17 BIO-ECONOMICS OF SHRIMP FISHERIES OF THE BRAZIL–GUYANA SHELF: DEALING WITH SEASONALITY, RISK AND UNCERTAINTY

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17.1 Introduction

The use and management of shrimp and groundfish resources of the Brazil–Guyana shelf require a systematic integration of the resource biology and ecology with the economic and social factors that determine resource and fishers' behaviour over time. The approach suggested for the development of management strategies for shrimp and groundfish fisheries of this region, involves the following steps:

(i) Identify the set of **management questions** needed to be addressed by the working group,

(ii) Undertake **biological, economic and social assessment of the fishery**, i.e. estimate size and dynamics of the population structure, age structure of the catch, costs and revenues of alternative fishing methods, direct employment and export earnings,

(iii) Select the **performance variables** for the shrimp fishery,

(iv) Establish **limit and target reference points** for the selected performance variables,

(v) Identify **alternative management strategies** for the fishery with the specific policy instruments,

(vi) Identify different **states of nature** for those fishery variables and parameters (i.e. recruitment seasonality, natural mortality, unit costs of effort, catchability, etc.) that involve high levels of uncertainty,

(vii) Determine if **mathematical probabilities** can be assigned for the occurrence of the identified states of nature,

(viii) Build **decision tables** with and/or without mathematical probabilities,

(ix) Apply different **decision criteria** reflecting different degrees of caution or risk aversion to select the optimum management strategy,

(x) Estimate **the probabilities of exceeding the limit reference points** of performance variables for the alternative management strategies under consideration,

(xi) **Re-evaluate the fishery periodically** to establish new reference points and management strategies.

The use of *reference points* (Caddy and Mahon 1995, Die and Caddy 1997) as guides for resource administration represents an important step in the management process. Also, the recognition of the uncertainty present in various parts of the fishery system is fundamental for a precautionary approach to the decision making process. To aid this process, the use of fisheries specific mathematical models allow researchers, managers and resource users to experiment with different management options in order to observe the possible dynamic consequences on different parts of the system and corresponding performance variables.

17.2 The precautionary approach to shrimp fisheries management: dealing with risk and uncertainty

Butterworth *et al.* (1993) and Hilborn and Peterman (1996) among others have identified a set of sources of uncertainty associated to stock assessment and management procedures. These include uncertainty in resource abundance, in model structure, in model parameters, on behaviour of resource users, in future environmental conditions and in future economic, political and social conditions. To deal with these variety of uncertainties using a precautionary approach, it was suggested, in the Lysekil meeting (FAO 1995), the use of Bayesian and non-Bayesian decision theory (Perez and Defeo 1996, Defeo and Seijo 1999) and the incorporation of limit and target reference points to manage fisheries (Caddy and Mahon 1995). Under this approach, decision makers in fisheries are expected to select one management strategy, **d**, out of a set of **D** alternative strategies. When selecting a strategy, the fishery manager should be aware of the corresponding consequences. These consequences are likely to be a function of the cause-effect relationships specified in the fishery model, the estimated bio-economic parameters and the possible states of nature (Seijo *et al.* 1998). There is a probability that a target reference point (i.e. resource biomass, yield, rent, direct employment, export earnings, contribution to food security in coastal areas, etc.) may not be achieved because of inherent randomness of natural systems, incomplete knowledge of the fishery system and changes in economic and biological/ecological exogenous variables (Garcia, 1996a).

Monte Carlo analysis allows introducing the uncertainty associated with natural variations and imperfect knowledge about the system being assessed trough dynamic bio-economic analysis. The process consists of an iterative calculation of the performance variables, where in each trial a new value for the unknown parameter is generated with the specified probability density function.

17.3 Decision tables with and without mathematical probabilities

In decision theory, it is important to be able to estimate a loss of opportunities function, $L(d,\theta)$, which reflects the resulting losses of having selected strategy d when the state of nature occurring is θ.

If *prior* or *posterior* probabilities are available to build decision tables, the expected values (EV) and their corresponding variance (VAR) should be estimated for the selected fishery performance variable (e.g. net present value of the fishery, biomass, yield, direct employment, export earning, among others) as follows:

$$EV_d = \sum P_\theta PV_{\theta d}$$

$$VAR_d = \sum P_\theta (PV_{\theta d} - EV_d)^2$$

where P_θ are the probabilities associated to the different states of nature, $PV_{\theta d}$ are the values of the performance variable resulting from management decision d when state of nature θ occurs. A *risk neutral* fisheries manager will select the management strategy that generates the maximum expected value with no consideration of the corresponding variance. A *risk averse* decision maker will tend to select the fisheries management strategy that generates the minimum variance. There are however different degrees of risk aversion and therefore the decision theory provides alternative criteria for increasing degrees of caution in decision making (Shotton 1995, Shotton and Francis 1997). To apply these concepts to the precautionary approach to fisheries we will describe in the following section decision criteria *with* and *without* mathematical probabilities.

17.4 Bayesian criterion

The Bayesian criterion is a procedure that uses *prior* or *posterior* probabilities to aid the selection of a management strategy. It indicates the shrimp fishery manager should select the decision that minimises the expected loss of opportunities. Decisions without experimentation use *prior* distributions estimated out of experiences that are translated subjectively into numerical probabilities. Shrimp fishery decisions that are based on experimentation can use *posterior* probabilities. Posterior probabilities are the conditional probability of state of nature θ, given the experimental data.

17.5 Decision criteria without mathematical probabilities

In the absence of sufficient observations to assign probabilities to possible states of nature, there are three decision criteria reflecting different degrees of precaution concerning selection of management strategies (Seijo *et al.* 1998, Defeo and Seijo 1999).

17.5.1 Minimax criterion

The Minimax criterion estimates the maximum loss of opportunities of each management strategy and selects the one that provides the minimum of the maximum losses. This criterion proceeds as if nature would select the probability distribution, defined for all possible states of nature, that is least favourable for the decision-maker.

17.5.2 Maximin criterion

This criterion uses the performance variable decision table that estimates the resulting values for a set of combinations of alternative decisions and states of nature. The criterion calculates a vector of the minimum values for the performance variable resulting from each alternative management decision. Then, the shrimp fishery manager proceeds to select the maximum of the minimum of those values. This is the most cautious of the decision theory approaches.

17.5.3 Maximax criterion

A risk prone fishery manager would tend to apply the Maximax decision criterion when selecting the management strategy. The criterion calculates a vector of the maximum values for the performance variable resulting from each alternative management decision. Then, the shrimp fishery manager proceeds to select the maximum of the maximum of those values and the corresponding decision that generates it.

17.6 Bio-economic model for a multi-species multi-fleet shrimp fishery

A short and long run dynamics model for the fishery was developed considering seasonality of recruitment and effort and integrating the dynamics of crustacean species harvested by heterogeneous fleets.

17.6.1 Biological sub-model

An estimation of stock size is needed as an input in order to initialise the model. Survivors through fishing seasons are calculated following equation (1):

$$N_{i,j,t+1} = N_{i,j,t} + \int_{t}^{t+DT} (N_{i,j-1,t-1} \cdot S_{i,j-1,t-1} - N_{i,j,t})dt \qquad (1)$$

where $N_{i,j,t}$ is the number of individuals of species i aged j in time t, $S_{i,j-1,t-1}$ is the survival rate of individuals of age j-1 in time t-1 and DT is the time increment, assumed in the spreadsheet as DT=1.

The survival rate of individuals at different ages over time is estimated as $S_{i,t}$=1-(1-exp(-$\Sigma F_{i,j,m,t}$ + M_i)) represents the selectivity pattern (both generated from the technological sub-model) and M_i is the natural mortality during the fishing season. Biomass by sex and age is determined by:

$$B_{i,j,t} = N_{i,j,t} \cdot (a_i \cdot L_{i,j}{}^{bi}) \qquad (2)$$

where, $L_{i,j}$ is the length of shrimp species i at age j and a_i and b_i are constants from species length-weight relationship. Length at age for the different species is calculated using the von Bertalanffy growth model:

$$L_{i,j} = Li_{\infty} \cdot (1 - e^{-ki \cdot (i - i_o)}) \qquad (3)$$

Total biomass of each shrimp species at the end of the month is determined by:

$$TB_{s,t} = \sum_{i=2}^{i=15} B_{i,t} \qquad (4)$$

Recruitment to the stock (age 1) for the following year could be considered constant or dynamic using alternative recruitment functions (e.g. Beverton-Holt), either deterministic or stochastic:

$$R_t = f\left[SSB_{it}, ENV_t, u_t\right] \qquad (5)$$

where SSB_{it} = the spawning stock biomass of species i at time t, ENV_t = the critical environmental factor affecting fluctuations in recruitment levels (e.g. precipitation in relevant watershed) and u_t = a random variable generated with the appropriate probability density function and variance to account for random and uncertain factors. For a sex specific population structure, the numbers of males and females entering the fishery could be calculated by multiplying R_t by the sex proportion.

Recruitment seasonality

Recruitment seasonality was modelled using a distributed delay model (Seijo *et al.* 1998). The model can be described as follows:

$$dR_1 = \frac{g}{DEL}(pl_{i,t} - R_{1,t}) \qquad (6)$$

$$dR_2 = \frac{g}{DEL}(R_{i,t} - R_{2,t}) \qquad (7)$$

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$$dR_g = \frac{g}{DEL}(R_{g-i,t} - R_{g,t}) \qquad (8)$$

where pl = shrimp postlarvae recruiting to the area, $R_{g,t}$= shrimp recruits to age 1, $R_{1,t}$, $R_{2,t}$, ..., $R_{g,t}$ are the intermediate rates of the delay process used to represent the distribution of seasonal recruitment, DEL = average maturation time and g = order of the distributed delay.

17.6.2 Technological / Economic sub-model

To initiate this sub-model, current effort (total fishing days) for each fishing season is needed. Furthermore, the length of the closed season is required. The first step is to calculate the seasonal fishing mortality per fishing gear. Fishing mortality is calculated by age according to the following equation:

$$F_{t,s,i,g} = f_{t,g} \cdot SEL_{s,i} \cdot q_{s,g} \qquad (9)$$

where $f_{t,g}$ = the fishing days per gear in each fishing season, $SEL_{s,i}$ represents the selectivity pattern by age, while s represents the sex. Current number of fishing days is required to initialise the model. The amount of fishing days by gear in subsequent years is calculated endogenously by the model, as will be explained below. The catchability coefficient is denoted by q and is estimated in the model by the Baranov (1918) area swept method.

To estimate the catch by gear, age and sex in the fishing season t, the following catch equation is used:

$$C_{t,i,j,m} = \left[\frac{F_{t,i,j,m}}{F_{t,i,j,m} + M_i}\right] \cdot \left[1 - e^{-(F_{t,i,j,m} + M_t}\right] \cdot N_{i,j,i} \qquad (10)$$

Catch throughout the year is estimated by:

$$TC_{m,t} = \sum_{j=1}^{24} C_{t,i,j,m} \qquad (11)$$

Numbers of vessels ($NV_{t,m}$) involved in a year is calculated by relating total fishing effort applied in a year to total fishing days per vessel:

$$NV_{t,m} = \left(\frac{f_{t,m}}{TFDV}\right) \qquad (12)$$

where $TFDV$ is the total fishing days per vessel in a year.

17.6.3 Economics sub-model

To predict the new effort per gear (total fishing days) in the next season, the dynamic of the effort is modelled using Smith's approach (Smith 1969):

$$f_{t+DT,m} = f_{t,m} + \int_{t}^{t+DT} (\phi \cdot \pi_{\mathrm{m,t}}) dt \qquad (13)$$

where ϕ is a positive constant (Smith 1969) and PP_t is the private profit generated over time from the economics sub-model. If ϕ is equal to zero, then effort is constant throughout time. Furthermore, the technological sub-model allows evaluating changes in the duration of the closed season.

The revenue per fleet is calculated using:

$$TR_{m,t} = \sum_{i,j} C_{i,j,mt} \cdot p_{i,j} \qquad (14)$$

where $p_{i,j}$ is a vector of ex-vessel prices per age (size). Profits generated by each fleet per fishing season is calculated as:

$$\Pi_{m,t} = TR_{m,t} - TC_{m,t} \qquad (15)$$

where $TC_{m,t}$ are total costs of fleet type m in season t. The total profit per year is determined by adding the monthly profits over the year. The total costs per gear are separated in variable and fixed cost.

Net present value for the fishery

Net present value (NPV) was calculated according to equation

$$NPV_m = \sum_{t=0}^{T} \frac{\Pi m_t}{(1-\delta)^t} \qquad (16)$$

where δ is the discount rate. The time period simulated was 4 years. Different rates of discount were used in the analysis to reflect different prices of time.

The above described model was applied to the Trinidad – Venezuela shared shrimp fishery of the Gulf of Paria.