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修士論文

マイワシ資源の回復を目指す資源管理方法の探索

Exploring effective management strategies to recover the Japanese sardine stock from depletion

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1. INTRODUCTION

The Japanese sardine (*Sardinops melanostictus*) is a valuable marine living resource of Japan, and a highly variable one. This variability, probably led by environmental processes (Yatsu et al. 2005), resulted in a four-years recruitment failure during the late 1980's which in turn, when coupled with excessive fishing, led to severe stock depletion with biomass levels falling one order of magnitude between 1987 and 1992. A TAC based management was introduced in 1997 (Nishida et al. 2007) but it has done little to reverse this trend, as biomass has kept falling steadily to current levels, two orders of magnitude below those of 1987.

1.1. Life history of the Japanese sardine

The Japanese sardine is a coastal-pelagic fish that forms large schools, migratory, moving northward in summer and tending also to move more inshore, the reverse as temperatures begin to drop. It feeds mainly on zooplankton, especially copepods, but also phytoplankton.

Sardines breed from December to the beginning of May, earlier in the southern than the northern parts of range, in bays and in coastal parts of open sea; fishes mostly mature in second year. They live up to 5-6 years and their size usually range from 15 to 20 cm. (Whitehead 1985)

1.2. Historical background

1.1.1. Japanese sardine stock trends

Due to its high numbers and importance to Japan, the Japanese sardine has been widely studied, with extended research literature and complete annual stock assessment reports being performed since 1996 and available to the public from 2001. A good reconstruction of the earlier stock history is given by Wada and Jacobson (1998) who presented a complete recount of the late half of the twentieth century. The trend, shown in fig. 1-1, indicates the extreme variability of the stock with periods of depletion and recovery. Before the 70's the stock was at low levels but from 1971~1972 stock size started increasing rapidly until it reached record levels in the late 80's. It is notable how before the 70's the exploitation rate was low but then starts rising as the biomass increased and the stock became profitable.

To understand what happened next it is better to use a new source of information, such as the data presented in the latest Japanese stock assessment annual report (Nishida et al. 2007), shown in fig. 1-2. Here it can be seen how during the early 90's there were decreases of an order of magnitude in biomass and catch in less than a decade, which clearly shows a collapse of the stock. Biomass kept falling down until the last 5 years where it seems that it has stabilized around the 130 thousand tons level. An important difference must be noted in the period after the collapse when compared with that before the 70's when the stock was low, the rate of exploitation stayed at high levels even after the stock decreased.

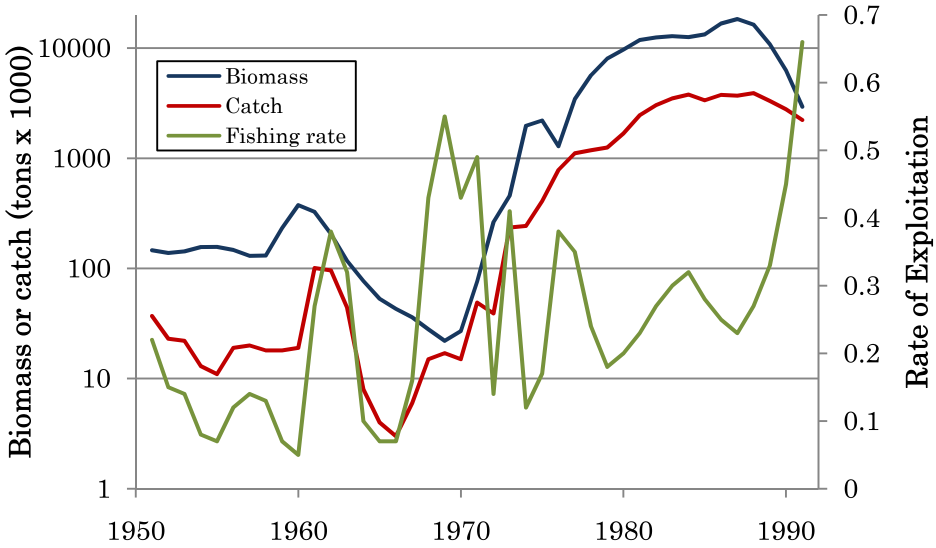

Figure 1-1. Yearly changes for the period of 1951-1991 in biomass, catch and rate of exploitation of the Pacific stock of the Japanese sardine. Data from Wada and Jacobson (1998)

1.1.2. Reasons behind the stock collapse.

It is now clear that the stock collapse of the early 90's was due to natural causes: a recruitment failure for four consecutive years (1988-1991) (Watanabe et al. 1995) undermined the ability of the stock to maintain its numbers as it did not allow population turnover for almost a generation (fig. 1-3). The recruitment failure coupled with high fishing rates ultimately lead to the current status of the fishery.

The cause of the recruitment failure has been widely studied and debated as well, with several opinions on its ultimate causes, but most authors accept that there is a negative correlation between recruitment processes and the sea surface temperature (SST) of the Kuroshio extension southern area (KESA) (figs. 1-3 and 1-4), which is the nursery area of the sardine (Yatsu et al. 2005). It has also been recognized that this correlation presents prolonged alternate periods of favorable and unfavorable conditions, or regimes, and that these regimes change between each other in an abrupt and fast fashion, called regime shifts (Wada and Jacobson 1998; Yatsu et al. 2005).

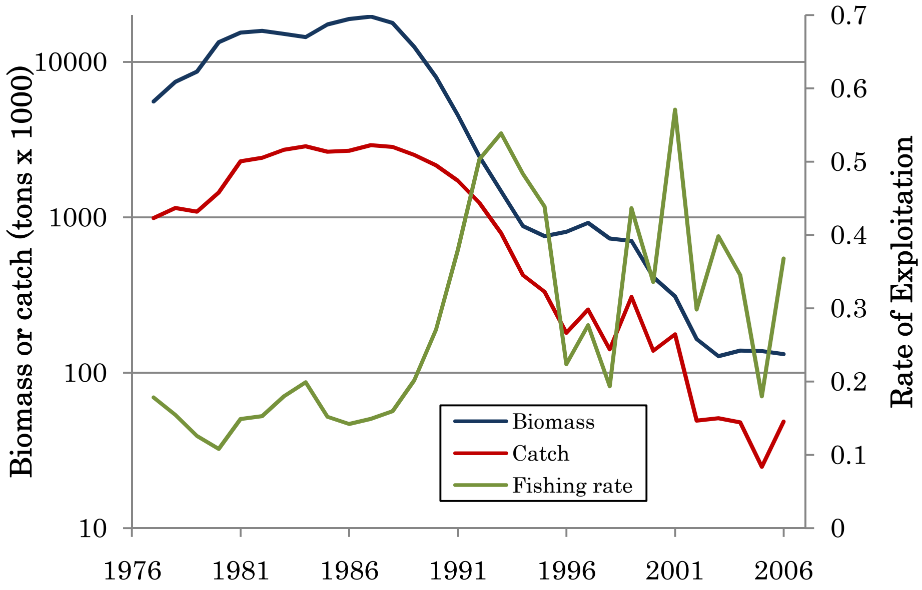

Figure 1-2. Yearly changes for the period of 1976-2006 in biomass, catch and rate of exploitation of the Pacific stock of the Japanese sardine. Data from (Nishida et al. 2007)

The mechanism behind the relation between the environment and recruitment is still not very clear, but many options like optimal growth temperatures (Takasuka et al. 2007), food abundance related to the mixed layer depth (Nishikawa and Yasuda 2008) or habitat variability (Itoh et al. 2009) have been considered.

1.3. Fishery resources management in Japan

Fishery resources management by means of catch quotas is a relatively recent introduction in Japan. Even after the introduction of the 200-nautical miles economic exclusive zones in 1970 by the United Nations Convention on the Law of the Sea, it was not until 1994 that Japan adopted this convention, which would be later ratified in 1996 approving the introduction of fishery resource management by the means of TACs (total allowable catch).

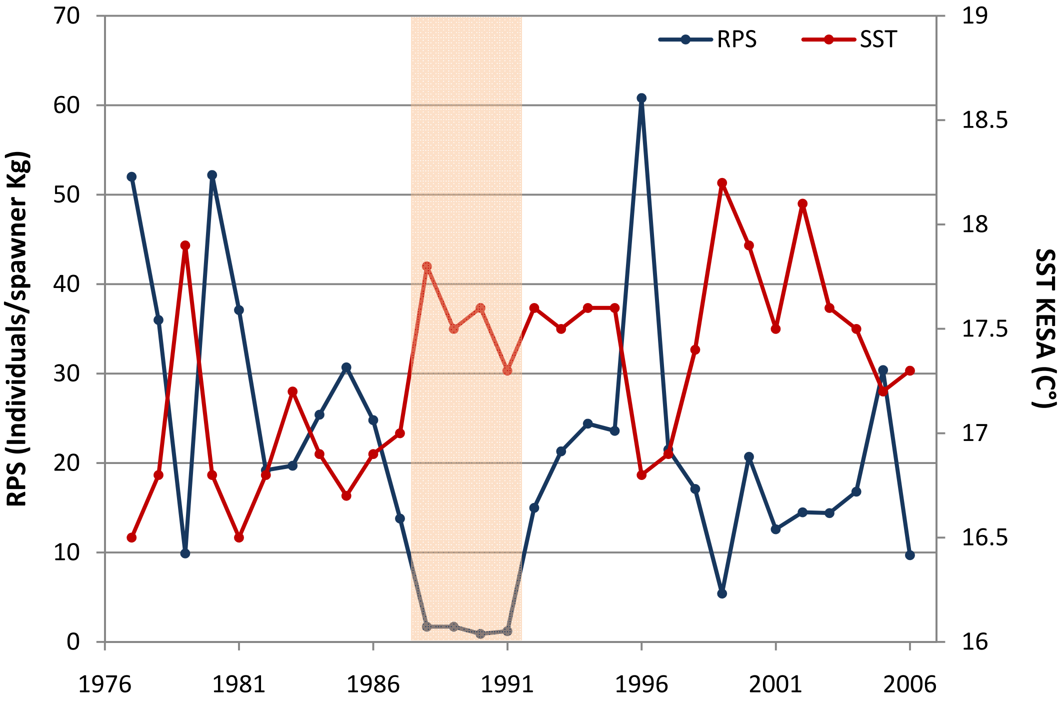

Figure 1-3. Recruits per spawner (RPS) of the Pacific stock of the Japanese sardine and sea surface temperature (SST) of the Kuroshio Extension southern area (KESA) between 1976 and 2006. The orange band shows the four-year recruitment failure. Data from Nishida et al. (2007)

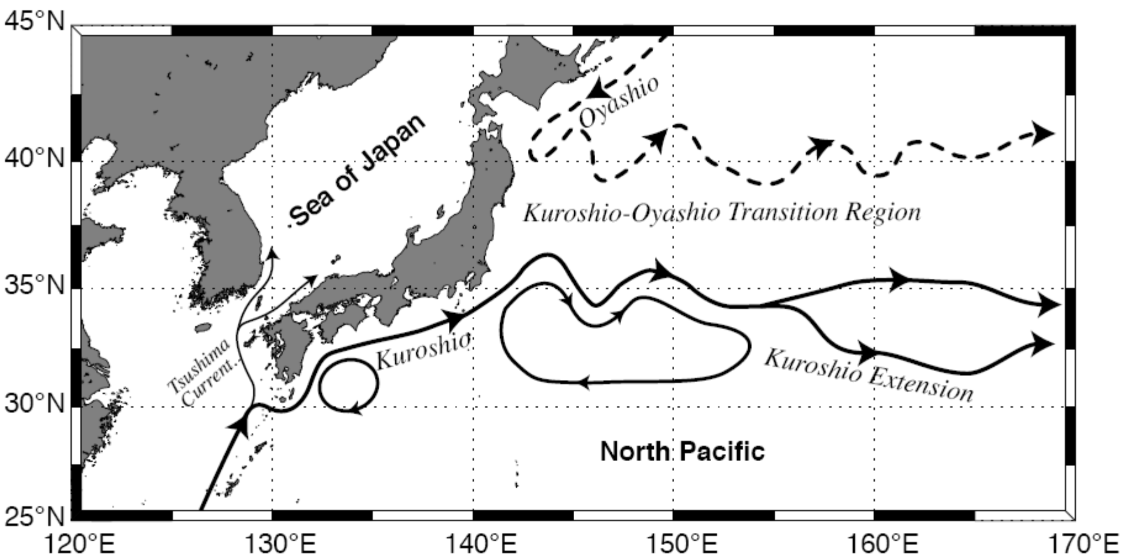

Figure 1-4. Map showing the general hydrography of the northwest Pacific. Nursery area of the Japanese sardine is located in the Kuroshio Extension southern area (~31-35°N and 150-164°E). Figure courtesy of Dr. S. Itoh.

Since then marine resources in Japan are managed according to the Allowable Biological Catch (ABC) guidelines (Fisheries Agency of Japan and Fisheries Research Agency 2007). This document describes several management strategies according to data availability which are essentially model based strategies with clear and quantitative procedures to calculate ABC. Being a data rich stock, in the case of sardine ABC is specified by a management decision rule, or catch rule. Management objectives are specified according to this catch rule and simulations to predict future states of the stock under different fishing pressures are used as scenarios. However close examination revealed that the simulations used to make predictions could be flawed, as recruitment is simulated bootstrapping the recruits per spawner (RPS) values of the last 10 years, all of which had low levels (i.e. it ignores environmental variation), and it does not consider alternative scenarios which are also plausible. This is a clear example what has been called 'the shifting baseline syndrome' (Pauly 1995), an undesirable condition involving high risks while tending to preserve the *status quo*. It could be argued that using the RPS values of the last 10 years would give a conservative management, however due to uncertainty, worst case scenarios have the undesirable effect of generating mistrust between decision makers and shareholders, ultimately leading only to lengthy haggling and discussions on how to set quotas, which has led to a broad acceptance that worse-case scenarios have to be avoided (Butterworth 2007). Although this is not strictly a 'worst case scenario', its undesirable effects have been seen in the Japanese sardine fishery and have resulted in the continuous setting of very high quotas, as can be seen in fig. 1-5.

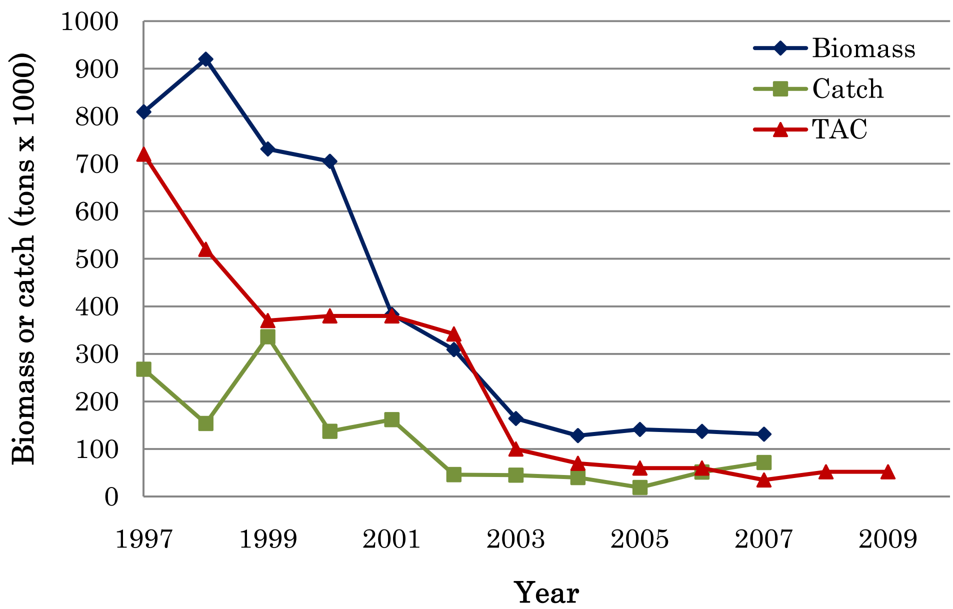

Figure 1-5. Yearly values of stock biomass, actual catches and catch quotas (TAC -total allowable catch-) for the Pacific stock of the Japanese sardine since the introduction of TACs in 1997 to 2009. Note how quotas have been set at high values and that actual catches have almost always been below the quota. Data from Nishida et al. (2007)

Using a management strategy based on possibly flawed predictions and only one population dynamics scenario potentially contradicts the recommendations of the FAO Precautionary Approach Guidelines which states that decision rules are required for precautionary management measures and that the feasibility and reliability of the management options needs to be evaluated, so that "a management plan should not be accepted until it has been shown to avoid undesirable outcomes" (FAO 1995).

1.4. Management strategy evaluation using operating models

For this study I used a management strategy evaluation framework, which involves computer intensive methods to help to determine the most suitable management approach for different management objectives.

This framework has received various names, but it is mainly known as *Management Strategy Evaluation* (MSE) (Smith et al. 1999) or as *Operating Management Procedure* (OMP), as proposed by Butterworth (see for example refs. Butterworth and Bergh (1993); Rademeyer et al. (2007)). The MSE/OMP framework was developed from the Revised Management Procedure of the International Whaling Commission, and has been described as "a set of rules for calculating annual catch limits from available stock information where the rules are determined with the assistance of models of the dynamics of the stock" (Kirkwood 1997). Such models are called Operating Models (OM), and they are used to simulate the "real" dynamics of the stock under different assumptions, as well as the assessment-management process and its uncertainties.

1.5. Purpose of this study

Following the FAO Precautionary Approach recommendations, I aim to evaluate the performance, potential for stock recovering and robustness to uncertainties of different management strategies. Good OMs are essential for MSE thus I intend to construct a full OM for sardine that is highly flexible but still reliable under a wide range of assumptions and scenarios. I also propose a management strategy that can adapt to the different stock and environmental conditions, and compare its performance against ABC and a basic management strategy.

Later I discuss the implications of uncertainty and of different management priorities for the selection of the most adequate strategy, focusing my discussion on stock recovery objectives.

2. DEVELOPMENT OF THE OPERATING MODEL

To evaluate different management options and their robustness to uncertainty, traditional evaluation methods like the use of past data are not very useful, since they only account for already observed states of the system, while analytical methods would present as terribly difficult, therefore we needed to take a different approach to the problem at hand. The solution was found through modeling the population dynamics not as a single "correct" model, but as a series of different models representing plausible scenarios or sets of assumptions, and then testing the management strategies over each single model, an MSE approach.

For this study, I constructed a three-section OM constituted by a stock dynamics section, a stock assessment section and a management section, related among them as shown in fig. 2-1. The stock dynamics section contains all the different assumptions about the population inner dynamics (like various recruitment processes, presence or absence of environmental effects and fishing selectivity by age), the stock assessment section was modeled so that it resembles the actual assessment process, and the management section contains the three different management strategies that I wanted to evaluate.

2.1. Data

Data on biomass, weight, numbers, mean fecundity, fishing mortality and catches structured by age class (0 to 5+) and year (1976-2006) as well as recruitment by year (also 1976-2006) was taken from 2007 Japanese Stock Assessment Report (Nishida et al. 2007).

Data on SST for KESA was obtained from two sources: the Japanese Meteorological Agency (JMA) (reported in Yatsu et al. (2005)) and the British Atmospheric Data Centre (BADC) ukmo-hadisst database (UK Meteorological Office 2006, 2009). Following the findings of Yatsu et al. (2005), I used the average SST of the winter months (January to March) in the nursery grounds in KESA, 31-35°N and 150-164°E. Original data had the form of monthly SST averages for 1° blocks. Only data from 1950 to 2008 was taken.

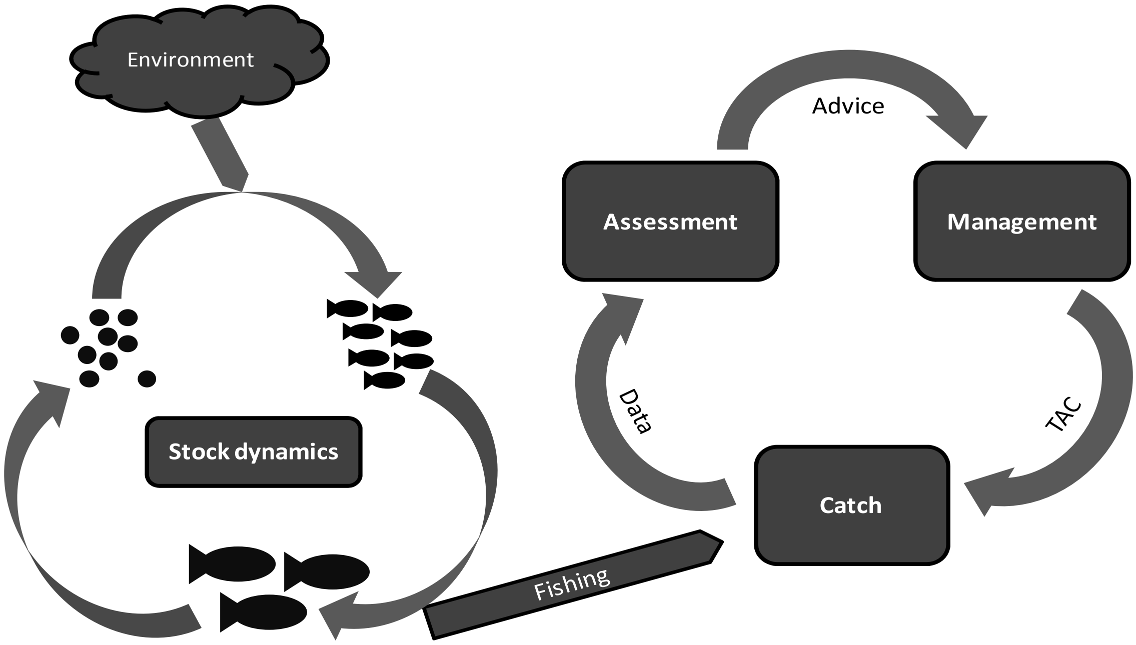

Figure 2-1. Simplified scheme showing the relations among the three sections (stock dynamics, stock assessment and management) in the operating model.

2.2. Stock dynamics section

The Stock dynamics of sardine were simulated using an age-structured model on which three main processes were controlled: recruitment, survival and growth.

2.2.1. Recruitment:

Three possible stochastic stock-recruitment models were considered. A Ricker model (Hilborn and Walters 1992)

$$R = Se^{\alpha+\beta S}e^{\varepsilon} \tag{1}$$

where α and β are parameters, S is the spawning stock biomass (see below) and ε is an error term. For convenience, (1) was rewritten as

$$\ln RPS = \alpha + \beta S + \varepsilon\,, \tag{2}$$

where RPS is recruits per spawner.

The second model was a modified Ricker model with environmental effects (Basson 1999)

$$R = Se^{(\alpha+\beta S+\gamma E)}e^{\varepsilon} \tag{3}$$

again, rewritten for convenience as

$$\ln RPS = \alpha + \beta S + \gamma E + \varepsilon \tag{4}$$

where α, β and γ are parameters and E is an environmental covariate, in this study the SST of KESA.

Parameters were estimated from the data for recruitment and biomass in Nishida et al. (2007) (data period 1976-2006) using maximum log likelihoods with log-normal distribution, thus ε are independent, normally distributed errors, $\varepsilon \sim N(0, \sigma_\varepsilon^2)$. For equation (3) parameter estimation, environmental data from either BADC or JMA was also used thus providing two different sets of parameters. Estimated values for all parameters as well as each model's fit (given by AIC) are shown in table 1.

Table 1. Parameter values and AIC for all recruitment models

Model/Parameter	α	β	γ	σ_ε	AIC
Ricker	3.611	-0.000156	--	1.268	171.6
Ricker with environment JMA	30.187	-0.000156	-1.559	1.119	161.2
Ricker with environment BADC	22.744	-0.000156	-1.136	1.203	168.4

Spawner stock biomass, *S* in year *t* is given by the equation

$$S_t = \sum_{a=1}^{5} N_{a,t} w_{a,t} g_a \tag{5}$$

where $N_{a,t}$ is the number of fish in the cohort of age a in year t, $w_{a,t}$ is the average bodyweight of age a in year t and g_a is the fecundity index (ratio of mature individuals) of age a, assumed constant across time (table 2).

Table 2. Fecundity index for all age-classes

Age	0	1	2	3	4	5+
Fecundity index	0	0.5	1	1	1	1

ln*RPS* was capped at 6 ln(recruits/kg spawner) for stock biomass values below 500,000 tones and at 4 ln(recruits/kg spawner) for stocks higher than that. These maximum values correspond to the maximum observed values in the historical data (Nishida et al. 2007).

2.2.2. Weight-at-age:

Body weight in sardines is highly variable and appears to be negatively correlated with the total stock biomass (fig. 2-2), thus modeling age-specific body weight as constant with respect to year did not seem appropriate. To simplify the model, instead of using a growth model like Von Bertalanffy's model, the weight-at-age of a single age class a in a given year t was assumed to be a linear function of the stock biomass of the form

$$w_{t,a} = m_a + p_a B_{t-1} + \varepsilon_a \tag{6}$$

where m and p are parameters, $w_{t,a}$ is the average weight of an individual of age class a in year t, B_{t-1} is the total stock biomass in year $t-1$ and ε is a normally distributed error term, $\varepsilon \sim N(0, \sigma_\varepsilon^2)$. Parameters were estimated by linear regression and the obtained values are shown in table 3.

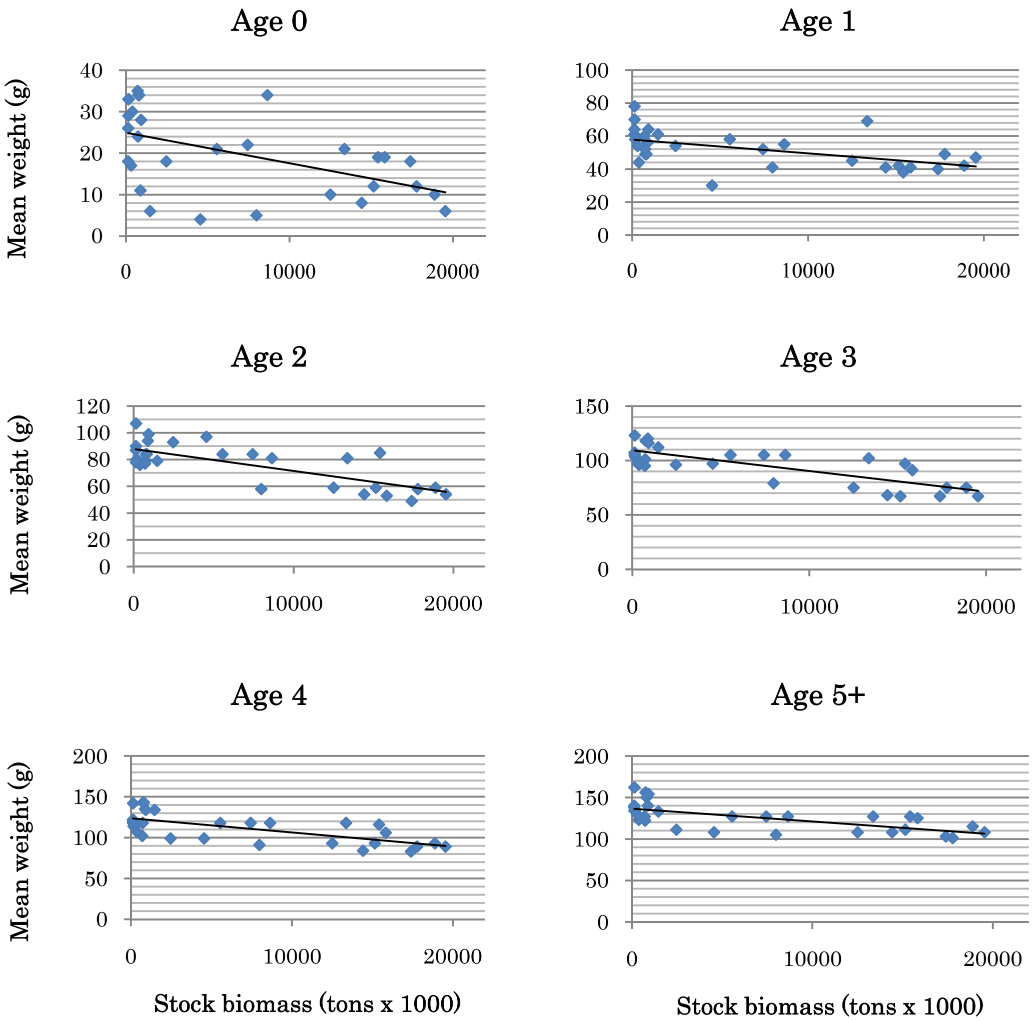

Figure 2-2. Correlation between mean weight-at-age and stock biomass showing the central trend calculated with linear regression.

Table 3. Estimates of parameters of the density-dependent weight-at-age model using linear regressions.

Age class	m_a	p_a	σ	R^2	P
0	24.9	-0.00074	8.66	0.27	<0.01
1	57.8	-0.00083	9.34	0.29	<0.01
2	87.8	-0.00164	10.45	0.56	<0.001
3	109.3	-0.00190	10.66	0.63	<0.001
4	123.6	-0.00173	13.34	0.48	<0.001
5+	136.4	-0.00153	12.39	0.45	<0.001

2.2.3. Survival and catch dynamics (including age selectivity processes)

An age-structured model was used, which means that the modeled population is divided into age-classes or cohorts. Each one of these enters the fishery through recruitment at age 0 and from there its numbers decline exponentially driven both by natural and fishing mortalities. Survival, or how many individuals of age a survive from year y to $y+1$, was derived from the cohort analysis initially developed by Pope (1972) and modified by Hiramatsu (2001). The survival process is thus defined as

$$N_{a+1,y+1} = N_{a,y} e^{-M-F_{a,y}} \tag{7}$$

where $N_{a,y}$ is the number of individuals of age a at the beginning of year y, M is the natural mortality coefficient which is assumed constant and to have a value of 0.4 (Nishida et al. 2007), and $F_{a,y}$ is the fishing mortality for age a in year y (see below). Assuming that catch is taken on a single pulse in the middle of the year, it can be defined as

$$C_{a,y} = N_{a,y}(1-e^{-F_{a,y}})e^{-M/2} \tag{8}$$

where $C_{a,y}$ is the catch in number of age-class a individuals on year y.

Since the maximum age-class is a plus group including ages 5 and older, to calculate the number of individuals of this age-class in year $y+1$, assuming that $F_p=F_{p-1}$ equation (7) can be modified as

$$N_{p,y+1} = N_{p,y} e^{-M-F_{p,y}} + N_{p-1,y} e^{-M-F_{p-1,y}} \tag{9}$$

where $N_{p,y}$ is the size of the plus group in year y and $F_{p,y}$ is the fishing mortality for the plus group on year y, defined as in equation (8).

Fishing mortality is also very variable across different age-classes and time and was not found to be correlated with any of the population variables studied (stock and cohort biomass and numbers, weight-at-age, recruitment and SST) so the age specific $F_{a,y}$ was assumed to be random and to follow a normal distribution $N(\mu, \sigma^2)$ with parameters μ and σ estimated from past data.

2.2.4. Environmental data generation

Since the OM is not spatially explicit there was no need for a detailed model to generate SST data; instead, it was generated randomly from past data. However, it is important to consider that sardines show good and bad production regimes and that these seem to be related to environmental variation (Wada and Jacobson 1998), so to imitate this behavior first the winter average of the SST in KESA for each of the last 58 years (1950-2008) was assigned to either favorable or unfavorable regimes based on the year's reproductive success, as defined by Wada and Jacobson (1998). Unfavorable regime was thus assumed to happen during 1951-1970 and 1988-2008 and favorable during 1971-1987.

Having defined the regimes, to generate environmental time series an algorithm was built to continuously draw values at random from a given regime set. Regime shifts were also simulated randomly and had a probability P to occur in a given year. Due to the apparent bidecadal nature of regimes, P was assigned a value of 0.05 and assumed constant across time so that in average a regime shift would occur every 20 years.

This procedure was applied independently to each of the two datasets used. The typical behavior of the algorithm is shown in fig. 2-3.

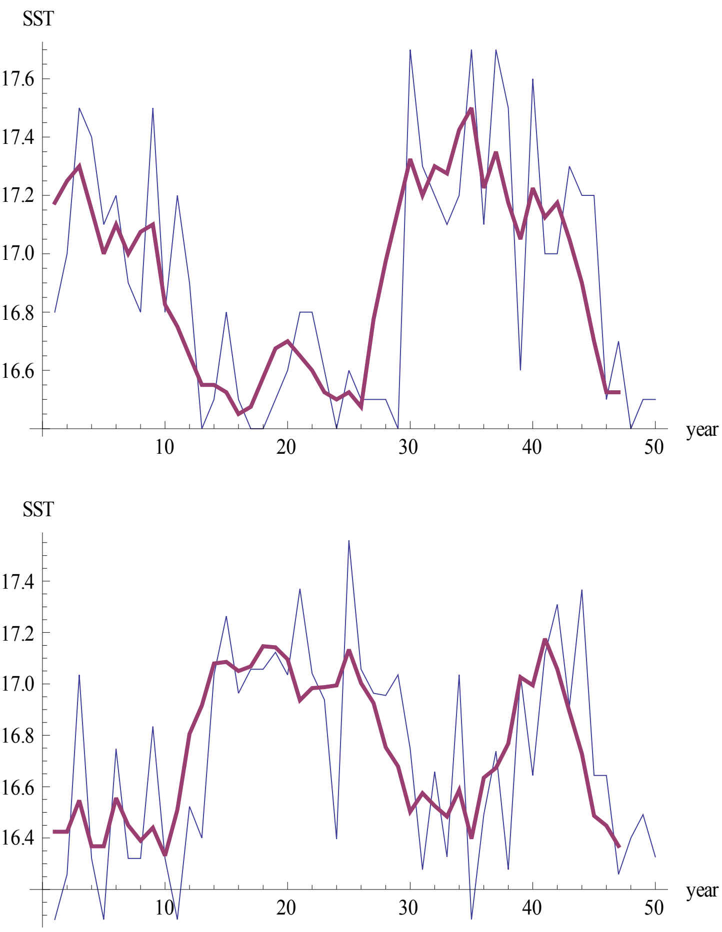

Figure 2-3. Example 50-year SST time series generated using the described algorithm (see above) with JMA (upper) and BADC (lower) datasets. Thin blue and thick purple lines correspond to yearly SST and moving average (n=4) respectively. Note the regime shifts occurring approximately every 20 years.

2.3. Assessment section:

The catch rules considered use two data inputs, stock biomass and SST. SST is assumed to be measured without error but not stock biomass, which is estimated by actual biomass plus random error, and follows a simple equation

$$\hat{B}_y = B_y e^{\varepsilon} \quad (10)$$

where ε follows $N(\mu,\sigma^2)$. In this case μ gives the bias and σ gives the error. Recruitment was estimated the same way

$$\hat{R}_y = R_y e^{\varepsilon} \quad (11)$$

2.4. Management section:

Using the data obtained through the assessment process, management is performed according to one of three predefined management decision rules, or catch rules. Management follows the sequence *data gathering (assessment)→fishing mortality calculation→quota setting→catch*. The quota is assumed to be caught completely unless it is higher than 0.6 of the total biomass which is defined as the upper catch limit and corresponds to the historical maximum fishing rate.

2.4.1. Constant fishing mortality strategy (hereafter referred as CF)- Also known as 'constant fishing effort policy', CF is a widely used basic management strategy that is independent of any reference points where the same fishing pressure is applied across all values of stock biomass (Hilborn and Walters 1992) (fig. 2-4a).

2.4.2. Japanese allowable biological catch guidelines catch rule (hereafter referred as ABC) - A feedback management strategy, it uses two biomass reference points (B_{ban} and B_{lim}) and a fishing mortality one (F_{lim}). F_{lim} sets the maximum F allowed, B_{lim} can be considered a "security level" below which F decreases linearly until it reaches B_{ban}, the fishery closure level where F becomes 0 (fig. 2-4b). It is more conservative than CF because a lower F is given when the stock size is below a critical level.

2.4.3. Environmental based management catch rule (hereafter referred as EBM) - A modification of ABC based on an idea by King and McFarlane (2006) and also a feedback strategy, EBM has the same three reference points plus an environmental one which acts as a threshold to switch between alternative states. The environmental threshold is given by the SST and was set arbitrarily at 17.1°C, value slightly above the middle point between the average temperatures of good and bad regimes identified by Wada and Jacobson (1998). If the SST is higher than this threshold, the catch rule is modified by a factor λ = 0.6, whose value was selected through simulations (fig. 2-4c). This strategy is the most conservative among the three strategies because F is reduced further when the environment is unfavorable.

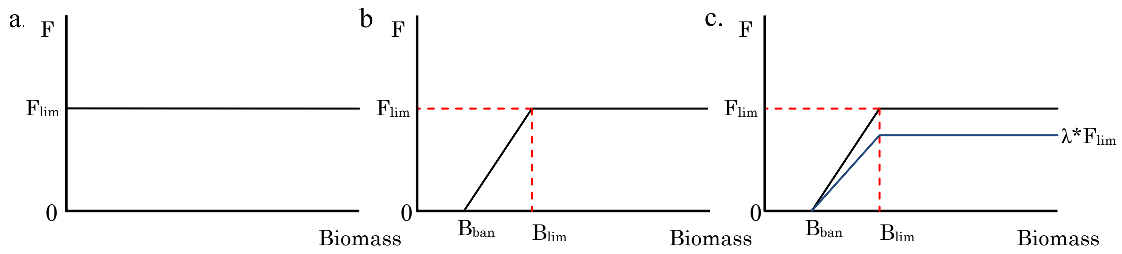

Figure 2-4. Catch rules for the evaluated management strategies: Constant fishing mortality (CF) (a), Japanese ABC guidelines (b) and environmental based management (EBM) (c), showing biomass reference points (B_{lim} and B_{ban}) and F values. For CF, the same F is maintained across all biomass levels; for ABC and EBM, above B_{lim}, F has a maximum value of F_{lim}; between B_{lim} and B_{ban}, F decreases as biomass does; below B_{ban} F is 0. In EBM, when the environmental proxy crosses some value, F is modified by a factor λ.

2.4.4. Quota calculation

The fishing quota is given by a TAC which is calculated using equation (8) written as

$$TAC_y = \hat{B}_{y-\Delta t}(1-e^{-\hat{F}})e^{-M/2} \tag{12}$$

where TAC_y is the quota for year y, $\hat{B}_{y-\Delta t}$ is the estimated biomass for year y-Δt, Δt is the time lag between assessment and management and $\hat{F}$ is the fishing mortality estimated from the catch rule using $\hat{B}_{y-\Delta t}$. An upper limit for the TAC_y value was set at $0.6B_y$, which is the highest historical fishing rate observed (Nishida et al. 2007).

2.5. Underlying assumptions

For the construction of this model a few important (but hidden) assumptions had to be made. First, the OM does not consider any economical or social dynamics. This is a major flaw in the model however for the objective of this work I only needed to assume that all management decisions are taken with scientific advice as the only driver.

Another major hidden assumption is that only environmental trends on short- and mid-term scales are considered, this means that only inter annual and bidecadal (regime shifts) are included, while the possible effects of long-term trends like climate change and global warming are ignored.

A third hidden assumption is that, except for environmental influences, the population is assumed to be ecologically isolated i.e. the population is closed (no immigration/emigration processes) and there are not any interactions with other species (like predation/competition). This assumption highly simplifies the model but prevents a more comprehensive picture of the small pelagic fisheries system, which is known to be correlated.

2.6. Study scenarios and details

2.6.1. Sources of uncertainty

Uncertainty had to be explicitly taken into account and the six sources of error identified by Francis and Shotton (1997) served as a useful start points. These six sources are: process, observation, model, error structure, estimation and implementation uncertainties.

Process uncertainty arises from natural variability, not error, and is defined as 'random variation in demographic rates and processes' (Francis and Shotton 1997). In the model it is represented by the uncontrolled stochasticity present in recruitment, weight-at-age and age-selectivity.

Observation uncertainty arises during data collection through measurement and sampling error, thus it exists in the assessment process where actual biomass is unknown and estimated with error.

Model uncertainty arises from lack of information in the workings of the system and as such appears in the multiple recruitment scenarios considered. Error structure uncertainties were not explicitly included in the model as all processes were assumed to follow a normal or log-normal distribution.

Estimation uncertainties, which arise from the effect of the previous three sources, is related to the process of parameter estimation and is also considered in the multiple recruitment scenarios, more clearly in the difference between the parameters of similar models estimated using environmental data from the alternative sources (BADC and JMA).

Implementation uncertainties or "the extent to which management policies will be successfully implemented" (Francis and Shotton 1997) is also not directly included, as the quota set by the model is assumed to be caught completely, however the existence of time lags between assessment and management could be considered related to implementation uncertainties, as the assessment from any given year is not available for management purposes until the next one.

2.6.2. Simulations/Scenarios considered.

Since reality is not completely understood, to study the effect of the different sources of uncertainty various scenarios had to be considered. Differences in recruitment and environmental influence on this presented three scenarios given by the different recruitment models, while time lag between assessment and management, and nature of the quota set presented two scenarios each (1-year lag and no lag, and quota as a fishing mortality value or as a catch quota, respectively).

Using Monte Carlo simulations with 1000 iterations, each scenario was evaluated over a comprehensive range of F_{lim}, between F_{lim} = 0.05 and 1.8.

2.7. Model behavior

Before proceeding with the evaluation, the OM had to be checked to test if it behaved in a realistic manner. This was done visually, checking that during simulations the stock would not rise above historically observed levels, that it would not increase rapidly even under high fishing mortality values or that it would not collapse easily under low *F*s.

2.8. Performance statistics

I selected depletion risk, mean biomass and mean catches as performance statistics. Depletion risk was defined as the probability of the stock to fall below certain level. Since the stock is already depleted, with current biomass levels estimated around 131,000 tons, I arbitrarily set the depletion level at 100,000 tons, a level close to current one. This index should be interpreted as the probability of further depletion.

Mean biomass and mean catch should not be understood as predictors of future behaviors but as indicators of management potential. Due to high variability of the stock, mean, and not minimum or maximum values, were chosen.

Variance of catches was not used because on one hand catches variability is dependent both in management and natural sources and the later could easily mask the effect of the earlier. On the other hand, values of catch variance tend to be difficult to interpret and make sense of for people without a strong background in stock assessment theory (and even those with it) (Butterworth and Punt 1999), so this information will not be presented.

To summarize, performance statistics were summed across scenarios. No weightings were used. Performance statistics were not summed across F_{lim} values. For easiness of visualization, profiles were drawn across values of F_{lim} for the three performance statistics. To evaluate relative performance, results were normalized dividing by the overall lowest performing management strategy's outcome values.

It seems important to remind that it is not the purpose of this study to search for the optimal value of F_{lim} but the general evaluation of the different catch rules across a wide range of possibilities.

2.9. Sensitivity to uncertainty

The effect of different levels of environmental influence and time lags between assessment and management on the relative performance of the three described management strategies was evaluated.

3. RESULTS

3.1. Model performance

The operating model showed to perform according to expectations as is shown in fig. 3-1. High variability can be observed, especially under low fishing pressures, but no anomalous behaviors were observed under any scenario.

When evaluated using JMA data the environment had a stronger influence on recruitment than when analyzed using BADC data, as can be observed in both the value of the γ parameter of the recruitment equations (higher on JMA) and model fitting (lower AIC for JMA indicating better fit) (table 1). This is based on the assumption that the estimate of λ from JMA data shows a strong environmental effect on recruitment and that an estimate from BADC data shows a weak effect.

3.2. Evaluation of management strategy performance

Figures 3-2 and 3-3 show the summarized performance statistics profiles across values of F_{lim}. All management strategies presented responses of the same shape but different magnitude. In all cases higher biomass represented lower depletion risk, with biomass monotonically decreasing and risk increasing in a logistic fashion as F_{lim} increases. As F_{lim} increased, catches initially increase until a maximum is reached and from there decrease. Long and short term responses were different and as such will be analyzed separately.

On the long term (fig. 3-2), as F_{lim} increases depletion risk increases in a logistic fashion with a sharp increase between F_{lim}≈0.3~0.8 for CF and F_{lim}≈0.7~1.2 for both ABC and EBM. EBM, which is the most conservative strategy, shows the best performance with ABC following closely while CF presents a considerably worse behavior. The 50% risk of depletion levels were reached at F_{lim}≅0.82, 0.75 and 0.46 for EBM, ABC and CF respectively. High biomass potential levels were observed at low levels of F_{lim}, and then decreased rapidly in an exponential fashion as F_{lim} increases. As before, EBM shows the best overall performance followed by ABC and CF as showing the worst of the three. Catch potential showed its maximum levels at low F_{lim} values, between 0.2 and 0.3. These levels were similar for all three strategies, with ABC being only slightly better, while at lower F_{lim} values EBM had the best performance, again followed by ABC and then CF. Although EBM performance in catch may be worse in some cases, no remarkable differences were detected in the long term case, and only 10-15% decreases in catch (when compared with CF) was detected. This shows EBM works well taking account of the management objective of recovering the stock from depletion with the lowest risk.

Since biomass and catch potential present high variability, it can be useful to look at their relative instead of absolute performances (fig. 3-3). Both show the same response shape with all three strategies having a similar behavior at low F_{lim} levels and a strong difference at higher ones, where EBM clearly displays a superior performance to that of ABC and CF. CF has the worst performance of the three, with EBM and ABC showing biomass levels more than four times larger at the highest difference.

Short term results show that feedback strategies still present lower risk and higher biomass potential than CF, but catch potential was similar for all three strategies. It is also noteworthy that ABC and EBM show no appreciable difference.

3.3. Sensitivity to environmental effects

Figures 3-4 and 3-5 show the performance statistics for the different environmental effects scenarios. No difference was observed at low F_{lim} levels; at higher levels it was observed that under strong environmental influences EBM clearly outperformed both ABC and CF in the long term, while in the remaining scenarios EBM and ABC performed similarly and outperformed CF. These results indicate that management outcomes are sensitive to environmental influences. Since EBM is the most conservative rule, it still produces the best results

3.4. Sensitivity to time lags between assessment and management

Figures 3-6 and 3-7 show the performance statistics for the different time lags. No major difference in the relative performance of the management strategies was observed between scenarios, which indicates that time lags may not be a major source of variation between strategies. Only a small difference could be appreciated in biomass, where CF registered lower levels when a time lag was present.

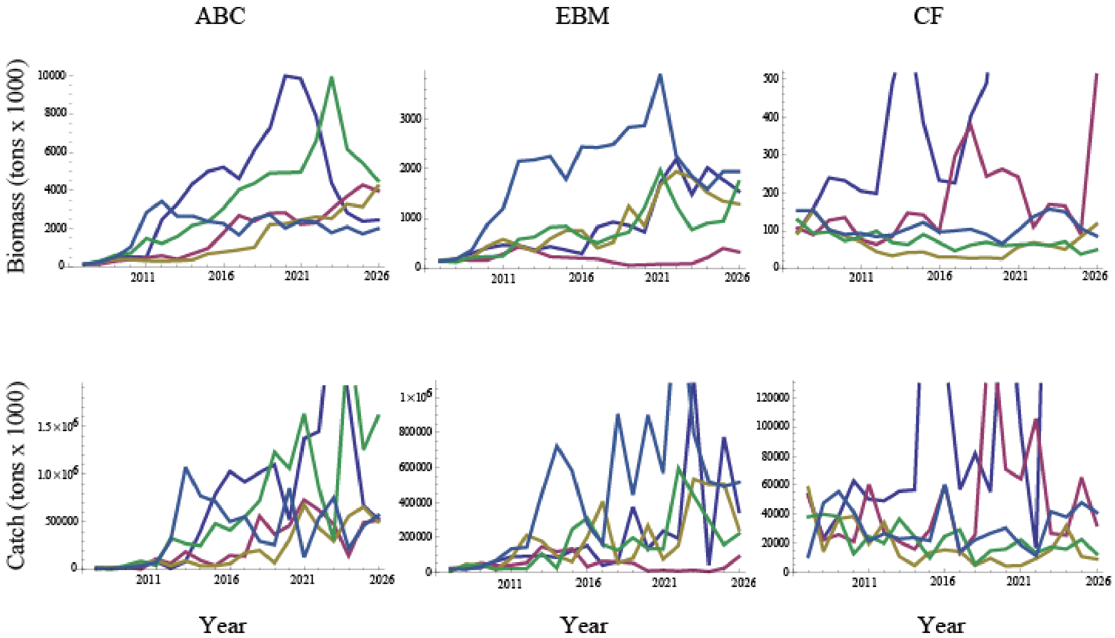

Figure 3-1. Sample future projections for 20 year using strong environmental effects (λ = -1.56) and F_{lim}=0.8, showing 5 iterations. 20 year projections are run using each of the management strategies evaluated: allowable biological catch (ABC), environmental based management (EBM) and constant fishing mortality (CF). Note how in some iterations the biomass presents behaviors similar to those seen in the past, like those seen in figure 1-2. Different colors show different iterations.

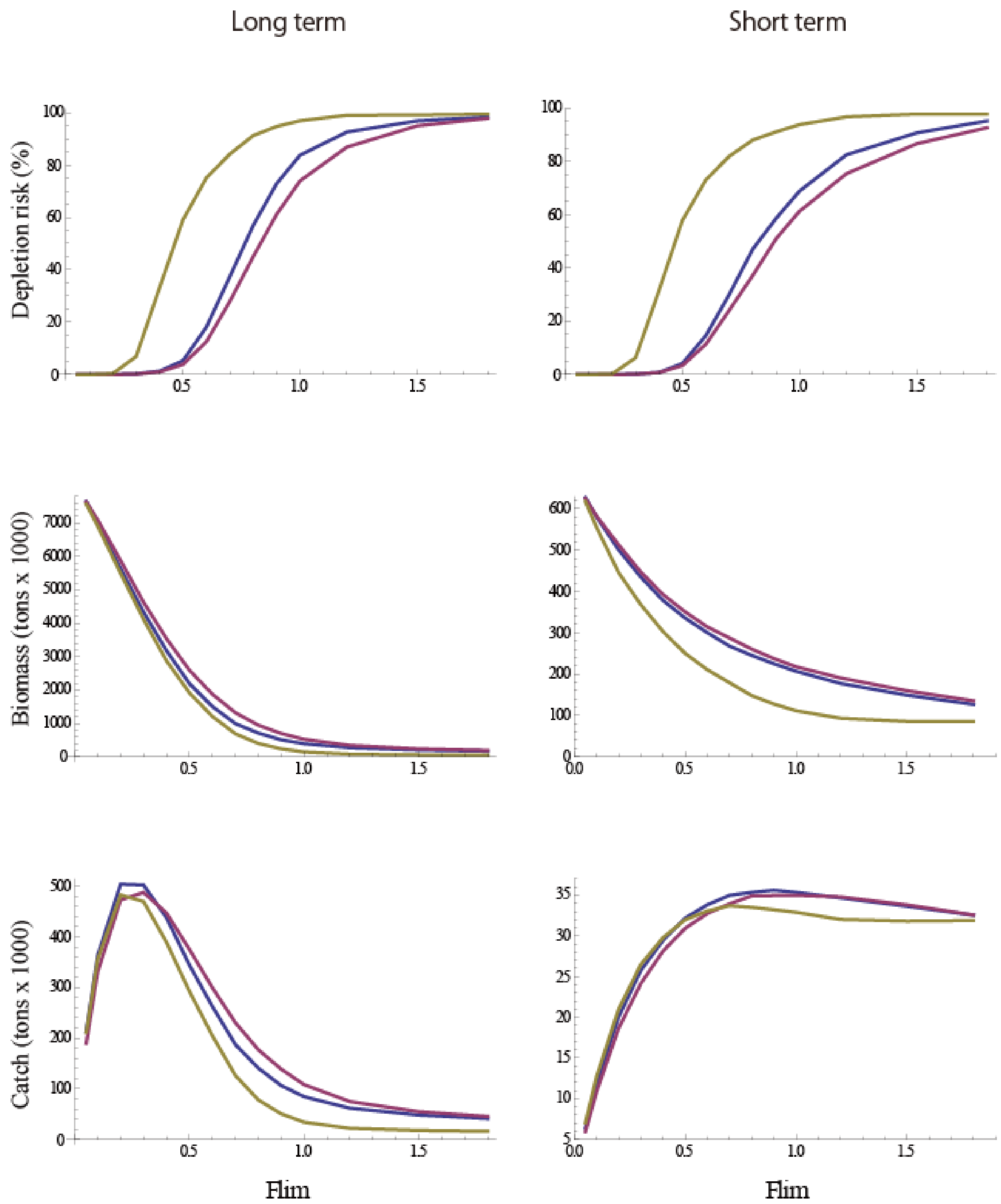

Figure 3-2. Performance statistics profiles for the three management strategies across a range of F_{lim} values evaluated both over short (5-year) and long (20-year) terms. Lower risk, higher biomass and higher catches are desirable. Note how catches are maximized at different values of F_{lim} when considered long and short terms. Green, blue and purple lines correspond to CF, ABC and EBM respectively.

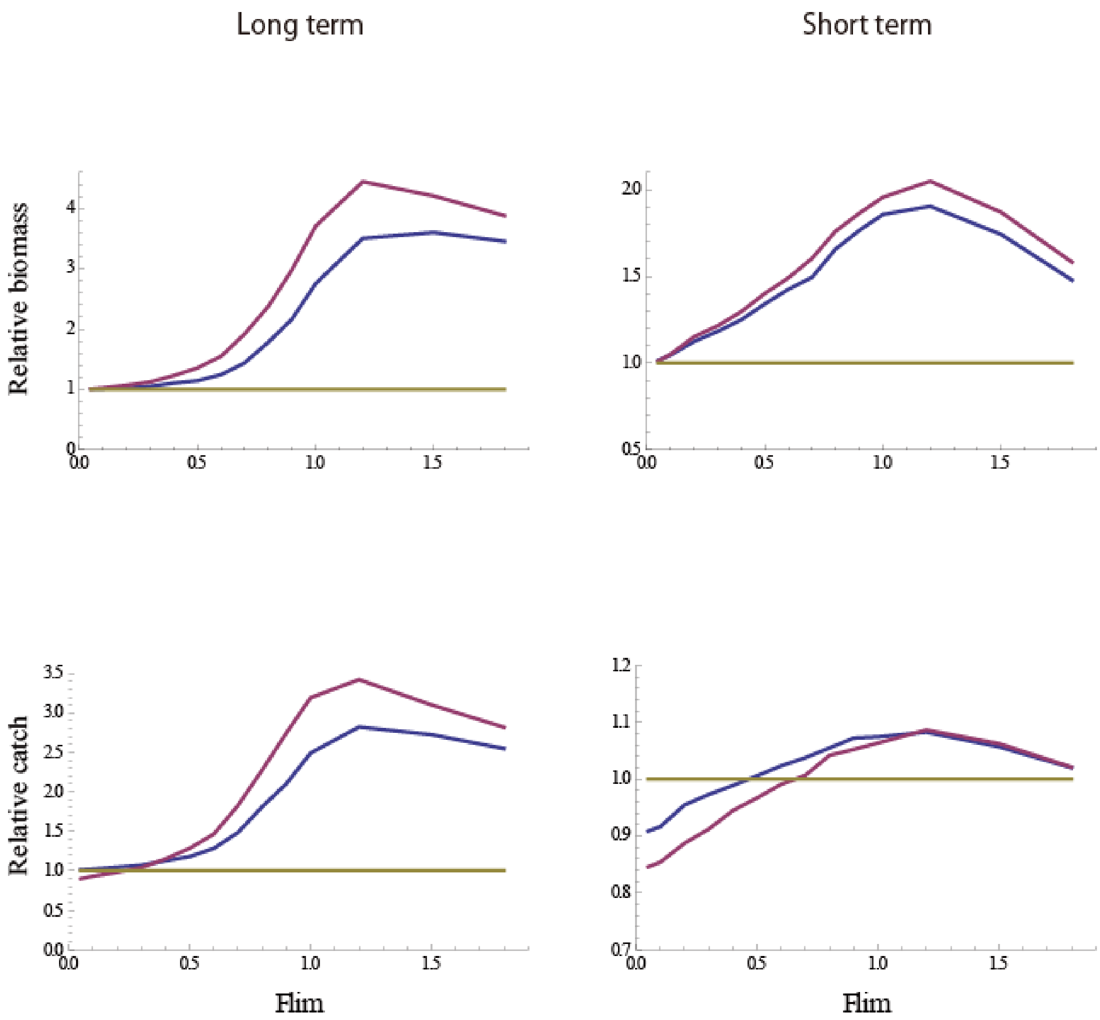

Figure 3-3. Relative performance statistics profiles for the three management strategies across a range of F_{lim} values evaluated both over short (5-year) and long (20-year) terms. Higher biomass and catches are desirable. Note how in the short term ABC behaves very similar to EBM. Green, blue and purple lines correspond to CF, ABC and EBM respectively.

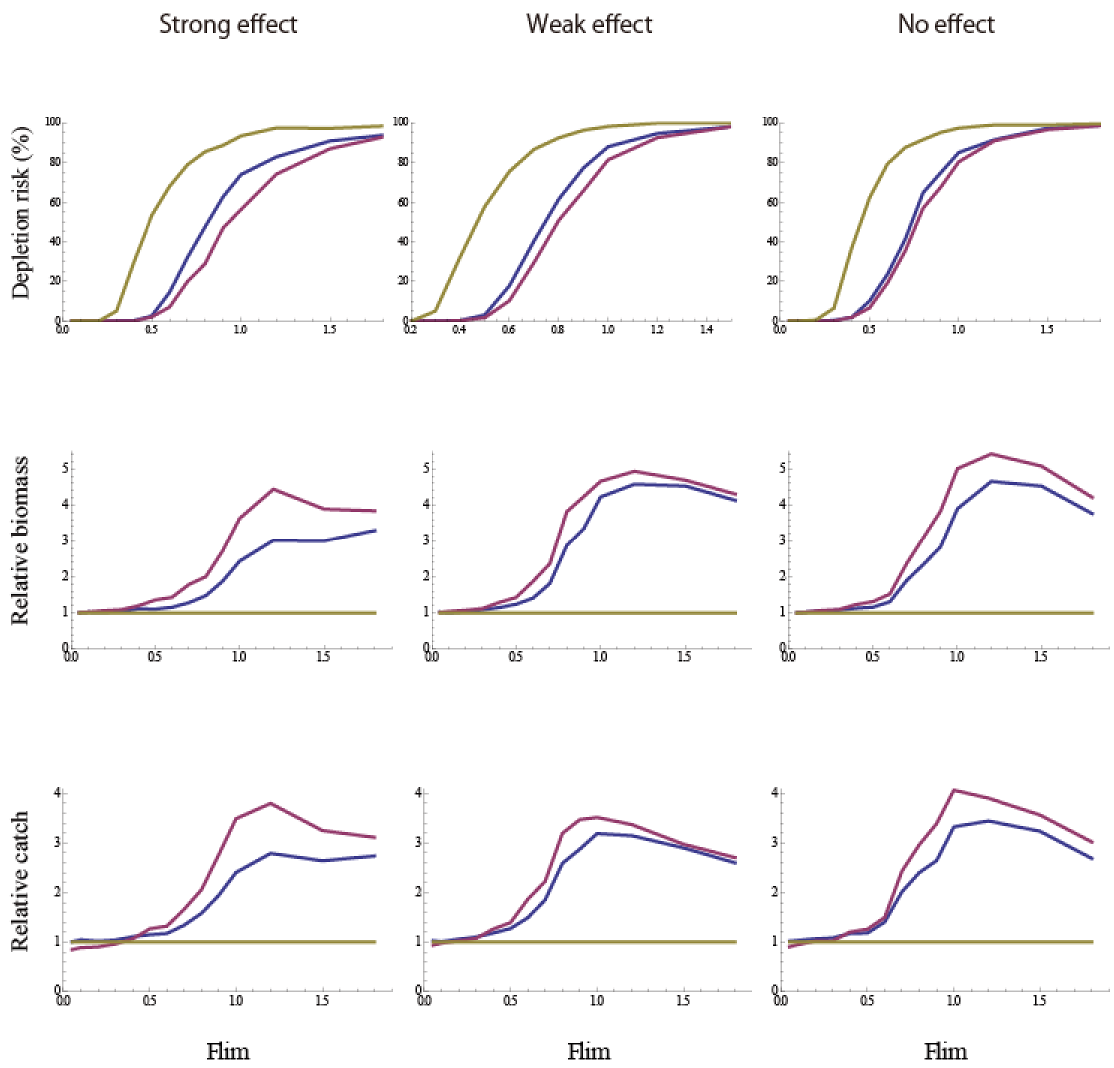

Figure 3-4 Results of sensitivity to environmental effects for the three management strategies comparing performance statistics profiles across a range of F_{lim} values evaluated over the long (20-year) term. Biomass and catch profiles are normalized. Lower risk, higher biomass and higher catches are desirable. Note how under weak and no environmental effect ABC behaves very similar to EBM, but differences arise when strong effects occur. In all cases feedback control strategies outperform CF, except at very low levels of F_{lim} where behavior of the three strategies is similar. Green, blue and purple lines correspond to CF, ABC and EBM respectively.

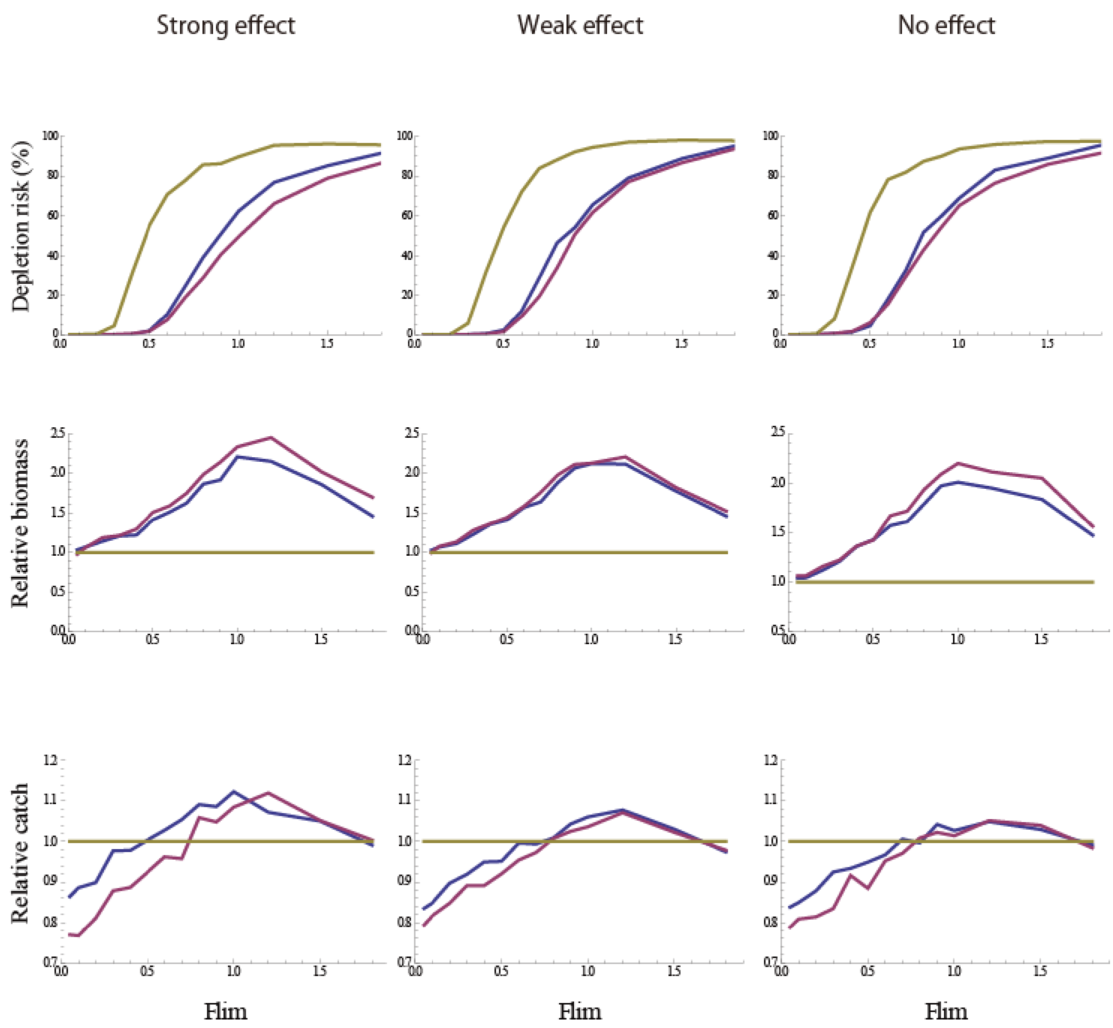

Figure 3-5 Results of sensitivity to environmental effects for the three management strategies comparing performance statistics profiles across a range of F_{lim} values evaluated over the short (5-year) term. Biomass and catch profiles are normalized. Lower risk, higher biomass and higher catches are desirable. Note how under all levels of environmental effect ABC behaves very similar to EBM. Differences between CF and feedback control rules exist in risk and biomass, but catches present a similar behavior. Green, blue and purple lines correspond to CF, ABC and EBM respectively.

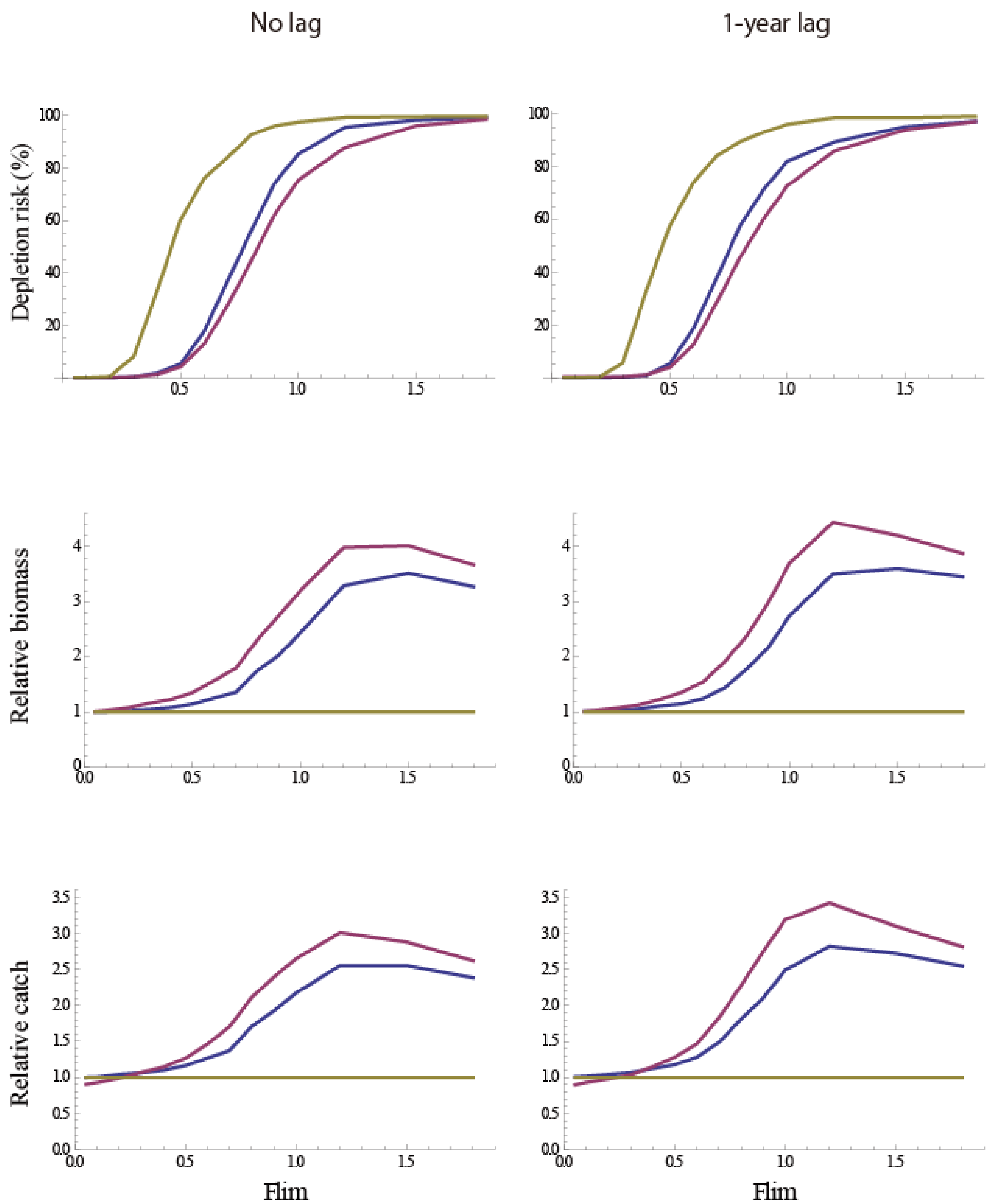

Figure 3-6. Results of sensitivity to time lags for the three management strategies comparing performance statistics profiles across a range of F_{lim} values evaluated over the long (20-year) term. Biomass and catch profiles are normalized. Lower risk, higher biomass and higher catches are desirable. Note how ABC behaves very similar to EBM regardless of a time lag. In all cases feedback control strategies outperform CF, except at very low levels of F_{lim} where behavior of the three strategies is similar. Green, blue and purple lines correspond to CF, ABC and EBM respectively.

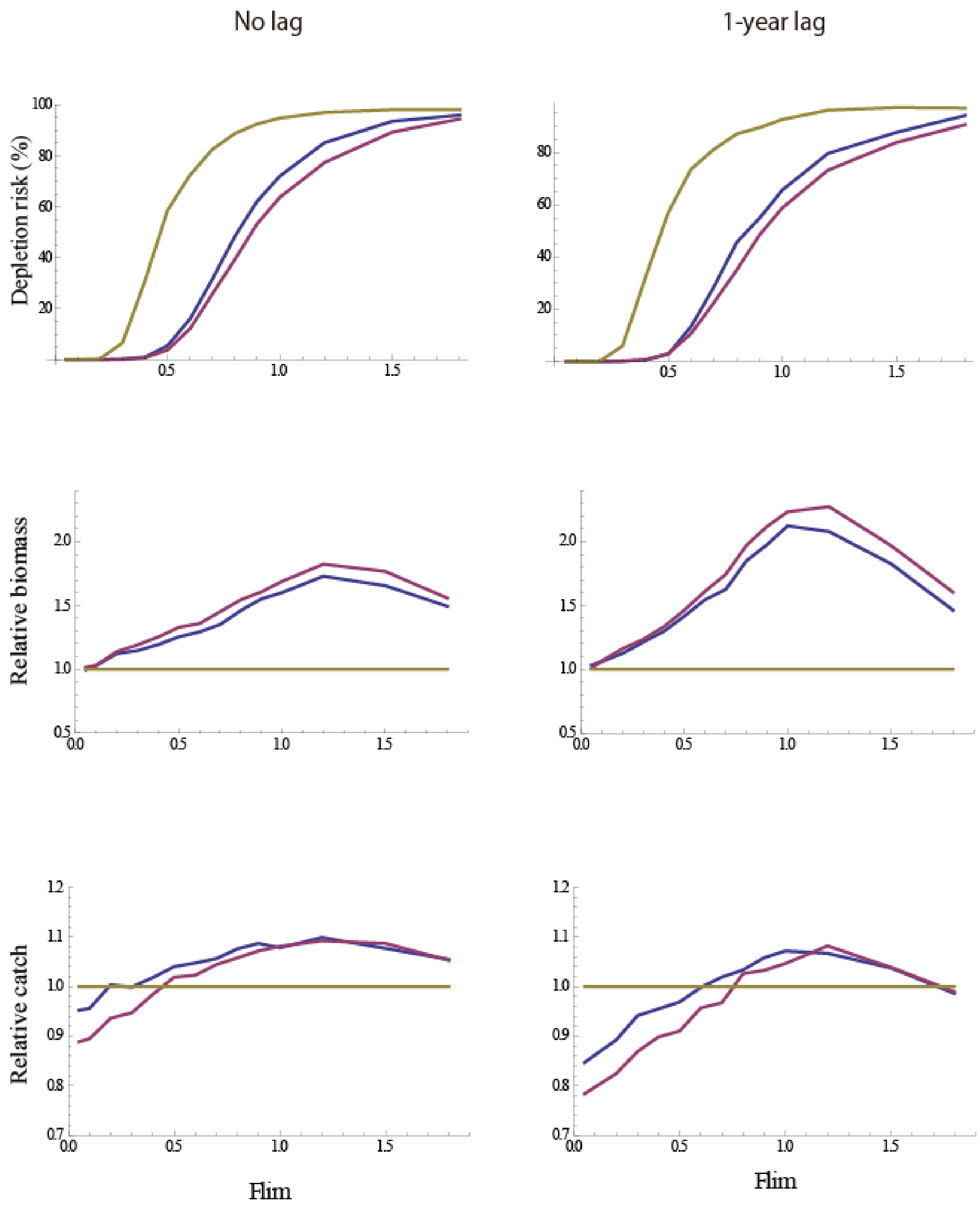

Figure 3-7. Results of sensitivity to time lags for the three management strategies comparing performance statistics profiles across a range of F_{lim} values evaluated over the short (5-year) term. Biomass and catch profiles are normalized. Lower risk, higher biomass and higher catches are desirable. Note how ABC behaves very similar to EBM regardless of a time lag. Differences between CF and feedback control rules exist in risk and biomass, but in catches present a similar behavior. Green, blue and purple lines correspond to CF, ABC and EBM respectively.

4. DISCUSSION

4.1. Model

Model complexity has to depend on its objectives and every new parameter or complexity level needs to be justified. It is widely accepted that simplicity is desirable in models used for prediction; operating models on the contrary can benefit from the additional complexity allowing direct control over the sources of uncertainty and thus enabling more detailed analysis. Although it is usually preferable to have simple models that can be easily controlled, traced and understood, the Japanese sardine presented an interesting case where simple models tend to produce unrealistic results and behavior, thus more complex models did provide a good solution, as shown in this study that incorporates environment dynamics, different recruitment models and weight-at-age density-dependence.

4.2. Management strategy evaluation

The selection of performance statistics was appropriate as it permitted to observe differences between the different strategies evaluated.

From the three strategies evaluated, no 'best one' can be singled out. CF strategy performed poorly under most cases and as such should be avoided. Feedback control rules (ABC and EBM) performed more satisfactorily but differences between them are more blurry. EBM apparently could be considered as the best option from most performance indexes but it does introduce additional complexities into the management process which may be undesirable, as it implies that quotas could reduce from one year to the next one even if biomass stays at a stable level. On the other hand EBM shows an important reduction of risk when compared with ABC, more notably when environmental influences are strong making it an ideal candidate for risk adverse management objectives like those of a stock recovery program.

ABC's long term performance is sub-optimal but it does not present the uncertainties that EBM carries making it a better choice for short term objectives. Short term thinking tends to be disregarded as unsustainable but it can present a reasonable case when big economic uncertainties are at play. High discount rates may be the clearest example of this, where high present values would present a strong incentive against conservation of the resource (Clark 2006) as could easily happen in a scenario of social insecurity and high resource variability, such as is the case of the South African small pelagics' fisheries (Butterworth and Bergh 1993). If it could be proven that the Japanese sardine will recover easily with good environmental conditions, disregard of the fishing pressure imposed on it, short term thinking would also present a reasonable case as environmental variation would become the main source of uncertainty, as it has been shown that environmental variability should be considered a source of higher discount rates (Clark 2006).

There are ways that could avoid these potential dilemmas, for example if small pelagic fishes are indeed strongly dependent on environment and a feedback strategy like EBM is applied, assuming that quotas are enforced the final cumulative effect would probably be the same as those a target switching strategy like was described by Katsukawa and Matsuda (2003), reducing economic uncertainties while ensuring resource sustainability. This possibility should be explored in more detail.

This study shows the importance of strategy evaluation and the necessity of clear *a priori* objectives to be defined in any management decision making scenario. It is clear that there are no 'silver bullets' in fisheries management, higher catches will almost invariably bring lower biomass and increasing risk, long-term objectives stand at odds with short-term benefits and so on. Selection of management strategies will always involve trade-offs and thus needs to be based on objectives set beforehand.

4.3. Implications for current management practices

All three management strategies could be directly applicable to current management, as all the data needed is already being collected both by the Japanese Fisheries Research Agency and the Japan Meteorological Agency.

Initially I wanted to evaluate the current management approach so that it could be compared side by side with the strategies shown here; however, lacking economic data and knowing that there is difference between ABC, TAC and actual catch, it became clear that it would be almost impossible to simulate it, as the driver force behind the actual fishery's dynamics appears unknown. A theoretical model could still be developed but the high subjectivity and lack of clear decision rules would make it very hard to compare with rule-based management. These facts alone already render the current management approach as undesirable under the FAO Precautionary Approach paradigm which demands that management procedures have clear objectives and involve pre-specified decision rules which were evaluated in advance (FAO 1995).

Prediction-based management has the undesirable effect of leaving the TAC setting decision open to discussion where energy is wasted in arguments over quota haggling and assessment results, often lead by agendas rather than scientific means. On the contrary, MSE based management frameworks, by predefining the actions that should be taken given existent data, can reduce haggling time and pressure to address short-term issues, creating the opportunity to focus more on longer-term research efforts (Butterworth 2007).

MSE also has the advantage of indicating areas where research should be prioritized. Given the sensitivity of management strategies to environmental effects, this seems a good candidate for research prioritization. Other sources of uncertainty like sensitivity to bias in assessments and model selection should be evaluated, as these could provide valuable information for managers.

Another implication of the present study is the strong necessity for an in-depth economic research of the fishery. As was seen in the previous discussion, the importance of economic factors cannot be stressed enough. Differences between TAC, ABC and actual catches suggest that the fishery could be being driven entirely by economic behavior with no actual ecological control. Data from the last five years (fig. 1-2) show an almost complete stop in the decreasing trend of the stock, stabilizing around 150000 tons. ABC and TACs have also stabilized, however the direction of causality is obscure. It could be that TACs are being respected generating a stabilizing effect, but it is also possible that a point of bionomic equilibrium has been reached. This is a distressing possibility that needs to be explored.

5. CONCLUSIONS

For any management strategy selection process to be sensible, clear management objectives must be stated a priori, as it was shown that there is no single best approach for all cases. Different management strategies work better under different objectives.

MSE has the advantage of pointing areas where research efforts should be concentrated. This study showed that focusing research in the strength of the link environment-recruitment would give valuable information for management, as selection the relative behavior of strategies seemed to be sensitive to this factor. It also seems imperative to conduct an economic study of the fishery, as this seems a key driving factor of many aspects of its dynamics, but other sources of uncertainty could also be explored.

If the Precautionary approach is to be taken into account in current management in Japan, given the currently depleted status of the stock it is necessary to adopt a long-term thinking framework and that recovery should become a priority. MSE presents itself as a good tool under such a framework, as its procedures and methods coincide with most of the recommendations from the Precautionary approach.

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7. REFERENCES

Basson M (1999) The importance of environmental factors in the design of management procedures. Academic Press Ltd, pp 933-942

Butterworth DS (2007) Why a management procedure approach? Some positives and negatives. Ices Journal of Marine Science 64: 613-617

Butterworth DS, Bergh MO (1993) The development of a management procedure for the South African anchovy resource. Canadian Special Publication of Fisheries and Aquatic Sciences 120: 83-99

Butterworth DS, Punt AE (1999) Experiences in the evaluation and implementation of management procedures. Ices Journal of Marine Science 56: 985-998

Clark CW (2006) The Worldwide Crisis in Fisheries. Economic Models and Human Behavior. Cambridge

FAO (1995) Precautionary Approach to Fisheries. Part 1: Guidelines on the precautionary approach to capture fisheries and species introductions FAO Fisheries Technical Paper. No 350, pp 52

Fisheries Agency of Japan and Fisheries Research Agency (2007) Guidelines for calculating ABC - 2007 version (In Japanese), pp 10

Francis R, Shotton R (1997) "Risk" in fisheries management: a review. Canadian Journal of Fisheries and Aquatic Sciences 54: 1699-1715

Hilborn R, Walters CJ (1992) Quantitative Fisheries Stock Assessment Choice Dynamics And Uncertainty. Hilborn, R. And C. J. Walters. Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. Xv+570p. Routledge, Chapman and Hall, Inc.: New York, New York, USA; London, England, Uk. Illus. Maps: XV+570P

Hiramatsu K (2001) VPA (Virtual Population Analysis) (*in Japanese*). In: Asociation JFRC (ed) The Textbook of Stock Assessment Methods, Kanagawa, pp 104-128

Itoh S, Yasuda I, Nishikawa H, Sasaki H, Sasai Y (2009) Transport and environmental temperature variability of eggs and larvae of the Japanese anchovy (Engraulis japonicus) and Japanese sardine (Sardinops melanostictus) in the western North Pacific estimated via numerical particle-tracking experiments. Fisheries Oceanography 18: 118-133

Katsukawa T, Matsuda H (2003) Simulated effects of target switching on yield and sustainability of fish stocks. Fisheries Research 60: 515-525

King JR, McFarlane GA (2006) A framework for incorporating climate regime shifts into the management of marine resources. Fisheries Management and Ecology 13: 93-102

Kirkwood GP (1997) The revised management procedure of the International Whaling Commission. In: Pikitch EK, Huppert DD, Sissenwine MP (eds) American Fisheries Society Symposium; Global trends: Fisheries management, pp 91-99

Nishida H, Ishida M, Noto M, Kawabata A, Watanabe C (2007) Stock assessment for the Pacific stock of Japanese sardine *Sardinops melanostictus*. *(In Japanese)* Marine fisheries stock assessment and evaluation for Japanese waters (fiscal year 2006/2007). Fisheries Agency and Fisheries Research Agency of Japan

Nishikawa H, Yasuda I (2008) Japanese sardine (*Sardinops melanostictus*) mortality in relation to the winter mixed layer depth in the Kuroshio Extension region. Fisheries Oceanography 17: 411-420

Pauly D (1995) Anecdotes and the shifting baseline syndrome of fisheries. Trends in Ecology & Evolution 10: 430-430

Pope JG (1972) An investigation of the accuracy of virtual population analysis using cohort analysis. Fish. Res. Bull. Int. Commn. NW Atlant. 9: 65-74

Rademeyer RA, Plaganyi EE, Butterworth DS (2007) Tips and tricks in designing management procedures. Ices Journal of Marine Science 64: 618-625

Smith ADM, Sainsbury KJ, Stevens RA (1999) Implementing effective fisheries-management systems - management strategy evaluation and the Australian partnership approach. ICES J. Mar. Sci. 56: 967-979

Takasuka A, Oozeki Y, Aoki I (2007) Optimal growth temperature hypothesis: Why do anchovy flourish and sardine collapse or vice versa under the same ocean regime? Canadian Journal of Fisheries and Aquatic Sciences 64: 768-776

UK Meteorological Office HC (2006, 2009) HadISST 1.1 - Global sea-Ice coverage and SST (1870-Present). British Atmospheric Data Centre

Wada T, Jacobson LD (1998) Regimes and stock-recruitment relationships in Japanese sardine (Sardinops melanostictus), 1951-1995. Canadian Journal of Fisheries and Aquatic Sciences 55: 2455-2463

Watanabe Y, Zenitani H, Kimura R (1995) Population decline of the Japanese sardine Sardinops melanostictus owing to recruitment failures. Canadian Journal of Fisheries and Aquatic Sciences 52: 1609-1616

Whitehead PJP (1985) FAO species catalogue. Vol.7. Clupeoid fishes of the world (Suborder Clupeoidei). An annotated and illustrated catalogue of the herrings, sardines, pilchards, sprats, shads, anchovies and wolf-herrings. Part 1. Chirocentridae, Clupeidae & Pristigasteridae

Yatsu A, Watanabe T, Ishida M, Sugisaki H, Jacobson LD (2005) Environmental effects on recruitment and productivity of Japanese sardine Sardinops melanostictus and chub mackerel Scomber japonicus with recommendations for management. Fisheries Oceanography 14: 263-278