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An analysis of harvest strategies and information needs in the purse seine fishery for the Brazilian sardine

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Abstract

This paper evaluates a range of constant harvest rate, constant escapement, and effort control strategies in the purse seine fishery for the Brazilian sardine by accounting for uncertainties in the processes controlling recruitment and catchability. Control strategies are evaluated with a delay-difference simulation model representing three hypotheses about sardine stock–recruitment relationship, involving the effect of spawning stock size, depensation and cyclic environmental regimes. Strategies are compared by the predicted average catches, catch variability, and probability of stock collapse. Results from simulations are also used to evaluate the relative merits of different types of policies and to evaluate the relative values of reducing the uncertainties about sardine recruitment dynamics. Better understanding of the processes controlling recruitment is mostly needed if the fishery is to continue being managed by effort control. Constant harvest rate policies provide better trade-off among the performance indicators and appears more robust to uncertainties on the prevailing ecological processes controlling recruitment. Results from this analysis are used to discuss the type of research that would most likely provide the information needed to improve the quality of decisions in the purse seine fishery.

Keywords: Brazilian sardine; Environmental regime; Harvest strategies; Stock–recruit; Decision analysis

1. Introduction

Sardine, *Sardinella brasiliensis*, is a short-lived species inhabiting coastal waters of the southeastern Brazilian Bight (Fig. 1). The species attains a total length of 25 cm and a maximum age of 4 years, but becomes mature with approximately 17 cm and 1 year of age (Cergole, 1995). The spawning strategy of the Brazilian sardine is coupled to periods of favorable environmental conditions for egg and larvae survival in the Bight (Bakun and Parrish, 1990). The main oceanographic characteristic of the region is the seasonal presence of cold, nutrient-rich south Atlantic central water on the inner shelf, i.e. 10–50 m deep (Pires-Vanin and Matsuura, 1993). Sardine spawning occurs mainly during spring and summer, in the enriched environment formed downstream of the upwelling center of Cabo Frio (Bakun and Parrish, 1990).

The southeastern Brazilian Bight ecosystem is conditioned by cyclical oceanographic events that control changes in the patterns of energy flow and the productivity of biological communities (Pires-Vanin et al., 1993; Vasconcellos, 2000). The seasonal upwelling cycle is nested in a hierarchy of environmental cycles with different time scales, ranging from days to dec-

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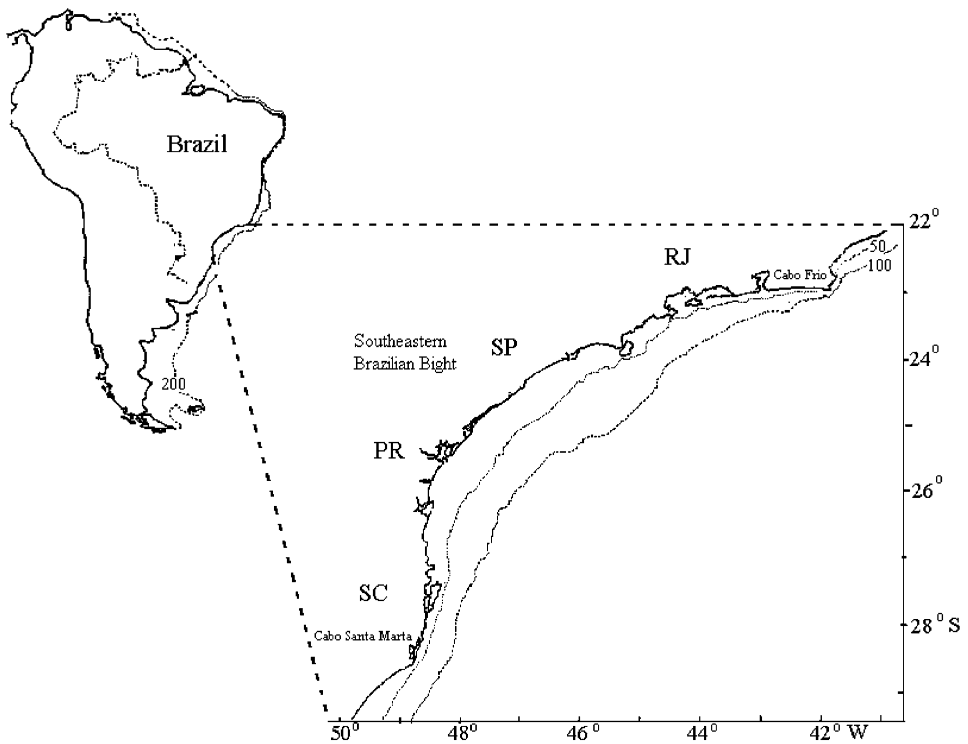

Fig. 1. Detail of the southeastern Brazilian Bight, which encompasses the distribution area of sardine, *S. brasiliensis*, and the fishing area of the purse seine fleet. Sardine distribution area includes the coastal region of four states, Rio de Janeiro (RJ), São Paulo (SP), Paraná (PR) and Santa Catarina (SC). Depth is expressed in meters.

ades. On one hand, physical processes such as pulses of favorable wind stress, storms, and small-scale eddies with low residence time, all influence biological processes at short time scales. Cycles in many marine fish populations, particularly small pelagic fishes such as sardines, bear, on the other hand, close correspondence to the long-term climatic-oceanographic regimes of the oceans (Steele, 1985; Lluch-Belda et al., 1989; Bakun, 1996). Bakun (1996), for instance, compiled examples of synchronous decadal oscillations in several fish populations that were geographically isolated from each other, but apparently driven by a common environmental property (periods of intensification of the El-Niño). These low-frequency population cycles varied among species, but were generally characterized by a period of rapid population growth in the decade from the mid-1970s to the mid-1980s followed by stock declines after the mid-1980s. According to Bakun, the Brazilian sardine followed the pattern of "crashing" after the mid-1980s.

1.1. The purse seine fishery for sardine

Until the early 1900s sardine catches were mainly by artisanal fishers and used as food by coastal communities (Diegues, 1995). This artisanal fishery still exists in most states, catching sardines in bays and estuaries along the coast, using cast nets and seine nets. Today, however, most of the sardine catches come from an industrial fishery based on purse seiners. The first purse seiners appeared ca. 1910 and gradually diverged from the artisanal and small-scale sector, mainly during the 1930s with the introduction of power engines (Diegues, 1995). During 1967–1978 government tax incentives (Código de Pesca, Lei 221, 1967) attracted a considerable amount of capital to the fishing sector which expanded the number of industries for catching and processing fish products for export, and resulted in unprecedented changes in the fishery. Sardine became the main Brazilian fishery resource in terms of volume, with total annual catches

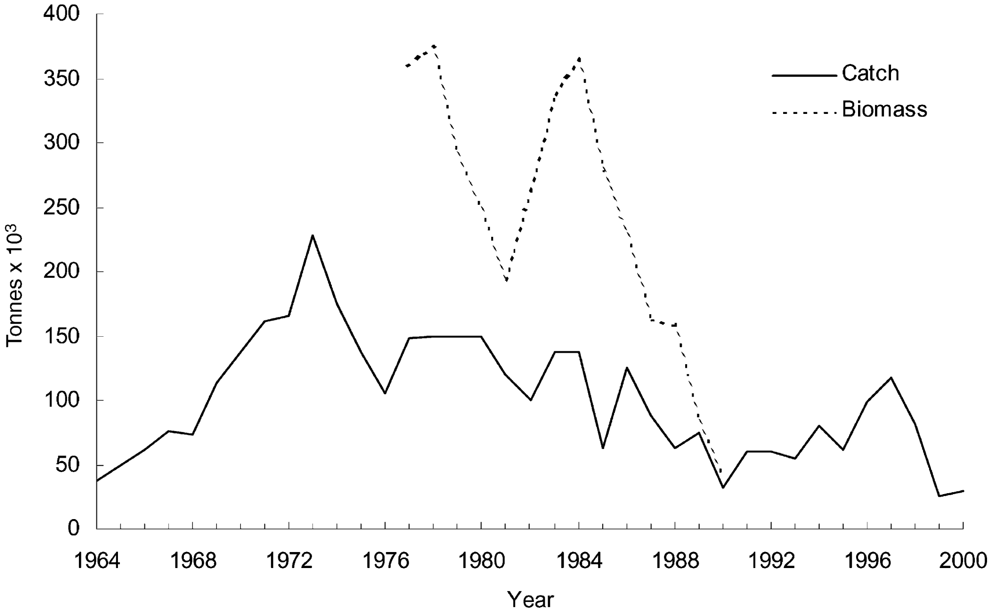

Fig. 2. Sardine landings and the reconstructed stock biomass in the southeastern Brazilian Bight (sources: IBAMA; Vasconcellos, 2000). Stock biomass data are available only for the period from 1977 to 1990.

increasing from ca. 38,000 t in 1964 to a historical peak of 228,000 t in 1973 (Fig. 2). Average landings during 1983–1987 period was 124,000 t per year, accounting for 31.8% of the total fish catches in the region and about 25% of the total Brazilian marine catch (IBAMA, 1995).

Another program of government incentives aimed at the modernization of the fleet lasted from 1983 to 1985. It resulted in an increase in fleet capacity (tonnage) of approximately 300% compared to the 1970s, a doubling of the number of fishing vessels, and the introduction of technological innovations (e.g. sonar and power block) that considerably increased the fishing power of purse seiners (Valentini and Cardoso, 1991). The fishery experienced a marked decrease in catches, mainly from 1987 to 1990, which culminated with the collapse of the stock and a crisis in the commercial/industrial sector (IBAMA, 1995). It is estimated that between 1977 and 1990 the stock biomass declined from ca. 350,000 t to less than 80,000 t, with an average fishing mortality rate of 0.8 per year (Fig. 2; Vasconcellos, 2000). Since the collapse of the fishery there is no indication of a significant stock recovery (Habiaga, 2000). Catches increased from 1992 to 1997 reaching ca. 118,000 t, but decreased again to less than 30,000 t in 2000 (Cergole, 2000).

Similarly to other marine pelagic ecosystems subjected to intense fishing, the decline in sardine biomass was followed by a marked increase in the biomass of anchovy, a small pelagic species also abundant in the area (Castello et al., 1991). The decrease in sardine biomass was also accompanied by an increase in catches of triggerfish, *Balistes capriscus* (Zavala-Camin and Lemos, 1997), which is a semi-pelagic species as adult and pelagic planktonic feeders as juveniles. The understanding of the causes of stock collapse and ecosystem changes has been of particular concern for sardine stock assessment and management (Castello et al., 1991; Saccardo and Rossi-Wongtschowski, 1991; IBAMA, 1995; Rossi-Wongtschowski et al., 1996).

1.2. Stock–recruitment

Several processes can influence the productivity of an exploited fish population. Hilborn and Walters (1992) argued that sum of density-dependent, environmental and multispecies effects on a stock is likely to be most important during the fish early life stages, when larvae and juveniles are more vulnerable to suboptimal environmental conditions, predation and competition for food. In a fisheries assessment analysis the net effect of density-dependent effects on juvenile survival and recruitment is usually represented by a stock–recruitment relationship. Environmental and multi-species effects are represented by deviations from the underlying stock–recruitment curve. The focus on stock–recruitment relationships has a practical basis, since it directly links a control variable (stock) and a rate of future stock production (recruitment) (Hilborn and Walters, 1992).

Three hypotheses have been proposed to explain stock–recruitment dynamics of the Brazilian sardine between the 1970s and 1990s (Cergole, 1995; Vasconcellos, 2000; Fig. 3):

1) *Recruitment decreased in response to a gradual decline of the spawning stock biomass due to overfishing*. For this scenario, recruitment is a

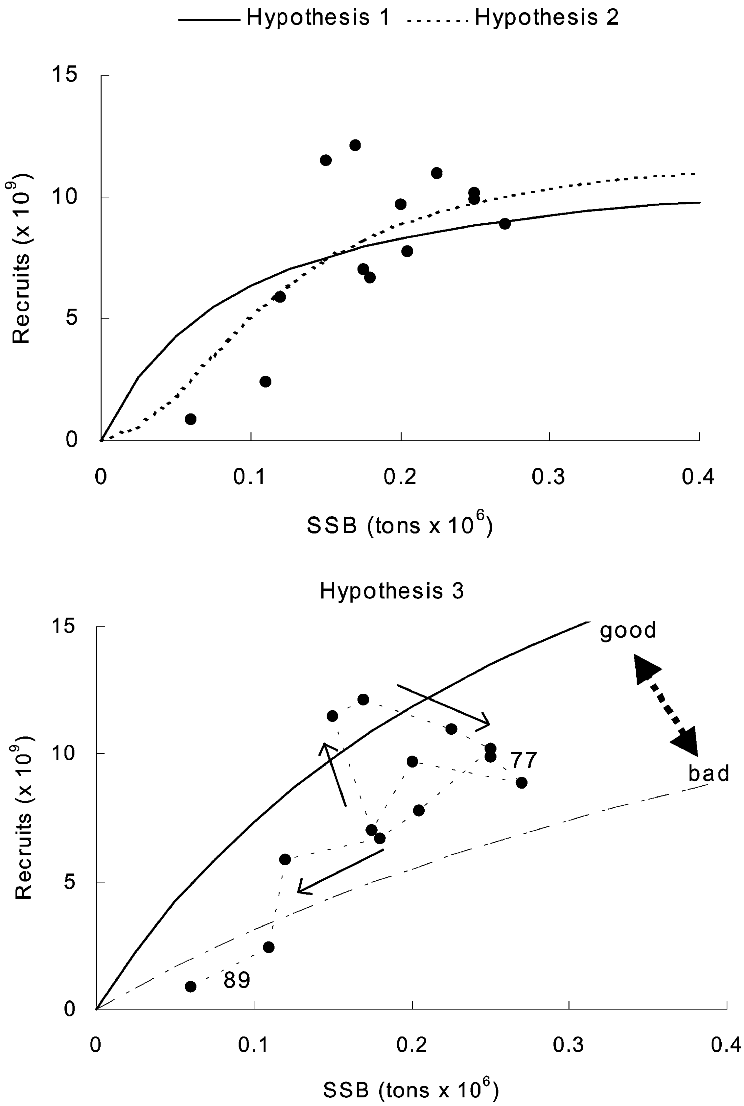

Fig. 3. Graphic representation of the three hypothesis used to describe the relationship between sardine spawning stock biomass and recruitment. Hypothesis 1 is that recruitment is a function of stock size; hypothesis 2 assumes depensation at low stock sizes; and hypothesis 3 assumes that stock–recruitment relationship oscillate between "good" and "bad" environmental regimes affecting the marine carrying capacity.

function of stock size, and environmental processes impose inter-annual recruitment variability. This hypothesis is consistent with the decrease in recruitment that accompanied the decrease in spawning biomass from 1977 to 1989.

2) *Recruitment declined in response to overfishing and is forced to stay at low levels due to depensatory mechanisms*. According to this scenario, recruitment is a function of stock size but recruitment is depressed by depensation at low stock sizes. Depensation is a reduction in recruitment at low stock sizes beyond the reduction that might be expected based on a simple stock–recruitment curve. Several processes can contribute to depensation in stock production including competitive exclusion, increased predation mortality at low stock size, reduction of intraspecific diversity, or even behavioral processes such as the "school trap" phenomenon (Cury et al., 2000).
3) *Recruitment declined as a result of overfishing and recruitment failures caused by long-term, low-frequency environmental effects, according to Bakun's "dome-shaped" regime hypothesis* (Bakun, 1996). In this case, recruitment is characterized by a nonstationary relationship between stock and recruitment driven by low-frequency environmental cycles. Recruitment time series present a decadal signal superimposed on the interannual variability.

This paper evaluates through a simulation model the impact of harvest strategies and controls on the sardine fishery given uncertainties about stock–recruitment dynamics, and discusses the relative values of reducing these uncertainties in a quantitative decision analysis aimed at maximizing fisheries yield. Results of simulations of catch, escapement and effort control strategies are used to recommend the type of information needed to improve the quality of decisions in each case.

2. Methods

Fishing strategies were evaluated with a Monte Carlo simulation model based on delay-difference equations (Deriso, 1980; Hilborn and Walters, 1992). The delay-difference model was chosen because it allows a simpler yet efficient representation of survival, growth and recruitment processes without the need to keep separate track of the numbers and sizes of fish in different age groups (Hilborn and Walters, 1992). The model predicts next year's biomass (B_{t+1}) and numbers (N_{t+1}) according to the equations:

$$B_{t+1} = s_t[\alpha N_t + \rho B_t] + w_k R_{t+1} \quad (1)$$

$$N_{t+1} = s_t N_t + R_{t+1} \quad (2)$$

where w_k is the weight at recruitment age k (years), $s_t = \mathrm{e}^{-M}(1 - h_t)$ the total survival rate, M the instantaneous natural mortality rate (=0.95 per year; Cergole, 1995) and h_t the exploitation rate. The exploitation rate can be calculated as the ratio of catch/biomass in a given year, or as a function of fishing effort, i.e., $h = 1 - \mathrm{e}^{-qE}$, where E is the effort and q the catchability parameter. Catchability was represented by an inverse function of stock abundance:

$$q_t = \gamma B_t^{-\theta} \quad (3)$$

where γ is a proportionality constant and θ (always > 0) is the degree to which catchability increases with declining stock size.

The delay-differential model assumes growth in mean body weight at age (w_a) can be described using a Ford–Walford plot and linear model $w_a = \alpha + \rho w_{a-1}$, where α is the intercept, ρ the slope (equal to e^{-K}), K the growth constant of von Bertalanffy's equation, and the intercept with $w_a = w_{a-1}$ line equal to W_∞. Sardine parameter values for α (=0.025) and ρ (=0.896) were obtained by regressing data on weight at consecutive ages from Cergole (1995). Schnute (1987) improved Deriso's delay-difference model by introducing more realistic assumptions and equations for growth and fishery mortality. However, both forms of representation are likely to produce similar results and conclusions.

Recruitment (R_{t+1}) is included in the model as functions representing three different stock–recruitment hypotheses (Cergole, 1995; Vasconcellos, 2000; Table 1; Fig. 3). Following Hilborn and Walters (1992) high frequency variations around recruitment levels expected based on a stock–recruit or regime hypotheses are assumed to follow a lognormal distribution.

Table 1
Hypotheses, models and parameters used to predict recruitment rates in the delay-difference model[a]

Hypothesis	Model	Parameter values
1) Recruitment is a function of stock size	$\text{Recruits} = \frac{a\text{SSB}^x}{1+(\text{SSB}^x/K)}\,e^v$	$a = 135, K = 0.0888, x = 1, v = 0.4$
2) Recruitment is a function of stock size with depensation at low stock sizes	$\text{Recruits} = \frac{a\text{SSB}^x}{1+(\text{SSB}^x/K)}\,e^v$	$a = 867, K = 0.0138, x = 2, v = 0.4$
3) Recruitment is a function of stock size and low frequency environmental regimes	$\text{Recruits} = \frac{a\text{SSB}}{1+(a\text{SSB}/K)}\,e^v$, $a = \exp^{-M_1}, K = \frac{M_1}{M_2(\exp^{M_1}-1)}$	$M_{1,t} = -3.576 + 1\sin\left(\frac{t\pi}{10}\right)$, $M_2 = 0.152, v = 0.4$

[a] Hypotheses 1 and 2 are represented by a Beverton-Holt stock–recruitment function modified to include depensatory effects (Myers et al., 1995). Hypothesis 3 is represented by a modification of the Beverton-Holt function according to Walters and Parma (1996). In the latter, the density-independent mortality risk (M_1) follows a sinusoidal trend with period of 10 years, thus representing decadal regimes in marine carrying capacity.

2.1. Management strategies

Three types of management strategies (constant harvest rate, constant escapement and effort control) were evaluated in this analysis. For constant harvest rate strategies the total allowable catch in a given year is defined in advance based on a constant exploitation rate. For the constant escapement strategy the total allowable catch was defined in advance based on a minimum stock escapement goal. Effort control is the status quo policy in the sardine fishery. It attempts to control fishing mortality by limiting the total fishing effort using license control (number of boats) and closed seasons (time fishing). In the analysis of this strategy, effort is measured by the number of trips with adjustments for the mean tonnage of boats.

Uncertainties in population status and dynamics of the Brazilian sardine make management decisions on the optimal level of effort and total allowable catch difficult. Uncertainties about biological production, and the relationship between current catches and the future state of the stock, is represented by the three hypotheses about sardine stock–recruitment relationship described above (Fig. 3; Table 1). In the analysis of management strategies all three hypotheses were assumed equally plausible.

Another source of uncertainty, particularly important for effort control, is due to questions about whether catch rates vary independently of stock size as a result of changes in catchability (Pitcher, 1995). Shoaling pelagic fish have highly aggregated distributions which makes them relatively easy to capture at low population sizes with purse seiners (MacCall, 1990; Pitcher, 1995). The combined effect of behavioral adaptations and fishing technology seems to be responsible for an observed inverse relationship between sardine stock size and catchability (Vasconcellos, 2000). Uncertainties in the relationship between stock biomass and catchability were assumed in this analysis to be described by marginal posterior probability distributions for catchability parameters γ and θ (Eq. (3)) estimated by Vasconcellos (2000) (Fig. 4).

Catch control strategies usually rely on estimates of stock biomass by direct methods, such as acoustic surveys and egg production, which are usually accompanied by large uncertainties (MacLennam and Simmonds, 1992). In the simulation model, uncertainties in the estimation of stock biomass at sea were introduced by including a normally distributed error around the simulated true stock biomass (Frederick and Peterman, 1995), where

$$B_{\text{est}} = B_{\text{t}} + B_{\text{t}}\text{CV}w$$

B_{est} is the estimated stock biomass in year t, B_{t} is the true biomass, CV the coefficient of variation of the biomass estimation procedure ($0 < \text{CV} > 0.5$), and w is a normally distributed variable with mean 0 and variance 1. Parameters values were chosen to produce a level of error comparable to those reported in stock assessment procedures (Frederick and Peterman, 1995).

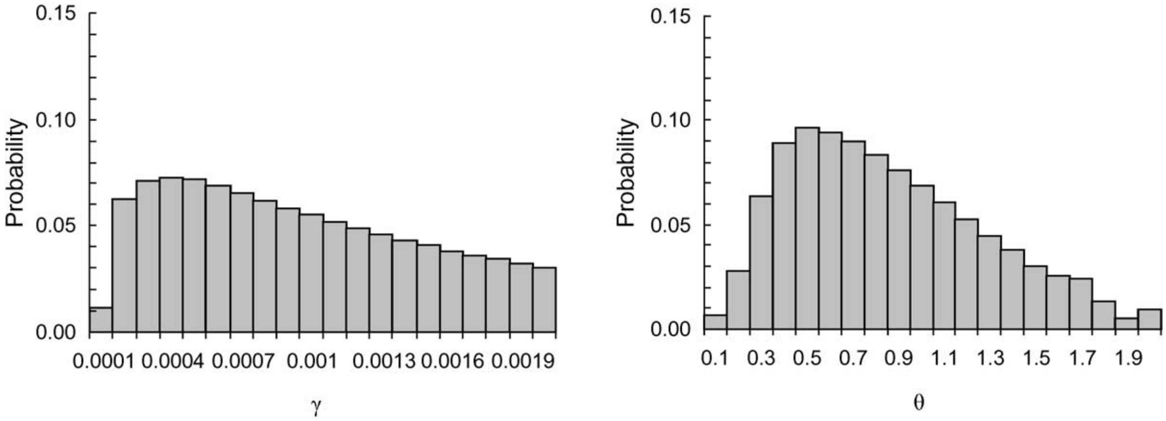

Fig. 4. Marginal posterior probability distribution of catchability parameters γ and θ (from Eq. (3)) for the Brazilian sardine fishery based on stock biomass and catchability parameter from 1977 to 1983 (Vasconcellos, 2000).

2.2. Evaluation of management strategies

Three criteria were used in the evaluation of management strategies for the Brazilian sardine fishery: average catches, catch variability, and the probability of stock collapse. Performance indicators were calculated as: the average catch during 10 years of simulation (x); catch variability was measured by the coefficient of variation (s/x) of catches during 10 years of simulation, being s the standard deviation of catches in the period; and the probability of collapse was measured as the proportion of cases (Monte Carlo simulations) in which the spawning stock was driven below the historical lowest size, i.e., approximately 50,000 t. These criteria were selected because they represent three types of objectives commonly observed in fisheries management: (i) Maximize yield: in effect, the increase in fisheries catches represent more fish to the industry, more economic opportunities to the capture sector and, consequently, more job offers; (ii) Maximize catch stability: very often, the major interest with a management plan is to guarantee the stability or low variability of catches, and therefore maintain a constant supply of fish to the industry and (iii) Minimize the chances of fishery collapse: that is a fundamental objective to any fisheries management plan, considering the ecological and economic costs associated with the collapse of fisheries.

The expected outcomes of the different combination of fishing strategies and controls were obtained following the steps below (Fig. 5):

1) For each strategy type (constant harvest rate, constant escapement, and effort control), several management options were defined by test runs of the model and/or by taking into account the history of the fishery. Specifically in the case of strategies of effort control, effort levels applied between 1977 and 1983 were used as reference to define alternative effort levels. An age at first capture of 1.5 years (approximate age of first maturity) was used as an additional measure in the simulation where effort control was applied. That was necessary to make the effort control policy comparable to the management strategy currently adopted for the Brazilian sardine, which combines effort limitation and a minimum fish size in the capture (size of first maturity).
2) Simulations were run for 10 years having as starting conditions the average spawning stock biomass between 1977 and 1983 (~250,000 t), and a sinusoidal environmental forcing that produces (if hypothesis 3 is assumed true) a crashing of the Brazilian sardine in the late 1980s, as proposed by Bakun (1996). On the other hand, when simulations were done using hypotheses 1 or 2 recruitment varied only according to changes in stock size. The choice of a 10 years time horizon was because it is realistic with the time horizon of decision makers. Besides, it enables the evaluation of management strategies and of the expected value of reducing uncertainties on environmental processes affecting production

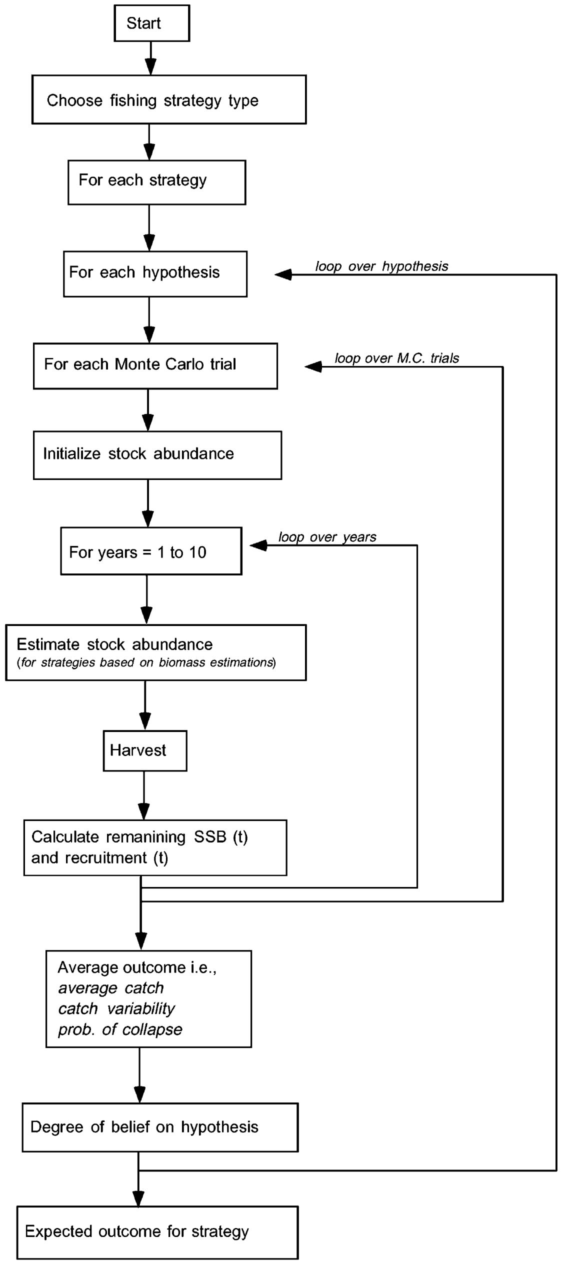

Fig. 5. Monte Carlo simulation procedure used in the evaluation of the outcomes of fishing strategies for the Brazilian sardine using a delay-difference model.

(see next section) according to the scale in which these processes operate. Setting the starting conditions to the late 1970s makes the simulation analysis retrospective, i.e., the model simulates what might have happened over many realizations of past events if different harvest policies have been used.

3) The expected outcome ($E(\mu)$) of a given fishing strategy was calculated as the average performance outcome obtained in 1000 Monte Carlo simulations, weighted by probabilities of the recruitment functions (assumed equally likely; Table 1) and the catchability parameters (Eq. (3); Fig. 4) used in the model, i.e.,

$$E(\mu) = \Sigma_i(p_i Z_i)$$

where μ is the performance indicator (average catch, catch variability, probability of collapse), p_i the probability of hypothesis i (recruitment function, catchability parameters) used in the simulation, and $Z_i = \sum_j \mu_j / 1000$ the average performance in 1000 Monte Carlo simulations (j) ran under hypothesis i. To calculate $E(\mu)$, Monte Carlo simulations were run for each possible combination of recruitment functions and catchability parameters, and the average results obtained after 1000 Monte Carlo trials were multiplied by the combined probabilities of the respective function and parameters used in the simulations.

2.3. Valuing new information: the expected value of perfect information (EVPI)

Simulation results were used to evaluate the benefits of reducing uncertainties about sardine stock–recruitment dynamics. Benefits were measured contrasting the expected catch given current uncertainties and the expected catch given perfect information about the processes affecting sardine recruitment (represented in the three hypotheses described in Table 1, Fig. 3). This value, termed the EVPI, represents the maximum, or upper bond, on what we should be willing to pay for research that will generate new information that reduces uncertainties.

Two steps are necessary to calculate the EVPI (Walters, 1986; Morgan and Henrion, 1990). First the expected value of a decision made with perfect information must be calculated. Imagining that we could identify which stock–recruitment relationship exists (and which environmental regime will occur), so that we could choose the optimal action for that state, then the value of a decision made with perfect information would simply be the forecasted result of that decision. However, at this point in time we are uncertain about stock–recruitment relationships and environmental regimes, so the expected values of outcomes for each optimal action for each possible state of nature must be weighted by the probability of occurrence of those states. Therefore, the expected value with perfect information (EVwPI) is calculated as:

$$\mathrm{EVwPI} = \sum_i [p(i)\,\mathrm{Max}(i)]$$

where $p(i)$ is the probability of state i occur, and $\mathrm{Max}(i)$ the best outcome for state of nature i. For instance, in a situation where the objective of a fisheries management decision is to maximize yield, $\mathrm{Max}(i)$ will be maximum yield obtained with a management strategy (catch or effort control) if hypothesis i (e.g., stock–recruitment relationship and environmental regime) is assumed correct. The probability $p(i)$ in this example is the product of the probabilities of the stock–recruitment relationship and of the environmental regime.

To calculate the EVPI, then EVwPI needs to be subtracted from the maximum expected value under uncertainty, i.e. that takes uncertainty into account (EIU), i.e., EVPI = EVwPI − EIU.

In this sense, EVPI indicates the total cost or value loss resulted from being uncertain. EVPI was computed for an optimal exploitation rate policy and for an optimal effort level policy. The same modeling procedure outlined in Fig. 5 was used in the calculations, but with different starting conditions. The objective in this case was to find the fishing strategy (exploitation rate and effort level) that would maximize the yield from the sardine fishery during 10 years after the collapse, i.e., after the early 1990s when the spawning stock biomass was about 70,000 t. The uncertain processes considered in this analysis were the stock–recruitment relationship (Fig. 3 and Table 1), the relationship between stock size and catchability (Eq. (3); Fig. 4), and the future environmental regime, i.e., whether a favorable or unfavorable environmental regime will occur in the next 10 years. Two scenarios were tested in the evaluation of EVPI for effort control: the first assumes a perfect knowledge about the relationship between stock size and catchability, with catchability parameters γ and θ fixed to the most likely values in Fig. 4, i.e. 0.0004 and 0.5, respectively; the second scenario accounts for uncertainties in the stock catchability relationship and evaluates policy outcomes for the whole range of possible values for parameters γ and θ (Fig. 4).

3. Results and discussion

Fig. 6 shows the expected results of catch and effort control strategies for the Brazilian sardine obtained with model simulations having as starting conditions the spawning stock biomass and environmental conditions for the late 1970s. Strategies of catching a constant proportion of the stock and allowing a constant escapement produce the highest yields among the strategies tested. The maximum expected yield is approximately 355,000 t for the constant escapement policy, 328,000 t for the constant exploitation rate policy, and 223,000 t for the constant effort policy.

The performance of constant escapement strategies are particularly sensitive to errors in biomass estimates. The general effect is of decrease in average yield, increase in catch variability and in the chances of stock collapse with the increase in coefficient of variation of the biomass estimation method (Fig. 6). The adoption of more conservative escapement levels does not reduce the relatively high probabilities of stock collapse when the error in the biomass estimation is larger than 30%. Variations of this magnitude are commonly observed in sardine stock assessment work. For example, Deriso et al. (1996) obtained a CV of 33% for biomass of Pacific sardine using a catch at age analysis. In acoustic estimation methods errors usually occur due to variations in the adjustment of ecosounders, changes in the acoustic properties of fishes, and the efficiency with which surveys cover the complete distribution area of the stock (MacLennam and Simmonds, 1992). Misund (1997), for instance, reported differences of ca. 100% in the estimation of herring biomass obtained between surveys in the same year. Similarly, acoustic assessment of sardine biomass in the 1988 spawning season (Castello et al., 1991) produced a confidence interval for stock biomass between 38,000 and 77,000 t, corresponding to a coefficient of variation in the order of 30%.

Strategies of catching a constant proportion of the stock annually are less sensitive to errors in biomass

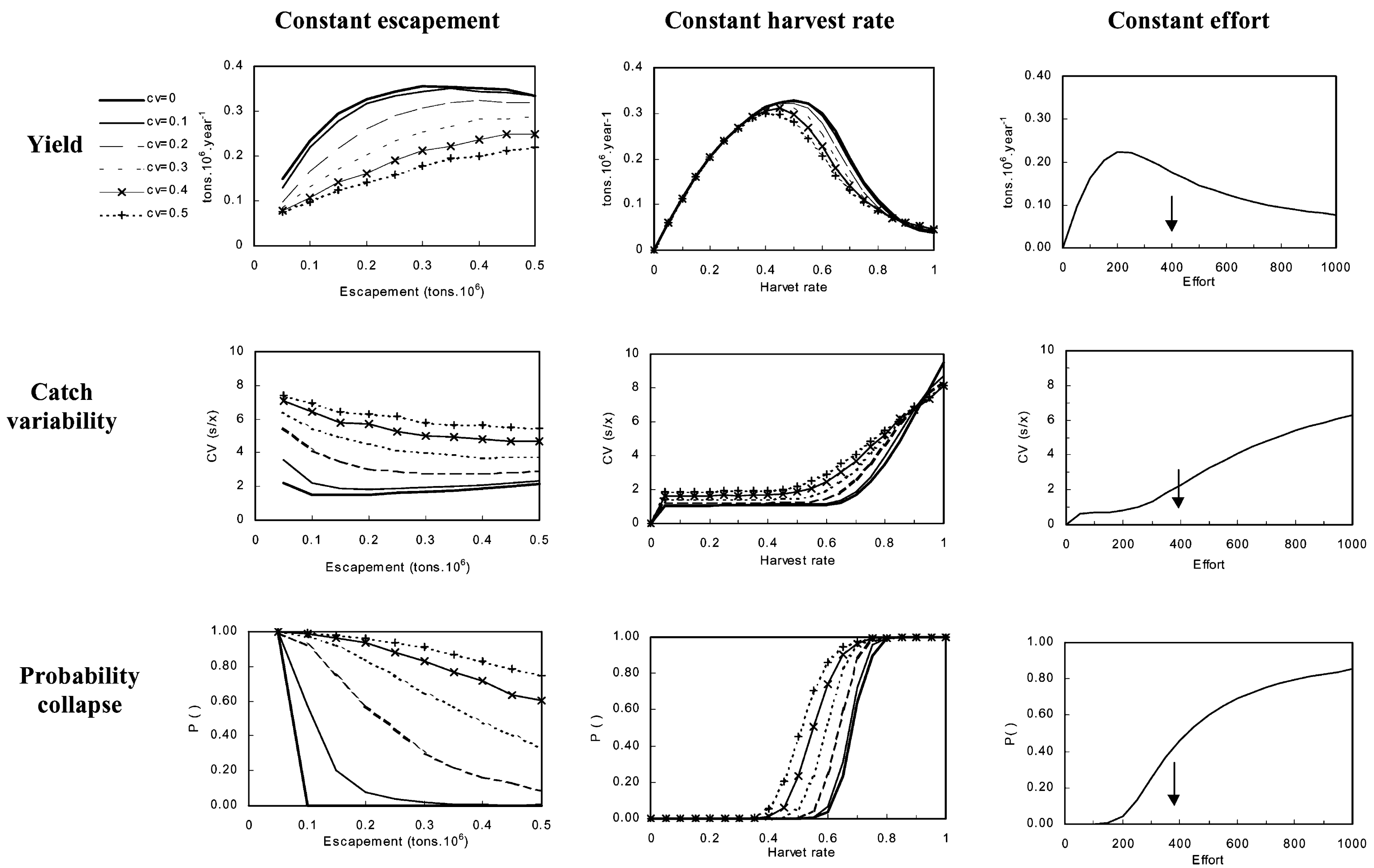

Fig. 6. Outcomes of fishing strategies for the Brazilian sardine based on a constant stock escapement, constant harvest rate, and constant effort. CV is the coefficient of variation of the biomass estimation procedure used in the catch control strategies. The arrow indicates the approximate effort level in the period from 1977 to 1983. Effort index is measured as the product of number of trips per year and the mean tonnage of boats.

Table 2
Results of the analysis of the EVPI for harvest strategies for the Brazilian sardine after the collapse[a]

Harvest strategy	Best strategy	Expected yield (t per year)	EVPI (t per year)	EVPI (%)
Harvest rate	0.45	215,851	8,949	3.9
Effort				
q known	150	98,978	32,907	33.2
q uncertain	150	123,649	43,617	35.3

[a] The objective function is the maximization of yield. Two scenarios were tested in the evaluation of EVPI for effort control strategies: the first assumes that the parameters defining the relationship between stock size and catchability are known; in the second scenario catchability parameters are uncertain.

estimates than constant escapement policies. The increase in the coefficient of variation of estimations has very little influence over the expected average yield, but increases the variability of catches to a moderate degree and increases the probability of stock collapse dramatically for relatively high harvest rates (Fig. 6). For a harvest rate of 0.5, the chances of bringing the stock to collapse increases from less than 1% to more than 50% when CV increases from 0 to 0.5.

The expected yield under effort control peaks at ca. 220 effort units, with a probability of stock collapse of less than 20%. Fig. 6 also represents the approximate fishing effort applied to the stock in the period from 1977 to 1983, which was very close to the predicted optimal effort level. Considering that since then the purse seine fleet has doubled in size and became more technologically equipped with sonar and power blocks, it is suggested that chances of stock collapse increased considerably during the following decade.

Table 2 shows the calculated optimal fishing strategies (for the maximization of yield), the corresponding average expected yield, and the EVPI about stock–recruitment processes for the Brazilian sardine fishery after the collapse. Higher expected yields are predicted with constant harvest rate strategies, as has been previously suggested. With constant harvest rates strategies the expected gain of reducing uncertainties is less than 4% of the expected yield obtained when decisions are made under uncertainty about stock–recruitment dynamics. With a constant effort strategy the EVPI is ca. 33% of the expected yield of a best strategy under uncertainty about stock–recruitment dynamics, and increases to 35% if the stock–catchability relationship is also assumed uncertain.

Walters (1986) suggests three reasons why the value of learning, measured as a upper bound by EVPI, is often not as large as one would intuitively expect: first, because optimal policies for each of the various hypothesis considered need not differ substantially from the policy that provides the maximum expected value; second, stock–recruitment hypothesis may predict nearly the same yield across a wide range of harvest policies; and finally, because the optimal harvest rate tend to be close to the optimal policy for those hypothesis that were assigned high initial probabilities. The first reason seems to explain the differences encountered in the EVPI between constant harvest rate and effort control strategies (Fig. 7). While optimal harvest rates are relatively similar among the three hypotheses, the optimal effort levels differ considerably depending on the stock–recruitment hypothesis used in simulations. On the other hand, the uncertainty about the relationship between stock size and catchability has only a minor influence on the choice of an optimal effort policy. As can be observed in Fig. 8, the predicted optimal effort policies are relatively similar across a wide range of catchability parameters that were assigned high probabilities. Also noticeable in Fig. 8 is the significant effect of the hypotheses about sardine stock–recruitment dynamics on the optimal effort policy that maximizes fisheries catches.

One conclusion from the above results is that uncertainties on stock–recruitment dynamics will have very little influence on the choice for an optimal constant harvest rate strategy for sardine. On the other hand, with constant effort strategies, the effect of catchability varying with stock biomass complicates the choice for an optimal fishing effort level. Much more conservative effort levels are predicted when

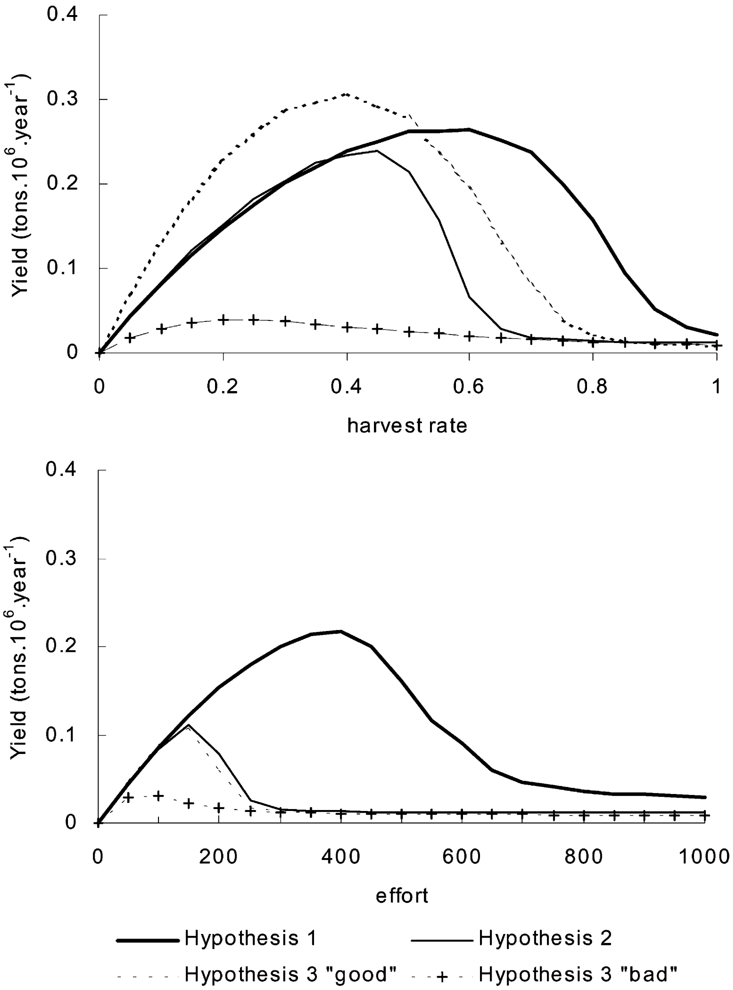

Fig. 7. Predicted yield under a constant harvest rate and constant effort strategies, and according to three different stock–recruitment hypotheses. Recruitment predicted by hypothesis (function) 3 depends on the prevailing environmental regime, differentiated between "good" and "bad" as indicated by Fig. 3.

recruitment is influenced by environmental regimes and/or when depensation occurs at low spawning stock biomass, compared to when recruitment is a simple function of stock biomass (Figs. 7 and 8). These results predict an expected gain to the status quo effort control policies with an improvement in the understanding of the factors determining the reproductive success of the Brazilian sardine.

This improvement will come with the difficult task of unraveling the effects of long-term environmental factors and the effect of stock size and fishing, which are normally confounded (Walters and Collie, 1988). Environmental cycles of intermediate periods superimposed on stock production dynamics can obscure any underlying relationship between recruitment and spawning biomass (Armstrong and Shelton, 1988). In fact, most accounts of stock collapses during the last decades have at their core the endless debate about whether it was the result of fishing or of environmental effects. Among the best documented examples are the sardine/anchovy collapses in coastal upwelling systems (Pauly and Tsukayama, 1987; Barnes et al., 1992), the decline in recruitment of groundfish stocks off east coast of North America (Walters and Maguire, 1996) and the "Thompson-Burkenroad" debate on the causes of recruitment

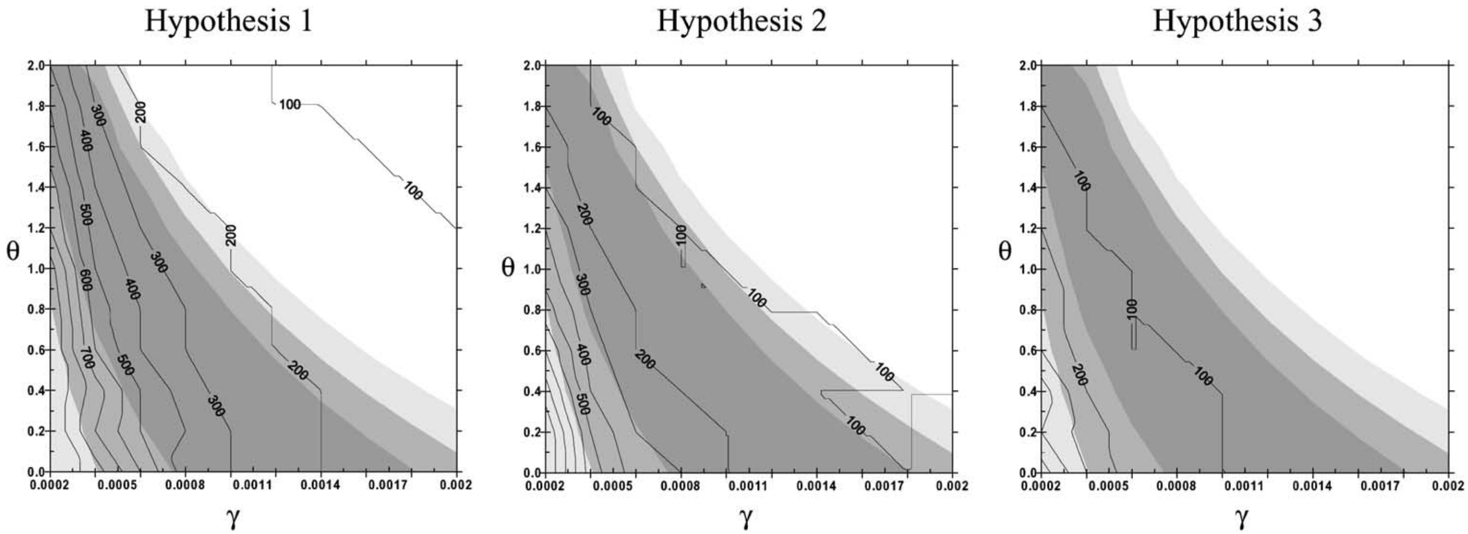

Fig. 8. Optimal effort isopleths predicted for the combination of catchability parameters γ and θ, and the three recruitment hypotheses described in the text (Table 1). The shaded areas in each graph represent the likelihood of the respective combination of catchability parameters (the darker the shading the higher the likelihood of the parameters). Results for hypothesis 3 were obtained assuming an unfavorable environmental regime.

fluctuations in the stock of Pacific Halibut (Parma and Deriso, 1990). In these cases the understanding of how environmental changes affect fish productivity would be very valuable to fishery management. Yet, it is argued that such understanding will not be achieved by continued correlative and biological process studies and will instead require sound management experiments in which environmental studies are coupled with deliberate manipulation of stock sizes through changes in harvest policies (Walters and Collie, 1988; Walters, 1998).

The analysis carried out in this paper suggests that status quo measures of effort control currently applied in the management of the Brazilian sardine are particularly inadequate in optimizing stock production while avoiding high risks of stock collapse due to the combined effect of a large fleet capacity, changes in catchability with stock size, and the uncertain stock–recruitment dynamics. Nonetheless effort control policies have in their favor the simple and relatively low-cost assessment and enforcement procedures required to their implementation, compared to the data intensive and expensive assessments normally employed in catch control policies. Given the current uncertainties about stock–recruitment dynamics, the management of the Brazilian sardine based on effort control policies will demand the adoption of precautionary measures, such as the effective reduction in the effort and fleet capacity. A reduction in effort at least to the level observed during the late 1970s is a suggested measure to recover the productive capacity of the fishery. Also, strategies of effort control are more likely to succeed if accompanied by auxiliary measures of control of the minimum age of recruitment to the fishery, which has been shown to increase the resilience of the stock to overfishing (Vasconcellos and Pitcher, 1998).

Better trade-off between average catch, catch variability and the probability of collapse can be achieved with strategies of catch control, such as the one obtained with a constant harvest rate policy. The predicted optimal harvest rates are very conservative compared to the ones usually applied to small pelagic stocks, but are consistent with the sustainable fishing rates proposed for the species. A metanalysis carried by Patterson (1992) showed, for instance, that most cases of small pelagic stock collapse occurred when F (fishing mortality) was higher than 0.6 M (natural mortality). Conservative fishing rates result from the possibility of sub-optimal environmental conditions, represented in the model by low frequency regimes in recruitment success, and can also be expected from the forage role of small pelagics in marine ecosystems (Mackinson et al., 1997; Vasconcellos, 2000). Constant harvest rate strategies are considered very robust strategies to cope with the inherent uncertainties created by climatic effects on marine fish populations (Walters and Parma, 1996). They are usually implemented by fishing control systems that rely on annual biomass estimates and on simple feedback rules that specify the proportion of the adult stock, or the total allowable catch, to be harvested each year. The success of catch control systems, specially those based on constant escapement, is however dependent on the accuracy of the stock assessment which often suffers from large uncertainties in parameters and variables (e.g., catch at age, relative index of abundance) used in the estimation procedure. The critical information for the success of catch control systems is therefore the frequency and accuracy of stock abundance estimates, which may call upon a combination of data from surveys (e.g., acoustic assessments of spawning biomass and recruitment), better monitoring of catch composition (age and size) used in virtual population analysis, tagging experiments, and may as well rely on the active participation of resource users in data collection (Walters and Pearse, 1996).

The evaluation of harvested strategies for the Brazilian sardine considered only the biological trade-off involved between two types of widely applied fishing strategies, namely input (effort limitation) and output (catch limitation) controls. It was out of the scope of this work to discuss the likely socio-economic consequences of adopting one or other type of strategies and controls, neither was the objective of the analysis to examine all the possible combinations of strategies and controls for this fishery. Nonetheless, the results obtained here are expected to enrich this discussion which will require, to be effective, the active participation of resource users.

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