ELSEVIER

Fisheries Research 41 (1999) 273–283

FISHERIES RESEARCH

Modeling of the Pacific sardine *Sardinops caeruleus* fishery of the Gulf of California, Mexico

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Received 5 May 1998; accepted 22 January 1999

Abstract

We used a stochastic age-structured model with density-dependent recruitment to study the fishery and population dynamics of the Gulf of California Pacific sardine (*Sardinops caeruleus*) stock for the period 1972–1973 to 1989–1990. To determine the value of fishing mortality (F) which corresponds to the long-term optimum yield and cost–benefit ratio (C/B), we simulated fished population trajectories over a period of 50 years. Our results indicated a good fit between observed and predicted annual recruitment and catch. Quasiperiodic oscillations of a five year periodicity for an unfished population faded with increasing F. Maximum yield and C/B were obtained with F=0.475 and 0.275, and the simulated population began declining with $F\geq0.5$ and >0.3, respectively. It is proposed that $F<0.25$ would be adequate for this fishery. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Simulation; Recruitment; Catch; Pacific sardine; Gulf of California; *Sardinops caeruleus*

1. Introduction

In theory, the correct administration of a fish stock assumes precise knowledge of rates of recruitment, growth and mortality. In reality, however, as a general rule, there is great uncertainty in that respect, and due to poor management prescriptions resulting of such uncertainty, this might result in fisheries collapsing. The situation is obviously aggravated if management is based on results of an incorrect model specification due to introduction of model uncertainty. Explicit incorporation of uncertainty is a key component of modern fishery science. A fundamental ingredient in fisheries management is consideration of pre-established reference points whose calculated values serve as guidelines for decision making (Caddy and Mahon, 1995).

In the present paper, we explore values of fishing mortality rate (F) such that both biological and economic yield are optimized over the long run. With this purpose we develop a stochastic age-structured, density-dependent recruitment, dynamic simulation model for the Gulf of California Pacific sardine

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PII: S0165-7836(99)00023-5

(*Sardinops caeruleus*) fishery, integrated with a cost–benefit analysis.

The small pelagic fishery of the Gulf of California is the most voluminous one in Mexico (Cisneros-Mata et al., 1996). During the 1988–1989 fishing season, small pelagic landings reached 312 000 t, of which 292 000 t (about 96%) were Pacific sardine. However, this has been a highly variable fishery from the beginning (Cisneros-Mata et al., 1995), as is common for sardine and anchovy fisheries elsewhere (Sharp and Csirke, 1983). Abundance changes are a result of both deterministic and stochastic factors (Cisneros-Mata et al., 1996).

2. Data and methodology

We built an age-structured simulation model of the Pacific sardine population, incorporating the stock–recruitment relation by Shepherd (1982):

$$R_t = \frac{a \times P_{t-1}}{1 + (P_{t-1}/b)^c}, \qquad (1)$$

where R is the recruitment, P the spawning stock biomass, a the maximum expected rate of recruits per adult, b the biomass level above which density-dependent effects dominate, and c is a measure of the strength of density dependence.

Using catch and effort data, the numbers of individuals at-age were estimated by Cisneros-Mata et al. (1995) using virtual population analysis (VPA) (Pope, 1972; Jones, 1984) for the period of 1972–1973 up to and including 1989–1990 (Table 1). With the results from VPA, Cisneros-Mata et al. (1995) fitted Shepherd's stock–recruitment model using the Marquardt nonlinear algorithm in the program FISHPARM. The resulting parameter values were a=2.697 recruits per adult; b=1.417×10^{10} individuals; and c=6.499 (r^2=0.77; N=13).

Because the unexplained variability of recruitment is quite large (Allen and Basasibwaki, 1974; Walters, 1986), a stochastic variability generator was incorporated:

$$R_t = (R_t \times (cv/2)) + (R_t \times cv \times \beta), \qquad (2)$$

where cv is the coefficient of variation of recruitment and β is a uniform random number between 0 and 1. A value of cv=0.8 was estimated using annual recruitment data from results of VPA. The initial condition (age class vector) in this simulation was the numbers-at-age corresponding to those estimated by VPA for 1972/1973 (See Table B in Cisneros-Mata et al., 1995).

Simulations proceeded computing annual recruitment (numbers at age class 0) with Eqs. (1) and (2) for the deterministic and stochastic versions, while numbers-at-age for age classes 1–6 years were computed as

$$N_{a,t} = N_{a-1,t-1} e^{-(M+F_t)}, \qquad (3)$$

where a is age class and t refers to years. Annual values of fishing mortality rate F were estimated from numbers-at-age derived from the VPA (Cisneros-Mata et al., 1995), and a constant rate of natural mortality M=0.77 per year was considered. M was previously estimated (Cisneros-Mata et al., 1991) using Pauly's (1984) empirical formula. Numbers were then transformed to biomass (B_t) by multiplying N_t (numbers alive in the cohort at time t) times W_t (mean weight at age t). Fishable biomass is the sum of age classes 1–6 years plus 50% of age class 0 (R). Spawning biomass is the sum of age classes 1–6 years. Annual total catch was then estimated by multiplying annual value of F times the fishable biomass.

Because the main purpose of this work was to estimate long-run reference values of F using simulations, we first tuned the model using real data. Output from the simulation model was compared to observed catch data from the fishery corresponding to the period 1972–1973 to 1989–1990 (Table 1), and with recruitment data estimated using VPA. Next, 50 years were simulated (1990–1991 to 2039–2040), systematically increasing F to find the F value resulting in maximum yield and that at which the population begins to decline. For the stochastic version, 10 model runs were averaged for each F level.

Simulations of the period 1990–1991 to 2039–2040 started with the number of individuals during the 1989–1990 fishing season. Recruits (age class 0) were computed through Shepherd's model with numbers-at-age classes 1–6 in the 1989–1990 fishing season. The number of individuals per age class (1–6) for the 1990–1991 season were estimated using Eq. (3). This process was repeated for each year in the simulation until the end of the period. Values of F varied from 0 to 1.

Table 1
Catch, effort, fishing mortality (F) and number by age by fishing season (Pacific sardine of Gulf of California, Mexico)

Fishing season	Catch	Effort	F	Number by age						
				0	1	2	3	4	5	6
1972/1973	9924	381	0.0338	3 712 574 000	1 828 364 000	554 549 000	131 834 000	21 167 000	5 500 000	1 000 000
1973/1974	16 180	750	0.0732	1 943 336 000	1 682 751 000	886 306 000	221 927 000	34 954 000	1 763 000	100 000
1974/1975	36 648	1271	0.2495	1 335 048 000	870 927 000	716 326 000	335 851 000	72 292 000	14 690 000	595 000
1975/1976	51 263	1878	0.3191	2 935 449 000	575 088 000	291 270 000	224 441 000	85 838 000	19 967 000	4 801 000
1976/1977	8802	373	0.0303	5 389 424 000	1 321 901 000	212 965 000	34 096 000	11 975 000	2 403 000	546 000
1977/1978	32 600	1112	0.0944	7 077 535 000	2 442 327 000	585 900 000	79 448 000	1 728 000	119 000	12 000
1978/1979	24 627	732	0.0829	9 151 337 000	3 135 967 000	917 703 000	192 859 000	6 185 000	240 000	1000
1979/1980	77 566	1588	0.1747	5 874 631 000	4 090 689 000	1 264 492 000	290 707 000	21 628 000	1 476 000	1000
1980/1981	93 989	2133	0.1873	8 562 187 000	2 682 036 000	1 528 759 000	348 017 000	37 453 000	8 882 000	600 000
1981/1982	71 425	1271	0.2445	9 955 486 000	3 949 767 000	987 030 000	428 444 000	18 877 000	3 190 000	2 047 000
1982/1983	111 523	1584	0.0958	14 500 033 000	615 188 000	1 377 710 000	130 533 000	17 897 000	2 904 000	463 000
1983/1984	146 467	1839	0.2185	22 115 802 000	6 626 972 000	1 851 061 000	537 762 000	4 379 000	607 000	108 000
1984/1985	169 076	2281	0.0825	28 562 340 000	10 078 614 000	2 081 420 000	367 509 000	13 873 000	362 000	21 000
1985/1986	240 226	3160	0.1209	23 633 075 000	13 203 679 000	4 145 572 000	686 667 000	46 353 000	5 218 000	43 000
1986/1987	272 574	3534	0.2233	11 851 629 000	10 637 752 000	5 270 339 000	1 564 716 000	138 469 000	16 989 000	2 104 000
1987/1988	261 363	3371	0.2052	9 961 348 000	5 432 792 000	4 184 076 000	1 572 530 000	260 840 000	34 653 000	2 459 000
1988/1989	294 095	3776	0.4237	5 810 251 000	4 682 059 000	2 297 139 000	1 250 580 000	290 648 000	64 595 000	7 548 000
1989/1990	109 942	1630	0.2622	3 316 850 000	2 222 967 000	1 547 267 000	450 867 000	163 179 000	51 179 000	11 950 000

Table 2
Physical data, costs (in US dollars), and operating characteristics of a representative boat in the Pacific sardine fishery of the Gulf of California

Vessel characteristics	
Type of vessel	Purse seiner
Keel length	25 m
Engine Hp	520
Market value	\$ 350 000
Annual variable costs	
Gear loss	\$ 5000
Fuel	\$ 50 400
Lubricants	\$ 10 800
Food	\$ 12 000
Crew share	28% of gross earnings
Annual fixed costs	
Depreciation and interest costs	\$ 35 000
Insurance	\$ 14 000
Business expenses	\$ 35 000
Maintenance and repairs	\$ 42 000
Operating characteristics	
Operating days per year	240
Catch per fishing trip	70 t
Catch per boat year	[illegible]

Fishing is regarded mainly as an economic activity (Chávez, 1994; Chávez and Arreguín-Sánchez, 1994; McGarvey, 1994); thus, a rough cost–benefit (*C/B*) analysis was conducted. Costs included fixed and variable costs and crew shares (Table 2). Income was based on the landed sardine price. All costs were considered fixed due to the difficulty of predicting trends under the highly variable economic situation currently prevailing in Mexico. Most data for this analysis were provided by the local office of the Fishing Chamber. Data on price and depreciation rate of an average fishing vessel were obtained directly from the insurance policies. A thorough economic analysis should consider variability of data used; our present study, however, pretended to be a rough approximation only, and a more detailed examination is beyond our present goals. For the same reason, a discount rate was not considered here. As with catch, the *C/B* rate was analyzed for the period of available data (1972/1973–1989/1990), then *C/B* rates were estimated for each F level in the simulated period.

Fishing mortality F and fishing effort E in number of fishing trips were available for the same period considered, and the catchability coefficient ($q=F/E$) was estimated for each fishing season from 1972–1973 to 1989–1990. An average q was then computed and used as constant in the simulations. Although studies have shown that q might not be linear in F (Arreguín-Sánchez, 1996), for the period considered here, a linear relationship was found ($r=0.59$, $p<0.05$). Hence, for the simulated period (1990–1991 to 2039–2040), E's were calculated for each F level multiplying F by $q=0.0001$, regarded as constant.

3. Results

The behavior of the model was examined by comparing simulated catch and recruitment data to those observed for the 1972–1973 to 1989–1990 seasons (Figs. 1 and 2). Although simulation output and observed data show the same general trends for both landings and recruitment, there are periods during which the simulated results for recruitment overestimate or underestimate those resulting from VPA analysis (Fig. 1(A) and Fig. 2(A)). Those are years of either poor or good recruitment during which the model fails to simulate them adequately (Fig. 1(B) and Fig. 2(B)). Catches show the greatest difference during the 1975–1976 season (Fig. 1(C) and Fig. 2(C)).

It is not surprising to find important deviations of predicted and observed recruitment data for the last two seasons of the series. This is a common characteristic when one uses VPA, where accuracy is lowest for the last age classes of the series (Pope, 1972; Jones, 1984).

Simulation of the sardine population size for 1990–1991 to 2039–2040 with $F=0$ (no fishing) shows five-year cycles both in numbers and biomass, caused by density dependence and the age structure of the model (Fig. 3(A) and (B)).

The deterministic version of the model predicts decreasing amplitude of these oscillations as F increases (Fig. 3(C) and (D)) to slightly less than 0.5. Above this value the population collapses (Fig. 3(E) and (F)). The long-run yield as a function of F (Fig. 4(A)) shows that optimal yield (OY) is obtained at $F=0.475$, while *C/B* has high values (1.4) at low levels of F and beyond $F=0.475$ (*C/B*=1.1), the function plummets, reaching a *C/B*=1 at $F=0.5$ (Fig. 4(A)).

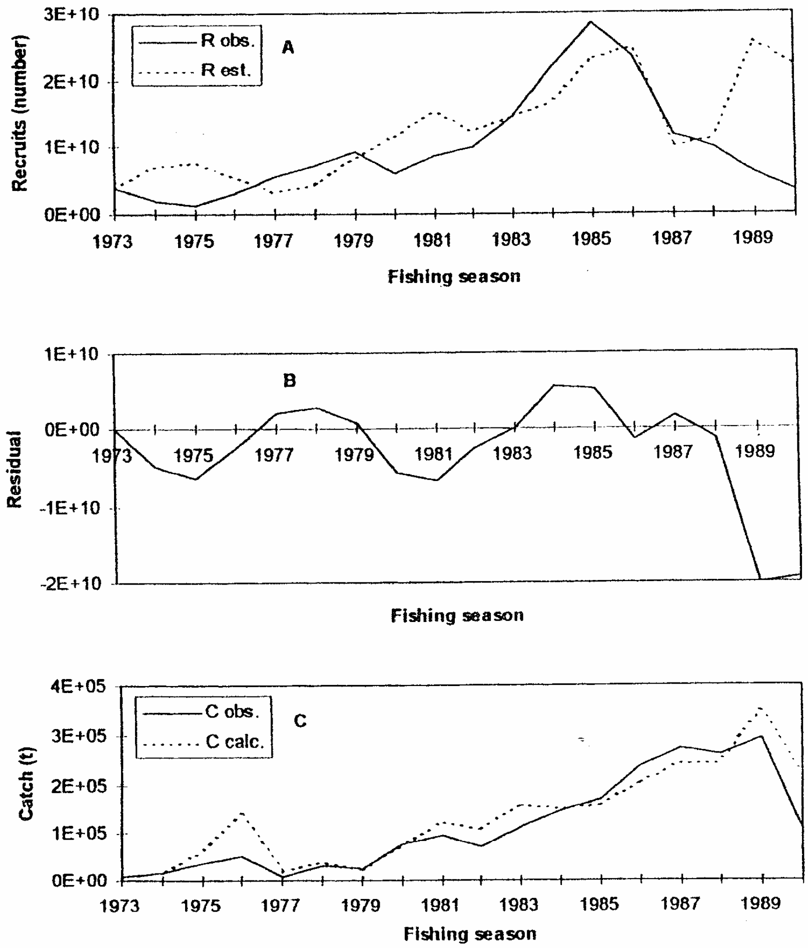

Fig. 1. Comparison between VPA and deterministic model simulation values: (A) recruitment, (B) recruitment residuals and (C) yield.

As for the model with incorporated stochastic variation, its behavior is very similar to the former, but although the oscillations are damped as F increases, they never totally disappeared (Fig. 5(A)–(F)). Fig. 4(B) shows that OY is obtained by $F=0.275$ and C/B behaves similarly to that of the deterministic version, but plummeting occurs at $F=0.3$, and $C/B=1$ at $F=0.3$ (Fig. 4(B)).

4. Discussion

Very likely the differences between observed and simulated catch and recruitment are caused by environmental variability, not included in this simulation model (e.g., Wespestad and Terry, 1984; Hall et al., 1988). However, the model proved to be an appropriate tool for analyzing dynamic long-term trends of

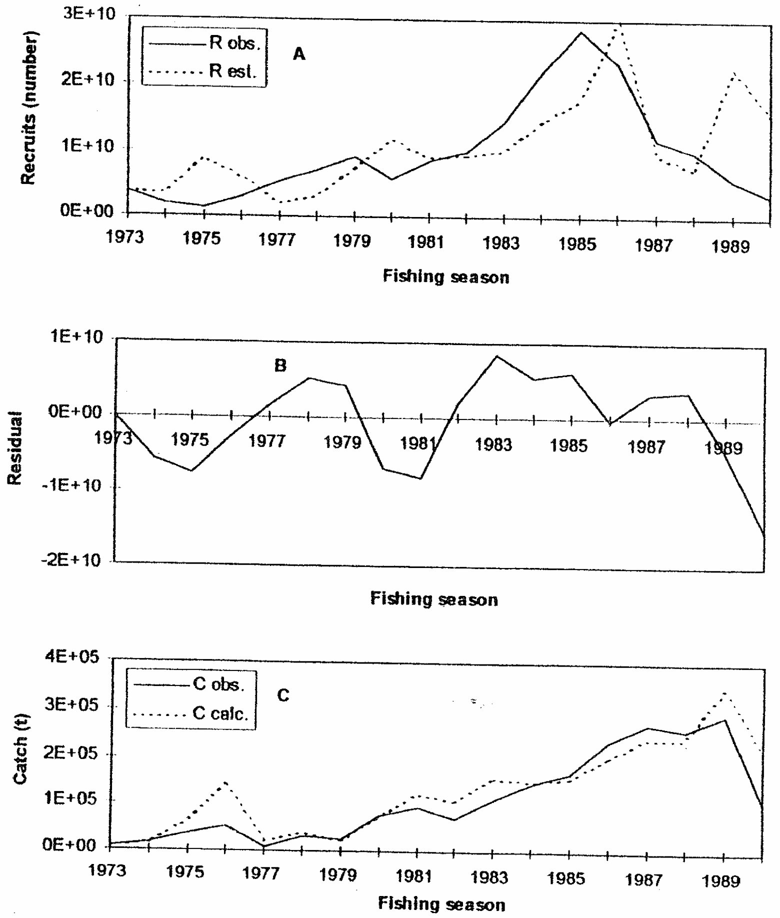

Fig. 2. Comparison between VPA and probabilistic model simulation values: (A) recruitment, (B) recruitment residuals and (C) yield.

the Pacific sardine in the Gulf of California, and the expected long-term yields for various levels of fishing mortality (Wespestad and Terry, 1984). The large difference in recruitment for 1989/1990, the last year of the series used to fit the model, as mentioned above, most probably reflects weakness of VPA. It is unlikely that this might have influenced results of the simulation because, as shown in Figs. 3 and 5, all population trajectories quickly attain stable oscillations and steadily decline when fishing mortality is introduced.

The five-year cycles in the sardine population size resulting from age structure and density dependence were also found by Cisneros-Mata et al. (1996). This accounts for the cyclic pattern observed in the residuals (Fig. 1(B) and Fig. 2(B)). Oscillation damping

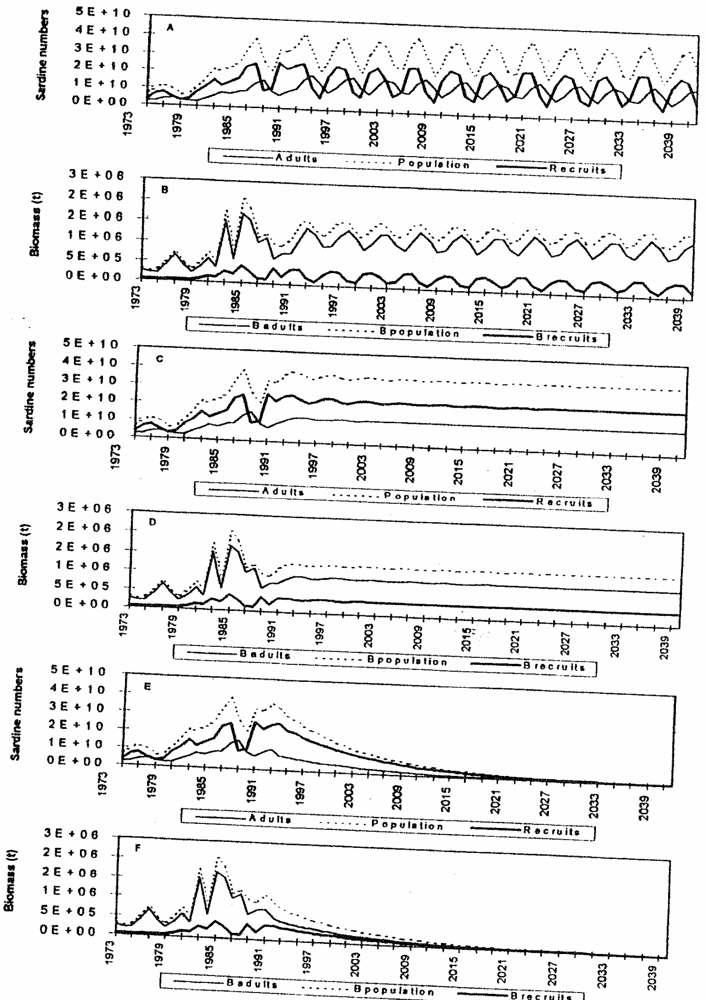

Fig. 3. Observed tendencies over 50 years of the deterministic Pacific sardine abundance and biomass model simulation. $F=0$ (A, B), $F=0.25$ (C, D), $F=0.7$ (E, F).

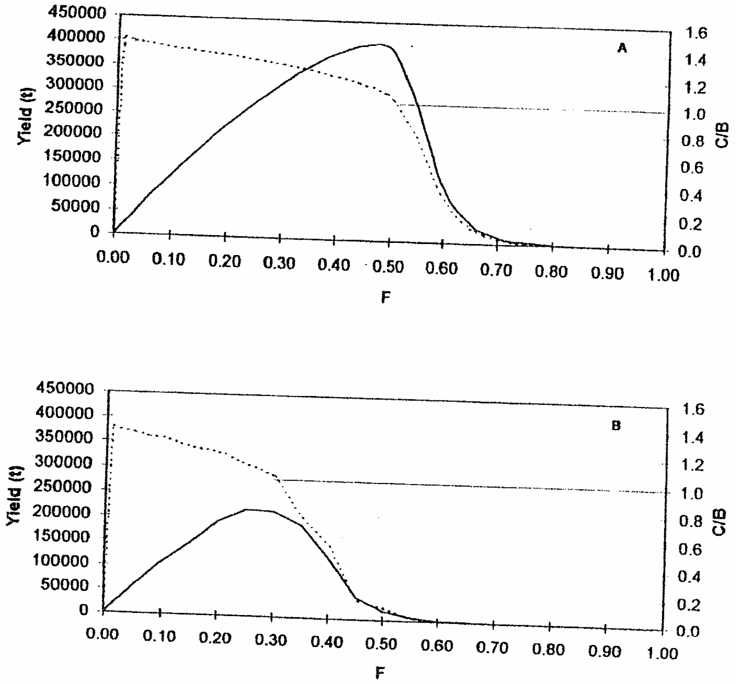

Fig. 4. Annual mean yield and cost/benefit ratio (C/B) as function of F: (A) deterministic model and (B) probabilistic model.

as a result of intensified fishing (up to F=0.475) also agrees with previous authors (Ricker, 1954; Basasibwaki, 1972 as quoted by Allen and Basasibwaki (1974)), who have pointed out that an unstable population may be stabilized by taking a large enough catch. This can be intuitively explained due to the fact that F reduces the size of the parental stock, which given a very strong density dependence in turn increases an otherwise low recruitment level. The same argument can be used to explain why a moderate F will produce increased parental stock size when the stock size is at moderate levels.

The simulations also showed that from the biological and economic viewpoint (the C/B rate), population yield might be increased at most to the levels of F exerted during the 1989–1990 fishing season (F=0.26), which would result in a yield of about 220 000 t with C/B=1.1. This is a relevant result because if the population is harvested at the level of optimum yield (F=0.475 deterministic model or F=0.275 probabilistic model), there is a high possibility of collapse because of the increased negative slope of the yield curve beyond this level (Fig. 4(A) and (B)). Furthermore, even if these models incorporate random variation, it is likely that there is even higher variability than that considered because of environmental variations (Parrish et al., 1983; Wespestad and Terry, 1984; Winters et al., 1985; Huato-Soberanis and Lluch-Belda, 1987; Lluch-Belda et al., 1989; Jacobson and MacCall, 1995).

One relevant result is that the deterministic and stochastic models yield seemingly similar results for the tuning period (1972–1973 to 1989–1990). Nevertheless, over the long-run the stochastic model gives more realistic results because maximum biological yield and the corresponding F value are in agreement

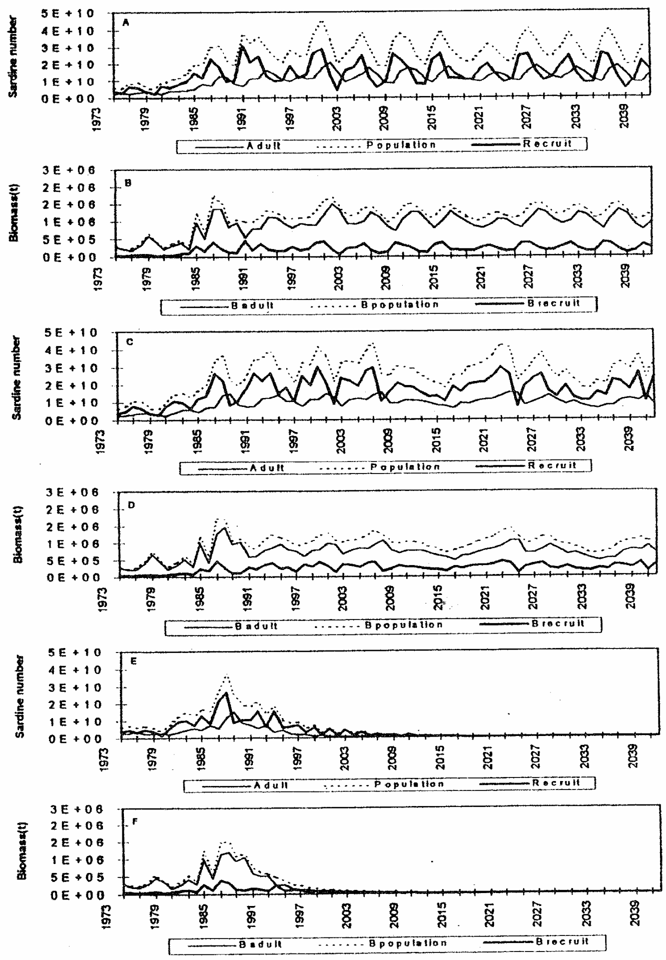

Fig. 5. Observed tendencies over 50 years of the probabilistic Pacific sardine abundance and biomass model simulation. $F=0$ (A, B), $F=0.25$ (C, D), $F=0.7$ (E, F).

with historic catches over the 30 year period of existence of this fishery (e.g. Cisneros-Mata et al., 1995). The deterministic model, by contrast, results in F and MSY which are far larger than the ones ever registered. Consequently, the stochastic model proved to be a more reliable tool to develop management prescriptions for this fishery.

Although F corresponding to MSY for the stochastic version is 0.275, this would yield economic returns slightly below their maximum (MEY). An F value of 0.25 would not only produce higher economic returns, and be safer biologically, but will reduce intrinsic population oscillations, which for management purposes is a desirable characteristic of an exploitable resource. Thus we conclude that a reference value of $0.9F_{MSY}$ is the best option for this fishery. Results of the deterministic analysis are also in agreement with this reference F value in terms of biological and economic optimality.

Illustrating this point, the Pacific sardine population in the Gulf of California reached peak landings during 1988–1989 (292 000 t), after which they collapsed during 1990–1991 to 1992–1993 to a minimum of 7000 t. Later, yields increased from 1993–1994 to 1995–1996, reaching again 200 000 t (Cisneros-Mata et al., 1996), seemingly related to high environmental variability (as shown by sea surface temperature and upwelling indices) in the Gulf of California.

Acknowledgements

We thank F. Arreguín Sánchez, D. Lluch Cota, and two anonymous reviewers for critical review of this work in manuscript form, and E. Glazier who edited an early English version. Partial financial support for MONM was granted by CONACYT.

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