5 DEVELOPMENT OF A MULTISPECIES-MULTIGEAR PER - RECRUIT MODEL THAT INCORPORATES PARAMETER VARIABILITY

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5.1 Introduction

The purpose of fisheries management is to ensure the sustainable utilisation of fish stocks over time in an effort to promote the economic and social well-being of the harvesting fishers (Hilborn and Walters 1992). Essentially, sustainable management is dependent on the ability of fisheries managers to determine at what levels of fishing effort (or fishing mortality) and at which gear selectivity scenarios the catch of a species is sustainable and that the spawning stock remains adequate.

In many fishery scenarios abundance indices such as catch-per-unit-effort or biomass survey and/or length- or age-based catch data are not available. When abundance indices are available, these are often temporally disjunct and of little quantitative value. As a result the use of data intensive stock assessment methods such as *Ad hoc* tuned-Virtual Population Analysis (Pope and Shepherd 1985; Butterworth *et al*. 1990), integrated analysis (Deriso *et al.* 1985) and age-structured production models (Punt 1994; Booth and Punt 1998) cannot be applied. For these reasons per-recruit models (Beverton and Holt 1956, 1957) are favoured.

A per-recruit modelling approach, which allows for the easy evaluation of per-recruit to changes in fishing mortality and age-at-selectivity, has been widely applied in both marine and freshwater environments (Pulfrich and Griffiths 1988; Blay and Asabere-Ameyaw 1993; Booth and Buxton 1997; Thompson and Allison 1997). These models, however, assume that the parameters considered are constant and that the system is in a steady state (Punt 1993). In addition, these models have traditionally treated the target species in isolation from its environment, as well as from other species and from other gears. Since most fisheries present a scenario where many species are caught by each gear in a multigear fishery and in which interactions exist between species and their environment, the use of single species models in managing these fisheries is inadequate. These 'traditional' per-recruit models allow for the evaluation of the response of the per-recruit of a single species to changes in fishing mortality and age-at-50%-selectivity in a single fishery. Management advice based on the assessment of a fishery in isolation is inadequate when there are a number of fisheries harvesting the stock at differing ages-at-selectivity (Djama and Pitcher 1997). It has also long been recognised that when a common gear harvests a number of species, it is impossible to manage each species at its optimum level (Beverton and Holt 1957; Anderson 1975, Mitchell 1982; Pikitch 1987). For these reasons, Murawski (1984), Pikitch (1987) and Weyl *et al*. (in prep) have developed yield- and spawner biomass per-recruit models that account for the interaction of different species captured by the same gear or for different gears harvesting the same species at different selectivities.

5.2 The development of a multispecies-multifishery per-recruit model

Multispecies-multi-fishery per-recruit models are based on an extension of the traditional per-recruit models. A concise review of these "traditional" models is provided before showing the specific points of departure from the "traditional" approach.

The fundamental assumption of all per-recruit analyses is that the parameters for recruitment, growth, mortality and selectivity are temporally invariant, with the stock in a steady state situation. Under these assumptions, the composition of the stock is then calculated by considering a cohort during its lifespan (Beverton and Holt 1957). The relative proportion of fish at age *a* ($\widetilde{N}_a$), is defined recursively as:

$$\widetilde{N}_a = \begin{cases} 1 & \text{if } a = 0 \\ \widetilde{N}_{a-1} e^{-(M+S_{a-1}F)} & \text{if } 1 \le a < \max \\ \widetilde{N}_{\max-1} e^{-(M+S_{\max-1}F)} \Big/ \left(1 - e^{-(M+S_{\max-1}F)}\right) & \text{if } a = \max \end{cases} \quad (1)$$

where S_a is selectivity at age *a*, *F* is the instantaneous rate of fishing mortality on fully recruited cohorts, *M* is the instantaneous rate of natural mortality and *max* is the maximum recorded age, essentially a lumped plus-group.

Weight-at-age is described as:

$$W_a = \alpha(l_a)^{\beta} \quad (2)$$

where l_a is the length-at-age determined using any suitable growth model and α and β are the parameters describing the length-weight relationship.

Yield-per-recruit (*YPR*) and spawner biomass-per-recruit (*SBR*) as a function of fishing mortality (*F*) were determined by:

$$YPR_F = \sum_{a=0}^{\max} w_a S_a F \widetilde{N}_a \left[1 - e^{-(M+S_aF)}\right] \Big/ \left(M + S_aF\right) \quad (3)$$

$$SBR_F = \sum_{a=0}^{\max} \psi_a w_a \widetilde{N}_a \quad (4)$$

and biomass-per-recruit (*BR*) as function of age are determined as:

$$BR_a = w_a \widetilde{N}_a \quad (5)$$

where ψ_a is the proportion of mature fish at age *a.*

In a multigear fishery, the number of fish at age *a* is determined by the relative fishing mortality rate of each gear and its inherent selectivity. The total mortality rate (Z) is increased with each gear due to the additive effect that each gear has on the total fishing mortality rate (F) such that for *j* fisheries:

$$Z_a = M_a + \sum_j S_a F_j \quad (6)$$

For example, when three fisheries, 1, 2 and 3, are active the relative number-at-age of species *i* ($\widetilde{N}_{ia}$), is described as:

$$\widetilde{N}_{ia} = \begin{cases} 1 & \text{if } a = 0 \\ \widetilde{N}_{i,a-1} \exp(-(M_a + (S_{a1}F_{a1} + S_{a2}F_{a2} + S_{a3}F_{a3}))) & \text{otherwise} \end{cases} \quad (7)$$

where *M* is the rate of natural mortality, S_a , S_{a2} and S_{a3} are the selectivities for age class *a* of the three fisheries under consideration and F_{a1}, F_{a2} and F_{a3} are the proportional fishing mortality rates (yr^{-1}) for each of the three fisheries.

Since the fishery targets each species, the coefficients of proportionality between fishing effort and fishing mortality (i.e. the catchability coefficients) will vary between species due to differences in their availability and vulnerability to the various gear (Murawski 1984).

At any given level of effort, the F for each species in a multispecies fishery will be different. Catchability coefficients were estimated using the linear relationship:

$$F_{ij} = q_i \times f_j \qquad (8)$$

where q_i is the vector of catchability coefficients of species i and f_j is the vector of standardised effort in fishery j. Although alternative forms of Equation 8 have been suggested for various species (Peterman and Steer 1981), in this study the relationship between f and F is assumed to be linear for all species. The fishing mortality of species i in each fishery j (F_{ij}) could be determined by the proportional contribution of the catch (kg) of species i by each gear to the total catch of that species in all gears.

The spawner-biomass-per-recruit for each species i (SBR_i) in a multigear fishery is then determined by:

$$SBR_i = \sum_{a=0}^{\max} \psi_{ia} w_{ia} \tilde{N}_{ia} \qquad (9)$$

and yield-per-recruit for species i (YPR_i) in a multispecies fishery was determined by :

$$YPR_i = \sum_{a=0}^{\max} \left[(w_{ia} \tilde{N}_{ia} (1 - \exp(-(M_i + \sum_j S_{iaj} F_{ij}))) \frac{\sum_j S_{iaj} F_{ij}}{M_i + \sum_j S_{iaj} F_{ij}} \right] \qquad (10)$$

where w_{ia} is the mass of species i at age a, S_{iaj} is the selectivity for age class a of species i by fishery j, F_{ij} is the instantaneous rate of fishing mortality rate (yr^{-1}) for species i for all fisheries j under consideration, M_i is the rate of natural mortality of species i and *max* is the maximum recorded age for species i.

The annual yield of each species i in all fisheries (Y_i) can be estimated by the equation:

$$Y_i = YPR_i \times R_i \qquad (11)$$

where YPR_i is the yield-per-recruit of species i and R_i is the number of recruits of species i at equilibrium level. The level of pristine recruitment R_i is a complicated parameter to estimate. Values can be obtained by cohort analysis, stratified sampling of juveniles or reparameterising 11. Assuming that given an annual total catch Y_j from j fisheries harvesting species i, then the number of recruits R_i is calculated as:

$$R_i = \frac{Y_j}{YPR_i} \qquad (12)$$

The yield of all species in the fishery j (Y_j) was calculated by:

$$Y_j = \sum_i Y_i \qquad (13)$$

and to obtain the total yield from all fisheries, all individual fishery yields were summed as:

$$Y_{total} = \sum_j Y_j \qquad (14)$$

Gross annual revenue GR_i for a species i from all fisheries can simply be estimated as:

$$GR_i = Y_i \times P_i \qquad (15)$$

where P_i is the price be unit weight of species i.

The total gross revenue from all species and all fisheries is simply:

$$GR_{total} = \sum_{j} GR_j \quad (16)$$

5.3 Calculation of biological reference points

Various biological and target reference points (BRPs and TRPs) can be estimated within a per-recruit framework (see Caddy and Mahon, 1995 for a thorough discussion on the topic).

The most commonly used BRPs and TRPs calculated from the yield-per-recruit curve are: F_{MAX} (= F_{MSY}) – the value of fishing mortality corresponding to the maximum of the yield-per-recruit curve and $F_{o.x}$ – the value of fishing mortality corresponding to where the slope of the yield-per-recruit curve is *x*% of the slope at the origin. Similarly, the most commonly used BRP/TRPs calculated from the spawner biomass-per-recruit curve is $F_{SB(x\%)}$ – the value of fishing mortality corresponding to where spawner biomass-per-recruit curve is *x*% of the pristine, unfished estimate.

5.4 Incorporating variability into the assessment framework

Due to the inherent difficulty in the estimation of various life history and fishery parameters, such as L_{∞}, K, t_0, M, q and a_{50}, the sensitivity of the per-recruit models to variability in these parameters needs to be assessed. A bootstrap estimation procedure is the most suitable routine used to estimate the standard error and confidence intervals of the BRP/TRPs generated by the model.

In the bootstrap procedure a large number (at least 500) (U_{500}) of random parameter samples (M_U: U=1,2,…,U_{500}) were generated, each with its inherent error structure (*inter alia* normal, uniform or log-normal) and a corresponding set of $(\hat{F}^1, \hat{F}^2, ..., \hat{F}^{U_{500}})$ TRPs computed for each set of resampled input parameter sets.

The variance of $\hat{F}$ is estimated as:

$$Var(\hat{F}) = \frac{1}{U_{500} - 1} \sum_{U=1}^{U_{500}} \left[\hat{F}^U - \overline{F}\right]^2 \quad (17)$$

where $\overline{F}$ is the mean of the $\hat{F}$ vector.

The standard error for the TRP $\hat{F}$ is estimated as:

$$SE^{\hat{F}} = \sqrt{\frac{Var(\hat{F})}{U_{500}}} \quad (18)$$

The percentile method is used to estimate 95% confidence intervals, where the 2.5% and 97.5% quartiles from the sorted $\hat{F}$ vector are chosen to represent the upper and lower 95% confidence intervals, respectively (Buckland 1984).