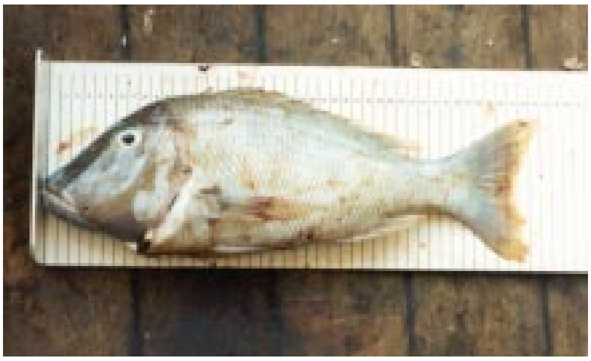
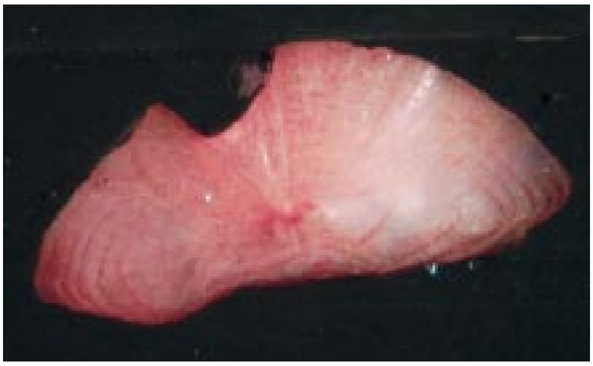
Implementing management guidelines arising from Project R6465 - an assessment of utility

Final Technical Report





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1 Executive Summary

The purpose of this project was to implement guidelines arising from FMSP project R6465 'Growth parameter estimation and the effects of fishing on size-composition and growth of snappers and emperors: Implications for management' in the inshore fishery of the British Indian Ocean Territory (BIOT; Chagos Archipelago). The project examined the utility of simple age-based methods of stock assessment for two species of demersal reef fish in BIOT (Chagos Archipelago). The project also examined the costs involved in undertaking this approach. In doing so, the project developed guidelines for the assessment of demersal tropical fish species both within BIOT (Chagos Archipelago) and in other areas of the tropics. Fisheries targeting such species form important sources of protein and income for artisanal and semi-industrial fishers. This purpose is directly relevant to the FMSP goal of improving the livelihoods of poor people through sustainably enhanced production of land/water interface systems.

Fisheries management in the British Indian Ocean Territory has routinely been based on the outputs from length-based methods applied to length frequency data. As such its management is typical both of demersal fisheries in the Indian Ocean (e.g. Mauritius, Seychelles) and throughout the tropics. However, due to the long-lived, slow growing nature of the species, outputs from length-based methods of biological and fishery parameter estimation are uncertain. This has knock-on effects on the management of such stocks.

Project R6465 addressed constraints to management and development arising from the use of uncertain growth parameter estimates in fishery models such as yield-per-recruit. This project found that the use of age-based methods of growth parameter estimation led to improved management of long-lived, slow growing species, such as the study species *Lethrinus mahsena* and *Aprion virescens*. A number of guidelines were developed for data collection, assessment and management. These were used to derive the aims of the current project.

- **assessments should be made at as fine a spatial scale as possible**
  Studies performed during Project R6465 indicated that localised populations of *L. mahsena* may exist within BIOT (Chagos Archipelago). This has implications for the assessment and management of this species. Sampling for the current project allowed a more detailed examination of spatial patterns to be made, with the aim of clarifying whether meta-populations exist at this location.

- **use age-based methods for estimating growth parameters for long-lived, slow growing species** and **ensure young individuals are present in samples**
  Project R6465 noted that age-based methods of growth parameter assessment resulted in the most accurate and precise assessments. This approach was also found to be the most cost-effective. During that project, age-based growth parameters were estimated for *L. mahsena* and *A. virescens*. However, it was noted that individuals at extremes of the length and age range strongly influenced the growth parameter estimates arising from age-based methods. Such individuals were not well sampled. Individuals from these extremes were specifically targeted during the data collection programme for the current project. This allowed improved growth parameter estimates to be derived.

- **estimate total mortality through age-based methods**
  The results of Project R6465 indicated that the length-based methods of total mortality currently used in BIOT (Chagos Archipelago) have a number of drawbacks. These included the need to employ uncertain growth parameter estimates in the estimation of this parameter, and the potential for density dependent growth to bias total mortality estimates. The current project therefore examined the use of age-based methods of estimation, which eliminates the need for growth parameter estimates, and minimises the impact of density dependent growth.

  During Project R6465, an otolith weight-age relationship was developed for *L. mahsena*. The use of this relationship resulted in representative age frequencies, without the need to assess large numbers of individual otoliths. The method offers potential savings in both time and money. Ideally, one would wish to use these relationships again in later years. However, this assumes that such relationships are constant over time. As an preliminary investigation, the consistency of the relationship was re-examined in the current study using otoliths collected during the 1999 observer programme.

- **accurately assess the current fishing mortality level**
  Project R6465 demonstrated that improved stock assessments, and hence management, are obtained by tuning management targets to the current level of fishing mortality. Accurate estimates of total and natural mortality (M) are needed to estimate fishing mortality. Improved estimates of total mortality are gained through the use of age-based methods of assessment. Currently, estimates natural mortality are reliant on empirical methods, the accuracy of which is unknown for the study species. The value of natural mortality is highly influential in stock assessments. The uncertainty over the value of natural mortality is therefore an important source of uncertainty in stock assessments. An independent estimate of this parameter is therefore required to reduce this uncertainty. Attempts to estimate this parameter were made during the current study.

By applying these guidelines to the BIOT (Chagos Archipelago) inshore fishery, the current project derived improved stock assessments for the study species (*L. mahsena* and *A. virescens*). These assessments indicated that the stocks of these species were generally being exploited sustainably, and that the current management approach within BIOT (Chagos Archipelago) is performing successfully.

Based on the results of the studies performed in the current project, a number of generic guidelines for managers of tropical demersal fisheries were developed:

- use age-based methods to assess total mortality where an age-otolith weight relationship is available;
- derive an age-otolith weight relationship where possible - this method is the most cost-effective method of total mortality estimation;
- where such a relationship is not available, cost-benefit analyses indicate that the use length-based methods of total mortality estimation, combined with age-based growth parameter estimates are the most efficient;
- obtain an independent estimate of M;
- Ensure individuals at extremes of the age and length range are present in samples used to estimate von Bertalanffy growth parameters. This may require sampling with different gears which catch such individuals. Where reasonable age-based growth parameter estimates are already available, this is of lower priority than the independent estimation of M;
- assessment of maturity parameters (length- or age-at-maturity) is a low priority;
- examine the potential for using age-based methods to assess indicator species

appropriate to the aims of management;
- ensure data describing the whole of the fishery (CPUE data) continues to be collected.

Specific recommendations were also developed to improve assessments within BIOT (Chagos Archipelago) in the future:

- assess *L. mahsena* at the scale of meta-populations (i.e. data can be combined over more than one statistical area). Apply the worst case scenario from the meta-populations across BIOT (Chagos Archipelago), unless a closed area management approach could be effective. Collect data across the statistical areas encompassed by meta-populations for more local studies;
- collect other fishery data such as CPUE at the scale of statistical areas;
- as there was no indication of localised meta-populations for *A. virescens*, this species should be assessed across the whole of BIOT (Chagos Archipelago), and by statistical areas;
- cost-benefit analyses indicated that the use of the age-otolith weight relationship was the most cost-effective method to estimate total mortality. Where the relationship holds between years, the age-otolith weight relationships for *L. mahsena* should be used to derive age frequencies for total mortality estimation. Such a relationship could not be derived for *A. virescens*. The most cost-effective approach in this case is to use age-based growth parameter estimates and length-based methods to estimate total mortality for this species;
- growth parameter estimates for both species were improved. However, additional sampling using different gear types could further improve growth parameter estimates for these species;
- continue to collect data describing the whole fishery (e.g. CPUE), at the scale of statistical areas.

Further work required:
- Indications of the level of natural mortality of *L. mahsena* were estimated. However, definitive assessments were not obtained. Uncertainty in stock assessments is therefore introduced at this point. There is therefore a need to obtain an independent estimate of M through methods described in the FTR;
- examine the potential for assessing other indicator species appropriate to the aims of management. Given the conservation goal of the BIOT Authorities, suitable species include members of the Serranidae;
- examine the feasibility of tagging studies to examine the extent and interactions between meta-populations of *L. mahsena*.

2 Background

The aim of this project was to implement guidelines from FMSP project R6465 'Growth parameter estimation and the effect of fishing on size-composition and growth of snappers and emperors: Implications for management' in the 'inshore' fishery of the British Indian Ocean Territory (Chagos Archipelago). The project examined the utility and costs of moving towards an age-based methodology of stock assessment at this location.

The British Indian Ocean Territory (Chagos Archipelago) is located in the central Indian Ocean. The 'inshore' fishery is prosecuted by Mauritian mothership-dory ventures which fish for demersal snappers and emperors. The fishery is managed by the BIOT Administration of the Foreign and Commonwealth Office. To inform this management, stock assessments have been routinely performed using length-based methods applied to length frequency data collected during observer programmes. As such, its current stock assessment and management methods are typical both of demersal fisheries in the Indian Ocean (e.g. Mauritius), and throughout the tropics. However, as a result of the long-lived, slow growing nature of target species, outputs of length-based methods of biological and fishery parameter estimation are uncertain. This has a knock-on effect on the management decisions for the area which are based on this information.

FMSP Project R6465 addressed constraints to management and development arising from the use of uncertain length-based growth parameter estimates in analytical fishery models such as yield-per-recruit. The project examined improvements to management arising from the use of age-based methods of growth parameter assessment (the use of otoliths to determine age). Guidelines for data collection, assessment and management of long-lived, slow-growing species were developed to aid target institutions manage fisheries in the Indian Ocean targeting such species (Seychelles, Mauritius, BIOT (Chagos Archipelago)). Fisheries based on these species are important in tropical countries as sources of both employment and protein.

In 1999, otoliths were collected during the annual observer programme operating within BIOT (Chagos Archipelago). This observer programme supplies information for the assessment and management of the demersal 'inshore' fishery. This data collection programme allowed a number of Project R6465 guidelines to be implemented in BIOT (Chagos Archipelago):

- stock assessments should be made at as fine a spatial scale as possible;
- use age-based methods for estimating growth parameters for long-lived, slow growing species, and ensure young individuals are present in samples;
- estimate total mortality through age-based methods;
- accurately assess the current fishing mortality level.

The implementation of these guidelines during the current project resulted in improved biological and fishery parameter estimates for the study species. Biological reference points for management purposes were derived, based on these parameter estimates. The current study also assessed whether the suggested data collection and age-based approaches were appropriate for use in BIOT (Chagos Archipelago). The utility and cost of moving towards an age-based methodology was indicated. As such, outputs from this project have relevance for other locations in the tropics, and will assist institutions in assessing the potential for applying the examined methods locally.

Assessments within BIOT (Chagos Archipelago) extend the uptake of recommendations from Project R6465; the Seychelles Fishing Authority have already taken up project guidelines and are utilising age-based methods to assess the status of local demersal fisheries.

3 Project Purpose

Long-lived, slow growing species, such as those of the snapper and emperor families, form the basis of valuable fisheries important to the livelihoods of many small scale fishers in developing countries. As these fish are high-level predators with low reproductive capacity, they are easily overfished. A widespread demand for management exists in order to sustainably manage and develop these fisheries.

Project R6465 developed a number of guidelines for the improved assessment and management of such species in the tropics. The purpose of the current project was to implement guidelines from Project R6465 in the 'inshore' fishery of the British Indian Ocean Territory (Chagos Archipelago). Also, the utility and costs of moving towards an age-based methodology of assessment were examined. In this way, outputs should further assist target institutions assess the potential for applying these methods locally.

This project purpose is directly relevant to the goal of developing improved strategies and plans for the management of capture fisheries important to poor people.

4 Research Activities

Using the sampling programme recommended by Project R6465, otoliths of the study species (*L. mahsena* and *A. virescens*) were collected from BIOT (Chagos Archipelago) during the annual observer programme. These were sectioned and stained at CEFAS (Lowestoft) using the procedures described in the final report for Project R6465. Otoliths were examined by the researcher, and an age assigned to each fish based on the number of annual increments counted in the otoliths. The resulting length-at-age data formed the basis of the subsequent studies.

Historically, the area of BIOT (Chagos Archipelago) has been divided into a number of 'statistical areas', across which data were collected. These areas do not have a biological basis, however. Length and age data collected in each statistical area for the current study were examined to identify consistent spatial patterns from which the presence of localised meta-populations could be inferred. Mean length and age were then compared to the level of fishing effort applied in each area to examine whether differences could be explained by the impacts of fishing. Mean length-at-age (a proxy for growth rate) was also examined by sample area to examine whether area differences in length or age structure resulted from variations in growth rate.

Stock assessments were performed for the study species by re-estimating biological and fishery parameters. Growth parameters for the study species were re-estimated using length-at-age data from the current project combined with that collected during Project R6465. Age frequencies were derived for each species at varying spatial scales. These were used to estimate total mortality through catch curves, and to estimate age at capture. This approach eliminated uncertainty resulting from the use of growth parameter estimates. Attempts were made to obtain an independent estimate of natural mortality for *L. mahsena*, by relating local estimates of total mortality to the level of fishing effort applied. Stock assessments were then performed by estimating and comparing the current level of fishing mortality (F_{curr} = Z-M)) for each species with estimates of the management reference effort level $F_{0.1}$. Reproductive parameters (sex ratio, length- and age-at-maturity) were also calculated.

During Project R6465, an otolith weight-age relationship was derived for *L. mahsena* from BIOT (Chagos Archipelago), as well as for a number of other locations. Ideally, one would wish to use these relationships each year to estimate age frequency distributions from data sets of otolith weight. However, this assumes that these relationships are constant over time. As a first examination of this, the age-otolith weight relationship for *L. mahsena* in BIOT (Chagos Archipelago) was re-estimated using data collected for the current study (1999 data). The relationship derived using these data was then compared with that derived during Project R6465. To re-examine the utility of this approach, the 1999 relationship was then used to derive an age frequency distribution, which was compared with the underlying age structure estimated through counts of otolith increments. Total mortality was then estimated using the age structures derived through each approach, and the resulting estimates were compared.

Examination of the utility of total mortality assessment methods requires an assessment of costs involved in each approach. However, examining costs alone does not take into account the benefits of using different methods. Therefore, a cost-benefit analysis was performed to indicate which approach was the most cost-effective. Costs were calculated for the three study methods of total mortality estimation: length-based (length-converted catch curve of Beverton and Holt's Z estimator), and age-based (through otolith increment counts or the use of an age-otolith weight relationship). The costs involved were related to benefits resulting from each approach, as assessed during simulations performed during Projects R6465 and R7522. Benefits were assessed based on the management goals of the BIOT Authorities: resource conservation, while allowing Mauritian vessels to fish as they have in the past. Therefore, both the amount by which the spawning stock biomass was greater than 20% of unexploited levels, and the level of catch obtained, were examined in each year of the simulation. The costs of each method were then related to the benefits, to calculate the net present worth.

5 Outputs

The studies described in the previous section focussed on obtaining improved estimates of total mortality using age-based methods. The utility and costs of the approaches used were examined. The implementation of Project R6465 guidelines resulted in a number of outputs. These led to the derivation of further guidelines for the assessment both of tropical demersal fisheries in general, and for the inshore fishery in BIOT (Chagos Archipelago) in particular. The outputs of the studies described in Section 4, and their accompanying generic and specific guidelines, are detailed below, by project aim.

Spatial scale of assessments

Evidence for localised meta-populations of *L. mahsena* in BIOT (Chagos Archipelago) was identified. Assessment of *L. mahsena* should be assessed at the scale of these meta-populations, and the worst-case scenario applied across the location. Data collection should be spread across the statistical areas encompassed by these populations to allow more localised studies to be made. No evidence for localised populations of *A. virescens* was found. Therefore, this species should be assessed across BIOT (Chagos Archipelago), and by statistical area.

Use age-based methods to estimate growth parameters, and ensure young individuals are present in samples

The sampling strategy derived in Project R6465 was used during the current study. For both species, additional otoliths were collected from extremes of the size range found in the catch. Inclusion of these date in assessments led to the derivation of improved growth parameter estimates for the study species. However, it was noted that further sampling with different gears specifically targeting individuals from these under-sampled lengths and ages would be required to efficiently improve the estimates of growth further.

Estimate total mortality through age-based methods

Age-based methods of total mortality estimation are more robust to the effects of density dependent growth and do not require the use of potentially biased growth parameters. Using this approach, estimates of total mortality were derived for the study species.

The derivation of an age frequency through counts of otolith increments incurs notable additional costs over that of length-based methods, due to the large number of otoliths that must be read. For *L. mahsena*, however, studies performed during Project R6465 indicated that the otolith weight of this species could be used as a proxy for age. The otolith weight-age relationship was re-confirmed during the current study, supporting the theory that the relationship was consistent between years. For this species, and for this location, the relationship can be used to routinely estimate total mortality. However, it is suggested that where changes in fishing pressure and environmental conditions occur, the relationship is re-assessed.. While the use of otolith weight-age relationships incur greater costs than the use of length-based total mortality assessment methods, the use of age-based total mortality estimates in stock assessments resulted in greater benefits, assessed against criteria of conservation and fishing yield. The level of *L. mahsena* total mortality in BIOT (Chagos

Archipelago) should therefore be routinely estimated using otolith weight.

When an age frequency is derived from otolith increment counts, however, the additional benefits resulting from the use of age-based total mortality estimation methods were outweighed by the greater costs involved. As a result, the cost-benefit analysis indicated that, where an age-otolith weight relationship was not available, the most cost-effective approach was to estimate age-based growth parameters (see Project R6465), and use length-based methods of total mortality estimation. This approach should therefore be taken for *A. virescens* in BIOT (Chagos Archipelago).

Accurately assess fishing mortality
For the study species, estimates of fishing mortality depend on the accuracy of total and natural mortality estimates. Estimates of total mortality were improved through the use of age-based methods. However, uncertainty remained due to the lack of an independent estimate of natural mortality. This parameter has been estimated using empirical methods, the accuracy of which is uncertain for the study species.

Indications of the level of natural mortality for *A. virescens* in BIOT were obtained during Project R6465. For *L. mahsena*, indications of the natural mortality level were obtained during the current study by comparing annual estimates of total mortality with the level of fishing pressure exerted in each year. However, uncertainty in these estimates remained. There is a need to improve these estimates to further reduce this uncertainty. Approaches through which this might be achieved were suggested.

Stock assessments
Using the guidelines, improved stock assessments were generated for the study species. On the whole, both *L. mahsena* and *A. virescens* in BIOT (Chagos Archipelago) appear sustainably exploited. However, there were indications that *L. mahsena* stocks in the south region of the Great Chagos Bank were over-exploited. This concern resulted from high estimates of total mortality for this area. It is thought that this may result from factors other than fishing, since the length or age structure of *L. mahsena* showed no relationship to the level of fishing effort applied.

Overall, the study indicated that it is feasible to employ age-based methods to assess the impacts of fishing on exploited populations of demersal reef fish within BIOT (Chagos Archipelago), and in other tropical demersal fisheries.

Guidelines
A number of generic and specific guidelines arose from the research. A number of potential studies were also identified to further improve the stock assessments for species caught in BIOT (Chagos Archipelago) and other demersal fisheries. These included studies to improve the estimates of natural mortality, the knowledge of the spatial distribution of stocks, and on the stock assessment methods.

Generic guidelines for tropical fisheries targeting long-lived, slow growing species

For routine assessment of total mortality:

- use age-based methods to assess total mortality where an age-otolith weight relationship is available. This cost-effective approach reduces uncertainty since growth parameter estimates are not required;
- derive an age-otolith weight relationship where possible;
- where such a relationship is not available, use length-based methods of total mortality

estimation combined with age-based growth parameter estimates. This method is more cost-effective than the construction of an age frequency using counts of otolith increments.

To minimise uncertainty in subsequent assessments of F_{curr} and $F_{0.1}$:

- obtain an independent estimate of M, either by estimating Z in lightly exploited populations, or by relating annual estimates of total mortality to the level of fishing effort;
- if trials using alternative fishing gears for targeting small and large individuals can be undertaken, perform studies to improve growth parameter estimates. However, where reasonable age-based growth parameters are available, this is of lower priority than the independent estimation of M;
- assessment of maturity parameters is a low priority.

For management:

- examine the potential for assessing other indicator species appropriate to the aims of management (see guidelines from project R5434); e.g. where conservation is the main aim of management, examine vulnerable species such as those from the Serranidae;
- ensure data describing the whole of the fishery (CPUE data) continues to be collected.

Guidelines specific to the BIOT (Chagos Archipelago) inshore demersal fishery

When performing stock assessments for the study species:

- assess *L. mahsena* by meta-populations, and apply worst-case scenario across BIOT (Chagos Archipelago);
- while data for this species should be collected by meta-population, ensure data is collected across statistical areas encompassed by these populations to allow localised studies to be undertaken;
- assess *A. virescens* across BIOT (Chagos Archipelago), and by statistical areas;
- continue to collect CPUE data by statistical area.

Estimate total mortality:

- for *L. mahsena* using the age-otolith weight relationship (re-assess the relationship following large changes in fishing mortality or the environment);
- for *A. virescens* use estimated age-based growth parameters and length-based total mortality estimation methods.

Future work:

- continue to obtain age-based estimates of total mortality for *L. mahsena* until sufficient data are available to obtain an independent estimate of M;
- as aim of management is conservation, use age-based methods of growth and mortality to assess the status of a vulnerable species in BIOT (Chagos Archipelago), e.g. members of the Serranidae;
- identify information on meta-populations of *L. mahsena* through tagging studies. Such studies may identify whether ontogenic migration causes differences in total mortality between areas of the Great Chagos Bank, and the extent of meta-populations. Such studies are of lower priority than the previous two points.

6 Contribution of Outputs

6.1 Towards DFID 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 was 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 by 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 stocks represent an important source of nutrition and income for fishers and dependent communities throughout the Indian Ocean, and more widely in other tropical areas such as Africa, the Caribbean, and Pacific. The potential for rapidly overfishing demersal fish stocks of snappers and emperors means that these important resources must 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. The project has also examined the utility of using these methods in tropical demersal fisheries, indicating their implementation to developing countries through example in BIOT (Chagos Archipelago). Adoption by target organisations will contribute directly to the project goal described above.

6.2 Promotion of outputs

The guidelines developed will be directly relevant to the BIOT Authorities. However, they are also highly relevant to the government organisations responsible for fisheries management in Seychelles and Mauritius, and to fisheries management institutions elsewhere in the tropics. 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 approaches for promoting project outputs were pursued, and will continue to be pursued beyond the life of the project. National workshops have been held by the project to disseminate results and develop and promote management guidelines, while results were also disseminated at international symposia (see below). A briefing document will be prepared for the BIOT Authorities to detail the advantages and trade offs involved in the guidelines suggested. A number of scientific papers are to be produced after the completion of the project.

On the basis of the outputs from Project R6465, the Seychelles has already moved towards age-based assessment methodologies. The results of the current project support that move and refine the methodologies employed. Results also highlight further methods that can be routinely employed for relatively low levels of expenditure. Results of the project were received enthusiastically in both Seychelles and Mauritius. In Mauritius, financial constraints have prevented a move towards age-based methodologies. The results of the current study will add extra weight to the move towards using age-based approaches in routine stock assessments.

Guidelines developed through this study will continue to be applied in relation to the British Indian Ocean Territory (Chagos Archipelago) inshore fishery. In this way, there will be additional support for their uptake in both Seychelles and Mauritius, where MRAG continues to work collaboratively within the target organisations through fisheries commissions related to the BIOT (Chagos Archipelago) fisheries.

6.2.1 Publications

Pilling, G.M.; Grandcourt, E.M. and G.P. Kirkwood. The utility of otolith weight as a method for ageing the emperor *Lethrinus mahsena* and other tropical species. Submitted to Fishery Bulletin.

A number of other publications are planned based on the outputs from this project.

6.2.2 Internal reports

None

6.2.3 Other dissemination of the results

Dissemination workshops were undertaken at Albion Fisheries Research Centre (AFRC) in Mauritius and at the Seychelles Fishing Authority (SFA) 28th and 29th November 2000.

Presentation entitled 'Are length-based methods appropriate when managing long-lived, slow growing species?' at the 9th Coral Reef Symposium, October 23-27th 2000, Bali.

Presentation entitled 'Managing demersal fisheries in the tropics: are methods based on length good enough?' at University of Hong Kong, on the 3rd November 2000.

1. Introduction

The aim of this project is to implement guidelines from FMSP project R6465 'Growth parameter estimation and the effect of fishing on size-composition and growth of snappers and emperors: Implications for management' in the "inshore" fishery of the British Indian Ocean Territory (BIOT; Chagos Archipelago). The project will examine the utility and costs of moving towards an age-based methodology of assessment in this region. Outputs from the project will further assist target institutions assess the potential for applying these methods locally.

The British Indian Ocean Territory (Chagos Archipelago) is situated south of the Maldives, in the central Indian Ocean. The "inshore" fishery in this area is prosecuted by Mauritian mothership-dory ventures which fish for demersal snappers and emperors on the banks of this location. The fishery is managed by the BIOT Administration of the Foreign and Commonwealth Office. As part of this management, stock assessments have been routinely performed using length-based methods applied to length frequency data (see Figure 1.1). The basis for management decisions in this region is therefore typical both of the demersal fisheries in the Indian Ocean (e.g. Mauritius), and throughout the tropics. However, as a result of the long-lived, slow-growing characteristics of these species, outputs from such length-based methods of biological and fishery parameter estimation are uncertain (see Pilling *et al.*, 1999). This uncertainty is therefore transferred to the management decisions based on such information.

Project R6465 addressed constraints to management and development arising from the use of such uncertain growth parameter estimates in analytical fishery models such as yield-per-recruit. The project examined the improvements to management arising from the use of age-based methods of growth parameter assessment (the use of otoliths to determine age). Age-based methods were found to be more appropriate when assessing long-lived, slow-growing species. They resulted in more accurate growth parameter estimates, improving stock assessments. Guidelines for data collection, assessment and management of species with these life-history characteristics were developed to aid target institutions in the Indian Ocean (Seychelles, Mauritius and BIOT (Chagos Archipelago)) in the sustainable management of fisheries targeting the Lutjanidae (snappers) and Lethrinidae (emperors). Such fisheries are important in such tropical countries as sources of both employment and protein.

As part of the management regime for BIOT (Chagos Archipelago), an annual observer programme for the inshore fishery is operated, in collaboration with authorities from Mauritius. A British and a Mauritian observer collect catch, effort and biological data from vessels operating in the fishery, covering 50% or more of the total vessel fishing days in the zone in any one year.

Guidelines developed in Project R6465 were implemented during the 1999 inshore observer programme. As part of this, a targeted sampling programme for the collection of otoliths from the study species *Lethrinus mahsena* and *Aprion virescens* was initiated. Relevant guidelines were:

- **stock assessments should be made at as fine a spatial scale as possible**
  During stock assessments, the assumption is made that the population is homogenous across the region. However, studies performed during Project R6465 indicated that localised populations of *L. mahsena* existed within the Great Chagos Bank of BIOT

(Chagos Archipelago). Otoliths from both study species collected for the current project were sampled from a number of statistical areas within BIOT (Chagos Archipelago) (Figure 1.2). The resulting data will be analysed to clarify the existence and extent of meta-populations at this location. These studies have the potential to influence both the way and the spatial scale at which stock assessments are performed in this location.

- **use age-based methods for estimating growth parameters for long-lived, slow growing species** and **ensure young individuals are present in samples**
  Simulations performed during Project R6465 indicated that age-based methods resulted in the most accurate and precise von Bertalanffy growth parameter estimates. This method was also found to be the most cost-effective. Validation studies enabled age-based methods of growth assessment to be used for *L. mahsena* and *A. virescens* from the study locations of that project, including BIOT (Chagos Archipelago). However, it was noted that individuals from extremes of the size range were highly influential on age-based growth parameter estimates. Such individuals were under-represented in samples. During data collection for the current project, additional samples were obtained from these extremes. This provides the opportunity to improve growth parameter estimates for the two study species further. Such improvements should result in more accurate stock assessments, and hence management, of the study species in BIOT (Chagos Archipelago).

- **estimate total mortality through age-based methods**
  Project R6465 noted that length-based methods of total mortality assessment had a number of drawbacks. These included the need to employ uncertain growth parameter estimates in the method, and the potential for density dependent growth to bias resulting total mortality estimates. The use of age-based methods of assessment (see Figure 1.1, length-at-age) avoids the need to use growth parameter estimates, reducing uncertainty in total mortality estimates when compared to those derived using length-based methods. Analysis of age data collected during the current project will allow improved total mortality estimates to be derived for the study species for the 1999 fishing season. Also, the increased level of sampling undertaken for the current project allows more localised assessments of total mortality to be undertaken (see below).

  Otolith weight has been suggested as a non-subjective and rapid method to assess the age of individuals. The feasibility of using otolith weight to estimate study species age was examined during Project R6465. This method proved feasible for *L. mahsena*, allowing representative age frequencies to be derived without resorting to the assessment of large numbers of individual otoliths. The method therefore offered potential savings in time and money for fishery management institutions in developing countries. However, the age-otolith weight relationship requires re-assessment, to ensure it is consistent between years. As a first assessment of this, otoliths collected during the current study will be used to re-derive an otolith weight-age relationship. The utility of this method will be re-examined.

  Frequently, the ultimate aim of routine age data collection is to perform an age-based VPA (Figure 1.1). A new project funded under DFID's FMSP will examine the implications of using length- and age-based methods of growth and stock assessment for species with different life history strategies, including long-lived, slow growing species such as *L. mahsena*.

- **accurately assess the current fishing mortality level**
  Project R6465 indicated that stock assessments should be tuned to the current level of exploitation. An accurate assessment of the level of fishing mortality is therefore required. Estimates of natural mortality (M) are therefore needed. This parameter is

highly influential in stock assessments. Uncertainty in the estimation of this parameter is an important source of uncertainty in stock assessments.

Independent estimates of natural mortality have been lacking. This parameter has therefore been estimated using empirical formulae. An indication of the level of M for *A. virescens* in BIOT (Chagos Archipelago) was obtained during stock assessments performed for Project R6465. No independent estimate of natural mortality could be derived for *L. mahsena*. Subsequent assessments therefore incorporated the uncertainty arising due to the use of empirical M estimates. In the current study, data will be analysed in an attempt to derive independent estimates of this influential parameter.

Work performed during the current project will derive biological reference points for management purposes. These will be estimated using improved parameter estimates arising from implementation of Project R6465 guidelines for the use of age-based methods (see above). It will assess the applicability of suggested data collection and age-based analysis methods, to examine whether these are appropriate for use in routine stock assessments in BIOT (Chagos Archipelago). The utility and costs of moving towards an age-based methodology will be indicated. As such, outputs from this project will have relevance for other locations in the tropics, assisting institutions in assessing the potential for applying these methods locally.

Performing the assessments described will extend the uptake of guidelines from Project R6465; the Seychelles Fishing Authority have already taken up project guidelines and are utilitising age-based methods of growth parameter assessment in Seychelles demersal fisheries. As shown in the simulations performed during that project, the use of this approach should result in improved management decisions in these locations when compared to the length-based methods previously employed.

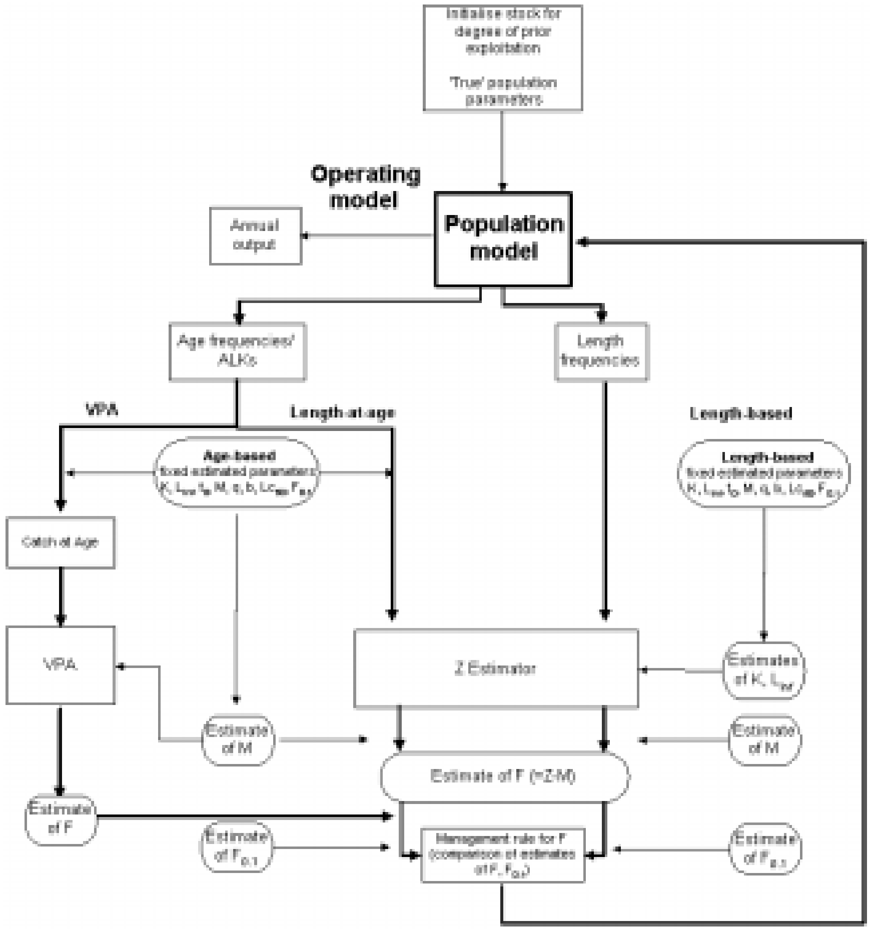


Figure 1.1 Flow diagram detailing the basic procedures involved in length-based (using length frequencies), length-at-age (age frequencies to derive total mortality estimates) and full age-based (collecting a series of age frequencies to perform VPA) methods.

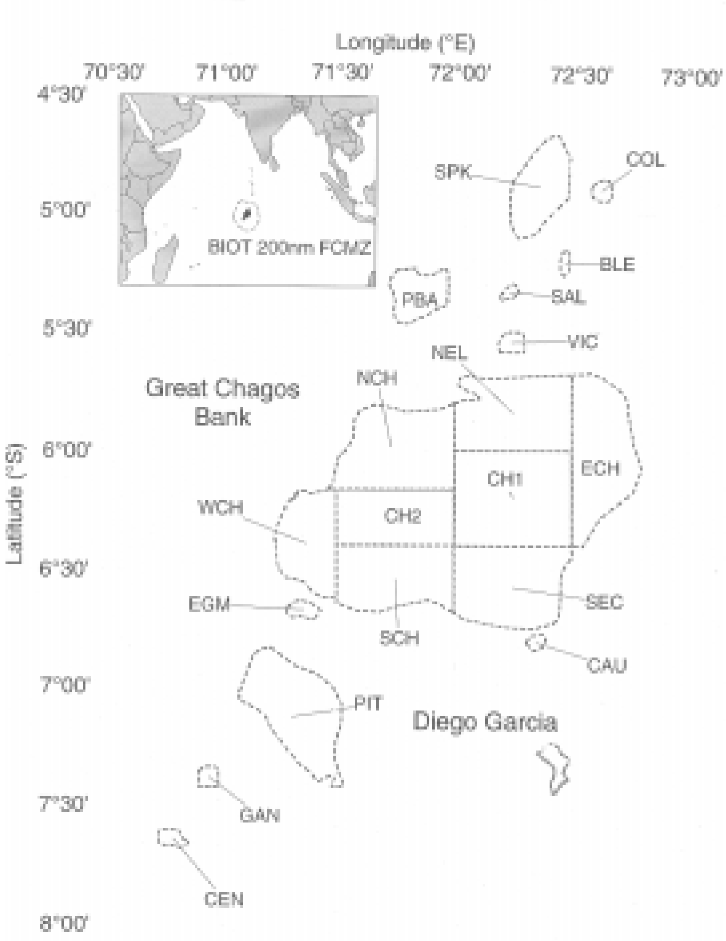


Figure 1.2 Chart of BIOT (Chagos Archipelago), indicating statistical fishing sectors

Code	Location	Code	Location	Code	Location
BLE	Blenheim Reef	EGM	Egmont Islands	SAL	Salomon Islands
CAU	Cauvin Bank	GAN	Ganges Bank	SCH	South Great Chagos Bank
CEN	Centurion Bank	NCH	North Great Chagos Bank	SEC	Southeast Great Chagos Bank
CH1	Central Great Chagos Bank 1	NEL	Nelson Island	SPK	Speakers Bank
CH2	Central Great Chagos Bank 2	PBA	Peros Banhos	VIC	Victory Bank
COL	Colvocorresses Reef	PIT	Pitt Bank	WCH	West Great Chagos Bank
ECH	Eastern Great Chagos Bank				

2. Otolith preparation and assessment

2.1 Introduction

Age can be assessed by counting regularly formed increments on hard tissues (Manooch, 1987). These are thought to relate to regular/seasonal changes in the environment or biology of the fish. A number of 'hard parts' have been employed to age fish species. These have included their vertebrae (e.g. Liu and Yeh, 1991), scales (e.g. Carlander, 1987;Van Oosten, 1923), urohial bones (e.g. Espinosa and Pozo, 1982) and spines (e.g. Edwards, 1985). For snappers and emperors, however, the most common hard part used for ageing is the otolith.

Project R6465 validated rings found in sectioned otoliths of *Lethrinus mahsena* and *Aprion virescens* as annual, using specimens from the waters of the Seychelles and Mauritian banks. Results from the validation technique were less conclusive where the temporal range of samples throughout the year was truncated. This problem was encountered when analysing samples from BIOT (Chagos Archipelago). However, the assumption of validation for this location was felt valid; otoliths showed an identical ring structure to those from locations where validation was successful, and data from available months indicated a comparable pattern in marginal increment to that found in validated locations. Otoliths of these species could therefore be used for ageing.

To perform assessments for the current project, a collection of *L. mahsena* and *A. virescens* otoliths from BIOT (Chagos Archipelago) were required. This section describes the collection and preparation of those otoliths, and methods used to assess the age of individual fish using these specimens.

2.2 Methodology

Otoliths from *L. mahsena* and *A. virescens* were collected during the 1999 BIOT (Chagos Archipelago) inshore observer programme. The collection procedure followed guidelines developed in Project R6465.

The UK observer was requested to collect at least 100 randomly sampled otoliths from each species, from each statistical area visited during the observer programme. However, vessel operations and the abundance of each species in the catch frequently meant that fewer than 100 individuals could be sampled within the available time. This was particularly true for *A. virescens*. In addition to random sampling, a non-random sample was also obtained. Targeted sampling from relatively large and small individuals, which would be under-represented in a random sample, was performed to improve the age-based growth parameter estimates derived for these species during project R6465.

Sectioning and staining was performed at CEFAS (Lowestoft) using the procedures described in the final technical report for project R6465, and in Pilling et al. (2000). To summarise, otoliths were embedded in black polyester resin, and a 0.5mm transverse section was taken through the centre ('nucleus') of the otolith using a diamond cutting blade (Bedford, 1983). The section was then stained using acidified neutral red (Richter and McDermot, 1990).

Otoliths were examined using a Leica binocular microscope with zoom lens and up to x60 magnification, under reflected light. Age was first assessed as an integer, assuming a 'birthday' of January 1st (Pilling et al., 1999). A 'decimal age' was then calculated, based on the difference between this birthday and the date of capture; an individual assessed as a 4year old caught on the 1st July would therefore have a decimal age of 4.5yrs.

2.3 Results

Table 2.1 indicates the number of *L. mahsena* and *A. virescens* individuals sampled for age, by statistical area within BIOT (Chagos Archipelago).

Table 2.1 Number of otoliths sampled by species and area within BIOT (Chagos Archipelago).

Area	*L. mahsena*	*A. virescens*
CAU	15	38
ECH	44	32
NCH	100	49
NEL	100	50
PIT	99	100
SCH	100	34
SEC	100	39
SPK	100	100
WCH	75	26
TOTAL	733	468

2.4 Discussion

Routine otolith age assessment was achieved without problems. However, the batch of otoliths collected during 1999 was slightly harder to read that those obtained during 1997 for Project R6465. No obvious reason could be put forward for this difference. Cursory examination of the width of the final (last year's) growth increment did not show any signs of notably decreased growth when compared to the width of the previous increments (bar that expected due to the decrease in growth rate with age). There were no signs that the coral bleaching event experienced in BIOT (Chagos Archipelago) during 1998 (Sheppard, 1999), along with many other tropical locations around the world, had led to a decrease in the growth rate in that year.

Length-at-age data estimated from *L. mahsena* and *A. virescens* otoliths were used to perform the following assessments:

- stock structure and spatial distribution (Chapter 3),
- estimation of biological and fishery parameters to derive stock assessments (Chapter 4).
- examination of the otolith weight-age relationship (Chapter 5)

Assessment of the costs and benefits of age- and length-based approaches to total mortality estimation were also examined (Chapter 6). The results of these studies are summarised to examine the utility of age-based approaches for the assessment of long-lived, slow-growing species in BIOT (Chagos Archipelago) and other tropical countries (Chapter 7).

3. Spatial Studies

3.1 Introduction

In the past, stock assessments for BIOT (Chagos Archipelago) have been carried out using length-based methods. These have been applied using data collected at two spatial scales, that of the location as a whole, and that of smaller statistical areas dividing the location (Figure 1.2). These statistical areas have been derived arbitrarily. Information has not been available to design these areas on a biological basis. Indeed, assessments at this more detailed spatial scale are frequently limited to those areas in which sufficient data have been collected (e.g Mees et al., 1999).

It is thought that the distribution of *L. mahsena* populations may be localised. This opinion was put forward by MRAG (1996b) for stocks of this species on the Mauritian banks. The distribution of fish may be controlled by patchy substrate, leading to isolated groups of fish with little lateral exchange or adult migration. There is therefore the potential for such localised meta-populations to exist within BIOT (Chagos Archipelago). If correct, the statistical areas, and hence the assessments performed, may bear little relation to the true underlying population structure.

Localised populations may exhibit differences in growth and mortality rates. Hence estimates of these parameters could indicate the existence and extent of such populations. However, the length-based methods used historically to estimate growth and total mortality are not sufficiently accurate to assess differences in these factors at such a local spatial scale. This was noted when such assessments were performed during FMSP project R5484. In addition, for many areas there are insufficient time series of data available to perform assessments of growth or mortality when data were segregated at such a local level (MRAG, 1996c; Mees and Rousseau, 1997).

Although length-based parameter estimates are too inaccurate to identify meta-populations, the examination of catch length structure might indicate the existence and extent of such populations. Such studies were undertaken during Project R6465 to assess the effects of fishing on exploited *L. mahsena* populations in BIOT (Chagos Archipelago). Consistent differences in sample mean length between areas on the Great Chagos Bank were identified over a number of years. This implies that meta-populations may exist in this location. However, comparisons of mean length at the local scale are potentially biased through variations in growth rate and the impacts of fishing through density dependent growth. Indeed, evidence for density dependent growth in *L. mahsena* was noted in Project R6465.

Age structure will be less affected by the influences of density dependent growth, and hence will be more demonstrative of the true population characteristics. Examinations of mean age by statistical area undertaken during Project R6465 showed comparable differences to those found in mean length between areas. Age data indicated that differences in length did not result from either variations in growth rate, which was comparable between statistical areas, or the level of fishing pressure experienced (the removal of larger/older individuals through gear selectivity). However, the age data were spatially and temporally limited, and hence uncertainty remained over the patterns found.

No evidence for *A. virescens* meta-populations in BIOT (Chagos Archipelago) were found during Project R6465. However, data available for that study were relatively limited, and conclusions for this species were therefore tentative.
This study aims to clarify the existence and extent of meta-populations of *L. mahsena* and *A. virescens* within BIOT (Chagos Archipelago). The study will examine patterns in length, age and growth rate, based on a more extensive sample than that available for Project R6465. Outputs will inform routine stock assessments performed in BIOT (Chagos Archipelago), improving the management of resources by detailing the spatial level at which they should be undertaken (Chapter 4).

3.2 Methodology

Catch sample mean length and age were compared by statistical area. Mean age was calculated using individual ages assessed through otolith increment counts. Mean length and age for each statistical area were compared using the GT-2 test (Hochberg, 1974). For display purposes, upper and lower 95% comparison intervals around each mean were calculated through Gabriel's method (Gabriel, 1978).

Mean length or age were compared to the level of cumulative fishing effort (man days) applied in each area, through linear regression. This examined whether differences between statistical areas resulted from the direct effects of fishing. A student's *t*-test was used to assess the significance of trends identified with increasing fishing effort.

Differences in mean length and age could also result from varying growth rates between statistical areas. Mean length-at-integer age (a proxy for growth rate) for each statistical area were compared for significant differences using the GT-2 test. Differences were related to the level of cumulative fishing pressure (per km^2) applied since inshore logbook data collection was initiated in 1991, and to demersal CPUE (kg per man day per km^2) achieved in 1999, through regression. The significance of identified trends in mean length-at-age with CPUE and cumulative effort was examined using a students *t*-test.

3.3 Results

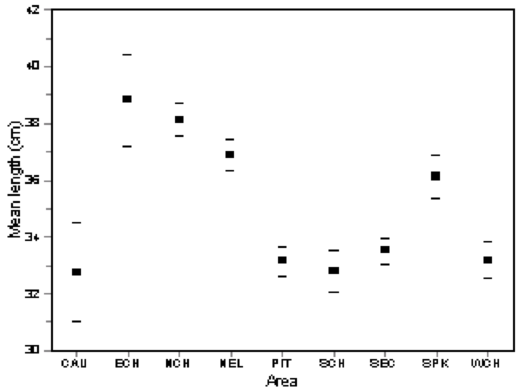
Mean length, age, and growth rate (mean length-at-age) were compared by statistical area within BIOT (Chagos Archipelago) to identify spatial differences in stock structure. This study was performed using data from both *L. mahsena* and *A. virescens*. Results are presented by species.

3.3.1 *Lethrinus mahsena*

Mean length and age

Significant differences in *L. mahsena* catch mean length and age were found between statistical areas (Figure 3.1). Catch mean length and age in the north and east areas of the Great Chagos Bank (NCH, NEL, ECH) and Speakers Bank (SPK, to the north of the Great Chagos bank) were significantly larger than those from both south and west areas of the Great Chagos Bank (SCH, SEC,), and from Pitt and Cauvin Banks (PIT and CAU, to the SW and SE of that bank).

a) Mean fork length



b) Mean age

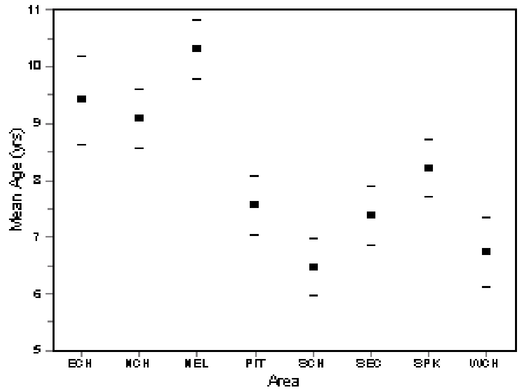


Figure 3.1 Gabriel's plots of 95% comparison intervals by the GT-2 method for a) mean fork length and b) mean age of *L. mahsena* from different statistical areas within BIOT (Chagos Archipelago) during 1999.

No consistent pattern was found when either mean length or mean age by area was related to the level of fishing pressure (man days per km^2 from 1991), indicating that spatial differences in mean length and age between areas did not result from the effects of fishing.

Historical length and age data were examined to see whether similar patterns were found. Pattern in mean *age* found in the current study could only be compared with those found in 1997. While mean ages between years were not directly comparable, the pattern of differences between areas was consistent between the two years. Length data were available to allow comparisons of mean *length* by area back to 1995 (Figure 3.2). 1996 data were not be included, since there were insufficient data for meaningful comparisons when segregated at the level of statistical areas. Where areas were present in the data for different years, the pattern in mean length was consistent.

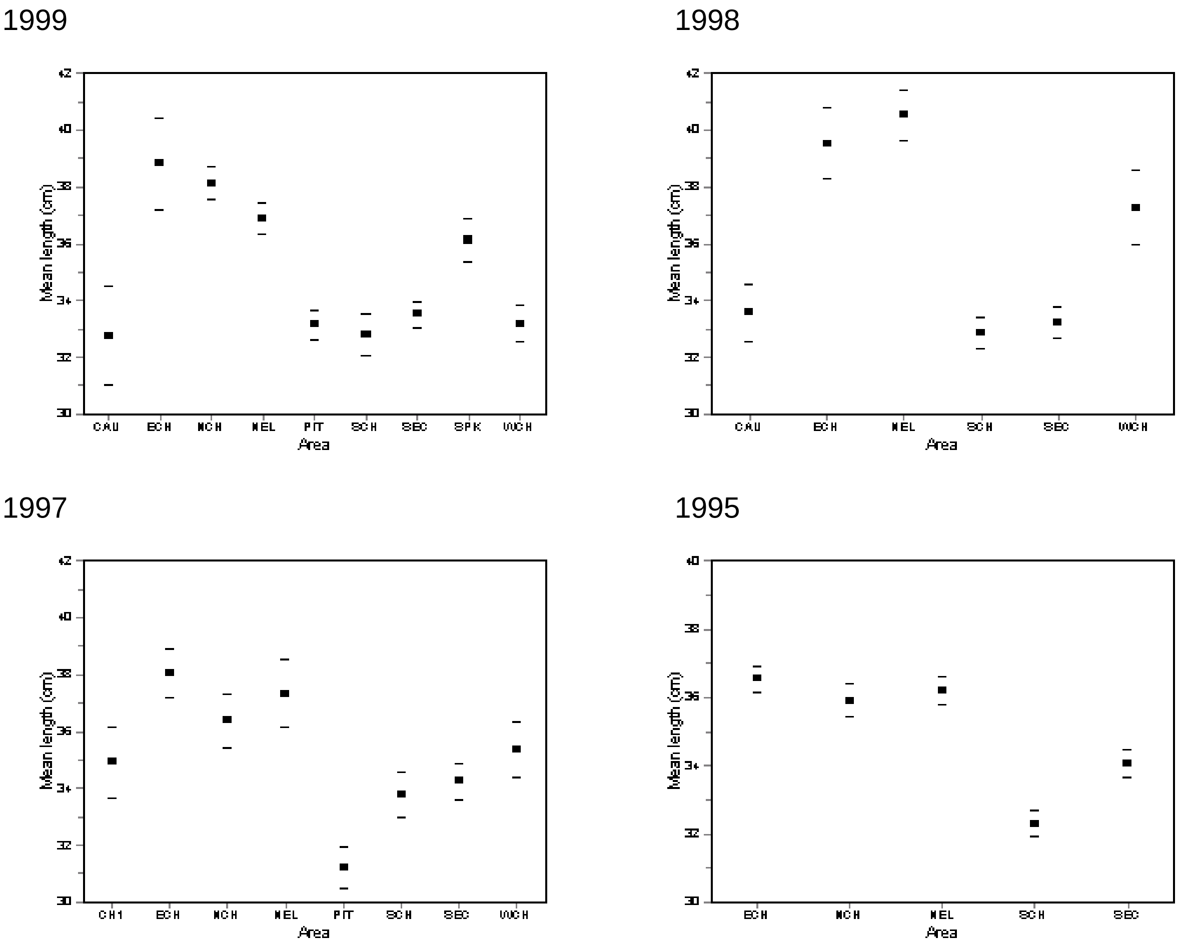


Figure 3.2 Gabriel's plots of 95% comparison intervals by the GT-2 method for mean fork length of *L. mahsena* from different statistical areas within BIOT (Chagos Archipelago) in years from 1995 to 1999.

Growth rate

Differences in mean length between areas could be caused by localised differences in growth rate. However, comparisons of mean length-at-age (a proxy for growth) between areas using the GT-2 test indicated no significant spatial differences in growth rate at any age. As an example, Figure 2.3 presents the results for the comparison at age 8 years. Differences in mean length between areas do not result from variations in growth rate.

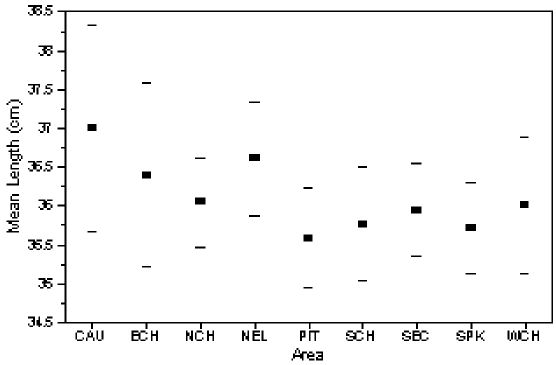


Figure 3.3 Gabriel's plot of 95% comparison intervals by the GT-2 method for *L. mahsena* mean length-at-age 8 years by area within BIOT (Chagos Archipelago).

3.3.2 *Aprion virescens*

Mean length and age

Significant differences in *A. virescens* catch mean length and age between statistical areas were identified (Figure 2.4). For example, catch mean length at Centurion bank, Gangees bank and western Great Chagos Bank (CEN, GAN, WCH) were significantly lower than in the majority of other statistical areas sampled. In contrast, underlying mean ages in each statistical area were not significantly different. The exception was at Cauvin bank, where mean age was significantly larger than that in many other areas.

a) Mean fork length b) Mean age

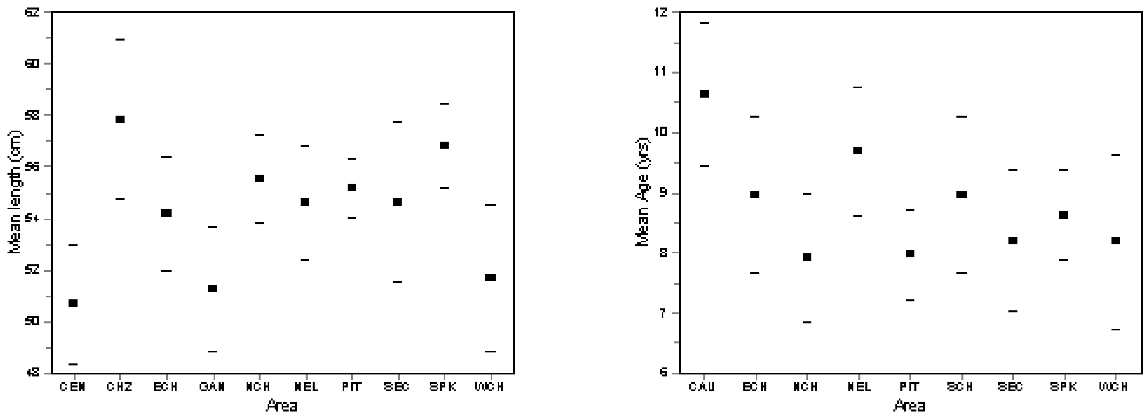


Figure 3.4 Gabriel's plots of 95% comparison intervals by the GT-2 method for a) mean fork length and b) mean age of *A. virescens* from different statistical areas within BIOT (Chagos Archipelago) during 1999.

A. virescens mean catch length showed a significant negative relationship when compared with the level of cumulative fishing effort exerted in each statistical area (Figure 3.5, *t*-test *P*=0.01). However, no pattern was found when mean catch age was compared to the level of cumulative fishing effort applied in each statistical area.

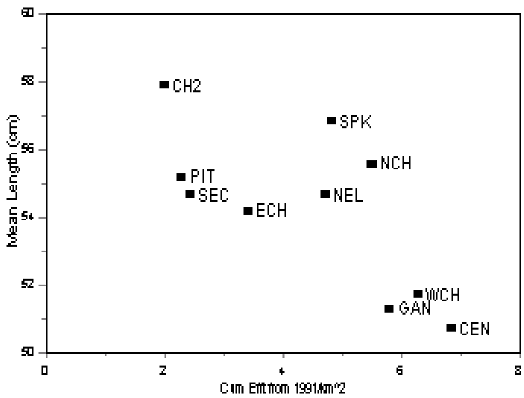


Figure 3.5 1999 mean fork length (cm) of *L. mahsena*, by statistical area, against cumulative fishing effort since 1991 (man days km^{-2}).

Growth rate

Examination of mean length-at-age by statistical area indicated that growth rates were generally comparable between statistical areas. The only consistent difference in growth rate was between north and northeast Great Chagos Bank (NCH, NEL) and Pitt Bank (PIT). The mean length at NCH and NEL for ages 5 to 7 years was significantly larger than that from PIT (e.g. Figure 3.6), implying increased growth rates at the younger ages in the former locations.

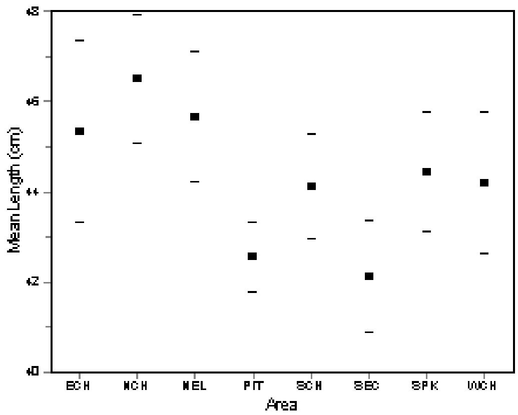


Figure 3.6 Gabriel's plots of 95% comparison intervals by the GT-2 method for *A. virescens* mean length-at-age 5 years by statistical area within BIOT (Chagos Archipelago).

3.4 Discussion

Currently, the statistical areas used to divide BIOT (Chagos Archipelago) data are arbitrary. Insufficient data have been available to re-assess the boundaries of these areas on a biological basis. It has been noted that *L. mahsena* may form localised meta-populations due to patchy substrate distribution (MRAG, 1996b). In turn, additional evidence for localised populations was identified during Project R6465 (Pilling et al., 1999). Therefore, assessments performed in BIOT (Chagos Archipelago) based on the statistical areas may bear little resemblance to the actual underlying population structure. The studies described in this chapter aimed to clarify the existence and extent of *L. mahsena* and *A. virescens* meta-populations, improving the management of resources by informing the spatial scale at which assessments should be undertaken.

To identify spatial differences in stock structure, the length, age and growth of exploited *A. virescens* and *L. mahsena* was examined at the scale of the statistical areas within BIOT (Chagos Archipelago).

Significant differences were found in *Aprion virescens* mean length by statistical area within BIOT (Chagos Archipelago). Differences related to the level of cumulative fishing effort applied in each area. However, mean age did not show comparable significant differences between areas. No differences in growth between areas could be identified to cause these differences. The lack of differences in mean age may therefore result from the sample sizes in each statistical area for this species. There are no consistent indications of *A. virescens* meta-populations within BIOT (Chagos Archipelago).

Significant differences in the catch length and age structure of *Lethrinus mahsena* were found between areas of the Great Chagos Bank, and neighbouring banks. Catches in the east and north of the Great Chagos Bank (including Speakers bank, to the north of the Great Chagos Bank) were comprised of relatively large, old fish. In contrast, catches in the west and south of the bank (including Pitt and Cauvin banks to the south and southeast of the Great Chagos Bank) comprised significantly smaller, younger fishes. Although mean sizes and ages were not directly comparable, an identical pattern was found in data collected during 1997 for project R6465 (Pilling *et al*, 1999). In turn, the pattern in mean length by area (for those areas with sufficient samples) was consistent with that found in length frequency data back to 1995 (Figure 3.2). Differences in catch mean length and age between statistical areas were therefore consistent between years. Differences in stock structure did not result from fishing pressure; no significant relationship was found when the mean lengths or ages from each statistical area were related to the level of cumulative fishing effort per unit area applied (see also Pilling et al., 1999).

Differences could result from spatial variations in growth rate, due to varying local conditions or to density dependence. However, no significant differences in mean length-at-age (a proxy for growth) were found between statistical areas. Differences could also result from varying local levels of natural mortality, or ontogenic migrations between locations. However, no data were available to examine these possibilities.

The results of the studies performed suggest that there are indeed localised meta-populations of *L. mahsena* within BIOT (Chagos Archipelago), as defined by the consistent pattern found in mean length and age. The potential extent of these populations is presented in Figure 3.7. The existence of localised meta-populations of *L. mahsena* on the banks of Chagos has implications for the data collection and stock assessment approaches employed for this species in this location. It is frequently difficult to collect sufficient data from each individual statistical area to allow analysis; vessels move frequently between areas, limiting the time available in which data can be collected. Data collection and analysis at the larger spatial scale of the meta-population would save time and effort. This would also be more biologically relevant.

The identification of meta-populations of *L. mahsena* informs the spatial scale at which assessments should be made (Chapter 4). Based on results of the current chapter, stock assessments for *L. mahsena* will be performed at the spatial levels of BIOT (Chagos Archipelago) as a whole, by individual statistical areas, and at the level of meta-populations. Given the lack of evidence for meta-populations of A. virescens, in BIOT (Chagos Archipelago), stock assessments for this species should be performed at the scale of the location as a whole. In addition, specific sampling of statistical areas should be undertaken in heavily exploited regions.

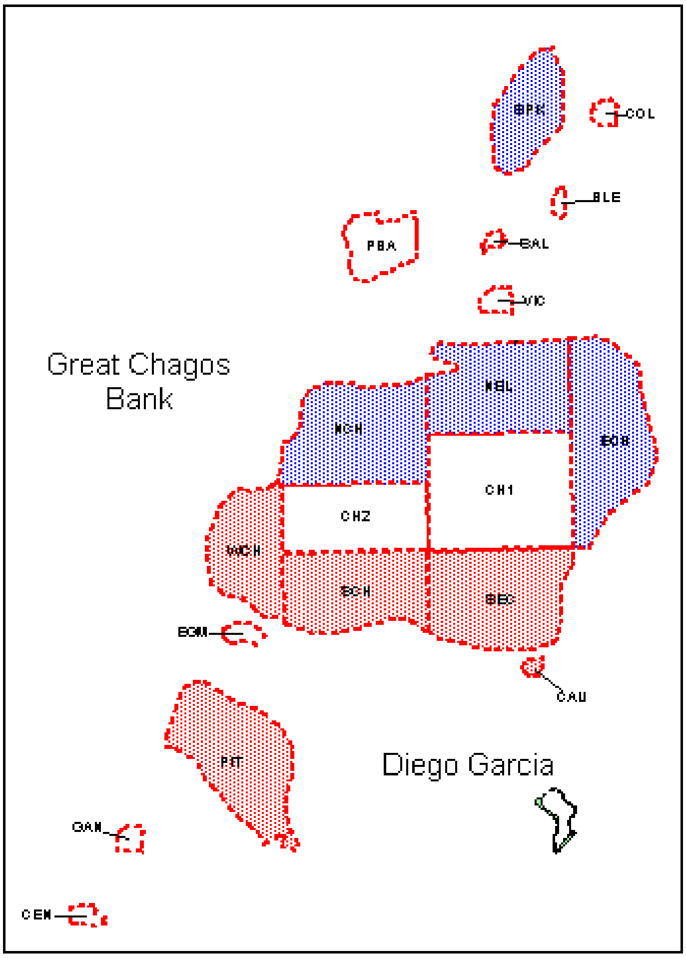


Figure 3.7 Chart indicating the distribution of the two *L. mahsena* meta-populations. Populations with similar demographic characteristics on banks separate from the Great Chagos Bank also shown.

4. Parameter assessment

4.1 Introduction

In the past, stock assessments in BIOT (Chagos Archipelago) have been based on the results of length-based methods of assessment. However, the accuracy of such biological and fishery parameter estimates is uncertain for long-lived, slow growing species (such as snappers and emperors). Project R6465 examined the accuracy of length-based growth parameter estimates for long-lived, slow-growing species. The project also examined the knock-on effects of using these parameters in stock assessments and the resulting management decisions. The results were compared to the management resulting from the use of age-based methods growth parameter estimates. Length-based methods of growth assessment were found to overestimate both L_∞ and K. Poor management resulted where these parameters were employed in further assessments. Age-based methods resulted in the most appropriate stock assessments, and hence management for these species.

When estimating growth parameters using actual length-at-age data from *L. mahsena* and *A. virescens* populations, it was noted that the presence or absence of samples from extremes of the age range were highly influential on age-based growth parameter estimates. The number of such individuals was limited in samples obtained for Project R6465. During the 1999 BIOT (Chagos Archipelago) observer programme, individuals from these size classes were targeted. Given the importance of growth parameters in stock assessments, as identified in Project R6465, improvements in growth parameter estimates resulting from the incorporation of these additional samples should have knock-on effects on the quality of stock assessments performed.

Figure 1.1 showed the steps required for stock assessments base on length- or age-based methodologies. Work performed during Project R6465 indicated that the use of length-based methods to assess total mortality diluted the advantages gained through the use of age-based growth parameter estimates in assessments. That project suggested the use of age-based methods of total mortality estimation. This approach does not require the use of growth parameter estimates, thereby avoiding the incorporation of uncertainty in those parameters in the stock assessment process. Improvements gained from substituting an age-based total mortality assessment will be assessed during Project R7522 through simulation. Age-based methods of total mortality estimation will be used in the current study.

Estimation of total mortality through age-based methods is one of the first stages in deriving stock assessments for the study species. The second is to estimate the level of natural mortality (M), so that estimates of current fishing mortality can be derived (F_{curr} = Z-M). At present, estimates of M are derived using the empirical formulae of Pauly (Pauly, 1980) or Ralston (Ralston, 1987). This adds uncertainty to estimates of fishing mortality, since a species' natural mortality level may not conform to the 'average' assumed by those formulae. Work during Project R6465 indicated that this parameter is highly influential in stock assessments, influencing the value of parameters such as $F_{0.1}$, as well as F_{curr}. In order to reduce the level of uncertainty in stock assessments, therefore, natural mortality needs to be estimated independently of empirical formulae. This will be attempted in the current study.

Assessed parameters will be used to estimate current fishing mortality (F_{curr}) and yield per recruit (specifically $F_{0.1}$) for *L. mahsena* and *A. virescens* stocks in BIOT (Chagos Archipelago). The status of these species will then be assessed by comparing these values. Outputs from Chapter 3 will be used to inform the spatial scale at which assessments should be performed.

One of the recommendations from Project R6465 was that stock assessments should be tuned to the level of fishing mortality applicable to that fishery. However, the tuning levels derived in that project were based on length-based estimates of total mortality. In contrast, the current study employs age-based methods to estimate this parameter. Uncertainty still remains over the accuracy of fishing mortality estimates, due to the lack of an independent estimate of M. Therefore, assessments performed in the current study could not be tuned, contrary to the recommendations from Project R6465.

Prior to this project, insufficient data were available to estimate important reproductive parameters for the study species. Such parameters act as inputs into many stock assessment approaches. In turn, they increase knowledge on the impacts that fishing may have on exploited populations. Data collected during the 1999 observer programme allows estimates of these reproductive parameters to be derived for these species in BIOT (Chagos Archipelago) for the first time.

This chapter will describe the results of work performed to derive improved assessments of the status of *L. mahsena* and *A. virescens* stocks in BIOT (Chagos Archipelago). Assessments will be performed using length-at-age data collected during the 1999 inshore fishery, minimising uncertainty in assessments. The resulting stock assessments will be compared to those derived using the length-based approaches historically used in this location.

4.2 Methodology

This section details the methods through which the otoliths collected from BIOT (Chagos Archipelago) in 1999 were used to estimate biological and fishery parameters for *L. mahsena* and *A. virescens*. The methods then used to derive stock assessments for these species are described.

4.2.1 Growth parameters

Length-at-age data collected during 1999 were compared with that collected during the 1997 fishing season. As no significant differences were found in the mean length-at-age of the two samples (GT-2 test, $P>0.1$), these data were combined. Von Bertalanffy growth parameter estimates for each species were then re-estimated using least-squares methods.

4.2.2 Reproductive parameters

The overall sex ratio of males to females was calculated for BIOT (Chagos Archipelago) from randomly sampled specimens. Sex ratio at length was also assessed at those length classes where more than five individuals of each sex were present.

The proportion of individuals mature at length was assessed using data from females only. On the eight point maturity scale used, individuals of stage 4 or greater were considered mature. The resultant plots were assessed for the length and age at which 50% of females were mature (Lm_{50}, Am_{50}). Both values were assessed by fitting a logistic equation to the percentage of mature individuals (P(*x*)) in each size class (*FL*):

$$P_x = \frac{100}{1 + e^{(a.FL \; + \; b)}}$$

where *a* and *b* are fitted parameters and Lm_{50} (or Am_{50}) = -b/a.

4.2.3 Age structure, total mortality, and age at first capture

Integer ages estimated from otolith increment counts were used to derive age frequency distributions for both species, for 1999. Distributions were derived for the whole Archipelago ('all BIOT'), for each statistical area (where sufficient data were present), and for each of the meta-populations identified in Chapter 3 (*L. mahsena* only). A catch curve was then applied to each age frequency to estimate total mortality. The resulting estimate was compared to that derived for 1997.

The age at which 50% of individuals were vulnerable to the gear (Ac_{50}) was estimated from the ascending limb of the age-based catch curve. This estimate was used in the calculation of yield-per-recruit. Estimates were derived for the whole of BIOT (Chagos Archipelago). This ensured the effect of differences in population structure unrelated to the level of fishing, or sample size, was minimised.

4.2.4 Natural and fishing mortality

A number of the statistical areas within BIOT (Chagos Archipelago) are considered to be 'lightly fished'. As such, if total mortality estimates can be derived using data from these areas, they should correspond closely to the level of natural mortality. However, as a result of their lightly fished nature, insufficient data from either species could be collected to derive an estimate of total (and hence natural) mortality during the time period vessels were operating in these areas.

Natural mortality can also be estimated by relating annual estimates of total mortality to the level of fishing mortality applied in each year. However, there were insufficient years of age-based estimates to derive natural mortality estimates through this approach. Therefore an alternative approach was used. Estimates of total mortality derived for each *statistical area* for 1999 were related to the level of fishing effort applied in that area. Total mortality estimates were compared to the level of fishing pressure applied in 1998 (man days km^{-2}); fishing effort in 1999 will not affect the population structure sampled in that same year. The effort applied in the previous years fishing will have a more significant effect. Assuming a linear relationship is found, extrapolation of the line back to the point at which the level of fishing effort is zero provides an indication of M. Data limitations meant that this approach could only be undertaken for *L. mahsena*.

F_{curr} was calculated by subtracting the estimates of natural mortality from that of total mortality (F_{curr} = Z-M).

4.2.5 Yield-effort curve and stock assessment

Yield-per-recruit was estimated within an EXCEL spreadsheet, using the method of Beverton and Holt (Beverton and Holt, 1957) and the parameters estimated through the approaches described above. $F_{0.1}$, the fishing mortality at which the gradient of the yield-per-recruit curve was 10% of that at F=0 (Caddy and Mahon, 1995), was then calculated. This reference point was used for stock assessments in project R6465, and has been shown to be appropriate for *L. mahsena* through simulations performed both in that project and FMSP project R7041 ('Software for estimating potential yield under uncertainty').

To assess stock status, the relative values of F_{curr} and $F_{0.1}$ were compared. Estimated fishing mortality was expressed as a percentage of the $F_{0.1}$ estimate. Based on this comparison, the overall stock status was indicated.

4.3 Results

Biological and fishery parameters were estimated for *L. mahsena* and *A. virescens* stocks in BIOT (Chagos Archipelago). Using these parameter estimates, stock assessments were performed to examine the status of these exploited populations. Results are presented below, by species.

4.3.1 *Lethrinus mahsena*

Growth parameters

Mean length-at-age data from 1999 were not significantly different from that in 1997/1998 (GT-2 test, P>0.1). Therefore, data were combined to re-estimate growth parameters for *L. mahsena* (Figure 4.1).

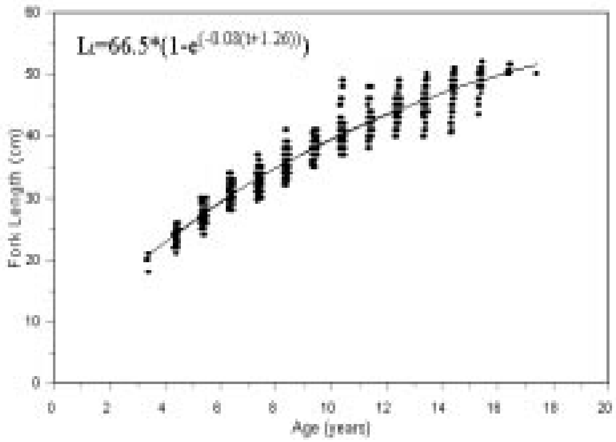


Figure 4.1 Growth curve for *L. mahsena* from BIOT (Chagos Archipelago).

L. mahsena growth parameter estimates were slightly improved by the increase in the number of individuals at the extremes of the sampled length and age range. However, the lack of young individuals in particular still affected estimates. The lack of these individuals is likely to result in the under-estimation of K and t_0, and over-estimation of L_∞. If growth follows the von Bertalanffy function, t_0 is generally negative, so that individuals have reached positive lengths at the time of birth. Setting t_0 equal to zero should therefore indicate a likely maximum value for the K estimate (Table 4.1). The resulting growth curve fitted the available data reasonably. These estimates were felt likely to resemble those resulting from re-estimation of parameters with the inclusion of addition data sampled from young individuals.

Table 4.1 *L. mahsena* von Bertalanffy growth parameter estimates based on length-at-age data where t_0 is unconstrained, and constrained to zero.

Parameter	Unconstrained	t_0 constrained to zero
L_∞	66.5	57.7
K	0.08	0.12
t_0	-1.26	0

Reproductive parameters

The sex ratio of males to females in the *L. mahsena* catch sample from BIOT (Chagos Archipelago) as a whole was 1:1.2 (ratio=0.81). This ratio was skewed towards females, but to a lesser extent to that identified in project R6465 (ratio in 97/98 was 0.35). The sex ratio by length is displayed in Figure 4.2.

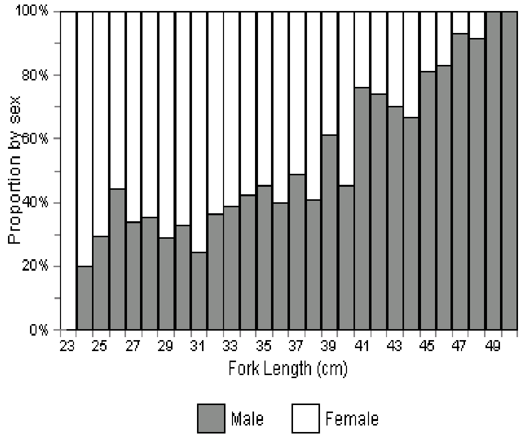


Figure 4.2 Sex ratio at length for *L. mahsena* in BIOT (Chagos Archipelago).

The proportion of males at length increased with increasing size, implying this species is protogynous. An identical pattern was found in data from other locations in the Indian Ocean examined during Project R6465.

Data from female specimens were used to estimate the length and age at maturity. Few mature individuals (stages 4 and greater) were identified in the samples, and the resulting pattern of maturity at length or age was unclear. Hence estimates of Lm_{50} or Am_{50} could not be derived.

Age structure, total mortality, and age at first capture

The catch age structure for the whole of BIOT (Chagos Archipelago) is presented in Figure 4.3, along with that for 1997. No significant difference was found between the mean age of these two samples (Welch's Approximate t-test, *P*>0.2). The form of the age distributions were not significantly different (Kolmogorov-Smirnov test, *P*>0.1).

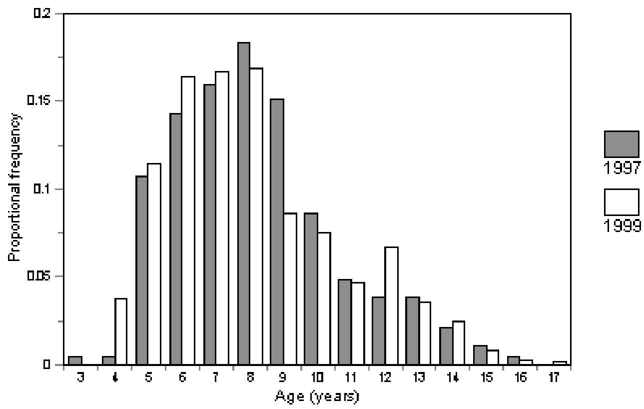


Figure 4.3 Catch age frequency distributions for 1999 and 1997 for BIOT (Chagos Archipelago).

Age structures of the meta-populations identified in Chapter 3 were also examined (Figure 4.4).

a) North and east

b) South and west

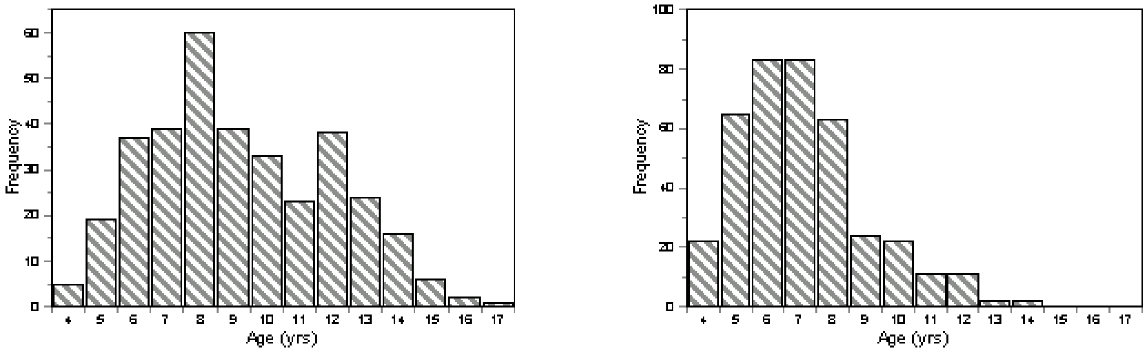


Figure 4.4 Catch age frequency distributions for *L. mahsena* by meta-population.

The increased number of older individuals between the north and east region (Figure 4.4a) compared to the south and west region of the Great Chagos Bank (Figure 4.4b) is clearly seen. This resulted in the higher mean age in this meta-population.

Using age-based catch curves, age frequency distributions were used to estimate total mortality for the whole of BIOT (Chagos Archipelago), for each meta-population, and for statistical areas within BIOT (Chagos Archipelago). These estimates are summarised in Table 4.2. The estimate for the whole of BIOT (Chagos Archipelago) is comparable to that estimated using data from 1997. Total mortality estimates could not be derived for individual statistical areas in 1997 (Project R6465) as insufficient data were available.

Table 4.2 Total mortality estimates derived from age-based catch curves for 1999, and comparison with those derived for 1997.

Area	Z estimate	
	1999	1997
All BIOT	0.43 +/- 0.15	0.40 +/- 0.10
North and east	0.44 +/- 0.19	-
South and west	0.55 +/- 0.14	-
PIT	0.42 +/- 0.19	-
SCH	0.57 +/- 0.46	-
SEC	0.38 +/- 0.32	-
SPK	0.31 +/- 0.13	-
WCH	0.39 +/- 0.05	-

Using data for the whole of BIOT (Chagos Archipelago) Ac_{50} was estimated at 3.9 years (Lc_{50}=21.6-22.5cm).

Natural and fishing mortality, and $F_{0.1}$

The level of fishing effort per unit area (man days km^{-2}) applied in each statistical area was related to the corresponding total mortality estimate (see Table 4.2). An increasing increasing trend in the total mortality estimates with increasing fishing effort was found (Figure 4.5).

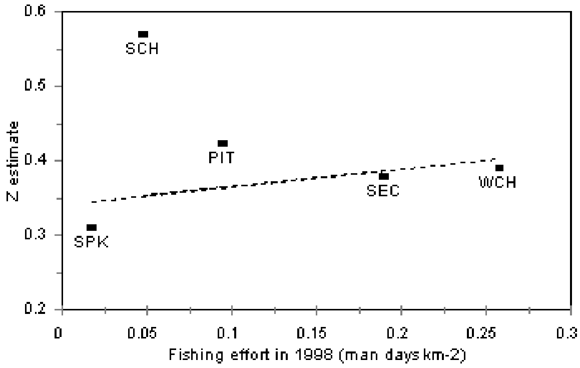


Figure 4.5 Relating 1999 age-based estimates of total mortality to the level of fishing effort (man days km^{-2}) applied in 1998 to estimate natural mortality.

The total mortality estimate for the south Great Chagos Bank (SCH) was notably higher than the general trend. This does not appear to result from the effects of fishing, as no correlation between mean length of *L. mahsena* in each statistical area and the level of fishing effort was found (Chapter 3). The high level of total mortality for this area may result from factors other than fishing, such as a higher rate of natural mortality, or ontogenic migration. The assessment performed above assumes that factors such as natural mortality are comparable between areas. Therefore, the total mortality estimate for SCH was excluded from the assessment. The regression line crossed the Y-axis (where F=0) at M=0.34.

As a result of the problems with the assessment, uncertainty in this estimate of natural mortality remains. Factors such as variations in the natural mortality rate, or ontogenic migration, invalidate the assessment, while the resulting estimate of M is based on only four points. As a result of these problems, the estimate of M is highly uncertain.

Due to the uncertainty over the estimate of M, empirical formulae of Pauly and Ralston were used to estimate natural mortality for each species. This was performed using the age-based growth parameters derived earlier. For Pauly's equation, 27°C was used as the average sea surface temperature (Nautical Almanac for the Indian Ocean). The resulting two estimates tended to encompass the estimate derived above (M=0.34). Hence the use of the empirical estimates resulted in cautious and bullish stock assessments (see also Pilling et al., 1999).

Using growth parameter and mortality estimates presented above, estimates of natural mortality (through empirical formulae), fishing mortality (F_{curr} = Z-M), and $F_{0.1}$ were derived. Resulting estimates for the whole of BIOT (Chagos Archipelago) (Table 4.3) and each meta-population (Table 4.4) are presented.

Table 4.3 Estimates of natural and fishing mortality, and $F_{0.1}$ derived for *L. mahsena* for the whole of BIOT (Chagos Archipelago).

Growth estimates	M estimator	Natural mortality (M)	Fishing mortality (F)	$F_{0.1}$
t_0=-1.26	Pauly	0.27	0.07	0.27
	Ralston	0.18	0.17	0.18
t_0=0	Pauly	0.36	0.16	0.36
	Ralston	0.26	0.25	0.24

Table 4.4 Estimates of natural and fishing mortality, and $F_{0.1}$ derived for *L. mahsena* by meta-population.

Meta-population	Growth estimates	M estimator	Natural mortality (M)	Fishing mortality (F)	$F_{0.1}$
North and east	t_0=-1.26	Pauly	0.27	0.17	0.27
		Ralston	0.18	0.26	0.18
	t_0=0	Pauly	0.36	0.08	0.36
		Ralston	0.26	0.18	0.24
South and west	t_0=-1.26	Pauly	0.27	0.28	0.27
		Ralston	0.18	0.37	0.18
	t_0=0	Pauly	0.36	0.19	0.24
		Ralston	0.26	0.29	0.34

Tables 4.3 and 4.4 indicate that a range of fishing mortality levels are potentially plausible for the BIOT (Chagos Archipelago) inshore fishery. Therefore, a conservative approach to stock assessment and management is required.

Stock assessment

To illustrate the uncertainty arising in assessments based on length-based approaches, Figure 4.6 presents the results of stock assessments derived for 1999 using *length-based* methods of assessment for a range of estimated input parameters. Current fishing mortality is expressed as a percentage of the management level $F_{0.1}$. Caution is warranted where $F_{curr}/F_{0.1}$ is greater than 100%, while the stock is assumed to be sustainably exploited where $F_{curr}/F_{0.1}$ is less than 100%. A high proportion of the uncertainty arises through the use of growth parameters in the estimation of total mortality. Assessments for an area can indicate under-exploitation, or over-exploitation, dependent on the growth parameters used. Note that these assessments are all derived using Pauly's natural mortality estimate alone. An additional level of uncertainty is introduced where uncertainty over the correct natural mortality estimate is taken into account.

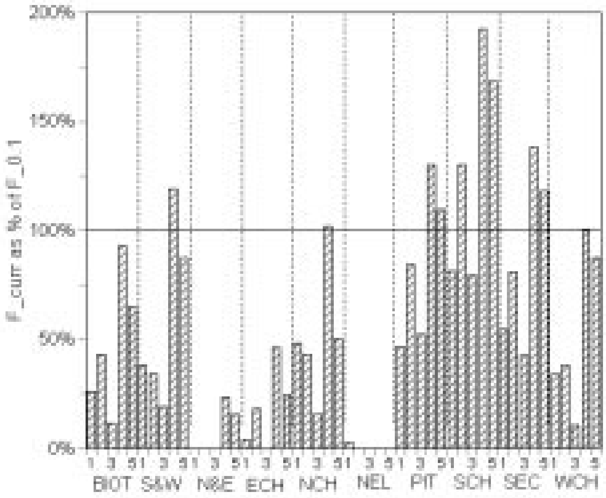
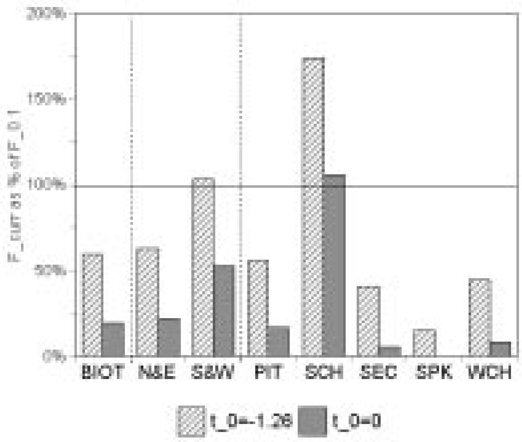


Figure 4.6 Stock assessments based on F_{curr} and $F_{0.1}$ estimates for *L. mahsena* derived through length-based methods. M derived through Pauly's empirical formula. 1-5 relate to growth parameters used. 1. Bautil and Samboo, 1988; 2. Pilling et al., 1999, age-based estimate; 3. Pilling et al., 1999, age-based, t_0=zero; 4. Pilling et al., 1999, length-based estimate; 5. Dalzell et al., 1992.

To reduce the level of uncertainty in assessments, age-based methods of total mortality estimation were used in the current study. This removed the need to use growth parameters at this stage. F_{curr} as a percentage of $F_{0.1}$ is shown in Figure 4.7 by spatial scale and natural mortality estimate.

a) Pauly's M



b) Ralston's M

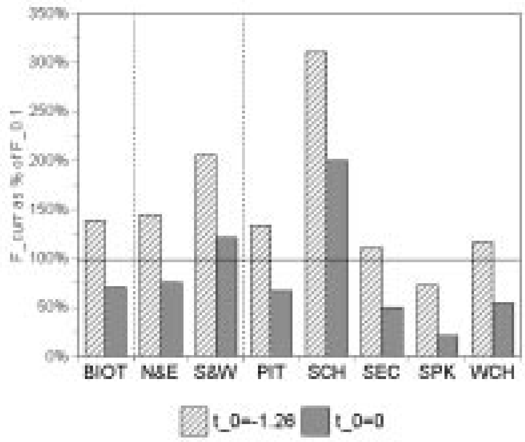


Figure 4.7 Stock assessments derived based on the relationship between F_{curr} and $F_{0.1}$, estimated using a) Pauly's M, b) Ralston's M.

Assessments based on Pauly's M generally indicate that *L. mahsena* is exploited sustainably. However, in the south and west meta-population, and in particular the south of the Great Chagos Bank (SCH), there is evidence of over-exploitation. Where Ralston's M estimate was used, there is more evidence of over-exploitation. However, this is generally only found when the un-constrained growth parameter estimates were used. Assessments based on the constrained growth parameter estimates show an identical pattern to that where Pauly's M was used. However, the magnitude of the F_{curr} and $F_{0.1}$ estimate (and hence their relation to the 100% line) changes.

4.3.2 *Aprion virescens*

Growth parameters

Mean lengths-at-age data collected during 1999 were not significantly different from those estimated for 1997 (GT-2 test, *P*>0.25). Therefore, data from these years were combined, and growth parameters for *A. virescens* in BIOT (Chagos Archipelago) re-estimated (Figure 4.8).

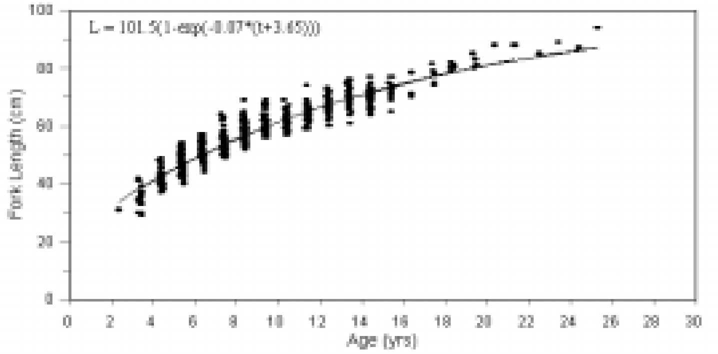


Figure 4.8. Growth curve for *A. virescens* from BIOT (Chagos Archipelago).

Growth parameter estimates were improved by the increased number of individuals at the extremes of the sampled length range. However, as found for *L. mahsena*, the sample still lacked individuals from the youngest age classes. Therefore, growth parameters were estimated with t_0 constrained to zero (Table 4.5). However, constraining this parameter resulted in a poor fit to the data collected from older individuals. Little confidence can be placed in these constrained estimates.

Table 4.5 *A. virescens* von Bertalanffy growth parameter estimates based on length-at-age data where t_0 is unconstrained, and constrained to zero.

Parameter	t_0	
	unconstrained	constrained to zero
L_∞	101.5	77.9
K	0.07	0.16
t_0	-3.65	0

Reproductive parameters

The sex ratio of males to females across the whole of BIOT (Chagos Archipelago) was 1 : 0.83 (ratio = 1.20). The ratio was skewed towards males, as found in Project R6465 (ratio in 1997 was 1.33).

The sex ratio by length is displayed in Figure 4.9. As found in project R6465, the sex ratio at length remained relatively constant with increasing size. The ratio was slightly skewed towards males across the size range.

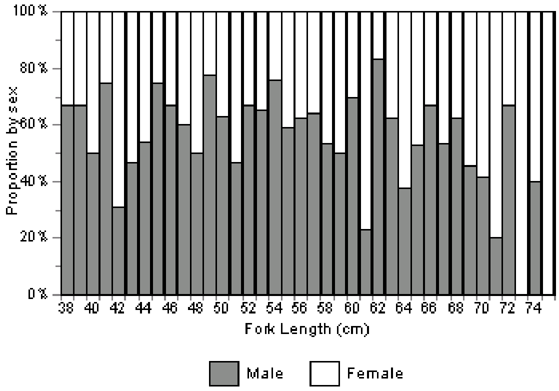


Figure 4.9 Sex ratio at length for *A. virescens* in BIOT (Chagos Archipelago).

The length and age at maturity was assessed using data from female specimens. The proportion of mature and immature individuals at length or age is presented in Figure 4.10.

a) By length b) By age

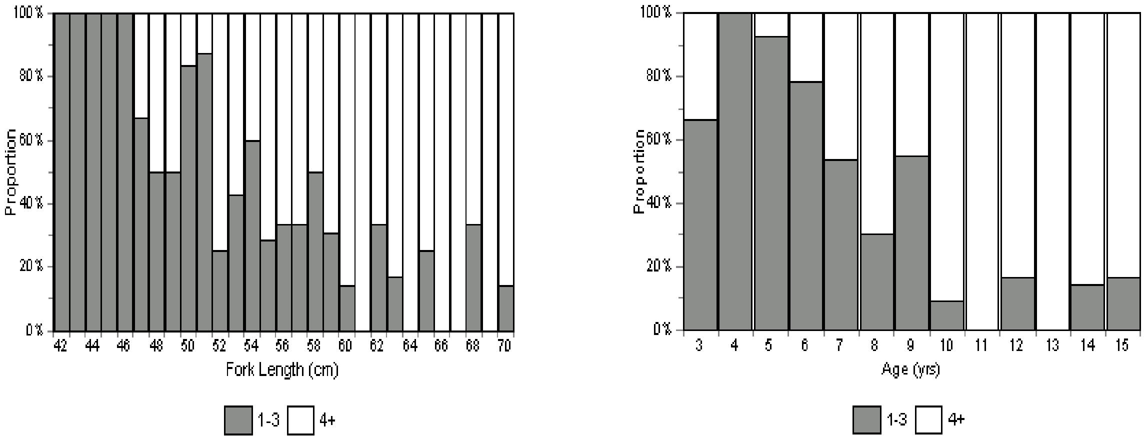


Figure 4.10 Proportion of *A. virescens* individuals mature at a) length and b) age from BIOT (Chagos Archipelago).

From the ogive fitted to the data (see Section 4.2.2), the length at maturity (Lm_{50}) was 53.5cm, while age at maturity (Am_{50}) was 7.7 years.

Age structure, total mortality, and age at first capture

A. virescens catch age structure for the whole of BIOT (Chagos Archipelago) is presented in Figure 4.11. That estimated for 1997 is also presented for comparison. Both the forms of age frequencies and mean ages from the two samples were significantly different (Welch's Approximate *t*-test, $P<0.05$; Kolmogorov-Smirnov test, $P<0.05$). There was a slightly greater proportion of older individuals in the 1999 sample, increasing the mean age.

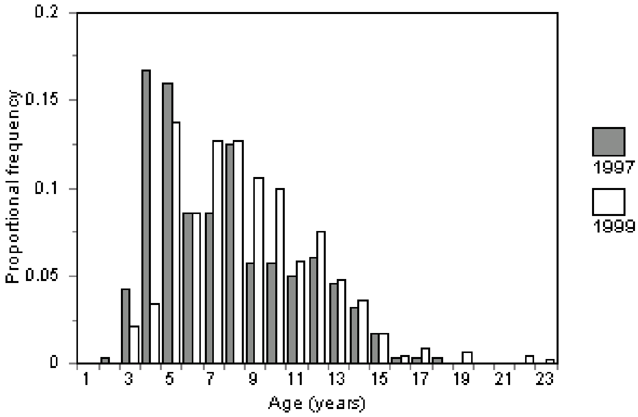


Figure 4.11 Catch age frequency distributions for 1999 and 1997 for BIOT (Chagos Archipelago).

Age-based catch curves were used to estimate total mortality for the whole of BIOT (Chagos Archipelago), and for areas within BIOT (Chagos Archipelago) where sufficient data were available. Estimates are summarised in Table 4.6.

Table 4.6 Total mortality estimates derived for 1999 and 1997, using age-based catch curves.

Area	Z estimate	
	1999	1997
All BIOT	0.23 +/- 0.08	0.17 +/- 0.06
PIT	0.15 +/- 0.10	-
SPK	0.38 +/- 0.27	-

An estimate of Ac_{50} of 3.9 years was derived from the age-based catch curve. Based on this value and the re-estimated growth parameters, Lc_{50} was calculated as 36.3 - 42.2cm.

Natural and fishing mortality, and $F_{0.1}$

Estimates of natural mortality were derived using empirical formulae and estimated growth parameters. Fishing mortality (F_{curr} = Z-M) and $F_{0.1}$ estimates were then derived for the whole of BIOT (Chagos Archipelago), and each statistical area (Table 4.7). Indications of the level of natural mortality in this species were derived during Project R6465, and estimated to be around M=0.17. This is comparable to the empirical estimate derived using Ralston's formula using unconstrained growth parameter estimates.

Table 4.7 Estimates of natural and fishing mortality, and $F_{0.1}$ derived for *A. virescens* by statistical area within BIOT (Chagos Archipelago).

Area	Growth estimates	M estimator	Natural mortality (M)	Fishing mortality (F)	$F_{0.1}$
All BIOT	t_0=-3.65	Pauly	0.22	0.01	0.26
		Ralston	0.16	0.07	0.19
	t_0=0	Pauly	0.41	< 0	0.46
		Ralston	0.35	< 0	0.37
PIT	t_0=-3.65	Pauly	0.22	< 0	0.26
		Ralston	0.16	< 0	0.19
	t_0=0	Pauly	0.41	< 0	0.46
		Ralston	0.35	< 0	0.37
SPK	t_0=-3.65	Pauly	0.22	0.16	0.26
		Ralston	0.16	0.22	0.19
	t_0=0	Pauly	0.41	< 0	0.46
		Ralston	0.35	0.03	0.37

Stock assessment

Stock assessments for *A. virescens* resulting from the use of length-based methods are presented in Figure 4.12. As seen for *L. mahsena*, for a given location the growth parameters used strongly influence the outputs of assessments. For assessments derived using age-based approaches, the percentage by which estimates of F_{curr} exceeded those of $F_{0.1}$ is presented in Figure 4.13.

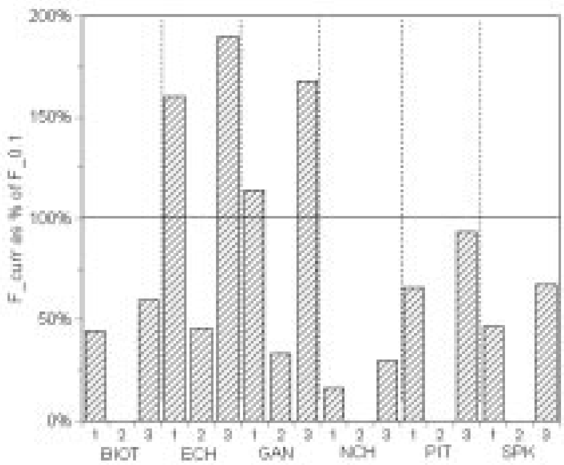
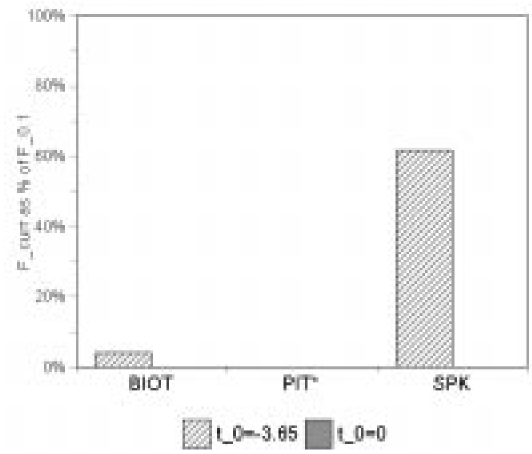


Figure 4.12 Stock assessments based on F_{curr} and $F_{0.1}$ estimates for *A. virescens* derived through length-based methods. M derived through Pauly's M. 1-3 relate to growth parameters used. 1. Pilling et al., 1999, age-based estimate; 2. Pilling et al., 1999, age-based, t_0=zero; 3. Pilling et al., 1999, length-based estimate.

a) Pauly's M



b) Ralston's M

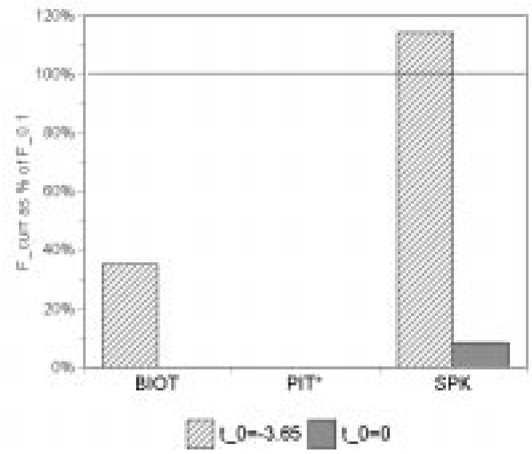


Figure 4.13 Stock assessments derived based on the relationship between F_{curr} and $F_{0.1}$, estimated using a) Pauly's M, b) Ralston's M. * Estimates of F_{curr} for Pitt Bank (PIT) were less than zero (M>Z).

Generally, A. virescens appears under-exploited. Only where Ralston's M and the unconstrained growth parameter estimates are used (resulting in a natural mortality estimate close to that derived during Project R6465) does there appear to be some evidence of over-exploitation at Speakers Bank (SPK).

4.4 Discussion

The aim of the work described in this chapter was to derive improved age-based fishery and biological parameter estimates for the two study species in BIOT (Chagos Archipelago): *L. mahsena* and *A. virescens*. Using these improved estimates, stock assessments were derived to examine the status of these exploited resources through age-based methods.

4.4.1 Growth parameter estimates

Age-based growth parameter estimates for both species were derived during Project R6465. However, these age-based estimates suffered due to a lack of individuals at the extremes of the size range. Data collected for the current project encompassed samples at these extremes. Their inclusion in assessments resulted in improvements to the growth estimates for these species (K and t_0 increased, L_∞ decreased). As identified during Project R6465, growth parameter estimates for *L. mahsena* appear comparable to those estimated by Bautil and Samboo (1988) for Nazareth Bank. Those for *A. virescens* are notably lower than previous literature estimates derived using length-based methods. Further improvements are still possible with additional sampling at extremes of the size range.

By constraining t_0 to zero, likely maximum values for K (and minimum values for L_∞) were obtained. For *L. mahsena*, these were felt to correspond more closely to the growth parameters that would result from further sampling of young individuals, compared to the unconstrained estimates derived in the current study. In contrast, setting t_0 equal to zero for *A. virescens* resulted in a growth curve which did not fit well with length-at-age data for older individuals. Based on the current sample, it seems unlikely that such constrained parameters represent realistic estimates for *A. virescens*. For both species, further sampling is likely to result in population parameter values between the two parameter sets estimated.

If the selectivity of gears remains consistent between years, additional otolith sampling at the extremes of the sample range would be an exercise in diminishing returns. The current gear cannot catch individuals above or below a certain size. Therefore, the possibility of using different gear sizes to specifically collect individuals from these extremes should be examined. The feasibility of pursuing this within BIOT (Chagos Archipelago) is discussed in Chapter 7.

4.4.2 Reproductive parameters

The reproductive characteristics of *L. mahsena* and *A. virescens* within BIOT (Chagos Archipelago) was examined.

Studies of sex ratio at length supports the general opinion that *L. mahsena* is a protogynous hermaphrodite. This was first suggested by Bertrand (1986) based on data from specimens caught at Saya de Malha, and supported by studies performed during Project R6465 for the Mauritian banks and Seychelles. Results from Project R6465 suggested that the stimulus for sex change was under exogenous/social control. The removal of a higher proportion of males from the population due to fishing (gear selectivity) may therefore be compensated for by changes in the length/age at which sex change occurs. This may reduce the impacts of fishing on the reproductive capability of the population.

Reproductive parameters could not be estimated for *L. mahsena*, due to a lack of mature individuals in samples. Estimates were derived for other locations within the Indian Ocean during Project R6465; Am_{50} estimates for this species at the Mauritian banks and Seychelles ranged from 4.8 to 7.6 years, However, there was evidence that Am_{50} may be considerably lower than this, since mature individuals were found at around 17cm. Bertrand (1986) indicated that the onset of maturity at Saya de Malha was at age 3 years, approximately 19cm, supporting this opinion. The value of Am_{50}/Lm_{50} for *L. mahsena* in BIOT (Chagos Archipelago) therefore remains uncertain.

For *A. virescens*, sex ratio remained relatively constant across the size range, slightly skewed towards males. A comparable pattern was found during Project R6465. Fishing is therefore unlikely to affect the sex ratio of the population, and hence is unlikely to lead to sperm or egg limitation at current levels of exploitation.

Reproductive parameters were successfully derived for *A. virescens* in BIOT (Chagos Archipelago). Age at maturity for this location was estimated at Am_{50}= 7.7 years (Lm_{50}=53.5cm). This value was lower than estimates for this species in Seychelles derived during in Project R6465 (Lm_{50}=65cm), but larger than that estimated from other areas identified in the literature (Lm_{50}=41-47cm) (Brouard and Grandperrin, 1985;Everson et al., 1989;Talbot, 1960).

4.4.3 Age structure and estimation of total mortality

Project R6465 indicated the advantages, in terms of improved management, resulting from the use of age-based growth parameter estimates in stock assessments. However, employing length-based methods at later stages of the assessment process (e.g. to estimate total mortality) diluted the advantages gained through the use of age-based growth parameters. Project R6465 therefore recommended that age-based methods be used at all stages of the assessment process. As a result, the level of total mortality experienced by study stocks was estimated using age-based catch curves.

When examined at the level of BIOT (Chagos Archipelago) as a whole, there were no significant differences in the catch age structure of *L. mahsena* estimated for 1997 and 1999. Estimates of total mortality for the whole of BIOT (Chagos Archipelago) in these years were also comparable. Changes in fishing pressure over time do not appear to have resulted in changes in the population structure.

Significant differences in the catch age structure of *A. virescens* for 1999 and 1997 were noted. These differences were largely at younger age classes. Differences therefore affected the ascending limb of the catch curve. Impacts on the descending limb, represented by older age classes, were limited; the action of natural and fishing mortality on the population reduced the effects of variation in recruitment. As a result, the total mortality estimate in 1999 for *A. virescens* was comparable to that estimated for 1997.

Estimates of total mortality for *L. mahsena* were also derived at the level of meta-populations (Chapter 3). Estimates for the south and west region were higher than those for the north and east region. However, 95% confidence intervals for the two total mortality estimates overlapped, indicating that total mortality in these locations could be comparable. In both 1999 and 1997, catch age structures by region showed notable differences. Fewer old individuals were present in the south and west region. Fishing pressure did not appear to be the cause of differences in age structure between the two regions (see Chapter 3). Differences did not appear to result from inadequate sample sizes. Possible explanations for these differences include a higher natural mortality rate in the south and west region. Alternatively, the ontogenic migration of older individuals from this region could also result in such a decrease in older individuals. This will be discussed further in Chapter 7.

By statistical area, estimates of total mortality for *L. mahsena* were relatively comparable. The exception was that for south Great Chagos Bank (SCH). The estimate for this area was notably larger than those for other areas. 95% confidence intervals for the SCH estimate were wide, overlapping those from other statistical areas. Estimates of total mortality in the statistical areas comprising the south and west region were generally comparable to the overall level of mortality in the north and east region. In these areas, differences in mean age (Chapter 3) did not affect the estimate of total mortality.

Due either to a scarcity of data from sampled locations, or lack of a cohesive catch curve, estimates of total mortality for *A. virescens* by statistical area were limited to those from Pitt Bank (PIT) and Speakers Bank (SPK). The estimate of total mortality for Speakers bank was high, but again 95% confidence intervals for the two areas overlapped. The lack of areas sampled meant that no conclusions could be drawn on the existence of regional differences in total mortality of this species.

4.4.4 Estimation of natural and fishing mortality

To estimate current fishing mortality, and hence perform stock assessments, estimates of natural mortality were required. Attempts were made to derive estimates of this parameter independent of empirical formulae, to reduce uncertainty in stock assessments.

An independent estimate of natural mortality for *L. mahsena* was derived by relating 1999 total mortality estimates calculated for each statistical area to the level of fishing effort applied in each area in 1998. The resulting estimate (M=0.34) was comparable to that derived for the related species *L. nebulosus* in Kuwait (M=0.36; Carpenter and Allen, 1989), and within the range of estimates for other lethrinid species (M=0.2-0.51). However, there remains considerable uncertainty over this estimate. Natural mortality levels for this species may vary between statistical areas, including those areas used to estimate natural mortality. This would violate one of the assumptions made in the analysis. There were also very few points in the analysis. It is therefore recommended that continued efforts are made to derive an independent estimate of natural mortality for *L. mahsena*. Approaches may include specific sampling from lightly exploited populations so that age-based total mortality levels can be related to the natural mortality level directly, or the continued collection of age data to derive annual total mortality estimates to improve estimates using the approach performed during the current study.

As a result of uncertainty over the independent estimate of natural mortality, empirical estimates of this parameter were also derived. It was noted that outputs of such formulae are highly sensitive to differences in growth parameter estimates. Although growth parameter estimates for these species have been improved through the use of age-based methods, uncertainty in these estimates remains due to the lack of young individuals in samples. Hence the outputs of empirical formulae for M are also uncertain. A level of uncertainty is therefore transferred to the stock assessments. This is discussed in Section 4.4.5. It should be noted, however, that resulting empirical estimates encompassed the independent estimate of natural mortality. As a result, use of these empirical estimates led to conservative and bullish assessments of stock status.

Independent estimates of natural mortality for *A. virescens* could not be derived using data collected during the current project. No estimates of the natural mortality rate for *A. virescens* were found in the literature. However, an indication of the value of M was identified during Project R6465. Total mortality estimates derived during that project were comparable to empirical estimates of natural mortality. Given the low exploitation rate of this species in BIOT (Chagos Archipelago), it was suggested that these total mortality estimates were comparable to the natural mortality rate, providing an estimate of M in the range of 0.17-0.19. In the current study. Empirical estimates were also derived using the age-based growth parameter estimates.

4.4.5 Stock assessments

Comparisons of length- and age-based assessments in the current study indicated that length-based estimates commonly indicated that stocks were over-exploited. When managing conservatively, it is prudent to act on the 'worst-case' scenario, in this case the outputs from length-based methods. As indicated by the studies described in the final report for Project R6465, however, the results of length-based methods of assessment are highly uncertain for long-lived, slow growing species. The use of length-based growth parameters can lead to inappropriate management decisions, which may result in either the over- or under-exploitation of the resource. In contrast, the use of age-based growth estimates improved management performance, offering the best information on the status of the stock. As a result, the current study concentrates on the results of age-based assessments.

Stock assessments were based on the relative values of F_{curr} and $F_{0.1}$ estimates. Concern was warranted where F_{curr} was greater than $F_{0.1}$.

Both sets of growth parameters derived for *L. mahsena* (constrained and unconstrained) were used to estimate natural mortality through empirical formulae. As indicated above, the use of empirical natural mortality estimates led to both optimistic and conservative stock assessments. When stocks of this species were assessed at the level of BIOT (Chagos Archipelago) as a whole, there were no indications of overexploitation regardless of the estimate of natural mortality used. This view is supported by stock assessments performed during Project R6465 for 1997, and by simulations performed during DFID FMSP project R7041 'Software for estimation of the potential yield of fisheries under uncertainty'. That project devised software allowing complex fisheries stock assessments to be performed, calculating commonly used reference points with confidence limits to incorporate parameter uncertainty. The tutorial for the programme, in which parameters for *L. mahsena* from BIOT (Chagos Archipelago) are employed to explain how the package should be used, forms Appendix 1 of this report.

Examined by meta-population, the *L. mahsena* stock at the north and east Great Chagos bank appeared to be exploited sustainably. In contrast, care appears warranted for the south and west population; although the use of Pauly's M estimate indicated sustainable stock exploitation, the use of Ralston's M indicated a fishing mortality of around twice the level of $F_{0.1}$. This resulted from the high total mortality estimate for this region. As noted, this total mortality estimate may not be a realistic indication of the level of fishing. High total mortality estimates may actually result from a higher level of natural mortality in this area, or through ontogenic migration. Therefore the status of the stock in the south and west region may be less serious than indicated by the assessment. However, there is a need to continue monitoring the impacts of fishing at this location.

The level of natural mortality (M) for *A. virescens* indicated by Project R6465 studies (M=0.17-0.19) was comparable to empirical natural mortality estimates derived using growth parameter estimates where t_0 was unconstrained. Since growth estimates where t_0 was set to zero appear inaccurate (Section 4.4.1), stock assessments derived using these unconstrained growth parameter estimates for this species are concentrated on here. Assessments indicated *A. virescens* stocks were being exploited sustainably; fishing mortality was around, or below, the level of $F_{0.1}$. This proved irrespective of the empirical natural mortality estimate used. Slight concern was warranted based on the assessment for Speakers Bank (SPK) where Ralston's natural mortality estimate was used. Overall, the current level of exploitation appears sustainable. This mirrors the findings of Project R6465.

An important input into management decisions is information on the relative values of the length at maturity (Lm_{50}) and length at capture (Lc_{50}). If individuals are caught before they have a chance to reproduce (Lc_{50}<Lm_{50}), there is the potential for fishing to have a strong impact on a population.

For *L. mahsena* in BIOT (Chagos Archipelago), length at maturity could not be estimated. However, from Project R6465, Lm_{50} in Seychelles and from Nazareth bank ranged from 26-31cm. From the current study, the length at capture in BIOT (Chagos Archipelago) is between 21.6-22.5cm, less than those length at maturity estimates. However, it should be noted that a degree of uncertainty remains over the estimate of Lm_{50} in BIOT (Chagos Archipelago), with some evidence that Lm_{50} is as low as 19cm. Further biological sampling is required before a definitive estimate can be derived. The length at maturity for *A. virescens* could be estimated. Lm_{50} (53.5cm) for this species was greater than the length at capture (36-42cm) in BIOT (Chagos Archipelago). For both species, therefore, individuals may be caught before they have an opportunity to reproduce. High levels of fishing mortality may impact on the reproductive capability of the population (although in the case of *L. mahsena*, this impact may be reduced by the exogenous control of protogyny). Whilst fishing occurs within sustainable limits at present, the fact that Lc_{50} is less than Lm_{50} for both species indicates that continued monitoring of exploited stocks is essential.

Overall, *L. mahsena* appears to be exploited sustainably when assessed at the level of the location as a whole. When assessed at the level of the meta-population, there is some concern over the stock in the south and west region of the Great Chagos Bank. However, this concern is tempered by the fact that the signals may not result from fishing itself, but rather from variations in the natural mortality rate or ontogenic migration. The stock in the north and east region appears exploited within sustainable limits. *A. virescens* stocks also appear to be exploited sustainably. Overall, therefore, the conservation goal of the BIOT Authorities appears to be met by the current management regime. However, continued monitoring of exploited stocks is required.

5. Otolith weight

5.1 Introduction

Estimation of total mortality through length-based methods requires the use of growth parameter estimates. This introduces uncertainty to resulting stock assessments. The use of age-based methods to estimate this parameter, as recommended by Project R6465, reduces the uncertainty in stock assessments (see Chapter 4).

However, construction of an age frequency distribution requires the assessment of a large number of otoliths, either to construct an age frequency directly from otolith increment counts, or to derive an age-length key to convert length frequencies into age frequencies. For large-scale assessment programmes, this is likely to be an expensive undertaking. An alternative, cheaper method is therefore required through which resource-limited developing tropical countries could obtain the benefits of age-based methods. One potential approach is to develop a relationship between age and the weight of the otolith (Boehlert, 1985; Worthington et al., 1995a). As material is deposited on the outside of the otolith during the year, its size and weight should increase over time (Fowler and Doherty, 1992). If otolith weight or size can be related to age, a calibration curve can be developed (Ferreira and Russ, 1994). Using otolith weight to assess age should be much cheaper than counting increments in otolith sections, offering considerable financial benefits to resource-limited countries.

Otolith weight has been found to be a good predictor of age in an increasing number of fish species. These have ranged from pilchard (*Sardinops neopilchardus*) from Australia (Fletcher, 1991) to cod (*Gadus morhua*) and plaice *(Pleuronectes platessa*) from the Baltic (Cardinale et al., 2000). Such studies have generally concentrated on temperate species, for which otoliths are routinely used in assessments (but see Luckhurst et al., 2000).

FMSP Project R6465 examined whether an age-otolith weight relationships could be derived for *Aprion virescens* and *Lethrinus mahsena*. A relationship could not be derived for *A. virescens*, due to the otolith structure of this species; otoliths were small, delicate, and prone to breaking, rendering the method unsuitable for routine use. In contrast, an otolith weight-age relationship was successfully derived for *L. mahsena* in each study location, including BIOT (Chagos Archipelago). However, the high level of variation in otolith weight at age in this species meant that the relationship could not discriminate between individual age classes, and hence could not estimate individual length-at-age. In contrast, the relationship was capable of deriving reasonably accurate age frequency distributions. Total mortality estimates which were comparable to those derived assessed through otolith increment counts could then be derived.

To use otolith weight-age relationships routinely, there is a need to confirm that the relationship holds between years. The current study therefore aimed to estimate the *L. mahsena* age-otolith weight relationship for BIOT (Chagos Archipelago) in 1999, and compare that to the relationship derived for 1997. In turn, the method's suitability was re-confirmed by comparing the age structure derived using the relationship with that estimated through otolith increment counts. Since the aim of this process is currently to estimate total mortality, this parameter was estimated from age structures estimated through the two estimated age structures, and compared.

5.2 Methodology

L. mahsena sagittal otoliths were collected from BIOT (Chagos Archipelago) during 1999. Two sets of samples were taken. To derive an otolith weight-age relationship, a non-random sample of otoliths was obtained; targeted sampling from relatively large and small individuals, which would be under-represented in a random sample, was performed to improve the accuracy of the otolith weight-age relationship. To test the utility of the relationship, random samples of otoliths were also collected. In both cases, otoliths were cleaned before storing.

Clean otoliths were weighed on a Sartorius electronic scale, to the nearest 0.001g. This weight was then related to the age of the fish, as described in Chapter 2. As otolith weight-at-age should increase through the growth year, it was related to the 'decimal age' estimated for each fish. Otolith weight was plotted against estimated age. The relationship was assessed using linear regression, with otolith weight as the dependent variable, and age as the independent variable. The relationship for 1999 was compared to that derived for 1997 (Pilling *et al*, 1999) using the GT-2 test (Sokal and Rohlf, 1995).

The 1999 age-otolith weight relationship was used to estimate individual age, as a continuous variable, from the weight of each otolith in the random sample. Estimated decimal ages were rounded down to the nearest integer, and an age frequency derived. This was compared to the underlying age structure estimated through otolith increment counts using the Kolmogorov-Smirnov test. Total mortality estimates were then derived through catch curves from age frequency distributions estimated using the otolith weight-age relationship, and through otolith increment counts (see Section 4.3.1). Total mortality estimates were then compared.

5.3 Results

The regression coefficients of the otolith weight-age relationship derived using the six hundred and seventeen otoliths sampled from across BIOT (Chagos Archipelago) in 1999 is presented in Table 5.1, along with the standard errors and r-squared values. The parameters of the relationship calculated for the location using data from 1997 are also presented. The plot of age and otolith weight is presented in Figure 5.1.

Table 5.1 Relationship between otolith weight (grammes) and assessed partial age (yrs) for *L. mahsena* in 1999 and 1997, for BIOT (Chagos Archipelago).

Year	Otolith weight = a+b*age				r^2
	a	SE	b	SE	
1999	-0.044	0.039	0.034	0.001	0.838
1997	-0.048	0.041	0.035	0.001	0.877

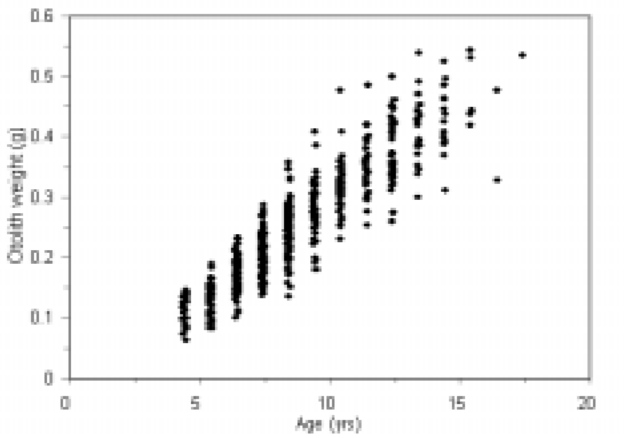


Figure 5.1 Plot of the relationship between age (yrs) and otolith weight (g) for *L. mahsena* from BIOT (Chagos Archipelago).

The relationships derived for 1999 and 1997 were not significantly different (GT-2 test, *P*>0.3). The overall fit of the 1999 relationship was poor, with only 37% of estimated ages correct (Table 5.2).

Table 5.2 Accuracy of the otolith weight-age relationship for *L. mahsena*.

Year	Percentage of estimates:	
	identical to true age	greater than 1 year different
1999	37%	16%
1997	40%	30%

The otolith weight-age relationship was used to estimate age frequency distributions from the weights of the random otolith sample. The resultant distribution was compared to age frequencies assessed directly from otolith increment counts (Figure 5.2).

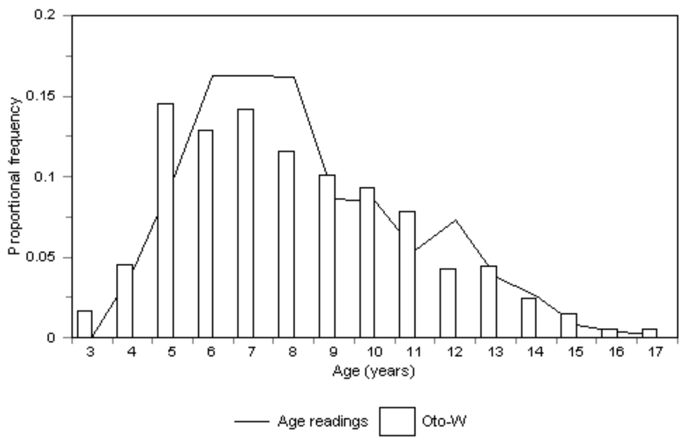


Figure 5.2 Comparison of the catch age structure estimated through otolith increment counts (age-readings) with that estimated using the otolith weight-age relationship (oto-w).

The forms of the two distributions were not significantly different (Kolmogorov-Smirnov test, *P*>0.1).

The frequency distribution estimated using the age-otolith weight relationship was used to assess mortality using an age-based catch curve. The resulting estimate of total mortality is presented in Table 5.3, and compared with that derived using the age structure estimated through otolith increment counts.

Table 5.3 Estimate of total mortality derived from age frequency distributions obtained directly through otolith readings, and through the age-otolith weight relationship. 95% confidence intervals are also presented.

Method	Estimate of total mortality (Z)	95% confidence interval
Age-otolith weight relationship	0.36 +/- 0.11	0.25 - 0.47
Otolith readings	0.43 +/- 0.15	0.27 - 0.58

Total mortality estimates were comparable, and their 95% confidence intervals overlapped.

5.4 Discussion

The reading of otoliths can introduce bias through subjective assessments of the ages assigned to individuals. To minimise this bias, the use of otolith weight has been suggested as a non-subjective method of age assessment (Boehlert, 1985; Worthington et al., 1995a, 1995b). Once a relationship between age and otolith weight has been determined, errors of this type are only introduced during the estimation of otolith weight. These errors are easier to quantify and correct (Richards et al., 1992).

During FMSP Project R6465, a relationship between the weight of *L. mahsena* otoliths, and estimated age of individuals was derived. It was noted that for this method to be routinely employed in BIOT (Chagos Archipelago), it must be confirmed between years to ensure that the relationship is consistent. To examine this, an otolith weight-age relationship was derived for *L. mahsena* using 1999 data, and compared with that estimated during project R6465. Age distributions estimated using the otolith weight-age relationship for 1999 and through counts of otolith increments were compared, and used to estimate total mortality using catch curves.

Otolith weight explained 84% of the variation in age in the 1999 relationship, comparable to the 88% explained by the 1997 relationship. However, the r^2 value does not identify the utility of the otolith weight-age relationships for estimating individual ages. The relatively slow growth rate of *L. mahsena*, combined with the notable variation in otolith weight within ages, reduced the precision of the otolith weight-age relationship. This was particularly true at older ages, where the level of overlap in otolith weight-at-age was greatest. As a result, otolith weight could not accurately discriminate between individual age classes, and hence could not be used to accurately assess individual ages, as noted by Pilling et al. (1999). A similar conclusion was reached by Worthington et al. (1995a) for the damselfish *Pomacentrus moluccensis* and *P. wardi*.

As noted during Project R6465, however, the otolith weight-age relationship was capable of deriving reliable catch age frequency distributions. In the current study, that derived using the relationship for BIOT (Chagos Archipelago) was not significantly different from the age structure assessed through otolith increment counts. Total mortality estimates obtained through catch curves derived from the two age frequencies were also similar.

These results confirmed the findings of Project R6465; otolith weight can be used to age *L.*

mahsena individuals where the goal is to derive an age frequency distribution. In turn, the current study has identified that the otolith weight-age relationship appears to be consistent between years. However, it should be noted that the relationships derived for *L. mahsena* from different locations in the Indian Ocean during Project R6465 were significantly different. This may be related to differences in local environmental variables, although insufficient data were available to examine this in depth. Alternatively, differences could relate to fishing pressure. Therefore, while the relationship for this species in BIOT may be consistent over time, this may only hold if the level of fishing pressure, recruitment, or environmental conditions remain stable. If changes in these factors (e.g. coral bleaching events) occur between years, the relationship should be re-confirmed.

The age-otolith weight relationship derived offers a feasible, objective, and economic method to estimate the level of total mortality for exploited *L. mahsena* populations in BIOT (Chagos Archipelago). The financial savings involved in the use of this method to estimate total mortality rather than during individual age estimates will be examined within the current project. However, an examination of costs alone ignores the financial or conservation benefits which may result. A cost-benefit analysis is required to examine this.

6. Cost-benefit analysis

6.1 Introduction

The aim of the current study is to assess the utility of age-based methods for their practical application in BIOT (Chagos Archipelago). Following the validation of otoliths of *L. mahsena* and *A. virescens* in FMSP Project R6465, otoliths have been used to assess the stocks of these species in BIOT (Chagos Archipelago) (Chapter 4). This has reduced the uncertainty in stock assessments compared to those derived historically using length-based methods. However, the question arises that, given the additional costs involved in using age-based methods, is the use of such methods financially viable? As verified in Chapter 5, an age-otolith weight relationship can be used to estimate total mortality for *L. mahsena*. This method may offer considerable savings over the routine assessment of age frequencies through the reading of a large number of otoliths. However, the use of such a relationship may remain more expensive than approaches based on length.

Simple assessments of cost alone do not take into account the potential benefits arising from more expensive age-based methodologies. As shown in Project R6465, the use of age-based growth parameters offered considerable benefits above those arising from the use of length-based approaches. To compare the two methods, a cost-benefit analysis was used. This indicated that benefits obtained by using age-based growth parameter estimates in stock assessments (increased catch revenue) outweighed the costs involved in estimating these parameters.

In this chapter, the costs involved in three methods of total mortality assessment will be examined. These methods are through length-based catch curves, and through catch curves based on age frequencies derived using either otolith increment counts, or via otolith weight. Based on the results of simulations performed during Projects R6465 and R7522, these costs will be compared with benefits arising from the use of each method. The study will answer whether the advantages of using age-based methods of total mortality assessment for snappers and emperors are outweighed by the costs involved in this approach.

6.2 Methodology

In this section, the methods used to calculate the costs and benefits are described for the three approaches; the use of length-based methods (using age-based growth parameters[1]), age-based methods (the derivation of an age frequency from otolith increment counts, and the use of an age-otolith weight relationship). For each, a cost and benefit time stream was derived spanning 20 years, the projected lifespan of the equipment employed in age-based methods. From these time streams, the net present value of each method was assessed.

[1] Project R6465 showed that the use of age-based growth parameters was more cost-effective than using length-based growth parameters when using length-based methods of total mortality estimation.

6.2.1 Costs

When calculating costs, the assumption was made that the observer programme, the method through which both length and age data are collected, would occur regardless of the assessment method used. Costs involved in the observer programme were therefore equal whether collecting length or age data, and hence these costs are ignored in the computations.

Of the three assessment methods examined, that using the age-otolith weight relationship was only valid for *L. mahsena*. Given the importance of this species within the BIOT (Chagos Archipelago) inshore fishery, and to ensure that cost for the three methods were directly comparable, costs were calculated for the assessment of this species alone. These costs are indicative of those incurred through the routine assessment of additional species through length- or age-based methods.

Costs were constrained to those incurred in estimating total mortality alone. Growth parameter estimation using age-based methods was assumed to have been carried out previous to that stage, as has occurred for *L. mahsena* in BIOT (Chagos Archipelago).

Costs incurred under each method were broken down into different classes. These are presented in Table 6.1, along with the methods to which they refer.

Table 6.1 Cost classes incurred by each assessment method.

Cost class	Method		
	Length-based	Age-based	Otolith weight
Preparation	✗	✓	✓
Age assessment	✗	✓	✓
Data analysis	✓	✓	✓
Assessment & derivation of management	✓	✓	✓

The stages of each method included in each cost class are detailed below. It was assumed that the use of the otolith weight-age relationship required a number of otoliths to be sub-sampled each year for full age assessment. This would allow the consistency of the relationship to be confirmed between years (Chapter 5). As noted in that chapter, it is suggested that re-confirmation of the relationship occurs following changes in fishing effort or environmental factors. This calculation therefore represents the 'worst-case' situation for this method.

Preparation
Incurred only by those methods employing otoliths.

'Preparation' covered the costs of postage to and from CEFAS (who were assumed to be performing the sectioning and staining of otoliths), and the actual costs incurred in sectioning and staining. The latter are calculated as a cost-per-otolith, using prices quoted by CEFAS.

The use of otolith weight also incurs costs under preparation, due to the requirement to prepare the sub-sample of otoliths needed to confirm that the age-otolith weight relationship holds between years.

Age-assessment
Incurred only by those methods using otoliths.

Costs incurred at this stage for 'age-based' and 'otolith weight' approaches were the wages of staff reading the otoliths. The average time taken to read an otolith was estimated, and multiplied by both the number of otoliths to be assessed, and the rate of pay charged by the reader.

In addition, the otolith-weight approach incurred costs related to the weighing of the otolith sample. This was calculated based on the average time taken to weigh an otolith, the number of otoliths, and rate of pay.

Data analysis
Incurred by all methods.

Data analysis included the cost in wages of examining and organising collected data, and its use to assess total mortality. For otolith weight, for example, this would include the confirmation and use of the age-otolith weight relationship to derive an age frequency distribution, and the subsequent estimation of total mortality through a catch curve.

The time taken to perform these assessments was estimated based on experiences gained during the current study. Costs were then calculated based on the rate of pay selected.

Assessment and derivation of management
Incurred by all methods.

This category included the costs involved in performing a stock assessment based on the data analysis, and deriving management decisions. Estimates of the time involved in deriving this estimate was based on experiences gained through the current study.

Capital items
Specific capital items are required to perform the work needed for each total mortality assessment method. A microscope is required for both age-based methods (direct reading and the use of otolith weight). An electric balance is also required to accurately assess otolith weight. For length-based methods, a measuring board is required. It was assumed that none of the specialist equipment necessary to perform the work was available. The cost of capital items was included as a one-off payment in year zero.

Cost time stream
A cost time stream was developed to perform the cost-benefit analysis. Costs were first incurred at time zero, and comprised:

- startup costs (i.e. the costs of those capital items required to perform each method);
- costs incurred through the collection of data, assessment of total mortality, and derivation of stock assessments and management.

Costs incurred annually after year zero were confined to the routine collection and analysis of data to establish total mortality (and hence fishing mortality).

6.2.2 Benefits

The objective of fisheries management in BIOT (Chagos Archipelago) is conservation, while allowing Mauritian vessels to fish as they have previously done. The method of calculating benefits arising from different assessment methods must therefore related to these objectives.

Benefits for each stock assessment approach were calculated using outputs from management strategy simulations performed during FMSP Projects R6465 and R7522. Readers should refer to the FTRs for these projects for details of the methods. The outputs from R6465 were used to calculate benefits from length-based approaches to total mortality estimation (using age-based growth parameter estimates). Outputs from R7522 indicated the benefits resulting from the use of age-based methods to estimate total mortality, either through otolith increment counts, or through the use of otolith weight. The assumption is therefore made that the use of these two methods produce identical total mortality estimates. Chapter 5 noted that the use of otolith weight resulted in an age frequency distribution which was not significantly different from the true underlying age structure. Resulting total mortality estimates were also comparable. The use of the same age-based simulations to represent both these approaches is therefore considered valid.

Benefits were assessed from simulations initiated at the fishing mortality level equivalent to $F_{0.1}$ for *L. mahsena*; $F=0.4yr^{-1}$. These simulations were tuned (i.e. the management reference effort level $F_{0.1}$ multiplied) so that the mean level of fishing mortality at the end of the simulation process (year 20) was equal to $F_{0.1}$.

To relate to the aims of management in BIOT (Chagos Archipelago) two indicators of benefit were selected, based on spawning stock biomass and fishery yield.

Spawning stock biomass

The success of the management goal of conservation was assessed by examining the annual level of spawning stock biomass during the simulation period.

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. The former was taken as the appropriate level for the *L. mahsena* fishery in BIOT (Chagos Archipelago).

This rule was then used as the basis on which to assess whether the conservation goal ($SSB>20\%SSB_0$) was achieved using each stock assessment methodology. From the 100 simulation trials performed for each assessment method, the average SSB in each year of the 20 years of simulation was assessed. The biomass by which this average exceeded the biomass representing 20% of unexploited biomass ($20\%SSB_0$) was calculated. To ensure that the costs and benefits were in the same units, the commercial value of this biomass in GB£ was calculated, based on the price of this species at Mauritian markets. The average benefit value in each year was then discounted over time to create the benefit time stream (see Section 6.2.3).

Total catch

The most extreme method to ensure conservation of a stock is to ban fishing completely. Such an approach cannot be taken in the BIOT (Chagos Archipelago) fishery due to the need to ensure that Mauritian fishing vessels can fish in the area, under licence. For such vessels, the level of sustainable catch is important.

The average catch in each year of simulation was calculated using outputs from the 100 trials of each simulation run. To ensure that costs and benefits were in the same units, the commercial value of the catch was calculated as described above for spawning stock biomass, in GB£. The value in each year was then discounted over time to create the benefit stream (see Section 6.2.3).

6.2.3 Cost-benefit analysis

The benefit and cost time streams derived through the methods above were used to calculate the net present worth of each total mortality assessment method. For each year, incremental costs and benefits were discounted, using the appropriate discount factor for that year. For each method, the present worth of the net benefit stream was then summed (years 1-20), and the present worth of the cost stream (year 0) subtracted.

As found during project R6465, no information was available on the lending rates charged by the larger development agencies (e.g. Asian Development Bank, World Bank). The lending rate of more local institutions (Bank of Mauritius, Development Bank of Seychelles) was around 10%. Perhaps more appropriate for BIOT (Chagos Archipelago) would be the lending rate of the Bank of England, currently around 6%. Given these values, and the levels commonly used in other studies (Gittinger, 1982), a discount rate of 8% was selected.

6.3 Results

This results section first details the costs incurred in undertaking each total mortality assessment methodology. The benefits arising from their use is then assessed through simulation outputs. Finally, the cost-benefit analysis is described, and the method which results in the greatest benefit for a given financial outlay identified.

6.3.1 Costs

Costs in each class were calculated based on those incurred during the current project (i.e. based on CEFAS quotes and research assistant costs). The resulting costs for each method are presented in Table 6.2.

The cost of performing assessments using otoliths is largely determined by the number of otoliths to be read/weighed. To provide indicative costs for BIOT (Chagos Archipelago), the costs involved in sampling and preparing the number of fish examined in the current study were assessed.

Table 6.2 Annual cost of assessing total mortality in *L. mahsena* through each potential method for the whole of BIOT (Chagos Archipelago). All costs in GB£.

Cost class	Item	Method		
		Length-based	Age-based	Otolith weight
Preparation	Postage	0	25	25
	Sectioning/ staining	0	1,663	222
Age assessment	Otolith reading	0	667	269
Data analysis		40	40	80
Assessment/ management		80	80	80
TOTAL		120	2,475	676

Length-based methods were the cheapest. Although the use of the age-otolith weight relationship was almost six times more expensive than the use of length-based methods, it was notably cheaper than estimating total mortality through individual otolith readings (‘age-based’ in the above table). The cost of sectioning and staining had the most notable impact on the overall costs of the age-based assessment methods. It should be noted that the costs of using otolith weight would be further reduced if there were no need to confirm the relationship between years (e.g. if fishing mortality were constant and the level of variation in recruitment was low, as appears to be the case in this species).

Capital costs
Each approach to total mortality estimation incurred costs through the need to purchase of capital items. For age-based approaches, these included a microscope (based on the purchase of a Leica MZ6 microscope at GB£2,600), and a suitable set of electronic scales (e.g. Adams Equipment WP250 at GB£960). Length-based methods also incurred the cost of purchasing a measuring board (GB£150, based on prices quoted by CEFAS).

Cost time stream
Costs calculated above represent the annual costs of performing mortality assessments through length- or age-based methods. These were used to estimate the cost time stream. Following year zero, when both assessment and capital costs are incurred, costs are confined to the assessment costs only (Table 6.2). To calculate present worth, the cost time stream was discounted at 8% (Table 6.3).

Table 6.3 Discounted time stream (at 8%) by total mortality estimation method.

	Length-based	Age-based	Otolith weight
Year 0	220	5,075	4,236
Year 1	111	2,291	626
Year 2	103	2,122	579
Year 3	95	1,964	536
Year *n*	$120 * \left(\frac{1}{1.08}\right)^n$	$2,475 * \left(\frac{1}{1.08}\right)^n$	$676 * \left(\frac{1}{1.08}\right)^n$

6.3.2 Benefits

Outputs from the simulations performed during FMSP Project R6465 (length-based Z estimation) and R7522 (age-based Z estimation) were used to calculate the benefits arising from the use of each method. Note that the use of age-based methods to assess total mortality (through otolith increment counts and otolith weight -age relationships) are assumed to be equivalent; see ‘age’ in the graphs below.

The average annual spawning stock biomass under the three assessment methods, expressed as the amount by which the spawning stock exceeded the conservation measure of 20% of unexploited spawning stock biomass is presented in Figure 6.1. Simulations were initiated at $F=0.4yr^{-1}$, with tuned management reference effort levels.

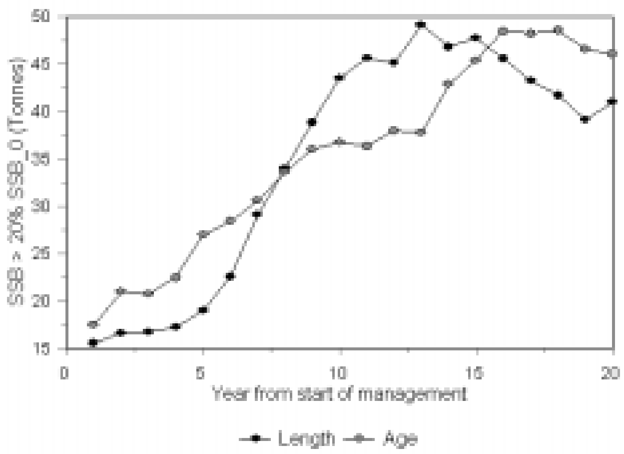


Figure 6.1 Average amount (tonnes) by which the SSB of *L. mahsena* exceeded 20% of SSB_0 in each year after initiation of management. Management based on length- or age-based growth and total mortality assessment methods.

The average annual yield derived from each management simulation initiated at $F=0.4yr^{-1}$, with tuned management reference effort levels is presented in Figure 6.2.

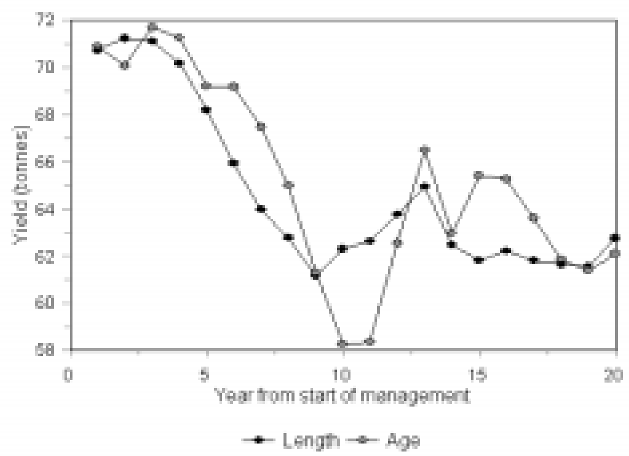


Figure 6.2 Average yield (tonnes) of *L. mahsena* in each year after initiation of annual management, derived using length- or age-based total mortality assessment methods.

6.3.3 Cost benefit analysis

The estimates of net present worth resulting for each assessment methodology, based on each benefit assessment criteria, is presented in Table 6.4.

Table 6.4 Net present worth for each assessment methodology, based on the two criteria for benefit. Assessed at an initial $F=0.4yr^{-1}$, using tuned management target values.

Benefit criterion	Length-based	Age-based	Otolith weight
SSB	301423	283234	301735
Yield	1322077	1296152	1314653

Judged against the conservation goal of the BIOT authorities, the use of otolith weight to estimate total mortality proved the method with the highest net present worth. Relatively high startup costs were outweighed by the rapid recovery of the spawning stock biomass over the first seven years when compared to the other methods.

Where the goal was to maximise yield, the use of length-based methods proved the most appropriate, with the use of otolith weight having a marginally lower net present worth. Since the method resulted in a relatively low catch in the second year following management, and had relatively high startup costs, discounting meant the advantages gained later in the simulation period were lost.

6.4 Discussion

The aim of this chapter was to assess the use of age-based methods of total mortality estimation in terms of the costs incurred and benefits obtained from their use to derive management, and compare these to more traditional length-based approaches.

Cost-benefit analysis was used to assess the value of age-based methods of total mortality estimation. This was compared to the value of the length-based methods currently used. Value was assessed in relation to the two goals of management in BIOT (Chagos Archipelago); conservation, while allowing Mauritian fishing vessels to fish as they have in the past.

6.4.1 Costs

The cheapest method of assessment proved to be using length-based methods to assess total mortality. This approach incurred minimal startup and annual costs. While the use of otolith weight led to relatively high initial costs (purchase of microscope and scales), annual costs following this initial outlay were only slightly greater than those incurred using length-based methods. Finally, assessing total mortality through counts of otolith increments (‘age-based’) was the most expensive approach, both in startup and annual costs. This resulted from the need for considerable numbers of otoliths to be prepared (sectioning and staining).

The costs calculated here assume that growth parameters have already been estimated through age-based methods. This is the case in BIOT (Chagos Archipelago) for the assessment of *L. mahsena*. For species where growth parameter estimates must also be estimated, Project R6465 indicated that the approach taken to estimate these parameters (length-based or age-based[2]) did not affect the costs involved. The need to estimate growth parameters would therefore have little effect on the current cost-benefit analysis.

Costs involved in the preparation of otoliths for reading were based on quotes from CEFAS (Lowestoft). It is expected that institutions in other countries, with lower overheads and cheaper labour, would be less expensive. This would further enhance benefits resulting from the use of otolith weight.

6.4.2 Benefits

Benefits were based on the outputs of management strategy simulations modelling the use of length- or age-based methods to estimate total mortality as part of the stock assessment approach.

[2] Where otoliths for this purpose were prepared in-house.

Assessment of benefits was based on the goals of fisheries management in BIOT (Chagos Archipelago); conservation, while allowing Mauritian vessels to fish. Benefit was therefore assessed as the amount by which the spawning stock biomass exceeded 20% of unexploited levels, and as the yield obtained from the fishery. Given the conservation goals of the BIOT Authorities, the former assessment was given more weight in the interpretation of the results.

The age-based approach to total mortality estimation showed additional benefits when compared to the use of length-based approaches. Age-based estimates resulted in a more rapid increase in the level of the spawning stock biomass, up to year eight after management was initiated. Use of age-based total mortality estimates would ensure a more rapid recovery of stocks following exploitation. The conservation goals of the BIOT Authorities would therefore be achieved more rapidly.

Both assessment methods allow vessels to fish as they have done in the past, fulfilling the second aim of management. However, the use of length-based total mortality estimates allowed slightly higher initial catches. After the first year, te use of age-based total mortality estimates resulted in greater benefits in terms of yield from the fishery, up to year nine.

6.4.3 Cost-benefit analysis

Net present worth analysis based on the costs and benefits calculated indicated that the use of otolith weight to estimate an age frequency distribution (and hence estimate total mortality) was the most cost-effective assessment approach. The slightly greater costs of this approach, when compared to the use of length-based methods, was outweighed by benefits resulting from stock assessments incorporating age-based total mortality estimates.

The use of length-based methods of assessment was the second most cost-effective approach, due to the relative cheapness of the method. The derivation of age frequencies through otolith increment counts (and hence total mortality estimates through age-based catch curves) was very expensive. This outweighed the benefits of using age-based total mortality estimates in stock assessments. As a result, this approach was the least cost-effective.

6.4.4 Summary

For species such as *L. mahsena*, where an age-otolith weight relationship has been derived (see Chapter 5), the use of this method in the estimation of total mortality is the most cost effective approach. Where otolith weight-age relationships cannot be derived, as in the case of *A. virescens*, length-based total mortality estimation methods are the most cost-effective. Such methods require growth parameter estimates as inputs. Cost-benefit analysis performed during Project R6465 indicated that the estimation of these parameters though age-based methods was the most cost-effective approach.

7. Management and the assessment of utility

The use of length-based methods to assess growth and mortality in long-lived, slow-growing species results in uncertain parameter estimates. As noted by Mees and Rousseau (1997) and Pilling et al. (1999), management advice is sensitive to such uncertainty. As shown by the simulations described in Pilling et al. (1999), uncertainty in growth parameters devolves into uncertainties in estimates of other parameters such as mortality, length-at-capture and yield per recruit. These parameters are inputs into stock assessments, upon which management decisions are based.

Uncertainty resulting from the use of length-based growth parameter estimates can clearly be seen in historical biological assessments of the status of *L. mahsena* and *A. virescens* stocks in BIOT (Chagos Archipelago) (Tables 7.1 to 7.4). Dependent on the growth parameter estimation methods used, assessments may indicate that the stock in a given location or statistical area is over- or under-exploited. Management decisions based on such assessments are uncertain.

To alleviate the constraint to management arising from the need to use uncertain length-based growth parameters, Project R6465 examined whether age-based methods could be used to estimate growth parameters for the study species. This proved feasible for two study species. The method led to the derivation of improved growth parameter estimates, which reduced, but did not eliminate, uncertainty. While stock assessments were improved by the use of improved growth parameter estimates, benefits were diluted by the need to use length-based methods to estimate other parameters, such as total mortality. Such methods require growth parameters as inputs, and can be affected by density dependent growth. The project suggested that employing age-based methods of total mortality estimation may limit uncertainty arising at this stage.

The current study aimed to implement a number of the guidelines derived during Project R6465, namely:

- perform stock assessments at as fine a spatial scale as possible;
- use age-based methods to estimate growth parameters for long-lived, slow-growing species, and ensure young individuals are present in samples;
- estimate total mortality through age-based methods to minimise uncertainty;
- accurately assess the current fishing mortality level.

During the project, guidelines were implemented in the British Indian Ocean Territory (BIOT; Chagos Archipelago). Biological reference points for management purposes were derived, using improved biological and fishery parameter estimates arising from the implementation of guidelines detailed above. In doing so, the project aimed to assess the applicability of these data collection and analysis methods, with particular reference to BIOT (Chagos Archipelago). The costs of moving towards an age-based methodology were also examined (Chapter 6). The current chapter discusses the results obtained during this study, in the light of the project aims, and assesses both appropriate management strategies for the region, and the utility of the methodology.

7.1 Spatial scale of assessments

The first aim of the project was to examine the spatial scale at which assessments should be performed. Currently, data collection in BIOT (Chagos Archipelago) is based on statistical areas. These areas have been designed arbitrarily; data were not available to relate these to the actual stock distribution at this location. These statistical areas are therefore unlikely to resemble the actual underlying stock structure. If the spatial distribution of species could be identified, it would influence both the way in which data are collected, and the scale at which stock assessments are performed.

Studies undertaken during project R6465 noted that there was evidence for localised *L. mahsena* meta-populations on the Great Chagos bank. Although no evidence for such localised populations was found for *A. virescens*, data used to assess the spatial distribution of this species was limited. Further data were therefore collected during the current study to examine the distributions of the study species further.

The current study confirmed that there was little indication of localised meta-populations of *A. virescens* on the banks of BIOT (Chagos Archipelago). This may result from the fact that this species is a relatively mobile predator, being less constrained to particular areas of habitat. In contrast, studies for *L. mahsena* indicated that localised meta-populations of this species were present on the Great Chagos Bank. Two distinct population structures were noted, forming the south & west and north & east populations. The latter population included older, larger individuals, which were notably absent from the former. These differences in the length and age structure were found to be consistent over a number of years.

The impacts of the existence (or otherwise) of meta-populations for these species on the data collection and stock assessments will be discussed in later sections of this Chapter.

7.2 Improved growth parameter estimates

Simulations performed during project R6465 indicated that additional costs involved in performing age-based growth parameter assessments was offset by additional benefits generated through their use in stock assessments to derive management advice. In that project, length-at-age data were collected, and used to estimate improved growth parameters for the study species. However, individuals from the extremes of the length and age range were under-sampled. The presence of data from these extremes was noted to be very influential on the growth parameter estimates. Studies indicated that additional otolith samples from the extremes of the length and age range would result in further improvements.

The sampling programme undertaken for the current project was based on that recommended in Project R6465. Otolith samples from extremes of the size range were specifically targeted. By combining these samples with length-at-age data collected for project R6465, growth parameter estimates for the study species in BIOT (Chagos Archipelago) were improved.

Despite improvements, additional sampling from extremes of the length and age range could improve growth parameter estimates for these species further. As noted in Chapter 4, however, with the current gear used, this is an exercise in diminishing returns. Alternative gears (e.g. smaller or larger hook sizes) which are more likely to catch individuals at the extremes of the current size/age range should be employed.

7.3 Estimation of total mortality

The third aim of the project was to estimate total mortality (Z) through age-based methods. This was achieved for both species by counting the number of increments in a relatively large number of randomly sampled otoliths. This required an extended period of otolith reading.

When compared to the use of length-based methods of total mortality estimation, age-based methods do not require the input of uncertain growth parameter estimates. In turn, the age structure is less affected by density dependent growth, evidence for which was identified for *L. mahsena* during Project R6465. The use of age-based methods to estimate total mortality therefore eliminates a source of uncertainty in the stock assessment process. However, due to the large number of otoliths that must be read, this method incurs additional costs when compared to length-based approaches.

For *L. mahsena*, however, the weight of an otolith can be used as a proxy for the age of a fish. This relationship allows age distributions to be rapidly and accurately developed. For BIOT (Chagos Archipelago), the relationship was shown to be consistent between the two years examined. The cost-benefit analysis described in Chapter 6 indicated that the use of an age-otolith weight relationship was the most cost-effective method to estimate total mortality. While the method incurred higher costs when compared to the length-based approach, the relationship resulted in greater benefits, assessed against criteria of conservation. Therefore, the use of this relationship is recommended for the routine estimation of *L. mahsena* total mortality. The method allows the benefits of age-based methods to be obtained for a relatively small outlay.

For species for which an age-otolith weight relationship had not been calculated, the most cost-effective approach was to estimate age-based growth parameters (see Project R6465), and use length-based methods of total mortality (Chapter 6).

7.4 Estimation of fishing mortality

The fourth project aim was to obtain an accurate estimate of the level of fishing mortality. This required accurate estimates of total and natural mortality (F=Z-M).

Estimates of total mortality were improved through the use of age-based methods (Section 7.3). However, a degree of uncertainty in fishing mortality estimates remained due to the lack of an independent estimate of natural mortality. The value of natural mortality has a significant impact on stock assessments, since it also strongly influenced the estimate of $F_{0.1}$.

Although indications of the level of natural mortality were derived for the study species, definitive estimates have not been obtained. Currently, therefore, estimates of natural mortality are derived using empirical formulae (e.g. formulae of Pauly or Ralston). The accuracy of such estimates for the study species is unknown. Uncertainty is therefore introduced into the stock assessment process at this point. Methods to improve the independent estimates of natural mortality are discussed in Section 7.6.1.

7.5 Stock assessments

The results obtained in the current study have a number of implications for the management of the long-lived, slow-growing species within BIOT (Chagos Archipelago). These implications are discussed in the following sections.

7.5.1 Spatial scale of assessments

Before management can be derived, the spatial scale at which stock assessments should be performed must be selected.

Given the lack of evidence for localised meta-populations of *A. virescens* on the banks of BIOT (Chagos Archipelago), assessments were performed at the spatial scale of the bank as a whole. However, given the need for precautionary management, assessments at the level of the statistical area were also made to assess for localised impacts of fishing.

For *L. mahsena*, the work described in Chapter 3 indicated that localised meta-populations of this species were present on the Great Chagos Bank. Assessments of these stocks could therefore be made at the scale of the bank as a whole, more finely at the scale of these meta-populations, or even more finely at the scale of the statistical areas. It was useful to perform assessments for *L. mahsena* at all three spatial scales.

Performing assessments of the status of *L. mahsena* stocks at the scale of identified meta-populations has additional advantages in terms of data collection. When collecting data at the scale of individual statistical areas, the frequent movement of vessels meant that required sample sizes could not be obtained from every area. This problem was encountered during Project R6465. Collecting at the larger spatial scale of the meta-population would make it easier to obtain the required numbers of otoliths within the time available.

When collecting data from meta-populations, otoliths should continue be collected across statistical areas encompassed by these populations. This allows more localised effects of fishing to be identified; in the current study, the reason for concern over the *L. mahsena* stock in the southwest region was identified as a particularly high level of total mortality in the south Great Chagos Bank area. This is discussed further in the next section.

7.5.2 Stock assessment and management

The aim of management in BIOT (Chagos Archipelago) is conservation, while allowing Mauritian vessels to fish as they have previously done. With this aim in mind, the results of the stock assessments are discussed.

As shown in Project R6465, length-based methods of total mortality assessment (using either length- or age-based growth parameter estimates) result in highly uncertain stock assessments, and frequently inappropriate management decisions. The use of age-based methods of total mortality reduces the uncertainty in such assessments. In this study, the status of stocks in BIOT (Chagos Archipelago) are therefore examined using age-based estimates.

When assessed at the scale of the bank as a whole (and by statistical area), *A. virescens* generally appears sustainably exploited, with the fishing mortality level around the level of $F_{0.1}$. However, slight concern was noted where assessments were derived based on Ralston's M; the estimated level of fishing mortality was slightly greater than $F_{0.1}$. Although assessments at the scale of the statistical areas were limited by the data available, assessments again generally indicated sustainable exploitation of this species.

At the scale of the bank as a whole, *L. mahsena* stocks also appear sustainably exploited. However, when assessed at the scale of meta-populations, there was some concern over the population in the SW region. Acting in a precautionary manner, the worst-case assessment for a meta-population should be applied across the location. This would indicate that some reduction in effort is required in BIOT (Chagos Archipelago). However, the assessment for this region was strongly influenced by data from the south Great Chagos Bank area (SCH), where the population appeared to be over-exploited. This resulted from a high total mortality estimate. As discussed in Chapter 4, this estimate appears to have resulted from factors other than fishing, since the stock structure of this species showed no relationship with the level of fishing effort applied. Potential causes include an increased level of natural mortality in this area, or ontogenic migration. With this in mind, the meta-populations of *L. mahsena* appear sustainably exploited, although continued monitoring is required. The potential for management through closed areas should also be examined.

The current fishing mortality level appears appropriate to achieve the aims of management for both species. The licencing scheme currently in operation is therefore functioning appropriately. Stocks of these species remain vulnerable to the impacts of fishing, however. The length at capture (Lc_{50}) for both species was lower than the corresponding length at maturity (Lm_{50}). As a result, individuals can be caught before they reach maturity. As stated, continued monitoring of the stock is required.

7.6 Assessment of utility

This study has indicated that it is feasible to employ age-based methods to assess the impact of fishing on exploited populations of demersal reef fish within BIOT (Chagos Archipelago). The use of age-based methods of growth and total mortality assessment is recommended in this and other tropical demersal fisheries, since it reduces the uncertainty of routine stock assessments.

In BIOT (Chagos Archipelago), age-based growth parameter estimates have already been derived for *L. mahsena* and *A. virescens*. In turn, an age-otolith weight relationship has been derived for *L. mahsena* at this location. Where the otolith weight of a species could be used as a proxy for age, this method proved the most cost effective.

An otolith weight-age relationship could not be derived for *A. virescens*. The use of age-based methods to estimate total mortality (through individual otolith readings) was not cost effective. In this case, the use of age-based methods to estimate growth parameters and length-based methods to estimate total mortality was recommended (see Project R6465).

For routine assessments of these two species in BIOT (Chagos Archipelago) these are the most appropriate approaches. However, there is a need to obtain an independent estimate of natural mortality for the study species. One method of obtaining this is through the use of annual total mortality estimates. The most accurate technique to estimate this parameter is currently though age frequency distributions. Hence where estimates of natural mortality are required, the use of age-based methods to estimate total mortality is recommended, regardless of whether an age-otolith weight relationship is available.

7.7 Remaining uncertainty

While the current study has answered a number of questions regarding the status of stocks in BIOT (Chagos Archipelago), there remains a number of areas in which uncertainty remains. These are discussed below.

7.7.1 Natural mortality

The estimate of natural mortality was highly influential in stock assessments, through its impact on the estimates of both F_{curr} and $F_{0.1}$ (Section 7.4). The use of Ralston's natural mortality estimates generally indicated a 'worse case' compared to assessments derived using Pauly's

M. Where the use of either natural mortality estimate resulted in consistent stock assessments, uncertainty was reduced. However, where outputs from the use of either M estimate conflicted, as was common, uncertainty remained. To minimise this uncertainty, an accurate estimate of M, independent of empirical formulae, is needed.

The lack of an independent estimate of M also affected assessments of *L. mahsena* population structure. Different rates of total mortality were estimated for the meta-populations of *L. mahsena* identified on the Great Chagos Bank, due to the differences in the stock structure. However, it was unknown whether these differences were driven by variations in the underlying natural mortality level, rather than the level of fishing mortality. Estimates of fishing mortality for these populations were therefore uncertain.

Lightly fished areas are commonly the small banks of the archipelago (e.g. Colvocoresses reef, Gangees bank). Estimates of natural mortality could be obtained at these areas (Z=M in lightly exploited populations). Vessels generally fish in these locations for only one day, however. This is a short time period for observers to collect sufficient samples to estimate total mortality. In turn, vessels may not visit these locations each year. An alternative approach, relating annual Z estimates to the level of fishing effort, requires further annual total mortality estimates before a convincing natural mortality estimate can be derived. To this aim, the age-otolith weight relationship for *L. mahsena* (Chapter 5) provides a cost-effective method of estimating total mortality.

7.7.2 Population distribution

The lack of older individuals in the SW region of the Great Chagos Bank may result from a higher level of natural mortality. Alternatively, it may result from ontogenic migration, the movement of older individuals from this location as they age. Such migration would invalidate the use of catch curves to estimate total mortality in these areas; their use assumes there is no immigration or emigration from the region, and that natural mortality is constant.

Performing a tagging survey in the region may identify:

- whether individuals moved from this location, where they migrated to, and at what stage of their life;
- the extent of meta-populations;
- whether meta-populations were distinct stocks, and hence should be managed as such.

The issue of whether meta-populations are distinct is important. If there is no flow of individuals or gametes between stocks, then the meta-populations should be assessed as separate entities. However, if there is interconnection between these two populations, they should be managed as a unit.

The urgency of a tagging study is reduced by the management approach suggested; where the conservation aim is maintained by managing based on the more heavily exploited population. There are also a number of difficulties which may be encountered when performing tagging experiments in BIOT (Chagos Archipelago):

- a large number of fish would need to be tagged within a season in the area required. The vessel may therefore need to remain in a location for a relatively extended period. The historical pattern of fishing indicates this is unlikely. Therefore, the tagging programme must run over a number of years, or there must be financial incentives for the vessel to remain in one area for an extended period;
- fishing vessels may not return to the same locations in the following year;
- tagging would need to be carried out while on board the dories - fish will be dead by the

time they are returned to the mothervessel. Given the space available on board dories, this may not be practical;

- species targeted (*L. mahsena*) must be from relatively shallow depths to minimise the stresses resulting from barotrauma;
- the level of natural mortality after tagging, as a result of predation by sharks for example, may be high.

It is suggested that approaches to derive independent estimates of M for each meta-population are examined first. This may answer whether differences are due to the level of natural mortality, rather than migration, identifying whether such a tagging programme is required. If a tagging programme is considered, the feasibility of such an approach should be trialed. It should be noted that both approaches are based on commercial data. While a research cruise could be undertaken to target areas for these studies, this would represent an additional cost to management.

7.7.3 Stock assessment method

Guidelines developed during Project R5434 suggested that while coral reef fisheries, such as that in BIOT (Chagos Archipelago), are multispecies in nature, the use of single species approaches is valid (e.g. Huntsman et al., 1983; Polovina, 1987; Polovina and Ralston, 1986). Single species assessments are appropriate for the economically most important species of a multispecies fishery. The examination of *L. mahsena* is therefore appropriate at locations such as the Mauritian banks; this species forms over 90% of the catch weight on Saya de Malha bank (Ardil, 1986; Bertrand et al., 1986), and over 50% on other banks (MRAG, 1997).

For BIOT (Chagos Archipelago), however, it must be noted that setting the fishing mortality level to the value of $F_{0.1}$ calculated for *L. mahsena* may result in the overexploitation of more vulnerable species (e.g. members of the Serranidae). Since the aim of management in BIOT (Chagos Archipelago) is conservation, guidelines devised in Project R5434 state that another indicator species representing the most vulnerable species, should also be assessed.

Examination of a further species using age-based methods would require the validation of the annual nature of otolith increments. Given the additional costs involved, such studies should undertake a phased approach:

- initial sampling and assessment of the presence of rings in the otoliths of study species to examine the nature and legibility of ring structures;
- sampling of otoliths to achieve validation (monthly samples).

It should be noted, however, that formal validation was not achieved for either *L. mahsena* or *A. virescens* from BIOT (Chagos Archipelago; Pilling et al., 1999). Due to the fishing season, samples could only be collected from a limited number of months. The annual nature of the bands was assumed based on the similarity in both ring structure and pattern of marginal increment (in months where data were available), to that from these species in other locations where validation was achieved. This problem is likely to occur for other species sampled from BIOT (Chagos Archipelago).

For fisheries management in BIOT (Chagos Archipelago), biological assessments such as those performed here form part of a suite of stock assessment methods. These include the comparison of the level of total catch against the estimated potential yield for the fishery, and examination of CPUE data. This study has improved the biological assessments. Currently, effort controls based on the most vulnerable part of an exploited population remain the most feasible option. This is evaluated annually, and changes in the management actions can be taken at any time.

7.7.4 Reproductive parameters

Information on the maturity characteristics of *L. mahsena* (length-at-maturity) in BIOT (Chagos Archipelago) is lacking. This parameter is useful to support stock assessments. Based on available information, individuals of both species may be caught prior to maturity, and hence populations are more vulnerable to fishing. However, the final report from Project R5434 (MRAG, 1996a) indicated that the estimation of this parameter is not as important as the estimation of parameters such as Lc_{50} and M. As a result, the collection of reproductive data should remain a relatively low priority in BIOT (Chagos Archipelago).

7.8 Guidelines

The studies performed during the current project have allowed a number of guidelines to be developed. These supplement those guidelines derived in Project R6465.

7.8.1 Generic guidelines for tropical fisheries targeting long-lived, slow growing species

For routine assessment of total mortality:

- use age-based methods to assess total mortality where an age-otolith weight relationship is available. This cost-effective approach reduces uncertainty since growth parameter estimates are not required;
- derive an age-otolith weight relationship where possible;
- where such a relationship is not available, use length-based methods of total mortality estimation combined with age-based growth parameter estimates. This method is more cost-effective than the construction of an age frequency using individual otolith increment counts.

To minimise uncertainty in subsequent assessments of F_{curr} and $F_{0.1}$:

- obtain an independent estimate of M, either by estimating Z in lightly exploited populations, or by relating annual estimates of total mortality to the level of fishing effort;
- if fishing trials with different gears can be performed, improve growth parameter estimates. However, where reasonable age-based growth parameters are available, this is of lower priority than the independent estimation of M;
- assessment of maturity parameters is a low priority.

For management:

- examine the potential for assessing other indicator species appropriate to the aims of management (see guidelines from project R5434);
- ensure data describing the whole of the fishery (CPUE data) continues to be collected.

7.8.2 Guidelines specific to the BIOT (Chagos Archipelago) inshore demersal fishery

When performing stock assessments for the study species:

- assess *L. mahsena* by meta-populations, and apply worst-case scenario across BIOT (Chagos Archipelago), unless there is the potential for closed area management;
- while data for this species should be collected by meta-population, ensure data is collected across statistical areas encompassed by these populations to allow detailed studies to be undertaken;
- assess *A. virescens* for the whole of BIOT (Chagos Archipelago), and by statistical

areas;
- continue to collect CPUE data by statistical area.

Estimate total mortality:

- for *L. mahsena* using the age-otolith weight relationship;
- for *A. virescens* use estimated age-based growth parameters and length-based total mortality estimation methods.

Future work:

- continue to obtain age-based estimates of total mortality for *L. mahsena* until sufficient data are available to obtain an independent estimate of M;
- as aim of management is conservation, investigate the use of age-based methods of growth and mortality assessment to assess the status of a vulnerable species in BIOT (Chagos Archipelago), e.g. members of the Serranidae;
- identify information on meta-populations through tagging studies: examine whether ontogenic migration causes differences in total mortality and the extent of meta-populations. This is a low priority.

7.9 Conclusions

This study has made a number of important findings for both the assessment and management of the BIOT (Chagos Archipelago) inshore demersal fishery, and for similar demersal tropical fisheries targeting long-lived, slow growing species. The study has developed further justifications for the use of otolith data in routine stock assessments, supporting the move of the Seychelles Fishing Authority (SFA) and BIOT Authorities towards using age-based assessment methods, as recommended by the outputs of project R6465. Through the uptake of the results of these studies by target institutions, benefits should be obtained through improved fisheries management, resulting in sustainable resource utilisation.

Further improvements to management could be obtained through more sophisticated assessment methods. Frequently, the ultimate aim of routine age data collection is to perform an age-based Virtual Population Analysis (VPA). This aim has already been expressed by staff at SFA. A new project being prepared under DFID funding will examine the implications of using length- and age-based methods of growth and stock assessment for species with different life history strategies, including long-lived, slow growing species such as *L. mahsena*. As part of this, the study will simulate the use of age-based VPA. This will examine the cost-effectiveness of this method. It will answer whether the use of resources for this goal is appropriate when assessing species of importance to the demersal fisheries of Seychelles, Mauritius and BIOT (Chagos Archipelago), or whether appropriate results can be obtained more readily using cheaper approaches. These studies will have obvious relevance not only to the BIOT Authorities, SFA and AFRC (Mauritius), but also to other fisheries institutions throughout the tropics.

Table 7.1 Comparison of biological parameter estimates for *Aprion virescens* with previous years.

Parameter	*Aprion virescens*							
	1997(a)	1997(b)	1997(c)	1997(d)	1999(a)	1999(b)	1999(c)	1999(d)
		Length		Age		Length		Age
K	0.35	0.26	0.09	0.09	0.35	0.26	0.09	0.07
L_∞	78	104	93.7	93.7	78	104	93.7	101.5
Lmin	33	33	33	-	20	20	20	-
Lmax	88	88	88	-	86	86	86	-
Lm_{50}	53.5							
Lc_{50}	48.3	49.9	39.3	49.2	44.2	52.2	42.4	42.2
N	354	354	354	281	1319	1319	1319	468
Z	0.88	1.73	0.17	0.17	0.69	1.43	0.30	0.23
M	0.68	0.51	0.27	0.18	0.69	0.52	0.27	0.16
F	0.20	1.22	M>Z	M>Z	0	0.91	0.03	0.07
F/Z	0.23	0.71	-	-	0	0.64	0.10	0.30
F/M	0.29	2.39	-	-	0	1.75	0.11	0.44

Table 7.2 Comparison of biological parameter estimates for *Lethrinus mahsena* with previous years.

Parameter	*Lethrinus mahsena*										
	1995(a)	1996(a)	1996(b)	1997(a)	1997(b)	1997(c)	1997(d)	1999(a)	1999(b)	1999(c)	1999(d)
	Length						Age	Length			Age
K	0.32	0.32	0.1	0.32	0.1	0.07	0.07	0.32	0.10	0.07	0.08
L_∞	58.9	58.9	61	58.9	61	67	67	58.9	61.7	67.0	66.5
Lmin	23	19	19	20	20	18	-	20	20	20	-
Lmax	49	54	54	50	50	52	-	55	55	55	-
Lm_{50}						26-31					
Lc_{50}	29.4	26.5	26.5	34	34.2	24.1	30.4	30.9	31.3	28.5	22.5
N	718	554	554	1359	1359	645	645	3224	3224	3224	733
Z	0.92	1.14	0.39	1.11	0.38	0.44	0.40	1.26	0.47	0.27	0.43
M	0.69	0.69	0.32	0.69	0.32	0.25	0.27	0.70	0.32	0.25	0.26
F	0.23	0.45	0.07	0.42	0.06	0.19	0.13	0.56	0.15	0.02	0.25
F/Z	0.25	0.39	0.18	0.38	0.16	0.43	0.33	0.44	0.32	0.07	0.58
F/M	0.33	0.75	0.22	0.61	0.19	0.76	0.48	0.80	0.47	0.10	0.96

Table 7.3 Comparison of biological parameter estimates for *Lethrinus mahsena* for statistical areas within BIOT, with previous years.

Parameter	*Lethrinus mahsena*											
	ECH				NCH			NEL				
	1994(a)	1999(a)	1999(b)	1999(c)	1999(a)	1999(b)	1999(c)	1996(a)	1996(b)	1999(a)	1999(b)	1999(c)
K	0.32	0.32	0.1	0.07	0.32	0.1	0.07	0.32	0.1	0.32	0.1	0.07
L_∞	58.9	58.9	61.7	67	58.9	61.7	67	58.9	61.7	58.9	61.7	67
Lmin	19	28	28	28	26	26	26	24	24	21	21	21
Lmax	52	51	51	51	51	51	51	50	50	49	49	49
Lm_{50}	26-31											
Lc_{50}	-	38.1	38.1	38.2	35.0	39.6	34.2	30.4	30.5	28.8	31.4	29.7
N	214	57	57	57	417	417	417	226	226	469	469	469
Z	0.77	0.96	0.34	0.35	1.15	0.59	0.43	1.06	0.35	0.60	0.33	0.18
M	0.69	0.69	0.32	0.27	0.69	0.32	0.27	0.69	0.32	0.69	0.32	0.27
F	0.08	0.27	0.02	0.08	0.46	0.27	0.16	0.37	0.03	M>Z	0.01	M>Z
F/Z	0.1	0.28	0.06	0.23	0.40	0.46	0.37	0.35	0.09	-	0.03	-
F/M	0.12	0.39	0.06	0.30	0.67	0.84	0.59	0.54	0.09	-	0.03	-

Table 7.3 Comparison of biological parameter estimates for *Lethrinus mahsena* for statistical areas within BIOT, with previous years. Contd.

Parameter	*Lethrinus mahsena*															
	PIT							SCH								
	1994 (a)	1997 (a)	1997 (b)	1999 (a)	1999 (b)	1999 (c)	1999 (d)	1997 (a)	1997 (b)	1998 (a)	1998 (b)	1998 (c)	1999 (a)	1999 (b)	1999 (c)	1999 (d)
K	0.32	0.32	0.1	0.32	0.1	0.07	0.08	0.32	0.1	0.32	0.1	0.07	0.32	0.1	0.07	0.08
L_∞	58.9	58.9	61.7	58.9	61.7	67	66.5	58.9	61.7	58.9	61.7	67	58.9	61.7	67	66.5
Lmin	19	20	20	21	21	21	-	20	20	25	25	25	23	23	23	-
Lmax	52	48	48	49	49	49	-	46	46	45	45	45	47	47	47	-
Lm_{50}	26-31															
Lc_{50}	-	26	26.1	29.2	29.3	31.2	29.4	27.2	27.3	33.5	33.7	33.7	29.0	29.1	29.4	29.1
N	215	230	230	579	579	579	99	196	196	227	227	227	284	284	284	100
Z	1.15	1.69	0.57	1.49	0.52	0.59	0.42	1.61	0.54	3.5	1.23	1.05	1.92	0.67	0.70	0.74
M	0.69	0.69	0.32	0.69	0.32	0.27	0.27	0.69	0.32	0.69	0.32	0.25	0.69	0.32	0.27	0.27
F	0.46	1.00	0.25	0.80	0.20	0.32	0.15	0.92	0.22	2.81	0.91	0.80	1.23	0.35	0.43	0.47
F/Z	0.40	0.59	0.44	0.54	0.38	0.54	0.36	0.57	0.41	0.80	0.74	0.76	0.64	0.52	0.61	0.64
F/M	0.67	1.45	0.78	1.16	0.63	1.19	0.56	1.33	0.69	4.07	2.84	3.20	1.78	1.09	1.59	1.74

Table 7.3 Comparison of biological parameter estimates for *Lethrinus mahsena* for statistical areas within BIOT, with previous years. Contd.

Parameter	*Lethrinus mahsena*														
	SEC									WCH					
	1997 (a)	1997 (b)	1998 (a)	1998 (b)	1998 (c)	1999 (a)	1999 (b)	1999 (c)	1999 (d)	1996 (a)	1996 (b)	1999 (a)	1999 (b)	1999 (c)	1999 (d)
K	0.32	0.1	0.32	0.1	0.07	0.32	0.1	0.07	0.08	0.32	0.1	0.32	0.1	0.07	0.08
L_∞	58.9	61.7	58.9	61.7	67	58.9	61.7	67	67	58.9	61.7	58.9	61.7	67	67
Lmin	23	23	24	24	24	23	23	23	-	26	26	24	24	24	-
Lmax	46	46	48	48	48	49	49	49	-	50	50	51	51	51	-
Lm_{50}								26-31							
Lc_{50}	34	34	27.7	24.8	28.4	30.4	30.4	30.8	30.5	37	36.7	27.9	27.9	28.0	27.9
N	292	292	229	229	229	690	690	690	100	74	74	356	356	356	72
Z	2.84	0.97	1.46	0.55	0.47	1.60	0.56	0.57	0.38	2.60	0.61	1.32	0.45	0.40	0.39
M	0.69	0.32	0.69	0.32	0.25	0.69	0.32	0.27	0.27	0.69	0.32	0.69	0.32	0.27	0.27
F	2.15	0.65	0.77	0.23	0.22	0.91	0.24	0.30	0.11	1.91	0.29	0.63	0.13	0.13	0.12
F/Z	0.76	0.67	0.53	0.42	0.47	0.57	0.43	0.53	0.29	0.73	0.48	0.48	0.29	0.32	0.31
F/M	3.12	1.94	1.12	0.72	0.88	1.32	0.75	1.11	0.41	2.77	0.91	0.91	0.41	0.48	0.44

Table 7.4 Comparison of biological parameter estimates for *Aprion virescens* for statistical areas within BIOT, with previous years.

Parameter	*Aprion virescens*												
	ECH		GAN		NCH			PIT			SPK		
	1999 (a)	1999 (b)	1999 (a)	1999 (b)	1994 (a)	1999 (a)	1999 (b)	1999 (a)	1999 (b)	1999 (c)	1999 (a)	1999 (b)	1999 (c)
K	0.19	0.07	0.19	0.07	0.35	0.19	0.07	0.19	0.07	0.07	0.19	0.07	0.07
L_∞	93.6	101.5	93.6	101.5	78	93.6	101.5	93.6	101.5	101.5	93.6	101.5	101.5
Lmin	28	28	32	32	29	32	32	27	27	-	32	32	-
Lmax	77	77	78	78	79	80	80	85	85	-	79	79	-
Lm_{50}							53.5						
Lc_{50}	53.7	54.3	44.6	44.6	-	49.9	50.2	57.1	56.7	57.3	50.8	50.9	50.9
N	100	100	85	85	102	166	166	370	370	100	184	184	100
Z	1.55	0.75	1.22	0.54	0.82	0.59	0.27	1.01	0.45	0.15	0.80	0.37	0.38
M	0.43	0.22	0.43	0.22	0.68	0.43	0.22	0.43	0.22	0.22	0.43	0.22	0.22
F	1.12	0.53	0.79	0.32	0.14	0.16	0.05	0.58	0.23	M>Z	0.37	0.15	0.16
F/Z	0.72	0.71	0.65	0.59	0.17	0.27	0.19	0.57	0.51	-	0.46	0.41	0.42
F/M	2.60	2.41	1.84	1.45	0.21	0.37	0.23	1.35	1.05	-	0.86	0.68	0.73

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9. Appendix 1. Example analysis from the 'yield' software. Authors G. Kirkwood and S. Nicholson.

Example analysis

We present here an example analysis of yields and yield reference points using data for *Lethrinus mahsena*, one of the main species taken in fisheries for snappers and emperors in the western central Indian Ocean, on banks of the Chagos Archipelago, the Seychelles, and Mauritius.

The aim is to illustrate how to collate and enter appropriate information on the biological and fishery parameters and their uncertainties, and how to interpret the results from the various analyses carried out using the software. In order to avoid duplication and to keep this example analysis down to a reasonable length, we omit details on the mechanics of using the software. Instead, links are given at appropriate places to relevant sections of the Help files, where comprehensive information on these aspects may be found.

For users unfamiliar with the types of analyses carried out in this software package, we suggest that you first simply read through the example analysis, diverting to appropriate sections of the help files for more information as needed. Having done so, we then suggest that you attempt to repeat the analyses, as suggested in the text. Before doing so, however, we strongly suggest that you print out this section of the help files, as you will find that switching back and forth between analysis and the help files is tedious at best.

Parameters for *L. mahsena*.

A data file containing estimates of parameters and their uncertainties for *L. mahsena*, **LmahDat.txt**, has been distributed along with the software. After starting the Yield software, load this parameter file (see Load parameters). The name of the species and the data file should then appear in the header of the main form.

Biological and fishery parameters contained in the loaded data file may be inspected (and changed or entered; see Entering parameters) using the **Parameters** menu. The first item on that menu is **Von Bertalanffy…**, which allows the von Bertalanffy growth parameters and their uncertainties specified in the parameter file to be inspected (see Entering von Bertalanffy parameters). Selecting this menu item will reveal that uncertainties have been specified for L_∞ and K, but not for t_0. Delving further, you will find (see Choose distribution for uncertainty in Linfinity) that L_∞ has been specified to have a normal distribution with mean = 53.6 and CV = 0.08; K has a lognormal distribution with mean = 0.128 and CV = 0.17; and t_0 has a value fixed at 0.

Where did these values come from? The best potential source of information for these and all the other parameters obviously is data collected directly for the species and from the fishery itself. This is the source used for the *L. mahsena* parameters. For the growth parameters, both length frequency distributions and age-length data were collected for each of the main fisheries in the western central Indian Ocean during a UK Department for International Development (DFID) funded project carried out by MRAG Ltd. The results were described in Pilling et al (1999)[3] and in a PhD thesis by Dr G. Pilling

[3] Pilling, G. M., Mees, C. C., Barry, C. J., Kirkwood, G. P., Nicholson, S., and Branch, T. (1999). Growth parameter estimates and the effects of fishing on size-composition and growth of snappers and emperors: Implications for management. Final report to the Department for International

(1999)[4]. For *L. mahsena*, the length frequency data were analysed using the Elefan method as implemented in the LFDA software (MRAG, 1992)[5], and estimates of von Bertalanffy parameters were obtained by non-linear regression analysis of the age-length data. The means and CVs quoted are the means and CVs of the sets of estimates obtained (there were 12 in all).

As for the distributions, there is an element of arbitrariness in their selection. With just 12 individual estimates, it is rather difficult to identify an appropriate distribution with any degree of certainty. The distribution of estimates of $L_{¥}$ was roughly symmetrical; hence the choice of the normal distribution. The distribution of estimates of K was also reasonably symmetrical, but there was a hint of a slightly longer tail towards higher values of K. More importantly, however, it is known that K must be greater than zero. Negative values can be avoided by using a lognormal distribution, which in any case can also be reasonably close to symmetrical; see the plot of the selected distribution for K.

Users with experience in estimating growth parameters may be rather suspicious of the relatively low levels of variability in $L_{¥}$ and K, and even more so of the apparently certain and suspiciously round value of t_0. They have every right to be. It is usually impossible when analysing the types of length frequency data available using the Elefan method to obtain any estimates of t_0. However, such is not the case when estimating growth parameters using age-length data. In practice, the age-length data available contained very few observations for small ages and lengths. The implication of this is that it is actually very difficult to estimate all three von Bertalanffy parameters with any precision at all: the data were compatible with quite large negative values of t_0 (which went with low K and high $L_{¥}$ values) or small values of t_0 (which went with high K and low $L_{¥}$ values). The estimates used here in the end were those corresponding to $t_0 = 0$. Taking this approach almost certainly underestimates the true uncertainties in growth parameters, but it suffices for this example.
A final, rather technical point should also be made here. Even ignoring the parameter t_0, it is almost universally observed that when estimates of $L_{¥}$ and K are being calculated, either using individual data sets or combining sets of estimates from different data sets, there tends to be a high negative correlation between the two. In the *L. mahsena* case, the correlation is as high as –0.89. When originally specifying the software, we were well aware of this issue, but given the almost complete lack of cited estimates of the correlation between $L_{¥}$ and K in the literature, we decided to ignore it. In retrospect, this may not have been the right decision, and later versions of the software will allow the user at least to enter a value for the correlation between $L_{¥}$ and K. The current version assumes that the two parameters are independent. (Note that in Dr Pilling's final analyses, account was taken both of individual variability in growth parameters and of estimated correlations between all three growth parameters, but this requires methods far beyond the scope of this software package).

How might users collate the information needed to specify means and CVs for von Bertalanffy parameters? If they are lucky, data will be available (or can be collected) from their fishery to allow direct estimation of mean values at least. Note, however, that no reliable estimates of growth parameter uncertainty are available from any currently-used method for analysing length frequency data, so there still remains a problem there. Fortunately, even if no direct estimates are available for your species and fishery, the excellent and comprehensive database FishBase 98[6] almost certainly will have recorded estimates of biological parameters for the species concerned or a closely related species. This should allow at least a rough idea to be gained as to appropriate mean values and likely ranges of values of the von Bertalanffy growth parameters. Be warned, however, that some judgement still needs to be used when using data from related species. For example, even if attention is restricted to lethrinid species, recorded pairs of estimates of $L_{¥}$ and K range from (16.2, 0.86) for *L. genivittatus* in New Caledonia to (106, 0.061) for *L. olivaceus* in the Yemen. Given the *L. mahsena* data, neither is at all likely for this

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Development. MRAG Ltd, 401pp.

[4] Pilling, G. M. (1999) The effects of fishing on the growth and assessment of snappers and emperors. PhD thesis, University of London, 511pp.

[5] MRAG (1992) The Length Frequency Distribution Analysis (LFDA) package, Version 3.10. User manual. Marine Resources Assessment Group Ltd, 68pp.

[6] http://www.fishbase.org/

species.

Turing to length-weight parameters (see Entering Length-weight parameters), you will see that only single values have been entered in the *L. mahsena* data set. Length-weight data are perhaps the easiest biological data of all to collect and analyse, and in most cases they show relatively low levels of variability. That was certainly the case with the *L. mahsena* data, and we have opted not to specify uncertainties around the entered values.

If length-weight parameters are the easiest to estimate, the next parameter, the natural mortality rate, is almost certainly close to the hardest. Fortunately, the empirical relationship developed by Pauly (1980) and FishBase 98 come to our rescue again. Two options are available after selecting the **Natural mortality…** item from the **Parameters** menu: the user can enter a single value (or distribution) for the natural mortality rate, or use Pauly's (1980) empirical relationship (see Enter natural mortality rate, Enter parameters for Pauly's equation). For *L. mahsena*, we also had no reliable direct estimate of the natural mortality rate available, so for this example we have opted to use Pauly's relationship. The temperature entered (27°C) was extracted from the Nautical Almanac for the Indian Ocean. No uncertainty has been specified about this temperature.

While estimates of the natural mortality rate are available from FishBase 98 for at least some species, many of these have been calculated using Pauly's equation. Unless you have available an estimate or estimates of the natural mortality rate that you consider to be quite reliable, we would suggest in most cases that you use the Pauly's equation option, and certainly that you use this option rather than enter a single value that itself was calculated using this relationship. The reason is that, if you use the **Enter parameters for Pauly's equation** option directly, then the uncertainties you entered for the von Bertalanffy parameters will automatically be taken into account in the simulations, and they will by themselves induce uncertainties in the value of the natural mortality rate.

The next parameters to be entered are the maturity and capture parameters (see Maturity and Capture). For *L. mahsena*, we have opted to enter lengths, rather than ages, and we anticipate that this choice will be made most times when the software is used (if for no other reason that ages are often so hard to estimate directly). Based on data collected from the fisheries, the (knife-edge) length at maturity has been set to have a lognormal distribution with mean = 27.6 cm and CV = 0.05. The mean and CV were estimated from data on the lengths at which 50% of the fish first attained maturity, and the lognormal distribution was used because the ogive of proportions mature at length was rather steeper at low lengths than at higher lengths, suggesting that the distribution of length at 50% maturity had a slightly longer tail towards higher lengths.

The length at first capture was set at a constant value of 22.8 cm. This, of course, is one of the parameters that can, in principle, be changed by management regulation (e.g. by setting minimum landing sizes, or mesh sizes). Although actual mean lengths at first capture differ amongst the different fisheries in the western central Indian Ocean, there seems little point in reflecting this in the uncertainties in this parameter. However, if the mean length at first capture tended to differ substantially between years in an individual fishery, then it would be entirely appropriate to specify uncertainties about this parameter.

The next items to specify are the seasons (see Spawning and Fishing seasons). Three things need to be set. The first is the time step interval. Here, we have set this as Monthly. This is not strictly necessary in order to specify the spawning and fishing seasons, which have been taken to occur all year round based on available information. However, using a yearly time step is likely to lead to inaccuracies in the numerical calculations for a species that only lives for a maximum of 15 – 20 years, so Months is the appropriate time step for this species.

The last set of parameters to enter are those for the stock-recruitment relationship (see Choose type of stock recruit relationship). This is even harder that setting the natural mortality rate, and at least one of the values entered here is, to be honest, partly a guess. It may seem rather odd to admit this in what is a demonstration of the use of the software, but in many cases, it is likely that this will also be the situation facing the typical user, especially those in developing countries with relatively little information available about their fishery. It therefore seems appropriate to attempt to demonstrate what can be done in such cases.

The first choice to be made is of the form of stock-recruit relationship. That is relatively easy. The only two real possibilities in the current context are Beverton and Holt, or Ricker. The Ricker relationship, most commonly seen in the context of salmon stocks, is generally thought to apply in circumstances where there is either very substantial cannibalism or where there are restricted spawning areas. Neither is thought to apply to *L. mahsena*, so a Beverton and Holt relationship seems the most appropriate, as it is likely to be in most cases. With regard to the parameters (see Beverton and Holt SRR- Standard formulation, Beverton and Holt SRR- Steepness formulation), whichever is chosen, there are essentially two to specify.

One of these is the so-called steepness parameter. There is some external information available on typical values of this parameter. This comes from the data originally collated by Myers *et al* (1995)[7], now included in FishBase 98. Based on values included in this database for related species, Mees and Rousseau (1997)[8] identified a lower limit for a related parameter that was equivalent to a steepness parameter of 0.8. On those grounds, we have chosen to assume that the steepness parameter is uniformly distributed between 0.8 and 0.95.

The second parameter is the maximum (or unexploited) number of recruits (or SSB). This parameter is, of course, entirely stock-specific. Small stocks will have a small maximum number of recruits; large stocks will have a large number. The value of that number will be a function of the fecundity of the stock, the productivity of the waters in which it spawns, the size of the available spawning or nursery areas, and so on. Regrettably, such information cannot be gleaned from estimates obtained from related species, or the same species in different areas. If you are very fortunate, then an abundance survey may have been carried out prior to or shortly after the fishery was discovered. This may well provide estimates of the unexploited number of recruits or of the adult biomass. If so, then it is a relatively trivial matter to enter an appropriate value (with uncertainties) once the **Use estimates of biomass or recruits** option is selected. Alternatively, in other cases, estimates are sometimes available of biomass per unit area (perhaps between certain depth ranges in which the stock is found). Again, such information can in principle readily be used in conjunction with widely-available bathymetric information.

Failing this, there is little else to fall back on, and an educated guess must be made. Fortunately, at least in terms of the reference points for the fishing mortality rate, this matters much less than might be imagined, as will be seen later. One possible approach is to choose a value for the unexploited number of recruits that produces a maximum sustainable yield that is of the same order of magnitude as catches, or preferably, other estimates of potential yields.

For the shallow banks of the Chagos Archipelago, the potential yield for commercially important handline species may be approximated by comparison with yields observed in similar areas in the Indian Ocean. For example, Sanders (1988)[9] assumed that the potential yield of the Chagos Bank would be equivalent to that observed on the more heavily exploited Saya de Malha bank north of Mauritius (0.22 t km^{-2}). In the Seychelles, the sustainable yield in shallow water strata was estimated to be 0.168 t km^{-2} (Mees, 1992)[10]. However, catch rates in the Chagos Archipelago are less than in Seychelles or on the Saya de

[7] Myers, R. A., Bridson, J. and Barrowman, N. J. (1995) Summary of world-wide stock and recruitment data. *Can. Tech. Rep. Fish. Aquat. Sci.* 2024(4): 327.

[8] Mees, C. C. and Rousseau, J. A. (1995) The potential yield of the lutjanid fish *Pristipomoides filamentosus* on the Mahé Plateau, Seychelles: managing with uncertainty. *Fish Res.* 33: 73-87.

[9] Sanders, M. J. (1988). Summary of the fisheries and resources information for the southwest Indian Ocean. In: Sanders M. J., Sparre P., Venema S. C. (Eds). *Proceedings of the Workshop on the Assessment of the Fishery Resources in the Southwest Indian Ocean*. FAO/UNDP: RAF/79/065/WP/41/88/E: 187-230.

[10] Mees, C. C. (1992). Seychelles demersal fishery - an analysis of data relating to four key demersal species: *Pristipomoides filamentosus*, *Lutjanus sebae*, *Aprion virescens*, *Epinephelus chlorostigma*. SFA/R&D/019. Seychelles Fishing Authority, Victoria. 43pp.

Malha bank. Thus, a more conservative estimate of 0.100 t km^{-2} may be more appropriate for the Chagos Archipelago.

The estimated area of the Chagos Archipelago less than 70m in depth is 8587 km^2. Using the above figures, estimates of the sustainable annual yield for the shallow sector of the Chagos Archipelago range from around 860 to 1,900 t (Mees *et al.*, 1999)[11]. Using the mean values only for all other input parameters, some simple experimentation suggests that an unexploited number of recruits of 25 millions produces a mean MSY of 1430 t, which is roughly in the middle of this range. This value was therefore used for R0, but no uncertainty was allowed, to reflect the somewhat arbitrary nature of the value.

The final parameter to enter on this form is the CV of inter-annual recruitment variability. In many cases, this will also be an elusive parameter. For *L. mahsena*, age frequency data were available for a number of years, and it was therefore possible, using an assumed constant value for *M*, to project backwards and estimate numbers at age 0 in a number of years. The CV of these estimates was 0.25. Should such data not be available (as it most likely will not be for your fishery), then it should be possible to select at least a plausible value using the Meyers et al (1995)[12] and FishBase 98 data. It may be sensible to try different analyses with different CVs (see later).

The last information to enter serves essentially as documentation of the analysis: the fishery description (see Fishery description). For the example data file, you will see the species name and a brief description of the fisheries.

Now that everything has been entered, it is time to see if they are all compatible and within sensible ranges. This is achieved using the **Cross-check parameters** menu item (see Cross-check parameters). Selecting this item, you should find that all parameters are consistent. So they should be, given that we set up the example parameter file! It is, however, worth following through the example in the help file for this menu item, in which the value of the natural mortality rate is deliberately changed to something silly, just to gain practice in seeing what to do if the parameters are found not to be consistent. But if you do so, don’t forget to change the natural mortality rate back to what it was originally before proceeding.

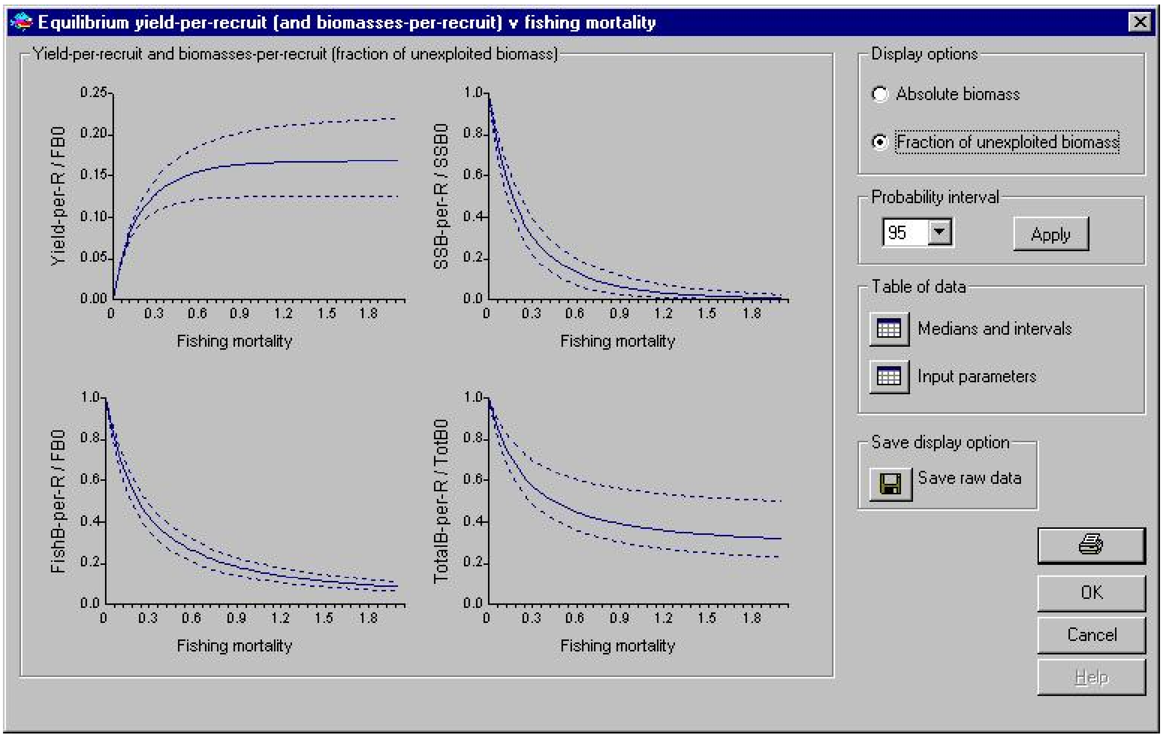
If you had been entering a new data set, it would now be worthwhile saving the parameters (see Save parameters), though this is not necessary in this case.

Yield-per-recruit analyses

The first analysis to carry out is of the equilibrium yield-per-recruit (see Equilibrium yield-per-recruit and related help files). Select **Yield-per-recruit v F…** from the **Equilibrium** menu. Accept the range of values of *F* over which the calculations will be performed (click **OK**). After a while, a series of plots will appear. Those illustrated below are displayed as fractions of unexploited biomass (see Calculate equilibrium yields and biomasses per recruit). This is frequently the most useful display option, as absolute values are not really important.

[11] Mees, C. C.; Pilling, G. M. and C. J. Barry (1999). Commercial inshore fishing activity in the British Indian Ocean Territory. In: Sheppard, C.R.C and M.R.D. Seaward (eds) *Ecology of the Chagos Archipelago*. Linnean Society Occasional Publications 2, 350p.

[12] Myers, R. A., Bridson, J. and Barrowman, N. J. (1995) Summary of world-wide stock and recruitment data. *Can. Tech. Rep. Fish. Aquat. Sci.* 2024(4): 327.



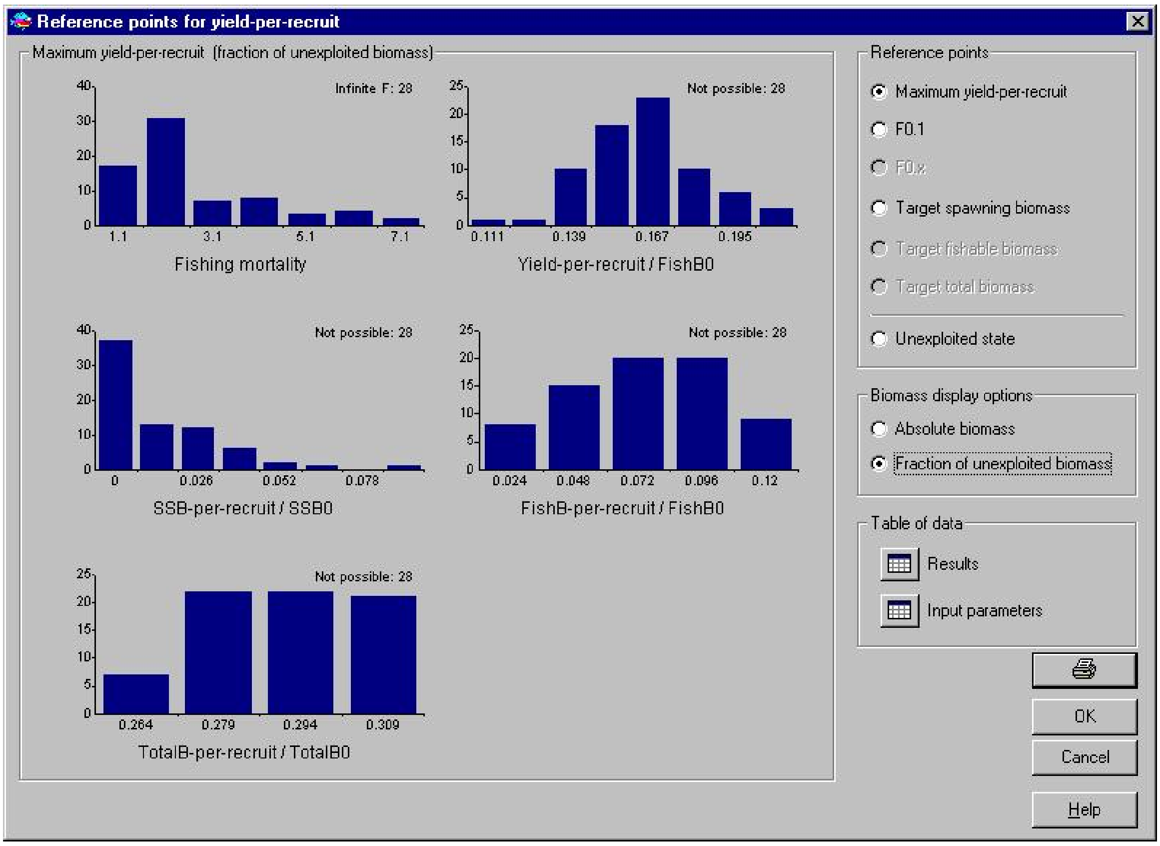
Note that when you do these calculations, the results will not be identical to those illustrated in this example analysis. This is because you will have used different sets of random numbers (see Random seed). They should, however, not be too different!

The top-left plot shows that the median yield-per-recruit, as a fraction of unexploited fishable biomass, reaches a maximum or close to one at values of *F* above about 1.3. Recall the mean value of *M* was around 0.39, so the *F* producing the median maximum yield per recruit is at least 3 times *M*, which is quite a high value. The upper 97.5% confidence band for relative yield-per-recruit is still rising as *F* reaches 2.0, while the lower 2.5% confidence band may have reached a maximum for *F* somewhere over 1.1. Yield-per-recruit plots that suggest the maximum occurs at high values of F are very common. Whether or not this occurs is largely determined by the relative values of *M* and *K*, and even more so by the relative values of the length at first capture and length at maturity. This should not be taken to suggest that the stock can withstand almost any level of fishing mortality, as the remaining plots show.

The other plots show the relationship between various biomasses-per-recruit, as a fraction of their unexploited level, and *F*. Here, we shall only comment on the relative SSB-per-recruit. Whether one looks at the median, or at either confidence band, it is clear that levels of *F* that produce yields-per-recruit at or near the maximum will also reduce the SSB to levels that are a tiny fraction of its unexploited level. Remember that yield-per-recruit analyses explicitly assume that recruitment is unaffected regardless of how low the SSB falls. This is extremely unlikely when the SSB is reduced to levels seen in the plot for high values of *F*.

Before moving on, if you wish to keep a record of your analyses, you may wish to print out a copy of this form. Also, if you want to see the results in more detail, you can do so clicking the **Medians and intervals** button.

The next step in the analysis is to calculate yield and biomass per recruit reference points (see What are reference points?, Calculate equilibrium yield-per-recruit reference points). Select **Yield-per-recruit reference points…** from the **Equilibrium** menu. You will see three reference points have been checked for calculation (Maximum yield-per-recruit, $F_{0.1}$ and the target SSB/Initial = 0.2). Click **OK** to accept these and in time a results form similar to the one below will appear. The first to be illustrated is that for maximum yield-per-recruit. Again, the display option chosen is as a fraction of unexploited biomass. For more details, see Equilibrium yield-per-recruit reference points: Interpreting the results.



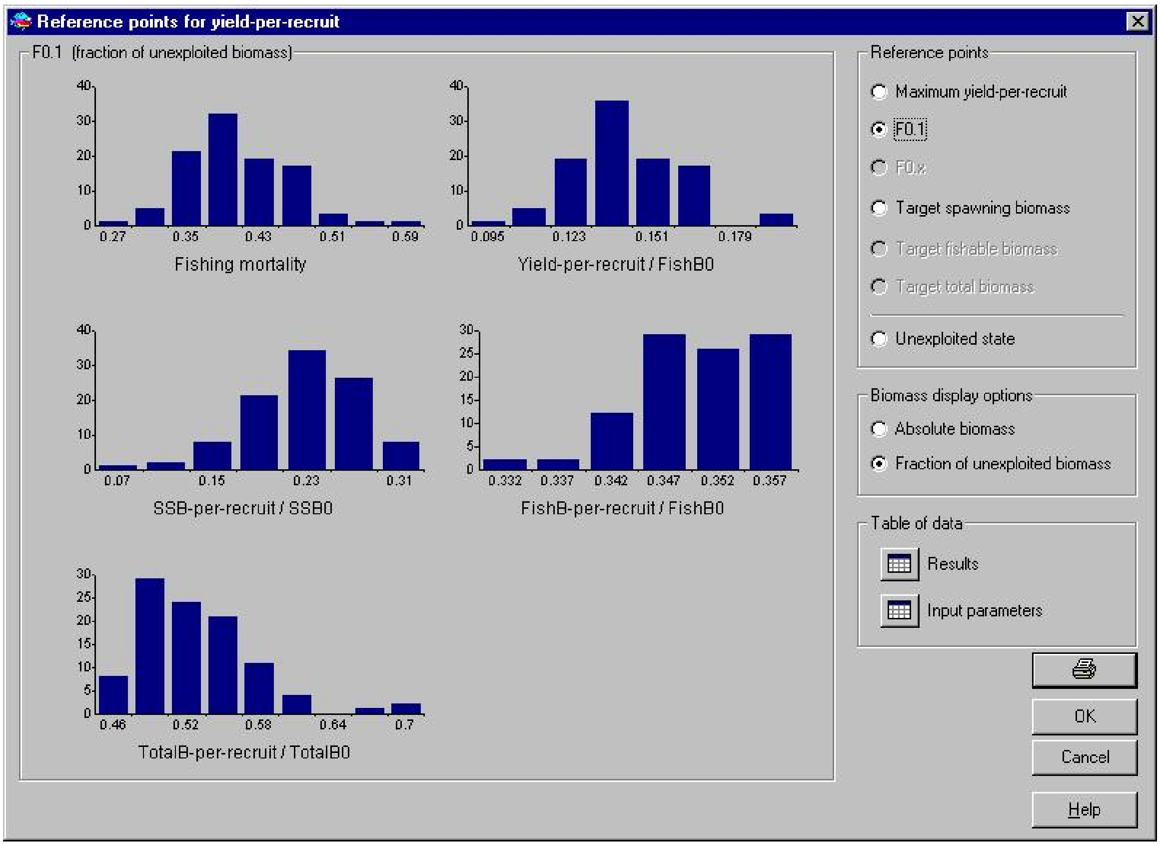
This form displays five histograms. The top left one is of the fishing mortality rate that produces the maximum yield-per-recruit. The way in which these results are calculated is explained in detail in the Simulating under uncertainty section of the Help files. For the purposes of explanation here, we simply note that 100 simulations were carried out (you can check this by selecting **Number of simulations** in the **Options** menu, but don't do so right now, as the results form will then disappear and it will have to be produced again). The numbers appearing on the x-axis of the histogram correspond to the mid-points of each histogram bin. Thus the first bin, labelled 1.1, in this case refers to values of F in the range 0.6 – 1.6, the second to 1.6 – 2.6, and so on.

The largest frequency (for *F* in the range 1.6 – 2.6) has around 30 observations. Note the occurrence of 28 cases of "infinite" F. Quotes are used here because any *F* greater than around 20 times the mean value of *M* used (0.392) is treated as being effectively infinite. Over 50% of the time, the *F* producing the maximum yield-per-recruit exceeded 2.4. This confirms the impression given by the yield-per-recruit plots discussed above.

The SSB-per-recruit histogram also confirms the impression given by the earlier plots: the largest of all the values of SSB-per-recruit was less than 11% of its unexploited value. Note that, while the first bin (labelled 0) of this histogram nominally refers to values in the range –0.0065 to 0.0065, since negative values of SSB-per-recruit are impossible, it actually refers to the range 0 to 0.0065. Defining algorithms for automatic labelling of histograms is difficult, and we have not always got it absolutely right. This is why the user is offered the option of producing a table of results, which can be transferred to your favourite graphics package to produce final publication-quality plots.

Clearly, the maximum yield-per-recruit reference point is not one that can safely be used as a management target for this species.

The next reference point to examine is the $F_{0.1}$ reference point. Selecting results for $F_{0.1}$ produces the following form (again using the **Fraction of unexploited biomass** display option).

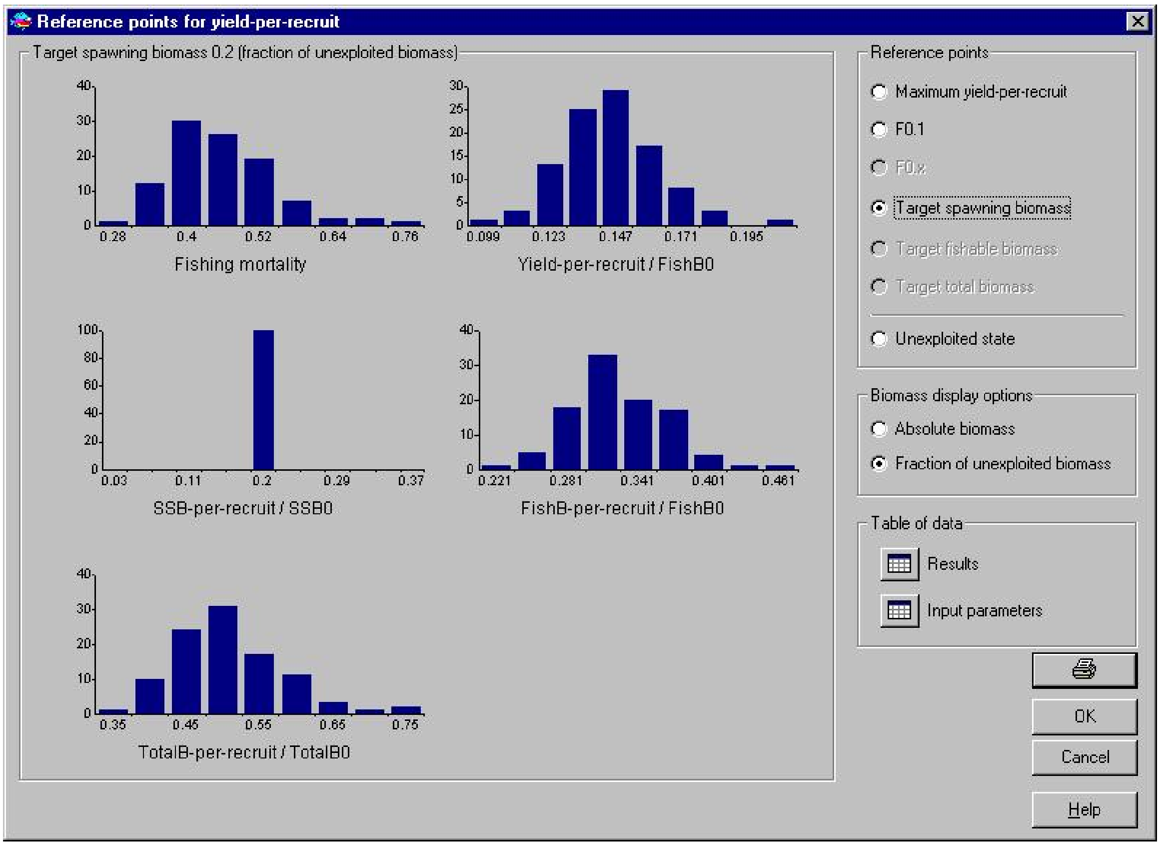


As explained in the What are $F_{0.x}$ reference points? Help item, the $F_{0.1}$ yield-per-recruit reference point has a rather odd definition, but it has proved rather useful in practice, especially in circumstances, such as the ones seen here, when the maximum-yield-per-recruit reference point is obviously not particularly useful.

The most frequently occurring value of $F_{0.1}$ lies in the range 0.37 – 0.39, and the maximum in the range 0.57 – 0.61. Compared with the mean *M* (0.392), these are obviously more sensible values of *F*. Also, in the majority of cases, the SSB-per-recruit corresponding to $F_{0.1}$ exceeds 20% of its unexploited level, a proportion often treated as one below which one would prefer not to fall.

We will need the median and confidence limits for the estimated $F_{0.1}$ later. Clicking on the Results button will produce a table of the results of all 100 simulations. Select and copy the Fishing mortality column, paste it into a spreadsheet, and then sort the column in ascending order. It is then simple to estimate the median and lower and upper 2.5%iles of $F_{0.1}$. For the example illustrated above, the median was 0.40, with a 95% confidence interval of 0.31 – 0.54.

This comparison can be revisited by examining the third reference point calculated, which determines values of F the produce an equilibrium SSB-per-recruit that is 20% of its unexploited level. Typical results are illustrated below.



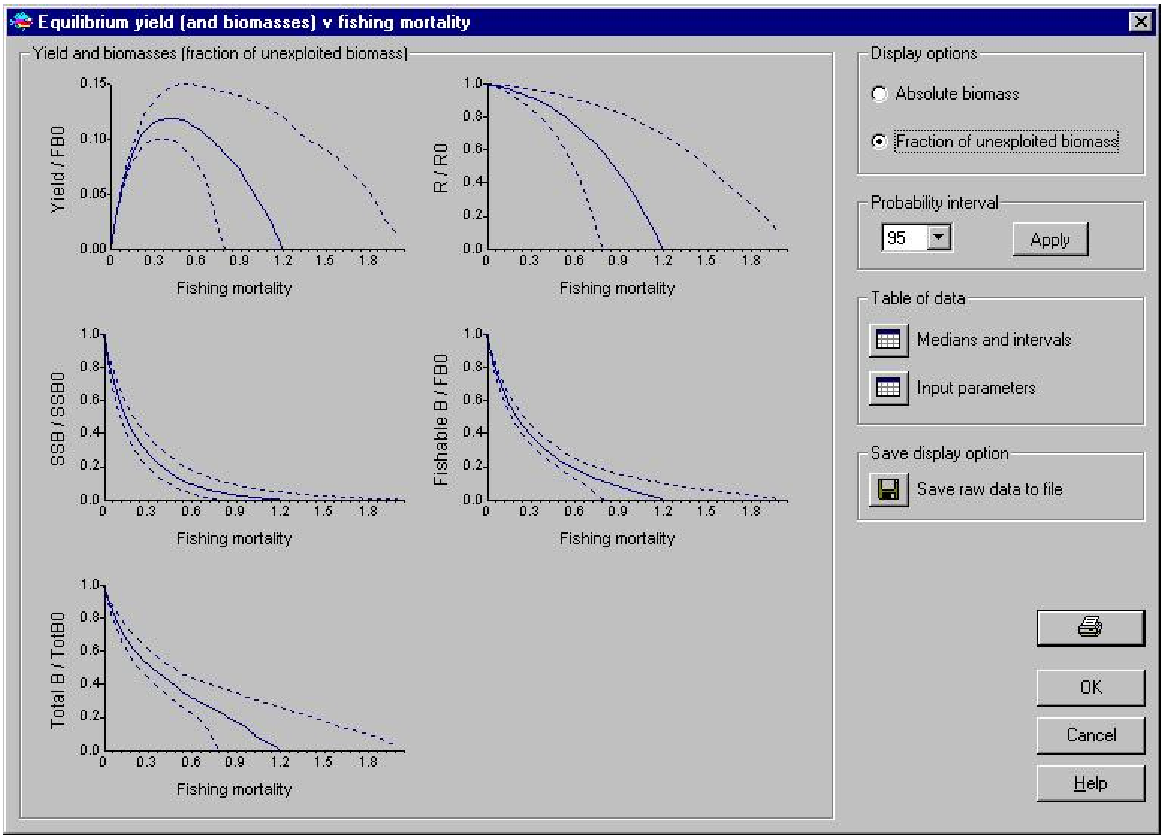
The most obvious result in this form is in the histogram for SSB-per-recruit/SSB0. As it should, it shows that in every case, this ratio was 20%. Looking at the histogram of values of *F* that produce this, we see that most frequently, these fell in the range 0.37 – 0.43, and all fell between 0.25 and 0.79. As one would have expected, these reference point *F* values are slightly higher than those for $F_{0.1}$.

Using the table of results, the median SSB-per-recruit reference point *F* was 0.45 with 95% confidence interval 0.31 – 0.70.

Equilibrium yield analyses

We turn now to equilibrium yield analyses. These are described in detail in the Equilibrium yield and related sections of the help files. Equilibrium yield analyses allow the user not to have to assume that recruitment remains constant regardless of how low the SSB falls, but this gain is achieved only at the expense of having to specify the stock-recruitment relationship, which we have seen can be difficult at best. In this section, we attempt to illustrate the analyses that can be carried out, and how to get around these difficulties (at least partially).

Select **Equilibrium yield** from the **Equilibrium** menu and accept the range of *F* values shown. After a while, the following form appears, after the **Fraction of unexploited biomass** display option has been selected.

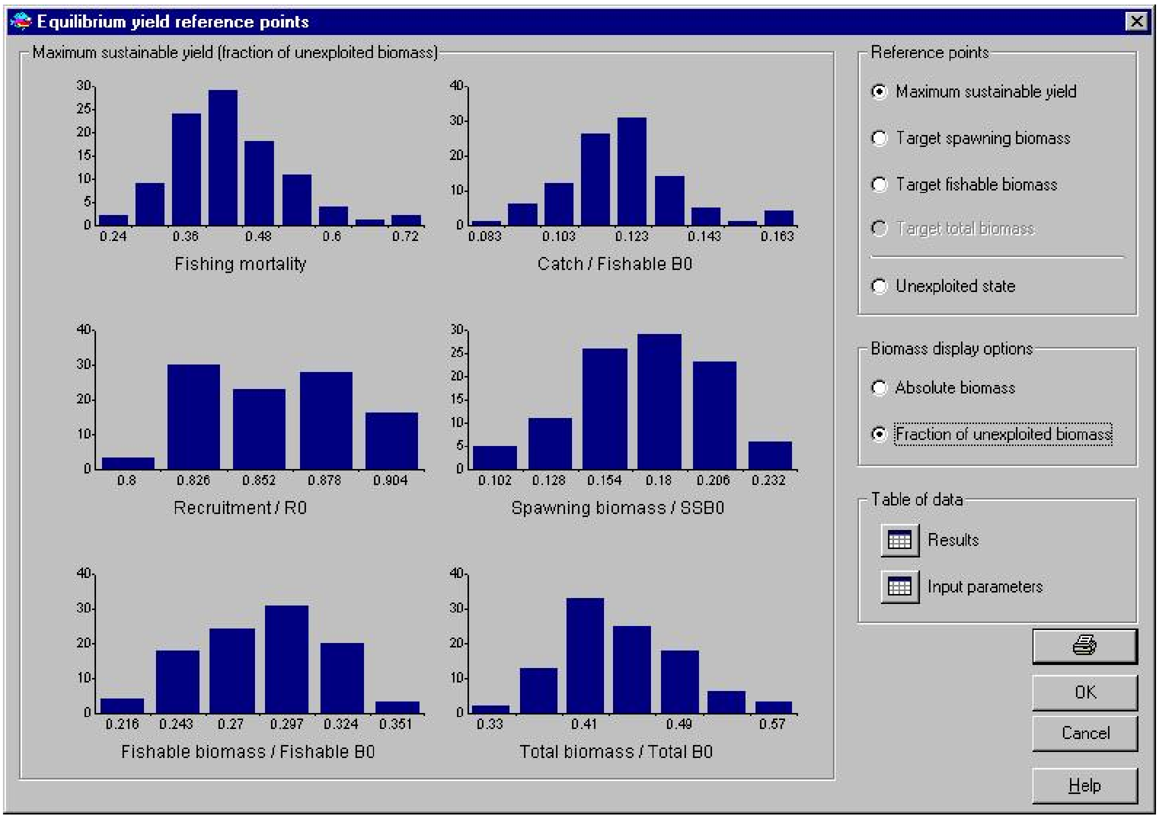


Comparing these plots with the corresponding ones for yield-per-recruit demonstrates starkly what a difference it can make when recruitment is assumed to decline with declining SSB. The plot of relative yield against *F* suggests that in 97.5% of the simulations, the stock was nearly extinguished when *F* reached a level of 2. For the median, the maximum yield occurred at an *F* around 0.4, and for the lower 2.5%ile, *F* had to lie in the range 0 – 0.8 to produce any sustainable yield at all. The other plots show a similar story. In particular, to achieve a median SSB/SSB0 ratio of 20%, the corresponding *F* value seems to be around 0.4.

One other interesting point to note is the shape of the plot of yield against *F*. The standard Schaeffer biomass dynamic model suggests that the yield curve is symmetric. This curve is clearly asymmetric, with a peak shifted towards lower values of *F*.

If you had been able to use a direct estimate of the unexploited number of recruits or SSB when entering the parameters of the stock-recruitment relationship, then the other display option (**Absolute biomass**) becomes much more relevant. While this is not the case here, on selecting that display mode (try it and see), you should find that the median maximum yield (MSY) is around 1400 tonnes, but the MSY could lie between approximately 750 and 2750 tonnes. This is a fairly high level of uncertainty if you were wishing to set annual quota based on the estimated MSY! Remember that, because you will be using different random numbers, the actual values you get will differ from those quoted here.

Let us turn now to the equilibrium yield reference points (see Equilibrium yield reference points and related help files for more details). Select **Equilibrium yield reference points** from the **Equilibrium** menu and accept the options checked, noting that an additional reference point has been asked for: that producing a fishable biomass at 50% of its unexploited level. This has been added to the example at this stage because the much-used Schaeffer biomass dynamic model suggests that the MSY can be taken when the fishable stock has been reduced to 50% of its unexploited level.



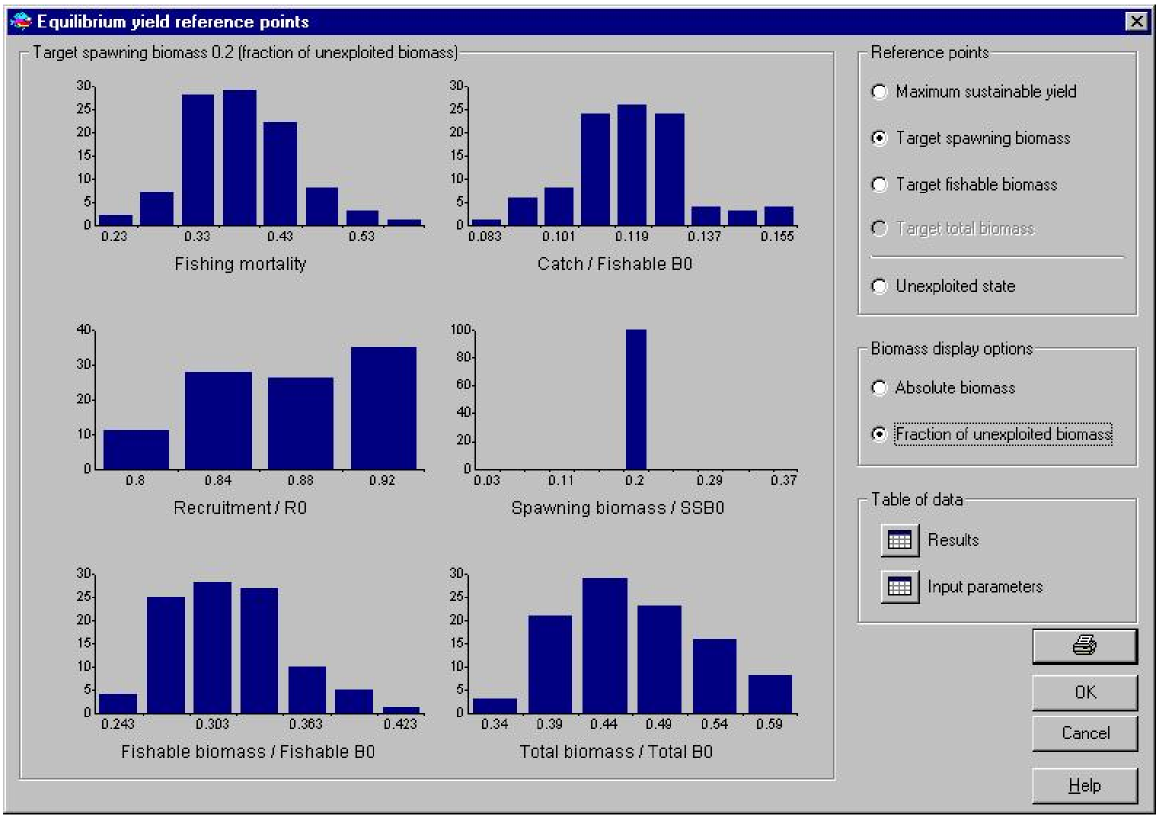
The most frequently occurring values of F_{MSY} lie in the range 0.39 – 0.45, with a range extending from 0.21 to 0.75. Using the table of results, we find that the median value of F_{MSY} is 0.41 with 95% confidence limits of 0.27 to 0.70. Looking at the histogram of values of SSB/SSB0, we see that in the clear majority of cases, these are less than 20% when the stock is being fished at F_{MSY}.

This latter observation, of course, can be interpreted in two ways. On the one hand, given the concern often expressed about reduction of the SSB to levels below 20% of its unexploited level, it might be suggested that even fishing at a mortality rate that produces the MSY may be rather less safe than might have been imagined. On the other hand, it could equally be argued that, for this species and fishery, associating dangers of stock collapse with a 20% SSB/SSB0 level is being rather too conservative. Reaching a considered view on this must be delayed until we have seen the results of calculating the transient SSB reference point, when recruitment variability is also taken into account. However, for the moment it is worth recalling that we have assumed that the steepness parameter of the Beverton and Holt stock-recruitment relationship lies between 0.8 and 0.95. By definition, this means that when the SSB has been reduced to 20% of its unexploited level, the recruitment lies between 80% and 95% of its equilibrium unexploited level.

The last point to note from these histograms is that, most frequently, the maximum yield occurs when the fishable biomass is around 30% of its unexploited: quite a long way below the 50% suggested by the Schaeffer model.

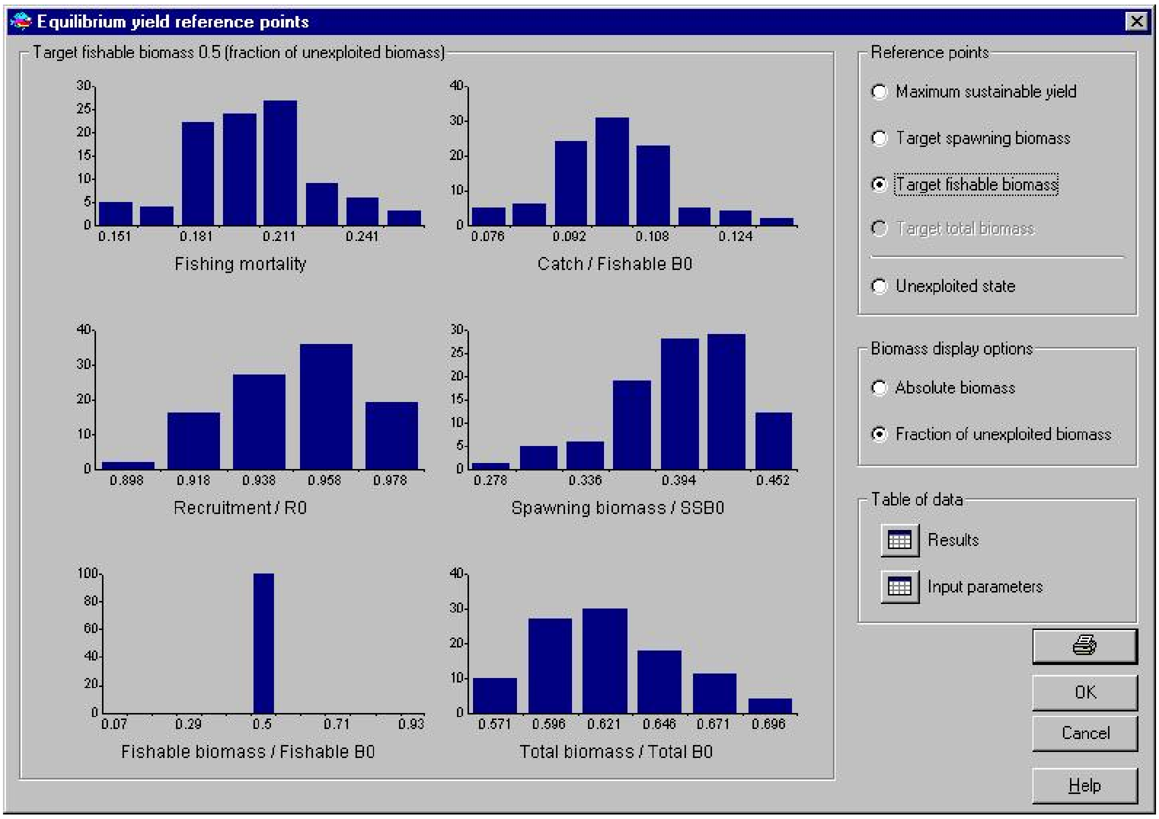
Reverting to an absolute biomass display option confirms our earlier views as to the likely MSY levels. The catch histogram indicates that the most frequently occurring MSYs lie in the range 1500 – 1700 tonnes, but the MSY could be as low as 400 tonnes and as high as 2800 tonnes. Remember, however, that these absolute biomass plots must be taken with a large grain of salt, because we were forced to use a somewhat arbitrary value for the unexploited number of recruits. We will return to this point a little later.

Now look at the target spawning biomass reference point. Histograms displayed as fractions of unexploited biomass are illustrated below. Recall that the target is 20% SSB/SSB0.



Recall that earlier we noted that when fishing at F_{MSY}, in the majority of cases the SSB/SSB0 ratio was less than 20%. That implies, of course, that if we shift our target to a 20% SB/SSB0 ratio, the reference point *F*s to achieve that should be less than those to achieve MSY. The above histograms clearly support this. Now, the mode occurs between 0.355 and 0.405, and using the table of results, the median was estimated to be 0.37, with 95% confidence interval 0.25 – 0.54.

Finally, look at the 50% target fishable biomass reference point. Again, we would expect this to be achieved at a considerable lower value of F, given the median fishable biomass ratio producing MSY was estimated earlier to be 30%. The histograms below clearly support that contention. Now, the mode occurs at an *F* around 0.211. Using the table of results, the median was estimated to be 0.20, with 95% confidence interval 0.15 – 0.26.



All these results seem consistent (they should be as long as the calculations have been performed correctly!). But recall that one of the stock-recruitment parameters was somewhat arbitrarily selected (the unexploited number of recruits, R0 = 25 million). We asserted earlier that this may not be as big an obstacle to getting reliable results as may be expected.

To see this whether or not this is so, let us go back and alter the value for the unexploited number of recruits by a factor of 10 either way. Via the **Parameters | Stock-recruit relationship** menu item, alter R0 from 25 million first to 2.5 million and the recalculate the MSY reference point. When we did this, we found that the median F that produces MSY was 0.43, with 95% confidence interval 0.31- 0.64. Naturally, the median MSY was much smaller (around 152 tonnes, not coincidentally, about 10 times smaller than when R0 was 25 million).

Now repeat the process, but now change R0 to 250 million, 10 times larger than it was. We found that the median F that produces MSY was 0.42 (95% confidence interval 0.28 – 0.68), but the MSY is now (again not coincidentally) about 10 times larger.

Recalling that the median value of F_{MSY} when R0 was 25 million was 0.41, it appears that our assertion was correct. At least in terms of estimating fishing mortality reference points, it does not appear necessary that R0 is estimated with precision. However, in terms of estimating the MSY itself, of course, it is clear that considerable precision is needed.

Transient analyses

Finally we turn to the last set of analyses. These allow us to get away from the restrictive assumption that the population is at equilibrium and to take account of interannual variability in recruitment.

First we calculate the transient yield reference point (see Calculate the transient SSB reference point and What is the transient SSB reference point?).

Note that this calculation will take considerable time when a monthly time step is used. If you have a relatively slow computer, and have got rather bored waiting for the results to appear on earlier calculations, we suggest you first change the time step interval (using the **Parameters | Seasons** menu item) to Yearly.

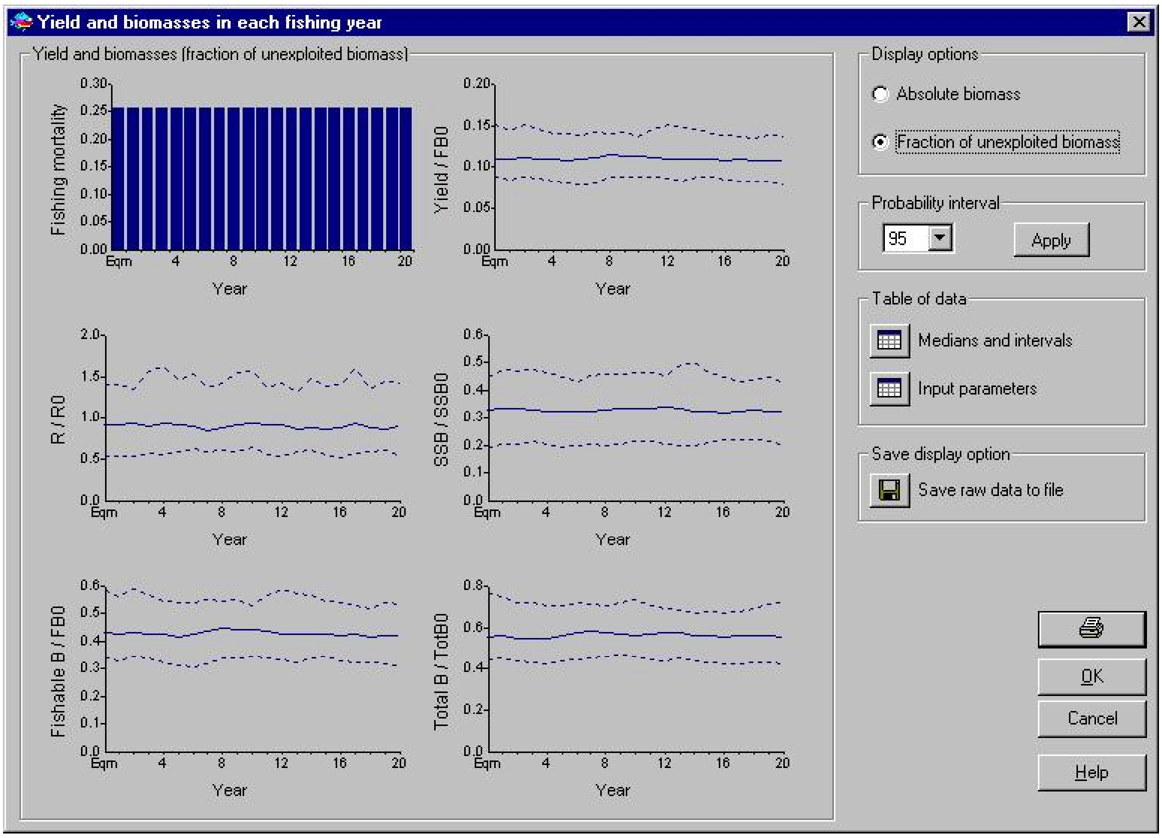
Accept the targets that appear on the reference point form, including the target of 20% SSB/SSB0. After some time, you should find that the fishing mortality rate that ensures that only 10% of the time does the SSB fall below 20% of SSB0 over the 20 years is around 0.26, which is the value we obtained.

This value is rather less than the median F_{MSY} (0.41), but then we would expect that because that F on average reduces the SSB to less than 20% of its unexploited level even when there is no recruitment variability. A fairer comparison would be with the median F that reduced the equilibrium SSB to 20% of its unexploited level. That median F was 0.37, with a lower 2.5%ile of 0.25. The transient SSB reference point F is again well below the median; indeed it is close to the lower 2.5%ile.

What this implies is that, with even relatively modest amounts of recruitment variability (and a CV of 0.25 does merit being described as modest), the risks of the SSB falling below specified low levels can be rather greater than might have been imagined.

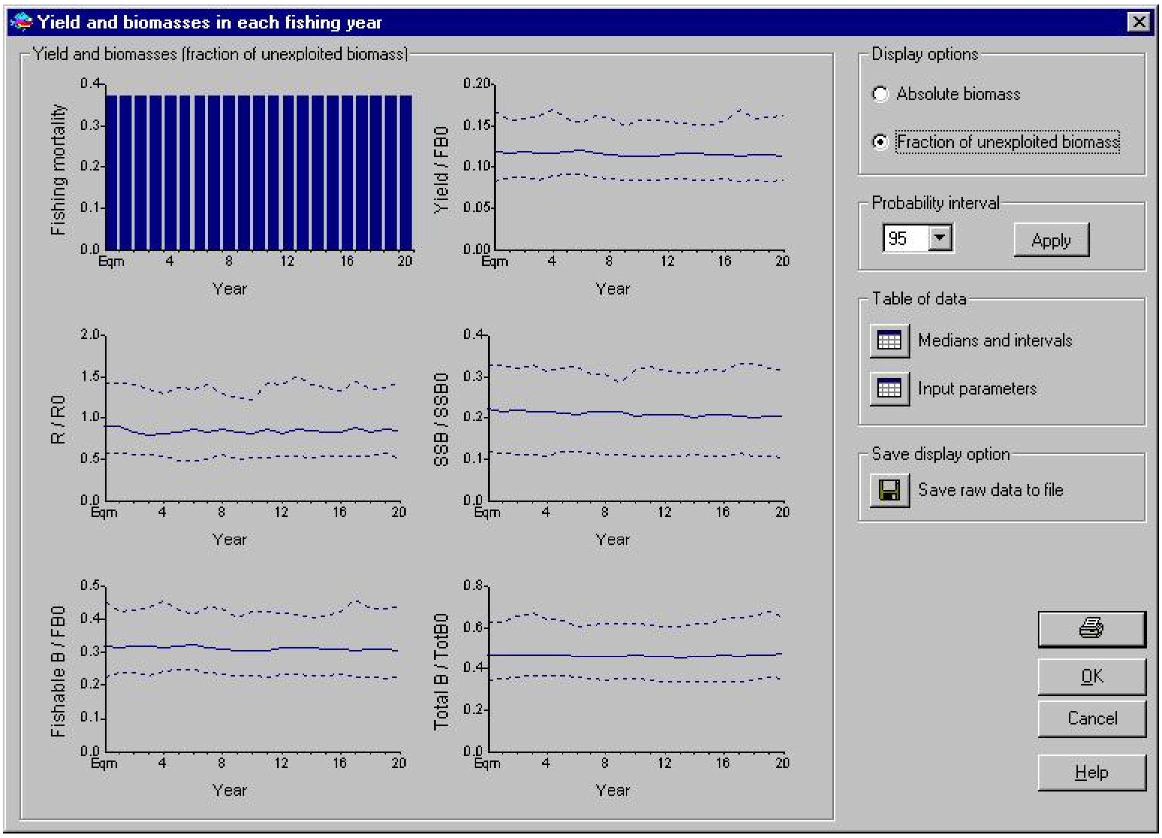
The effects of recruitment variability on future projections can also be examined using the **Projections…** item of the **Transient** menu (see Transient projections). Select this item and try projecting forward for 20 years with an F of 0.26, and also starting with an equilibrium F of 0.26 (or whatever value you found for the transient SSB reference point).

You should find your results resemble those shown below, when the fraction of unexploited biomass display option is selected.



As expected, this shows that 95% of the time, the SSB/SSB0 rations lay between 0.2 and around 0.45. Note that the median SSB/SSB0 ratio is around 0.32. Again, this gives an idea of the effects of recruitment variability.

Given this, it is of interest to examine projections using the median F_{MSY} reference point (0.41) and the median equilibrium SSB reference point (0.37). Using the smaller value first, the results are shown below.



Now the median SSB/SSB0 ratio hovers just above 0.2, but the lower 2.5%iles lie around 0.1. If you repeat this exercise with the median F_{MSY}, you should find that the median SSB/SSB0 ratio now lies below 0.2, and the lower 2.5%ile is consistently around 0.09.

While there may well be arguments that a 20% SSB/SSB0 level is not particularly dangerous for this species, a level less than 10% certainly is more dangerous: if the steepness parameter really is as low as 0.8, when the SSB is 9% of SSB0, the recruitment predicted from the stock-recruitment relationship is only 62% of its unexploited level.

Summary

All that is left now is to collate the results and see what conclusions we can draw.

All the various reference point fishing mortality rates we have calculated are listed in the table below, excepting the maximum yield-per-recruit reference point F.

Reference Point	2.5 %ile	Median	97.5 %ile
$F_{0.1}$	0.31	0.40	0.54
Equilibrium 20% SSB-per-recruit	0.31	0.45	0.70
F_{MSY}	0.27	0.41	0.70
Equilibrium 20% SSB	0.25	0.37	0.54
Equilibrium 50% fishable biomass	0.15	0.20	0.26
Transient 20% SSB		0.26	

Looking first at the medians, we see that with the exception of the fishable biomass reference point (which arguably can be discounted since the target level of 50% is probably rather too high), all the median equilibrium reference point Fs are similar and approximately equal to the mean value of *M* (0.39). This quite often is the case. The transient SSB reference point F is, however, rather lower; indeed it is lower than the lower 2.5%iles of the main equilibrium reference point Fs. On the basis of these results, it would not be unreasonable to conclude that a suitable precautionary target level for the fishing mortality rate might be in the range 0.25 – 0.35.

Parameter uncertainty has obviously played an important role in this analysis, given the rather wide confidence limits for the reference point Fs. It also played a part in the calculation of the transient SSB reference point. To see this, we deliberately removed all uncertainties in the biological and fishery parameters (but retained the recruitment variability). With no parameter uncertainty, the transient SSB reference point F was recalculated to be 0.31. As time passes, one would expect that the extent of parameter uncertainty will be reduced, and thus uncertainty in the equilibrium reference point Fs will reduce. However, the passage of time will not affect recruitment variability. This analysis therefore suggests that even apparently conservative equilibrium reference points may be rather less conservative than they appear, when interannual recruitment variability is taken into account.

What does the analysis imply for the Chagos Archipelago fishery for *L. mahsena*? At present, it is believed that this fishery is relatively lightly exploited, with an F of the order of 0.2. The analysis therefore suggests that an increase in F of up to 50% may lead to increased sustainable catches. However, the primary concern of the current management regime for the Chagos Archipelago is to ensure stock conservation, rather than to maximise sustainable resource exploitation. On those grounds, the regime appears to be performing well.