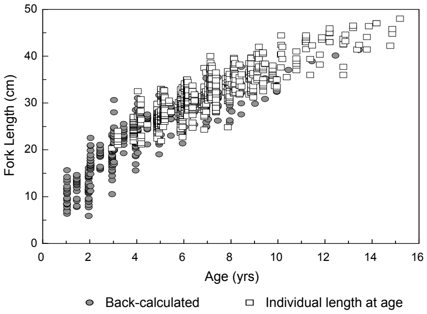
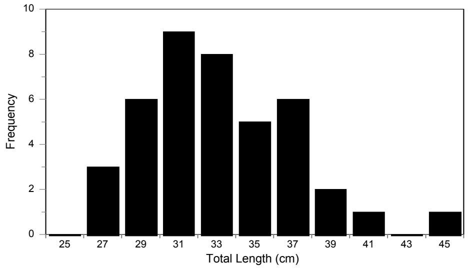
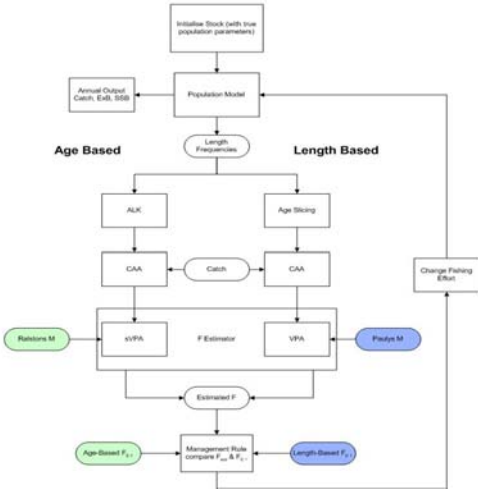
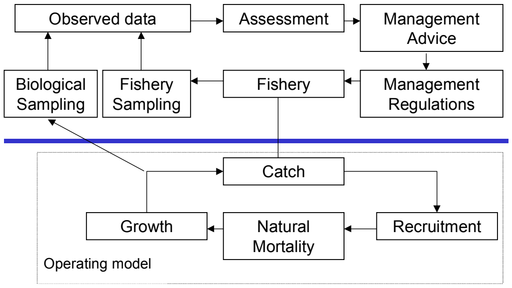
Investigation of the implications of different reef fish life history strategies on fisheries management

Final Technical Report









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Front cover:
Length-based and age-based assessment methods for *Lethrinus mahsena* (left) and *Siganus sutor* (right). Images available from Fishbase: www.fishbase.org (Froese and Pauly, 2000)

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Final Report – Administrative Details

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TITLE OF PROJECT	R7835: Investigation of the implications of different reef fish life history strategies on fisheries management	
PROGRAMME MANAGER / INSTITUTION	Professor John Beddington MRAG Ltd 47 Prince's Gate London SW7 2QA	
	FROM	TO
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Final Technical Report

1 Executive Summary

This study forms part of a cluster of previous Fisheries Management Science Programme (FMSP) projects (R6465 and R7522) that have specifically looked at the overall performance of length-based and age-based methods for managing reef species with different life history strategies.

The purpose of this project was to address the constraints to management and development arising from the use of uncertain estimates of fishing mortality in stock assessments incorporating analytical fishery models such as yield per recruit. Through management strategy simulations, the project demonstrated that the use of fully age-based methods of assessment (using catch-at-age distributions and simple age-based virtual population analysis models) in the estimation of current fishing mortality led to improved management performance. Guidelines for the management of moderately short-lived fast growing, and long-lived, slow growing demersal reef fish were developed. These fisheries are important in tropical countries as sources of both employment and protein. The project purpose is therefore directly relevant to the FMSP goal of improving the livelihoods of poor people through sustainably enhanced production of land/water interface systems.

This study has examined the range of analytical stock assessment tools available to developing countries. This has helped to gauge the relative importance of each currently being used. Through literature reviews, information on the performance of each stock assessment tool has been described. This description was kept deliberately basic, since the performance of a methodology will vary with parameters such as the biology of the species examined and the historical pattern of exploitation. For each assessment method, the pattern of its use across the globe was examined. Through a multivariate statistical analysis (PCA), variables that may influence the use of age-based and length-based methods in a particular fishery were identified.

The growth (life history) of a fish or fish stock may influence the methodology used to assess a stock. Faster growing species appeared to be assessed most frequently through length-based methods, while slower growing species appeared to be assessed through age-based methods. This would appear appropriate, since the results of length-based methods are likely to be more accurate for faster growing fish, since modes in the length frequency data will be more widely spaced. However, this pattern was comparable to that found in the bias of growth parameters estimated through length-based and age-based approaches. Length-based methods tended to overestimate K and underestimate L_∞ for long-lived, slow-growing species (Pilling et al. 1999).

There was therefore uncertainty over the influence of the growth estimation method on the growth parameter estimates. Hence a further assessment was made, with the growth parameters excluded. This examined the influence of the other parameters on the use of each growth assessment method. The most important factors were GNP and latitude, which were positively correlated. The use of age-based parameters appears limited to richer nations, which are generally at higher latitudes, and important industrial fisheries, which are also generally found in higher latitudes.

Management strategy simulation was then used as a tool to study the overall management performance of both fully length-based and age-based assessments. Studies performed during FMSP project R6465 (Pilling et al. 1999) indicated that age-based growth parameter estimates resulted in the most accurate management actions for long-lived, slow growing species. Despite this, management based on biological reference points derived using these parameter estimates still showed considerable variability. In part, this resulted from uncertainty that remained in the growth parameter estimates, despite the improvements resulting from the use of age-based growth parameter estimation methods. Variability also resulted from the use of length-based methods to assess biological parameters and reference points.

FMSP project R7522 (Pilling et al. 2000) suggested that the use of further age-based approaches could reduce this uncertainty. These approaches included the use of age-based total mortality estimation methods and avoided the need to use uncertain growth parameter in the process. The results indicated that age-based methods of total mortality using age-frequencies improved the ability of fisheries managers to accurately manage a fish stock. If available, age-frequencies can be estimated using an otolith weight-age relationship. However, in the current FMSP project (R7835) a more pragmatic approach has been taken by using of an age-length-key. In addition to these changes, this study has been extended to investigate the suitability of length-based and age-based methods of assessment for reef species with different life histories. It was originally intended to investigate a range of species with different life history strategies. However, a crucial limiting factor determining the selection of species was the need to have back-calculated lengths at age providing the historical growth information for individual fish. This allowed the calculation of a covariance matrix for individual growth parameters. Due to several factors including time contraints, this was eventually limited to two species only; *Lethrinus mahsena* and *Siganus sutor*. In the absence of good information, it was felt inappropriate to simulate individual growth parameters for additional species.

The results of the management strategy simulation, which used more realistic estimated catch-at-age data rather than actual age-frequencies, have demonstrated that fully age-based methods of assessment consistently out-perform length-based methods for both moderately short-lived, fast growing and long-lived, slow growing reef species.

Length-based methods have been shown to be consistently less accurate, which could either lead to very precautionary management with high levels of under-exploitation, or high levels of over-exploitation of the stock. In contrast, with exception to very heavily exploited fisheries, age-based methods are considered more likely to manage the stock around optimal levels, leading to long-term sustainability of the resource. Two important features of the results that underpin the success of age-based methods were:

(i) Provide accurate estimates of the target level ($F_{0.1}$), and
(ii) Estimate accurately, annual levels of fishing mortality (F_{curr}).

In addition, it was found that the management performance of both length-based and age-based methods was greatly impaired by the impact of gear selectivity on the length-frequency or length-at-age samples. High F_{start} levels reduced the number of older individuals within the population, thus making it more difficult to estimate the growth parameters (e.g. no large fish to accurately estimate L_∞). Since growth parameters are used to estimate the target fishing level ($F_{0.1}$), it was not unexpected to see a decline in management performance with increasing F_{start} levels. For *L. mahsena* in particular, it was found that the initial value for the length-at-capture, coupled with a high F_{start} level ($F_{start} > F_{0.1}$), produced a narrow band of size ranges that were inappropriate to fit a growth model.

Within a heavily exploited fishery, it would be difficult for a fisheries manager to obtain large specimens. However, a dedicated sampling programme could be introduced by the manager to get sufficiently small fish to estimate growth parameters reliably. To mimic this management behaviour in the model, the length-at-capture (Lc_{50}) was reduced from 30.5 cm to 22.1 cm. The reduction in the length-at-capture was therefore undertaken for technical reasons we do not recommend that this approach is used to manage the fishery which might otherwise target juvenile fish.

By improving the growth parameter estimates, this action would also have reduced the bias in Ralston's or Pauly's estimates of natural mortality (M), further improving the assessment. At high F_{start} levels, this could impair the ability to estimate both the growth parameters and natural mortality.

A number of guidelines for the management of both moderately short-lived, fast growing and long-lived, slow growing reef species were developed. The guidelines developed will be of relevance to fisheries management institutions in developing countries where local artisanal and industrial fisheries target species of different life histories. The scientific community will also benefit from the information.

Implementation of the management guidelines arising from this project is required in order to achieve DFID goals. In order to reach both a national (in collaborating countries) and international audience of target organisations, a number of means for promoting project outputs were pursued, and will continue to be pursued beyond the life of the project. A number of scientific papers are to be produced after the completion of the project, and recommendations from the cluster of DFID projects are to be included in a new FAO fisheries technical report on the use of FMSP stock assessment tools. The results will also be disseminated through the World Wide Web (FMSP web site).

2 Background

Small-scale artisanal fisheries are important to the livelihoods of many millions of people in the developing world. These fisheries are highly diverse, and target species with a wide range of life history strategies. For example, floodplain river fisheries in Bangladesh support the livelihoods of at least 1.5 million people and contribute around 10% of annual export earnings and up to 60% of animal protein supplies. These fisheries are dominated by *r*-selected species with high rates of reproduction and growth; for example *Hilsa sp.* (shads) represents around 30% of Bangladesh total fish production (Hossain *et al*, 1987). In Indonesia, fast growing species (e.g. sardines) are important for artisanal fisheries in the region. Reef fish important to the livelihoods of artisanal fishermen in East Africa (e.g. Tanzania, Mozambique), such as rabbitfish (*Siganus sutor*), mullet (Mullidae) and Kungu (*Lutjanus bohar*) represent more 'moderate' growing species. Such species support the livelihoods of over 50,000 families in Mozambique, while catches supply over 20% of the animal protein consumed in the country. Finally, snappers and emperors (e.g. *Lethrinus mahsena*) represent slow growing species of considerable importance to the livelihoods of both artisanal fishermen and the general population of tropical islands in the western Indian Ocean, Caribbean and Pacific. In Barbados, for example, the fishing industry represents a major social and economic asset, employing 6,000 people either directly or indirectly, offering employment to young women and men in the post-harvest sector, and contributes 20% of animal protein supplies.

Biological sustainability of the natural resource base is a fundamental requirement for any fisheries management strategy, and must be assured to guarantee the livelihoods of the millions of people relying on them. A number of management tools exist to allow this. In developing countries, length-based methods of assessment are commonly employed to estimate growth parameters for use in further methods to assess resource status, and identify potential management or development interventions (e.g. *Hilsa*: van der Knapp *et al*, 1987; *Sardinella*: Pet *et al*, 1997).

A number of studies have examined the accuracy and precision of such length-based growth estimation methods through simulation (e.g. Hampton and Majkowski, 1987; Rosenberg and Beddington, 1987; Basson *et al*, 1988; Isaac, 1990). These studies found that a number of individual factors (including growth rate, growth variability, and recruitment variability) interact to bias the outputs of length-based estimation methods (L_∞ and K). These studies generally concentrated on faster growing species, to which length-based methods are thought more applicable. Despite this, Hampton and Majkowski (1987) found that ELEFAN (Pauly 1987), a commonly used growth estimation method, still overestimated L_∞ by 11-23% and underestimated K by 16-36%. Such studies examined the effects of inaccuracies in growth parameter estimates in isolation. In practice, uncertainty in growth estimates is subsequently compounded by their use in further methods to derive stock assessments, upon which management is based. The impact of this uncertainty has not been examined for such fast growing species.

When assessing the impact of uncertainty in stock assessments on the management of such artisanal fisheries, the diversity of life history strategies exhibited by target species cannot be ignored. Different assessment tools may be appropriate for fish with different life history strategies; while length-based growth assessment methods are felt most applicable for relatively fast growing species, they are expected to perform less well for long-lived, slow growing species, whose biological characteristics result in the superimposition of successive modal classes, reducing the information with which length-based methods derive growth estimates.

FMSP project R6465 investigated the constraints to fisheries development resulting through the use of such length-based methods for long-lived, slow growing snapper and emperor species. Such species are of considerable importance to the livelihoods of artisanal fishermen in the tropics. Simulations undertaken during the project indicated that length-based methods were indeed inappropriate for the assessment of growth in species with such a life history strategy. This project also examined the ‘knock-on’ effect of using such biased growth parameter estimates in stock assessments to derive management, through management strategy simulations. Decisions resulting from the use of these length-based growth parameters led to very poor management performance, indicating significant potential impacts on the livelihoods of artisanal fishermen relying on such fisheries.

Project R6465 indicated that alternative age-based methods of growth assessment were feasible for two of the three tropical species examined. This contributed to the expanding number of tropical species for which validation has been successful. Such species include *Hilsa*, for which validation was achieved by Quddus et al (1994), as well as other fast growing species important to artisanal fisheries of Bangladesh (e.g. Rohu, *Labeo rohita* (Khan and Jhingran, 1975); Catla, *Catla catla* (Jhingran, 1968)), indicating that age-based assessments are feasible for such species.

Simulations performed during project R6465 indicated that the use of age-based growth estimates resulted in improved management. Such methods are rarely employed in developing countries due to the perception that the methods are expensive, and that rings relating to a regular time scale are not deposited in the hard parts of tropical fish species. However, simulations and cost-benefit analyses performed during FMSP project R6465 showed that age-based methods were the most appropriate and cost-effective for growth assessment in the long-lived, slow growing species studied. However, the use of length-based methods in subsequent stages in the management process tended to dilute the advantages gained by using age-based growth parameters. A project extension, FMSP project R7522 (Pilling et al. 2000), included the use of age-based total mortality estimation methods and avoided the need to use uncertain growth parameter estimates in the estimation process. The results indicated that age-based methods of total mortality estimation improved the ability of fisheries managers to accurately manage a fish stock.

If available, age-frequencies could be estimated using an otolith weight-age relationship, otherwise a pragmatic approach of generating an age-length-key associated with catch-at-age data can be used.. The latter can be used directly within more complex stock assessment models such as Virtual Population Analysis (VPA). This method can also be applied using length data. However, the use of length data requires growth parameters to convert length into age. It thereby relies on the accuracy of these estimates, which have been shown to be uncertain. This is one of the reasons why age-based VPA is receiving considerable interest in a number of developing countries that have the ability to age important species e.g. Namibia and Seychelles (in the latter country, this ability was generated through the work performed in FMSP project R6465).

Studies have not examined the impact that different fish life history strategies can have on the accuracy of outputs from length-based methods of growth assessment. Are these methods more appropriate for faster-growing, rather than slower-growing species, and are they therefore suitable for application in artisanal fisheries targeting such species? Is there a continuum of life history strategies, along which the use of age-based growth assessment methods becomes advisable? No studies have examined the implications of using growth estimates to derive stock assessments, and hence management, for species with different life history strategies. From the results of project R6465, uncertainty arising from the use of such growth parameters in stock assessments may be considerable. If this held regardless of a species' life history strategy, the impact on the livelihoods of millions of poor people could be severe.

Age-based VPA avoids the use of potentially biased growth parameter estimates, or further length-based assessment methods. However, the method does require a considerable time series of data, and therefore funding over an extended period. No studies have examined whether VPA is universally more appropriate than alternative analytical methods, or merely for species with particular life histories; can suitable management be derived using cheaper methods?

3 Project Purpose

This project aims to examine alternative stock assessment approaches to determine whether length-based or age-based methods are more appropriate. Two reef species with different life-history strategies were selected (*Siganus sutor* and *Lethrinus mahsena*) that are considered important to the livelihoods of poor people.

Simulations performed during FMSP project R6465 indicated that the use of age-based growth parameter estimates resulted in improved management for long-lived, slow growing tropical demersal species such as *L. mahsena*. However, the use of length-based methods in subsequent stages in the management process tended to dilute the advantages gained by using age-based growth parameters. A project extension, FMSP project R7522, included the use of age-based total mortality estimation methods using age-frequencies and avoided the need to use uncertain growth parameters in the process. Age-frequencies could be estimated using an otolith weight-age relationship although a more common approach is to use an age-length-key. The results indicated that age-based methods of total mortality estimation improved the ability of fisheries managers to accurately manage a fish stock.

The current study aims to build on the outputs of FMSP projects R6465 and R7522. This project has investigated the constraint to fisheries development resulting from the use of fully length-based methods of growth and stock assessment for fish species with different life history strategies. It has investigated using an age-structured assessment method (virtual population analysis; VPA): a) whether commonly used fully length-based methods result in effective management for fish species with different life histories, or whether b) fully age-based methods of assessment are more appropriate.

A series of recommendations and guidelines have been developed which are directly relevant to the goal of developing improved strategies and plans for the management of capture fisheries important to poor people.

4 Research Activities

This project was a desk-based study. A technique known as management strategy simulations was used to mimic the fisheries management process for artisanal demersal fisheries. Management strategy simulations analyse the behaviour of complex systems, such as the fisheries management process, using a simpler model of the system. This model was developed by modifying the 'YIELD' software developed during FMSP project R7041, 'Software for estimation of the potential yield of fisheries under uncertainty'. The effect on management performance of employing alternative total mortality estimation methods was investigated for an $F_{0.1}$ management strategy ($F_{0.1}$ is a biological reference point on which management targets can be based). The performance of management derived using stock assessments incorporating both fully age-based and length-based assessment methods in the estimation of current fishing mortality were compared. Management performance was assessed against conservation measures and fleet performance. Guidelines for management were developed based on the outputs of the simulation studies.

5 Outputs

The outputs from the management strategy simulations were used to develop stock assessment and management guidelines for fisheries in developing countries targeting both moderately short-lived, fast growing and long-lived, slow-growing species. A range of outputs has been provided for the cluster of FMSP projects addressing the above issue. The major issues are summarised below:

FMSP project R6465

- **Use of age-based growth parameter estimation methods for long-lived, slow growing species**

  Both fishing and density dependent growth affected the outputs of length-based biological and fishery parameter estimates, both directly (e.g. total mortality estimates), and indirectly through the effects on growth parameter estimates (e.g. natural mortality estimates derived using empirical formulae, and $F_{0.1}$ derived using those estimates).

  - Uncertainty and variability in growth parameter estimation led to poor management performance for both length-based and age-at-length based methods of assessment;

  - The use of length based components in stock assessment leads to inadequate management performance despite the use of accurate age-based growth parameter estimates.

FMSP project R7522

- **Use age-based methods of total mortality estimation when performing stock assessments for long-lived, slow growing species**

  The use of age-based methods total mortality estimates in stock assessments resulted in improved management performance, when compared to that derived using length-based total mortality estimates.[1] However, it was noted that care must be taken in using this approach where fishing mortality and/or recruitment variability is high.

- **Derive an independent estimate of natural mortality**

  Despite improvements in management performance gained by using age-based methods of growth and total mortality estimation, considerable uncertainty in management remained. A possible cause was the need to use empirical estimates of natural mortality (derived using Pauly's or Ralston's formulae) in stock assessments. Bias in the estimate of this parameter biases the values of fishing mortality and $F_{0.1}$, the two parameters used to derive management decisions. Therefore, to improve management performance further there is a need to derive independent estimates of natural mortality.

FMSP project R7835 (current project)

In addition to supporting the findings summarised above, the following recommendations are given for this project.

- **Age-based methods of assessment should be considered for moderately short-lived, fast growing reef species such as *Siganus sutor***

  Improved management performance is observed within both lightly and heavily exploited fisheries.

  Length-based methods of assessment are inaccurate and can lead to either very precautionary levels of fishing mortality and an under-exploitation of the stock, or more importantly, very high unsustainable levels of fishing mortality and an over-exploitation of the stock. In contrast, age-based methods of assessment are more accurate than length-based methods and are more likely to develop long-term sustainable fisheries around optimal values.

- **Age-based methods of assessment should be considered for long-lived, slow growing reef species such as *Lethrinus mahsena***

  Length-based methods of assessment are less accurate and can lead to either very precautionary levels of fishing mortality and an under-exploitation of the stock, or more importantly, very high unsustainable levels of fishing mortality and an over-exploitation of

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[1] Cost-benefit analyses performed during Project R7521 indicated that age-based total mortality estimation methods should only be used where an age-otolith weight relationship has been estimated. Where a relationship cannot be derived, length-based methods of total mortality are the most cost-effective. See the Final Technical Report from that project for more information.

the stock. In contrast, age-based methods of assessment are more accurate than length-based methods and are more likely to develop long-term sustainable fisheries around optimal values.

Caution should be given, however, to their application in heavily exploited fisheries. Under these circumstances, it is important to obtain good length-at-age samples to estimate growth parameters (L_∞, K t_0), and natural mortality (M).

- **Research should be targeted in developing countries to assess whether age-based techniques can be employed and are financially viable**

  Research should be targeted in developing countries within the tropics where the use of length-based methods are predominantly being used. A pre-requisite to applying age-based methods is to ensure that age can be determined and validated in the target species, such as those in R6465. If feasible, then the application of a range of different age-based assessment techniques must also be considered to ensure the most appropriate method is employed. In addition, a cost-benefit analysis similar to FMSP project R7521 would determine whether fully age-based assessment methods are financially viable.

6 Contribution of Outputs

6.1 Towards DFID's developmental goals

The work performed during the current project is directly relevant to the DFID developmental goal of elimination of poverty in poorer countries, based on improved livelihoods for poor people and sustainably enhanced production and productivity of renewable natural resource systems, through the application of new knowledge to renewable natural resource systems.

The project directly related to the aim of improved strategies and plans developed for the management of capture fisheries important to poor people. The project directly addressed the FMSP output OVI 1.1 'development of new and improved biomathematical and bioeconomic methods and models for stock assessment and fisheries livelihoods management, and appropriate data management systems'. Benefits will be delivered to the target poor by application of the knowledge generated from this project to develop improved fisheries management guidelines.

The target beneficiaries of this project were national and regional fisheries departments, and both small scale and semi-industrial fishing communities. Small-scale fisheries based on demersal (e.g. snapper and emperors) and semi-pelagic (e.g. rabbitfish) stocks represent an important source of nutrition and income for fishers and dependant communities throughout tropical areas including Africa, the Caribbean, Indian Ocean, and Pacific. The potential for rapidly overfishing species with different life-history strategies requires that these important resources be managed effectively to safeguard the livelihoods of rural communities who are dependent upon them. This project presented stock assessment and management guidelines based on analytical stock assessment models.

6.2 Promotion of outputs

The guidelines developed will be of relevance to fisheries management institutions in developing countries where local artisanal and industrial fisheries target both moderately short-lived, fast growing and long-lived, slow growing reef species. The scientific community will also benefit from the information.

Implementation of the management guidelines arising from this project is required in order to achieve DFID goals. In order to reach both a national (in collaborating countries) and international audience of target organisations, a number of means for promoting project outputs were pursued, and will continue to be pursued beyond the life of the project. A number of scientific papers are to be produced after the completion of the project, and recommendations from the cluster of DFID projects are to be included in a new FAO fisheries technical report on the use of FMSP stock assessment tools. The results will also be disseminated through the World Wide Web (FMSP web site).

On the basis of the outputs from Project R6465, the Seychelles and British Indian Ocean Territory have already moved towards age-based assessment methodologies. The results of the current project support that move, refine the methodologies used, and indicate important areas for continued research. To date, financial constraints have prevented Mauritius moving towards age-based methodologies. The results of the current study add further impetus to the move towards using otoliths in routine stock assessments, which is applicable to a wide number of species.

Through the circulation of the LFDA software package (developed in FMSP projects R4517 and R5050CB) MRAG has developed an extensive network of contacts with fisheries institutions around the world. The outputs of the current project, as well as those from Project R6465 have obvious relevance to institutions that currently employ the length-based methods available in LFDA to estimate growth parameters. Results of the studies will be circulated to these organisations as part of the dissemination process.

6.2.1 Publications

Pilling G.M. and A.S. Halls (2003). Age- or length-based methods of growth estimation. What drives the choice? NAGA, Worldfish Centre quarterly. Vol. 26 No. 2 April - June 2003. pp 4-7.

6.2.2 Internal reports

None

6.2.3 Other dissemination of results

The results will be written up to be included in a peer-reviewed journal publication.

The results from this study will also be combined with the recommendations generated from similar cluster projects (R6465 and R7522) to be included within an FAO Fisheries Technical Manual based on FMSP Stock Assessment Tools.

6.3 Follow-up action / research needed

The results have demonstrated that age-based methods of assessment are more accurate than length-based methods for both moderately short-lived, fast growing reef species and long-lived slow growing reef species.

Before uptake of this recommendation can be made, an additional number of key research areas are required. First, it is not a given that all reef species can be aged and successfully validated. For example, within FMSP project R6465, problems of ageing tropical reef fish were encountered for the snapper, *Pristipomoides filamentosus*. If however, ageing and subsequent validaton is successful, it still remains unclear exactly what age-based methods can be used and how? If ageing is feasible, then the application of a range of different age-based assessment techniques must also be considered to ensure the most appropriate method is employed. Furthermore, a cost-benefit analysis similar to FMSP project R7521 would determine whether fully age-based assessment methods are financially viable.

1 Introduction

1.1 Project aims

The current study builds on the outputs of FMSP projects R6465 and R7522. This project aims to develop improved management strategies for developing country fisheries important to the livelihoods of poor people by identifying the most appropriate analytical stock assessment technique (length-based or age-based) for fish species with different life history strategies. Specifically, it will produce:

1. A review of analytical models based on length-based and age-based methods of assessment used in developing countries, review of the characteristics of fisheries in which these methods have been employed, and the biological characteristics of those fish species targeted.

2. Guidelines for the use of length-based and age-based analytical methods of assessment for reef fish species with different life history strategies. These will be directly relevant to the goal of developing improved strategies and plans for the management of capture fisheries important to poor people.

3. New knowledge disseminated to developing country institutions and the scientific community.

1.2 Report Structure

A review of analytical models based on length-based and age-based methods of assessment is presented in Chapter 2. The biological characteristics of both a moderately fast-growing and slow growing species are described in Chapter 3. These characteristics provide the source of input parameters required for the management simulation model, described in Chapter 4. The results of the simulation exercise are then presented and discussed in Chapter 5. Finally, conclusions are drawn and recommendations are given in Chapter 6.

2 The use of analytical methods of stock assessment in fisheries

2.1 Introduction

A diverse range of stock assessment methods is available to the fisheries manager. However, the choice of method used will be limited by the information that can be collected, or the cost of processing the required data, for example. As a result, for a particular fishery the potential methods will be limited. For the methods that will be examined in this report, there are two underlying approaches; 'length-based', using length frequency data, and 'age-based', using age-at-length data.

The performance of each assessment method, i.e. the accuracy of advice that arises based on the results of the method, is likely to vary due to a range of factors. These include the life history strategy of the species studied, the fishery status, or the gears used. Indeed, in developing countries, stock assessment information for fish species is commonly derived using estimates from length-based methods. These include ELEFAN, which derives growth parameter estimates from length frequency data. The use of such methods frequently results from the perceived difficulty in ageing tropical fish, the practical problems of funding validation studies, and subsequent time and expense in age assessments. However, FMSP Project R6465 has indicated that there is considerable uncertainty over the suitability of length-based methods for assessing growth and mortality in long-lived, slow-growing species, leading to poor management performance, and potentially inefficient and unsustainable resource use (Pilling et al., 1999). For fish species with these life history characteristics, the use of outputs from age-based methods of growth assessment (length-at-age data derived using otoliths) was found to result in improved management performance. Cost-benefit analyses indicated that these methods were the most cost-effective, despite the additional costs involved in their use (Pilling et al., 2000). As a result of the outputs of Project R6465, two of the partner institutions of that project have moved towards the use of age-based techniques for the assessment of snappers and emperors in the Indian Ocean. In addition, the Seychelles Fishing Authority has expressed their desire to apply age-based methods to a range of species of importance to local fisheries. The ultimate goal of these assessments is to perform age-based VPA analyses, considered to be the 'state of the art' for stock assessments (Hilborn and Walters, 1992).

Whilst FMSP Project R6465 demonstrated that length-based methods were less suitable for long-lived, slow growing species than age-based methods, the question arises as to whether length-based estimation methods are appropriate for species with different fish life history strategies; does their use result in suitable management decisions? Do alternative age-based assessment methods result in improved management for all species, or merely those with particular life history strategies?

To achieve the aims of this review, an extensive literature search was performed. Information on the characteristics of the assessment methods, species managed and fishery characteristics were collated. Section 2.2 presents the methodology used to perform the literature review. Section 2.3 presents a review of the analytical models currently used in developing (and developed) countries. This review examines a range of methods from the more simple approaches employed (i.e. calculation of exploitation rate) to more complex methods such as Virtual Population Analysis. The review includes an assessment of where these methods have been employed, and the types of fishery for which they have been used. In section 2.4, a brief review of the literature on the performance of these assessment methods is presented. The performance of management has obvious implications for those fishers who rely on the resource for their livelihoods. In section 2.5, the inter-relationships between the locations in which these methods have been used, the characteristics of the countries and fisheries in which they have been employed, and the biological characteristics of the fish species managed is examined through a multivariate statistical technique known as Principal Component Analysis (PCA). Finally, section 2.6 aims to collate the findings of the review and discuss the implications of these findings.

2.2 Methods

2.2.1 Introduction

This section provides details of the methods used to undertake the literature review, which developed the information on which this report is based.

2.2.2 Methodology

The literature review was performed using references held at MRAG Ltd, and through resources available via Imperial College of Science, Technology and Medicine, and the World Wide Web. References were sought which detailed the stock assessment methodology used in each location for each species. The details presented in these references were collated within a spreadsheet.

Details were obtained from scientific papers and books. However, efforts were also made to obtain references from the grey literature: scientific reports from regional bodies such as ICES, NAFO, NOAA etc. These were found via the World Wide Web. Efforts were also taken to obtain references from regions around the world, to ensure that there was no bias towards the developed nations, which tended to produce the most reports (and post them on the World Wide Web).

2.2.3 Results

References were found detailing the stock assessment and growth assessment methods used to manage 611 distinct stocks around the globe. For each of these stocks, a range of information was collected.

	Information type	Description
1.	Scientific name	Genus and species name of the target species.
2.	Common name	The local name given to the species.
3.	Location	Country (or region, e.g. north Atlantic) in which the stock was assessed.
4.	Latitude and longitude	Location of the assessed stock, calculated to the nearest half a degree.
5.	Location GNP	The GNP ($billions in 1998) for each location was obtained from the World Bank Development Indicators, 2000. Where a region (e.g. Baltic Sea) was noted as the location, an average of the GNPs of all countries neighbouring that region was calculated. Dependent territories were given the GNP of their 'parent' country.
6.	FAO fishery status	The status of exploitation was gathered for each stock from the latest FAO Status of Fisheries report (FAO, 2000). The categories were: U Under-exploited, undeveloped or new fishery. Believed to have a significant potential for expansion in total production; M Moderately exploited, exploited with a low level of fishing effort. Believed to have some limited potential for expansion in total production; F Fully exploited. The fishery is operating at or close to an optimal yield level, with no expected room for further expansion; O Over-exploited. The fishery is being exploited at above a level which is believed to be sustainable in the long term, with no potential room for further expansion and a higher risk of stock depletion/collapse; D Depleted. Catches are well below historical levels, irrespective of the amount of fishing effort exerted; R Recovering. Catches are again increasing after a collapse from a previous high.
7.	Fishing gear	The fishing gear or combination of gears used to exploit each stock was noted (e.g., trawler, purse seiner, hook and line etc).
8.	L_∞	The value of L_∞ corresponding to the stock assessed was obtained either from the reference for that stock, or from ICLARM's Fishbase (Froese and Pauly, 2000). Where details for the exact stock were not available, details for a local stock were used. If details for a local stock did not exist, no information was entered. The length measure (fork length, total length etc) was also noted.
9.	K	The value of K corresponding to the stock assessed was obtained either from the reference for the stock, or from ICLARM's Fishbase (Froese and Pauly, 2000). Where details for the exact stock were not available, details for a local stock were used. If details for such a stock did not exist, no information was entered.
10.	Growth estimation method	The method used to estimate growth, be it length- (e.g. ELEFAN) or age-based (e.g. through otoliths or scales) was noted.
11.	Growth location and reference	The location corresponding to the estimate of growth was noted, along with the reference from which the growth parameter estimate was obtained.
12.	Trophic level	The trophic level inhabited by the relevant species was obtained from Fishbase (Froese and Pauly, 2000).
13.	Stock assessment method	The methods used to assess each stock were noted during the literature review. These were divided into three methods of increasing complexity: • Exploitation rate (E=F/Z) • Yield-per-recruit • VPA/cohort analysis These are described further in section 2.3.
14.	Stock assessment method reference	The reference detailing the stock assessment method used for each stock was noted. This data set was used as the basis for the analyses presented in the following sections.

2.3 Review of assessment tools

A range of analytical methods has been developed to help manage fish stocks around the world. This section aims to review three basic assessment tools to determine where they have been applied and what data source had been used (age-based or length-based).

First, a relatively simple assessment method is considered that calculates the exploitation rate based on estimates of fishing mortality (F) and total mortality (Z). More complex analytical tools are then considered such as yield per recruit analysis. This is not an assessment method, but rather uses input variables to calculate fisheries management reference points such as the maximum yield per recruit and F_{MYPR}.

Finally, there is range of assessment methods that can be used to estimate the total abundance of fish within a population in order to assess the stock status. These may be divided into methods that take length frequency data and a growth curve, and use cohort slicing to generate catch-at-age matrices, and those that fit directly to length-frequency data via a model of size at age. These data types can be used within compex analytical models such as Multifan CL (Fournier, Hampton and Sibert, 1998) and virtual population/cohort analysis. In addition, there are a number of potentially more advanced extensions to these methods, which include Bayesian components (e.g. McAllister and Kirkwood, 1998). For simplicity, only virtual population analysis (VPA) is considered in this review.

2.3.1 Exploitation rate

The exploitation rate is the fraction of an age class that is caught during the life span of a population exposed to fishing pressure. In terms of mortality rates, the exploitation rate (E) is defined as: $E = F / (F + M)$; where M is the natural mortality rate and F the rate of fishing mortality.

Total mortality can be estimated through methods such as catch curves (Ricker, 1975) using length or age frequencies, or other length-based methods such as Beverton and Holt's total mortality estimator (Beverton and Holt, 1956). Fishing mortality is generally estimated by subtracting an estimate of natural mortality from that of total mortality (above). Natural mortality can be estimated using empirical formulae, such as that developed by Pauly (Pauly, 1980) or Ralston (Ralston, 1987). Such formulae require growth parameter estimates as inputs, which can be derived through length- or age-based methods.

Gulland (1971) suggested that in an optimally exploited stock, fishing mortality should be about equal to natural mortality, resulting in a fixed $E_{opt} = 0.5$. This value is still used widely but has been shown to overestimate potential yields in many stocks by a factor of 3-4 (Beddington and Cooke, 1983).

The method has been used in a wide range of fisheries, frequently in developing countries where the facilities for more advanced methods have not been available, or where the value of the fishery has not warranted further analysis. As a result, exploitation rate tends to be calculated for fisheries prosecuted by more basic gears, such as traps and handlines. However, it has also been used to assess trawl fisheries (e.g. that for *Pseudotolithus senegalensis* in Sierra Leone (Payne and Coutin, 1988).

Exploitation rate has been estimated for fisheries as diverse as those for Hilsa (*Tenualosa ilisha*) in Bangladesh (Rahman et al., 2001), moontail bull's eye (*Priacanthus hamrur*) and thornycheek grouper (*Epinephelus diacanthus*) in India (Chakraborty and Vidyasagar, 1996), narrowbarred Spanish Mackerel (*Scomberomorus commerson*) in Oman (Al-Hosni, 1999) and axillary seabream (*Pagellus acarne*) in the Canaries (Pajuelo and Lorenzo, 2000). Indeed, 43% of the references examined in the literature review described stocks that had been assessed through the calculation of exploitation rate. Figure 2.1 shows the distribution of stocks identified during the literature review which have been assessed by calculating the exploitation rate, based on either length- or age-based growth parameter estimates.

All stocks identified as being assessed through the estimation of exploitation rate are in the tropics. The majority (90%) of cases where the exploitation rate has been calculated used length-based growth parameter estimates. This supports the opinion that such relatively straightforward assessment approaches are likely to be used where data on the species to be studied is lacking. It is also likely to be related to the fact that computer packages such as FiSAT (Gayanillo et al., 1994) and LFDA (Holden et al., 1995), which can estimate growth parameters through length-based methods, also contain options to estimate exploitation rate. Hence this represents a logical next-step in the assessment following the length-based estimation of growth parameters.

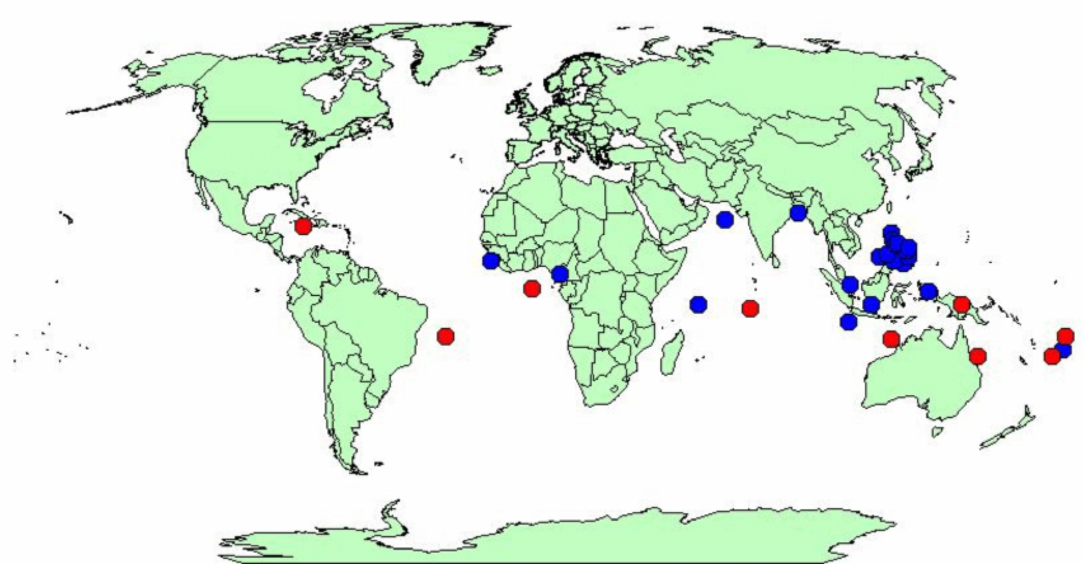


Figure 2.1 Distribution of fish stocks whose status has been assessed by calculating the exploitation rate (E=F/Z). Calculations involving length-based growth parameter estimates are shown by the blue circles. Those involving age-based growth parameter estimates are shown by the red circles.

2.3.2 Yield per recruit

Yield-per-recruit models were first developed by Beverton and Holt (Beverton and Holt, 1957) and have been used extensively in temperate fisheries, and their use in tropical fisheries has expanded. The yield-per-recruit model assumes a steady-state, and models growth and mortality to predict yield. However, such models do not account for reproduction, assuming recruitment is constant (but not specified).

The assumption is that the production of an entire fish stock can be modelled by the simple summation of the production of each cohort over its life span (from recruitment onwards):

$$Y = \int_t FNWdt$$

where Y is yield (weight), F is fishing mortality, and N and W are the number and weight of individuals alive at time t. Yield of the population/cohort is expressed as a function of the number of individuals at some earlier age, F, M, asymptotic weight, von Bertalanffy growth parameters and age at first capture. As a result, the models require reliable estimates of the growth parameters and natural mortality rate by species.

The yield per recruit model makes a number of assumptions:

- recruitment is constant, regardless of the age of entry into the fishery or level of fishing mortality. Generally, this will only occur if larvae come from another, unexploited area. Otherwise, a young age of entry into the fishery and a high fishing mortality will cause a decline in recruitment;

- all fish of a cohort are hatched on the same date;

- there is a complete mixing within the stock;

The model is generally more applicable to species with low natural mortality rates. For species with higher natural mortality rates, the yield per recruit curve may not reach a maximum within a reasonable range of fishing mortalities.

Yield per recruit models are commonly used to estimate optimum and target levels of fishing mortality and size of entry. For example, the maximum yield per recruit (M_{YPR}) has been a common reference point. However, yield per recruit does not take into account the impacts of fishing on the reproductive potential of the population. It is therefore likely that F_{MSY} is lower than F_{MYPR}. The value of $F_{0.1}$ (the mortality rate at which the gradient of the yield-per-recruit curve is 10% of the gradient at the origin) has gained favour as a more precautionary reference level (Gulland and Boerema, 1973), and has been used in many fisheries of the Northwest Atlantic (e.g. Rivard and Maguire, 1993). Where stock and recruitment data are available, yield-per-recruit can also be used to estimate reference levels relating to spawning stock biomass (e.g. minimum acceptable values of SSB/SSB_0). Yield per recruit has also been used to examine the likely impact of gear restrictions on exploited stocks (Demestre et al., 1997).

Multispecies yield per recruit models have been developed and used by Huntsman et al. (1983). They calculated a series of YPR models for important species in SE US reef fisheries, and identified a suitable age-at-capture applicable across species.

As yield per recruit allows fisheries managers to derive a range of biological reference points, as well as examine the effects of gear selectivity to define appropriate management based on gear restrictions, the method has become widespread. It has been used to assess fisheries in developed and developing countries throughout the globe (Figure 2.2). 40% of the managed stocks identified in the literature review had been assessed based on yield per recruit. These have ranged from migratory species such as lizardfish (*Saurida undosquamis*) in the south Taiwan Strait (Lee, 1997), crimson snapper (*Lutjanus erythropterus*) on the Great Barrier Reef (McPherson and Squire, 1990), to the black drum (*Pogonias cromis*) along the east coast of the United States (Jones and Wells, 2001).

The pattern between those stocks assessed using yield per recruit based on length- or age-based growth parameters is less distinct compared to that for the exploitation rate (Figure 2.1). However, there was a tendency for yield per recruit to be derived using age-based growth parameters (64% of the stocks studied) rather than length-based. There was some tendency for the use of age-based growth parameters in the assessment to be more common in temperate (higher latitudes) rather than tropical waters. However, age-based growth parameters were used in yield per recruit assessments in the SE USA 'Atlantic bight' and Hawaii, for example. It seems likely that the greater budget of the US fisheries department allows such approaches to be taken. Funding for age-based studies also explains the derivation and use of age-based growth parameters in Pacific islands such as New Caledonia (funded by ORSTOM, the French development group), in Seychelles (FMSP Project R6465), and the Caribbean (funded by ICLARM).

YPR has been used to assess fisheries exploited by a very wide range of gears. These include more basic approaches such as traps and handlines, through to trawlers and purse seiners (mainly fishing for small pelagic species).

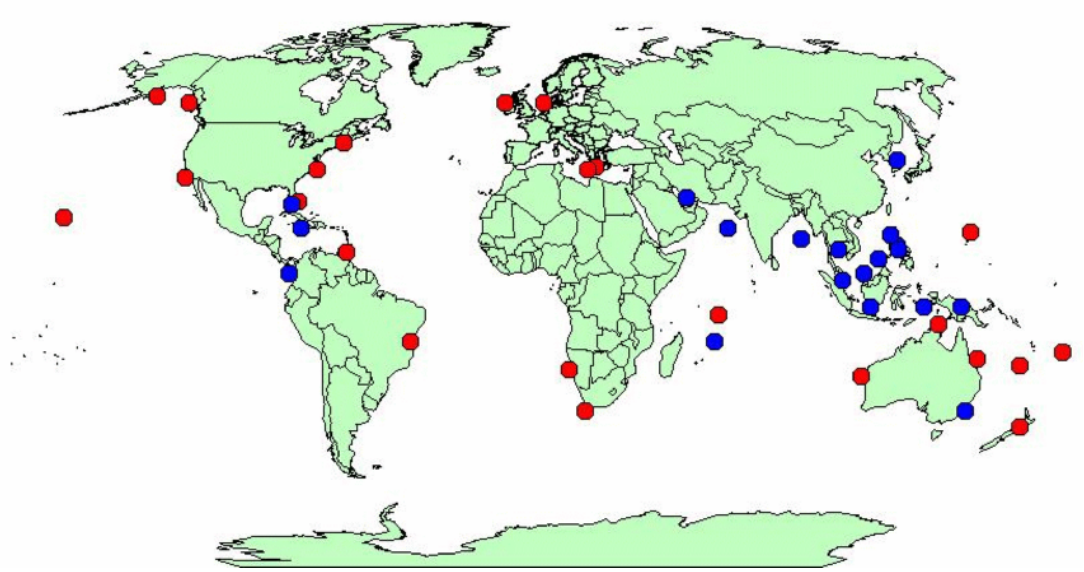


Figure 2.2 Distribution of fish stocks whose status has been assessed through YPR. Calculations involving length-based growth parameter estimates are shown by the blue circles. Those involving age-based growth parameter estimates are shown by the red circles.

2.3.3 Virtual population/cohort analysis

VPA/cohort analysis was first developed as purely an age-based method. The approaches have been applied widely to industrial fisheries in temperate waters, where the required historical data of catches-at-age exist. More recently, length-based methods have been developed which have enabled the approaches to be used in relatively data-poor tropical fisheries (e.g. Mees, 1992).

VPA calculates past stock abundances based on past catches. Fishing size-selectivity and changes in vulnerability over time can then be determined. The number of fish alive in each cohort for each past year is calculated, estimating the numbers that would need to be present to allow the catches actually achieved. Catch length or age data are required, along with estimate of growth and natural mortality, and the level of fishing mortality on the oldest age group.

The two basic formulae for single-species cohort analyses with knife-edge selectivity are:

$$C_{ay} = N_{ay} F_{ay} \frac{(1 - \exp(-(F_{ay} + M))}{F_{ay} + M}$$

$$N_{a+1,y+1} = N_{ay} \exp(-(F_{ay} + M))$$

For *n* age groups, there are therefore *n*+2 unknown parameters (*n* values of F_y, M and N_y). M and F are generally estimated independently for the oldest age group. The outputs of the model are age-specific estimates of population size, recruitment, and fishing mortality.

Pope's approximation (Pope, 1972) simplifies the methodology, based on the assumption that all catch is taken on a single day in mid-year (1st July), rather than continuously throughout the year. The basic equation is:

$$N_{ay} = C_{ay} \exp\left(\frac{M}{2}\right) + N_{a+1,y+1} \exp M$$

This approximation works well provided M<0.3 and F<1.2.

Based on Pope's method, a length-based cohort analysis was developed (Jones, 1974). This method assumes von Bertalanffy growth, and requires catch numbers within pre-defined length classes, estimates of M/K, L_∞ and terminal F/Z. The number of individuals attaining each length interval, survival rate and fishing mortality within each length interval are estimated, and where estimates of natural mortality are available, average population numbers. Steady-state conditions are assumed which makes the method unsuitable for short-lived species that experience large fluctuations in stock size and recruitment over short time scales (Pauly and Tsukayama, 1983).

The tuning of VPAs (using CPUE data or other abundance indices from commercial fisheries or research cruises) is a central problem in the use of these methods. As a result, further developments to the basic VPA/cohort analysis approach have been made to improve the methodology. These developments have included the use of *ad hoc* tuning methods (e.g. Laurec and Shepherd, 1983), through to integrated statistical methods such as ADAPT (Gavaris, 1988). A further development is XSA (eXtended Survivor Analysis) (Shepherd, 1999), which is now used to assess the majority of stocks in the ICES areas (Kell et al., 1999). The performance of these methods is discussed further in section 2.4.

VPA and cohort analyses have been used around the globe (Figure 2.3). However, the use of such methods has been reported with much lower frequency than the other two methods examined: 17% of stocks identified in the literature review had been assessed using VPA or cohort analysis approaches.

Length-based cohort analyses have tended to be used in tropical countries, including India (Chakraborty, 1996) and Mexico (Santamaria and Chavez, 1999). Length-based approaches accounted for 24% of the stocks where VPA had been used. The overwhelming majority of VPAs (76%) were age-based. Historically, the use of age-based VPAs have been concentrated in temperate waters such as the North Sea and Northwest Atlantic (e.g. Livingston and Jurado-Molina, 2000; Vinther, 2001), in fisheries exploited by industrial gears such as trawls and purse seines. However, richer nations have been able to apply such approaches to valuable tropical stocks (e.g. Manooch et al., 1998). Indeed, the proliferation of techniques for ageing (particularly for faster growing species) has allowed the use of age-based VPA for important stocks such as the sardine *Sardinella brasiliensis* in Brazil (Cergole, 1995). It seems likely that the expansion of age-based VPA in tropical countries will continue within the practical and financial constraints inherent in these locations. This expansion may be enhanced by the use of age-otolith weight relationships (e.g. Araya et al., 2001), which offer a relatively cheap method for ageing large numbers of individuals.

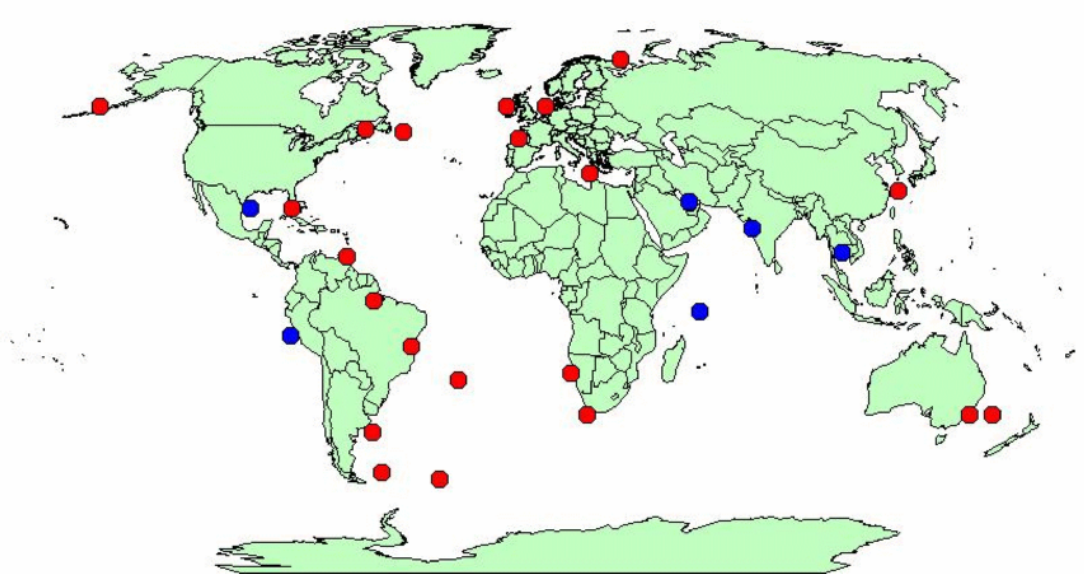


Figure 2.3 Distribution of fish stocks whose status has been assessed though VPA. Calculations using length-based approaches (e.g. length-cohort analysis) are shown by the blue circles. Those involving age-based approaches (e.g. VPA, Pope's cohort analysis) are shown by the red circles.

2.4 Performance of assessment methods

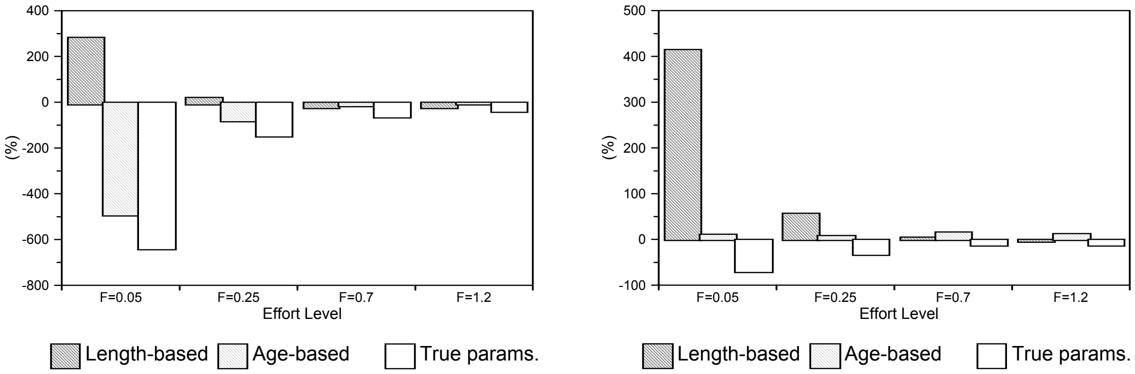
This section aims to provide a review of what is known on the performance of each of the assessment methods detailed in section 2.3. From the results of studies performed during FMSP Projects R6465 and R7522, it is very difficult to draw generic conclusions on the performance of each assessment method. Performance will depend on the growth rate of the species concerned, the level of individual variability in growth, and other factors such as the level of historical exploitation (i.e. whether the stock is under- or over-exploited). In light of this, the current section will provide a relatively superficial review of the performance of each method

2.4.1 Exploitation rate

To estimate the exploitation rate, estimates of total and natural mortality are required. FMSP Projects R6465 and R7522 examined the performance of alternative methods of total and natural mortality estimation, based on length- and age-based growth parameter estimates for the tropical emperor *Lethrinus mahsena*. This is a relatively long-lived, slow growing species. Using these mortality estimates, the pattern in the level of bias of exploitation rate estimates could be calculated (Figure 2.4). This was assessed for two combinations of total and natural mortality; Beverton and Holt's Z estimator and Pauly's M (which produced the best estimate of fishing mortality where length-based growth parameter estimates were used) and the length-converted catch curve and Ralston's M (which produced the best estimate of fishing mortality where age-based growth parameter estimates were used). The accuracy of exploitation rate estimated could also be examined using the outputs of FMSP Project R7522, which examined the use of age-based catch curves to estimate total mortality (derived from a catch age frequency distribution from otolith readings). The performance of these methods was examined at a range of fishing mortality (F) levels (Figure 2.4).

BH Z and Pauly's M

LCCC and Ralston's M



Age-based catch curve

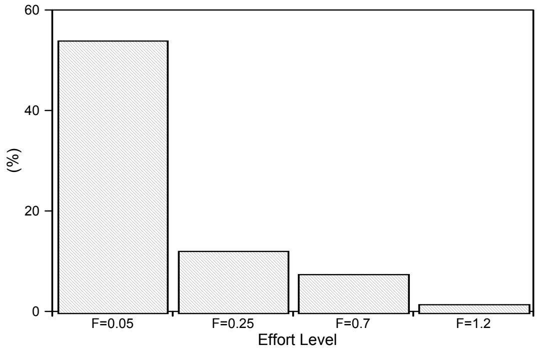


Figure 2.4 Bias in mean Exploitation rate estimates by estimation method and growth parameter source. Note no growth parameters used in age-based catch curve calculation. Bias (%) is calculated relative to the 'true' values used to simulate the population (Z = 0.4 + F).

In all cases, the estimate of exploitation rate improved with increasing fishing mortality levels. Those estimates from the age-based catch curve (and Ralston's M) were the most accurate at each fishing mortality level, although all estimation methods performed well at fishing mortality levels above F = 0.05 yr^{-1}. Where length-based methods of total mortality estimation were used, the most accurate method depended on the growth parameters used. This followed the pattern seen in the mortality estimates: Beverton and Holt's Z estimator and Pauly's M produced the best estimate of exploitation rate where length-based growth parameter estimates were used, while the length-converted catch curve and Ralston's M produced the best estimate of fishing mortality where age-based growth parameter estimates were used.

The influence of using estimates of the exploitation rate on management has not been examined. The pattern will depend on the life history of the fish. As a result, it is difficult to derive generalisations on the performance of this method. It is a fairly basic assessment that is likely to be a precursor to the assessment methods examined in the subsequent sections. The brief study described above suggests that appropriate management action would be taken, at least initially, provided the starting F is not very small, since only a small set of starting F values was examined.

2.4.2 Yield per recruit

There are two potential methods through which a yield-per-recruit curve can be derived for management purposes. The first is to examine the impacts of different length-at-capture on the stock (see section 2.3.2). The second is to use the curve to derive management reference points such as F_{MSY} and $F_{0.1}$ (Caddy and Mahon, 1995).

FMSP projects R6465 and R7521 examined the performance of management derived based on the reference point $F_{0.1}$ for *L. mahsena*. This was done through management strategy simulations, which simulated management running over a 20-year period (Pilling et al, 1999; Pilling et al. 2000). Management was assessed against performance measures including the level of final year fishing mortality, final year exploitable biomass (as a percentage of unexploited biomass), average catch, and the number of years in which the level of spawning stock biomass fell below 20% of unexploited levels.

When either length-based or age-based growth parameters, or either length-based or age-based total mortality estimation methods were used in stock assessments, management performance was poor (see Figure 2.5 displaying the variability in final year fishing mortality where age-based total mortality estimates were used - the target F-level was F = 0.4 yr^{-1}). The different performance measures showed a large degree of variability in outcomes, while the optimum level of each measure was achieved in only a low proportion of simulation runs. The best management performance was achieved by using age-based total mortality inputs, and age-based growth parameter estimates to estimate other parameter values (e.g. natural mortality, $F_{0.1}$). Considerable uncertainty remained, however. Tuning of the management reference level (here $F_{0.1}$) relative to the level of fishing effort was required to optimise management performance (so that, on average, final year fishing mortality was reached in the last year). This required that the level of fishing mortality is known accurately, something that relies on accurate estimates of total and natural mortality (currently reliant on empirical formulae).

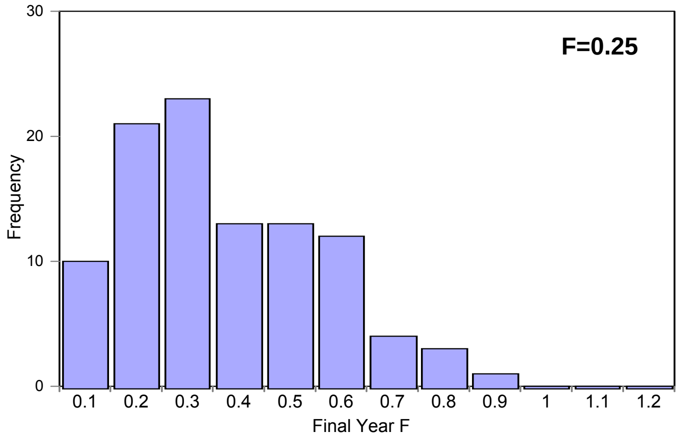


Figure 2.5 Histogram of final year fishing mortality levels where age-based total mortality estimates used in stock assessments, for a starting fishing mortality level of F = 0.25 yr^{-1}.

Some practical problems have been identified with the use of values such as $F_{0.1}$ for management purposes. Caddy and Mahon (1995) noted that accurate information on the level of catch is required to estimate current F-values under quota controls. However, the problems with accurate commercial catch reporting, particularly where there is fleet overcapacity, affects stock assessments. Under reporting means that F values are likely to be exceeded. A combination of this and the changes in $F_{0.1}$ that occur with changes in fishing pattern and input M values may explain the decline in several stocks under $F_{0.1}$ management control.

2.4.3 VPA

The assumptions underlying VPA can lead to serious bias. This section first lists the potential problems with these assumptions, and then briefly examines the performance of the various types of VPA.

- **Terminal F assumptions**

The outputs of VPA can be affected where catchability has increased while the stock has declined. In such cases, the assumption that terminal F has been constant leads to the over-estimation of stock size (Hilborn and Walters, 1992). This was shown by Sinclair et al. (1985) for several herring stocks in the Northwest Atlantic.

- **Incorrect natural mortality level**

Inaccurate estimates of natural mortality will bias all assessment procedures. However, within a VPA, if the value of natural mortality used is too large, the estimated cohort sizes are larger than they should be, and vice versa if M is too small. The impact of this inaccuracy is likely to be low where the trends, rather than the absolute numbers are examined. If M is constant, bias will depend on the relative magnitude of fishing and natural mortality. The impact will be greatest where fishing mortality is low relative to the level of natural mortality (Hilborn and Walters, 1992).

La Pointe et al. (1992) examined the effect of variable natural mortality (usually assumed to be constant) on the outputs of VPA. Variability in recruitment was found to be exaggerated under these conditions (see also Mertz and Myers, 1997). The level of exaggeration increased with increases in the value of true M, variation in M over time, relative error of the M used in the VPA, and the magnitude of M relative to the level of fishing mortality, and decreased with increases in the level of the true variation of recruitment. While the bias was generally small, its importance would be greater in short-lived species with high levels of natural mortality compared to the counteracting bias caused by ageing errors. Ehrhardt and Legault (1997) also found that uncertainty in the value of natural mortality had a large impact on the variability of allowable biological catch (ABC) for the Spanish mackerel *Scomberomorus maculatus* (K estimates for this species range from 0.2 to 0.48 yr^{-1}), with ABC showing a strong positive relationship with the value of natural mortality. The inclusion of a covariance between natural mortality and growth led to a decrease in the ABC variability relative to independent uncertainty in natural mortality and growth.

- **Aging errors**

Errors in age determination will produce systematic bias in the outputs of VPA. The effects of this on the assessment become more serious where the relative size of cohorts varies, with the strength of weaker cohorts likely to be over-estimated, and vice versa. The effect will depend on the relative strength of neighbouring cohorts and level of natural mortality (Hilborn and Walters, 1992).

- **Unit stock assumption**

VPA assumes no immigration or emigration from the stock. Immigration will lead to over-estimation of the cohort sizes, particularly if it occurs at older ages. Emigration, if related to population size, will act rather like natural mortality (Hilborn and Walters, 1992).

- **Tuning data**

Violation of the assumption that catch rate is proportional to abundance leads to extremely poor management performance (Patterson and Kirkwood, 1995). Violations may be common, due to temporal changes in gear efficiency and increasing catchability as stock size declines (Cooke and Beddington, 1984;Walters and Ludwig, 1994). Ehrhardt and Legault (1997) noted that such technology creep of increasing effectiveness of a unit of effort can mask declines in a stock assessed by tuned VPA.

The length of the catch-at-age data series available also affects the performance of management based on VPA. Punt (1997) found that management worsened as the number of years after the start of the fishery before data became available increased.

Caddy and Mahon (1995) note that systematic errors have been found in the estimation of abundance for Northwest Atlantic stocks using sequential population analysis methods (VPA and cohort analysis). Retrospective analyses, performed several years after the population estimates had been used to develop management advice, showed substantial differences between the historical and retrospective estimates of cohort size, sometimes of an order of magnitude or more. These differences have been attributed to misreporting of catch, trends in catchability, the assumption of constant natural mortality across age classes, and assumptions regarding partial recruitment to the fishery at various ages (Parma, 1993;Sinclair et al., 1990).

Punt (1997) examined the performance of management measures based on Laurec-Shepherd *ad hoc* tuned VPA, through Monte Carlo simulation. The study examined the effects of changing the initial state of the resource, time series of historical catches, productivity of the resource, observation and process error, and values of some of the biological parameters. Under an $F_{0.1}$-based management procedure, the results were reasonable. A high positive correlation between recruitment anomalies and the use of an overestimate of natural mortality, however, led to poor performance.

The analysis of Punt (1997) was based on the relatively simple *ad hoc* tuning VPA estimation approach. Alternative approaches may result in improved management performance. Patterson and Kirkwood (1995) showed that ADAPT VPA outperformed *ad hoc* tuned VPA, under the conditions they examined (which did not include uncertainty in catch-at-age data).

Shepherd (1999) noted that conventional methods for tuning VPA using abundance indices such as CPUE are very sensitive to observation error in the final year. These data are treated as though they were exact. The methods also ignore estimates of year class strength available from age groups other than the oldest in each cohort. Integrated statistical methods such as ADAPT avoid these shortcomings, but are computationally expensive. Simulation studies showed that XSA (Shepherd, 1999) performed better than older tuning methods (ICES, 1988), but is less computationally expensive than integrated methods.

2.5 Analysis of assessment methods

Section 2.3 detailed the three stock assessment approaches focused upon in this report. As noted, there are age-based and length-based approaches for each of these assessment methods. The studies described in section 2.4 indicated that these methods were used to assess stocks around the world. However, there appeared to be segregation between the approaches used (age-based or length-based) and latitude. Length-based methods appeared to be used more frequently in tropical areas, while age-based methods were more common at higher latitudes. In this section, we examine which factors describing a fishery may influence the use of age-based or length-based approaches to assessment and management in a particular area.

Biological, technical and country specific information was collected on 611 stocks through the literature review. To analyse the inter-relationship between these parameters, an ordination technique called Principal Component Analysis (PCA) was used. Ordination techniques produce a map of samples in two or three dimensions, where the distance between samples represents their similarity (estimated from the variables available). More accurately, the Euclidean distances between samples on the ordination attempt to match the corresponding dissimilarities in community structure (Clarke and Warwick, 1994), which are converted into the ordination by projection.

PCA assumes a linear response model, where the value of each variable increases or decreases with the value of the other variables. The success of a (two-dimensional) ordination is assessed as the percentage of the total variation explained by the first two principal components (Clarke and Warwick, 1994).

2.5.1 Methods

For each of the 611 stocks identified from the literature review, a range of information was collected (section 2.2). Only certain of these fields were used in the principal component analysis.

Transforming the data

The distribution of each of the variable data sets to be used in the PCA was examined for normality. Where the data set for each variable was not normally distributed, the variable was normalised by taking the natural log of x+1(Table 2.1).

Table 2.1 Requirement to normalise each variable through log transformation.

Variable	Log-transformed?
Location GNP	Yes
Latitude	Yes
Assessment method	No
Trophic level	No
L_∞	Yes
K	Yes

	Information type	Description
1.	Scientific name	The scientific name was used in the PCA as the primary identifier for the stocks. Numbered sequentially from 1 to 611.
2.	Common name	This was not used in the PCA.
3.	Location	Country or region was not used in the PCA (see latitude).
4.	Latitude	Latitude was used in the assessment, but absolute values were used. The factor examined in the PCA was therefore the distance from the equator (i.e. tropics), rather than the hemisphere in which the stock was located.
5.	Longitude	Longitude was not used in the assessment. It was noted that longitude gave little information on climate, or potential country wealth, and would add little to the PCA. For example, Indonesia is on the same longitude as Australia, Russia, and Japan.
6.	Location GNP	Location GNP ($billions) was used in the PCA.
7.	FAO fishery status	The status of exploitation categories (section 2.2) was numbered 0 to six for the analysis. After initial assessments, FAO fishery status was not included in the PCA. The definition of the status assessments was generally at a regional level, rather than for local stocks. This reduced the power of the stock status information. Also, many of the stocks for which data had been gathered did not have a corresponding FAO fishery status report, and hence could not be used in analyses where fishery status information was included.
8.	Fishing gear	Information on the fishing gear, or combination of gears used, was not included in the PCA. The type of gear used in the fishery did not appear to constrain the type of assessment method used (section 2.3).
9.	L_∞ and K	The value of L_∞ and K corresponding to the stock were included in the PCA.
10.	Growth estimation method	The method used to estimate growth was used in the PCA as the primary field used to divide the samples.
11.	Growth location and reference	The location corresponding to the estimate of growth was not used in the PCA.
12.	Trophic level	The trophic level inhabited by the relevant species was used in the PCA.
13.	Stock assessment method	The method used to assess each stock was used in the PCA. Specifically, the most advanced/complex method used for each stock was included in the PCA. For the purposes of the assessment, the analytical methods were divided into three general groups (in order of increasing complexity): 1 Exploitation rates (E=F/Z, generally based on catch curves estimated using length or age data) 2 Yield-per-recruit (estimated using age- or length-based growth parameters) 3 VPA/cohort analysis (age- or length-based)
14.	Stock assessment method reference	441 stocks out of the 661 identified during the literature review had data present in all the fields required for the PCA.

The PCA package used (Clarke and Warwick, 1994) cannot handle more than 100 samples at a time. Since the aim was to investigate the features of stocks that correlated with the use of length- or age-based approaches, 50 stocks where length-based growth parameter estimates were used in the stock assessments and 50 stocks where age-based growth parameter estimates were used. These were selected at random from the 441 stocks to form the data matrix for PCA. To examine the effect of randomly sampling the data on the ordination, the PCA was repeated with a second set of randomly sampled data.

2.5.2 Results

The process of randomly sampling from the 441 stocks identified did not affect the results of the PCA. Results are therefore presented for the first sample only.

The sample was first examined using a one-way ANOSIM. R^2 was 0.324, and the null hypothesis (that there were no differences between the characteristics of stocks examined using length- or age-based growth parameter estimates) was rejected (P<0.05%). To examine which factors were causing this difference, PCA was performed. A two-dimensional PCA ordination of the data is presented in Figure 2.6.

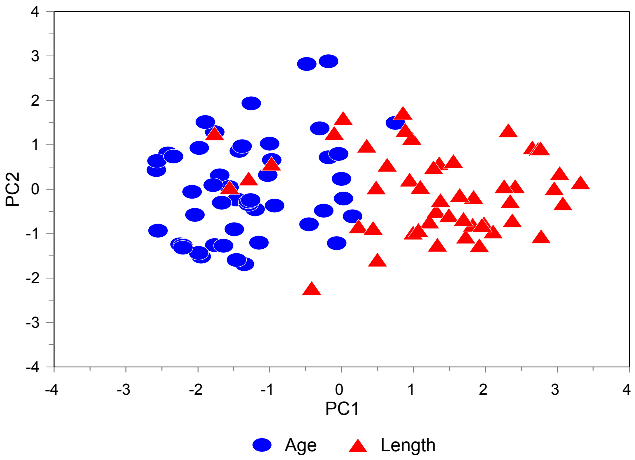


Figure 2.6 2-dimensional PCA ordination of stock characteristics where growth was assessed using length- or age-based methods.

Table 2.2 details the percentage variation in the samples explained by the principal components. The first two principal component axes explained 64% of the variation.

Table 2.2 Percentage of variation in each sample explained by the principal components.

Principal Component	% variation explained
PC1	47.1
PC2	17.0
PC3	13.2
PC4	10.6
PC5	8.7

The two variables explaining the majority of the variation in PC1 were the values of K and L_4. Those explaining variation in PC2 were trophic level and L_4 (Table 2.3).

Table 2.3 Coefficients in the linear combinations of variables making up the principal components. The first two variables explaining the variation in each principal component are in bold.

Variable	PC1	PC2
GNP	0.372	0.379
Latitude	0.413	0.359
Assessment method	0.383	0.407
Trophic level	0.275	**0.586**
L_4	**0.448**	**0.420**
K	**0.518**	0.206

The majority of the separation between stocks managed based on age- and length-based growth parameter estimates was along the PC1 axis (Figure 2.6). Therefore, the difference between the two sets of data is largely explained by the growth parameters of the stock.

From the pattern presented in Figure 2.7, length-based methods are generally used for species with faster growth rates and lower L_∞ values. In contrast, age-based methods are used on species with slower growth rates and larger L_∞ values. However, there is the possibility that this pattern may be an artefact of the growth parameter assessment method used: length-based methods tend to over-estimate K (particularly in long-lived, slow growing species with relatively high levels of individual variability in growth) while age-based methods tend to give lower estimates of K (Pilling et al., 1999).

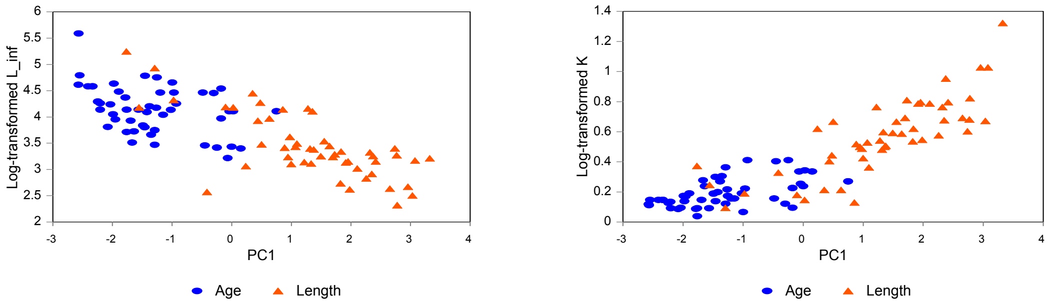


Figure 2.7 Relationship between PC1 and Log-transformed L_∞ and K.

The distribution of growth parameter estimates used in the PCA was examined. The patterns were comparable to those found for the 441 stocks (Figure 2.8). There was reasonable overlap in the distributions of L_∞, although length-based L_∞ estimates tended to be at the lower end of the range. For K estimates, however, length-based estimates tended to be larger, while age-based estimates tended to be toward the lower end of the range.

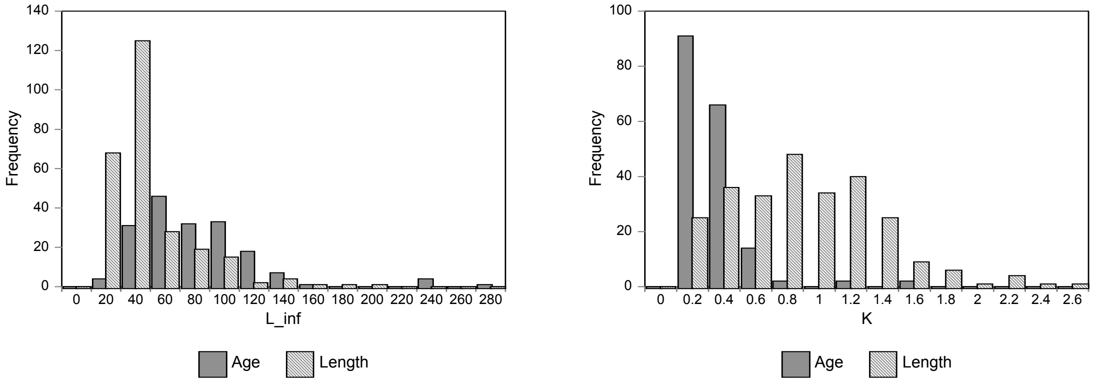


Figure 2.8 Frequency distributions of L∞ and K estimated through age- and length-based methods from the sample of 441 fish stocks.

This pattern is what one would expect to result from the outputs of FMSP project R6465 for *L. mahsena*, as described above. The question remains whether the correlation with PC1 therefore results from biases in the growth estimation method used, or the fact that length-based methods *are* generally used for faster growing species (i.e. the pattern shown in Figure 7 is correct).

To avoid the potential correlations between the growth parameter estimates used in the assessment method, the PCA was re-run with the four remaining variables only: GNP, Latitude, Assessment method, and trophic level. The resulting two-dimensional PCA ordination is presented in Figure 2.9.

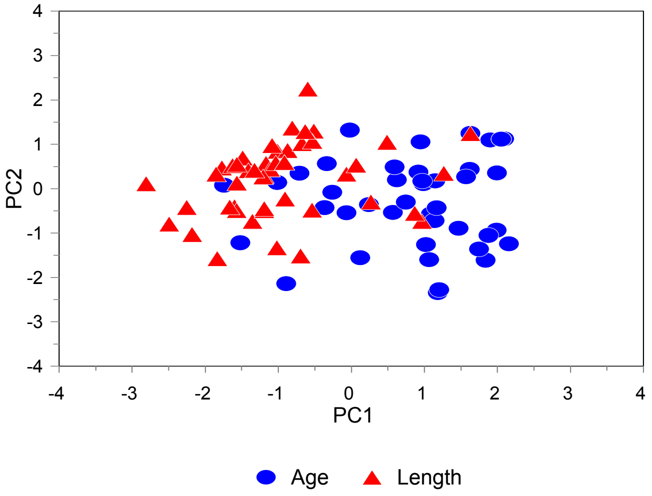


Figure 2.9 2-dimensional PCA ordination of stock characteristics where growth was assessed using length-based or age-based methods.

Table 2.4 details the percentage variation in the samples explained by the principal components. The first two principal component axes explained 69% of the variation. However, the ordination was not as clear as that found for the six variables (Figure 2.6).

Table 2.4 Percentage of variation in each sample explained by the principal components.

Principal Component	% variation explained
PC1	46.8
PC2	22.4
PC3	17.3
PC4	13.6
PC5	0.0

The two variables explaining the majority of the variation in PC1 were the values of GNP and Latitude. Those explaining variation in PC2 were trophic level and method (Table 2.5).

Table 2.5 Coefficients in the linear combinations of variables making up the principal components. The first two variables explaining the variation in each principal component are in bold.

Variable	PC1	PC2
GNP	**0.570**	0.075
Latitude	**0.567**	0.060
Assessment method	0.427	**0.682**
Trophic level	0.414	**0.725**

The majority of the separation between the stocks managed based on age-based and length-based growth parameter estimates was again along the PC1 axis (Figure 2.9). Therefore, when assessed against the four variables, the difference between the two sets of data is largely explained by GNP and latitude. Age-based methods tended to be used by countries with higher levels of GNP, which also tended to be at higher latitudes (Figure 2.10).

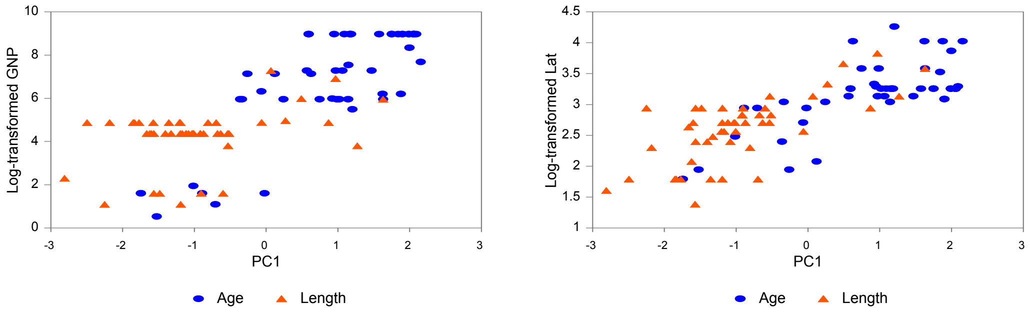


Figure 2.10 Relationship between PC1 and Log-transformed GNP and Latitude.

2.5.3 Discussion

The PCA where six variables were used indicated that the use of length-based or age-based methods of growth parameter assessment was correlated with the values of L_∞ and K. Length-based methods tended to be used to assess faster growing species (higher K and lower L_∞), while age-based methods were used on slower growing species (lower K and higher L_∞). Length-based methods may be more appropriate for faster growing species, since length frequency distributions are more likely to show modes that can be related to growth. However, it is uncertain whether this is a true pattern, or a result of the potential correlation between the growth parameter assessment method used, and the trend in the value of the growth parameters (Pilling et al., 1999). This question may be informed through the simulations performed as part of the current project. If this is a true pattern, then the recommendations of FMSP project R6465 that age-based methods of growth parameter assessment are used for long-lived, slow growing species, is already being followed.

To avoid the potential correlation between the growth parameter estimation methods and the growth parameters themselves, the PCA was performed without the growth parameter estimates in the data matrix. The resulting ordination indicated that the majority of the separation between length- and age-based methods was a result of the variables GNP and latitude. Age-based growth estimation methods tended to be used in countries with higher GNPs and higher latitudes. There was a significant degree of positive correlation between GNP and latitude (R^2 of regression = 0.21, t-test, $P<0.01$). The coefficients in the linear combinations were comparable for PC1 (Table 2.5), indicating that the two variables had nearly equal leverage on PC1.

The pattern of age-based methods being used in richer developed countries, which tend to be at higher latitudes is as expected from the patterns seen in Figures 2.1 to 2.3 in section 2.3. Latitude could be correlated with the commercial value of the stock studied. Industrial fisheries are generally in temperate or polar regions, and their importance may influence the use of more advanced methods. From the literature review, the more expensive methods (e.g. age-based VPA) also appeared restricted within the richer nation fisheries to those which are more valuable, be it financially, or in terms of employment etc. For example, within ICES more commercially valuable species are concentrated upon, with less important fisheries receiving less focus, diminished data collection and a concurrent reduction in the level of assessment that can be performed. There will also be a direct link between the GNP of countries and the potential for funding more advanced stock assessment studies.

The six variables examined in the current study are obviously not the only factors which may influence the use of particular stock assessment approaches. Other factors which could be included in such an analysis (but were outside the scope of the current, somewhat limited study) are:

- the depth of capture and water temperature, two variables which are likely to be correlated, and may influence the growth rate of species;
- the level of scientific/research funding available in each country (see discussion above);
- better estimates of exploitation rate/stock status - as found in the current study, the FAO status reports added little to the analysis, as they were too coarse in their focus. More accurate assessments, referring to each stock examined, could potentially be obtained through some of the references identified in the current study.

3 Biological characteristics of a moderately fast (*Siganus sutor*) and slow (*Lethrinus mahsena*) growing species

3.1 Introduction

The main objective of this study is to compare the performance of different assessment methodologies between species with varying life-history strategies. This chapter describes the biological characteristics of a moderately fast growing, short lived species, (*Siganus sutor*) and a slow growing, long-lived species (*Lethrinus mahsena*). Since FMSP project R6465 has already described the biological characteristics of *L mahsena* in detail, only a brief description is reported here for completeness. Finally, a summary of the biological characteristics for both species is given, which are required as input parameters for the simulation model described in Chapter 4.

3.2 A moderately fast growing species: *Siganus sutor*

3.2.1 Growth

To compare the methodology of length-based or age-based assessment techniques it was necessary to age a sample of *Siganus sutor* using otoliths. The results could then be used to describe growth using the von Bertalanffy growth equation. To ensure the banding pattern observed within the otolith corresponded to annual increments, a sample of otoliths was first validated using back-calculation of individual length-at-age data. This procedure was undertaken by CEFAS (see Pilling 2002; Appendix A). The range of total lengths and estimated ages from the 41 individuals sampled is presented in Table 3.1. Frequency distributions of length and age are presented in Fig. 3.1.

Table 3.1 Summary length and estimated age data for the *Siganus sutor* from Pilling (2002).

	Min	Max	Mean	SD
Total Length (cm)	26.4	43.7	32.3	3.8
Estimated Age (yr)	2	4	2.6	0.6

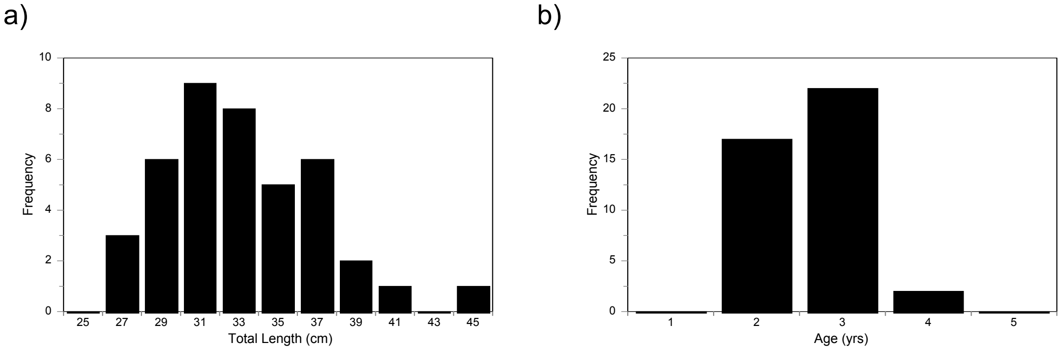


Figure 3.1 Frequency distributions of a) total length (cm) and b) estimated age (yrs) for the sample of *Siganus sutor*.

The results confirmed that there was a linear relationship between the fork length and otolith radius of *S. sutor*. The average back-calculated length-at-age from the sample is presented in Table 3.2.

Table 3.2 Average *Siganus sutor* back-calculated length-at-age from Pilling (2002).

Age (yrs)	Average length (cm)	SD	n
1	23.9	3.0	41
2	28.9	3.1	41
3	33.2	3.0	24
4	41.0	2.3	2

When related to L_{max} (43.7cm in this sample), on average 55% of *Siganus sutor* growth is achieved in the first year. The von Bertalanffy growth parameters were estimated using least squares with the mean back-calculated total lengths-at-age but had to constrain t_0 to zero. The constraint was necessary since the data were lacking small animals (cf. Fig. 3.1b). Although constraining t_0 to zero gave an improved fit to the growth model, there is no information about the variability of the parameter. This is necessary when deriving the covariance matrix (see below). To overcome this issue, back-calculated length-at-ages were run using Winbugs and the methods described by Pilling et al (2002). Uniformative priors were used for all growth parameters. It was assumed that L_∞ and t_0 have normal distributions whereas K has a log-normal distribution. The results are shown in Fig. 3.2. Estimates of the von Bertalanffy growth parameters for *Siganus sutor* from Fishbase: www.fishbase.org (Froese and Pauly 2000) and other sources are presented in Table 3.3.

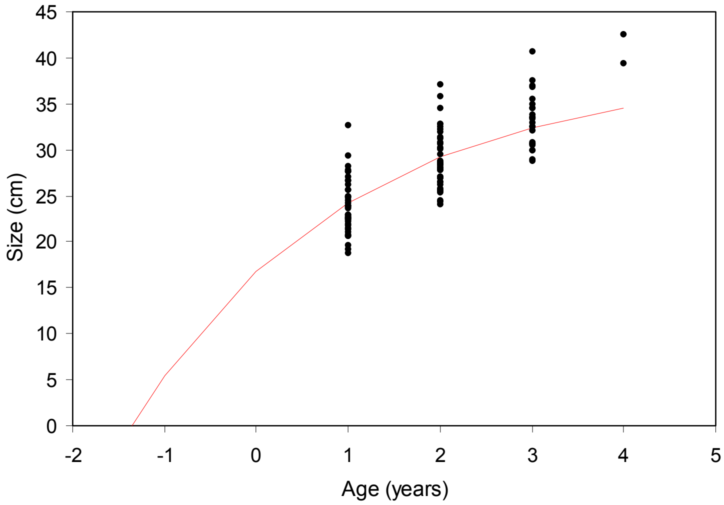


Figure 3.2 Back-calculated catch-at-age data from Pilling (2002) with growth curve fitted.

Table 3.3 Von Bertalanffy growth parameter estimates for *Siganus sutor* by location.

L_∞ (cm)	Measure	K (yr^{-1})	t_0	Location	Method	Reference
25.0	TL	1.5		Dar es Salaam	Lfreqs	Benno, 1992
36.2	SL*	0.87		Mombassa Is.	daily rings	Ntiba & Jaccarini, 1988
49.9	TL	0.66	0.06	Mauritius	annuli	Jehangeer, 1988
43.3	TL	0.65	-0.37	Seychelles	daily rings	Grandcourt, 1999
41.0	TL	0.75	0	Seychelles	annuli	Pilling, 2002
38.6	TL	0.42	-1.36	Seychelles	annuli	This study

* Standard length

In comparison to other studies, it can be seen that the current analysis estimates a low growth rate, K. This is considerably lower than is expected, and indicates that *S. sutor* in this study has only a moderate, rather than fast growth rate. This result may be attributed to the absence of small fish present within the sample, which has subsequently lowered the expected value of t_0.

Covariance matrix of growth parameters

Growth data used to estimate the mean growth parameters (cf. table 3.3) was used to calculate a covariance matrix for each parameter (L_∞, K and t_0). This was derived using a nonlinear random effects model (see Pilling et al. 2002).

Table 3.4 Mean von Bertalanffy growth parameters, variance and coefficient of variation (CV, %), derived using a non-linear random effects model.

Parameter	Mean	Variance	CV (%)
L_∞ (cm)	38.6	7.45	7.1
K (yr^{-1})	0.42	0.069	62.5
t_0	-1.36	0.026	-11.8

Based on the von Bertalanffy growth parameter sets simulated for the 10,000 individuals, a covariance matrix was derived:

$$\begin{bmatrix} 7.45 & -0.069 & -0.026 \\ -0.069 & 0.05 & 0.027 \\ -0.026 & 0.027 & 0.066 \end{bmatrix}$$

3.2.2 Length-weight

The asymptotic weight (W_∞) is a required input parameter within the Beverton and Holt's yield-per-recruit equation (Beverton and Holt, 1957) used within the simulation model. The asymptotic weight (W_∞) was calculated for *S. sutor* using the estimate of L_∞ in section 3.2 and the length-weight equation calculated from this study (*n* = 41) $W_\infty = 0.000057 * L_\infty^{3.27}$. This estimate is similar to that obtained for Mauritius (Samboo and Mauree 1988):

$$W_\infty = 0.0059 * L_\infty^{2.75}$$

Since the parameter values from Mauritius have been estimated from a larger dataset (n = 3,888), these have been selected for use in the in the simulation model.

3.2.3 Natural mortality

Pauly's empirical formula (Pauly's M equation)

Using the von Bertalanffy growth parameter estimates in section 3.2.1 above, and the average annual habitat temperature T (˚C), Pauly's estimate of natural mortality was obtained:

$$Ln(M) = -0.0152 - 0.279 * Ln(Linf) + 0.654 * Ln(K) + 0.463 * Ln(T)$$

In Pauly's analysis, the temperature used for shallow water species, such as the study species, was the sea surface temperature (Pauly, 1980). An average annual sea surface temperature of 27 ˚C was used for study areas in this report. An estimate of M was calculated as 0.93.

Ralston's empirical formula

Using the von Bertalanffy growth parameter K, from section 3.2.1 above, Ralston's M (Ralston 1987) estimate was obtained:

$$M = 0.0189 + 2.06 * K$$

An estimate of M was calculated as 0.88.

The estimates of natural mortality derived from both Pauly's and Ralston's method are comparable with the results of other studies on *Siganus sutor* within the same region (see table 3.5.

Table 3.5 Natural mortality estimates for *Siganus sutor* by location.

M (yr^{-1})	Location	Method	Reference
1.2	Mauritius	Pauly	Jehangeer (1988)
0.82 – 1.21	Mauritius	Pauly	Rathacharen et al. (1996)
0.631	Seychelles	Pauly	Grandcourt (2002)
0.93	Seychelles	Pauly	This study
0.88	Seychelles	Ralston	This study

3.2.4 Reproduction

There are few records available on the reproduction of *Siganus sutor* within the region. Rathacharen et al (1996) estimated the length at first maturity (Lm_{50}) within Mauritius as 18.0 cm.

3.2.5 Stock-recruitment

There is no information available on the stock-recruitment dynamics of *Siganus sutor*. Parameters describing stock-recruitment are used with the recruitment CV (see section 3.2.6 below) to generate a random distribution of recruitment in each year of the simulation (see also Pilling et al. 1999). The simulation model uses the Beverton and Holt equation to model stock-recruitment:

$$R = \frac{4hR_0S}{S_0(1-h)+S(5h-1)}$$

Where *R* is the number of recruits, *S* is the spawning stock biomass and *h* is referred to as the steepness function. Under these circumstances, the absolute value of R is irrelavent and an arbitrary value has been used.

In comparison with other moderately fast growing species, it is clear that *h* should not be lower than that previously used for *Lethrinus mahsena* in FMSP Project R7522 (0.879). Indeed, without further information, the stock-recruit parameters have been fixed to those used for *L. mahsena*:

R = 25 million fish
h = 0.879

3.2.6 Annual variation in recruitment

The literature did not provide estimates of the level of recruitment variation in Siganidae. An estimate of relative year class strength for *S. sutor* was therefore derived from the numbers of individuals-at-age, determined from otolith samples using the methods described by Pilling et al (1999). The level of annual variation in recruitment was estimated for Seychelles.

A catch curve was derived from the age frequency data obtained from random otolith samples from Seychelles. Deviations from the regression line of the descending limb were assumed to represent variations in year class strength (Doherty and Fowler, 1994). Total mortality was estimated independently from length frequency data (*n* = 598; Grandcourt 1999) and a length-converted catch curve (Z = 1.33). On the assumption of constant total mortality for all age classes, the total mortality estimate was used to back-calculate the numbers of individuals present at year zero required to account for the numbers found at each age (Table 3.6), based on a derivation of the exponential decay model:

$$n_0 = \frac{n_i}{e^{(-Z \cdot i)}}$$

where
n_0 = numbers at age zero
n_i = numbers at age i years
Z = total mortality

The coefficient of variation (CV, %) for numbers at age zero was then calculated using data from Pilling (2002). The results are shown in the table below.

Table 3.6 Numbers at age zero back-calculated from numbers at age (*i*) for Seychelles assuming constant total mortality across all ages (where Z = 1.33).

Age *i* (yrs)	Nazareth	
	No. at age *i*	No. at age zero
2	17	242
3	22	1 182
4	4	405
Mean		610
Standard Deviation		502
CV (%)		**82.3**

The recruitment CV for *Siganus sutor* is 82.3%. Since the data used by Pilling (2002) to estimate the CV omitted 1-year olds, this could be filled using data from Grandcourt (2002). Interestingly, if the data from Grandcourt is included, this does little to change the overall value (80.4%). For the purposes of the simulation model, the single data set of Pilling (2002) was used.

3.2.7 Seasons

Period of recruitment (spawning period)

The preliminary results from a new study to investigate the spawning aggregations (SPAG) of the main commercial species within the Seychelles has indicated that *Siganus sutor* spawns over a protracted period between November and February/March (Jan Robinson, pers. comm.). However, for the purposes of the model, it has been assumed that spawning occurs throughout the entire year (January – December).

Period of fishing

It has been assumed that fishing occurs throughout the year (January – December).

3.2.8 Age/length-at-capture

The length-at-age data collected by Pilling (2002) could not be used to determine the age-at-first-capture. First, it was not clear whether the samples had been collected at random, or whether it was part of a stratified sampling technique. Second, the small number of length measurements available (*n* = 41) constrains the data from displaying any useful information.

Length frequency data was available from the Seychelles (*n* = 598), following a recent study of the demographic characteristics of the main commercial species (Grandcourt, 2002). This data has been used in a modified length-converted catch curve (see Pilling et al. 1999) to estimate the age-at-first-capture. This is converted to length by re-arranging the von Bertalanffy growth equation and associated parameters (section 3.2.1). These estimates are compared with another estimate for the same species within the same region (Table 3.7).

Table 3.7 Age and length at first capture estimates for *Siganus sutor* by location.

Ac_{50}/Lc_{50}	Ac_{75}/Lc_{75}	Location	Reference
0.75 / 25.5 cm	-	Mauritius	Rathacharen et al. (1996)
1.49 / 18.0 cm	1.57 / 18.6 cm	Seychelles	This study

3.3 A slow growing species: *Lethrinus mahsena*

This information has previously been reported within R6465. Since these parameters have a wide spread impact on the determination of other parameters, they have been reproduced here for completeness and to aid comparison.

3.3.1 Growth

Using both back-calculated and individual length-at-age data (see Pilling et al, 1999), mean growth parameter estimates were derived using least squares:

L_∞ = 43.48 cm
K = 0.189
t_0 = -0.471 years

3.3.2 Covariance matrix of growth parameters

Growth data used to estimate the mean growth parameters (cf. section 3.3.1) was used to calculate a covariance matrix. This was derived using a nonlinear random effects model (see Pilling et al, 2002).

Table 3.8 Mean von Bertalanffy growth parameters, variance and coefficient of variation (CV, %), derived using a non-linear random effects model.

Parameter	Mean	Variance	CV (%)
L_∞ (cm)	43.48	45.25	15.5
K (yr^{-1})	0.189	0.095	163.1
t_0	-0.471	0.0025	-10.6

Based on the von Bertalanffy growth parameter sets simulated for the 10,000 individuals, a covariance matrix was derived:

$$\begin{bmatrix} 45.25 & -1.78 & 0.59 \\ -1.78 & 0.095 & 0.0025 \\ 0.59 & 0.0025 & 0.0248 \end{bmatrix}$$

3.3.3 Length-weight

The asymptotic weight (W_∞) is a required input parameter within the Beverton and Holt's yield-per-recruit equation (Beverton and Holt, 1957) used within the simulation model. The asymptotic weight (W_∞) was calculated for *S. sutor* using the estimate of L_∞ in section 3.3.1 and the length-weight equation presented in Samboo (1987).

$$W_\infty = 0.0000806 * L_\infty^{2.74}$$

3.3.4 Estimation of natural mortality

Pauly's empirical formula (Pauly's M equation)

Using the von Bertalanffy growth parameter estimates in section 3.3.1 above, and the average annual habitat temperature T (˚C), Pauly's estimate of natural mortality was obtained:

$$Ln(M) = -0.0152 - 0.279 * Ln(Linf) + 0.654 * Ln(K) + 0.463 * Ln(T)$$

In Pauly's analysis, the temperature used for shallow water species, such as the study species, was the sea surface temperature (Pauly, 1980). An average annual sea surface temperature of 27 ˚C was used for study areas in this report. An estimate of M was calculated as 0.53.

Ralston's empirical formula

Using the von Bertalanffy growth parameter K, from section 3.3.1 above, Ralston's M (Ralston 1987) estimate was obtained:

$$M = 0.0189 + 2.06 * K$$

An estimate of M was calculated as 0.41.

3.3.5 Reproduction

There are few records available on the reproduction of *Lethrinus mahsena* within the region. Lebeau and Cueff (1976) estimated the length at first maturity (Lm_{50}) as 27.5 cm. This was used in the simulation model.

3.3.6 Stock-recruitment

Similar to *Siganus sutor*, there is no information available on the stock-recruitment dynamics of *Lethrinus mahsena*. Parameters describing stock-recruitment are used with the recruitment CV (see section 3.3.7 below) to generate a random distribution of recruitment in each year of the simulation (see also Pilling et al, 1999).

In comparison with other long-lived, slow growing species, it is clear that *h* should not be higher that that used for Siganus sutor. Indeed, without further information, the stock-recruit parameters have been fixed to those used for *L. mahsena* used with FMSP project R6465:

R = 25 million fish;
h = 0.879

3.3.7 Annual variation in recruitment

Similar to *Siganus sutor*, the literature did not provide estimates of the level of recruitment variation in Lethrinidae. An estimate of relative year class strength for *L. mahsena* was therefore derived from the numbers of individuals-at-age, determined from otolith samples (see Pilling et al, (1999) for further details). The level of annual variation in recruitment was estimated for Nazareth bank.

A catch curve was derived from the age frequency data obtained from random otolith samples from Nazareth bank. Total mortality was estimated from the gradient of the catch curve's descending limb. On the assumption of constant total mortality for all age classes, the total mortality estimate was used to back-calculate the numbers of individuals present at year zero required to account for the numbers found at each age (table 3.9). The coefficient of variation (CV, %) for numbers at age zero was then calculated.

The variability seen in estimates of numbers-at-age is due to a combination of factors. These include variations in the size of the spawning stock biomass, and subsequent level of success in recruitment to juvenile grounds. The use of this estimate as the basis for annual recruitment variability ignores the contributions of spawning stock biomass.

Table 3.9 Numbers at age zero back-calculated from numbers at age (i) for Nazareth bank assuming constant total mortality across all ages (Z = 0.7).

Age *i* (yrs)	Nazareth	
	No. at age *i*	No. at age zero
6	185	12,147
7	137	18,067
8	79	20,925
9	38	20,217
10	12	12,823
11	7	15,024
12	8	34,487
13	5	43,293
14	2	34,783
15	-	-
16	1	70,161
Mean		28,193
Standard Deviation		17,200
CV (%)		**61.0**

3.3.8 Seasons

Period of recruitment (spawning period)

The main spawning period for *L. mahsena* was from October to February (Samboo and Mauree, 1988). However, within the simulation model, these have been fixed to assume that spawning is constant throughout the entire year (January – December).

Period of fishing

It has been assumed that fishing occurs throughout the year (January – December).

3.3.9 Age/length-at-capture

Age-at-capture (Ac_{50}) was calculated from the age-based catch curve derived for Nazareth bank. This catch curve was also used to calculate total mortality and the coefficient of variation (CV) in recruitment, as described above. Through the extrapolation of the total mortality regression line to younger ages, expected numbers at age were estimated. The shortfall when compared to the actual numbers at age found in the catch was assumed to result from gear selectivity. By dividing actual numbers at age by expected numbers at age, gear selectivity was described as a function of age. Linearisation of this selectivity function (*e.g.* Sparre and Venema, 1998) allowed Ac_{50} to be assessed through regression (Ac_{50} = intercept/-gradient).

3.4 Summary

Table 3.10 Biological parameters required by Yield software for *Siganus sutor*.

Parameter group	Parameter	Value	Source
Growth	L_∞ (cm) K (yr^{-1}) t_o	38.6 0.42 -1.36	This study
Length-weight	a b	0.059 2.75	Samboo and Mauree (1988)
Mortality	M (yr^{-1})	0.93	This study, Pauly estimate (27° C)
Reproduction	Lm_{50} (cm)	18.0	Rathacharen et al (1996)
Stock Recruitment Relationship (SRR)	Type: Beverton and Holt		Arbitrary values
	Recruitment, R (million)	25	
	Steepness, h	0.879	
Recruitment	CV (Seychelles)	82%	This study
Seasons			
	Recruitment	Jan – Dec	Arbitrary values
	Fishing	Jan – Dec	
Age/length and capture	Tc_{50} Lc_{50}	1.49 yrs 18.0 cm*	This study
	Tc_{75} Lc_{75}	1.57 yrs 18.6 cm	

* 10 cm was used for simulation purposes, see section 5.2.

Table 3.11 Biological parameters required by Yield software for *Lethrinus mahsena*.

Parameter group	Parameter	Value	Source
Growth	L_∞ (cm) K (yr^{-1}) t_o	43.48 0.189 -0.471	This study
Length-weight	a b	0.0806 2.74	Samboo (1987)
Mortality	M (yr^{-1})	0.53	This study, Pauly estimate (27° C)
Reproduction	Lm_{50} (cm)	27.5	Lebeau and Cueff (1976)
Stock Recruitment Relationship (SRR)	Type: Beverton and Holt		Arbitrary values
	Recruitment, R (million)	25	
	Steepness, h	0.879	
Recruitment	CV (Nazareth Bank)	61%	Pilling et al (1999)
Seasons			
	Recruitment	Jan – Dec	Arbitrary values
	Fishing	Jan – Dec	
Age/length and capture	Tc_{50} (Lc50)	3.29 yrs 22.1 cm	This study
	Tc_{75} (Lc75)	4.17 yrs 23.7 cm	

4 Management strategy simulation

4.1 Introduction

Management strategy simulation is a technique that uses computer simulation studies to model and analyse the behaviour of complex systems (all the processes that occur in fisheries management) by using a simpler model of the system. A fisheries simulation model should consider processes that occur both under the water (i.e. processes directly concerned with the fish stock), and processes that occur above the water (i.e. fisheries processes). These processes and their relationships are illustrated in Fig. 4.1.

Below the water, the dynamics of the fish stock are simulated and the effect of fishing on it. Above the water, each of the processes from fishing, data collection, annual assessment, management advice and the effects of management actions on the resources need to be modelled in some way. Being in a computer program, the true state of the fish stock is known at all times in a simulation model. This knowledge would not, however, be available to either the scientist doing the assessment, or to the manager.

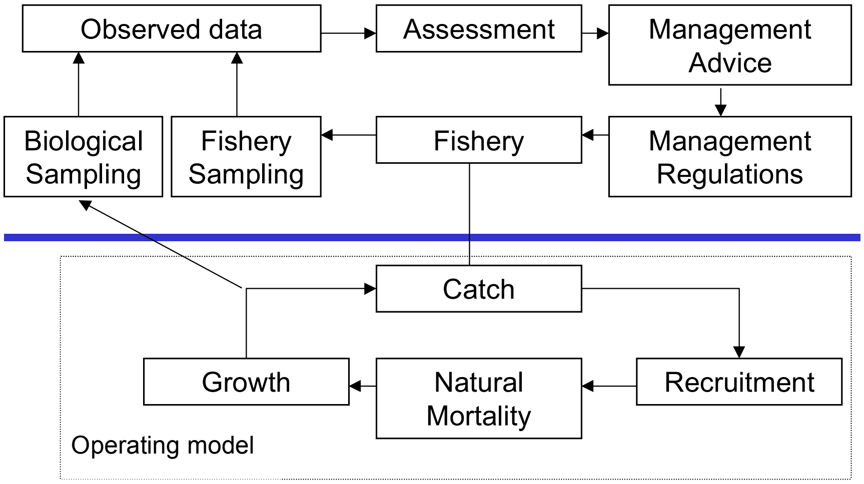


Figure 4.1 Processes that must be modelled in management strategy simulations for fisheries.

The key to understanding the behaviour of this system is that the entire management process has to rely on imperfect information. For example, data inaccuracy and bias can occur in one or more of the processes simulated. Proper understanding of the system as a whole must take account of possible imperfections in each part of the system. In general, until now, most attention has been paid to improving the methods used in assessment. Management strategy simulation has been devised as a way to analyse the system as a whole. Similarly, up to this point the present study has examined uncertainties in assessment of growth and the effects of that uncertainty on biological reference points used to derive management advice. The present chapter describes the results of a simulation model for the whole system.

4.2 Historical overview of management simulations

The current study has evolved out of two DFID-funded projects; R6465 'the effects of fishing on the growth of snappers and groupers' and R7522 'the potential for improved management performance with age-based stock assessment components'. To help establish what changes have occurred between each project and why, this section provides a brief overview of the main processes that occur within the management simulation model. The overall simulation process can be divided into three stages:

(i) The initial setup, using true population parameters.
(ii) Estimation of growth and natural mortality parameters, and target fishing levels.
(iii) Simulation of the fishery using either length-based or age-based methods.

The initial setup and generation of fixed parameters values (i & ii above) are conducted separately from the main fishery simulations (iii above) and have not markedly changed between each project. The following sections therefore describe the initial setup and estimation of performance measures before comparing the management simulations between each FMSP project.

4.2.1 Initial setup and parameter estimation

The fish population is initiated for a certain degree of prior exploitation using the true (or known) population parameters (cf. section 3.4) until the stock reaches an equilibrium state at that level of exploitation. The time it takes to reach equilibrium will depend on the initial level of fishing mortality, and the time it takes for the youngest cohort of the population to pass through the fishery (i.e. all fish have been subject to starting fishing mortality).

Within R6465, simulations were run for a range of starting fishing mortalities to represent a range of states from lightly exploited to over-exploited. Pilling et al. (1999) had shown that the target fishing mortality for *Lethrinus mahsena* was around 0.41. Simulations were run with a range of F_{start} values about 0.4 (0.05, 0.25, 0.7 and 1.2 yr^{-1}) that represent the range of estimates of current fishing mortality across the three fisheries studied within the Indian Ocean (Seychelles, BIOT and Nazareth Bank). Unlike *L. mahsena*, little or no information was available on the range of fishing mortalities from different fisheries for *S. sutor*. Without additional knowledge of specific fisheries, a range of values has been selected arbitrarily. These are 0.5, 0.75, 1.25 and 1.50 yr^{-1} that represent a range about the optimal value of 0.87 (see section 5.1)

Having established the model at equilibrium, samples of 400 fish were taken at random over five successive years from the population to estimate growth parameters (L_{inf}, K, t_o) using either length-based or age-based methods (see below). Growth parameters, estimated from the sampled population are also required inputs to derive length-based or age-based estimates of natural mortality and fishing target levels through a Beverton and Holt's yield-per-recruit model. A summary of these processes is shown in Fig. 4.2.

Growth parameter estimation

Age-based methods assume that the sampled fish are aged using otoliths (yrs) and measured (cm, fork length) to obtain length-at-age data. These data are used to fit a von Bertalanffy Growth function using least squares.

Length-based methods do not have any prior information on length-at-age data. Instead, fish are measured (cm, fork length) and used to generate length frequency distributions for each of the sampled five years. Length frequency data are then used to estimate growth parameters using the ELEFAN routine within computer programme Length Frequency Data Analysis (LFDA, Holden et al. 1996).

The growth parameters, estimated from either method, are used in all subsequent management simulations (see section 4.2.2 below). Growth parameters are required to calculate:

(i) Natural mortality (Pauly's and Ralston's method)
(ii) Age at first capture (Length-converted catch curve)
(iii) Target fishing level (Beverton and Holt's yield-per-recruit)

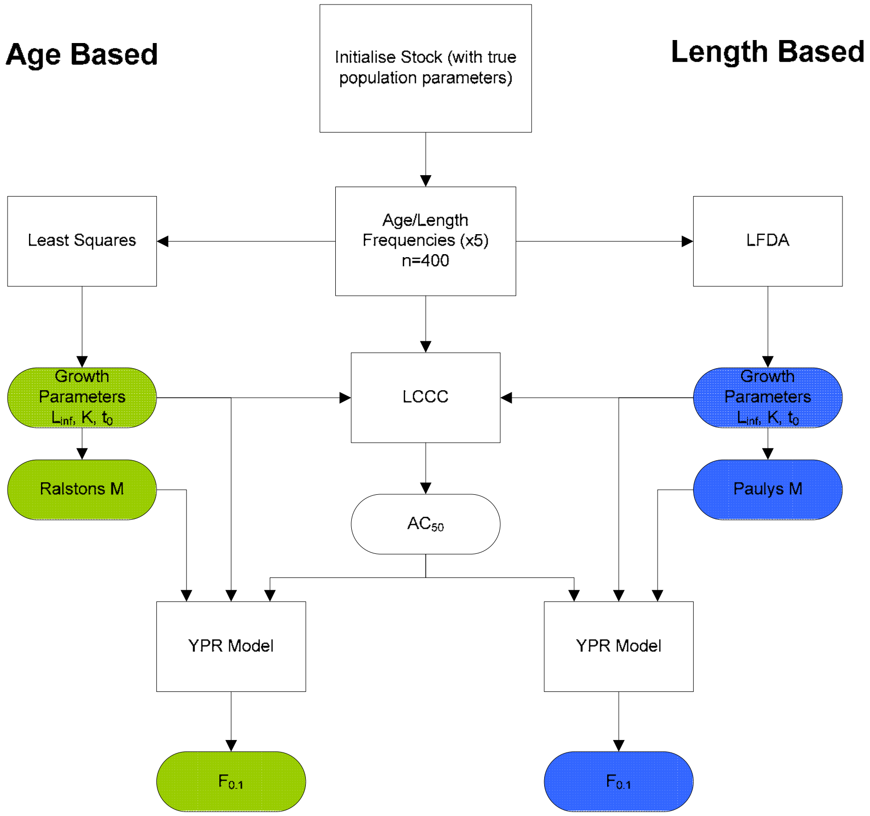


Figure 4.2 Schematic diagram to illustrate the procedures used to derive age-based (yellow) and length-based (blue) growth parameters, natural mortality and target fishing levels.

Natural mortality (Ralston's and Pauly's estimate of M)

Using fixed growth parameters derived from either length-based or age-based methods, an estimate of natural mortality was calculated. It has previously been demonstrated that the Ralston equation is more suitable for age-based methods, whereas the Pauly equation is more suited to length-based methods (Pilling et al. 1999). These findings have been preserved in the current project although these have not been fully evaluated for *S. sutor*.

Age-at-capture (Ac$_{50}$, Lc$_{50}$; Length-converted catch curve)

The length-converted catch curve used to estimate length-based estimates of total mortality (Z), had been extended in FMSP projects R6465 and R7522 to estimate age- and length-at-capture (see Sparre and Venema, 1998). A standard set of criteria selected the points for the regression on the ascending limb. The start of the regression was selected using an iterative process that searched backwards in the data until the first non-zero length frequency was identified. From this starting cell, the value of the observed over expected frequency (*i.e.* selectivity ogive) was assessed until it reached, or exceeded the value of one (100% selectivity). The end point of the regression was taken as the cell within this range that contained the largest value of the selectivity ogive that was still less than one.

The age-at-first-capture (Ac_{50}) was estimated from the regression (Ac_{50} = intercept/-gradient). Lc_{50} was then calculated using a re-arranged von Bertalanffy growth function and the fixed growth parameters estimates (length-based or age-based, depending on the method used).

Target fishing level ($F_{0.1}$; Beverton and Holt's yield-per-recruit model)

Biological reference points, such as the maximum sustainable yield (MSY), can be used to gauge the performance of management. Without detailed knowledge of stock-recruit dynamics, the maximum yield-per-recruit has been calculated from a Beverton and Holt yield-per-recruit model (Beverton and Holt, 1957) within an Excel ^{TM} spreadsheet. The level of fishing effort required to maximise this yield can also be calculated (F_{MYPR}) and compared with the current estimated level of fishing mortality (F_{est}) to gauge the level of exploitation.

Since estimates of the maximum yield-per-recruit can lead to unsustainable estimates of F_{MYPR}, an alternative more precautionary target fishing level of $F_{0.1}$ has been used. $F_{0.1}$ is the fishing mortality rate at which the increase in yield-per-recruit in weight for an increase in a unit of effort is only 10 percent of the yield-per-recruit produced by the first unit of effort on the unexploited stock (i.e., the slope of the yield-per-recruit curve for the $F_{0.1}$ rate is only one-tenth the slope of the curve at its origin) (Caddy and Mahon, 1995). The gradient of the yield-per-recruit curve was iteratively assessed at F=0.01 intervals, starting at F=0.01. $F_{0.1}$ was identified where the difference between the current gradient and 10% of the initial gradient was minimised.

A number of input parameters are required for a yield-per-recruit analysis. Ac_{50}, the age-at-capture, was calculated from the length-converted catch curve (see above). T_r, the age of recruitment to the fishing grounds, was calculated from the smallest known fork length from the sampled length frequency distribution (L_{min}). Natural mortality was estimated from one of two methods. The Ralston equation was used for age-based methods, whereas the Pauly equation was used for length-based methods. The asymptotic weight (W_4) was calculated for both *L. mahsena* and *S. sutor* using the fixed growth parameter estimate of L_4 and the length-weight parameters described in Tables 3.6 and 3.7 above.

4.2.2 Management Simulations

This section describes in more detail the development and changes that occurred within the management simulation models between successive FMSP projects. This section will help elucidate what has happened, when, and why the changes were deemed necessary.

Project R6465 'The effects of fishing on the growth and assessment of snappers and emperors'

The initial aim of this first model was to assess the effects of fishing and density dependent growth (DDG) on growth parameter estimates derived through length-based methods. However, this was later modified as it became clear from initial assessments that length-based growth estimates were significantly more biased than previously expected. It was also decided to examine the effects of fishing on age-based growth parameter estimates. The software used to run the simulation model, MIDAS, had not originally been designed to undertake age-based methods and a procedure was developed outside the model to cater for these changes within an MS Excel spreadsheet.

The management simulations were designed to look exclusively at the difference between growth parameter estimation procedures on the management of a long-lived species such as snappers and emperors. Within each simulated year, the estimated level of fishing mortality (F_{est}) was compared to the target level ($F_{0.1}$) and a decision made to change the level of fishing effort (see section 4.4 for more details). The revised level was then applied at the start of the following year to the true underlying population.

It was demonstrated that the results of the final assessment was sensitive to the selection of methods used to estimate both the total mortality (Z) and natural mortality (M). For example, assessments conducted on fixed age-based growth parameters were more accurate and precise if total mortality was calculated using a length-converted catch curve (LCCC) and the Ralston equation to estimate natural mortality (i.e. $F_{est} = Z - M$). Similarly, assessments conducted on fixed length-based growth parameters were more accurate and precise if total mortality was calculated using the Beverton and Holt (B & H) method and the Pauly equation was used to estimate natural mortality (see Fig 4.3).

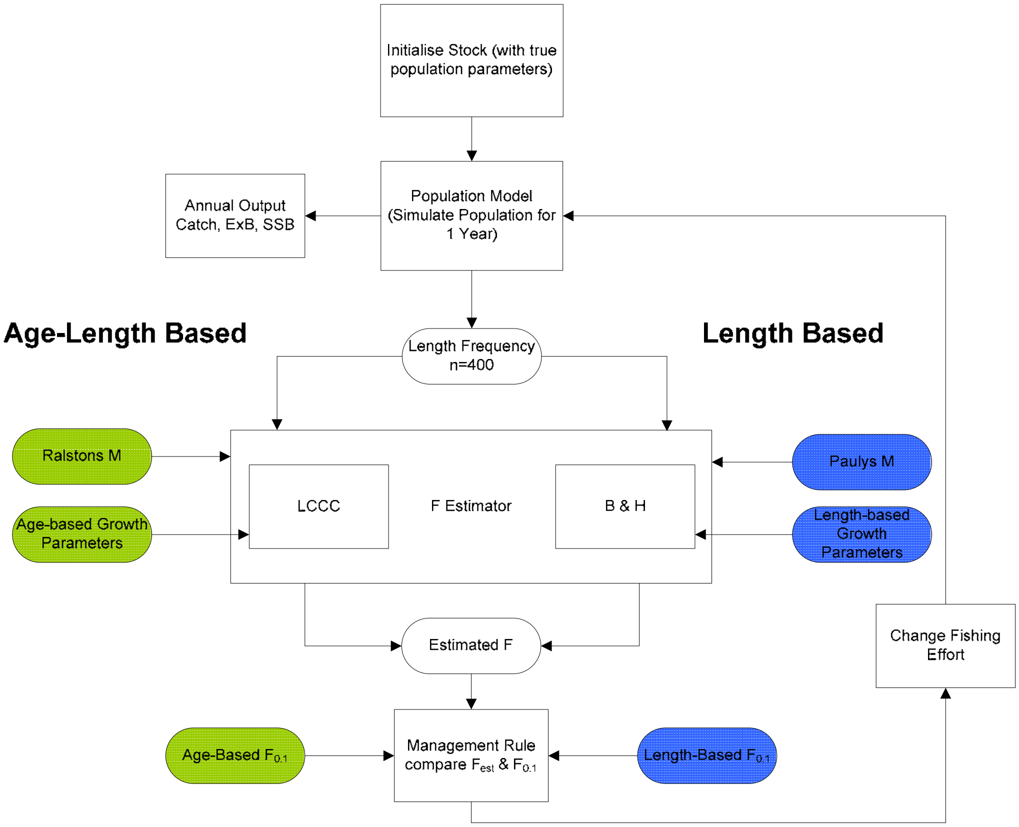


Figure 4.3 Schematic diagram to illustrate the processes and data used within R6465 to derive age-based (yellow) and length-based (blue) estimates of fishing mortality.

Project R7522 'The potential for improved management performance with increased age-based stock assessment components'

Management strategy simulations performed during FMSP project R6465 examined the impact of uncertainty in growth parameter estimates on the accuracy of stock assessments, and hence management performance. The use of age-based methods to assess growth, and the use of these parameters in stock assessments, resulted in improved management performance. However, the use of length-based methods later in the stock assessment process diluted the gains made through the use of age-based growth parameter estimates (i.e. growth parameter estimates were used in the estimation of total mortality using length-based methods such as the length-converted catch curve or Beverton and Holt). The aim of the project was to assess whether the use of age-based methods to estimate total mortality results in improved stock assessments, and hence management performance. Using age-based methods of total mortality estimation avoids the need to use uncertain growth parameter estimates in the estimation of this parameter, thereby eliminating one source of bias in stock assessments, upon which management is based.

Fig. 4.4 details the stock assessment approach simulated in project R7522, and compares this with the approach simulated in project R6465. Fixed age-based growth parameters are used in each simulation to estimate subsequent biological and fishery parameters, since these resulted in the best management performance in project R6465. There are, however, important differences between the approaches used for each method.

It was assumed that the exact age of each sampled fish (*n* = 400) was known for fully age-based methods, creating an age frequency each year from the population, with no sampling or reading error. These were then used directly within a catch curve to estimate total mortality, and hence F (fixed age-based growth parameters were not required since the age of each fish were already known during the initial sample). For length-based methods, project R6465 had indicated that sampled length frequency distribution (*n* = 400) within a length-converted catch curve resulted in the best management performance when using fixed age-based growth parameters (i.e. the right hand side of Fig. 4.4 is identical to the left hand side of Fig. 4.3).

Finally, age-based growth parameters were used to estimate target F (section 4.2.1) that was compared to an estimate of current fishing mortality, F_{est}, in each year. A management rule (see section 4.4) was then applied at the end of the year to determine how fishing mortality should change, if at all, in the following year.

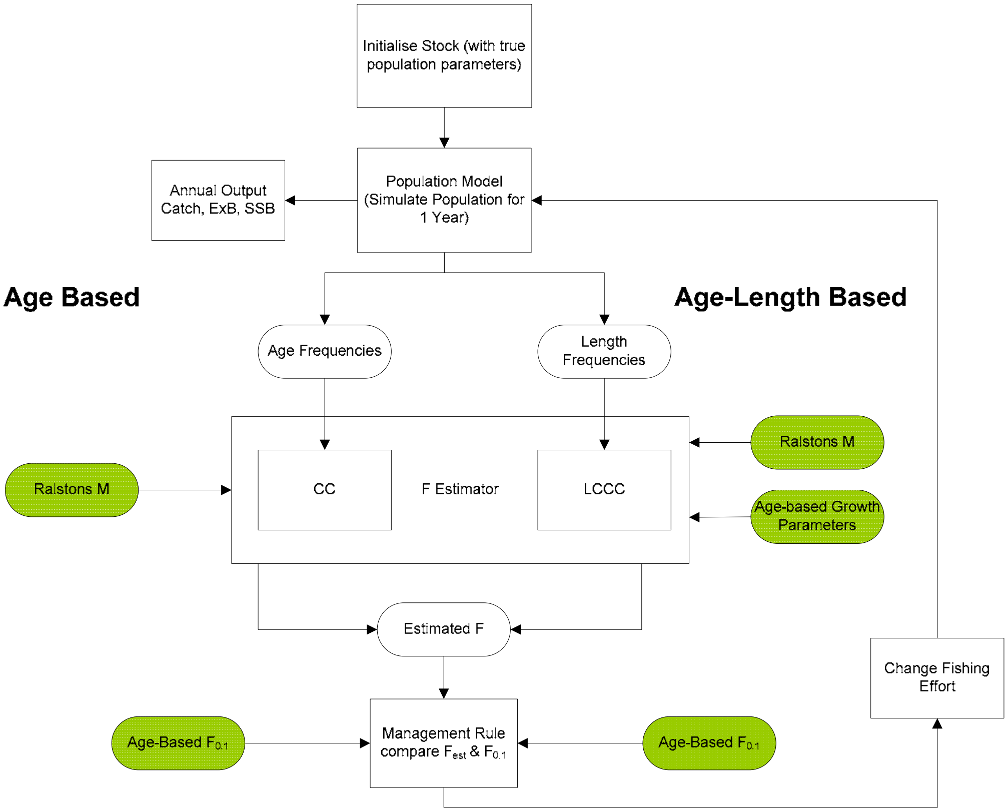


Figure 4.4 Schematic diagram to illustrate the processes and data used within FMSP project R7522 to derive true age based and age-length based estimates of fishing mortality. Both methods use age based growth parameters within the assessment (yellow boxes).

Project R7835 ‘Investigation of the implications of different fish life history strategies on fisheries management’

The current FMSP project attempts to simulate the entire assessment procedure more realistically and in doing so compare fully age-based methods with fully length-based methods. In many ways, this project is more similar to R6465 than R7522. The major changes between these methods are (i) the approach used to derive input data for the assessment, and (ii) the method used to estimate current fishing mortality (see Fig. 4.5).

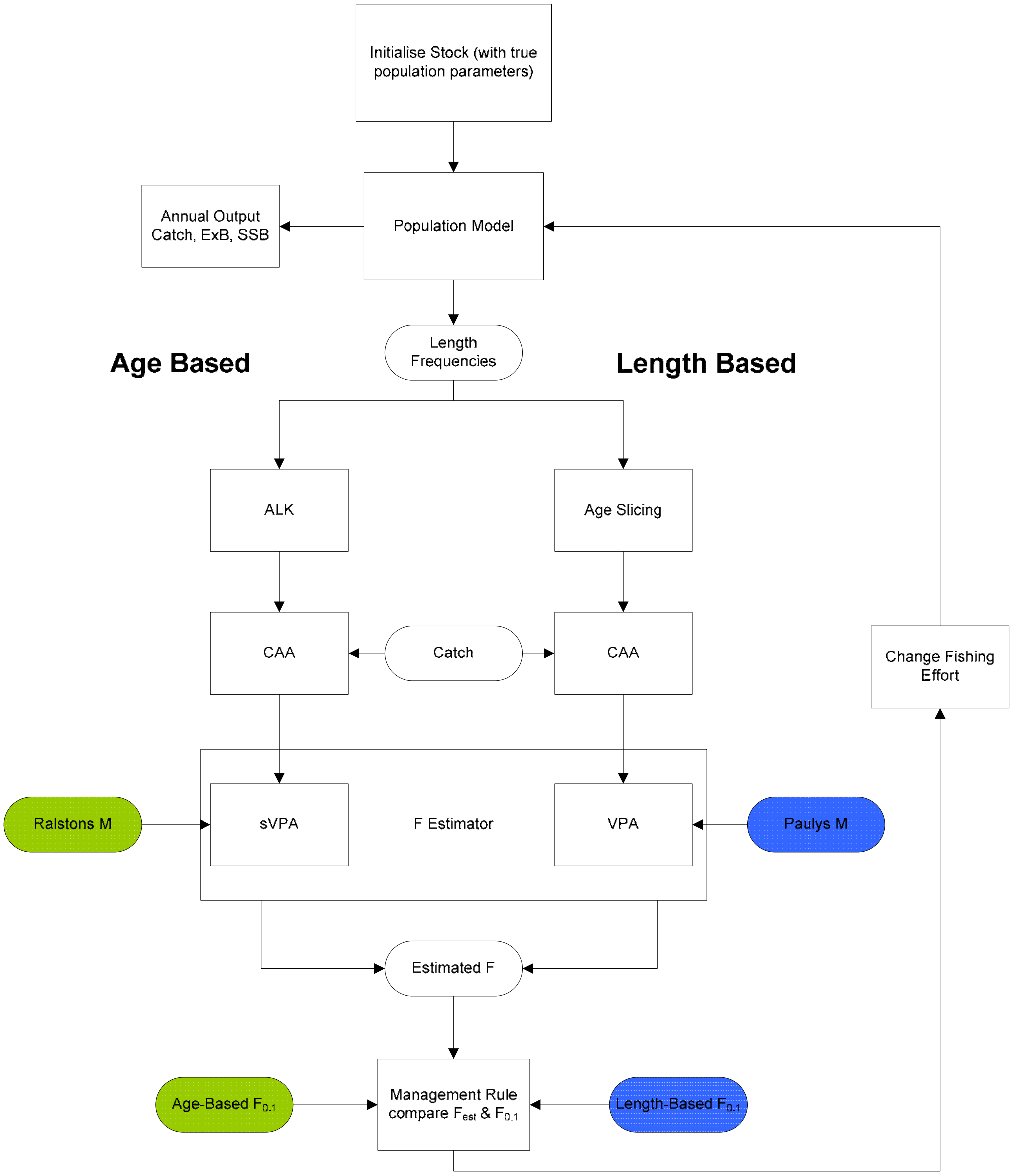


Figure 4.5 Schematic diagram to illustrate the processes and data used within FMSP project R7835 to derive age-based (yellow) and length-based (blue) estimates of fishing mortality.

Fully age-based methods require a cost-effective means of translating the sampled length of a fish into an age. Project R7522 had assumed that all fish sampled could be read, and done so without bias or error. In practice, this is unrealistic and an age-length key (ALK) is constructed from ageing a sample of the population. This key is then used to convert fish lengths sampled from the catch into ages. The aged sample is then raised to the value of the total catch to produce the catch at age (CAA) in numbers. Within the fully age-based method of assessment, an age-structured virtual population analysis (VPA) model now replaces the catch curve equivalent (see section 4.3.4 for more details).

In contrast, catch curves used for length-based methods (e.g. LCCC) are non-equilibrium methods, which were found to cause significant bias in the results (see section 4.3.1). A new method was developed to use a length-based VPA model (see section 4.3.3) that would provide a fair comparison to fully age-based methods. To undertake a length-based VPA, the catch at age in numbers was estimated through a process known as age slicing. In brief, the von Bertalanffy growth function is re-arranged to estimate the relative age of a fish (t) using the fixed length-based growth parameters (L_{inf}, K, t_o) and known sampled length L_t.

4.3 Estimation of fishing mortality

The historical overview of management simulations highlighted the current assessment procedures used to estimate fishing mortality have changed from length-based equilibrium methods, such as the length-converted catch curve or the Beverton and Holt, to specific age-based or length-based non-equilibrium methods (e.g. virtual population analysis; VPA). This section describes in more detail the problems associated with using non-equilibrium methods and how these issues were resolved.

4.3.1 Bias in existing length-based equilibrium methods

Length-based methods of estimating total mortality using non-equilibrium methods assume constant parameters (e.g. recruitment, mortality), and that the growth parameters are known exactly. It has been found that in cases where the initial level of fishing mortality is far from the target, there can be substantial changes in fishing mortality over the period of simulation, making these assumptions invalid. This results in a delay in the estimate of current fishing mortality reacting to changes in true effort level. This can be demonstrated through the use of a length-converted catch curve (see Fig. 4.6). At equilibrium, the estimated total mortality is based on a linear regression ($Z = 1.6$; $F_{start} = 1.2$). However, during 6 years of management of the fishery, fishing mortality is reduced on an annual basis in an attempt to reach a target value ($F_{0.1} = 0.4$). In doing so, the younger age classes (e.g. 2 to 5) are subject to a lower fishing mortality than the older classes (e.g. 6 to 10), causing the linear regression to ‘bend’ in year 6 (see Fig 4.6).

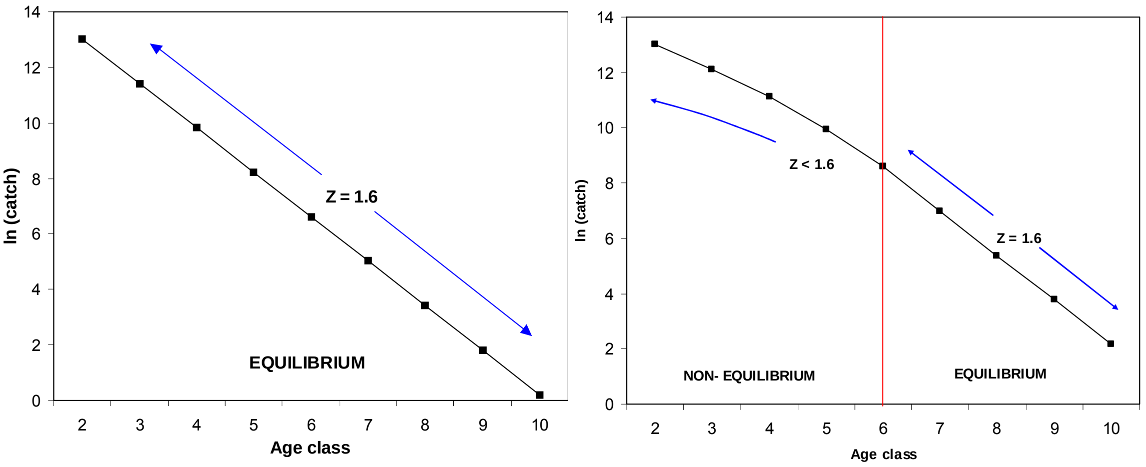


Figure 4.6 Observed bias in estimates of total mortality (-gradient) estimated from a length-converted catch curve over an eight year simulated period ($F_{start} = 1.2$, $F_{0.1} = 0.4$).

Non-equilibrium methods are no longer used in the management simulation, and have been replaced by length-based and age-based VPA methods (see sections 4.3.3 and 4.3.4 respectively).

4.3.2 Tuning

Throughout the development of the previous two FMSP projects, it was clear that length-based assessment methods had not detected changes in the true level of fishing effort. For low starting fishing mortality, mortality was generally underestimated, and so the true mortality continued to increase past the target (Fig. 4.7; left hand). For high starting effort (Fig. 4.7; right hand), the trend of decreasing fishing mortality continued past the target level, until a number of years later the catch structure reached a state that reflected the fact that it had recovered sufficiently. At this point, the trend in effort changed to the opposite direction, and again continued past the target.

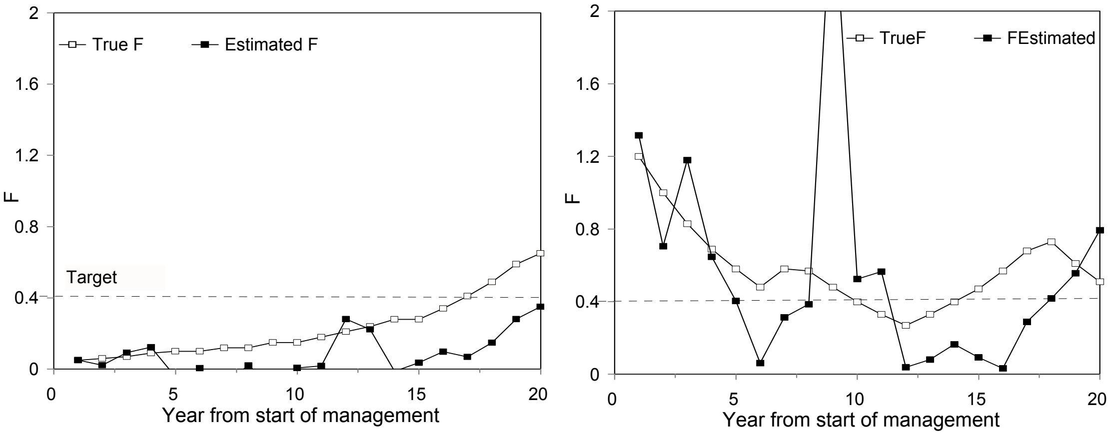


Figure 4.7 Simulation results showing true and estimated fishing mortalities starting at low (left; F_{start} = 0.05) and high (right; F_{start} = 1.2) values.

In both cases, the long-term result was an oscillation around the target fishing level. Therefore management performance, as measured by the true final year effort, was affected by the length of time that the simulations were run for. Whilst both previous FMSP project simulations had to be 'tuned' for optimal final year effort at the end of 20 years, this tuning would not have optimised management if simulations had been run for 15 or 25 years instead, say. Due to the oscillating nature of the true effort level, tuning simply shifted the mean value at 20 years.

In the current project, it was hoped to minimise the effect of these oscillations by choosing a management rule that allowed smaller changes in effort level than in the previous projects. However, in situations were the initial effort is substantially above or below the target level, a large initial change is effort in the first year of management is required otherwise the effort level cannot reach the target within the period of simulated management. Drastic initial changes (such as increasing fishing mortality three-fold within one year) were not considered to be realistic.

A new length-based method of estimating current fishing mortality was therefore developed which would:

- Enable non-equilibrium methods to be used for estimating F.
- Prevent the cyclical behaviour of estimating fishing mortality and therefore eliminate the need to tune the model.
- Improve the estimation of fishing mortality when starting values are high or low.

4.3.3 A non-equilibrium length-based method for estimating fishing mortality

Estimation procedure

Although the true level of fishing mortality each year is not known by the fisheries manager the relative level of fishing mortality can be determined each year by the management decision rule (see section 4.4). The known relative effort levels can therefore be used to improve the length-based assessment method.

The new method estimates what the expected catch in numbers at age would be, given the relative change in effort level, and minimises the sum of squared difference between the observed and expected catch in numbers at age. The minimisation is achieved by varying the initial population size, and estimate of the equilibrium fishing mortality prior to the start of management.

The procedure ages 400 fish each year from the length-frequency distribution sampled from the total catch using the method of age slicing (see Sparre and Venema 1998) to produce numbers at age. The number of sampled fish within each age class is then raised to the total catch based on a proportion of the total catch and sample biomass.

The minimisation is only conducted using the current year's data (i.e. 1 year). If the data were used from all available years, this would be comparable to conducting a length-based VPA. However, since the expected values are independent by year, due to the assumption of constant recruitment, only the current year is used within each minimisation procedure. A full description of the model algorithms is given in Appendix B.

Performance evaluation

The performance of the new length-based method to estimate current fishing mortality was compared to the previous length-converted catch curve method using an ad-hoc spreadsheet. The results demonstrate that the new method works very well, particularly when fishing mortality is decreasing. The following example shows a population starting at equilibrium subject to a high (F_{start} = 1.2) and low (F_{start} = 0.05) fishing mortality (Fig. 4.9). The new assessment method is applied from year 1, and the management rule changes the fishing mortality in the subsequent year by 20% to reach the target value of $F_{0.1}$ =0.41.

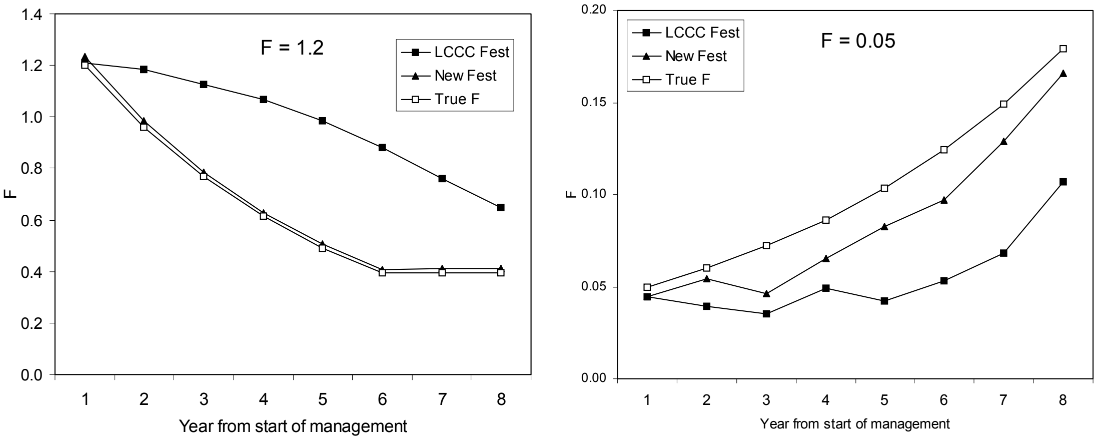


Figure 4.8 Performance of new non-equilibrium and previous equilibrium length-based methods compared to the actual known values of fishing mortality, starting at high (F_{start} = 1.2) and low (F_{start} = 0.05) values.

Thus the new method doesn't appear to respond so quickly to increasing effort from a low value as it does to decreasing effort from high value, but converges (close) to the true value faster than the old method. The exceptional performance of the new method observed at high starting fishing mortality levels and the reported difference between high and low starting values warrants further study.

4.3.4 A non-equilibrium age-based method for estimating fishing mortality

The latest age-based method no longer utilises a non-equilibrium length-converted catch curve to estimate Z, and hence calculate current fishing mortality. Instead, the simulation procedure uses a simple form of separable VPA. A separable VPA model separates the exploitation rate from the selectivity pattern, with the assumption that the age-dependent selectivity pattern remains constant over some significant period of time (FAO, 2001). Thus only the overall level of exploitation varies between years:

$$F_{ay} = S_a E_y$$

where F_{ay} is the fishing mortality on age *a* in year *y*;
S_a is the age-dependent selectivity pattern; and
E_y is an age-independent exploitation level.

The separable VPA model reduces the number of parameters to be estimated, and is most appropriate for longer time series with several age classes, where for each additional year of date, only one additional parameter is added to the model but a number of additional data points (equalling the number of age classes) are provided.

For this project, the simple form of the separable VPA using only catch-at-age numbers was used (see Pope and Shepherd, 1982). In brief, this estimates the current fishing mortality (F_{est}) by minimising the sum of squared difference between the observed and expected catch-at-age numbers using least squares.

Estimation procedure

In each year of the simulation, 400 fish are sampled at random from the total catch in numbers to generate a length frequency distribution. Individual sampled fish are then assigned to an age class using an age-length key (ALK; see below for more details). Unlike age slicing, an ALK enables variability to be incorporated in the length-at-age data. For example, fish within the same length class can have different ages.

The ALK is derived in each year of simulation from growth parameters estimated from age-based methods (otoliths). The sample numbers at age were then raised to estimate the total observed catch-at-age in numbers for each year using the proportion of total catch and sampled biomass. A matrix of observed catch ratios is then calculated from the observed number of fish caught at age in the current year (i.e. C_{ay}) as a proportion of the number of fish caught from the same cohort in the previous year (i.e. $C_{a-1,\ y-1}$). The ratio is log-transformed using a natural logarithm.

An expected catch ratio is calculated and compared to the observed catch ratio. The expected catch-at-age in numbers used to calculate the ratio in any year, can be derived using a simple catch equation with the separable fishing mortalities described earlier (F_{ay}). Briefly, the number of fish caught in each age class is determined by the proportion of the population that has survived to that age class and died due to fishing activities (i.e. F_{ay}), rather than natural causes (i.e. M).

To derive separable fishing mortalities, both the age-dependent selectivity pattern (S_a) and age-independent exploitation level (E_y) must be estimated. Two parameters are required to determine the selectivity pattern (β, a_{50}), whereas the current exploitation level (F_{est}) is calculated by the product of the initial level of fishing mortality at equilibrium (F_{equil}) and the overall change in fishing effort (F_{mult}). To the fisheries manager, F_{equil} is unknown and must be fitted together with β and a_{50} by minimising the sum of squared differences (SS) between the matrixes of observed and expected catch ratios. Unlike the equilibrium length-based method, the separable VPA uses all available information in each year.

The revised estimate of current fishing mortality (F_{est}) is then used each year in the management rule. Further details of the model algorithms can be found in Appendix B.

Age-length key

An age-length key (ALK) establishes for each length-group, the proportion of each age in that group. Without individual variability in growth, then all fish of the same length would be the same age. However, due to differences in growth rates, several ages may be present within a given length group. The proportion of these groups will depend on their relative proportions in the population as a whole, and hence on the recent mortality rates and on the relative strengths of the year-classes or cohorts. As these factors will vary from year to year, an age-length key constructed from otoliths collected in one year cannot, without risk of error, be applied to a length composition in another year to estimate the age composition in that year (Gulland and Rosenberg, 1992). In the model employed in this project, therefore, a new age-length key is estimated each year.

4.4 Simulation of management

Following initialisation and parameter setup described in section 4.2.1, management simulations were run over a period of 20 years. The software generated a number of annual outputs of the true population parameters (see Table 4.1). These are details that would not be known to the fisheries manager. The Yield software also simulated the catch length frequency and length-at-age distributions, for length-based and age-based assessments respectively (cf. Fig. 4.5).

To derive estimates of fishing mortality and $F_{0.1}$, fixed estimate input parameters for each F_{start} value (i.e. at year zero) is required (e.g. 0.05, 0.25, 0.7 and 1.2). These F_{start} values were derived in FMSP project R6465 for *L. mahsena* to represent the range of estimates of current fishing mortality across the study fisheries in the Indian Ocean. For *S. sutor*, a range of arbitrary F_{start} values was used around the optimal value of 0.87.

To take account of uncertainty in the estimation of parameters, 100 runs were performed, each one estimating the fixed input parameters. While this number of runs may be considered to be relatively low, the model is required to simulate the growth of individual fish (in order to generate length frequencies), which is a very time-consuming process. Furthermore, the model had three stages that required seperate user-input. These issues greatly increased the length of time a single simulation of 100 runs would take, which was typically between 3 – 4 hours.

Table 4.1 A list of the relevant outputs from the Yield software used in assessment of the performance of fisheries management. These are the 'true' population parameters, including fishing mortality (unknown to the stock assessment specialist), and the catch per annum.

Before initialisation: Unexploited equilibrium states

The unexploited biomass (ExB_0)

The unexploited spawning stock biomass (SSB_0)

Time 0-20: Exploited equilibrium state for F_{start}

The exploited biomass each year, ExB

The spawning stock biomass each year, SSB

Total catch per annum

Fishing mortality, F

Length frequency and length-at-age distribution

Management is based on estimates of current fishing effort (F_{est}; the fishing mortality level estimated by the fishery manager). Fishing mortality was increased or decreased by a preset percentage each year, moving the current effort towards the target effort (i.e. $F_{0.1}$). Management rules were set in the simulation model that determined the new fishing mortality applied to the stock (i.e. to be fed back into the Yield software). These rules adjust the *true* underlying F within the Yield software by the appropriate amount. The rule used in the current study was the fixed percentage change rule used in Project R6465. For this rule, it was considered to be more appropriate to increase by Y% if below the target, and to decrease by Z% if above the target, where:

$$Z = 100.\left[\frac{Y}{100 + Y}\right]$$

For example, the opposite of doubling fishing mortality (F x 2) is halving it (F / 2). In the simulations, the following percentages were used; if the estimated current fishing mortality was below the target value (i.e. $F_{0.1}$), the level of fishing mortality was increased by 20%. If current fishing mortality was above target value, mortality was decreased by 16.7%.

It should be noted that both length-based and age-based assessment techniques assume that the proportional change in fishing mortality prescribed by the manager is known and achieved exactly. The effect of this assumption is that both methods will perform better than they are likely to in practice.

4.5 Management performance measures

The study evaluated management performance by analysing three chosen performance measures. Two of these related to stock conservation measures, while the third evaluated fleet performance. The target values are specific to the input parameters used (e.g. Lc_{50}), and have been generated using the values given in Tables 3.10 and 3.11. Histograms of these outputs were produced for each performance measure (see Chapter 5).

Conservation measures:

- Final year ExB/ExB_0: the ratio of the final year (year 20) exploitable biomass (ExB) to unexploited biomass at equilibrium (ExB_0). This measure indicates how close to a target biomass management was able to leave the population at the end of the management period. The Yield software was used to calculate for both species the equilibrium ExB/ExB_0 ratio when $F = F_{MSY}$. The ratio for *Siganus sutor* is 0.25 and 0.32 for *Lethrinus mahsena*...

- The frequency over the 20-year management period with which the spawning stock biomass (SSB) dropped below a threshold value of unexploited levels (SSB_0)[2]. The threshold value was calculated for both species as the equilibrium SSB/SSB_0 ratio when $F = F_{MSY}$ using the Yield software. The ratio for *Siganus sutor* is 0.22, whereas for *Lethrinus mahsena* is 0.16.

  Indications that SSB frequently fell below the threshold value, equivalent to the equilibrium SSB/SSB_0 ratio, would suggest that there was an increased risk of recruitment overfishing. If SSB rarely fell below the threshold value during the 20 years, the population was likely to remain within sustainable levels for the majority of the simulated period and the probability of recruitment overfishing was low.

Fleet performance:

- Average catch: in order to compare the success of different scenarios, histograms of the average catch removed each year were plotted. Due to potentially large fluctuations in the total annual catch at the start of the management period, the average was calculated from the last 10 years of management (i.e. 10 – 19 yrs). Due to previous assumptions made about the level of recruitment, the values of catches should be considered as relative and not absolute values.

A summary of the values used to compare the performance of length-based and age-based assessments for both *Siganus sutor* and *Lethrinus mahsena* is given below.

Table 4.2 Summary of parameters used to estimate performance measures for both *Siganus sutor* and *Lethrinus mahsena* in the management simulations.

	Siganus sutor	*Lethrinus mahsena*
ExB_0	10 349	6 134
SSB_0	9 750	3 710
$Catch_{MSY}$	3 081	1 040

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[2] Mace and Sissenwine (1993) and Mace (1994) suggested that spawning stock biomass should not be allowed to fall below 20% and 30% of the initial biomass for stocks with average resilience to overfishing, and for little known stocks respectively.

5 The suitability of length-based and age-based methods for informing management based on species with different life histories

5.1 Introduction

The main objective of this project was to compare the performance of length-based and age-based methods for informing management based on both moderately short-lived, fast growing species and long-lived, slow growing species. Is one method more appropriate than the other for species of different life-history strategies, or should age-based methods, previous shown to be appropriate for long-lived, slow growing species be ubiquitous? This chapter reports the findings of simulations performed to test what technique is more appropriate for species of different life spans.

Clearly, species with different characteristics (e.g. growth rate, length-at-capture) will have different measures of management performance. However, within each species, management performance can also be affected by, for example, changes to the initial fishing mortality rate. These issues are described in more detail in section 5.2. The final results of the management simulations for each performance measure are then described; final year exploitable biomass (section 5.3), spawning stock biomass (section 5.4) and average catches (section 5.5).

5.2 Gauging management performance

During the initial runs of the simulation model, it was apparent that both length-based and age-based methods were particularly sensitive to:

(i) Initial fishing mortality rate
(ii) Length-at-capture

Changes to one or both parameters will impinge on the results and the interpretation of the measures used to gauge performance. These are discussed briefly below.

5.2.1 Initial fishing mortality rate (F_{start})

It is important to establish how changes in the initial fishing mortality rate might affect the interpretation of the performance measures used. A high F_{start} value implies that the initial population at equilibrium is already subject to high fishing mortality. In consequence, the biomass (spawning stock and exploitable) will already be at a low level and as a result catches are likely to be relatively poor. It is possible that if the target value and performance thresholds are set very low, decreases in fishing mortality determined by the management rule might not be sufficient to allow the stock to recover within the simulation period (20 years). This would also prevent catches from returning to sustainable levels (e.g. $Catch_{MSY}$).

Alternatively, low F_{start} values imply that the initial population at equilibrium is already lightly fished and with biomass levels relatively high, the simulations will generally start above optimal and threshold values. It is therefore less likely that biomass levels will fall below the target and threshold values as many times as a simulation starting with a high fishing mortality. A lightly exploited fishery will typically have high levels of biomass (spawning stock and exploitable) but comparatively low catches.

It is therefore important to take into consideration the starting level of fishing mortality when comparing the performance of different assessment methods. The initial fishing mortality is also sensitive to the length-at-capture since the latter will effect how much of the stock is available for exploitation (see below).

5.2.2 Length-at-capture (Lc_{50})

Lethrinus mahsena data are used here to illustrate the sensitivity of the performance measures to changes in length-at-capture. A value of Lc_{50} (30.5 cm) was obtained from the observed length frequency distribution sampled from the fishery operating at Nazareth Bank (see Pilling et al. 1999). This dataset was also used to estimate the 'true' growth parameters (L_∞, K and t_0) and co-variance matrix for *L. mahsena*.

It was found, however, that this relatively high value of Lc_{50} (70% of L_∞) truncated valuable length-at-age information from smaller individuals not sampled from the population. This reduced the amount of information available to fit a growth curve, and resulted in poor growth parameter estimation and management performance. This has been illustrated for length-based methods using Lc_{50} = 29 cm (Fig. 5.1). An arrow has been placed on each graph as a reference point to indicate where the optimal value should lie (cf. Table 5.1). Even when the growth parameters were fixed, rather than estimated, management performance was still impaired (Fig. 5.1; right hand side). Fixing growth parameters to their true value reduces the level of uncertainty within a range of additional parameters (e.g. natural mortality, Ac_{50}, $F_{0.1}$), and by starting the simulation at the optimal fishing mortality ($F_{0.1}$ = 0.82) the results form a benchmark to demonstrate the best possible performance at a high $Lc_{50.}$

To ensure a good size range of fish is available to estimate growth parameters reliably, the fisheries manager could institute a sampling programme. This would get a range of smaller fish, not otherwise possible from directly sampling the fishery. Within the model, this has been simulated by reducing the length-at-capture to 22.1 cm, This was estimated using length data obtained from both back-calculated and length-at-age samples (data from Pilling et al. 1999). This approach was undertaken for technical reasons only, and does not imply this action should be considered as a management objective of the fishery. Changes in the length-at-capture have been shown to alter the value of the performance measures used (Table 5.1).

Table 5.1 Changes to the length-at-capture and its affect on the performance measures for *Lethrinus mahsena*.

Lc_{50} (cm)	$F_{0.1}$	SSB/SSB_0	ExB/ExB_0	$Catch_{MSY}$
22.1	**0.623**	**0.156**	**0.323**	**1 040**
23	0.652	0.157	0.311	1 024
24	0.680	0.159	0.296	1 007
25	0.715	0.1623	0.272	983
26	0.739	0.166	0.249	967
27	0.770	0.172	0.207	952
28	0.798	0.176	0.134	956
29	0.825	0.1801	0.044	963
30	0.855	0.261	0.000	936
30.5	**0.871**	**0.341**	**0.000**	**906**

Table 5.1 shows that the target fishing mortality ($F_{0.1}$) increases with increasing Lc_{50}. This trend occurs because a higher length-at-capture protects a greater proportion of the adult population, thus enabling a higher proportion of the remaining fish to be caught without impinging on the population as a whole. The SSB/SSB_0 ratio increases with higher Lc_{50} values. Where the length-at-capture is greater than the length-at-maturity (Lm, 27.5 cm), fish between Lc and Lm are protected from fishing. Hence the higher the length-at-capture, the more are protected from fishing and the higher the ratio. The exploitable biomass ratio (ExB/ExB_0) decreases with increasing length-at-capture. This is because the number of fish available to be caught diminishes as the length-at-capture increases. The fact that the ratio reaches zero is simply an artefact of the model (all fish that reach Lc are immediately caught). Finally, the catch diminishes with increasing length-at-capture simply because there are less fish available to be caught, and is therefore constrained by the high Lc value.

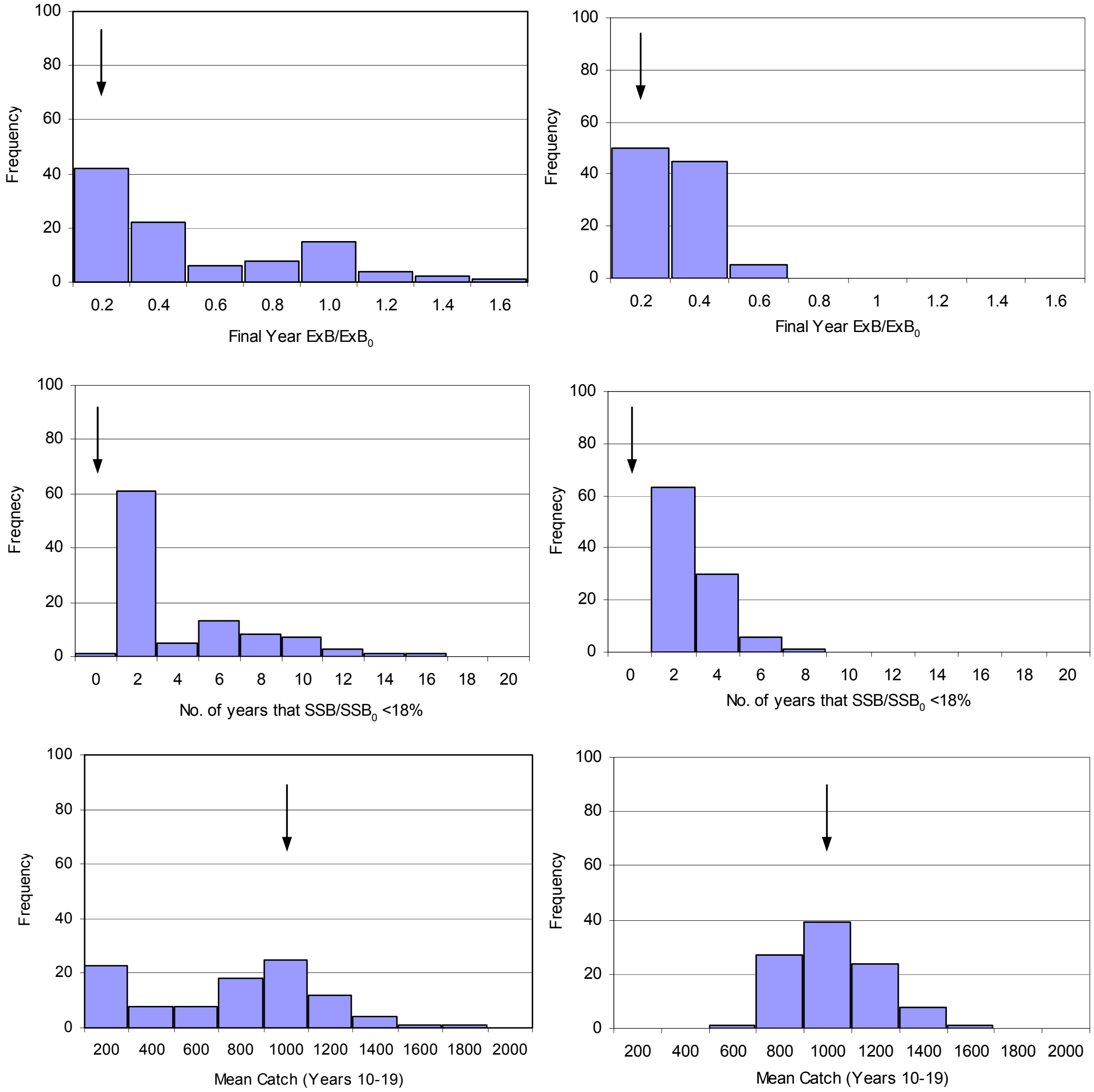

Figure 5.1 Histograms of each performance measure (top: ExB/ExB_0; middle: SSB/SSB_0; bottom: average catch) for **length-based** methods using *Lethrinus mahsena* using **generated** growth parameters (left) and **fixed** growth parameters (right) with Lc_{50} = 29 cm and an optimal starting fishing mortality $F_{start} = F_{0.1} = 0.82$.

All remaining simulations for *L. mahsena* have been conducted using the lower value of Lc_{50} (22.1 cm). This simulates a research programme that ensures that all size classes are sampled, even if they had to be obtained independently from the fishery.

Similar to *L. mahsena*, the value of length-at-capture for *Siganus sutor* was reduced to improve the initial estimates of growth (e.g. L_∞, K and t_0). This was reduced from 18 cm to 10 cm. This change also modifies the optimal values of the performance measures (see table 5.2 below).

Table 5.2 Changes to the length-at-capture and its affect on the performance measures for S*ignanus sutor*.

Lc_{50} (cm)	$F_{0.1}$	SSB/SSB_0	ExB/ExB_0	$Catch_{MSY}$
10.0	0.869	0.211	0.245	3 080
18.0	0.945	0.213	0.213	3 198

The table above demonstrates that the target fishing mortality ($F_{0.1}$) is higher for *S. sutor* than *L. mahsena* (cf. Table 5.1). It has therefore necessary to modify the range of initial fishing mortalities (F_{start}) to fit around this higher value. Without additional knowledge of specific fisheries, a range of values has been selected arbitrarily. These are 0.5, 0.75, 1.25 and 1.50.

5.3 Results

5.3.1 Final year exploitable biomass (ExB)

The ratio of the final year exploitable biomass (i.e. ExB in year 20) to unexploited biomass at equilibrium (ExB_0) was used as a measure of the probability of stock collapse. Using the parameters described in tables 3.10 and 3.11, the target ratio for *Siganus sutor* is 0.25, whereas for *Lethrinus mahsena* is 0.31. The results of 100 simulation runs have been plotted on a histogram, with an arrow marking the location of the target value. Values greater than these indicate that the fishery was under-exploited, while values less than these indicate the fishery could be over-exploitated. Ideally, there would be a narrow range of outcomes distributed closely around the target value. The results are shown here as histograms, where a value of ‘0.2’ relates to a class width extending from 0 to 0.2.

Siganus sutor

For length-based methods of estimating fishing mortality, there was a high level of variability in the final outcome (Fig. 5.2). The final exploitable biomass ratios ranged from 0.2 to 1.6 for all F_{start} levels examined. There is however, a clear trend towards lower values, which showed a skewed distribution in the results. Over 50% of cases fell below the target value at 0.2 for all F_{start} levels examined.

In comparison, the distribution of age-based fishing mortality estimates was considerably smaller, with a clear mode at the target ratio of exploitable biomass (Fig. 5.3). Between 40-50% of all age-based mortality estimates were found at the optimal value in comparison to less than 10% for length-based methods. However, although age-based methods performed comparatively better, it should be noted that they also permitted approximately 30% of runs to under-exploit the fishery while about 20% lead to over-exploitation.

Lethrinus mahsena

The distribution of outcomes from length-based methods was very similar to those previously described for *S. sutor* above. There was a high level of variability in the results, ranging from 0.2 to 1.6 for all F_{start} levels examined (Fig. 5.4). The results are highly skewed towards low ratios of exploitable biomass with 30 to 50% of all cases below the target. There is also clear evidence of a bi-modal distribution at higher F_{start} levels, with 10-15% of cases occurring at much higher ratios of exploitable biomass (0.8 - 1).

With exception to the highest F_{start} level examined (F=1.2), application of age-based methods were similar to *S. sutor* and lead to an improvement in the distribution of fishing mortality estimates (Fig. 5.5). However, the results tended to be biased towards higher estimates of F, with approximately 30-40% of cases occurring at 0.6. At the highest F_{start} level examined (F=1.2), the results showed an opposite bias towards low ExB/ExB_0 ratio values, with over 65% of cases falling below the target value.

Overall, age-based methods tended to out-perform length-based methods, leading if anything to a more precautionary management approach (bias towards higher ratios). Caution should be given, however, at high F_{start} values where age-based methods performed similar to length-based methods.

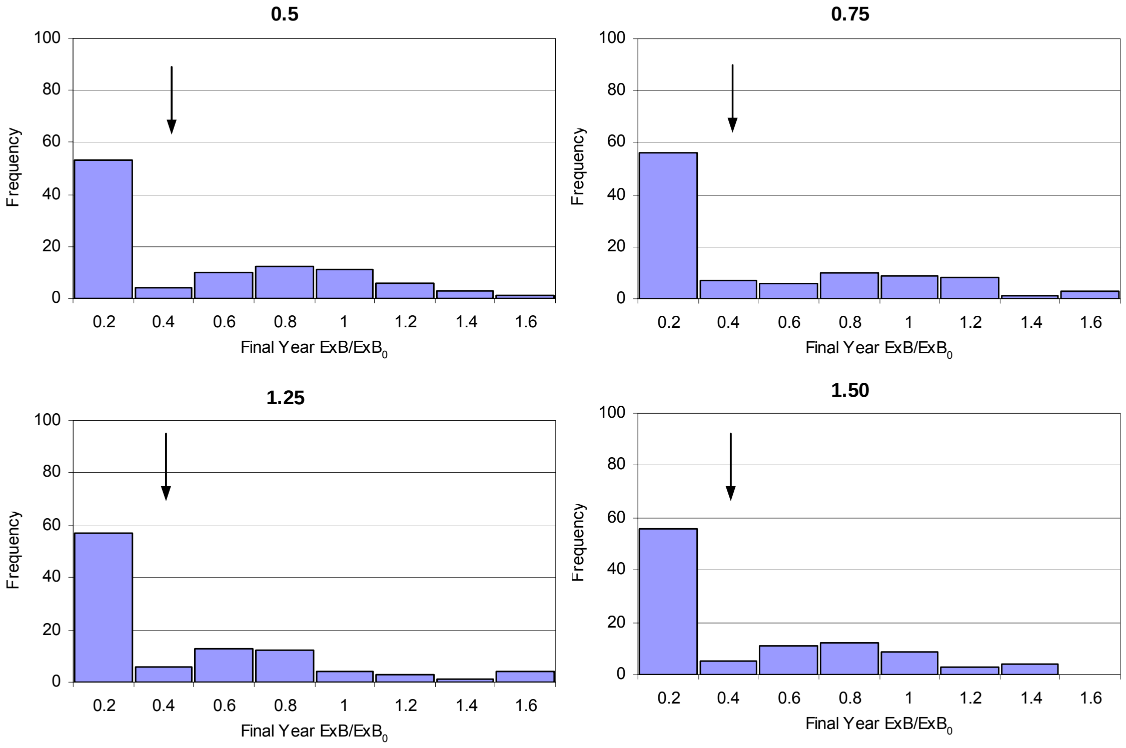

Figure 5.2 Histograms of final year ExB/ExB$_0$ for **length-based** methods for ***Siganus sutor*** for each F$_{start}$ (optimal value = 0.25).

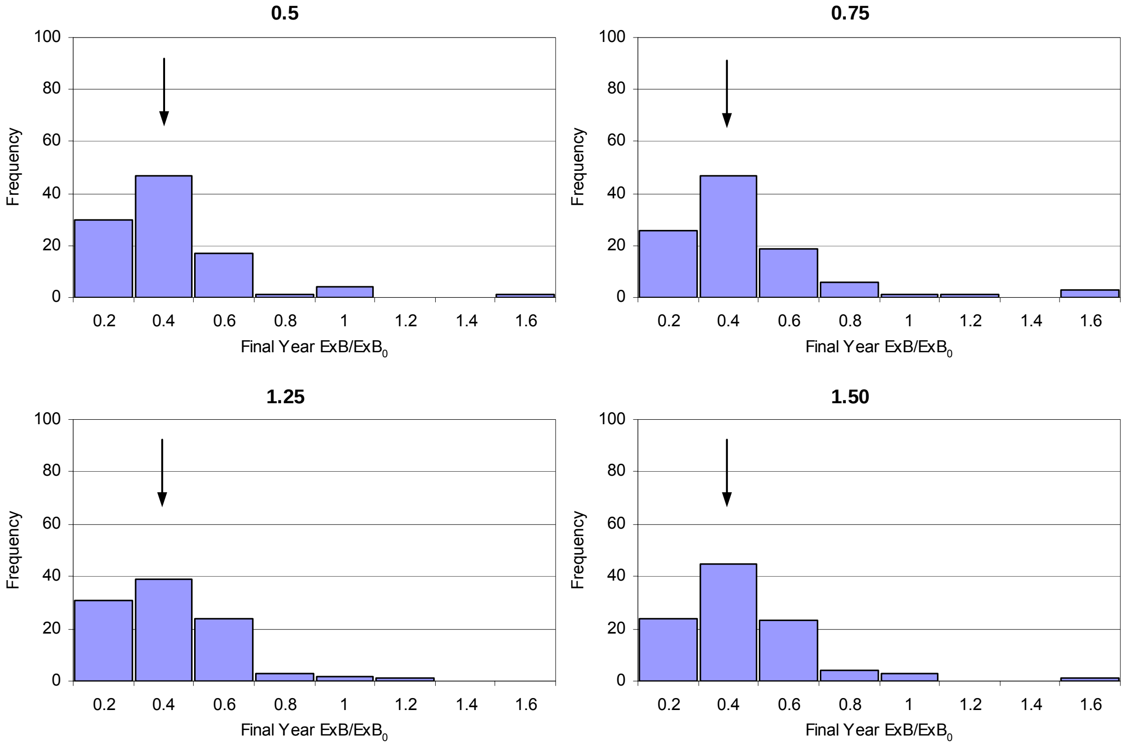

Figure 5.3 Histograms of final year ExB/ExB$_0$ for **age-based** methods for ***Siganus sutor*** for each F$_{start}$ (optimal value = 0.25).

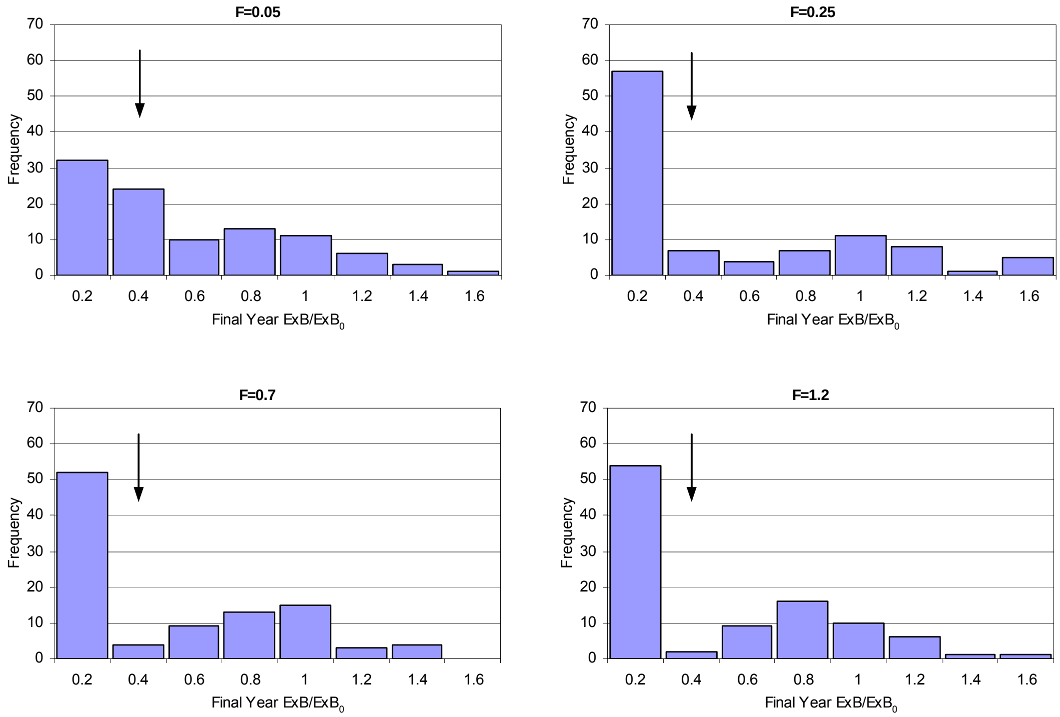

Figure 5.4 Histograms of final year ExB/ExB$_0$ for **length-based** methods for ***Lethrinus mahsena*** for each F_{start} (optimal value = 0.31).

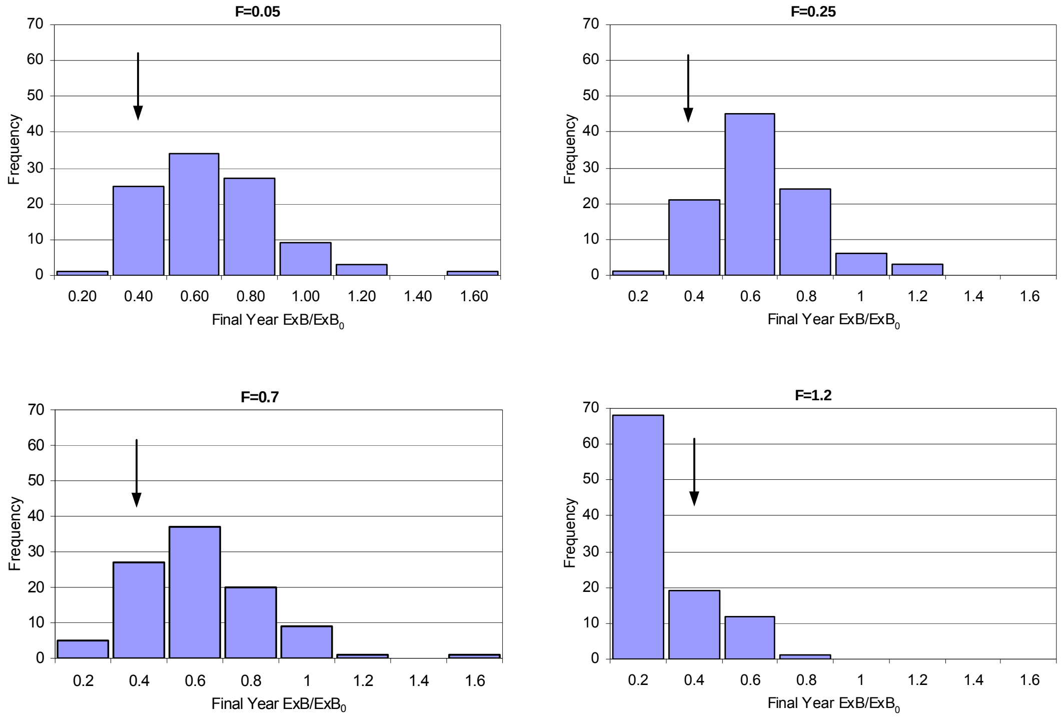

Figure 5.5 Histograms of final year ExB/ExB$_0$ for **age-based** methods for ***Lethrinus mahsena*** for each F_{start} (optimal value = 0.31)

5.3.2 Spawning stock biomass (SSB)

Spawning stock biomass is used in addition to the exploitable biomass as a conservation measure to assess the status of the stock. The frequency over the 20-year management period with which the SSB dropped below a threshold value of unexploited levels was used as a measure of sustainability. The threshold value, calculated for both species as the equilibrium SSB/SSB$_0$ ratio when F = F$_{MSY}$,, was obtained from the Yield software. Section 4.5 indicated that if SSB frequently fell below the threshold value there was a danger of recruitment overfishing. However, if the population rarely fell below these threshold values, this would indicate that the population was likely to remain within sustainable levels within the majority of the management period.

Section 5.2 also highlighted that the value of starting fishing mortality level (F$_{start}$) was an important consideration when attempting to gauge the results of spawning stock biomass performance measures. At the target fishing mortality level (F$_{0.1}$; 0.87 for *S. sutor* and 0.62 for *L. mahsena*) the spawning stock biomass threshold value was 22% for *Siganus sutor* and 16% for *L. mahsena*. Where starting levels of fishing mortality are greater than the optimal level (i.e. F$_{start}$ > F$_{0.1}$), the SSB is already below the threshold level of SSB$_0$ at the start of the simulation. Under these circumstances, no simulation run will ever have ‘zero years’ when the SSB/SSB$_0$ ratio is below the threshold level. The most appropriate management objective would therefore be to minimise the number of years in which SSB/SSB$_0$ falls below the threshold value.

The results are presented here in the form of histograms. With exception to the first class width, which represent zero values only, the remaining class widths represent 2 years (e.g. ‘4’ includes both years 3 and 4).

Siganus sutor

The spawning stock biomass threshold value for *S. sutor*, calculated from simulation outputs, was 22%. Figures 5.6 and 5.7 show the number of years within the 20-year simulation period that the spawning stock biomass ratio fell below this threshold for length-based and age-based methods respectively.

For length-based methods, there were no cases in which the spawning stock biomass never fell below the threshold value. Interestingly however, the results show a bi-modal distribution, with peaks at both low (years 2 to 4) and high (years 16 to 20) values. At low F$_{start}$ levels, between 20-30% of cases fell below the threshold value between 2 and 4 years. At higher F$_{start}$ levels, between 30-40% of cases always fell below the threshold value (i.e. in all 20-years).

Where age-based methods were used, there were also no cases in which the spawning stock biomass never fell below the threshold value. However, age-based methods performed considerably better than length-based methods for all F$_{start}$ levels examined. At F$_{start}$ = 0.5, the number of years in which the spawning stock biomass fell below 22% was between 2 and 14 years. As the F$_{start}$ level increased, the range in the number of years in which the spawning stock biomass fell below the threshold also increased. However, at F$_{start}$ = 1.5, only 2% of cases had a spawning stock biomass below the threshold value for the entire 20-year management period, in comparison to 42% for length-based methods.

Lethrinus mahsena

The spawning stock biomass threshold value for *L. mahsena* is 16%. Figures 5.8 and 5.9 show the number of years within the 20-year management period that the SSB fell below this threshold value for length-based and age-based methods respectively.

At low F_{start} levels of 0.05 and 0.25, length-based methods had shown 42% and 62% of cases had no years when the SSB was below the threshold value, respectively. This changed however, at higher F_{start} levels (0.7 and 1.2), where 56% of cases had never exceeded the threshold value throughout the entire 20-year management period. It is interesting to note that the distribution of results showed a similar bi-modal trend to that reported for *S. sutor*.

Where age-based methods were used, lower F_{start} levels resulted in good management performance, with SSB remaining above 16% of unexploited levels in 94% and 82% of the runs for F_{start} levels of 0.05 and 0.25 respectively (Fig. 5.9). At higher starting levels of fishing mortality (0.7 and 1.2), there is a notable decline in the performance of age-based methods. Both these higher values are above the target level of fishing mortality ($F_{0.1}$ = 0.62), and the stock is therefore already below the SSB threshold. However, it is only at the extreme value of F_{start} (1.2), that age-based methods perform relatively poorly, with over 80% of cases falling below the SSB threshold in every year of the management period.

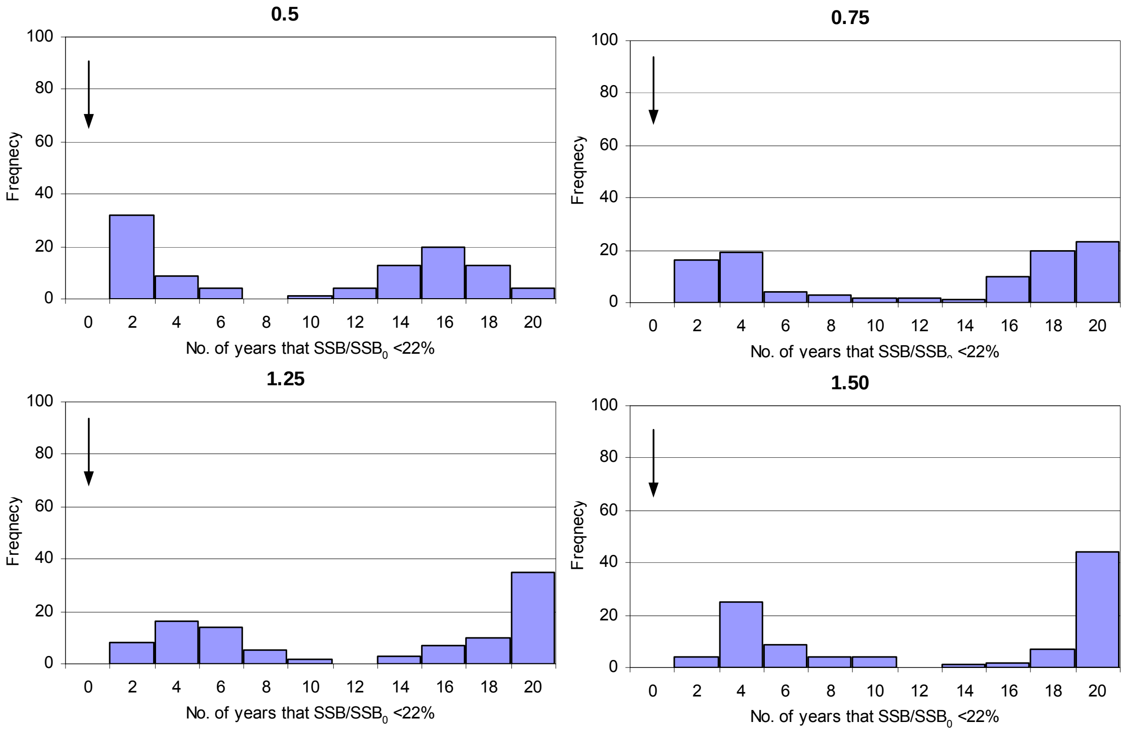

Figure 5.6 Histograms of the frequency over a 20-year management period that the SSB fell below 22% of SSB_0 for **length-based** methods for ***Siganus sutor*** for each F_{start}.

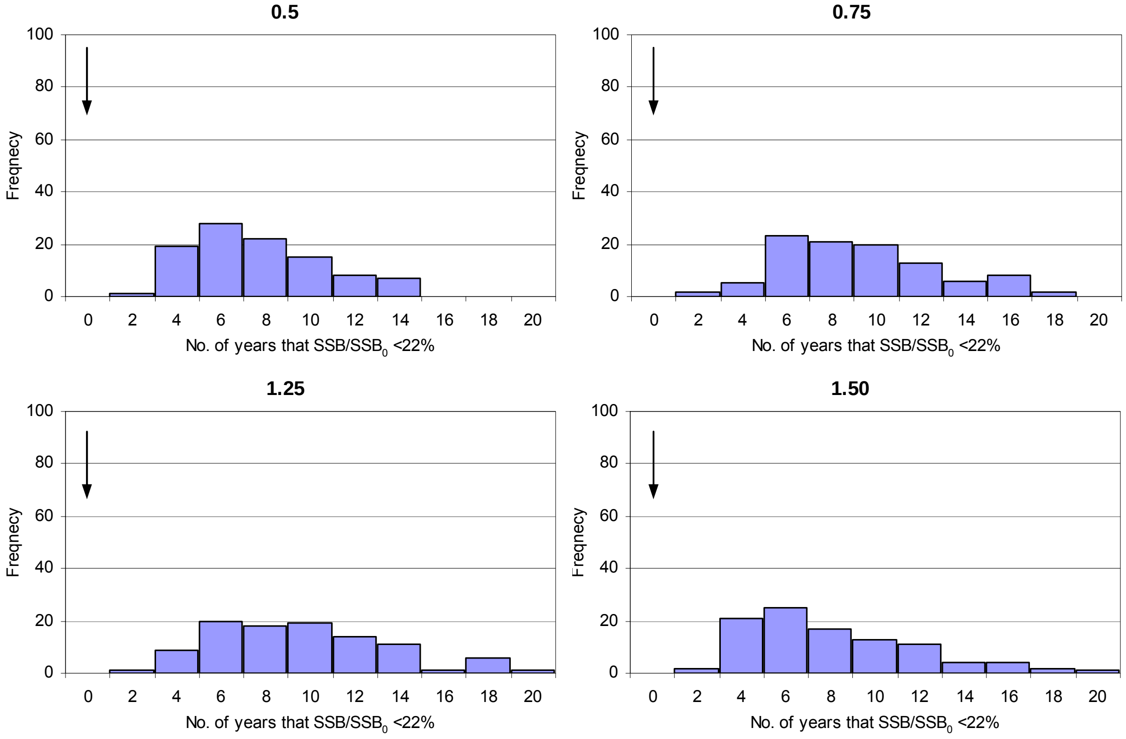

Figure 5.7 Histograms of the frequency over a 20-year management period that the SSB fell below 22% of SSB_0 for **age-based** methods for ***Siganus sutor*** for each F_{start}.

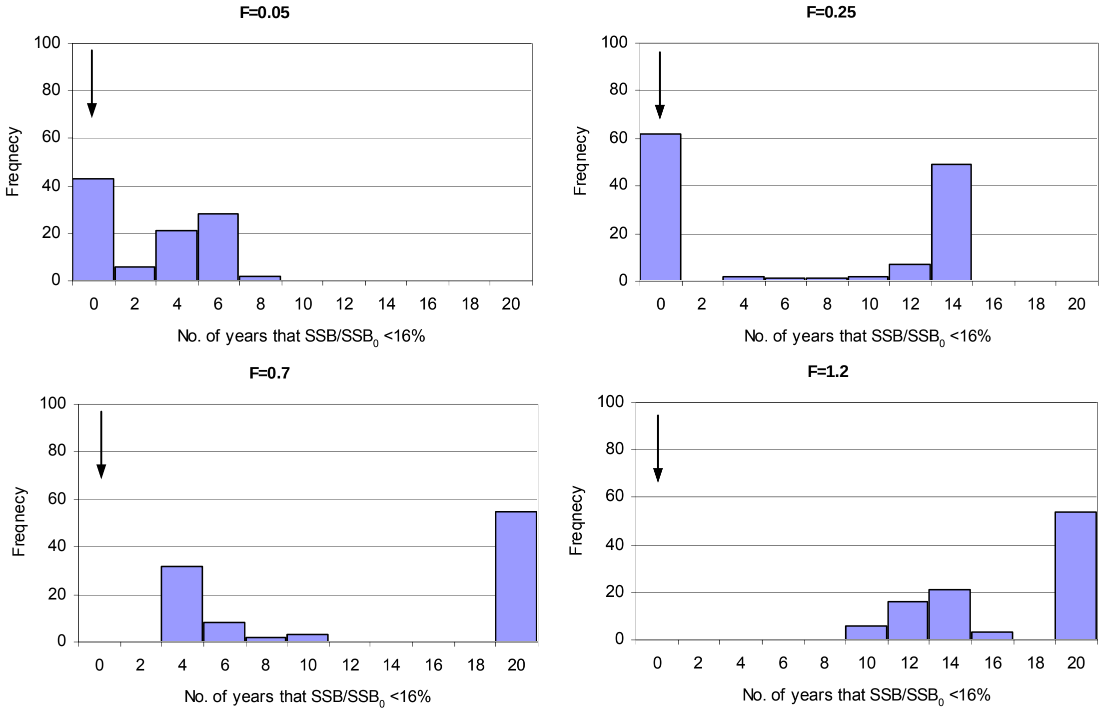

Figure 5.8 Histograms of the frequency over a 20-year management period that the SSB fell below 16% of SSB_0 for **length-based** methods for ***Lethrinus mahsena*** for each F_{start}.

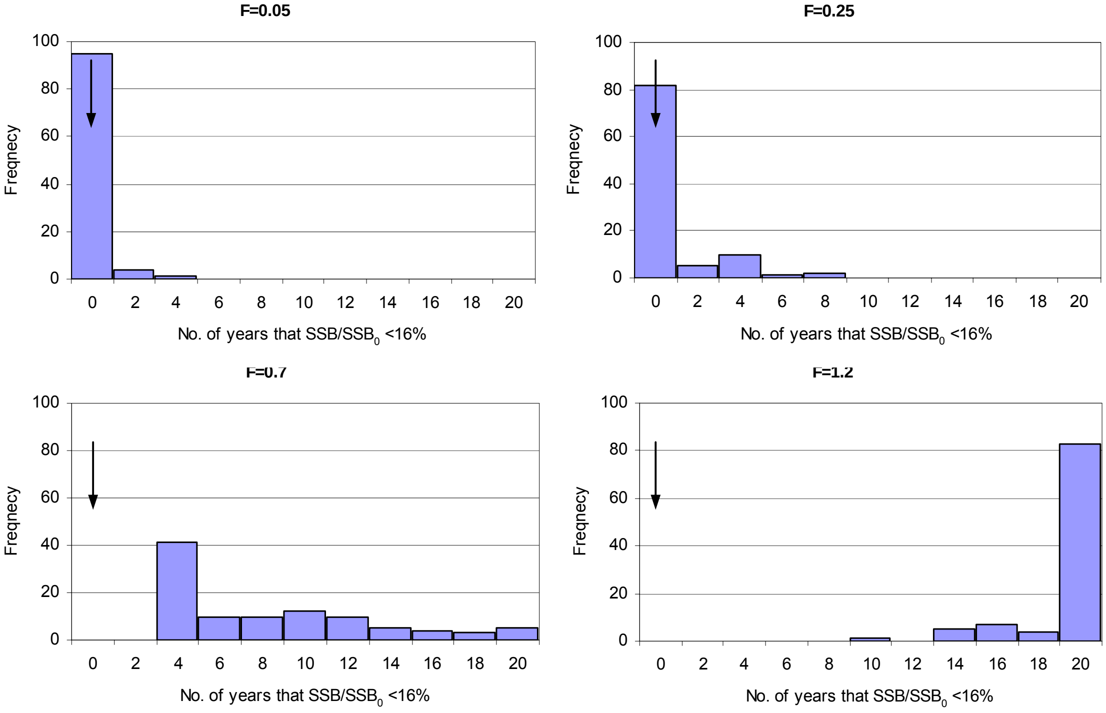

Figure 5.9 Histograms of the frequency over a 20-year management period that the SSB fell below 16% of SSB_0 for **age-based** methods for ***Lethrinus mahsena*** for each F_{start}.

5.3.3 Average catch

The average catch was used as a fleet performance measure to compare the success of each assessment method. Due to potentially large fluctuations in the total annual catch at the start of the management period, the average was calculated from the last 10 years of management (i.e. 10 – 19 yrs). The range of values obtained from the 100 simulation runs was then compared to the optimal value, the maximum sustainable yield (Catch_{MSY}). For *Siganus sutor* this was calculated as 3 080 units and 1 040 units for *Lethrinus mahsena*. Due to assumptions made about the level of recruitment, these values should not be considered as actual yields that can be taken from the fishery. Instead, they are relative values used for comparative purposes only. These have been plotted on each histogram with an arrow to assist comparison with the simulation results.

Siganus sutor

The average catch per year for each simulation can be compared to the optimal value, the maximum sustainable yield (from simulation outputs, Catch_{MSY} = 3 080 units). Figures 5.10 and 5.11 show the average catch per year for each starting effort for both length-based and age-based methods respectively.

For length-based methods, the results for all F_{start} levels show a skewed distribution in catches towards low values (1 000 units). Increasing the F_{start} level from 0.5 to 1.5 decreases the management performance by increasing the number of cases that have very low catches (from 38% to 54% respectively). The highest proportion of optimal catches is attained at the lowest F_{start} level (29% of cases).

Where age-based methods are used, optimal catches were obtained for F_{start} levels from 40-52% of cases. The remaining distribution of catches was found to be close to the optimum value for all F_{start} levels. In addition, a larger number of cases had higher catches than the equivalent length-based method.

The management performance of age-based methods has been shown to be very good, although without comparative analysis of the biomass, higher catches might lead to over-exploitation of the stock (see section 5.6).

Lethrinus mahsena

The average catch per year for each simulation can be compared to the optimal value, the maximum sustainable yield (from simulation outputs, Catch_{MSY} = 1 040 units). Figures 5.12 and 5.13 show the average catch per year for each starting effort for both length-based and age-based methods respectively.

For length-based methods, the pattern of results from each F_{start} level are similar to that previously described for the exploitable biomass (ExB, see section 5.3). The results are skewed towards lower values, although there is evidence of a bi-modal distribution at lower F_{start} levels.

At F_{start} = 0.05, a wide range of average catches was reported between 200 and 2,000 units, although two peaks in the number of catches were observed at 200 and 1 200 units. As the F_{start} level increased, the range of observed catches decreased (200 – 1 800 units at 0.25;

200 – 1 000 units at 1.2), and the number of small catches increased. At an F_{start} = 1.2, 81% of cases produced an average catch of 200 units.

In comparison to length-based methods, average catches derived from age-based methods were more evenly distributed around the optimal value. At low F_{start} levels (0.05) 19% of cases had an optimal catch, compared to only 4% for length-based methods. As the F_{start} level increased, the average catch declined until at F_{start} = 1.2, 39% of cases had an average catch of only 600 units. The distribution of catches may be linked to the available biomass at different F_{start} levels (see section 5.6).

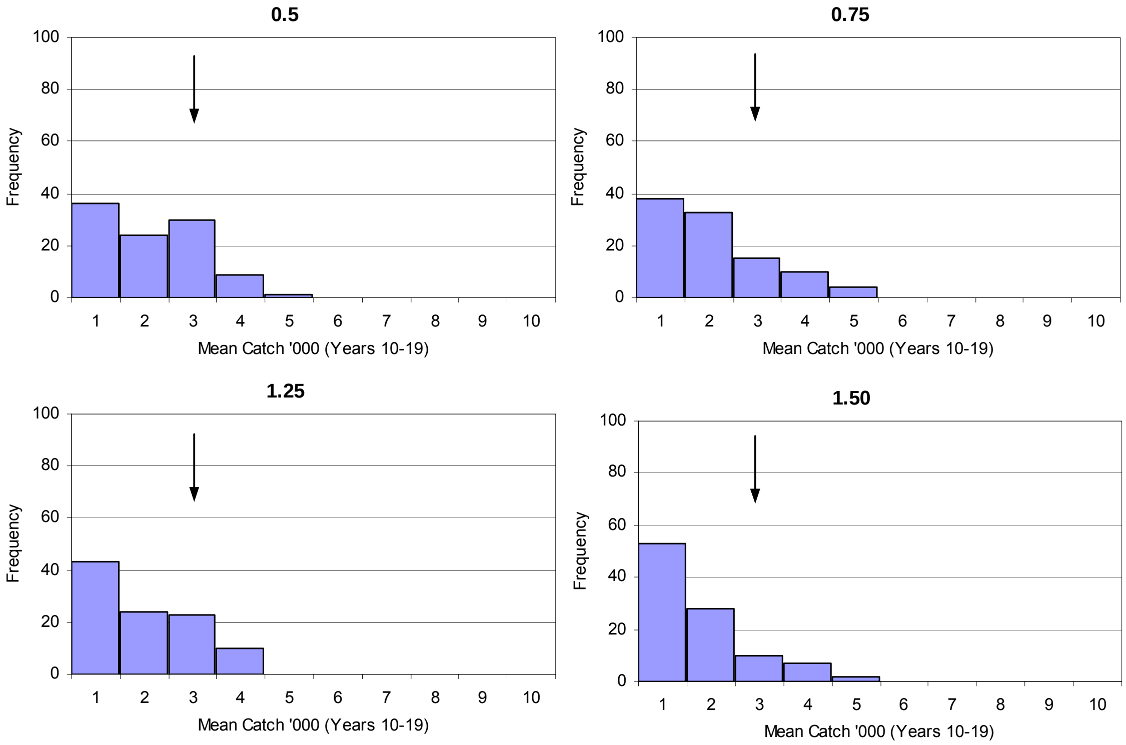

Figure 5.10 Histograms of the average catch for **length-based** methods for ***Siganus sutor*** for each F_{start} (optimal value = 3 080).

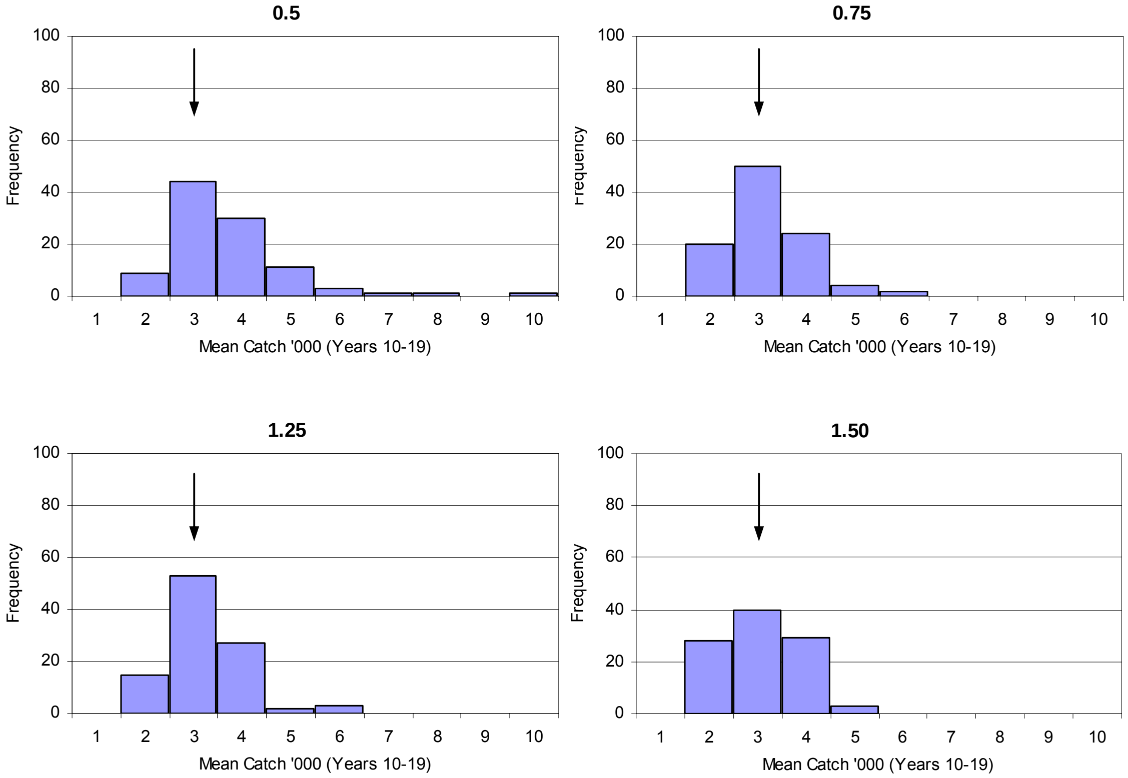

Figure 5.11 Histograms of the average catch for **age-based** methods for ***Siganus sutor*** for each F_{start} (optimal value = 3 080).

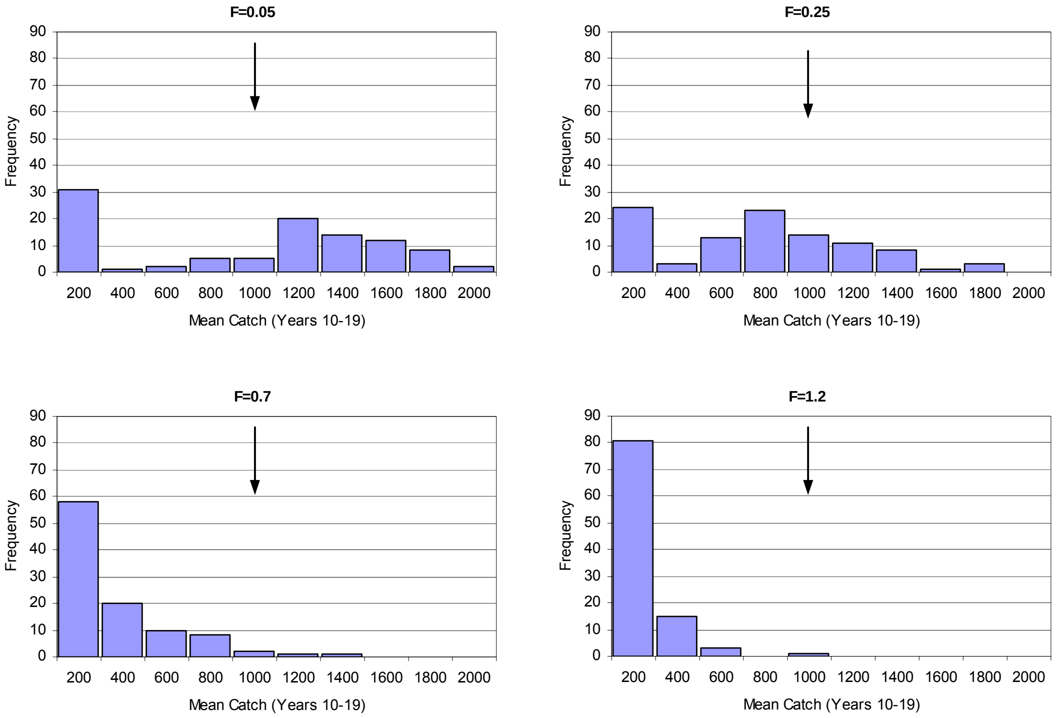

Figure 5.12 Histograms of the average catch for **length-based** methods for ***Lethrinus mahsena*** for all F_{start} (optimal value = 1 040).

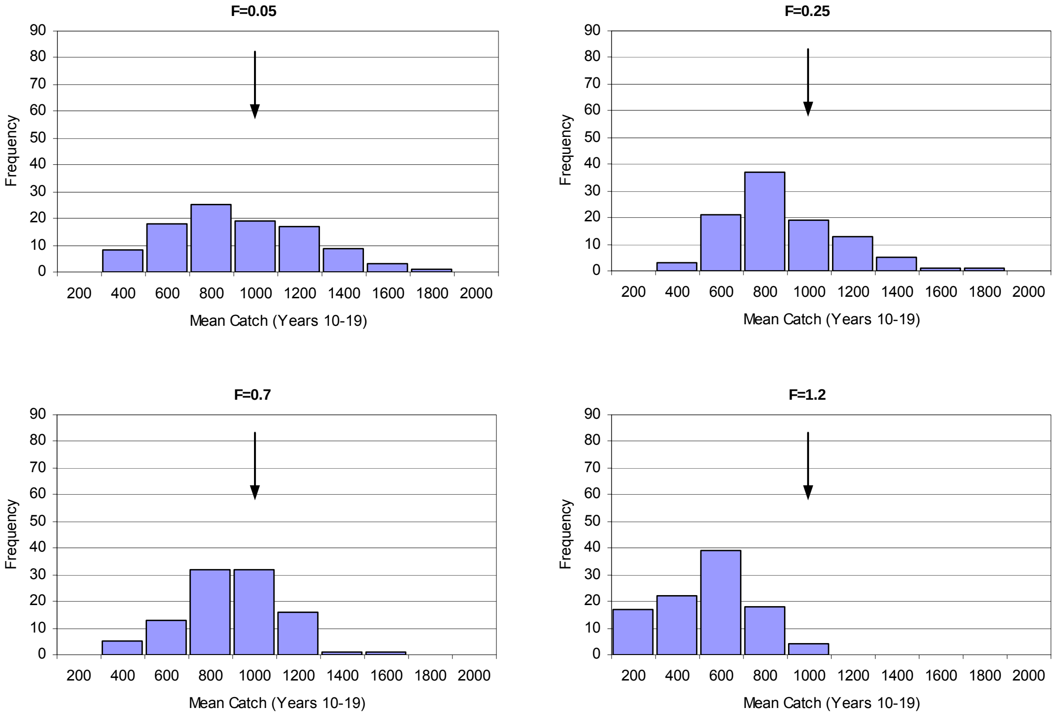

Figure 5.13 Histograms of the average catch for **age-based** methods for ***Lethrinus mahsena*** for all F_{start} (optimal value = 1 040).

5.4 Discussion

5.4.1 Synthesis of management performance

Several performance measures have been used to gauge the relative success of both length-based and age-based methods to manage a stock that will lead to long-term sustainability of the resource.

Exploitable Biomass

The ratio of the level of exploitable biomass (ExB) in the final year of the 20-year management period to that of the equilibrium exploitable biomass (ExB_0) was used to compare against a species-specific target value. The results showed clearly that age-based methods led to better management performance for moderately short-lived, fast growing reef species such as *Siganus sutor*. However, it should be noted that the results were not particularly accurate since they also permitted approximately 30% of runs to under-exploit the fishery while about 20% lead to over-exploitation.

The results were less obvious for long-lived, slow growing reef species such as *Lethrinus mahsena* (cf. Fig. 5.5). At the highest F_{start} level (1.2), a high frequency of low ratio values ($ExB/ExB_0 = 0.2$) was obtained from age-based methods, which were below the target value. The poor performance of age-based methods at high F_{start} levels is due partly to the assessment method, which produces underestimates of the true F (Fig 5.14, left). In addition, estimates of M calculated from age-based growth parameters may also be inaccurate due to the absence of larger individuals in a heavily exploited fishery. This is expected to lead to further bias in the assessments.

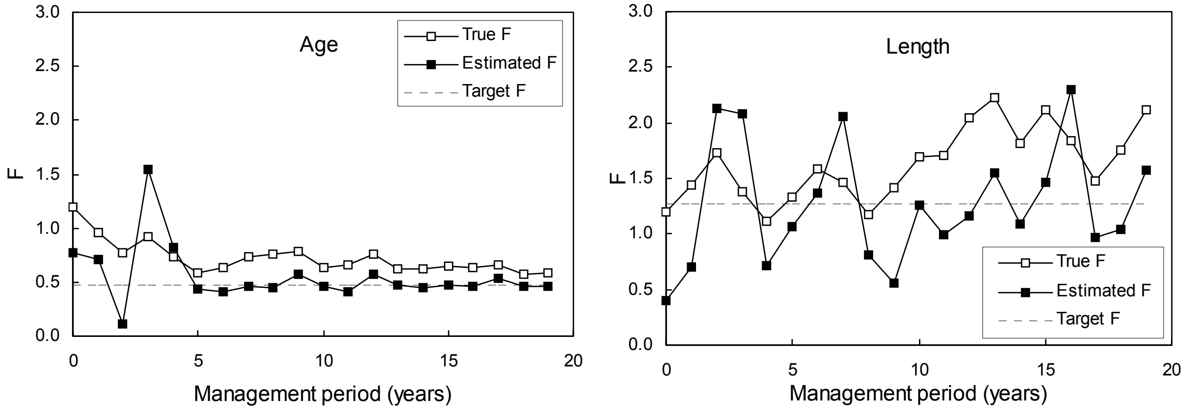

Figure 5.14 Example of an individual simulation run from age-based (left) and length-based (right) methods for *L. mahsena* with a starting fishing mortality of F = 1.2 (True $F_{0.1} = 0.62$).

In contrast, length-based methods of estimating fishing mortality are less accurate and can change substantially from year-to-year, even when they have reached the target value (Fig. 5.14 right). Clearly, this scenario also leads to an over-exploitation of the stock, but the overall management performance is a considerably worse than age-based methods.

Spawning stock biomass

Spawning stock biomass is used in addition to the exploitable biomass as a conservation measure to assess the status of the stock. The frequency over a 20-year management period with which the SSB dropped below a threshold (rather than target) value of unexploited levels was used as a measure of sustainability.

Throughout this chapter, this performance measure has been sometimes difficult to interpret fully. Careful consideration must be given to the results starting at different F_{start} levels, but the bi-modal distribution in the results generated from length-based methods were quite unusual (cf. Figs. 5.6 and 5.8).

Examination of individual simulation runs reveals that a bi-modal distribution can occur if F is consistently under- or over-estimated (Fig 5.15).

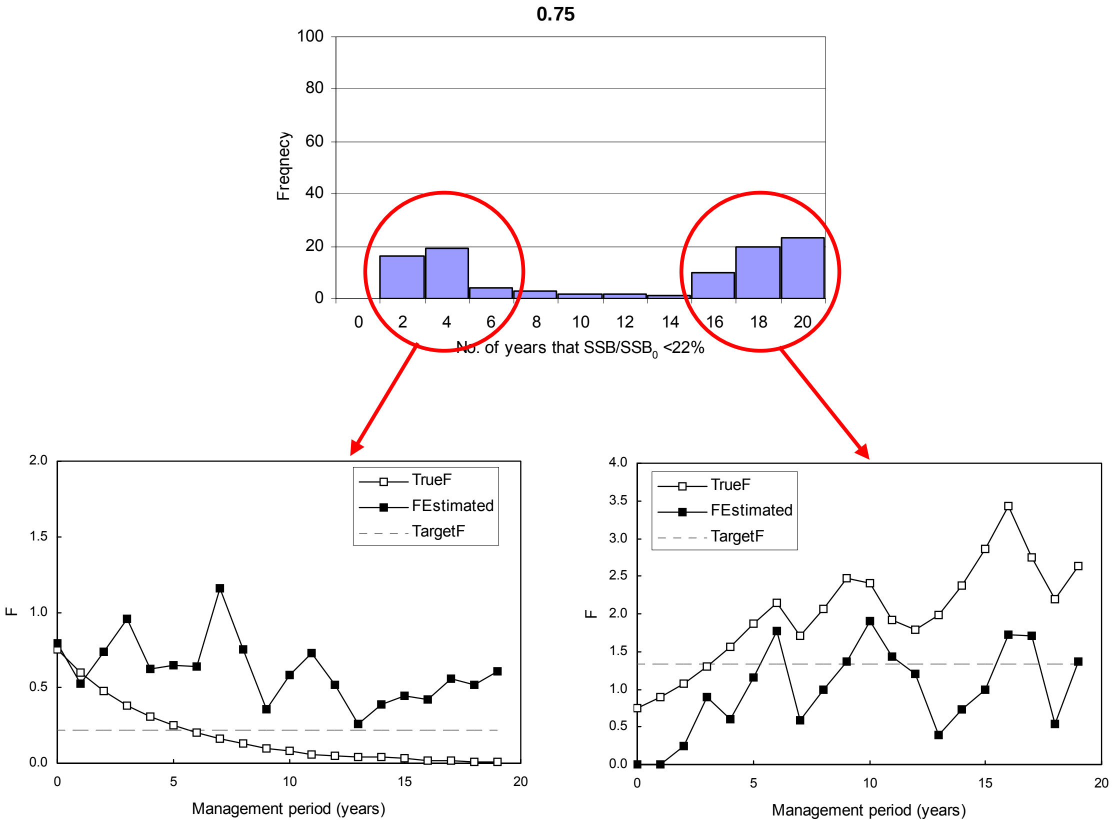

Figure 5.15 An example of length-based methods to determine the status of spawning stock biomass for *Siganus sutor* at a starting level of fishing mortality of 0.75 (top). The bi-modal distribution can be attributed to either very low or very high values in the true fishing mortality (bottom) (True $F_{0.1}$ = 0.87).

Average Catch

The average catch was used as a fleet performance measure to compare the success of each assessment method. Due to potentially large fluctuations in the total annual catch at the start of the management period, the average was calculated from the last 10 years of management (i.e. 10 – 19 years). These values were then compared to the optimal value, the maximum sustainable yield.

The level of catches is determined to a greater extent on the availability of exploitable biomass. Low catches observed for both length-based and age-based methods and for both species is due to the low level of exploitable biomass available.

5.4.2 Comparison of reef species with different life-history strategies

Moderately short-lived, fast growing species (*Siganus sutor*)

Length-based methods reduced the exploitable biomass below the target ratio in over 50% of cases for all starting levels of fishing mortality (F_{start}). Low values of exploitable biomass were reported even at relatively low fishing mortalities ($F_{start} = 0.5$), because the estimated target level ($F_{0.1}$) was set very high, which allowed the management rule to continue increasing fishing mortality far beyond sustainable levels. In contrast, the other remaining cases had enabled the exploitable biomass to recover to values around the equilibrium level (ExB_0). This observation could again be attributed to the poor estimation of the target level ($F_{0.1}$), which this time had been estimated too low. The inability of length-based methods to accurately estimate the true value of fishing mortality led the management rule to decline fishing mortality to very low levels.

In comparison, age-based methods reduced the exploitable biomass to reach the target ratio in 40 - 50% of cases for all starting levels of fishing mortality (F_{start}) examined. This was a considerable improvement over length-based methods, which had shown less than 10% of cases reach the target ratio. Exploitable biomass target ratios were achieved even at relatively high fishing mortalities ($F_{start} = 1.5$). This surprising result was due partly to an accurate estimate of the target fishing level ($F_{0.1}$), which enabled the management rule to decrease fishing mortality to sustainable levels.

The observed range of exploitable biomass also impinged on the average catch. At low F_{start} levels, the high proportion of cases that led to a low exploitable biomass also resulted in high catches, since there was sufficient biomass at the start of the management period to sustain relatively high catches. However, at higher F_{start} levels, the exploitable biomass was already at very low levels, and it requires a reduction in fishing mortality brought about by a low target value ($F_{0.1}$) to increase catches. The results show that at higher F_{start} levels, even a reduction in fishing mortality is not always sufficient to enable the stock to recover to produce optimal catches, and the majority are relatively poor.

The ability of age-based methods to exploit the population approaching optimal levels is also seen in the results generated for average catches. For all starting levels of fishing mortality (F_{start}) examined, the average catch was closely distributed around the optimal value (maximum sustainable yield).

An evaluation of the spawning stock biomass ratio is complex. Length-based methods have shown a bi-modal distribution that is partly attributed to the poor estimation of the target fishing level ($F_{0.1}$). In cases where the spawning stock biomass was reduced to below the threshold value in only several of the 20-year management period, it was found that the estimated target fishing mortality ($F_{0.1}$) was also very low. Hence, the overall reduction in fishing mortality required to reach the target level would lead to higher levels of spawning stock biomass. Conversely, in cases where the spawning stock biomass was reduced to below the threshold value for the majority of the 20-year management period, this was due to high levels of estimated target fishing mortality ($F_{0.1}$). A fisheries manager would have to exceed the optimal level of fishing mortality in order to reach the over-estimated target value. Obviously this greatly reduces the chance of long-term sustainability, and puts the stock in danger of over-exploitation.

Similar to length-based methods, there were no reported cases from the results of age-based methods in which the spawning stock biomass was kept above the threshold value for the entire 20-year management period. In comparison, the number of times that the spawning stock biomass fell below the threshold followed a normal distribution with a mode at 6 years. Although some of the cases from length-based methods perform better (2 - 4 years), these were obtained from exceptionally low target fishing levels ($F_{0.1}$), which caused the management rule to reduce fishing mortality to below optimal levels.

Long-lived, slow growing species (*Lethrinus mahsena*)

Length-based methods reduced the exploitable biomass below the target ratio in at least 30% of cases for all starting levels of fishing mortality (F_{start}). Low values of exploitable biomass were reported even at relatively low fishing mortalities ($F_{start} = 0.5$), because the estimated target fishing level ($F_{0.1}$) was set very high, which allowed the management rule to continue increasing fishing mortality far beyond sustainable levels. In contrast, the other remaining cases had enabled the exploitable biomass to recover to values around the equilibrium level (ExB_0). This observation could again be attributed to the poor estimation of the target level ($F_{0.1}$), which this time had been estimated too low. The inability of length-based methods to accurately estimate the true value of fishing mortality, led the management rule to decline fishing mortality to very low levels.

In comparison, when using age-based methods to estimate fishing mortality (F_{curr}), there was less variability than length-based methods about the exploitable biomass target ratio and the results were also more accurate. With exception to the highest F_{start} level, a higher proportion of cases were reported close to the optimal value (20-30%) or below. This suggests that age-based methods are likely to be more conservative or precautionary than length-based methods. In contrast, the highest F_{start} level ($F = 1.2$), showed a bias towards low ExB/ExB_0 ratio values, with over 65% of cases falling below the optimal value. The poor performance of age-based methods at high F_{start} levels was observed to be due to both the characteristics of the model and the assessment methodology.

Similar to *S. sutor*, the observed range of exploitable biomass had a direct impact on the level of catches. At low F_{start} levels for length-based methods, the high proportion of cases that led to a low exploitable biomass also resulted in moderately high catches, since there was sufficient biomass at the start of the management period to sustain relatively high catches. However, at high F_{start} levels, the exploitable biomass was already at very low levels, and it requires a reduction in fishing mortality brought about by a low target value ($F_{0.1}$) to increase catches. The results have shown that even at high F_{start} levels, a reduction in fishing mortality is not always sufficient to enable the stock to recover within the 20-year management period to produce optimal catches, and the majority are relatively low in comparison.

With exception to highest F_{start} level, age-based methods produced an average catch that was closely distributed around the optimal value (maximum sustainable yield). Similar to length-based methods, at higher F_{start} levels, the exploitable biomass is already at very low levels, and it requires a reduction in fishing mortality brought about by a low target value

($F_{0.1}$) to increase catches. The results show that at higher F_{start} levels, even a reduction in fishing mortality is not always sufficient to enable to stock to recover to produce optimal catches. As a result, the majority of catches are consistently below the maximum sustainable yield.

Length-based methods of assessment showed the results of the spawning stock biomass performance measure to be clearly bi-modal in distribution. At low F_{start} levels, a high proportion of cases (40-60%) never fell below the SSB threshold value. This was partly attributed to a low estimate of the target fishing level ($F_{0.1}$), but also to the inaccuracy of length-based methods to estimate fishing mortality (F_{curr}). Hence, the overall reduction in fishing mortality required to reach the target level would lead to over-precautionary levels of fishing mortality, and an under-exploitation of the stock. Conversely, in cases where the spawning stock biomass was reduced to below the threshold value for the majority of the 20-year management period, these were partly due to over-estimates of the target fishing level ($F_{0.1}$). Under these circumstances a fisheries manager would have to exceed the optimal level of fishing mortality in order to reach the inaccurate target fishing value. Obviously this greatly reduces the chance of long-term sustainability, and puts the stock at higher risk of over-exploitation.

For age-based methods, at low F_{start} levels a high proportion of cases (80-90%) were reported to have maintained the spawning stock biomass above the threshold value for the entire 20-year management period. Unlike length-based methods, however, this was due to good management performance that had more accurately estimated both the target level ($F_{0.1}$) and the fishing mortality (F_{curr}). The improved accuracy of age-based methods also prevented the stock from being very under-exploited, which helped maintain catches around the maximum sustainable yield. With exception to the highest value examined, when the F_{start} level is above the optimal value (i.e. $F_{start} > F_{0.1}$), over 40% of cases are still reported to have only 3-4 years when the SSB was below the threshold value. This was because at higher F_{start} levels, the SSB was already starting below the threshold value.

At the highest F_{start} level examined (F=1.2) age-based methods showed little or no improvement in management performance over length-based methods. This was due partly to poor estimation of growth parameters brought about by the reduction of large individuals from the population by fishing activities.

6 Conclusions

This study forms part of a cluster of FMSP projects that have specifically looked at the performance of length-based and age-based methods for managing reef species with different life histories.

This study has reviewed the use of age-based and length-based methods in assessment worldwide, which has helped to gauge the relative importance of each method currently being used. Management strategy simulation has then been used to study the overall management performance of both length-based and age-based methods and provide a series of recommendations and guidelines for reef species with different life-history strategies.

Similar to previous studies, the objective was not to establish an optimum management strategy. As a result, the comparison of different management strategies was not central to the study. Therefore, the management rule used in Project R6465 was used. This rule was a fixed percentage management rule using a 20% increase and 16.7% decrease. As noted in Project R6465, alternative management actions may achieve different results in terms of management performance.

6.1 Review of length-based and age-based assessments

This study has examined the range of analytical stock assessment methods available to developing countries. This has concentrated on three methods of increasing complexity: exploitation rate, yield-per-recruit, and VPA/cohort analysis. As noted in section 2.3, all three approaches examined can be used based on length- or age-based growth parameter estimates (Exploitation rate, YPR), or length- or age-frequency data (VPA). However, there is a tendency to use age-based information within VPAs. Indeed, 76% of cases where VPA had been used to assess stocks used age-based methodologies.

Through literature reviews, information on the performance of each stock assessment method has been described. This description was kept deliberately basic, since the performance of a methodology will vary with parameters such as the biology of the species examined and the historical pattern of exploitation. For each assessment method, the pattern of its use across the globe was examined. Through a multivariate statistical analysis (PCA), variables that may influence the use of age- and length-based methods in a particular fishery were identified.

The growth (life history) of a fish or fish stock may influence the methodology used to assess a stock. Faster growing species appeared to be assessed most frequently through length-based methods, while slower growing species appeared to be assessed through age-based methods. This would appear appropriate, since the results of length-based methods are likely to be more accurate for faster growing fish, since modes in the length frequency data will be more widely spaced. This was examined in Chapter 5 and is discussed in section 6.2 below. However, this pattern was comparable to that found in the bias of growth parameters estimated through length- and age-based approaches. Length-based methods tended to overestimate K and underestimate L_∞ for long-lived, slow-growing species (Pilling et al. 1999).

There was therefore uncertainty over the influence of the growth estimation method on the growth parameter estimates. Hence a further assessment was made, with the growth parameters excluded. This examined the influence of the other parameters on the use of each growth assessment method. The most important factors were GNP and latitude, which were positively correlated. The use of age-based parameters appears limited to richer nations, which are generally at higher latitudes, and important industrial fisheries, which are also generally found in higher latitudes.

6.2 The suitability of length-based and age-based methods for species with different life history strategies

Studies performed during FMSP project R6465 (Pilling et al. 1999) indicated that age-based growth parameter estimates resulted in the most accurate management actions for long-lived, slow growing species. Despite this, management based on biological reference points derived using these parameter estimates still showed considerable variability. In part, this resulted from uncertainty that remained in the growth parameter estimates, despite the improvements resulting from the use of age-based growth parameter estimation methods. Variability also resulted from the use of length-based methods to assess biological parameters and reference points.

FMSP project R7522 (Pilling et al. 2000) suggested that the use of further age-based approaches could reduce this uncertainty. These approaches included the use of age-based total mortality estimation methods and avoided the need to use uncertain growth parameter estimates in the estimation process. The results indicated that age-based methods of total mortality estimation improved the ability of fisheries managers to accurately manage a fish stock. The use of age-frequencies, however, was considered unrealistic and the current FMSP project (R7835) has enabled use of an age-length-key. In addition to these changes, this study has been extended to investigate the suitability of length-based and age-based methods of assessment for species with different life histories. It was originally intended to investigate a range of species with different life history strategies. However, a crucial limiting factor determining the selection of species was the need to have back-calculated lengths at age for individual fish in order to calculate the covariance matrix for individual growth parameters. Due to several factors including time contraints, this was eventually limited to two species only; *Lethrinus mahseana* and *Siganus sutor*. In the absence of good information, it was felt inappropriate to simulate individual growth parameters for additional species.

The results of the management strategy simulation, using a pragmatic management approach to data collection and analysis, have demonstrated that age-based methods of assessment consistently out-perform length-based methods for both moderately short-lived, fast growing species such as *Siganus sutor*, and long-lived, slow growing species such as *L. mahsena*.

Length-based methods have been shown to be consistently inaccurate, which could either lead to very precautionary management with high levels of under-exploitation, or high levels of over-exploitation of the stock. In contrast, with exception to very heavily exploited fisheries, age-based methods are more likely to manage the stock around optimal levels, leading to long-term sustainability of the resource. There are two important features of the results that underpin the success of age-based methods:

(iii) Provide accurate estimates of the target level ($F_{0.1}$), and
(iv) Estimate accurately, annual levels of fishing mortality (F_{curr}).

In addition, it was found that the management performance of both length-based and age-based methods was greatly impaired by the quality of the length-frequency or length-at-age samples. High F_{start} levels reduced the number of older individuals within the population, thus making it more difficult to estimate the growth parameters (e.g. no large fish to accurately estimate L_∞). Since growth parameters are used to estimate the target fishing level ($F_{0.1}$), it was not unexpected to see a decline in management performance with increasing F_{start} levels. For *L. mahsena* in particular, it was found that the initial value for the length-at-capture (Lc_{50} = 30.5 cm), coupled with a high F_{start} level ($F_{start} > F_{0.1}$), produced a narrow band of size ranges that were inappropriate to fit a growth model.

Within a heavily exploited fishery, it would be difficult for a fisheries manager to obtain large specimens. However, a dedicated sampling programme could be introduced by the manager to get sufficiently small fish to estimate growth parameters reliably. To mimick this management behaviour in the model, the length-at-capture (Lc_{50}) was reduced from 30.5 cm to 22.1 cm. The reduction in the length-at-capture was therefore undertaken for technical reasons, rather than a specific management objective, which might otherwise target juvenile fish.

By improving the growth parameter estimates, this action would also have reduced the bias in Ralston's or Pauly's estimates of natural mortality (M), further improving the assessment. At high F_{start} levels, this could impair the ability to estimate both the growth parameters and natural mortality. It is therefore essential to try and obtain independent estimates of natural mortality under these circumstances.

6.3 Recommendations and guidelines

- In comparison to age-based methods, length-based methods of assessment of reef fish are less accurate and can lead to either very precautionary levels of fishing mortality and an under-exploitation of the stock, or more importantly, increase the risk of developing very high unsustainable levels of fishing mortality and an over-exploitation of the stock.

- Age-based methods were more accurate at estimating target fishing levels ($F_{0.1}$), which greatly improved management performance.

- Age-based methods of assessment of reef fish are more accurate than length-based methods and are more likely to develop long-term sustainable fisheries around optimal values.

- Age-based methods of assessment should be considered for moderately short-lived, fast growing reef species such as *Siganus sutor*. Improved management performance is observed within both lightly and heavily exploited fisheries although there still remains a risk of over-exploitation.

- Age-based methods of assessment have been shown to lead towards more precautionary management performance than length-based methods and should therefore be considered for long-lived, slow growing reef species such as *Lethrinus mahsena*. Caution should be given, however, to their application in heavily exploited fisheries. Under these circumstances, it is important to obtain good length-at-age samples to estimate growth parameters (L_∞, K t_0), and natural mortality (M).

- Independent estimates of fishing mortality (M) should be obtained to help improve management performance, particularly for heavily exploited fisheries where larger individuals are often unavailable for growth studies.

- Additional research should be targeted in developing countries within the tropics where the use of length-based methods are predominantly being used. A pre-requisite to applying age-based methods are first to ensure that age can be determined and validated in the target species. If feasible, then the application of a range of different age-based assessment techniques should be considered to ensure the most appropriate method is employed. If ageing techniques are unavailable for routine stock assessment, it has been shown that management performance can be improved by estimating target fishing levels (e.g. $F_{0.1}$) using age-based techniques.

It is recommended that age-based methods are considered for BOTH fast-growing moderately short-lived reef fish species and slow-growing long lived reef fish species.

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Appendix A. Back-calculation of length-at-age data for *Siganus sutor* from Seychelles

The Centre for Environment, Fisheries & Aquaculture Science

Back-calculation of length-at-age data for *Siganus sutor* from Seychelles

For MRAG Ltd, London.

CEFAS Contract C1594

March 2002

Introduction

CEFAS was sub-contracted by MRAG Ltd to provide a short-term input to the DFID FMSP Project R7835: 'Investigation of the implications of different fish life history strategies on fisheries management'. The inputs required from CEFAS were:

- Ageing, using annual increments, of 75 otoliths of *Siganus sutor* (provided sectioned and polished by Seychelles Fishing Authority);
- Measuring of annual increments of above otoliths;
- Estimation of otolith size-age relationship;
- Back-calculation of individual length-at-age data.

Due to the shortfall in the number of otoliths provided by Seychelles Fishing Authority, the following additional work was performed:

- Prepare the data file of length-at-age data required for the BUGS computer program;
- Write a short report summarising the work performed and the results obtained.

Work was performed during March 2002.

Methodology

Sectioned and polished otoliths from *Siganus sutor* were provided by Seychelles Fishing Authority (SFA), along with information on the size (total length and fork length), sex and weight of each individual in the sample.

Individual age was assessed for each otolith on two separate occasions. Where the two estimated ages disagreed, the otolith was studied further and an age then assigned. Measurements of the total otolith radius, from nucleus to outside edge, and the distance along the selected growth axis between identified annual increments were then taken using the tools described in Millner and Whiting (1996). Measurements were performed out to the tip of dorsal lobe, at approximately 90° to the *sulcus acousticus*. A magnification of x80 was used.

Following the recommendations of Francis (1990) and Ricker (1992), the geometric mean regression (GMR) of total length at capture from otolith radius at capture was calculated. Back-calculated lengths-at-age for each individual were then derived using the following formula (Ricker, 1992):

$$TL_i = \left(\frac{TL_c - b}{O_c} . O_i \right) + b$$

where Tl_i is the estimated total length at age *i*
Tl_c is the total length at capture
O_c is the otolith radius at capture
O_i is the otolith radius at age *i*
b is the intercept of the GMR calculated using the Ricker procedure

Results

Although 75 otoliths were supposed to have been provided, only 50 slides were sent to CEFAS by SFA. Preliminary examination showed that 41 of these were suitable for use in the back-calculation of individual growth trajectories. The remaining nine could not be measured, either due to the lack of an otolith on the slide, or problems with sectioning[3].

The estimated age of usable otoliths was found to be consistent in 85% of cases. Estimates for the remainder were different by one year, and further examination enabled one age to be selected as the most likely for each individual. The range of total lengths and estimated ages from the 41 individuals sampled is presented in Table 1. Frequency distributions of length and age are presented in Figures 1a and 1b.

Table 1. Summary length and estimated age data for the *Siganus sutor* sample.

	Min	Max	Mean	SD
Total Length (cm)	26.4	43.7	32.3	3.8
Estimated Age (yr)	2	4	2.6	0.6

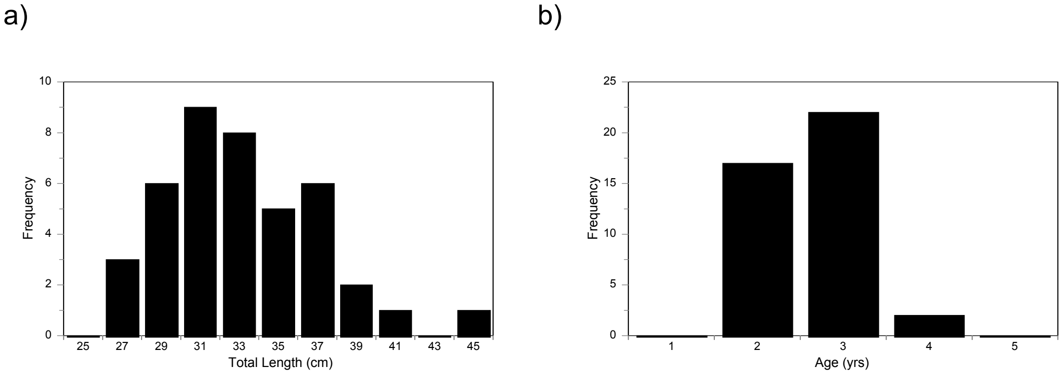

Figure 1. Frequency distributions of a) total length (cm) and b) estimated age (yrs) for the sample of *Siganus sutor*.

A linear relationship existed between the fork length and otolith radius of *Siganus sutor*, to which the geometric mean regression (GMR) of fork length from otolith radius was fitted (Fig 2).

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[3] Back-calculation requires the nucleus of the otolith to be clearly visible in the section. If the section has not been taken through the nucleus, or at an unusual angle through the otolith, increment widths will not follow that of the relationship between length and otolith radius. The problems with sectioning does not reflect badly on SFA's sectioning technique. It has taken CEFAS personnel a number of years to perfect the sectioning process.

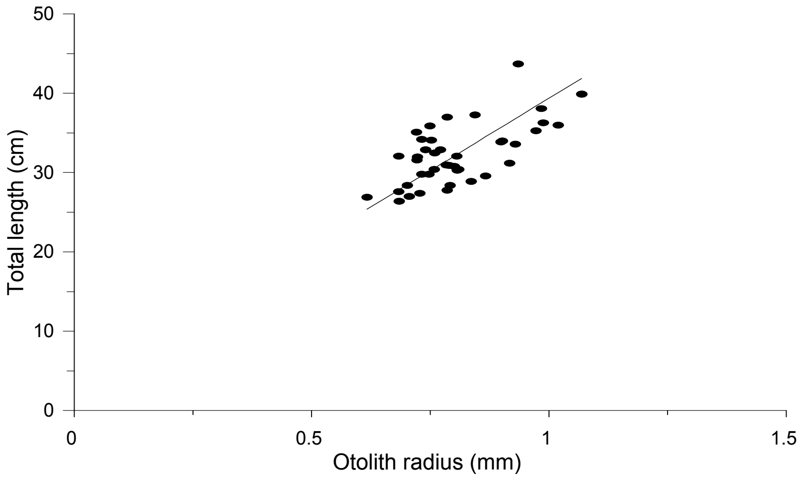

Figure 2. Geometric mean regression of total length (cm) from otolith radius (mm) for *Siganus sutor*.

The equation for the GMR was:

$$TL_c = 36.51 O_c + 2.85$$

Individual back-calculated length-at-age data is presented in the accompanying Excel file (SSUT_BACK_CAL_RICKER.XLS) and are arranged in the required BUGS format in SSUT_data.txt.

A simple graphical representation of individual back-calculated growth patterns is presented in Figure 3. This representation assumes that t_0 is zero, and does not represent individual von Bertalanffy growth curves.

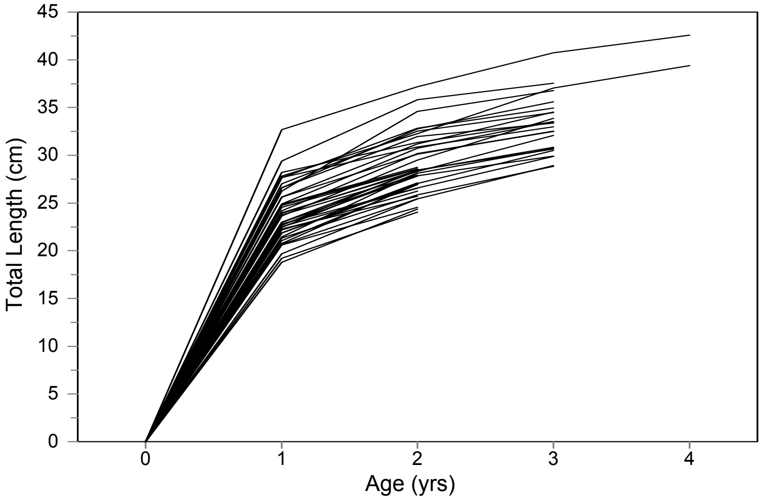

Figure 3. Back-calculated length at age for individual *Siganus sutor*.

The average back-calculated length-at-age from the sample is presented in Table 2.

Table 2. Average *Siganus sutor* back-calculated length-at-age from the Seychelles sample.

Age (yrs)	Average length (cm)	SD	n
1	23.9	3.0	41
2	28.9	3.1	41
3	33.2	3.0	24
4	41.0	2.3	2

When related to L_{max} (43.7cm in this sample), on average 55% of *Siganus sutor* growth is achieved in the first year.

Estimates of the von Bertalanffy growth parameters for *Siganus sutor* from 'Fishbase' and other sources are presented in Table 3. Von Bertalanffy growth parameters estimated using the mean back-calculated total lengths-at-age estimated through the current work (where t_0 was constrained to zero) are also presented.

Table 3. Von Bertalanffy growth parameter estimates for *Siganus sutor* by location.

L_∞ (cm)	Measure	K (yr^{-1})	Location	Method	Reference
25.0	TL	1.5	Dar es Salaam	Lfreqs	Benno, 1992
36.2	SL	0.87	Mombassa Is.	daily rings	Ntiba & Jaccarini, 1988
49.9	TL	0.66	Mauritius	annuli	Jehangeer, 1988
43.3	TL	0.65	Seychelles	daily rings	Grandcourt, 1999
41.0	TL	0.75	Seychelles	annuli	This study

Discussion

While ageing otoliths of *Siganus sutor* was not straightforward, separate readings resulted in consistent age estimates. Back-calculation indicated that there was a direct linear relationship between total length and otolith radius (at least over the range of ages and sizes examined).

Individual growth patterns show an exponential decrease in the increment width with increasing age, as expected. A preliminary estimate of L_∞ based on mean back-calculated length-at-age data from the current study (and assuming t_0 is zero), is similar to that estimated by Grandcourt (1999) for this species from Seychelles, while the estimated growth rate K appears slightly higher.

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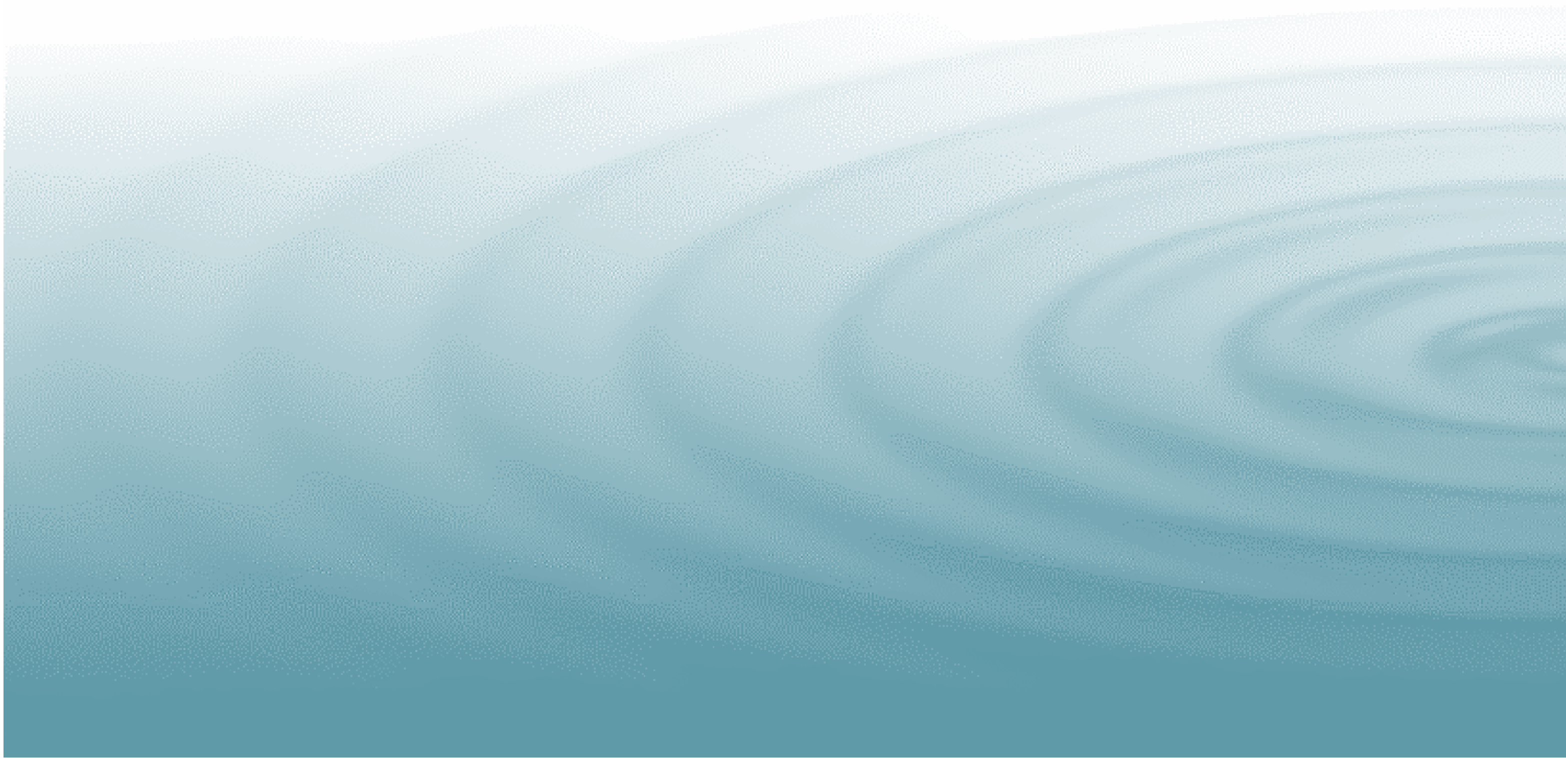

Appendix B. Yield Model Algorithms

A full description of the Yield model has been given within Pilling et al. (1999). This section details additional information on the new length- and age-based assessments.

Length-based non-equilibrium assessment

Although the true level of fishing mortality each year is not known by the fisheries manager the relative level of fishing mortality (F_{mult}) can be determined each year by the management decision rule. The known relative mortality levels can therefore be used to improve the length-based assessment method.

The new method estimates what the expected catch in numbers at age would be ($N_{y,t+a}$), given the total level of fishing mortality exerted in that year ($F_{total,y}$), the initial population size (N_a), and natural mortality (M):

$$N_{y,t+a} = N_a e^{-t(M)} \cdot e^{-F_{total,y}}$$

Where N_a is the initial population size, t is the time between successive ages, M is natural mortality from Pauly's equation, and F_{total} is the total fishing effort exerted on the age class (cohort). Total fishing mortality is dependent on the age class and the relative change in fishing effort throughout the fishing period:

$$F_{total,y} = F_{equil} \cdot \sum_{i=1}^{t} F_{mult\,y-i}$$

The procedure then minimises the difference between the observed and expected catch in numbers at age. The minimisation is achieved by varying the initial population size (N_a), and an estimate of the equilibrium fishing mortality prior to the start of management (F_{equil}).

$$SS = \sum_{a=1}^{\max} (\ln(N_{y,t+a}) - \ln(O_{y,t+a}))^2$$

The minimisation is only conducted using the current year=s data. Whilst it would be arguable to use all available years to date, this is comparable to conducting a length-based VPA. However the expected values are independent by year, due to the assumption of constant recruitment in expected values, and so only the current year is used.

Age-based non-equilibrium assessment

The latest age-based method does not calculate current fishing mortality using a length-converted catch curve to estimate total mortality. Instead, the simulation procedure uses a simple form of separable VPA. A separable VPA model separates the exploitation rate from the selectivity pattern, with the assumption that the age-dependent selectivity pattern remains constant over some significant period of time (FAO, 2001). Thus only the overall level of exploitation varies between years:

$$F_{ay} = S_a E_y$$

where F_{ay} is the fishing mortality on age *a* in year *y*;
S_a is the age-dependent selectivity pattern; and
E_y is an age-independent exploitation level.

The separable VPA model reduces the number of parameters to be estimated, and is most appropriate for longer time series with several age classes, where for each additional year of date, only one additional parameter is added to the model but a number of additional data points (equalling the number of age classes) are provided.

For this project, the simple form of the separable VPA, using only catch-at-age numbers, was used (see Pope and Shepherd, 1982). In brief, this estimates the current fishing mortality (F_{est}) by minimising the difference between the observed and expected catch-at-age numbers using least squares.

Estimation procedure

In each year, 400 fish were sampled at random from the total catch to generate a length frequency distribution. Individual sampled fish were then assigned to an age class using an age-length key (ALK). The ALK was itself derived each year from growth parameters estimated from age-based methods (otoliths). The sample numbers at age were then raised to estimate the total observed catch-at-age in numbers for each year (C_{ay}) using the proportion of total catch and sampled biomass.

For the observed catch-at-age in numbers, observed catch ratios O_{ay} were derived

$$O_{ay} = \ln \frac{C_{ay}}{C_{a-1,y-1}}$$

where both C_{ay} and $C_{a-1,\ y-1}$ represented catches that were greater than a minimum proportion (0.01) of the total catch in numbers for the years *y* and *y-1* respectively (otherwise a zero was entered).

The expected catch at age, a, in any year, y, can de derived using the separable fishing mortalities F_{ay}.

$$c_{ay} = N_{ay} \cdot \left(\frac{F_{ay}}{F_{ay} + M} \right) \cdot \left(1 - e^{-(F_{ay} - M)} \right)$$

Hence the expected catch ratios, E_{ay}, can be estimated:

$$E_{ay} = \ln \frac{C_{ay}}{C_{a-1,y-1}}$$

and therefore

$$E_{ay} = \ln\left(\frac{\frac{F_{ay}}{F_{ay}+M}\cdot(1-e^{-(F_{ay}-M)})\cdot e^{-(F_{a\text{-}1,\,y\text{-}1}-M)}}{\frac{F_{a\text{-}1,y\text{-}1}}{F_{a\text{-}1,y\text{-}1}+M}\cdot(1-e^{-(F_{a\text{-}1,\,y\text{-}1}-M)})} \right)$$

Thus the expected catch ratios only depend on the relative fishing mortalities (and natural mortality), and are independent of population sizes, N_{ay}.

where $F_{ay} = S_a E_y$ and

$$S_a = \frac{1}{1+e^{-\beta(a-a_{50})}}$$

where

$$\beta = \frac{\ln(3)}{a_{75} - a_{50}}$$

To derive separable fishing mortalities (F_{ay}), both the age-dependent selectivity pattern (S_a) and age-independent exploitation level (E_y) must be estimated. Two parameters are required to determine the selectivity pattern (β, a_{50}), whereas the age-independent exploitation level (E_y) is calculated by the product of the initial level of fishing mortality at equilibrium (F_{equil}) and the overall change in fishing effort (F_{mult}). E_y therefore represents the overall estimate of fishing mortality in year, y, (equivalent to F_{est}) and the pattern of selectivity (equation above) describes how much of this effort is directed at each age class.

To the fisheries manager, F_{equil} is unknown and must be fitted together with β and a_{50} by minimising the sum of squared differences (SS) between the matrixes of observed and expected catch ratios. Unlike the equilibrium length-based method, the separable VPA uses all available information in each year.

$$SS = \sum_{a=1}^{\max}\sum_{y=1}^{n}(E_{ay} - O_{ay})^2$$

The revised current age-independent exploitation level (F_{est}) is then used each year in the management rule.