	0.62	132
11			0.51	0.49	63
12		0.09	0.53	0.38	43
13			0.85	0.15	36
Year 1993					
0				1	
1				1	
2				1	
3	0.09	0.11		0.81	445
4	0.06	0.04	0.03	0.87	1300
5	0.06	0.15	0.04	0.75	1486
6	0.05	0.22	0.11	0.61	1936
7	0.05	0.22	0.23	0.50	1213
8	0.04	0.28	0.21	0.48	654
9	0.02	0.19	0.52	0.26	347
10		0.13	0.53	0.34	200
11	0.01	0.31	0.39	0.30	65
12		0.06	0.58	0.36	43
13		0.06	0.78	0.15	28

alike (Fig. 6a), with an initial increasing trend that decreases in the last years (2000–2003). The maximum from MSM was reached in 1997 (3,694,274 individuals) while in model I (3,258,833 individuals) was reached in 2001. Out of 12, eight MSM estimates were higher than model I estimates. Results from both models suggested an initial increasing trend and a slight decrease in the last years for the spawning biomass (Fig. 6b). In the initial years, model I estimates were higher than MSM estimates. This trend was reversed in the last years (1996–2003).

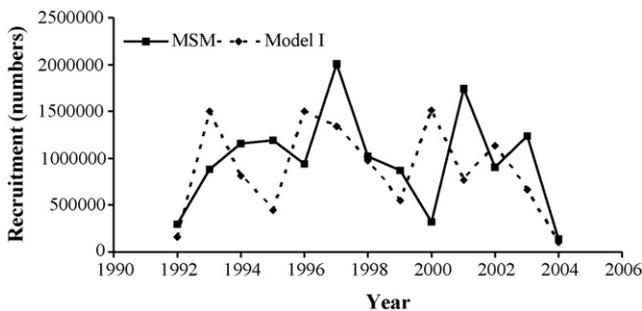


Fig. 5. Comparison of recruitment estimates from the single-species model (I) and the MSM from 1992 to 2003.

Table 2  
Chilean hake average suitability coefficients

Predator age	Prey age			Other food
	0	1	2	
0				1
1				1
2				1
3	0.573	0.374		0.054
4	0.658	0.203	0.117	0.023
5	0.484	0.399	0.099	0.017
6	0.322	0.431	0.212	0.036
7	0.126	0.539	0.323	0.012
8	0.086	0.631	0.273	0.010
9	0.034	0.474	0.485	0.007
10		0.577	0.416	0.007
11	0.012	0.389	0.595	0.004
12		0.124	0.871	0.004
13		0.088	0.910	0.001
Average	0.287	0.384	0.430	0.227

Overall, the highest suitability coefficient (0.910) corresponded to the plus group-age-2 combination (Table 2). Lowest suitability coefficients corresponded to the other food. The average suitability of age-1 hake as prey was 0.29, for age-2 hake was 0.38 and for age-2 hake was 0.43. Higher predation mortalities were observed for age-0 hake as prey (Table 3). Overall the hake’s highest predation mortality occurred in year 1997 (1.52) for the age-0 class. The lowest age-0 predation mortality corresponded to 1992. Increasing trends over time were observed for all age classes; however predation mortality of age-0 and age-1 decreased slightly in the last year. On the other hand, the full fishing mortality decreased appreciably in the last years. In the first years the level of fishing mortality was high. Starting in 1995, we observed a decreasing trend; all levels of full fishing mortality were smaller than 0.25 year<sup>-1</sup>, reaching the lowest level in 1998 (0.09 year<sup>-1</sup>).

The year 1998 was the year when the highest cannibalism on age-0 hake occurred (Fig. 7). The maximum biomass of age-1 hake consumed occurred in 2001 (249,250 t). Consumption of age-2 hake was smaller with a maximum in 2002 (127,888 t). Cannibalism started to increase in 1997 (Fig. 7)

Table 3  
Hake predation mortality (cannibalism) rate at age in central Chile

Year	Age-0	Age-1	Age-2
1992	0.17	0.04	0.01
1993	0.20	0.05	0.00
1994	0.32	0.03	0.01
1995	0.62	0.05	0.01
1996	0.85	0.13	0.01
1997	1.52	0.31	0.02
1998	0.71	0.31	0.01
1999	1.00	0.54	0.02
2000	0.79	0.78	0.03
2001	1.26	0.58	0.07
2002	1.20	0.36	0.11
2003	0.74	0.23	0.13
Average	0.78	0.28	0.04

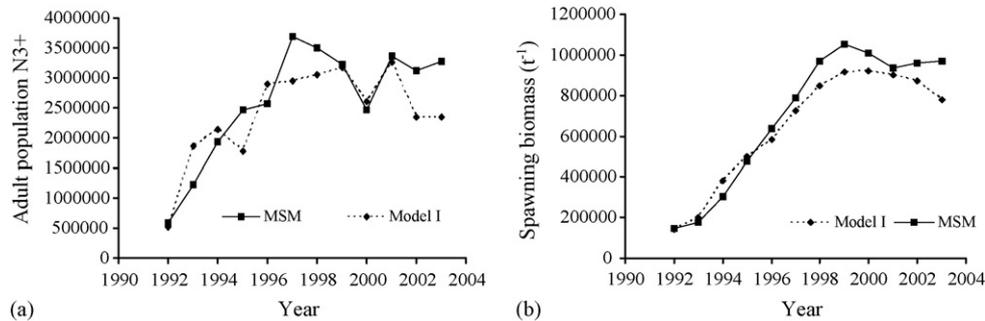


Fig. 6. Comparison of estimates from the single-species model (I) and the MSM from 1992 to 2003: (a) Chilean hake adult population N3+, and (b) Chilean hake spawning biomass.

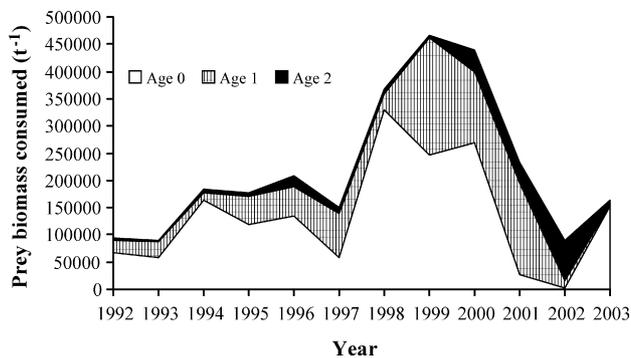


Fig. 7. Consumption of juvenile hake in the south-central zone off Chile estimated with MSM.

The posterior distribution of the suitability coefficient age-3 hake as predator and age-0 hake as prey combination, the age-1 hake predation mortality in 2001 and the age-0 hake predation mortality in 1992 and 1994 are shown below (Fig. 8a). The mode of the suitability coefficient posterior distribution was 0.542 while the MLE was 0.573. Similarly the mode of the age-1 predation mortality was 0.27 and the MLE was 0.30. The modes of age-0 M2 were 0.24 (1992) and 0.25 (1994). The corresponding MLE were 0.17 and 0.32.

Results from the sensitivity analysis suggested that the response variables were not sensible to perturbations of the other food parameter (Table 4). The largest percentage change corresponded to the age-1 predation mortality (25% perturbation). A 28 out of 32 percent changes were smaller than one percent (Table 4). The highest percentage changes corresponded to the

Table 4  
Percentage changes produced by perturbation of the “other food” parameter, M2: predation mortality, Avg: average, SSB: spawning biomass

Perturbation (%)	Age-0 M2	Age-1 M2	Average SSB	SSB <sub>1996</sub>	SSB <sub>2001</sub>
25	-4.29	-4.75	0.92	0.24	0.69
50	-1.44	-1.67	0.32	0.07	0.25
75	-0.48	-0.62	0.11	0.01	0.09
100	0.00	0.00	0.00	0.00	0.00
125	0.30	0.24	-0.06	-0.04	-0.04
150	0.48	0.54	-0.11	-0.03	-0.08
175	0.62	0.69	-0.14	-0.04	-0.10
200	0.73	0.81	-0.16	-0.04	-0.12

25% and 50% perturbations. However, all response variables were sensible to perturbations of the instantaneous rate of residual mortality and the annual predator ration. For example, a 125% perturbation of M1 caused a 38% change in the average spawning biomass of the Chilean hake, a 45% change in the spawning biomass in 2001, a 34% change in spawning biomass in 1996, a 17% change in average age-0 predation mortality and a 30% change in the average age-1 predation mortality. In general, the percentage change increased when the perturbation of the residual mortality augmented. Regarding the annual ration of the predator, a 25% perturbation produced a 103% change in the average spawning biomass. Percentage changes of the average spawning biomass decreased when the perturbation increased, for example, a perturbation of 200% caused a 7% change. This was not the case for the rest of the response variables; for example, a perturbation of 200% caused a 43% increase in the SSB in 1996 but a decrease of 42% in the SSB in 2002. The predation mortality estimates were also sensible to the perturbations of the ratio parameter. A perturbation of 150% produced a decrease of 50% in the average age-0 predation mortality.

#### 4. Discussion

This work is part of the effort to develop statistical models in a multispecies context (Livingston and Methot, 1998; Hollowed et al., 2000). In particular, we followed the approach suggested by Jurado-Molina et al. (2005b) to add the predation equations into a statistical age-structured model fitted to the total annual catch, spawning biomass from acoustic surveys and length composition data from the fishery and the surveys using the separable fishing mortality assumption (Doubleday, 1976; Pope, 1977). We did not want to make a formal stock assessment; instead we wanted to show that is possible to integrate the predation mortality equations in a statistical framework and consequently estimate the predation mortality, the suitability coefficients and their uncertainty via the SIR algorithm.

Hake plays an important role as predator in the demersal system in south-central area off Chile. High cannibalism has been observed for this species (Meléndez, 1984; Cubillos et al., 2003). This characteristic is shared with other species of hake such as *Merluccius productus* (Livingston and Bailey, 1985; Livingston et al., 1986), *Merluccius capensis* and *Merluccius paradoxus* from South Africa (Macpherson and Roel, 1987; Payne et al.,

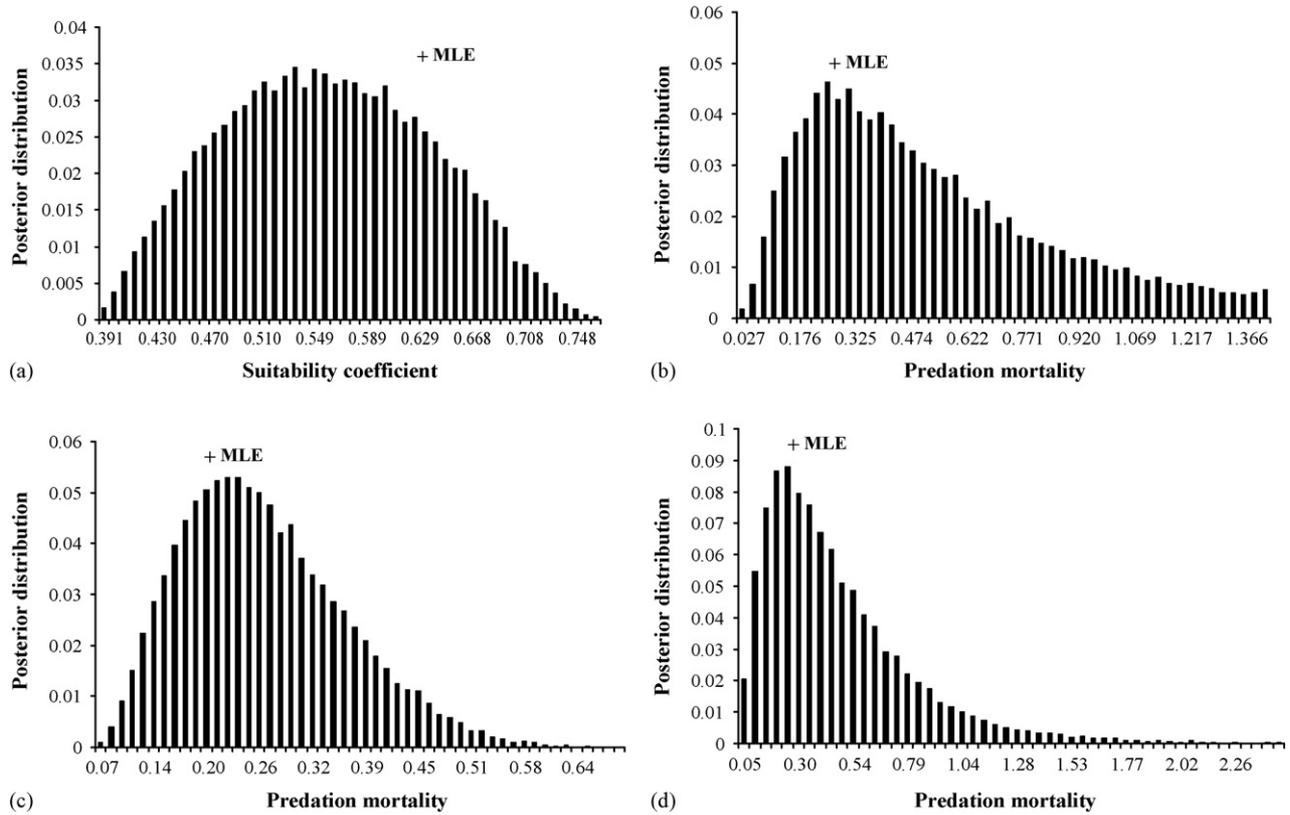


Fig. 8. Posterior distributions estimated with the SIR algorithm: (a) suitability coefficient for age-3 hake as predator and age-0 hake as prey, (b) age-1 hake predation mortality in 2001, (c) age-0 hake predation mortality in 1992 and (d) age-0 hake predation mortality in 1994.

1987; Punt et al., 1992). There is evidence indicating that cannibalism might be related with the intensity of annual classes of walleye pollock (Livingston and Lang, 1996) producing a population feedback mechanism (Laevastu and Favorite, 1988). The same process might be working for the Chilean hake, however more analyses need to be done including the potential factors affecting the intensity of cannibalism such as overlap of adult and juvenile populations. Preliminary results from the present work and the official stock assessment for the Chilean hake management suggest that the spawning biomass decreased slightly in the last years in spite of the fishing mortality decreasing. This contradictory result could be explained by the increase of cannibalism as the estimates of predation mortality from MSM suggest. However, more tests and a large data series are needed to explore this possibility.

Following the suggestion by Jurado-Molina et al. (2005b), our work shows a different approach can be taken in the estimation of the predation mortality and the suitability estimates. Instead of using the traditional MSVPA approach (deterministic model), we used the same MSVPA predation equations in a different framework; one where the separable fishing mortality assumption was used. This way, the predation equations can be used in a statistical catch-at-age model providing the advantages of including uncertainty in the estimation of parameters, task not possible with the current MSVPA technology. In addition, in this work we were able to fit the MSM to length composition data that is more available in several fisheries. No systematic deviations in the fits to hake total annual catch and hake spawning biomass

acoustic survey data were observed in both models (Fig. 2). In general the fit to the fishery and survey length composition were good (Figs. 3 and 4). In fact, contributions to the total likelihood by these two components were similar in both models. As shown, the single species model (I) fitted the data better than the MSM. This is due to the contributions of the annual catch and the survey spawning biomass data to the total likelihood. Due to the complexity of the model it is difficult to explain this difference but this scenario has also been found for the MSM set up for the eastern Bering Sea (Jurado-Molina, personal communication). MSM should be considered as work in progress that is not intended to replace the single species approach in fisheries management but to provide additional information that will be useful to assess the indirect effects of fishing in non-target species helping to build an ecosystem approach in fisheries management.

Excel and solver are not the ideal platform to estimate a likelihood profile or a posterior distribution due to the considerable amount of time needed to find a solution. However we were able to estimate the posterior distributions of some cases of the suitability coefficient and the predation mortality. A better platform for this type of analysis is the AD model builder or WinBUGS. Currently a version of MSM in AD model builder is under development for the eastern Bering Sea (Jurado-Molina, personal communication). This approach will help to facilitate the estimation of the uncertainty of parameters and indicators of performance of the fishery. At present, we have not set up a MSVPA model for the Chilean Hake. This is a future task that will allow the comparison of the estimates of predation mortality

and suitability coefficients from both types of models. However, Jurado-Molina et al. (2005b) found that the multispecies statistical model MSM and MSVPA produced similar estimates of predation mortality, suitability coefficients and abundance.

We assumed a residual mortality equal to the adult natural mortality for ages-0, -1 and -2 classes. Unfortunately, due to lack of data, we could not follow the approach taken by Jurado-Molina et al. (2005b) where they used as the residual mortality, the difference between the adult natural mortality and the average adult predation mortality. This might be the potential cause of the overestimation of the indicators with respect to the estimates with constant mortality (model I). In spite of this effect, the estimates from both models followed the same temporal trend. Leonart et al. (1985) found similar results for Cape hake (*M. capensis*) in the coast of Namibia using an extended version of VPA with cannibalism (CVPA). They found significant differences in number of fish at any given age, showing that the standard VPA could potentially underestimate the magnitude of younger age classes.

Results from the sensitivity analysis suggested that the model is sensitive to the instantaneous rate of residual mortality and the predator annual ration. M1 plays a similar role as the natural mortality in single-species models that are sensitive to this parameter. Therefore, the problems associated with the natural mortality in the single-species models are also found for M1 in the MSM, among them, the uncertainty of its value and the indirect influence in the estimation of the predation mortality and abundance. The addition of hake predators in the model will help to improve the estimate of the residual mortality following the method suggested by Jurado-Molina et al. (2005b). Therefore is necessary to establish a food habits program that includes the jumbo squid (*Dosidicus gigas*), Sea lion (*Otaria flavescens*) and the black conger (*Genypterus maculatus*) that seem to be the main hake predators (Claudio Gatica, personal communication). Juvenile predation mortality was also sensible to perturbations to the ration of hake as predator, which confirms previous results for the Bering Sea (Jurado-Molina et al., 2004) and the Georges Bank (Tsou and Collie, 2001). However, the estimation of the ration of hake was based on estimates of growth increments and growth conversion efficiency, thus there is less concern regarding the uncertainty of this parameter than the uncertainty on the residual mortality (Jurado-Molina et al., 2004). Previous analysis showed that the response variables were not sensible to the “other food” parameter (Jurado-Molina et al., 2004). Our results also confirm these results. No perturbation produced a percentage change in the response variable greater than 5%. Also an asymptotic relationship in the extreme perturbations was found, assuring that higher perturbations produced small percentage changes.

Previous work suggests that cannibalism of different species is influenced by the oceanographic conditions. Uzars and Plikshs (2000) analyzed the inter-annual variability of cannibalism in Baltic Sea cod (*Gadus morhua*) related to different periods of abundance of recruits and its distribution, associated with oxygen levels and the salinity of water masses. These authors suggest that the effect of cannibalism is negligible and that the dynamics of the stock is determined by the combined effect

of oceanographic and fishery variables. In addition, they point out that the changes in distribution have diminished the spatial overlapping of juveniles and adults causing a decrease of mortality by cannibalism. Wespestad et al. (2000) showed the existence of a relationship between the cannibalism and climate variability associated with warm and cold periods, transport and recruitment in the fishery of walleye pollock (*Theragra chalcogramma*). In this context, Cubillos et al. (2000) presented evidence of decadal variations in the biomass of Chilean hake (*Merluccius gayi*), whose small productivity between 1976 and 1987 agrees with the changes in abundance of its main prey in association with fluctuations in the physical environment. During this period, winds in the south quadrant were weaker, reflected in the upwelling index and the surface temperature, suggesting that the change in these indicators could be a local answer to global changes occurring in the Pacific in 1976 (Yáñez et al., 1992, 1998). Therefore, there is nothing impeding the assumption that this type of process could affect the hake population dynamics. Therefore, these aspects should be addressed to generate a tool that takes in account not only cannibalism but predation in general and the conditions under which it is produced. In this work, the time series is short, thus is not possible to make definitive conclusions about the trends of cannibalism in relation to different conditions of the physical environment. However, we have achieved the implementation of a model that allows the estimation of juvenile and adult hake abundance changes and the number of juveniles consumed, information that is not feasible to obtain with the traditional stock assessment methods applied for the management of this fishing resource. More work on stomach sampling, stomach contents analysis and modeling is needed. However, it is encouraging that these first steps towards ecosystem based management are taken outside the USA and Europe. In the future, simulations of the future dynamics of hake subjected to different levels of fishing mortality could tell us about the indirect effects of fishing as shown in the eastern Bering Sea (Jurado-Molina and Livingston, 2002).

This work is an initial step in the incorporation of trophic interactions in quantitative statistical models that could potentially improve the fisheries resources management in central Chile. Some assumptions that help to keep the model simple were used such as the hypothesis of constant suitability coefficients. This assumption was originally used in MSVPA (Sparre, 1991). Although this assumption is not completely correct, it has been shown that the suitability coefficients have a small variation (Rice et al., 1991; Jurado-Molina et al., 2005a) suggesting these coefficients reflect general predation patterns and not the special conditions of any particular year (Anonymous, 1989). Rice et al. (1991) suggested that in the context of the development of management advice from trophic models, it may be correct (and often necessary) to assume that preferences and vulnerabilities remain constant. We also assumed that the stomach was measured without error. This hypothesis was taken to facilitate the estimation process. Solver is not the adequate platform to estimate a large number of parameters that would have been necessary if stomach contents observation error would have been introduced in the model. Future versions of MSM set up in the

AD model builder platform or WINBUGS will allow this type of approach. The multispecies statistical model introduces all techniques used in the single-species stock assessment models to estimate the uncertainty in parameters and indicators. However, it is necessary to improve this model through the increase in the number of predator stomach samples. It is necessary that the stomach sampled include information of predation on adult hake that will allow a better estimate of the residual mortality. It is also necessary to develop a simplified version of the MSVPA that will allow the comparison of estimates of suitability coefficients and predation mortality. The development of these models is an important step in taking a broader approach for ecosystem-based management that will provide useful information to fisheries managers.

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## References

- Anderson, K.P., Ursin, E., 1977. A multispecies extension to the Beverton and Holt theory of fishing, with accounts for phosphorus circulation and primary production. *Medd. Dan. Fisk. -og Havunders NS* 7, 310–435.
- Anonymous, 1989. Report of Multispecies Assessment working Group. Copenhagen, 7–16 June 1989, ICES CM 1989/Assess: 20.
- Arancibia, H., Catrileo, M., Farías, B., 1998. Evaluación de la demanda de alimento en merluza común y análisis de su impacto en pre-reclutas. Informe Final Proyecto FIP 95-17, 18.
- Brett, J.R., Groves, T.D.D., 1979. Physiological energetics. In: Hoar, W., Randall, D., Brett, J. (Eds.), *Bioenergetics and Growth. Fish Physiology*, vol. 8. Academic Press, New York, pp. 279–352.
- Cerda, A., Aliaga, B., Dresner, R., Bobenrieth, E., Quiñónez, R., Sepúlveda, A., Galvez, M., Hernández, A., 1997. Evaluación Bioeconómica de la Pesquería Industrial de Jurel en la zona Centro-Sur. Fase I. Informe Final Proyecto Fondo de Investigación Pesquera, FIP 95-12, Subsecretaría de Pesca, Chile, 228, 168 pp.
- Cubillos, L., Núñez, S., Arcos, D., 2000. Cambios decadales en la biomasa de la merluza común (*Merluccius gayi*) en el centro-sur de Chile: Una consecuencia “bottom-up”? In: Cancino, J., Rudolph, A., Chong Lay-Son, J., Otaíza, R., Brante, A., Torres, F., Orellana, M., Cortés, N. (Eds.), *Resúmenes XX Congreso Ciencias del Mar, Concepción 2000. Soc. Ch. Cs. Mar, Univ. Cat. Sma. Concep.*, p. 231.
- Cubillos, L., Rebolledo, H., Hernández, A., 2003. Prey composition and estimation of Q/B for the Chilean hake, *Merluccius gayi* (Gadiformes-Merlucciidae), in the central-south area off Chile (34°–40°S). *Arch. Fish. Mar. Res.* 50, 271–286.
- Doubleday, W.G., 1976. A least squares approach to analyzing catch at age data. *Res. Bull. Int. Comm. NW Atl. Fish.* 12, 69–81.
- Gatica, C., Cubillos, L., 2004. Análisis talla-estructurado de los cambios de abundancia en *Merluccius gayi gayi* entre 1992 y 2000. *Rev. Invest. Mar.* 32, 71–87.
- Gislason, H., Sparre, P., 1987. Some Theoretical Aspects of the Implementation of Multispecies Virtual Population Analysis in ICES. International Council for the Exploration of the Sea CM 1987/G:51, Copenhagen.
- Gislason, H., 1991. The influence of variations in recruitment on multispecies yield predictions in the North Sea. *ICES Mar. Sci. Symp.* 193, 50–59.
- Haddon, M., 2001. *Modelling and Quantitative Methods in Fisheries*. Chapman and Hall/CRC, Boca Raton.
- Hilborn, R., Mangel, M., 1997. *The Ecological Detective: Confronting Models with Data*. Princeton University Press, Princeton, NJ.
- Hollowed, A., Ianelli, J., Livingston, P., 2000. Including predation mortality in stock assessments: a case study for Gulf of Alaska walleye pollock. *ICES J. Mar. Sci.* 57, 279–293.
- Jurado-Molina, J., Livingston, P.A., 2002. Multispecies perspectives on the Bering Sea Groundfish fisheries management regime. *N. Am. J. Fish. Manage.* 22, 1164–1175.
- Jurado-Molina, J., Livingston, P.A., Gallucci, V.F., 2004. Sensitivity analysis of the multispecies virtual population analysis model parameterized for a system of trophically-linked species from the eastern Bering Sea. *Cienc. Mar.* 30, 285–296.
- Jurado-Molina, J., Livingston, P.A., Gallucci, V.F., 2005a. Testing the stability of the suitability coefficients from the eastern Bering Sea. *ICES J. Mar. Sci.* 62 (5), 915–924.
- Jurado-Molina, J., Livingston, P.A., Ianelli, J., 2005b. Incorporating predation interactions to a statistical catch-at-age model for a predator–prey system in the eastern Bering Sea. *Can. J. Fish. Aquat. Sci.* 62, 1865–1873.
- Laevastu, T., Favorite, F., 1988. *Fishing and Stock Fluctuation*. Fishing Books Ltd., Farnham.
- Lillo, S., Rojas, M., Tascheri, R., Ojeda, V., Olivares, J., Balbontín, F., Bravo, R., Núñez, S., Braun, M., Ortiz, J., Torres, P., Véjar, F., Cubillos, L., Saavedra, A., 2003. Evaluación Hidroacústica de Merluza Común, Año 2002. FIP No. 2002–03, p. 182.
- Livingston, P., Bailey, K., 1985. Trophic role of the Pacific whiting, *Merluccius productus*. *Mar. Fish. Rev.* 47, 16–22.
- Livingston, P.A., Lang, G.M., 1996. Interdecadal Comparisons of Walleye Pollock, *Theragra chalcogramma*, Cannibalism in the Eastern Bering Sea. US Dep. Commer. NOAA Tech. Rep. NMFS, vol. 126, pp. 115–124.
- Livingston, P.A., Methot, R.D., 1998. Incorporation of predation into a population assessment model of eastern Bering Sea walleye pollock. In: Funk, F., Quinn II, T.J., Heifetz, J., Ianelli, J.N., Powers, J.E., Schweigert, J.F., Sullivan, P.J., Zhang, C.I. (Eds.), *Fishery Stock Assessment Models*. Alaska Sea Grant College Program, AK-SG-98-01, pp. 663–678.
- Livingston, P.A., Jurado-Molina, J., 2000. A multispecies virtual population analysis of the eastern Bering Sea. *ICES J. Mar. Sci.* 57, 294–299.
- Livingston, P.A., Dwyer, D.A., Wencker, D.L., Yang, M.S., Lang, G.M., 1986. Trophic interactions of the key fish species in the Eastern Bering Sea. *Inst. North Pacific. Fish. Commun. Bull.* 47, 49–65.
- Lleonart, J., Salat, J., Macpherson, E., 1985. CVPA, an expanded VPA with cannibalism. Application to a hake population. *Fish. Res.* 3, 61–79.
- Mcallister, M.K., Ianelli, N.J., 1997. Bayesian stock assessment using catch-age data and the sampling-importance resampling algorithm. *Can. J. Fish. Aquat. Sci.* 54, 284–300.
- Macpherson, E., Roel, B., 1987. Trophic relationships in the demersal fish community of Namibia. In: Payne, A.I., Gulland, J.A., Brink, K.H. (Eds.), *The Benguela and Comparable Ecosystems*. S. Afr. J. Mar. Sci. 5, 585–596.
- Magnusson, K., 1995. An overview of the multispecies VPA—theory and applications. *Rev. Fish Biol. Fish* 5, 195–212.
- Megrey, B., Weststad, V., 1988. A review of biological assumption underlying fishery assessment models. In: Wooster, W.S. (Ed.), *Fishery Science and Management: Objectives and Limitations. Lectures Notes on Coastal and Stuarines Studies*, vol. 28. Springer-Verlag, pp. 31–69.
- Meléndez, R., 1984. Alimentación de *Merluccius gayi* (Guichenot) frente a Chile central (32°05′S–36°50′S). *Bol. Mus. Nac. Hist. Nat., Chile*, 54 p.
- Mertz, G., Myers, R., 1997. Influence of errors in natural mortality estimates in cohort analysis. *Can. J. Fish. Aquat. Sci.* 54, 1608–1612.
- Payne, A., Rose, B., Leslie, W., 1987. Feeding of hake and a first attempt at determining their trophic role in the South African west coast marine environment. In: Payne, A.I., Gulland, J.A., Brink, K.H. (Eds.), *The Benguela and Comparable Ecosystems*. S. Afr. J. Mar. Sci. 5, 471–501.
- Pope, J.G., 1977. Estimation of the fishing mortality, its precision and implications for the management of fisheries. In: Steele, J.H. (Ed.), *Fisheries Mathematics*. Academic Press, New York.

- Punt, A., Leslie, R., Du Plessis, S., 1992. Estimation of the annual consumption of the food by Cape hake *Merluccius capensis* and *M. Paradoxus* off the South African west coast. Benguela trophic functioning. S. Afr. J. Mar. Sci. 12, 611–634.
- Rice, J.C., Daan, N., Pope II, J.G., Gislason, H., 1991. The stability of estimates of suitabilities in MSVPA over four years of data from predator stomachs. ICES Mar. Sci. Symp. 193, 34–35.
- Schnute, J., 1987. A general fishery model for a size-structured fish population. Can. J. Fish. Aquat. Sci. 44, 924–940.
- Sims, S.E., 1984. An analysis of the effect of errors in the natural mortality rate on stock-size estimates using virtual population analysis (cohort analysis). ICES J. Mar. Sci. 41, 149–153.
- Sparre, P., 1991. Introduction to multispecies virtual population analysis. ICES Mar. Sci. Symp. 193, 12–21.
- Tsou, T.S., Collie, J.S., 2001. Predation-mediated recruitment in the Georges Bank fish community. ICES J. Mar. Sci. 58, 994–1001.
- Uzars, D., Plikshs, M., 2000. Cod (*Gadus morhua* L.) cannibalism in the Central Baltic: interannual variability and influence of recruit abundance and distribution. ICES J. Mar. Sci. 57, 324–329.
- Wespestad, V., Fritz, L., Ingraham, W., Megrey, B., 2000. On relationships between cannibalism, climate variability, physical transport, and recruitment success of Bering Sea walleye pollock (*Theragra chalcogramma*). ICES J. Mar. Sci. 57, 268–274.
- Yáñez, E., Barbieri, M.A., Santillan, L., 1992. Long-term environmental variability and pelagic fisheries in Talcahuano, Chile. In: Payne, A., Brink, L., Mann, K., Hilborn, R. (Eds.), Benguela Trophic Functioning, S. Afr. J. Mar. Sci. 12, 175–188.
- Yáñez, E., Garcia, M., Barbieri, M., 1998. Pelagic fish stocks and environmental changes in the South-East Pacific. In: Durand, H.M., Cury, P., Mendelssohn, R., Roy, C., Bakun, A., Pauly, D. (Eds.), From Local to Global Changes in Upwelling Systems. Ortom, Paris, pp. 275–291.