The Development of an Operational Management Procedure for the South African west coast rock lobster fishery

by

Susan Joy Johnston

Supervised by Professors D.S. Butterworth and T.J. Stewart

Thesis presented for the degree of

Doctor of Philosophy

in the Department of Zoology

University of Cape Town

July 1998

The University of Cape Town has been given the right to reproduce this thesis in whole or in part. Copyright is held by the author.

The copyright of this thesis vests in the author. No quotation from it or information derived from it is to be published without full acknowledgement of the source. The thesis is to be used for private study or non-commercial research purposes only.

Published by the University of Cape Town (UCT) in terms of the non-exclusive license granted to UCT by the author.

University of Cape Town

For Patrick, Sasha and Kayla.

Declaration

I, S.J. Johnston, hereby declare that this thesis is essentially my own work and that no part of it has been submitted for a degree at any other university.

Signed by candidate
Signature removed

Susan Joy Johnston

July 1998

Abstract

This thesis considers the development of an operational management procedure (OMP) to provide scientific recommendations for commercial TAC for the South African west coast rock lobster (*Jasus lalandii*) fishery. This fishery has been under considerable stress in recent years as a result of overfishing and low somatic growth rates. Present catch levels, less than 2000 MT, are substantially smaller than levels recorded in the past. The present biomass (above 75mm carapace length) is estimated to be only six percent of the pristine level. At the start of this research, no long-term management strategy for the resource existed. Neither was there any robust, tested, scientific method available for setting the annual TAC for the fishery, which resulted in a time-consuming and unsatisfactory scientific debate each year in developing a series of *ad hoc* TAC recommendations.

The work presented in this thesis is thus aimed at answering two important questions.

i) Can an adequate mathematical model be developed as a basis to simulate the resource and its associated fishery ?

ii) Can a self-correcting robust OMP be developed for the resource ?

The first phase of this thesis is the development of a size-structured population model of the resource and the associated fishery. A size-structured model is necessary as lobsters are difficult to age and hence most of the data collected are on a size basis. Furthermore, important management issues, such as the legal minimum size which has changed over time, require a model able to take size-structure into account. This model is fitted to a wide range of data from the fishery, including CPUE (catch-per-unit-effort) and catch-at-size information, by maximising a likelihood function. The model is shown to fit reasonably well to all data, and to provide biologically plausible estimates for its six estimable parameters.

The development of the model required a number of important assumptions regarding the population (for example, the value of natural mortality) and the fishery (for example gear selectivity) to be made. The robustness of the model fit and subsequent biomass estimates to these assumptions is thoroughly examined by means of a number of sensitivity tests. Results indicate that key estimates provided by the model are robust to most of these underlying assumptions.

The size-structured model provides a framework to assess the performance of a number of candidate OMPs. The South African Sea Fisheries Advisory Committee endorsed a resource rebuilding strategy for the resource. A number (12) of candidate OMPs were subsequently developed which differed with respect to:

i) the level of target biomass recovery over 10 years; and

ii) the level of immediate TAC increase.

The candidate OMPs had an implicit feedback structure and hence were able to self-correct to a certain extent. They use a number of different types of data collected from the resource as inputs to an algorithm to set a TAC each year. The basic rationale is that if the input data indicate an increase in biomass, the TAC is increased, and *vice versa.*

A number of summary performance statistics are identified, which are used to compare the performance of these different OMPs. These statistics include average catch, average inter-annual catch variability, and the level of biomass recovery, and provide a basis to consider the different trade-offs between such factors for alternative candidate OMPs.

The robustness of the performance of the candidate OMPs is tested in deterministic trials (which ignore the noise associated with future observations of resource status) for a wide range of different factors (31 in total) - both uncertainties regarding the assumptions made in the size-structured assessment model, and uncertainties regarding the future. Their performances are shown to be adequately robust for the range of tests considered. A particular problem at present is an inability to confidently predict future trends in somatic growth, so that the high degree of robustness shown by these OMPs to different possible

growth scenarios is particularly reassuring. The OMPs show comparatively less robustness with respect to uncertainties concerning estimates of recent levels of recruitment and biomass.

Some robustness trials (those for which performance statistics showed the greatest difference from those for the baseline population model) are run incorporating stochastic effects (i.e. noise in indices of resource status such as CPUE), to determine the likely variability associated with the various OMP performance-related statistics.

The OMP precludes TAC reductions from one year to the next in excess of 15%. However, "exceptional circumstances" are defined for which the TAC recommended by the OMP can be over-ridden, in order to prevent serious unintended depletion of the resource. A set of rules of how to adjust the TAC in such an event are developed, which will be implemented when a "flag" is shown by the CPUE data. The selected exceptional circumstance rule is not expected to be implemented unless the resource status is much worse than indicated by the baseline population model.

The Sea Fisheries Advisory Committee selected the 20% biomass recovery - TAC'97 = 20% increase OMP from the various candidates presented, to be implemented for a three year period commencing in 1997. This OMP is essentially the least conservative of the 12 candidates advanced, providing the largest immediate TAC gain and the least level of recovery amongst the options considered. The TAC for 1997 was set to 1920 MT using this selected OMP.

The thesis concludes by suggesting topics needing further research attention for the review and possible amendment of this OMP three years hence.

Acknowledgements

I am indebted to Professor D.S. Butterworth for all his patient guidance and support. Professor T.J. Stewart is also thanked for his help and input in the initial stages of the thesis. Much thanks go to those who helped proof-read parts of this thesis: Jose De Oliveira, Jean Brown, Dave Pollock, Andy Cockcroft, Pedro Goosen and Dave Schoeman.

I am grateful to the Foundation for Research and Development (FRD) for partial funding for this study, as well as to a contract with Sea Fisheries for funding support. Thank you Mom and Dad for your never ending love, support and belief in my pursuit of this thesis. Finally, a big thank you to my husband Patrick who has always provided unending encouragement and support, and to my little girl Sasha who has had to learn to share my time with a computer!

Table of Contents

Declaration iii

Abstract iv

Acknowledgements vii

Table of Contents viii

Chapter 1: Introduction 1

Conventions 8

Chapter 2: Biological background 10

2.1 General 10

2.2 Habitat 11

2.3 Reproduction 12

2.4 Somatic Growth 15

2.5 Feeding 18

2.6 Predators 20

Chapter 3: The fishery 22

3.1 History of the fishery 22

3.2 Fishing gear 25

3.3 Management control measures 28

3.4 TAC setting procedure 32

3.4.1 Management strategies 32

3.4.2 Decision making procedure 33

3.5 Problems faced by the lobster fishing industry 34

3.6 Poaching and recreational catches 39

Chapter 4: Information from other lobster fisheries around the world 42

4.1 Major lobster fisheries 42

4.2 Discarded lobsters - effects on survivorship and growth 53

4.3 Stock-recruit relationships in lobster species 55

4.4 Somatic growth rates of lobsters 60

Chapter 5: Data available for conducting the assessment 66

5.1 Somatic growth data 67

5.2 CPUE (catch-per-unit-effort) data 69

5.2.1 Commercial trap CPUE data 70

5.2.2 Commercial hoopnet CPUE data 70

5.2.3 FIMS CPUE data 71

5.2.4 "New" commercial CPUE and FIMS CPUE data analyses 72

5.3 Catch-at-size data 72

5.3.1 Commercial trap catch-at-size data 72

5.3.2 FIMS catch-at-size data 73

5.4 Percent females in catch ($F^{\%}$) 73

5.4.1 Commercial trap sample data 73

5.4.2 FIMS $F^{\%}$ data 74

5.5 Historic catch record 74

5.6 Minimum legal carapace size limits 74

Chapter 6: Population dynamics models and assessments 76

6.1 Introduction 76

6.2 Data available 77

6.3 Surplus production models 77

6.4 Size-structured modelling approaches 83

Chapter 7: The "1870 size-structured" model **93**

7.1 Data available 93

7.2 Model structure 94

7.2.1 Recruitment 97

7.2.2 Natural survivorship 98

7.2.3 Gear selectivity 99

7.2.4 Discard mortality 100

7.2.5 Somatic growth rates 101

7.3 Parameter estimation procedure 102

Chapter 8: Size-structured model parameter estimation procedure - results **105**

8.1 Base case model 105

8.1.1 Parameter estimates 105

8.1.2 Fits to data 106

8.1.2.1 CPUE data 106

8.1.2.2 Catch-at-size data 108

8.1.2.3 Data on the percentage of females in the catch ($F^{\%}$) 109

8.1.3 Biomass trends 110

8.2 Sensitivity tests 111

8.3 Bootstrap estimates of variance 114

Chapter 9: Development of an Operational Management Procedure (OMP) **143**

9.1 Management procedures 143

9.2 Philosophy behind the development of an OMP for the west coast rock lobster 146

9.3 The components of an OMP 149

9.4 Data available for use in an OMP for west coast rock lobster 150

9.5 Candidate OMPs 150

9.6 The rationale underlying the form of the final set of candidate OMPs 153

9.7 Parameter values chosen for candidate OMPs 160

9.8 Projection of population in assessing the OMPs 160
9.9 Summary performance statistics 162
9.10 Robustness tests 162
9.11 Stochastic analyses 169
9.12 New data to be used in conjunction with the candidate OMPs 171

Chapter 10: Results of tests of OMP candidates and the final selection 175
10.1 Introduction 175
10.2 Base case deterministic results 176
10.2.1 Average annual catches (C_{ave}) 176
10.2.2 TAC variability (V) 177
10.2.3 TAC trajectories 177
10.2.4 Biomass trajectories 178
10.2.5 Effort trajectories 178
10.3 Deterministic robustness tests results 179
10.3.1 Robustness tests results for the 20% biomass recovery, - TAC'97 = 20% increase OMP 181
10.3.2 Robustness tests results for other candidate OMPs 185
10.3.3 Comparisons to a constant catch strategy 186
10.4 Stochastic analyses 187
10.4.1 Base case: stochastic results 188
10.4.2 Robustness tests: stochastic results 189
10.5 The OMP selected 190
10.5.1 TAC for the 1997 season 191

Chapter 11: Exceptional circumstances 230
11.1 Introduction 230
11.2 The Exceptional Circumstance (EC) rule 231
11.3 Results 235
11.4 Discussion 236

Chapter 12: Discussion and conclusions **247**

12.1 General discussion about the OMP developed 247

12.1.1 Strengths of the candidate OMPs 249

12.1.2 Weaknesses of the candidate OMPs 250

12.2 The selection between the candidate OMPs 250

12.3 Future research 252

12.3.1 Reassessment of the underlying operating model 252

12.3.2 Index of recruitment 254

12.3.3 Multi-criteria decision making (MCDM) techniques 255

12.3.4 Improved estimates of abundance 257

12.3.5 Future improved OMPs 258

12.3.6 Growth data 258

12.4 Final conclusions 258

Appendices

Appendix 1: Model specifications and assumptions **260**

A1.1 Length-weight conversions 261

A1.2 Equilibrium conditions 262

A1.3 Natural survivorship matrix *S* 262

A1.4 Gear selectivity 264

A1.5 Fishing survivorship matrix *H* 267

A1.6 The 1991 fishing season 268

A1.7 Somatic growth matrix *A* 270

A1.8 Recruitment *R* 274

A1.9 Commercial catch 275

A1.10 Poaching and recreational catches 276

A1.11 Biomass 277

A1.12 MSY calculations 278

Appendix 2: Model fitting procedure **282**

A2.1 Data 282

A2.2 The likelihood function 284

A2.3 Estimable parameters 290

Appendix 3: Somatic growth function **293**

A3.1 Introduction 293

A3.2 GLM'95 294

A3.2.1 Mature males 294

A3.2.2 Mature females 296

A3.3 GLM'96 297

A3.4 Juveniles 298

A3.4.1 Inter-moult period 298

A3.4.2 Moult growth increment 299

A3.4.3 Juvenile-adult interpolation 301

A3.5 Moult increment variance estimates 301

A3.5.1 Mature males 302

A3.5.2 Mature females 302

A3.5.3 Juveniles 303

A3.5.4 Interpolation between juveniles and adults 304

A3.6 Growth data for pre-data and post-data periods 305

A3.6.1 Pre-data period 305

A3.6.2 Post-data period 305

A3.6.3 ARMA growth scenario 306

Appendix 4: Data used in the size structured model **310**
A4.1 Somatic growth data 310
A4.1.1 Mature males 310
A4.1.2 Mature females 311
A4.1.3 Historic growth data series and future growth scenarios 311
A4.2 CPUE data 312
A4.2.1 Commercial trap CPUE data 312
A4.2.2 Commercial hoopnet CPUE 312
A4.2.3 FIMS CPUE 313
A4.2.4 New commercial CPUE and FIMS data analyses 314
A4.3 Catch-at-size data 315
A4.3.1 Commercial trap catch-at-size data 315
A4.3.1 FIMS catch-at-size data 316
A4.4 Percent females in catch ($F^{\%}$) 316
A4.4.1 Commercial trap sample data 316
A4.4.2 FIMS $F^{\%}$ data 316
A4.5 Historic catch record 317
A4.6 Minimum legal size limits 317

Appendix 5: Calculation of hoopnet selectivity scaling functions **331**

Appendix 6: Bootstrap method for variance estimation **336**
A6.1. CPUE 336
A6.2 Catch-at-size 337
A6.3 Percentage females in the catch ($F^{\%}$) data 337

Appendix 7: The candidate operational management procedures **339**
A7.1 The OMP computations 339
A7.2 Summary performance statistics 344

Glossary 346

References 354

Chapter 1: Introduction

The fishery for the South African west coast rock lobster (*Jasus lalandii*) is very important for a number of reasons. In financial terms, the fishery is one of the largest in South Africa, and supplies a major export market. The market value of the fishery in 1995 was around 145 million Rand. It is a labour intensive fishery, providing employment for over four thousand local fishers along the west coast of South Africa (P. Foley, pers. commn). A large recreational fishery for the west coast rock lobster exists - primarily among the more affluent sectors of the west coast population. More than 75 000 recreational permits were issued for the 1997 season. The recreational fishery supports many smaller industries involving, for example, fishing boats and gear. "Crayfish" , as the rock lobster is known locally, is a highly favoured item on most Cape Town restaurant menus, selling for a locally exorbitant price (over R100/kg).

The fishery began around 1870, and annual catches increased gradually until by the late 1940's and 1950's the resource was yielding between 10 000 and 20 000 metric tons (MT) annually (Figure 1.1). Smaller catches followed in more recent times as the resource was fished down, and during the 1980's, by which time the catches were TAC (total allowable catch)-limited, the fishery yielded 3800 MT per annum on average. Due to substantial reductions in the somatic growth rate of the lobsters in 1989 however, the fishery was placed under severe strain, with ever decreasing TACs being set subsequently. By 1995 the TAC set for the commercial fishery was only 1500 MT,

although this has since been gradually increased to 1920 MT for the 1997 season[1] as somatic growth rates have shown some improvement. The minimum legal carapace size limit of 89mm that had been enforced since 1929 was reduced briefly to 75mm in the second part of 1991, to 80mm in 1992, and then to 75mm since 1993, in an attempt to improve the CPUE (catch-per-unit-effort) and to allow for larger catches. By 1992 there were very few lobsters in the 89+mm size range, necessitating high effort levels to catch the TAC. This resulted in large quantities of undersized lobster caught having to be returned to the sea, leading to suspected discard mortality losses.

In the mid 1990's, the future of this once lucrative fishery was under question. The management of the resource and the size of the annual TAC became a hotly debated issue amongst scientists, industry members and the public. The need for a well-defined, thoroughly tested basis for setting the TAC over time without exposing the resource to undue risk, i.e. an operational management procedure (OMP), for west coast rock lobster had thus arisen.

A widespread failure to manage marine fisheries effectively is reflected in the condition of many marine stocks around the world, and is cause for great concern (Rosenburg *et al.* 1993; FAO 1995; Garcia and Newton 1997). The operating environments for

[1] The season is typically November through to June.

fisheries management are often characterised by the following (Cochrane *et al.* 1998):

i) decisions being made in the face of great uncertainty about the status, dynamics and future trends of the resources, and similar uncertainty about the social and economic status, dynamics and future behaviour of the fishery;

ii) decisions being made in the absence of any long-term strategy with at best poorly defined objectives which are usually conflicting;

iii) decisions being made by individuals or groups which are unrepresentative of the full range of interest groups; and

iv) difficulties in implementing or enforcing the management regulations agreed upon and in monitoring the fishery.

The concept of OMPs as a basis for managing living marine resources has become better known by fisheries managers through the development by the Scientific Committee of the International Whaling Committee (IWC) of the Revised Management Procedure (RMP) for the management of commercial whaling (Kirkwood 1992; 1997; IWC 1994). Over the last decade, an increasing number of marine resources have been managed by means of OMPs. The scientific TAC recommendations for the major marine fisheries in South Africa, those for hake (*Merluccius* spp.), pilchard (*Sardinops sagax*), and anchovy (*Engraulis capensis*), have been based upon OMPs for a number of years (Butterworth and Bergh 1993; Payne and Punt 1995; Butterworth *et al.* 1997; Cochrane *et al.* 1997). The pilchard and anchovy are the two most important species in the South African pelagic fishery and since 1991 have been managed on the basis of an OMP. An OMP has

also been used for the management of the South African hake fishery since the early 1990's.

An OMP is essentially a combination of the specifications of both how and when to collect particular data, the processing and analysis of these data and finally how to compute management recommendations such as an annual TAC using these data. When selecting an OMP, the ability to satisfy a conflicting range of objectives needs to be evaluated, as there is always conflict between, say, maximising the catch and minimising the risk. This evaluation usually requires the interaction between scientists, decision makers and the industry (Cochrane *et al.* 1998).

Púnt (1991) outlines the potentially desirable properties of OMPs. Of particular importance is that the OMP should be self-correcting, so that it automatically adjusts TACs (say) up or down as future information shows previous perceptions of the resource to have been too pessimistic or too optimistic respectively.

How is it possible to determine whether a particular OMP best satisfies the required management objectives ? Clearly the performance of an OMP cannot be determined by applying it to the real resource for a number of reasons (Punt 1991).

i) The time period required. Management objectives usually pertain to fairly lengthy time periods; therefore, if an experiment were to be performed it would simply take too long before results were available.

ii) Even after applying a management procedure to the resource over a long period, it would probably be impossible to determine the status of the resource relative to the associated target level with great precision. It would therefore be difficult to assess whether this management objective had been achieved.

iii) The consequences of a "bad" management procedure being applied to a real resource may be highly undesirable.

Because of these problems, the evaluation of alternative candidate OMPs reported in this thesis is carried out using mathematical models that simulate the real resource.

The work presented in this thesis is aimed at answering a number of key questions.

i) Can an adequate mathematical model be developed as a basis to simulate the resource and the associated fishery ?

ii) Can a framework be developed in terms of which a number of different candidate management procedures can be tested ?

iii) Can a self-correcting robust management procedure be developed for the resource ?

First, a biological overview of *J.lalandii* is provided (Chapter 2) as well as a review of the history of the west coast rock lobster fishery (Chapter 3). A brief account of how some of the other important lobster fisheries around the world are managed and certain common problems is given in Chapter 4. A general description of different types of approaches to

modelling fisheries and their relevance to west coast rock lobster stock assessment and management is outlined in Chapter 5. The data available for use in the assessment and management of the resource are described in Chapter 6.

The first step in dealing with the key questions listed above was to develop a size-structured model to simulate the resource and its associated fishery. The details of this model are given in Chapter 7. A size-structured model is necessary as lobsters are difficult to age and hence most of the data collected are on a size basis. Management issues such as the change in the legal minimum size limit also require the population to be modelled on a size basis. A model running from the inception of the fishery (1870) is developed, and is shown to provide a reasonable fit to a number of different data sets, including CPUE and catch-at-size information. A number of important assumptions regarding the population (such as the level of natural mortality) and the fishery (such as gear selectivities) are made. The robustness of the model fit and subsequent biomass estimates to these assumptions is thoroughly examined by means of a number of sensitivity tests. These results are presented in Chapter 8.

The size-structured model provides a framework in terms of which to assess the performance of a number of candidate OMPs. A set of key summary statistics of procedure performance, which are meaningful to both scientists and managers, are identified and reported. An OMP is developed for the resource which has an implicit feedback structure and hence is able to self-correct to a certain extent (Chapter 9). The

OMP uses a number of different types of data collected from the resource as inputs to an algorithm to set a TAC each year. The basic rationale is that if the inputs show an increasing biomass trend, then the TAC is increased, whereas if the inputs reveal a downward trend in biomass, the TAC is reduced.

A key requirement for an OMP is robustness to a number of important uncertainties. A wide variety of factors reflecting uncertainty is identified. The performance of a candidate OMP is then tested for each of these factors, to determine its overall robustness. Robustness to both uncertainties regarding assumptions made in the size-structured assessment model and to uncertainties regarding the future (such as in somatic growth rate changes and the stock-recruit relationship) is tested. Some of the trials run incorporate stochastic effects to determine the likely variability associated with the various OMP performance–related statistics such as average catch. These results are presented in Chapter 10.

"Exceptional circumstances" are identified for which the OMP-generated TAC is modified in order to offset the consequences of a very "bad" event happening (Chapter 11). This is seen as an additional safeguard to prevent further unintended depletion of the resource. The OMP developed in this thesis was used to set the commercial TAC for west coast rock lobster for the 1997/98 season, and will be used for setting the TAC for the following two seasons, after which it will be reviewed and modifications may be made.

Conventions

Throughout this thesis, a number of conventions apply. These are as follows:

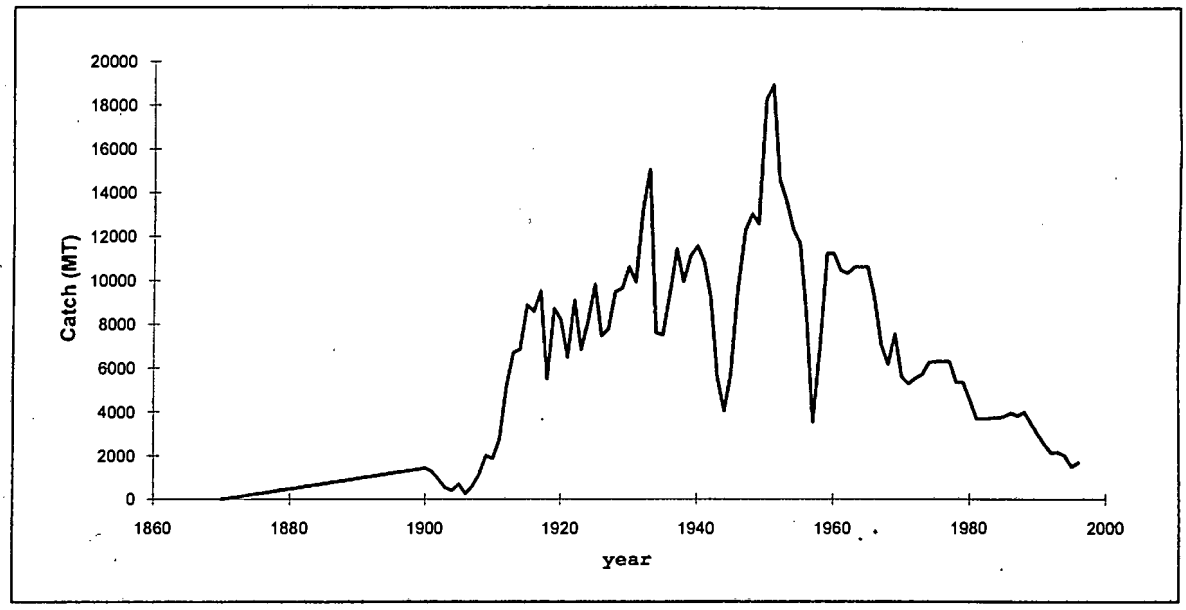
i) The season for the west coast rock lobster fishery typically begins in November and runs till about June the following year. To avoid continually stating both years pertaining to a single season, only the year in which the season begins is given. Thus the year 1997 refers to the season starting in November 1997 and ending June 1998.

ii) The term "operational management procedure" (OMP) as opposed to "management procedure" is used, as the term OMP has become common usage in South Africa. The qualification "operational" is intended to emphasise that the procedure provides a specific formula that yields some quantitative management level, i.e. that it is more than merely a conceptual approach.

iii) Size expressed in terms of length always refers to carapace length.

iv) "Area" means management area, whilst "area" means "surface area".

Figure 1.1: The historic commercial catch record for the west coast rock lobster.



Chapter 2: Biological background

2.1 General

The South African west coast rock lobster *Jasus lalandii* (H.Milne Edwards 1837) is one of over 20 lobster species occurring off the South African coast. Of these, only three occur in sufficient densities to be of commercial importance. These are:

i) *Jasus lalandii* - the west coast rock lobster;

ii) *Palinurus gilchristi* - the south coast rock lobster; and

iii) *Palinurus delagoae* - living off the eastern coast of South Africa.

The genus *Jasus* consists of 7 species, which occur exclusively in the southern hemisphere. These form the basis of lucrative fisheries in Australia, New Zealand, South Africa and on Tristan da Cunha (Pollock 1990).

The distribution of *Jasus lalandii* covers a wide geographical range of the coastline along the south and west coast of southern Africa, from about 23^{O} S near Walvis Bay in Namibia to about 28^{O} E near East London in the Eastern Cape of South Africa (Pollock 1987) - see Figure 2.1. The largest densities are found along the west coast from Luderitz in Namibia to Cape Hangklip near Cape Town. The cold waters off this stretch of coastline form part of the Benguela upwelling system, and are thus nutrient rich and highly productive, enabling this region to have produced one of the world's largest yield of any *Jasus* species (Pollock 1986).

Lobsters are rather different from vertebrate fish populations. They tend to be sedentary, difficult to age, long lived (*J.lalandii* can live up to 40 years (Pollock 1989)), K-selected and comparatively robust to handling. *J.lalandii* exhibits marked sexual dimorphism, with male and female lobsters growing to different sizes and at different rates. The sexes often occupy different parts of the habitat at certain times of the year.

2.2 Habitat

J.lalandii inhabits rocky substrates, where it finds both food and shelter from predators and strong wave action. The lobsters are usually found in association with the kelp species *Ecklonia maxima* and *Laminaria pallida*, as well as with the black or ribbed mussels *Aulacomya ater* and *Choromytilus meridionalis* (Heydorn 1968). The mussel forms the most important constituent of the lobsters' diet (Pollock 1979; Wickens and Field 1988). The kelp beds extend out to sea to depths of about 12-15 m, and thus the lobsters are found in their greatest densities down to this depth, although *J.lalandii* have been found in waters up to 200m deep. The kelp is thought to provide not only food and protection, but also to increase the aeration of the water (Heydorn 1968). The lobsters tend to congregate in large shelters such as crevices, caves and holes, and fierce competition exists for prime shelters. Intra-specific competition for space (shelter) is thought to play an important role in determining the population density of lobsters in certain areas (Pollock 1987). Lobsters are sometimes found on sandy and muddy bottoms for short periods of time, probably whilst foraging for food, or migrating away from low oxygen waters (Newman and Pollock 1971; Pollock 1982).

Both size and sex segregation is apparent. Pollock (1982; 1987) found the size composition of males gradually changes with depth, with small lobsters dominating in shallow waters and larger lobsters dominating offshore in deeper waters. It has been observed that juveniles tend to move offshore gradually as they approach maturity (Pollock 1973; 1979; Newman and Pollock 1974; Pollock and Beyers 1979). Females have also been observed to aggregate inshore (Pollock 1982) especially when in berry, when oxygen rich waters are required for the developing eggs. The inshore/offshore migrations that have been observed are usually associated with moulting and breeding cycles (Pollock 1982; Pollock *et al.* 1982). Tagging results suggest that there is little longshore migration of lobsters (Pollock 1986).

2.3 Reproduction

The life-cycle of *J.lalandii* is complex, as with other lobster species. Moulting is essential for reproduction, as eggs are fertilised internally. For copulation to occur, the female must have moulted and have a soft shell, whilst the male must have a sufficiently hard carapace. Both adult male and female lobsters moult annually, but at different times. Females moult in late autumn-early winter (April-June), with mating and oviposition taking place shortly after the moult (Heydorn 1965; 1969; Newman and Pollock 1971;1974a). The female moulting and spawning periods thus overlap. Adult males moult late spring-early summer (September-November) - about six months later than the females. During mating, spermatophores are deposited on the underside of the female

carapace and sperm reaches the eggs through narrow channels in the soft new shell (Pollock 1989). Fertilised eggs are released and form a mass in which the individual eggs are cemented to hairs, the ovigerous setae, on the underside of the female's tail. The females are then said to be "in berry" and are protected from fishing during this stage. Most mature females are in berry from July to late October.

Eggs hatch in October/November and form the first larval stage, the naupliosoma larva - a flat spider-like organism about 1.5mm in diameter. These larvae are released while the female is close inshore. Peak hatching in October/November may be synchronised with the onset of strong south-east winds which induce upwelling at this time of the year (Pollock 1986). Upwelling tends to shift the newly hatched larvae in the surface layers rapidly northwards and offshore by means of geostrophic currents and Ekman drift (Shannon 1985). The larvae are planktonic and float on the surface of the sea.

The naupliosoma larvae moult to form the phyllosoma larvae which drift around the Atlantic Ocean following the South Atlantic oceanic gyre for about a year, undergoing about 11 moults whilst growing larger (Patterson-Jones 1993). The final larval stage is the free-swimming puerulus larva - about 20mm in length. The larval cycle of *J.lalandii* is something of a mystery as it is not known exactly how these larvae return to the original breeding grounds. It appears that phyllosoma larvae possess a well developed capacity to delay metamorphosis until such time as they are exposed to particular environmental features, such as water temperature and salinity, which act as cues to

trigger the final larval moult into the puerulus (Pollock 1989). The puerulus has the capability of directional swimming, an attribute enabling it to cross the continental shelf to "home" populations (Pollock and Melville-Smith 1993). The puerulus larvae are found inshore in greatest numbers during December-April, with settlement taking place in depths of 10m or less amongst kelp beds (Pollock 1973).

Lobsters reach 60mm carapace length (CL) four years after puerulus settlement. Sexual maturity is reached at *ca* 65mm CL for females and *ca* 70mm CL for males (Heydorn 1965; Newman and Pollock 1974b; Pollock 1986). Beyers and Goosen (1987) show that size at onset of sexual maturity seems to be age-specific rather that size-specific. Thus, where growth rates are low, sexual maturity is reached at a smaller size. Reproductive output of both male and female lobsters increases with size (Heydorn 1965). Beyers and Goosen (1987) report that the number of eggs produced per female shows a positive correlation with CL. Similar results have been found for other palinurids (Berry 1971; Morgan 1972). Brood sizes of the females are large. For example, a female having an 89mm CL will carry about 190 000 eggs (Pollock 1989). Although many eggs are produced, only a few from each female will survive the planktonic stages, settle and reach maturity.

2.4 Somatic growth

The somatic growth of lobsters takes place through a number of moults, in which the exoskeleton is shed and replaced by a new one. Whilst the new exoskeleton is soft, the lobster is able to increase its size. Adult *J.lalandii* moult annually, with females moulting in late autumn-early winter, and males in late spring-early summer. Pollock (1973) studied the moulting of juvenile *J.lalandii*, and found that juveniles moult several times a year. Moult frequency decreases with increasing size, until an annual moult cycle is established. Correspondingly, the moult increment of juvenile lobsters increases with increasing size. Male and female lobsters were found to have similar moult increments up to a size of about 50-60mm CL. A sharp decrease in moult increment is evident in female lobsters at a size of about 50-60mm CL - the onset of sexual maturity, when energy reserves begin to be directed into gonad maturation (Pollock 1978). After attainment of sexual maturity, an annual moult cycle is adopted (Newman and Pollock 1974a).

The moult increments of adult male and female lobster decrease with increasing size. Male lobsters of up to 229mm CL and females lobsters of up to 140mm CL have been recorded (Gilchrist 1913). Adult female moult increments are comparatively smaller than those for males of the same size as large energy reserves are needed for reproduction (Zoutendyck 1990). At the historic average growth rate level, it would take a male lobster seven-eleven years to reach the pre-1993 minimum legal size of 89mm. A female lobster would on the other hand take more than 20 years to reach the same size (Pollock 1986).

Somatic growth rates vary between different areas, with smaller growth increments reported for lobsters in the northern part of the species' distributional range. Annual variations in the moult increment also occur, and differences within even localised areas have been reported (Heydorn 1965; Newman and Pollock 1974b; Pollock 1978; 1982; Pollock *et al.* 1982). The reasons for the differences in the moult increments are not clearly understood but one theory is that there are differences in the densities of rock lobsters in relation to the available food supplies (Pollock 1986). It has been hypothesised that differences particularly in the abundance of the black mussel *Aulacomya ater*, an important prey item, are responsible for the observed natural variations in growth. Newman and Pollock (1974a) suggest that the growth rates of rock lobsters are limited by food availability. In addition, Pollock (1979) showed that intraspecific competition by rock lobsters for suitable sizes of mussels is likely to be intense, particularly among the smaller sized rock lobsters; thus limited food supplies can still affect growth rates of rock lobsters even in areas where mussel biomass is high.

For the period until about 1989, the adult male annual moult increment was *ca* three-seven mm. However, since 1989 increments of both male and female lobsters declined drastically, and this low growth has persisted to the present, although some very recent recovery is evident (Cruywagen 1997). Lobsters now grow at only a fraction of their historic levels. Much research has been directed towards discovering the reason for this low growth, but no definite conclusions have emerged. Melville-Smith (1994) reports that low growth is likely to be linked to the food supply. It has been hypothesised that

anomalous wind conditions may have led to changes in the food availability to lobsters. This is supported by the observation that the south-east winds off the west coast have been less frequent and weaker in recent years, compared to years for which good lobster growth was recorded. These weaker winds have been accompanied by less oceanic upwelling. Melville-Smith (*op. cit.*) suggests that a possible result of less upwelling might be less phytoplankton available to filter feeders and detrital feeders. Since filter-feeders and detrital feeders are important food items of the lobster diet, if their biomass is reduced, this will affect the food consumption rates of the lobsters and hence effect their growth rates.

Mayfield (1998) examined the problem of the slow somatic growth rate observed since the late 1980's in adult male *J.lalandii* lobsters, with the aim of linking growth rate and food availability. An analysis comparing rock lobster diet and benthic community composition at two sites of contrasting somatic growth rates showed that despite vast differences in prey availability, the diet of the adult male lobsters from these two sites was similar. Mayfield (*op. cit.*) concluded that growth rate was not related to diet *per se*, but rather to the availability of preferred prey species.

Another possible hypothesis that could explain the reduced growth rates of lobsters at least in part, is the phenomenon of regeneration. A lobster which loses a limb is capable of regenerating that limb - but at an expense to its overall moult increment. Undersized lobsters which are caught and returned to the sea often sustain a number of injuries,

including the loss of limbs. In more recent years as the number of lobsters above the legal size for capture have decreased, the number of undersized lobsters being caught and returned to the sea has increased. Regeneration of lost limbs could therefore possibly be responsible for reduced moult increments.

Reduced somatic growth levels have now persisted for seven moult cycles. A prediction of future growth rates would be helpful to management, who must set total allowable catches (TACs) prior to obtaining results of the most recent year's growth rates from tag recapture data. Beyers and Goosen (1987) show that fecundity of females is higher in areas where growth rates of males are fast. Year-to-year variations in female fecundity may therefore possibly be an indicator of growth rates of adult lobsters (Melville-Smith *et al.* 1995), although further research is required to confirm this. In recent experimental work, Cockcroft (1997) has shown that the biochemical composition of the hepatopancreas of adult male *J.lalandii* lobsters can be used as an index to predict growth. He found that the relationship between the percentage lipid in the hepatopancreas tissue prior to moulting and moult increment was highly significant ($r^2 = 0.74$).

2.5 Feeding

J.lalandii has a varied diet. They have strong jaws, adapted for crushing a wide variety of hard shelled organisms. The most important food item is the mussel, *Aulacomya ater*, which constitutes about 65% of the diet (Heydorn 1965). Other foods consumed include sea urchins, crabs, amphipods, kelp, sea lettuce and other seaweeds and polychaete

worms. *J.lalandii* is also a scavenger, feeding on the remains of dead invertebrates. It forages by day and night, but only under calm conditions (Heydorn 1968). Lobsters can survive for weeks at a time without feeding, and hence do not feed whilst newly moulted and in soft shell (Zoutendyk 1988). Mouth parts must first harden before feeding can resume. Soft-shelled lobsters are also more vulnerable to predators, and hence will remain in sheltered crevices until their shells harden. Fishers therefore note a decrease in their catch-per-unit-effort (CPUE) at times corresponding to moulting, although the closed season is set to prevent much fishing when lobsters are newly moulted. Changes in feeding activity have been reported for several lobster species. Morgan (1974) found that feeding in *Panulirus cygnus* is lowest immediately prior to moulting and highest shortly after moulting. Lobsters have also been shown to increase their feeding activity as water temperature increases (Chittleborough 1970; McLeese and Wilder 1985).

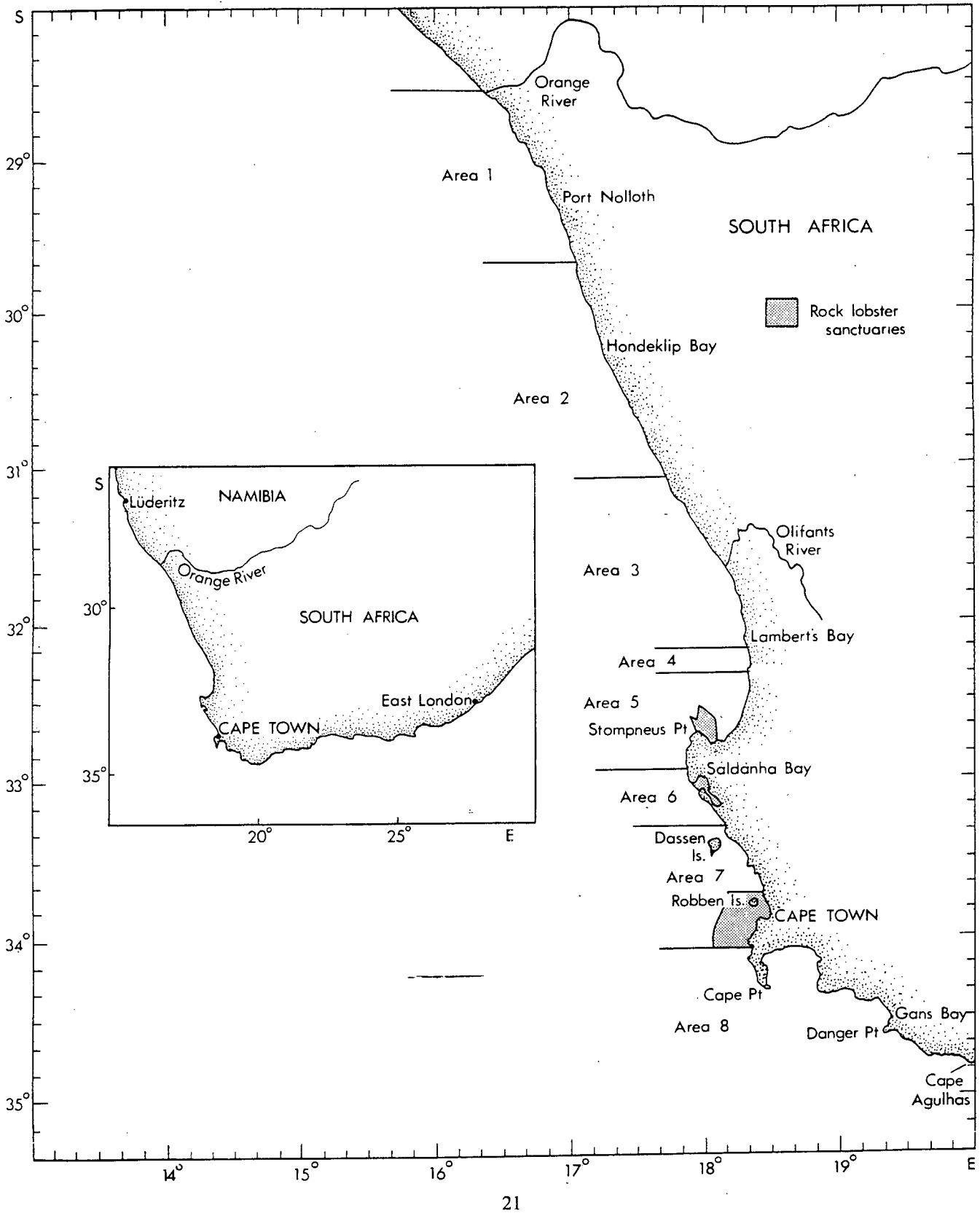
Pollock (1979) and Griffiths and Seiderer (1980) have shown that *J.lalandii* has a preference for small mussels which have thinner shells and are easier to crack open. Their studies suggested that lobster growth rates were directly affected by the relative abundance or production rates of small mussels, as mussels less than 10mm CL provided the major food source for male lobsters smaller than 90mm CL. Larger males were able to consume larger mussels (as well as the smaller ones) and hence have a wider size range of mussels to consume, reducing competition for food.

Under certain conditions such as high densities or starvation, large lobsters are known to become cannibalistic, preying on smaller lobsters in the population.

2.6 Predators

Both the larval and adult stages of *J.lalandii* are subjected to predation. *J.lalandii* produce large numbers of larvae (Heydorn 1965) which are subjected to high rates of mortality - probably caused mainly by plankton feeders. Rand (1959) reported that the Cape fur seal *Arctocephalus pusillus pusillus* preys on adult *J.lalandii*. Other predators include various octopus and dogshark species, Hagfish *Heptatretus hexatrema*, and birds such as cormorants. *J.lalandii* remains have been found in the stomachs of fish such as the red roman *Chrysoblephus laticeps* and musselcrackers *Cymatoceps nasutus* (Heydorn 1968). None of these predators of the post larval stages pose much of a threat however (Pollock 1986).

Figure 2.1: The geographic distribution of *Jasus lalandii* (from Pollock 1987), showing the various fishing Areas designated for management purposes, with the southern African coastline (inset).



Chapter 3: The fishery

3.1 History of the fishery

The west coast rock lobster fishery is divided into 8 fishing Areas: Areas 1 - 8 (see Figure 2.1). There is some argument as to whether the animals in the northernmost Areas (Areas 1+2) should be included with those further south as part of the "west coast rock lobster resource". It has been suggested that as the northern populations are distinctly more slower growing, they are excluded from assessment within this thesis.

Commercial exploitation of the west coast rock lobster *J.lalandii* commenced around 1870 (Gilchrist 1913). The fishery expanded rapidly in the early 1900's, with annual catches reaching an average of about 10 000 tons during the period 1920-1940. Fishing effort was increasing during this period as well, as more and more fishing vessels entered the fishery. During the war years (early-mid 1940's) catches dropped to very low levels, but subsequently rose dramatically, reaching the highest recorded levels in the history of the fishery. The maximum recorded commercial catch in one year was 18 926 tons, in 1951 (see Figure 1.1).

A minimum size limit of 3.5 inches (89mm) carapace length was introduced in 1933 (for all Areas), after minimum size limits of 2 inches, 3 inches and 4 inches had been enforced

previously. The 89mm size limit was to remain in place for Areas 3-8 until 1992. In 1946 a tail mass[1] TAC was introduced for the first time.

These measures were an attempt to control landings and protect the resource. Despite these measures, a marked decline in catches took place in the late 1960's and TACs could not be filled. The decline was particularly severe in the northern Areas (Zone A = Areas 1+2), where virtually uncontrolled exploitation had taken place since 1959 at a reduced minimum size of 76mm (Pollock 1986). A large decrease in yield from the Namibian grounds (north of Orange River) also occurred since the late 1960's (Pollock 1987). Although a drastic reduction in fishing activity has occurred since 1970 in Zone A, a decade later, there had been no recovery of the resource in this region (Pollock 1982). Pollock (1987) discusses how alterations in density dependent growth and natural mortality could have affected this lobster population, providing a possible explanation of the observed decline in yield in Zone A. Pollock and Shannon (1987) attribute the decline in these catches to a reduction in somatic growth rates and an increase in the natural mortalities of the lobsters which resulted from the reduction in the concentration of dissolved oxygen in these northern waters.

Catches are presently only a small fraction of the historic landings. This pattern of historical development of a fishery is a common one, where large yields are for an initial period sustained by a large pool of standing stock. This pool is gradually fished out, and catches become dependent on the annual surplus production of the resource alone. As for

[1] the mass of the lobsters "tail" or abdomen only

most lobster fisheries, there is a low ratio of sustainable yield to standing stock. The average annual historic catch for the west coast rock lobster is about three times larger than the estimated annual maximum sustainable yield of the resource (Bergh and Johnston 1992). CPUE (catch-per-unit-effort) data suggest that the depletion of the standing stock had come to an end by about 1970. Since then, catches have relied on the surplus production of the resource. Over the period 1981-1989, following large TAC reductions from 5352 MT (1979) to around 3800 MT for the 1980's, the resource CPUE doubled. The positive response of CPUE to the reduction in TAC at the beginning of the 1980's is argued to be an indication that the 3800 MT annual TAC subsequently caught was sustainable (Bergh and Barkai 1992). However, other hypotheses, such as exceptional recruitment during this period, have also been put forward to explain this observation. Since 1989, when somatic growth rates declined drastically, annual TACs have declined even further, and the TAC for the 1995 season was only 1500 MT - about 40% of the 1980's level. As a result of subsequent growth rate improvement, the TAC levels have increased somewhat to 1700 MT (1996 season) and most recently to 1920 MT for the 1997 season.

J.lalandii makes up the bulk of the South African lobster fishery. The other commercially harvested lobster, the south coast lobster *Palinuris gilchristi*, has brought in only about 400 MT annually over recent years. *J.lalandii* supports an important export market, with most of the lobsters exported to the east - for example, during the 1992 season, 1300 tons were sold to the Japanese market (where most lobsters are used at wedding celebrations).

The bulk of the lobsters exported are sold as "whole cooked" or "whole raw". At present the law requires that only 20% of the commercial harvest needs to be sold on the local South African market. The west coast lobster fishery in 1995 was worth 145 million Rand, and is the third highest earning fish resource in the country.

3.2 Fishing gear

Two forms of fishing gear are used by commercial fishers to harvest west coast rock lobsters - hoopnets (or ringnets) and traps. The first to be used were hoopnets, which were used exclusively until 1969 when trap gear was first introduced. Traps gradually became more popular, and since 1981 more that 80% of the commercial catch has been taken using traps.

Hoopnets

A hoopnet consists of a circular hoop of about 0.75m in diameter made of an iron rod, to which a conical shaped 100mm mesh net is attached (62mm mesh net in Areas 1+2; 90mm mesh net in Areas 3-9). The bait, usually fish heads, is suspended in the centre of the hoop to which a hauling line and surface float are connected by means of a three-piece bridle (Heydorn 1965). The net is pulled up after short intervals (typically some 30 minutes), trapping lobsters feeding on the bait at the centre of the ring. The lobsters are then sorted for size by hand. Up to 10 of these nets are carried in a dinghy - usually manned by a crew of two.

Traps

Traps are made of a metal rectangular frame enveloped in a mesh net. Until 1984 a 60mm mesh net was used. The traps have two conical entry holes, and one side is replaced by a large bag (maximum length of 400mm) made of mesh netting. Bait is placed in the centre of the trap. Each trap is connected to a surface buoy, but the traps are usually left in the water for long periods (usually at least 12 hours), and mostly overnight. The method of sorting was initially by hand, but in 1974 deck-grid sorters were installed on the boats to help speed the sorting process and to reduce the time undersized lobsters spent out of water. The traps are carried out to sea by boats manned by several fishers.

Hoopnets are usually deployed in shallow waters (< 15m). Traps, being larger and heavier than hoopnets, cannot be carried by small boasts or dinghies. Furthermore, strong wave action can roll the traps around. Traps are therefore deployed further out to sea in deeper waters. As the hoopnet dinghies are smaller and more agile, they are often able to get to the less accessible areas in calm conditions.

The two gear types have different efficiencies and selectivity functions. Newman and Pollock (1969) found that traps are about 2.5 times more efficient that hoopnets in terms of mass caught per day. Hoopnets tend to show an increased selectivity for larger lobsters. Heydorn (1969b) suggested that smaller lobsters were often kept away or chased out of the hoopnets by the aggressive behaviour of larger lobsters. On the other hand, Newman and Pollock (1974) suggested that large lobsters (especially males) were less catchable by

traps than smaller individuals. Pollock *et al.* (1982) report that the mean sizes of males and females caught by hoopnets were nearly always larger than the mean sizes of those caught by traps. Those authors reason that this is a consequence of the fact that hoopnets are able to be deployed in calm conditions near dangerous reefs or very close inshore in areas normally avoided by the larger trap-fishing vessels. The rock lobsters inhabiting these areas are often larger due to localised low exploitation rates caused by inaccessibility.

The catchability of lobsters also varies during the fishing season, and is linked in part to the moult cycles of the lobsters, as well as to environmental conditions (dissolved O_2 level, temperature, rough seas) and mating behaviour. At the beginning of the season (November) nearly all the males are recently moulted animals which would have just resumed feeding after a period (of some weeks) of starvation while preparing for and undergoing moulting. Shortly after moulting, once the shell and mouthparts have hardened sufficiently, males feed very actively, and this enhances their catchability (Pollock 1979; 1982; Pollock and Beyers 1979). Females, on the other hand, are in the middle of an intermoult period at this time and display no enhanced catchability. Pollock and Beyers (1979) confirmed this and found that male rock lobsters were more catchable by traps than females of the same size for at least three months after the moulting of males. Fewer females than males are caught by traps due to factors such as differences in availability, feeding and size.

Catchability differences have been observed for several other lobster species. Miller and Mohn (1993) note that mature females of several decapod species have lower catchability than males. Examples include *Homarus* spp. (Ennis 1978, Branford 1979) and *Panulirus cygnus* (Morgan 1979). Morgan (1974) notes that catchability differences in *Panulirus cygnus* may result from changes in the ways in which lobsters react to fishing, e.g. soft-shelled lobsters do not feed, changes in the effectiveness of the fishing effort, or changes due to weather conditions.

3.3 Management control measures

A number of management control measures have been applied to the west coast rock lobster fishery - some almost since the inception of fishing in the late 1800's. These measures are aimed at controlling both fishing effort and annual landings, whilst also providing a degree of protection to the reproductive component of the resource. The following are the measures currently in place.

i) **Minimum size limit**. A minimum legal carapace size limit of 89mm (3.5 inches) was imposed on the fishery from 1929-1991. Since the 1992 season the minimum size has been reduced, and at present stands at 75mm. The carapace length is measured from the tip of the rostrum to the mid-point of the posterior edge of the dorsal cephalothoracic shield. The minimum legal size limit north of the Brak River (that is for Areas 1+2) has been 76mm for 1959-1992, and 75mm since.

ii) **Closed Season**: The fishery is closed to both commercial and recreational fishers for certain periods of the year. For recreational fishers the closed season has generally been 1 May to 15 November. The recreational season was recently shortened in an attempt to reduce effort. The closed season for commercial fishers varies for different Areas. For Areas 3-7, the closed season is about 1 July to 31 October, depending on the moult and berry cycles in the fishing Areas. For Area 1 and 2, the closed season is 1 July to 30 September, and for Area 8 it is 1 September to 31 October. The rationale behind the closed season is that this is the period that the female lobsters are in "berry". Females become ovigerous in June and shed their eggs in October/November (and in some cases December). The closure of lobster fisheries over the period when females are carrying eggs is a control measure that is recognised in most countries. The reasons why this control measure is important are as follows (Melville-Smith 1993).

- The females moult (May/June) just prior to their coming into berry. Lobsters are very catchable in their early post-moult condition (when they actively feed after a period of starvation) and fishing at this time would increase the relative numbers of females caught by the fishers.
- When the egg bearing females are handled out of the water - many eggs get dislodged from the females' abdomen and are lost.
- When eggs in the late stage berry are stressed in any way, this can trigger the larvae to be released prematurely so that a low survival rate of these larvae can be expected.

iii) A prohibition of possession of **berried** females and lobsters in **soft shell** has been enforced from an early period. For the 1991 season only, the responsible Minister announced a ban on the harvesting of all females.

iv) **Gear regulations**: The mesh size of the nets covering traps has been restricted to 100 mm since 1985. Prior to 1985 the mesh size was 62mm. The increase in mesh size in 1985 to 100mm was aimed at reducing the numbers of undersized lobsters being caught in the traps. Deck grid sorters were introduced onto the boats in 1974 in an attempt to speed the sorting process, and to reduce the time undersized lobsters spent out of the water. From 1992, no traps have been allowed to be left in the water over weekends. This is to act as a deterrent to poachers who often raid traps at those times. A limited number of landing sites are available to the fishing boats. An inspector must be present when the catch is offloaded at port.

v) **Lobster sanctuaries**: A number of lobster sanctuaries exist, such as Robben Island, Hout Bay, Cape Peninsula, Saldanha Bay and St Helena Bay, as well as the area east of Cape Hangklip. These sanctuaries are used for research purposes, and to provide pristine lobster populations with high egg production levels.

vi) **TACs**: A tail mass production TAC was first introduced in 1946. In 1980 an association (The West Coast Sea Management Association) representing fishing companies and the fishers was formed. From the 1979 fishing season, a whole lobster

(landed mass) TAC system was introduced. A global total allowable catch (TAC) is determined annually. The TAC is then divided into a maximum allowable catch (MAC) for each of the eight fishing Areas based on the research results and fishing performance of the previous season. The fishery has a limited entry, with the TAC divided among 160 quota holders (in 1996) on a fixed percentage basis. There is a 15% "tolerance" level for each MAC - that is, if fishing performance is poor in one Area, up to 15% of the associated MAC may, with the approval of the SFRI[1], be caught in another Area with better fishing performance. This Area-by-Area quota system was designed to prevent uncoordinated movements of fishing effort over the Areas and to curtail effort in an Area of poor fishing performance. In the past, the Area MACs were adjusted upwards or downwards depending on Area indicators such as CPUE, estimated fishing mortality, changes in size-structure, somatic growth rate, FIMS (Fisheries Independent Monitoring Survey - see section 5.2.3) results, etc. At present, the areal split of the TAC is intended to reflect the proportions of the total abundance to be found in each Area, as indicated primarily by CPUE and FIMS data. The total number of vessels and the number of traps per vessel for each company is also restricted. This is aimed to limit effort.

vii) **Recreational catches**: There are a number of restrictions imposed on the public for recreational harvesting of west coast rock lobsters. A minimum size limit of 80mm is now enforced (5mm higher than the commercial minimum size). A person must be in possession of a valid licence before catching lobsters. A person may only catch a maximum of 4 lobsters per day. A maximum of 16 lobsters per car (or boat) is allowed at

[1] The South African Sea Fisheries Research Institute.

any one time if four permit holders are in the car or on the boat. The public may not sell their catch. No SCUBA gear may be used when catching the lobsters - hoopnets, handline or snorkelling methods are allowed to be used.

3.4 TAC setting procedure

3.4.1 Management strategies

Prior to the reduction in somatic growth rates (late 1980's) the management strategy for the west coast rock lobster was based on restricting the fishing mortality to $F \sim 0.3$ yr^{-1}. $F = 0.30$ yr^{-1} was calculated to correspond to F_{max} for the 89mm+ legal portion of the stock. The $F_{max} = 0.30$ yr^{-1} was evaluated from yield-per-recruit curves (Pollock 1986). The shapes of the yield-per-recruit curves were found to be similar for different natural mortality rates. Management also attempted to maintain high rates of economic returns (high CPUE) and to buffer the adverse affects of poorer-than-average recruitment on catches by maintaining a number of different age classes in the "legal sized" population, (i.e. the component of the population of sizes greater than the minimum size limit for commercial catches).

In the late 1980's, a drastic reduction in lobster somatic growth rates occurred, and TACs could not be filled. The $F = 0.30$ yr^{-1} management strategy fell away. In 1992 a new TAC setting procedure was implemented. This was called the 30/50 rule. Projections of the resource into the future were made for a number of different TAC/minimum size limit/future somatic growth scenario combinations using a size-structured model. A

constant catch strategy was assumed. For each size limit, a maximum TAC was calculated for which egg production levels were estimated to not drop below 50% of the "egg-per-recruit" levels for a zero F, and the harvest proportions not to increase above 30%. This 30/50 rule was used again for the 1993 season, with the added assumption that two more years of low growth would persist. As the low somatic growth persisted, and TACs continued to drop, pressure to develop a new management approach evolved. The management approach used for providing the 1994 and 1995 TAC recommendations was based on an 1870+ size-structured modelling approach (as described in Chapter 7). The model was used to project the resource ahead for five years under a number of future growth scenarios. A constant annual replacement yield, for which the biomass above 75mm at the end of a five year period would be the same as at the start of that projection period was calculated for each growth scenario. The model provided an estimate of replacement yield of about 1500 MT for 1995 under the assumption that somatic growth would remain low (at its 1989 to 1994 average) into the future. The 1996 TAC of 1700 MT was similarly based on a five-year replacement yield assuming this low growth for the future.

3.4.2 Decision making procedure

The Minister of Environment Affairs and Tourism is responsible for setting the annual TAC. Although the Minister has the final word, he is advised by the Sea Fisheries Advisory Committee (SFAC). The SFAC is a group appointed by the Minister who consider recommendations made by the Director of the Sea Fisheries Research Institute

(SFRI), and make a final recommendation on the TAC to the Minister. The SFAC takes into consideration both scientific advice and socio-economic concerns. The scientific advice is provided by the SFRI Director who is in turn advised by the Rock Lobster Working Group (RLWG)[2] of the SFRI. The RLWG has recently consisted of SFRI scientists, scientists from the University of Cape Town and scientists consulting for the lobster industry. The RLWG is appointed annually by the Director of the SFRI, and provides TAC recommendations based on scientific (biological) factors only. These recommendations are passed on to the Director of the SFRI who, after making adjustments to these recommendations if he sees fit, passes the advice on to the SFAC. This decision making procedure is depicted in Figure 3.1.

3.5 Problems faced by the lobster fishing industry

TACs of around 3800 MT were set during the 1980's. During this time the industry had no problems filling their quotas, and the CPUE actually increased from 1980-1985. During the 1990 fishing season, the industry was suddenly faced with a crisis. The moult increment preceding the 1990 season had been very low - tagging studies showed a 50-65% reduction in somatic growth rates of lobsters all along the west coast. As a result, the CPUE dropped sharply (by about 50%) and the industry were unable to fill the TAC, catching only about 75% of the 3760 MT allocated. As a result of the decrease in CPUE in 1990 and a prediction of continued low somatic growth for the forthcoming season, the SFRI recommended a TAC reduction of 1075 MT for the 1991 season from 3760 MT to

[2] A group of government, university and industry consultant scientists responsible for the assessment of and TAC recommendations for the west coast rock lobster resource/fishery.

2685 MT. The minimum size remained 89mm - the level set since 1933. At this stage, the fishery was virtually entirely dependent on newly recruited lobsters into the 89mm+ portion of the stock, with a correspondingly lower sustainable yield available from the resource (at 89mm minimum size limit). As somatic growth rate declines, fewer lobster grow into the legal sized portion. Towards the end of the season, the industry were far from filling their quotas, so as a temporary measure, the Minister reduced the minimum size to 75mm on 13 April 1992 for the rest of the season.

In 1992, two scientists from the University of Cape Town, Drs Amos Barkai and Mike Bergh, were funded by the fishing industry to embark on a study of alternative management options for the resource, to see whether a severe reduction in TAC could be avoided without jeopardising the biological state of the resource. Bergh and Barkai (1992) came up with a proposal to reduce the minimum size limit to 65mm. Their proposal was based on a mathematical model of the rock lobster resource. Estimates of sustainable yields at different minimum sizes were produced. The Bergh-Barkai model predicted that the mass of discarded undersized lobsters (smaller than 89mm) was about eight times the mass of legal size lobsters (89mm+). Many of these discarded lobsters die, with the result that, if a discard mortality rate of 10% was assumed, the model predicted a loss of more than 2000 MT of sublegal lobsters due to discard mortality (Barkai and Bergh 1992). Bergh and Barkai maintained that the population above 89mm had been overexploited. On 8 August 1991, Bergh and Barkai presented their proposal of a reduction in minimum size to 65mm to the West Coast Rock Lobster Sea Management

Committee (the industry). On 26 August 1991, the industry presented this proposal to a SFAC subcommittee.

There were a number of arguments offered in support of the Bergh-Barkai proposal. These included (Bergh and Barkai 1992):

i) allowing for a standing stock buffer for the industry against short term environmental changes such as low somatic growth rates;

ii) allowing the industry to operate at a reasonable effort level and hence reduce industry costs;

iii) largely eliminating the damage to undersized lobsters (because a much smaller percentage would be discarded);

iv) leading to an overall increase in the total biomass of the resource and an ultimate doubling of the 89mm+ biomass;

v) harvesting across the size spectrum in a genetically more balanced way; and

vi) allowing some adults to grow to full size.

The proposal was submitted to three international reviewers chosen by the SFRI. The main objection by the SFRI to the proposal was the risk placed on the resource through potential egg production declines. The original 65mm minimum size (and 3800 MT TAC) proposal was altered to consider a range of minimum size-TAC combinations. For each minimum size, the Bergh-Barkai model was used to calculate the maximum TAC which would ensure sustainable utilisation subject to two stipulations (30/50 rule):

i) exploitation would not reduce the egg production level to below 50% of the pristine level in any year; and

ii) exploitation would not remove more than 30% of the legal portion of the stock in any year.

The SFAC finally recommended a minimum size of 77mm and TAC of 2700 MT for the 1992 season. The Minister adjusted the SFAC's recommendations, and set the minimum size at 80mm and a TAC of 2200 MT. The TAC for 1992 was caught with relative ease. The minimum size limit for the 1993 season was reduced again - to 75mm - for economic (marketing) reasons after an application for some measure of relief by the industry. A large portion of the commercial catch is exported to the east - mainly to supply the Japanese wedding market. The industry were facing problems with the marketing of 80mm+ sized lobsters. It appeared that a guest at a Japanese wedding would be served either a whole small lobster (70-80mm) or half a large (90mm+) lobster. The 80-90 size range therefore fell in-between these two preferred sizes, and the industry were unable to obtain good prices for their catch. For this reason the minimum size was reduced to 75mm for the 1993 season, along with a TAC of 2200 MT, in order to assist the industry with the marketing of their lobsters.

The minimum size is still a contentious issue, with many of the public strongly opposed to the reduced minimum size limits for the commercial fishery. The minimum size for recreational takes by the public was reduced from 89mm to 80mm in 1993. Research on the implications of reducing the minimum size for west coast rock lobsters began as early

as the 1970's. Newman (1973) examined the possibility of reducing the minimum size and pointed out advantages in terms of improved yields as the minimum size was reduced. Newman's and other work (Newman and Pollock 1977; Pollock 1978; Wickens and Field 1985) had shown that higher yields are possible for males in slow growth areas and for females in all areas if the size limit were to be reduced. The reason is that the gain in mass achieved by waiting until the lobsters are bigger before harvesting them is more than offset by reduction of numbers through natural mortality.

NB The most important criticism and concern regarding the reduction in minimum size is the biological effect of reducing the female spawning biomass, resulting in reduced egg production. A decline in egg production could lead to recruitment failure in future years. The stock-recruit relationship for the west coast rock lobster is not well understood, but is likely to be difficult to determine, particularly given its lengthy planktonic life and the relatively advanced age at which recruitment to the fishery takes place. Another concern with reducing the minimum size was that, once reduced, it would be very difficult to increase again (Melville-Smith 1992). Melville-Smith cites three examples where this has been the case:

i) *Panulirus argus* (Gregory, Laisky and Combs 1992);

ii) *Homarus americanus* (Acheson and Reidman 1982); and

iii) *Jasus lalandii* in Namibian waters (Beyers and Wilke 1990).

(4) Finally, under the 89mm size limit, virtually no females were harvested in recent decades, so that the female spawning stock at least was near fully protected. Once the limit was

dropped, this protection became dependent upon the TAC set, and there were major concerns about the impact of known extra-TAC catches (see next section) in these circumstances.

Although the possibility of recruitment overfishing has been discussed, it should be noted that the population model developed here explicitly rules out recruitment overfishing, as a step-like recruitment function is implemented.

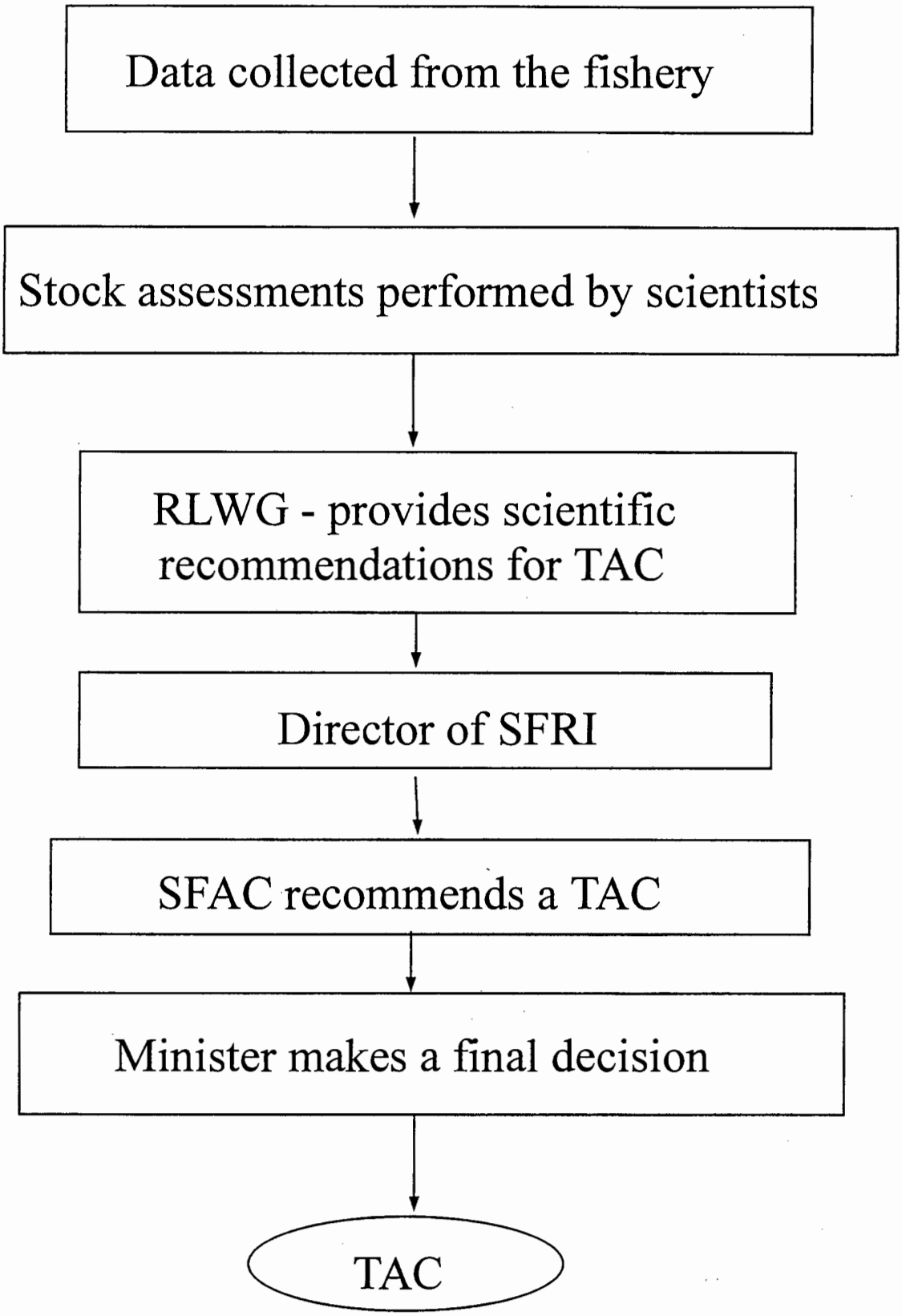
3.6 Poaching and recreational catches

In addition to the commercial catches, both poaching and recreational catches by the public contribute towards fishing mortality. Lobsters are found in relatively shallow waters, making them accessible to non-commercial fishers. West coast rock lobsters have been termed west coast "gold" - for a good reason. There is a large and well established local black market for lobsters. This has resulted partly from the regulation that only 20% of the commercial harvest needs to be sold on the local market (where lobster command lower prices than if exported) - resulting in a severe local shortage. Local restaurants, as well as individuals in the public, are willing to pay large amounts of money for the now very scarce lobsters. Poaching is estimated to be in the region of 500 - 2000 MT per annum (Patterson-Jones 1993). A number of measures have been implemented in order to curb poaching, such as the ban on commercial traps in the water over the weekends. Many poachers use highly sophisticated equipment, such as fast motor boats and radio systems, making it very difficult for the small policing force of Sea Fisheries inspectors to

catch them. A state-of-the-art policing unit would be required to eliminate, or at least drastically curb poaching. Although this would be expensive, the industry might be willing to fund such a unit, as they would be the ones who would benefit in the long run.

"Crayfishing" - the catching of rock lobsters, is a very popular pastime in the Western Cape. For example, more than 75 000 licences were granted for the 1997 season. Although only four lobsters may be caught per person per day, many of the public use non-fishing relatives' licences in order to increase their daily bag limit. As there are so many diving spots in the Western Cape, it is very difficult to control the recreational harvesting of lobsters. Although the commercial TACs have been reduced substantially as a result of the low somatic growth rates, there were no further limits placed on the recreational harvest until 1996 when the season was reduced by several weeks with the intent to achieve a reduction in the recreational catch. The 1995 recreational harvest of around 470 MT (as estimated by a telephonic survey) was more than 30% of the commercial TAC. In contrast, historical recreational catches of probably about 100 MT were only a small proportion of the 3800 MT commercial TACs in the 1980's. The public's share in the removals from the resource has therefore increased dramatically, and there is increasing pressure from the commercial fishing industry to place some controls on the ever increasing public catches.

Figure 3.1: The TAC setting procedure.



Chapter 4: Information from other lobster fisheries around the world

In this Chapter, major lobster fisheries elsewhere in the world are reviewed briefly. Then information on aspects of these fisheries of particular relevance to the assessment of the South African west coast rock lobster resource are considered, specifically discard mortality, stock-recruit relationships and somatic growth.

4.1 Major lobster fisheries

Lobster fisheries are found in both the northern and southern hemispheres, and are considered to be highly valuable. The main lobster fisheries include:

i) New Zealand and Tasmanian rock lobster fisheries for the southern lobster - *Jasus edwardsii;*

ii) Western rock lobster fishery in Australia - *Panulirus cygnus;*

iii) *Homarus americanus* fisheries of the USA and Canada, e.g. Maine lobster fishery; SW Nova Scotia and Bay of Fundy lobster fishery;

iv) UK lobster fishery - *Homarus gammarus;*

v) UK lobster fishery - *Nephrops norvegicus*; and

vi) South African west coast rock lobster fishery *Jasus lalandii.*

These rock lobster fisheries (excluding the *J.lalandii* fishery) are discussed in brief below, with important research and management aspects of each being highlighted.

New Zealand fishery for *Jasus edwardsii*

Ninety five percent of the New Zealand lobster fishery is for *J.edwardsii*. This fishery is New Zealand's most important inshore fishery with annual exports worth more than $NZ 100 million (Booth and Breen 1994). Landings since the 1950's have stabilised at between 3000 - 5000 tons per annum.

The fishery is divided into northern and southern substocks. A number of models have been developed and applied for the assessment of the fishery, including yield-per-recruit models (Saila *et al.* 1979). Estimates of MSY for the fishery have been made using surplus production models (Saila *et al.* 1979; Annala and Esterman 1986; Fogarty and Murawski 1986). In order to understand the implications of minimum size limits on the spawning biomass, Annala and Breen (1989) developed an egg-per-recruit model. Recent estimates indicate that the southern substock is well below its optimum size (Starr *et al.* 1997). Breen and Kendrick (1997) suggest that if removals stay at the same level and recruitment stays near its average level, stock biomass should increase to its optimum (B_{MSY}) level in 12 - 13 years.

Since 1990, the fishery has been managed with a system of individual transferable quotas (ITQs) involving nine management areas. The management goal is to ensure a maximum continuing yield from the fishery, taking into account the social and economic benefits for New Zealand and the fishing industry (Annala 1983). The concept of the use of decision

rules (Starr *et al.* 1997) has recently been introduced in the process of annual reviews of stock assessments, and may be used to determine TACs in the future (Annala and Sullivan 1997).

Tasmanian fishery for *Jasus edwardsii*

The Tasmanian rock lobster fishery targets the southern rock lobster *J.edwardsii* in the waters adjacent to Tasmania. The fishery includes both commercial and recreational components. The commercial fishery commenced in the 1800's and has been pursued for nearly 200 years (Winstanley 1973). At present (1998), about 800 people are directly employed in the fishery. In 1995 the fishery was worth over 40 million dollars and the total catch was 1820 MT. The recreational fishery comprises nearly 10 000 fishers and is estimated to take about 5% of the total catch (Punt and Kennedy 1997).

The first management regulations were implemented in 1885, and included a minimum size limit, and a ban on the possession or sale of lobster in soft shell or berried females. Since 1885, the fishery has been managed by a range of input and biological controls.

In the late 1970's, improvements in echo-sounders allowed more fishing grounds to be discovered. This, and further increases in effort, resulted in increased catches until these peaked in the 1984 season (2288 MT). During the following 10 years, fishing effort almost doubled, whilst at the same time catches declined. Furthermore, from 1980-1995

the annual catch rates of *J.edwardsii* in Tasmanian waters declined from 1.6 to 0.9 kg per pot lift (Punt and Kennedy 1997).

The declining catch rate, together with the rapid rise in effort became a real concern for managers and industry by the late 1980's. A need to change the management of the fishery to restrict catches and remove effort was recognised. It was reported (Tasmanian Department of Primary Industry and Fisheries 1997) that the fishery had been fished at an unsustainable level since the late 1970's, and this had resulted in a decline in the biomass.

The Tasmanian Government implemented a number of interim management measures in an attempt to reduce the catch levels, as the fishery was considered to be overexploited (Frusher 1996). These measures included delaying the start of and shortening the fishing season. These methods were not very effective in reducing catch levels (Tasmanian Department of Primary Industry and Fisheries 1997).

On the research front, the Tasmanian Department of Primary Industry and Fisheries began a fishery-independent pot-sampling project in 1992 to determine the level of exploitation in the fishery. A need for a stock assessment model to assess alternative catch limits arose. A spatially disaggregated size-structured model was developed (Punt and Kennedy 1997). This model is fitted to catch, effort and length frequency data, as well as to estimates of exploitation rates from experimental data. A Bayesian estimation framework is used to estimate the quantities needed for risk analysis.

In January 1997, the Tasmanian Government decided to implement a quota management system for the rock lobster fishery as the long term management strategy for the fishery. It is planned that the quota system will commence March 1998. The Government initially considered five different management options, including pot reduction, seasonal closure, pot buy-back, pot reallocation and the quota system. The quota management option was the selected option. The TAC is to be maintained below 1650 MT for 1998, and at 1500 MT for the next four years (Punt and Kennedy 1997).

Western Australian fishery for *Panulirus cygnus*

The western rock lobster *P.cygnus* supports one of the world's largest lobster fisheries (Caputi and Brown 1986), and is the largest single species fishery in Australia. The average annual catch over 1973-1983 exceeded over 10 000 tons. This resource has been commercially exploited since the late 1800's, and in 1897 the first regulation - a minimum size limit - was proclaimed (Brown and Caputi 1986). Since the developmental phase of this fishery, the catches have remained stable, partly due to strict control through a number of management measures. Since the early 1960's, management has relied on input control. Limited entry was introduced in 1963 when the number of vessels in the fishery was limited to 836 - this number has been reduced to a level of 611 (Hall 1997).

A number of surplus production models have been used (Morgan 1979) to assess the stocks of *P.cygnus*. These yielded MSY estimates of between 8000 and 8600 MT. Since 1969, the management of this fishery has been aided by estimates of abundance of puerulus settlement (9-11 months old) to predict the level of recruitment (five year olds) to the fishery four years later (Morgan *et al.* 1982; Phillips 1986; Phillips *et al.* 1994). Caputi and Brown (1986) also found relationships between the abundance of three-four year old juveniles and lobsters recruiting into the fishery. These indices provide an independent method to support or modify recruitment predictions based on indices of puerulus settlement.

In the early 1990's, with the aid of a size-structured model described by Walters *et al.* (1993) (which possessed a spatial and temporal structure that allowed the exploration of the consequences of alternative management strategies within each management zone), it was estimated that egg production had declined to 15-20% of the pre-exploitation level. Managers decided that this was unacceptably low and adopted 25% of the pre-exploitation egg production as the biological limit reference point above which the stock should be maintained (Hall 1997), i.e. a rebuilding strategy was agreed.

A number of alternative strategies, including output controls, were explored, but management decided to continue to use input controls to manage exploitation (Hall 1997). In 1993 a new management strategy was introduced. The management objectives are (Annala and Sullivan 1997):

i) a sustainable breeding stock of lobsters (presumably this means maintaining a breeding stock that will ensure sufficient egg production to meet the 25% pre-exploitation level), and

ii) to maximise the long-term economic and social benefit to the community.

It was accepted that effort should be adjusted annually to account for an increase in harvesting efficiency and changing levels of puerulus settlement, by varying the percentage of each fisher's trap holding that could be fished. In addition, a maximum size limit was introduced for female lobsters, in an attempt to increase the protection of the spawning stock (Hall 1997). There was also the introduction of a regulation that required fishers to release all females with visible setae, thus providing protection for all mature female lobsters for a large portion of the fishing season.

Homarus americanus fisheries

The *H.americanus* lobster fishery is shared by the USA and Canada. It is one of the most valuable components of the Canadian fishing industry. *H.americanus* is abundant throughout the western North Atlantic, with the main fishing grounds concentrated along the Maine coastline, the Bay of Fundy and the southwest coastline of Nova Scotia.

During the early 1970's, following a 20-25 year downward trend in landings, concern was raised that recruitment overfishing was occurring, and that landings would continue to decline. However, the trend unexpectedly reversed throughout the range of the species.

Catches since 1990 have been the best fishing in memory, with the highest recorded landings (Ennis and Fogarty 1997). This upward trend in catches is not well understood, but its widespread nature suggests a period of strong recruitment associated with favourable environmental or ecological factors (Fogarty 1995).

Aiken and Waddy (1986) studied environmental factors influencing recruitment of *H.americanus*, and found sea surface temperature to be the most important. Several studies relating temperature and lobster landings have since been conducted (Fogarty 1988; Campbell *et al.* 1991). Fogarty (1988) researched the effect that temperature has on the CPUE and catch of the Maine lobster fishery. Fogarty (*op. cit.*) found that a 0-1 year lag, as well as a six year lag, exists between catch and CPUE trends and temperature trends. It is known that lobster activity levels increase with an increase in water temperature, thus increasing their feeding and hence their vulnerability to capture. The six year lag indicates that environmental factors such as water temperature may influence the survival of lobsters during their early life history stages. Fogarty was able to accurately predict the next year's catch using temperature data. This work has important implications for the management of all lobster species, if similar relationships between water temperature and feeding can be established for those species.

Several stock assessment techniques have been applied to *H.americanus*. These include surplus production models (Jensen 1986), adapted Beverton-Holt dynamic pool models, and yield- and egg-per-recruit models (Campbell 1985; 1989). Fogarty and Idoine (1988)

applied a yield and egg production model based on size to a *H.americanus* population. The model explicitly considered individual variability in growth. Ennis (1986) studied the impacts which size limits and exploitation rates have on egg production, in an attempt to determine whether or not an increase in egg production in a population would result in an increase in recruitment. He reports that efforts to increase egg production levels would most likely increase recruitment.

Delayed recruitment models have been applied to *H.americanus* by Marchesseault *et al.* (1976) in order to help develop dynamic strategies for management. Fogarty and Idoine (1986) examined the relationships between successive life history stages of *H.americanus* for evidence of density-dependent control. They demonstrated an asymptotic relationship between the abundance of the final larval stage and stock size five-seven years later, indicating the possibility of density-dependent regulation between larval settlement and subsequent recruitment to the fishery.

Although recent catches have been high, these fisheries are characterised by high exploitation rates and minimum legal sizes that tend to be small in relation to size at maturation - conditions under which recruitment overfishing is a possibility (Ennis and Fogarty 1997).

The current management strategy is to define stock-management areas, to develop a conservation strategy, to reduce exploitation rates in the fishery and to increase the egg

production in the stock (Annala and Sullivan 1997). A target has been proposed for an egg production level of 5% of the pre-exploitation level. Present management is through input controls, although quotas apply in the offshore zone in Canada (Ennis and Fogarty 1997).

UK fishery for *Homarus gammarus*

This is a small boat fishery which was established in the late 1800's. Since 1900, landings have ranged from between 300-600 tons per annum (Bannister and Addison 1986). Models for stock assessment have included the development of a yield-per-recruit model by Addison (1986) which incorporates density-dependent mortality in large lobsters due to limitation of suitable holes in the substrate. Bannister (1986) and Bannister and Addison (1984) also used the Jones (1974; 1981) length cohort technique to estimate yield-per-recruit for a range of exploitation patterns for the *H.gammarus* fishery.

This fishery is characterised by a lack of both input and output controls, i.e. there is no limit on the total catch, vessel numbers or gear. There is, however, a minimum legal size limit (Annala and Sullivan 1997). Despite the lack of controls in the fishery, there is no evidence to suggest that it is a worse state than the North American lobster fisheries (Annala and Sullivan 1997). There is, however, a proposed management plan to limit effort and to protect berried females.

UK *Nephrops norvegicus* fishery

The Norwegian lobster *N.norvegicus* is the most valuable species caught in the Irish Sea fishery (Brander and Bennet 1989). This lobster inhabits muddy substrates, and forms part of the catch of the demersal trawl fishery. Landings reached a peak of 10 000 tons in 1979, and have remained at somewhat smaller but stable levels since. The Norwegian lobster is fished in both the Irish Sea and off Northwest England. The main control measures are annual TACs as well as a minimum carapace size limit. The implicit management objective is to optimise yields whilst maintaining adequate spawning stocks. At present, two models are used to provide scientific advice for the management of this fishery. The first is a quarterly yield-per-recruit model which incorporates seasonal data on growth, availability and exploitation. This model is used in conjunction with length cohort analysis to examine the consequences of changes in mesh size and minimum size limits on yield-per-recruit. The second is a multispecies model, which incorporates technical and biological interactions between Norway lobsters and cod, the predominant lobster predator, and their fisheries (Brander and Bennett 1989).

General

The various management controls for the fisheries described above (and for *J.lalandii*) are summarised in Table 4.1.

The overall management goal for lobster fisheries is generally their sustainable management or sustainable use of these resources (Annala and Sullivan 1997). Many of

the other management objectives are conflicting, and management authorities often experience difficulties when attempting to achieve more than one objective simultaneously for the same stock.

The selection of management mechanisms used to implement the management strategy is governed by the management objectives and the fisheries management philosophy and structure that are in place (Annala and Sullivan 1997). Two types of mechanisms are used.

i) input controls - these have traditionally been used to manage lobster stocks and include controls on fishing effort and on the size or type of lobster taken, and

ii) output controls - these are being increasingly used to manage lobster stocks by controlling the total quantity of lobsters taken from a single stock.

A summary of stock assessment models and management objectives for the various lobster fisheries discussed is provided in Table 4.2.

4.2 Discarded lobsters - effects on survivorship and growth

Depending on the handling procedure, undersized lobsters (though returned to the water) experience various degrees of exposure, displacement and damage which adversely affect their survival and growth (Brown and Caputi 1986). The extent of "discard mortality" in undersized lobsters has been researched by a number of authors. Brown and Caputi (1983) conducted a number of laboratory, field and tagging experiments for the Western

Australian lobster fishery. Their work estimated discard mortality to be 11.4 %. Davis (1981) studied the effects of injuries on the spiny lobster *Panulirus argus* in Florida, and the implications that discard mortality has for management. He found that, besides discard mortality, undersized lobsters returned to the sea often suffer from subsequent reductions in growth.

Davis (1981) reported that limb loss results in reduced growth. No relationship between the degree of injury and the degree of moult increment reduction was found by Davis - rather, he concluded that even minor losses cause a substantial shift in growth patterns. Davis found that injured juveniles grew 39% less than uninjured lobsters. Davis also estimated that about 22% of injured lobsters would be lost recruitment to the fishery (for animals above the minimum size) due to injuries.

Waugh (1981) studied injury-induced growth retardation in *P.argus.* He estimated a 25-51% growth reduction for males, and a 13-25% reduction for females. Davis and Dodrill (1981), studying growth retardation in Florida Bay, estimated growth reduction to be only 6.3 %. Injury is not the only factor involved in discard mortality and reduced growth of undersized lobsters - exposure is also an important factor. Brown and Caputi (1986) found that moult increments were substantially reduced for lobsters experiencing exposure. They also showed an increase in predation by octopus on exposed lobsters. The number of subsequent deaths of exposed lobsters were also found to increase in direct proportion to the length of exposure.

The effect of discard mortality is thus relatively large, and is taken into account in the size structured model developed in this thesis.

4.3 Stock-recruit relationships in lobster species

The relationship between the spawning stock and recruitment into the fishery (usually several years after spawning) is a crucial consideration for management, because of its importance for predictions, yet one which has proven to be difficult to describe or estimate. Spawning stock sizes vary continually, due not only to fishing pressure, but also to the vast array of environmental and biotic factors intrinsic to the marine ecosystem. How recruitment responds (on average) to these fluctuations has been the core of a large deal of research. However, the effects of "environmental noise" on larval survival rates, together with measurement error, usually obscure the simple deterministic picture managers would like to see (Cobb and Caddy 1989), and leads to considerable variability about any underlying relationship.

Traditional two parameter stock-recruit models take two forms:

(1) overcompensatory - Ricker (1954), and

(2) asymptotic - Beverton and Holt (1957).

Both these models incorporate the notion of density-dependent mortality. Ricker (1954) developed the following relationship:

$R = \alpha S e^{-\beta S}$

where R is the recruitment, S is the spawning stock, and α and β are estimable parameters. This gives a dome-shaped curve, reaching a maximum at some intermediate stock size. In contrast, the asymptotic curve described by Beverton and Holt (1957) is

$R = S/(\alpha+\beta S)$.

More flexible models with three or more parameters have been developed more recently (e.g. Paulik 1973; Shepherd 1982; Tang 1985) and have been applied to theoretical modelling of lobster populations (Bannister and Addison 1984).

Modelling work on *Jasus lalandii* (this thesis) has indicated that recruitment may be dependent not only on stock size, but that other factors may also play a role. Neither a Ricker nor a Beverton-Holt stock-recruit relationship could be successfully fitted to *J.lalandii* data ranging from 1870-1994. For either of these two functions, the predicted recruitment in recent years resulted in a population size too low to be able to sustain the observed catches. A time-dependent recruitment function is therefore used instead in the models described in this thesis. This function (as finally estimated - see Chapter 7) is illustrated in Figure 4.1. One possible justification for such a function is that once recruitment is depressed to a certain level, refugia are likely to exist which prevent any further recruitment decline. For example, Fogarty and Idoine (1986) suggest that a

possible explanation for the apparent resilience of the American *H.americanus* lobster population is that refugia exist in which some segment of the population is unexploited (or less heavily exploited), and that this segment is capable of supplying recruitment for the entire population. A problem for the *J.lalandii* resource, however, is that the recent very low somatic growth rates and resultant declines in spawning biomass may have had an impact on recruitment. As it is estimated to take about six or seven years from the time of spawning until a lobster reaches the current legal size limit of 75mm for this fishery, the effects of a possible recruitment reduction will only manifest themselves some time after the reduced growth rate period began. Projections into the future may therefore prove over-optimistic if the possibility of such a recruitment decline is ignored.

Much research has been focused on possible stock-recruit functions for other lobster species. However, there are few good examples of such relationships. Tang (1985), in his investigations into suitable stock-recruit relationships for crustaceans, modified the Ricker stock-recruit model in order to account for density-independent mortality through fluctuating environmental conditions in addition to the density-dependent mortality implicit in the Ricker model. Morgan (1980) studied the stock-recruit information for *P.cygnus* in Australia. The abundance of the spawning stock of *P.cygnus* was indexed by commercial records such as the catch-per-pot-lift of females carrying eggs. The settlement of the subsequent puerulus larvae about nine months later was measured using artificial seaweed frames. Morgan found that a Ricker stock-recruit curve fitted these data well.

Morgan *et al.* (1982) described a clear overcompensatory stock-recruit curve for *P.cygnus* - but this relationship has been effectively challenged by more recent work which shows that in some stocks, environmental factors are more influential than spawning stock in determining recruitment levels, and the effect of fishing effort on spawning stock needs to be more clearly defined (Caputi and Brown 1993; Caputi *et al.* 1995).

Although settlement of puerulus larvae varies from year-to-year, it is the density-dependent effects in growth and mortality between the puerulus stage and juvenile stage which are important in maintaining recruitment to the fishery. Fogarty and Idoine (1986) examined recruitment dynamics in the American lobster *H.americanus*. An asymptotic relationship between the final larval stage and stock size five-seven years later was demonstrated, indicating the possibility of density-dependence regulation between larval settlement and subsequent recruitment to the fishery. Fogarty and Idoine suggested that a recruitment mechanism of this type would be highly stabilising and could explain the apparent ability of lobster populations to sustain high levels of fishing mortality. American lobster populations are subjected to annual fishing mortality rates of 85-90%, yet few instances of stock collapse have been recorded. The postulated recruitment mechanism may reflect competition for a critical resource, and these authors proposed that shelter is an important limiting resource.

The dome-shaped Ricker stock-recruit relationship that has been fitted for a number of lobster species is characteristic of fish with high fecundities, in contrast, fish with low fecundities tend to have asymptotic stock-recruit relationships (Ennis 1985). The western rock lobster *P.cygnus* is highly fecund. Morgan (1972) reported eggs per females from 110 000 at 65mm carapace length, to nearly 700 000 at 120mm. By comparison, fecundity in the American lobster *H.americanus* ranges from about 50 000 to less than 35 000 at these sizes. On the basis of this, Ennis suggests that the stock-recruit relationship in *H.americanus* can be expected to be asymptotic rather than dome shaped. *J. lalandii* females produce between 80 000 eggs per female (65mm carapace length) to between 100 000 - 200 000 (90mm) (Beyers and Goosen 1987). *J.lalandii* is therefore a fecund lobster species, and following Ennis's argument, one might therefore expect a dome-shaped Ricker type stock-recruit function to be more likely for *J.lalandii*.

Several hypotheses have been proposed to explain the variable nature of *H.americanus* lobster stocks. The earliest known decline in landings between 1890-1920 was primarily caused by excessive fishing of immature lobsters so that the breeding stock was severely depleted. Thereafter, no one simple explanation can be applied to all regions, suggesting that environmental factors may play a role (Harding *et al.* 1983). Recruitment fluctuations in lobster populations have also been ascribed to environmental affects. Climate has been associated with the success of *H.americanus* recruitment. Dow (1969; 1977) suggested that the 20-30 year climatic cycles indicated by sea surface temperatures (SST) of Boothbay harbour affect recruitment to these lobster populations throughout their range.

His hypothesis is that an optimal thermal condition exists for some limiting stage in the life cycle of the lobsters, and enhanced recruitment follows this optimum up and down the coast with each climatic oscillation. Dow (1977) and Flowers and Saila (1972) show that post World War II Maine lobster catches correlate well with coastal SST lagged by five-eight years. Marchessault *et al.* (1976) argue that with the relatively high intensities of fishing and low stock sizes characteristic of exploited crustaceans, recruitment becomes almost entirely a function of fluctuations in environmental variables. Ennis (1986) suggests a number of causes of variability in recruitment of *H.americanus* which include variation in temperature, variation in annual river discharge, fishery induced variability in egg production, man-made interruption in larval supply and ecosystem changes.

A conclusion that emanated from a workshop on crustacean stock-recruit relationships was that models which incorporate stock-recruit relationships directly often lead to more conservative estimates for sustainable yields (Bannister and Addison 1986). Constant recruitment models have, however, often been used for a number of lobster populations (Fogarty 1980; Ennis 1980; Bannister and Addison 1984;1986; Campbell 1985). For example, Bannister and Addison (1986) assume that recruitment to the fishery of the European lobster *H.gammarus* is independent of the spawning stock, and apply yield-per-recruit analyses based on the established length cohort methods of Jones, to provide management advice.

4.4 Somatic growth rates of lobsters

Somatic growth rates of lobsters can be highly variable in space and time, and are affected by a number of factors. Using laboratory experiments, Chittleborough (1975) examined environmental factors affecting growth and survival of juvenile western rock lobster. He found that:

i) growth rates increased with temperature;

ii) mild oxygen deficiency reduced growth rates;

iii) food shortage reduced both the frequency of moulting as well as growth increments; and

iv) loss of limbs reduced growth.

He calculated that food supply was the dominant factor determining growth and survival.

A number of other factors also affect the somatic growth of lobsters, such as maturation, injuries, handling and exposure, and confinement in traps. Hunt and Lyons (1986) examined the growth of *P.argus* lobsters. They found:

i) a dramatic decrease in growth between 71-80mm;

ii) the growth of sublegal lobsters (<76mm) for both male and females is very similar;

iii) growth of mature females is about 33 % less than that of mature males;

iv) injuries caused a 40% reduction in growth of small (<60mm) lobsters; and

v) injuries did not appear to affect the growth of larger sized lobsters.

The reduction in growth rate among both sexes after the size at maturation is reached indicates a change in the focus of energy use from growth to development of gametes and associated secondary sexual characteristics associated with the onset of maturity.

Waugh (1981) observed an injury-induced growth reduction of between 13-51% among juvenile *P.argus* from the Bahamas. Hepper (1972) reports a 17% smaller growth rate for female *Homarus vulgaris* lobsters than for males.

The cause of the recently observed decreased somatic growth rate of *J.lalandii* (see Chapter 3) is not yet understood, although a number of hypotheses exist. Recent work by Mayfield (1998) indicates that reduced food availability is unlikely to have resulted in the observed low somatic growth rates. The reduced somatic growth could perhaps be related to injuries sustained by undersized lobsters (prior to the reduction of the minimum size to 75mm) as a result of having being through an intense and repeated "sieving" process.

Table 4.1: Management controls in lobster fisheries (Annala and Sullivan 1997).

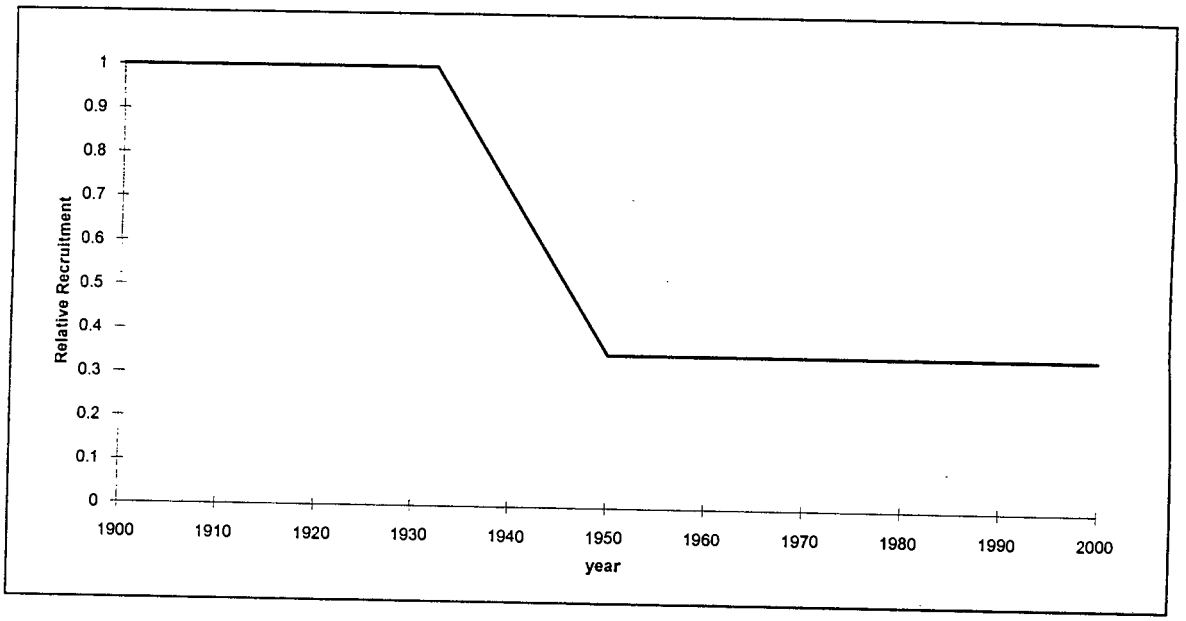
	South African *J.lalandii*	New Zealand *J.edwardsii*	Tasmania *J.edwardsii*	Western Australia *P.Cygnus*	USA *H.americanus*	Canada *H.americanus*	UK *H.gammarus*	UK *N.norvegicus*
Input controls:								
Limited entry	*[1]	*[2]		*	*	*		
Vessel size				*		*		
Gear restrictions	*			*	*	*		
Pot limits				*	*	*		
Escapement gaps	*	*		*	*	*		
Closed areas	*			*		*		
Closed seasons	*	*		*		*		
Minimum legal size	*	*		*	*	*	*	*
Condition eg berried		*				*		
Maximum legal size				*	*			
Output controls:								
TACs	*	*	*[3]			*		*
ITQs		*						
Bag limits	*	*		*	*			

[1] Implicit in the Quota Board.
[2] Implicit in the ITQ system.
[3] Applicable from March 1998.

Table 4.2: Summary of stock assessment models and management objectives for various lobster fisheries (information from Annala and Sullivan 1997).

Fishery	Stock assessment model/s	Management Objectives
South Africa *J.lalandii*	Size-structured dynamic population model, Surplus production models.	To rebuild biomass levels above 75mm by 20% by 2006.
New Zealand *J.edwardsii*	Yield-per-recruit, Egg-per-recruit, Surplus production models, and AD Model Builder version of a length-structured model	To ensure a maximum continuing yield from the fishery.
Tasmania *J.edwardsii*	Size-structured dynamic population model.	To harvest sustainably.
Western Australia *P.Cygnus*	Surplus production models. Size-structured dynamic population models.	To retain egg production levels above 25% pre-exploitation level. Improving the value of the fishery.
USA/Canada *H.americanus*	Surplus production models, Yield- and egg-per recruit models.	To increase egg production in the stock - aiming for egg production levels of 5% pre-exploitation level.
UK *N.norvegicus*	Yield-per-recruit models, multispecies models.	Optimise yields whilst maintaining adequate spawning stocks.

Figure 4.1: The recruitment function estimated for the size-structured model for South African west coast rock lobster.



Chapter 5: Data available for conducting the assessment

A number of data sets pertaining to the west coast rock lobster resource and its associated fishery are available. Some of these data sets contain long time series, such as the catch data series (from 1900), whereas the Fisheries Independent Monitoring Survey (FIMS) data are available for a relatively short time span only (since 1992). The work presented in this thesis was conducted in a number of stages. The first stage was the development of a size-structured stock assessment model of the resource and fishery. This work was completed during 1995. Data, such as the somatic growth rate and CPUE time series, which were used at the time of the model development have subsequently been updated, as new data have become available and improved analyses used to treat the raw data. The latter part of the work presented in the thesis - the development of an OMP (Operational Management Procedure) - provides a formula that will be applied to slightly different data series to those used in the initial model development stage. The various data series and their different treatments are described in full in Appendix 3 (somatic growth) and Appendix 4 (somatic growth, CPUE and FIMS).

In this thesis, the resource is treated as a single stock. This is for two main reasons:

i) some of the important data are available only for the resource as a whole - e.g. the historic catch data, and

ii) there is movement of lobsters between the various fishing grounds.

This section thus aims at discussing what data are needed for assessments on this basis. A brief description of the various data available is provided below.

5.1 Somatic growth data

The mean annual moult increment values for both males and females are required for input to the size-structured model. Moult increment data over a period of time (1969-1996) for mature males have been collected and documented by a number of authors and are summarised by Goosen and Cockcroft (1995). However, moult increment data for females are scarce, and are available for 1969-1972 (Newman and Pollock 1977) and 1992 (unpublished) only.

These somatic growth data (for both males and females) have been collected from a number of different fishing Areas along the west coast, between which the growth rates differ. Since the population modelling is conducted for the resource as a whole, some coast-wide index is required. General linear modelling techniques (GLMs) have thus been used to distinguish annual and spatial effects in growth rates for west coast rock lobsters. The GLMs used describe inter-annual and spatial variation in the somatic growth of the west coast rock lobster. Two different GLMs have been used to produce two slightly different somatic growth trends over time. At the time of the development of the size-structured estimation model, growth data up to and including 1995 only were available. Cruywagen (1995b) fitted a GLM to the data up to 1994, and Brown (1996a) extended his analysis to include moult increment data for 1995. This GLM is termed **GLM'95** and is

described fully in Appendix 3. The annual moult increment indices from this GLM are used both for fitting the model to data in the maximum likelihood estimation procedure used, as well as for projecting the population forwards into the future.

The next phase of this thesis deals with the development of an OMP for the resource. This work was performed during 1996 and 1997, at which stage somatic growth data for 1996 became available. Another GLM (with slightly different assumptions) was fitted to the full 1969-1996 data series. This GLM is termed **GLM'96**. The **GLM'96** data are used in calculating the 1997 TAC in conjunction with the selected OMP. The **GLM'96** is also described in Appendix 3. Both somatic growth data series are listed in Appendix 4.

In principle, the population model fitting exercise could have been repeated given the new data. However, both because addition of a few extra data would have meant little change and hence was not greatly relevant to the OMP estimation process, and also because the 1995 estimation had been formally agreed by the SFRI Rock Lobster Working Group as the basis on which to develop OMP tests, it was decided to continue with the 1995 assessment results.

The GLMs discussed above cover only the period 1969-1996. An average of the **GLM'95** values for 1969-1988 are used for the pre-data period 1870-1968. These values are assumed to represent the historic average somatic growth of the resource. Three possible somatic growth scenarios for projecting the resource into the future were selected by the Working Group:

i) LOW growth scenario - the somatic growth rate is assumed to remain at the 1989-1994 average level (which was a low growth period);

ii) HIGH growth scenario - the somatic growth rate is assumed to recover immediately to the 1969-1994 average level (note that this level is lower than the historic 1870-1968 level because the recent period of low growth values is included in the average);

iii) ARMA growth scenario - this scenario assumes that there is a gradual recovery of the somatic growth to the 1969-1994 average level according to an AR(1) model fitted to the preceding data (see Appendix 3.6.3).

The corresponding somatic growth values for these three scenarios are reported in Appendix 4, Table A4.1c.

5.2 CPUE (catch-per-unit-effort) data

Three different types of CPUE data are available for the west coast rock lobster fishery. These are the commercial trap CPUE, the commercial hoopnet CPUE and the FIMS CPUE data. All three CPUE data types are used in the maximum likelihood estimation procedure. As the likelihood-based model fitting analyses were completed in 1995, only data up to and including 1994 (for hoopnet and trap CPUE) and 1995 (FIMS CPUE) were used, due to data availability constraints. For the OMP application, where both the trap CPUE and FIMS CPUE are used as input to the OMP, new data became available and thus both the trap CPUE and FIMS CPUE data analyses were updated using different

techniques. The following is a brief description of the "original" CPUE data used in the likelihood.

5.2.1 Commercial trap CPUE data

These data have been collected by the SFRI from each of the commercial fishing Areas for the west coast rock lobster fishery. Data were available for 1975-1994. An area-weighted CPUE estimate has been calculated for each year (Cruywagen 1995a), to produce CPUE estimates which are representative of biomass of the resource as a whole (area-weighting is used as CPUE is presumed to be proportional to density, which must be multiplied by area to obtain abundance). These estimates are reported in Appendix 4 Table A4.2a, and are used in the likelihood estimation. The minimum size was reduced during the 1991 season from 89mm to 75mm. The CPUE for the 1991 season reported in Table A4.2a therefore corresponds to that for the first part of the season (min = 89mm); CPUE values for years from 1992 onwards are not comparable to those for earlier years because of this change.

5.2.2 Commercial hoopnet CPUE data

The commercial hoopnet CPUE data are collected in the same manner as the commercial trap data. Two types of hoopnet data are available - deckboat and bakkie. Bakkie data are collected from small fishing boats operating fairly close inshore. Deckboat data are collected from boats which are taken out further to sea by a larger "mother" boat. A GLM analysis was carried out to combine these two hoopnets data sources and to deal with

missing values (Brown 1996b). Data were available from 1987-1994. In the GLM only data from Areas 3-8 (to which the current assessment applies) are taken into account. These hoopnet data are listed in Appendix 4, Table A4.2b.

5.2.3 FIMS CPUE data

The fisheries independent monitoring programme (FIMS) for west coast rock lobster is described in full in an SFRI document (Anon., WG/08/95/WCL1). The main aim of FIMS is to monitor the abundance of the west coast rock lobster resource by providing annual relative abundance indices in a consistent manner which is independent of the problems of commercial CPUE data that can be biased as relative indices by changing fishing patterns. The four Areas sampled cover Area 3-8. Each stratum is stratified into shallow and deep regions, with the shallow regions sampled four times as heavily because of their likely greater rock lobster densities. The surveys are conducted over two two-week periods in each stratum. The FIMS data are obtained using traps, but with a 60mm mesh size, thus ensuring full selectivity for sizes of 60mm and larger. The FIMS CPUE data recorded thus represent the numbers of lobsters (not biomass) for the 60mm+ portion of the resource. Data were available for four years only: 1992-1995. The FIMS estimates for the four strata are area-weighted to produce an overall mean FIMS CPUE value for each year. These values are presented in Appendix 4, Table A4.2c.

5.2.4 "New" commercial CPUE and FIMS CPUE data analyses

Since the original analyses described above, new data (from 1995) have become available. This has allowed the analyses to be updated. The data from the "new" analyses have been used in conjunction with the selected OMP to calculate the 1997 TAC value.

A new form of commercial CPUE analysis is now preferred - this being based upon an extended GLM model. This CPUE GLM is described in Brown (1997b). The three methods used to catch west coast rock lobster, namely trapboats, bakkies and deckboats, have been used together in a GLM context to derive a combined index of abundance. A number of different GLM models were originally fitted to the data. The selected model includes both Year*Area and Month*Area interactions. The treatment of the FIMS data remained the same, except that now data for five years are available. The "new" trap CPUE and FIMS CPUE data are reported in Appendix 4 Table, A4.2d.

5.3 Catch-at-size data

Two sources of catch-at-size data are available: commercial trap data and FIMS data. Both these data series are used in the maximum likelihood estimation procedure.

5.3.1 Commercial trap catch-at-size data

The catch-at-size data series used in the likelihood function cover the period 1981-1994. These data were collected for the population component above the legal minimum size only. They have been collected from trap samples by the SFRI for each Area in each year

in 5mm size classes. A pseudo-weighting technique was used to weight the data from each Area to produce a catch-at-size frequency for each year. The aim of this weighting scheme was to retain the total sample size for each year, but to weight the individual Area data according to each Area's catch contribution in that year so as to obtain results most representative of the catch when considered as a whole (as in the assessments). These data are reported in Appendix 4, Table A4.3a-c, and the total sample sizes for each year are reported in Table A4.3d.

5.3.2 FIMS catch-at-size data

These data are available for 1992 - 1995 only. Data are for size classes ranging from 60mm+ in 5mm categories. The data were area-weighted. The FIMS catch-at-size data are reported in Appendix 4, Table A4.4a, and the FIMS catch-at-size sample sizes are reported in Table A4.4b.

5.4 Percent females in catch ($F^{\%}$)

Two sources for $F^{\%}$ estimates are available: the commercial trap samples and FIMS. Both these data series are used in the maximum likelihood estimation procedure.

5.4.1 Commercial trap sample data

This data series consists of catch-weighted $F^{\%}$ for 1981-1994 years and is reported in Appendix 4, Table A4.5a. Note that the percentages reflect the percent by **number** of

been made, but for many years it was 89mm. Recently the minimum size limit has been reduced and is at present 75mm (commercial). The minimum size limits that applied at various stages during the history of the fishery are reported in Appendix 4, Table A4.7.

Chapter 6: Population dynamics models and assessments

6.1 Introduction

Until about 1990, the assessment of west coast rock lobster resource involved little more than tag-return analyses and some simple yield-per-recruit calculations. As the fishery was in a fairly stable state during the 1980's, with TACs of around 3800 MT being harvested annually, no need was seen at that stage to develop more detailed analytical models of the resource and fishery, particularly because the 89mm size limit was considered as providing adequate protection to the female component of the resource. During the 1989 fishing season however, the fishery was placed under serious strain for the first time, with fishers unable to fill their quotas. A need to better understand the population dynamics of the resource had arisen. In 1990, the first size-structured model was developed by Barkai and Bergh (1990) in order to help understand and explain the then recent downward trends in catches in Zone A (Areas 1 and 2) - the most northern part of the South African west coast rock lobster resource. This model was subsequently extended to apply to the entire west coast resource.

Since 1990 a number of different modelling approaches have been developed and applied to the west coast rock lobster resource and fishery. These fall into two main categories: size-structured and surplus production type models. As lobsters cannot easily be aged, an analytical model of the resource must be based on size rather than age. Surplus

production models can, however, still be used in certain circumstances to obtain estimates of biomass trends and sustainable yields levels.

6.2 Data available

A number of data are available from the west coast rock lobster resource and the associated fishery, and are described in Chapter 5. A long time series of annual catches are available (from 1900). Indicators of resource abundance in the form of various CPUE data series are available for more recent years. A Fisheries Independent Monitoring Survey (FIMS) has been in place since 1992 to provide an index of the trends in resource abundance that is independent of the changes in fishing patterns. Furthermore, catch-at-size data are available from 1975. Tagging studies since 1969 provide data on the annual somatic growth rate of the lobsters. Most of these growth data are for the male lobster however, with relatively little data for the females.

6.3 Surplus production models

Simple surplus production models are frequently implemented to aid fisheries management, and usually make use of catch and fishing effort data. These models rely on a limited number of assumptions and can often provide robust estimates of sustainable yield. However, because these models are so simple, they cannot be used to address certain crucial management issues pertaining to lobster fisheries such as changes in minimum size. In their simplest form, they cannot take time delays into account, nor

departure from equilibrium, and they assume that the catchabilty of the fish remains constant.

Plaganyi (1991) assessed the dynamics of the Dassen Island (Area 7 - see Figure 2.1) sub-population of the west coast rock lobster resource using a surplus production model. Her study was aimed at investigating the value of a simple surplus production model as an alternative to more complex size-structured modelling approaches. Based on existing modelling work (Johnston 1991) which suggested that the surplus production curve for the resource is markedly skewed to the right, with B_{MSY} (the biomass at which MSY is achieved) at about $0.18K$, where K is the pre-exploitation biomass level, a surplus production function which could take this aspect into account was used. Specifically, Plaganyi used a Pella-Tomlinson surplus production model to reflect the dynamics of the resource at Dassen Island. The power parameter of the Pella-Tomlinson model was set at a value to achieve $B_{MSY} = 0.18K$. Plaganyi showed this surplus production model to be valuable in assessing the current state and productivity characteristics of the resource, but the model was unable to reproduce the low 1990 CPUE observation, which was presumed a result of very low somatic growth rates during the moult preceding the 1990 season.

Barkai and Bergh (1992) used Plaganyi's surplus-production model for the Dassen Island population, but included a new term (z_t) in the model to allow the intrinsic population growth rate to vary from year to year. This modified version of the Pella-Tomlinson model was as follows:

$$B_{t+1} = B_t + z_t r B_t \left(\left(\frac{K}{B_t} \right)^P - 1 \right) - C_t$$

where z_t = 1 in all years except for z_{1988} = 0.60, z_{1989} = 0.16 and z_{1990} = 0.16 (values chosen to reflect lower somatic growth rates in these years and hence better match the lower CPUEs for these years). This model was an improvement on Plaganyi's (admittedly at the expense of adding these extra parameters) as it was able to reproduce the CPUE trend more accurately, including the low 1990 CPUE estimate.

Davies (1992) used a similar surplus production model to that of Barkai and Bergh (1992) in his studies to compare the performance of size-structured versus surplus production models for the assessment of the west coast rock lobster resource. The surplus production model was fitted to the Dassen Island CPUE data series. Noise was introduced into the CPUE time series. Davies' results showed that the surplus production model was able to reproduce the observed CPUE trend adequately, but that there was a substantial positive bias (about 64%) in predictions of future biomass levels. This is due to the inability of this type of model to account for the delayed effect of poor growth on future resource biomass in projections. Davies therefore concluded that surplus production models are unsuitable for predictions, but can provide adequate estimates of sustainable yields.

Bergh and Barkai (1994) estimated sustainable yields for the west coast rock lobster resource using both a standard Fox surplus production model and a modified Fox model. The standard Fox model was fitted to catch and CPUE data from the resource from 1975

to 1989. These fits appeared unable to reproduce the sharp trends evident in the observed CPUE. This was thought to be due to the fact that at large values of the harvest proportion value, the model gets forced into the domain of the declining left hand limb of the Fox sustainable yield versus biomass curve, and thus tends to produce a decreasing CPUE trend, even though the observed trend showed a clear increase. To get around this difficulty, the Fox model was modified so that for $B < K/e$,

$SY = MSY\ [\ \gamma + B(1-\gamma)\ /\ (K/e)\ ]$, i.e. a linear decline in SY (sustainable yield) with decreasing values of B (biomass), where MSY is the normal Fox model MSY, and γ is the proportion of MSY that can be harvested as a SY when the entire biomass above 89mm is removed each year (such a SY is not zero because of recruitment from smaller sizes). This "modified" Fox model produced a better fit to the CPUE and the CVs of the parameter estimates were generally much smaller than those achieved with the standard Fox model. This modified Fox model was fitted to CPUE data for the resource from 1975-1989, but commenced in 1900, using recorded 1900-1989 catch data - this was a key change in the modelling of the resource as previously the population was assumed to be at equilibrium in the late 1970's. The fitting criteria also included a term for the mean harvest proportion from 1985-1987. Replacement yields for 1988 were calculated for both models and were estimated to be about 5000-6000 MT (for a 89mm minimum size limit).

A Pella-Tomlinson surplus production model was used by Johnston and Bergh (1994) to estimate the sustainable yields and current status of the sub-populations of the west coast

resource in various Areas. Most previous analyses had been targeted either on Area 7 (Dassen Island sub-population) or the resource as a whole. The surplus production model was fitted independently to data from each of the six Areas of the fishery (Areas 3-8), as well as to data representative of the resource as a whole. The purpose of the study was to identify whether an Area-by-Area approach was feasible for assessing the resource. The models were run from 1969 and fitted to CPUE data for the 1975-1990 period. The population was assumed to be at an equilibrium in 1969 corresponding to a given harvest level. Estimates of the biomass at the start of the 1990 season and MSY estimates for each Area as well as for the resource as a whole were obtained. Bootstrap estimates of variance for these estimates were also calculated. The surplus production estimators were shown to perform poorly. They appeared unable to distinguish whether the resource is characterised by having a large biomass (large K value) or a very large intrinsic rate of increase (or sustainable yield capacity) (large r). An Area-by-Area analysis using surplus production estimators was thus considered to be unsuitable for the west coast rock lobster resource.

Cruywagen and Cochrane (1994) modified both Schaefer and Pella-Tomlinson surplus production models to model male and female lobsters separately. These models were modified so that although males and females were modelled separately, their dynamics were inter-linked as the surplus production function for each component depended on the sum of the male and female biomass. The models were run from 1900. Both models estimated the 1994 female biomass as a proportion of pristine to be about 5-6 % - very

low levels which initiated considerable debate with regard to critical egg production levels necessary for the maintenance of recruitment to the resource.

Bergh and Barkai (1995) used the modified Fox surplus production model (as described in Bergh and Barkai 1994 - see above) to compare the performance of the west coast rock lobster resource under either a step-wise TAC reduction scheme or a constant catch level over the next five years. During previous years, extensive research efforts had been directed at improving the size-structured methodology for assessing the resource, and these authors felt that it would be worthwhile to attempt to extend the methods available for assessing the resource to include a simpler surplus production approach. They felt that consistency between results of such an approach and the size-structured model results would be of interest. Bergh and Barkai attempted to modify their Fox model so that it could take into account that the following parameters had changed over recent years:

i) somatic growth rates,

ii) legal minimum size limit, and

iii) catchability.

The manner in which these parameter changes were incorporated in the model was rather crude. The model also relied on size-structured model output for some of its inputs, and which leads to elements of circular reasoning when comparing the results to the size-structured model. The model was however argued to be of use for comparing the outcome of different TAC options over the next, say, five years.

6.4 Size-structured modelling approaches

Most of the analytic models developed for fishery stock assessments have been based on age, e.g. yield-per-recruit models. The reason for this is that mathematical expressions and resulting computations are much simpler for a variable such as age that is a simple linear function of time. For most fish species it is possible to determine the ages of the fish using scales or otoliths. A problem exists, however, for fish that cannot be easily aged. Fish found in the tropics, for example, do not manifest seasonal growth and hence lack otolith rings, as such which can be used to determine age. These fish are thus very difficult to age. Animals that moult, such as crustaceans, also pose a problem, as ageing of moulting organisms is almost impossible. A need to develop models that can be based on size as opposed to age clearly exists. Some of the earliest analytic models, e.g. Baranov (1918), considered the structure of populations in terms of length. Since then, however, for more than half a century, analytic models have been based almost exclusively on age. Since the 1980's, an awareness of the need to develop models based on size-structure developed, and the situation finally changed, with a number of new techniques based on size frequencies being developed. Size-structured models are now more feasible to implement than in the past, as the advent of computers has enabled more complex models to be relatively easily run given rapid numerical processing. Researchers now recognise that there is in fact a good fundamental reason for preferring length to age, as many of the important biological and fishery characteristics such as fecundity and gear selectivity are more closely related to size that to age (Gulland 1987).

Rosenberg and Beddington (1980) summarise the advantages underlying the development of length-based methods of stock assessment:

i) length data are simple and cheap to obtain,

ii) quite large sample sizes are feasible to acquire (as opposed to age-based samples, because ageing is relatively much more expensive in terms of resources),

iii) length is intrinsically more biologically meaningful than age, and

iv) both fishing mortality and natural mortality are likely to be size-dependent rather than age-dependent (because predators, including fisheries, are generally size-selective).

A number of different types of models which incorporate size-structure or use length frequencies have been developed. Lefkovitch (1965) and Usher (1971) suggested modifications of the Leslie (1945) model which allows the use of life-cycles and size classes. Sainsbury (1982) developed a size-structured model to examine the historical pattern of exploitation of the paua (*Haliotis iris*) which cannot be aged. Sainsbury's model is structurally similar to the Leslie matrix model. Shepherd (1987) developed a size-based model which is fully dynamic. Shepherd used a transition matrix which incorporates both length-specific growth and mortality functions. Schnute (1987) proposed a size-structured model for exploited fish populations. This model was deterministic. Schnute *et al.* (1989a, b) presented a statistical version of the Schnute (1987) size-structured model, and illustrated its application to stock assessment.

A number of methods have been developed for analysing length frequency samples, and associated computer programs, for example, ELEFAN (electronic length frequency analysis) have been produced (Schnute and Fournier 1980; Pauly and David 1981; Fournier and Breen 1983). These models aim to use length frequencies to estimate mortalities and von Bertalanffy growth parameters. Once the analysis of the size frequencies has produced these estimates, they can be used for either production modelling or yield-per-recruit analyses.

Many length-based stock assessment methodologies require a von Bertalanffy growth model to translate length into age so that the exponential decay cohort model can be applied, e.g. length-cohort analysis (Jones 1979;1984; Lai and Gallucci 1987;1988). These methods are limited in their applicability by a number of assumptions (Sullivan *et al.* 1990) on which they are based:

i) length distributions are in a steady state over time,

ii) recruitment into the fishery is knife-edged and constant in magnitude, and

iii) growth is a deterministic process with length-at-age being well defined.

Sullivan *et al.* (1990) developed a size-structured population model to be used to describe changes in population abundance over time. The model describes growth using a stochastic model based on the probability of individuals moving from one length class to another. A gamma distribution is used to represent variation in growth. The Sullivan *et al.* model makes no assumptions with respect to the steady state of length distributions or

knife-edge recruitment. Growth is included in the model dynamics by means of a length-based transition matrix.

A number of age- and size-structured population models have been developed and used in the study of the population dynamics of commercially harvested crustacean species. Botsford and his associates worked extensively on the population dynamics of the Dungeness crab off northern California using an age-based population model (Botsford and Wickam 1978; Botsford 1986). The model they used was aimed at determining the cause of cyclic fluctuations in the catches of the crabs. Botsford (1984) reports results from a size-specific model to study the effect of different somatic growth rates of the crab on their expected behaviour.

Caddy has made a number of important contributions both with respect to age-structured models (Caddy 1977;1986) and size-structured models Caddy (1979). Caddy took note that for crustaceans, the intermoult period is the fundamental biological time unit. Hence he developed (Caddy 1987) an integrated length-based model for crustaceans, which takes into account of the fact that growth occurs through a series of moults (in contrast to continuous growth).

Addison (1986) and Bannister and Addison (1986) worked extensively on length-based yield-per-recruit models for the lobster fisheries in England and Wales. A size-based model, similar to that developed by Caddy (1979) and subsequently modified by

Campbell (1985), is used by Shotton (1989) to evaluate policy options for lobsters and other moult-type fisheries. Campbell (1985) applied a yield- and egg-per-recruit model (developed by Caddy 1977; 1979) to model the lobster fishery in the Bay of Fundy. Schnute and Fournier (1980) presented a new approach to length frequency analysis which takes into account the biological structure in the mean lengths and standard deviations in length for various age classes. New parameters are defined for von Bertalanffy growth which prove to have greater biological meaning and numerical stability. Rosenberg *et al.* (1986) applied a length-structured approach for the analysis of krill population dynamics. Fogarty (1986) developed a model incorporating size-specific growth rates and a stochastic representation of lobster growth for *H.americanus*. The model was used to explore the effects of changes in the minimum size and of fishing mortality rates.

Since 1989 when somatic growth rates of the west coast rock lobster were observed to decline drastically (relative to previously recorded levels) the west coast rock lobster fishery has been under considerable strain, with TACs being progressively reduced as this low growth rate phenomenon has persisted. A need for detailed analyses of the west coast rock lobster resource and its associated fishery thus arose in order to attempt to answer the many questions both scientists and the industry were posing, such as:

- how has the sustainable yield of the resource been affected by the low somatic growth rate ?
- what will happen if the somatic growth rate remains low and does not recover ?

- will a change in minimum size ease the situation ?

- could a male-only fishery be advantageous ?

- how have egg production levels been affected ?

- what is the replacement yield ?

In order to answer these questions and to explore the dynamics of both the population and the fishery in detail, a size-structured model is required, which must also be sex-disaggregated to be able to predict the numbers of both male and female lobsters at different sizes over time.

Although Barkai and Bergh developed a size-structured model in 1990 to examine the northernmost zone for the west coast rock lobster resource, it was only in 1991 and 1992 that this was extended to encompass the whole of the west coast rock lobster resource. This size-structured model is a constant recruitment model and operates at a 1mm size interval, with males and females being treated independently. It has the novel feature of using a Beta probability distribution to model the movement due to growth of lobsters from one size class to the next (growth rates are known to be highly variable !). The model assumes an equilibrium population size-structure (under the calculated fishing mortality level) in the first year considered. This model is described more fully in Bergh and Johnston (1992), and has been used in a number of applications. For example, estimates of adult natural survivorship were obtained by fitting the model to pristine population size-structure information (Johnston and Bergh 1993). The pristine size-structure information was obtained from unfished protected populations (in sanctuaries)

and from catches made at the beginning of the fishery. The age of the sanctuary (i.e. the length of time since fishing was prohibited) at the time of the data collection was shown to be critical when estimating natural survivorship. A dynamic analysis was carried out to adjust for the bias associated with the age of the sanctuary. Estimates of annual survivorship ranged from 0.88 - 0.95 These estimates were also shown to be very sensitive to the assumptions concerning the somatic growth. This size-structured model was also used to investigate the impact of interannual fluctuations in moult increments on the *J.lalandii* fishery (Bergh and Johnston 1992).

Davies' (1992) comparison of the performance of a size-structured model to that of a surplus production model is discussed above in the context of biomass and sustainable yield estimation. He also reported that the size-based model was insensitive to the noise in CPUE and catch size composition data, provided that the historic mean moult increment time-series is well known. However, he found substantial estimator bias and increased variance for biomass estimates when random observation error was added to the time series for the historic mean moult increment.

A size-structured model was used alongside a surplus production model to estimate sustainable yields and current biomass status of sub-populations of the west coast fishery (Johnston and Bergh 1994). The size-structured models produced a good fit to the CPUE data for each Area, but did not fit to the catch size-structure information very well. A size-structured modelling approach was also used to determine the extent to which egg

production had been depleted relative to pristine levels in the southern regions of the fishery (Johnston and Bergh 1992). Egg production under equilibrium conditions was estimated for various levels of harvest proportions and minimum sizes.

Barkai and Bergh (1992) presented a new management strategy for the west coast rock lobster resource based on size-structured modelling analyses. Their recommendation was to reduce the minimum legal size limit from 89mm to 65mm. This work was sponsored by the industry who were particularly worried about the ever decreasing TACs since the time when the somatic growth rate decline commenced. They proposed a substantial increase in TAC in conjunction with this reduction in minimum size. The rationale behind these recommendations centred on the fact that at that time most of the biomass above 89mm had been exhausted (due to fishing), and due to the very low somatic growth rates only small amounts were recruiting into the component of the resource above the minimum legal size each year. In attempting to catch their quotas, fishers were forced to discard very large numbers of undersized lobsters which were brought up in the traps. Bergh and Barkai argued that about 15% of these discarded undersized lobsters would die as a result of their being caught and thrown back to the sea - resulting in a large and unnecessary mortality of lobsters. By reducing the size limit to 65mm, almost all lobsters caught in the traps would thus be of legal size and would be retained, reducing the discard mortality substantially. This would have a net positive effect on the biomass of lobsters in the long term, even though at 65mm a larger TAC would be taken.

The Barkai-Bergh model was based, however, on the very important assumption that during the 1980's the resource was able to sustain a harvest of at least 3800 MT at a harvest proportion (catch/89mm+ biomass ratio) of 0.40. This assumption was justified by Barkai and Bergh on the basis that the CPUE had increased over this period whilst the catch remained about 3800 MT annually. The model also assumed the population to be at equilibrium at the start of the 1980's - after nearly 100 years of exploitation with a wide range of catches. The Barkai-Bergh model and associated recommendations were subjected to external review. Reviewers' responses varied, but the main criticism was concerned with the 3800 MT sustainability assumption, which was considered to be not fully justified. Most scientists of the Rock Lobster Working Group (Sea Fisheries Research Institute) also had reservations about this assumption.

A need for a size-structured model which is not dependent on any assumptions concerning the sustainability of catch levels during recent years, and does not assume an equilibrium population size-structure in such years had clearly arisen. This led to the development by Johnston and Butterworth (1995) of the "1870 size-structured model" that is presented in this thesis. This model contains the following features.

i) The 1870 model makes no assumptions as to the sustainability or otherwise of the catches taken during the 1980's.

ii) More importantly, it does not assume the population to be in equilibrium at any stage except in the first year, 1870, when the fishery commenced. The model thus provides a non-equilibrium population size-structure for 1975+ (the

- period for which data are available, to which the model is fitted).

iii) Annual catch from the time series of catch data is used to update the population each year from 1870 to the present.

iv) An important new feature of this model was the way in which somatic growth is modelled. General linear modelling analyses provide annual moult increment indices for males and females from 1969 to the present. The model uses these values in conjunction with a normal probability distribution to model the variability in growth for each size class of lobsters.

v) The model allows for "shrinkage" (i.e. negative somatic growth) - a phenomenon that has been observed since the growth rates have declined.

vi) The model attempts to use as much data available for the resource as possible when estimating the various estimable parameters. Three main types of data are incorporated into a likelihood function: CPUE data, catch size-structure data and the percentage of females in the catch each year.

Chapter 7: The "1870 size-structured" model

7.1 Data available

All data (and their associated analyses) are described fully in Appendix 4. Three types of data are used in the model.

i) Input data to the model:

- somatic growth data
- historic catch series
- minimum size limits over time

ii) Data used in the maximum likelihood estimation: only data up to 1994 (and 1995 for FIMS) are used (for reasons given below):

- CPUE data (trap and hoopnet)
- FIMS CPUE data
- catch-at-size data (traps and FIMS)
- percentage females in catch ($F^{\%}$) data (traps and FIMS)

iii) Data used for projections and the Operational Management Procedure (OMP) implementation (used from 1992 onwards):

- somatic growth data
- trap CPUE data
- FIMS CPUE data

At the time of the development of the size-structured model, data up to and including 1994 (and 1995 for FIMS) only were used as these were the data available at the time the assessment upon which the OMP evaluations were to be used was agreed by the SFRI Rock Lobster Working Group. The analyses of these raw data to provide composite values representative of the west coast rock lobster resource as a whole were in some cases done in a slightly different manner to the analyses of data that became available subsequently. For example, the trap CPUE data (1975-1994) used in fitting the model were obtained using area-weighted commercial trap CPUE data. The trap CPUE data (for years up to and including 1996) used for the TAC calculations in conjunction with the selected OMP were obtained using a general linear model (Brown 1997a) - see Chapter 5 for further details.

7.2 Model structure

The model used for the analyses in this thesis is a size-structured model which is described fully in Appendix 1. A size-based model is appropriate for the stock assessment of west coast rock lobster for a number of reasons. Lobsters are very difficult to age, and hence most data collected for *J.lalandii* have been based on size, such as the catch-at-size data, growth increments-at-size data etc. Another important reason is that the question of what legal minimum carapace size to set is a very important management issue, and the model must be able to provide sustainable yield estimates for different minimum sizes.

The aim of the size-structured model that is presented here is twofold:

i) to be able to take full account of the various data that have been collected from the west coast rock lobster fishery and population itself in an assessment procedure that provides robust estimation; and

ii) to provide a basis to project the population forward into the future in order to investigate a range of future management options.

The model for the population starts in 1870 (when industrial catching commenced) with the assumption that the population was in a pristine state, and hence an equilibrium size-structure can be used for the initial population size-structure at that time. This avoids the questionable realism of the alternative of assuming an equilibrium structure for, say, 1975 as in some earlier models (see Chapter 6). Running the model forward from 1870 thus provides the (non-equilibrium) size-structure for 1975. The fit of the population dynamics model to data for the 1975-1995 period, and the projection of the results under various possible future harvest levels, depend only on this "input" 1975 size-structure, i.e. it does not matter what gave rise to that structure. Hence, this approach can be thought of as providing a more defensible "Base-Case" 1975 population size-structure than the equilibrium assumption method as described in Bergh and Johnston (1992), given the proviso that the sensitivity of results to variations in this input size-structure is examined.

Although early (hoopnet) catch-at-size data are available for the fishery, such as Gilchrist's 1913 data from hoopnets, and similar data from the mid-1930's, these data are not included amongst those to which the model is fitted because their reliability must be

open to question, given their antiquity and the uncertainty surrounding the details of the methods used for the data collection. For example, it is unclear whether or not they are representative of the overall catch in the years concerned. While this information could be taken into account in the overall fit of the model, that could result in the goodness of fit to more contemporary data (1975+) being considerably diminished. The price of a poorer fit to recent data does not seem warranted in circumstances of severe reservations about the earlier data, particularly since a good fit to recent data is paramount for future projections to be considered reliable.

The model has a vector-matrix structure and operates at a 1mm size interval scale, with males and females being treated separately. The dynamics of the model assumes that the fishery is a pulse fishery and hence has a discrete structure, in contrast to a continuous fishery model. The model calculates the initial equilibrium population size-structure in 1870 as a starting point. The population is then projected forwards to the present time taking changes in somatic growth, fishing mortality, natural mortality, discard mortality and recruitment into account.

A "Base Case" model is developed, which models the population and fishery to what is considered to be to the best of current knowledge (as reflected by discussions in the SFRI's RLWG). A number of assumptions regarding recruitment, natural survivorship, gear selectivity, discard mortality and somatic growth rates are made. These assumptions

are described below. The candidate OMPs considered later (see Chapter 10) are tested for robustness to a number of changes in these assumptions.

7.2.1 Recruitment

The model is essentially a constant recruitment model, with recruitment not being explicitly dependent on the spawning biomass level. However, recruitment does drop over time in a step-like manner, with the year and magnitude of the decrease being estimated when fitting the model to the data.

An attempt was made to incorporate a functional relationship between recruitment and spawning biomass explicitly, by fitting to either a Ricker or a Beverton-Holt stock-recruit function, but the resulting fits to the data were very poor. This was because a very steep left arm is needed for the stock-recruit function given the historic catch series, but this then indicates a sudden biomass decline in recent years which is not consistent with the CPUE data. The difficulty is that a large initial recruitment is required to enable the population to sustain the large historic catch levels. However, this high recruitment level produces biomasses that are far too large for more contemporary periods - indicating that some recruitment decline must have occurred which needs to be taken into account in the model. A step-like recruitment function is therefore used, which involves the assumption that recruitment declines from its initial to a lower level over a number of years (Figure 7.1). The year in which the decline begins (y^*) as well as the level to which the

recruitment declines to (R_2) are estimable parameters of the model (as is the initial recruitment level, R_1).

7.2.2 Natural survivorship

Estimates of natural survivorship are required for the size-structured model. Natural survivorship is related to natural mortality by $S = e^{-M}$, where S is the annual natural survivorship, and M is the instantaneous rate of natural mortality. Estimates of natural survivorship for the west coast rock lobster were obtained using a size-structured modelling approach in conjunction with sanctuary size-structure information which was assumed to correspond to that of a pristine resource (Johnston and Bergh 1993). Values of adult annual natural survivorship of between 0.88 and 0.90 for male lobsters were estimated. Although a single estimate for females was obtained (0.95), this was based on one small data set, and thus little confidence can be placed in it. Due to different somatic growth rates, one would expect that male and female lobsters may have different natural survivorship levels.

The adult male survivorship level is set equal to 0.90, whilst the adult female survivorship level is an estimable parameter of the model, subject to constraints of a minimum of 0.85 and a maximum of 0.95. The 0.95 constraint was based upon the Johnston and Bergh (1993) estimate indicated above (although this is probably a poor estimate). The 0.85 constraint was based upon the supposition that it seems unlikely that female survivorship could be that much lower than that for males. Both male and female

natural-survivorship are assumed to be constant over time. Given the relatively weak basis upon which these natural survivorship values have been fixed, tests of the sensitivity of the model results to alternative assumptions are examined, as reported in Chapter 8.

7.2.3 Gear selectivity

Two forms of fishing gear have been used in the west coast rock lobster fishery:

i) **hoopnets** (ringnets) which were used exclusively until 1969; and

ii) **traps** which were introduced in 1969 and have gradually become the dominant form of gear.

At present, more than 85% of the commercial harvest is caught using traps. The two gear types have different selectivities. One of the reasons for the difference is that in hoopnets, the larger lobsters are able to chase out smaller individuals, which results in a relatively higher selectivity for larger lobsters. The trap gear on the other hand is not subject to this effect, as once a lobster is trapped it cannot be chased out of the trap. Besides these mechanical selectivity differences between the gear, there are also differences between the locations where the different gears are predominantly deployed. Because lobster distribution is both sex- and size-dependent, the resultant availability differences have to be reflected in the model by different selectivities. Furthermore, different portions of the stock reside in different parts of the habitat at certain times of the year. For example, females come close inshore during breeding. Hoopnets are set mainly close to shore, where the larger lobsters are also found to reside. Traps, on the other hand, are usually set

further offshore in deeper waters. Thus, although the gear selectivities are time-dependent, i.e. change through the year, this is ignored in the model which treats the fishery as a pulse-fishery. This is not an unreasonable assumption, as most of the catch being taken in the first few months of the season.

For both hoopnets and traps, male and female selectivity functions are defined separately in the model. The male and female hoopnet selectivities are defined in relation to the male and female trap selectivities respectively (see Appendix 5).

7.2.4 Discard mortality

Although it is obvious that fishing mortality arises as a result of lobsters being caught and removed from the sea, another form of fishery-induced mortality also needs to be considered - discard mortality. A certain proportion of undersized lobsters that are caught and returned to the sea die as a result of their capture. This discard mortality can result from geographic dislocation, vulnerability to predators, physical injury, etc. (Davis 1981; Waugh 1981; Davis and Dodrill 1981; Brown and Caputi 1983;1986). A value of 10% for discard mortality is used in the model. Although this value is similar to the estimate of discard mortality of 11.4% calculated for *Panulirus cygnus* in Western Australia by Brown and Caputi (1983), there is no strong justification for using the 10% value. The effect of this assumption is therefore examined through a number of sensitivity analyses (see Chapter 8).

7.2.5 Somatic growth rates

An important part of this modelling exercise overall has been the development of a detailed somatic growth model. The results from the size-structured model are highly sensitive to the somatic growth rates of the lobsters. As it is the low growth rates of recent years in particular that have put the resource and fishery under considerable strain, the accurate representation of the annual moult cycle increment is of special importance.

A thorough literature survey of all available *J.lalandii* growth data was conducted. Moult increments were found to have varied quite considerably over time and from Area to Area. General linear modelling analyses (Cruywagen 1995; Brown 1996a) were used to isolate the time dependence, i.e. to estimate the important inter-annual moult increment variations. Variance estimates for the mean annual growth increment values were also calculated.

The growth models are described in detail in Appendix 3. At the time of the development of the size-structured model, growth data were available for the period 1969-1995 only. The model assumes that the growth rates were unchanged for the period 1870-1968 and these are set equal to the averages for the 1969-1988 period. This was because the low growth observed since 1989 is seen to be an anomaly and not part of the normal natural inter-annual historic growth variation that would be expected.

Growth rates for the future are modelled in terms of a number of different future growth rate scenarios. These are also described in Appendix 3, and include use of time-series models.

7.3 Parameter estimation procedure

The model contains a number of parameters whose values are estimated in the process of fitting in terms of maximum likelihood criterion (see Appendix 2 for details). These parameters are as follows:

i) R_1 (pristine recruitment);

ii) R_2 (reduced current level of recruitment - note $R_2^* = R_2 / R_1$)

iii) y^* (year at which R_1 decline commences);

iv) P_1 (female trap selectivity parameter - length axis-intercept value);

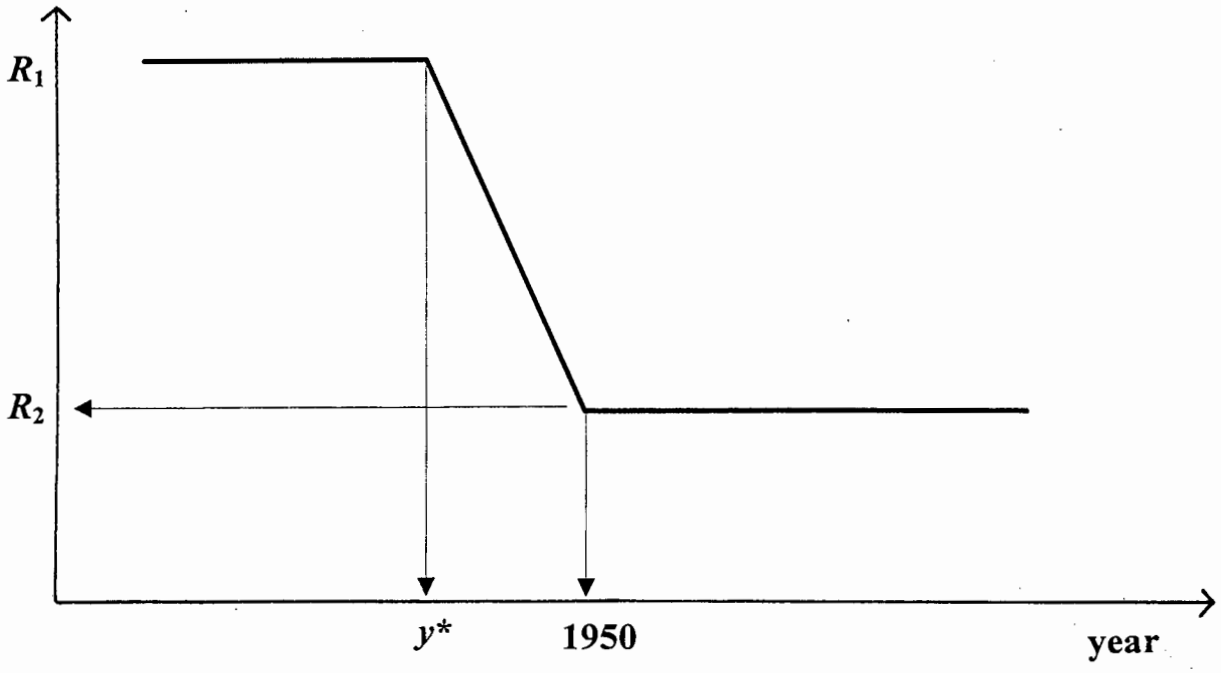
v) P_2 (female trap selectivity parameter - scaling factor); and

vi) S^f (female annual natural survivorship).

A number of different data sets from the fishery are available. These include commercial CPUE estimates (hoopnet and trap), FIMS (Fishery Independent Monitoring Survey) CPUE estimates, catch-at-size data (trap and FIMS), and percent-females-in-the-catch (FIMS and trap). These data, together with all other input data for the model, are presented in Appendix 4.

A simplex estimation Fortran software routine, called AMOEBA (Press *et al.* 1986) was used to maximise the likelihood with respect to the estimable parameters. This routine carries out a downhill simplex minimisation (Nelder and Mead 1965) of an objective function with multiple parameters. The objective function includes variances that are estimated during the estimation procedure.

Figure 7.1: The recruitment function used in the "1870 size-structured" model.



Chapter 8: Size-structured model parameter estimation procedure - results

8.1 Base Case model

8.1.1 Parameter estimates

The parameter values estimated for the Base Case model fit to the available data are reported in Table 8.1. The standard errors for the parameter estimates are given later (Table 8.4). The residual standard deviation (σ) values for trap CPUE and hoopnet CPUE data are similar (0.34 and 0.31 respectively). The σ value estimated for the FIMS CPUE is lower at 0.19.

None of the values of the six parameters (R_1 ... S^f) found by the non-linear search routine seem unrealistic (nor are any a reflection of the constraints imposed on the estimates - see Appendix 2, section A2.3). It is interesting to note that the female annual natural survivorship (S^f= 0.87) is estimated to be slightly lower than that assumed for males (S^m= 0.90). The estimate for the female trap selectivity scaling value (P_2 = 0.78) is consistent with the supposition by field biologists that females are less selected than male lobsters by the traps because they tend to be found inshore of the region where traps are placed. The model estimates the contemporary recruitment level (1950+) to be about 35% of pristine (1870) recruitment. It is evident that a high pristine recruitment is required in order for there to have been sufficient lobsters for the large catches in the 1940's and

1950's to have been taken. This high level of recruitment must be reduced for more recent years in order to produce reasonable fits to the CPUE data. Maintenance of recruitment at levels necessary to achieve the catches of the 1940's and 1950's precludes the lower catches of the 1980's leaving the resource at a sufficiently low level for the abundance decline at the end of that decade, which is indicated by the CPUE data, to have occurred.

8.1.2 Fits to data

8.1.2.1. CPUE data

The Base Case model fits to the three CPUE data series are illustrated in Figures 8.1a, 8.2a and 8.3. For the trap CPUE and hoopnet CPUE, the 1995 observed and estimated values are included in the Figures (for comparative purposes), although these data were not included in the likelihood as they were not available at the time the model estimates were finalised. The fits to all three CPUE series are fairly good. Recall that the likelihood function includes a weighting factor which gives greater weight to more recent data values (see Appendix 2, section A2.2), with the aim of fitting the model more closely to the most recent data, as is most pertinent given the importance of accuracy for the projections required for OMP evaluation.

The trap CPUE fit appears to be poor for the 1994 data point. The data used in the likelihood showed a 37% decrease in CPUE between 1993 and 1994 (as shown in

Figure 8.1a). These CPUE data (Table A4.2a in Appendix 4) are as adopted by the SFRI RLWG at the time (mid-1996) when model estimates were finalised for OMP evaluation purposes. More recent data analyses making use of a GLM standardisation procedure (Brown 1997b) have shown this decrease to be far less - about 13%. The fit to this 1994 data point would thus be better if values from this more recent GLM analysis had been used in the likelihood. It is also important to bear in mind that for all three CPUE data series, the model estimated CPUE values for 1994 and 1995 are greater than the observed values - indicating that the model may be somewhat over-estimating recent biomass values! A recent recruitment decline, not taken into account in the model, is one possible explanation for this observation, though the associated residuals are not so large as to suggest a statistically significant effect.

The trap CPUE residuals[1] (Figure 8.1b) show a systematic trend - the estimated CPUE values being larger than those observed for the 1975-1981 period, and then the reverse for the 1982-1992 period. This indicates that there is some additional and unexplained non-random variation still present. The model is unable to reproduce the large observed trap CPUE increase from 1980 to 1985. A number of factors which are not taken into account in the model could have been responsible for this increase, for example, a number of good year-classes as a result of better than average recruitment, or an increase in the availability of the lobsters due to favourable environmental conditions continuing over a number of years.

[1] Note that these residuals are for log CPUE (see Appendix 2) and have been standardised by dividing by their estimated standard deviation.

The hoopnet CPUE residuals (Figure 8.2b) show similar features to the trap CPUE residuals. However, this data series starts only in 1987, and so imposes less constraint on the model which is able to fit it better than the trap CPUE series. Comments on the fit to the FIMS CPUE data would be premature, given that there are only four data points in this series.

8.1.2.2. Catch-at-size data

The observed and model-estimated trap catch-at-size percentages are shown in Figures 8.4-8.12. As many of the plots show similar features, results are shown only for a selection of years, with those for males and females shown separately. Note that observations for the 75-90mm size range became available only from 1993, following the reduction in size limit at that time.

MALES

The fits to the male data are good up to the year 1993 (Figure 8.10a). For 1994 and 1995 the fit deteriorates somewhat, with the model overestimating the number of larger sized lobsters.

FEMALES

The overall fit to the female data is fairly good, although a systematic trend for the years 1981-1990 is apparent - the model overestimates for the 90mm[2] size class and underestimates for the 95mm size class. These discrepancies, while consistent over the period indicated, are not too large. The data for the 75-85mm classes over the 1993-1995 period are well represented by the model.

[2] Remember that the size class 90mm refers to lobsters 90,91..94 mm in size.

Plots of the root mean square errors against $\sqrt{n_e}$ (the transformed estimated values - see equation A.2.11 in Appendix 2) are shown in Figure 8.13. These results indicate that the weighting as described in Appendix 2 results in residuals which show no obvious deviation from homoscedasticity.

The fits to FIMS catch-at-size data (Figure 8.14-8.17) are reasonably good. The model does generally overestimate the percentage of males caught from the 60mm size class, and also the percentage caught from the larger size classes. The former observation is of some concern, as it could be indicative of lower incoming recruitment. However, the fact that there does not seem to be a translation of this effect to larger sizes over time suggests that it is more likely related to selectivity or natural mortality rate assumptions. The residuals show no obvious deviation from homoscedasticity (Figure 8.18).

8.1.2.3. Data on the percentage of females in the catch ($F^{\%}$)

The fit to the $F^{\%}$ data from the trap catches (Figure 8.19a) is good, although the model overestimates $F^{\%}$ for the last two years (1994 and 1995). The residuals reflect a slight systematic trend (Figure 8.19b), showing how the model initially underestimates $F^{\%}$ until 1986 when it starts to overestimate $F^{\%}$ slightly. The fit to the FIMS $F^{\%}$ data (Figure 8.20) shows that the model consistently and substantially overestimates the $F^{\%}$ in recent years. The reason for this is unclear, although is likely to be linked to the location and timing of the FIMS sampling (very close inshore, and close to the moulting phase of

the females). This is broadly consistent in directional terms with the deviations in the fit to the trap $F^{\%}$ data, though of a much bigger magnitude.

8.1.3 Biomass trends

The estimated biomass trends for B_{75} (both-sex biomass above 75mm carapace length) and B^{sp} (female spawning biomass reflected by B_{65} for females alone) are illustrated in Figures 8.21 and 8.22 respectively. The B_{75} value at the start of the 1996 season is estimated to be 20.3 '000 MT - only 6% of the pristine level (Table 8.2). From Figures 8.21b and c it is evident that the male portion of B_{75} was eroded at an earlier stage than the female portion. By 1950, the male portion was only 54% of its pristine level, whilst the female portion was still 90% of its pristine level. This can be explained by the fact that at the minimum legal size of 89mm (enforced for most of the period of the fishery), relatively few females were caught, thus providing a refuge of sorts for the female lobsters. This refuge has been drastically reduced over more recent years due to a combination of factors including the recruitment decline estimated to have occurred since the 1930's, the reduced somatic growth rates since about 1989 and the reduction of the minimum legal size to 75mm.

The female spawning biomass (Figure 8.22) is estimated to have remained close to pristine levels until about 1940 when the recruitment decline began to have an influence. Although recruitment is estimated to now be only 34% of the pristine level, the 1996 estimate for B^{sp} is 17.9 '000 MT - only 21% of the pristine B^{sp} level. This is near to the

The female spawning biomass (Figure 8.22) is estimated to have remained close to pristine levels until about 1940 when the recruitment decline began to have an influence. Although recruitment is estimated to now be only 34% of the pristine level, the 1996 estimate for B^{sp} is 17.9 '000 MT - only 21% of the pristine B^{sp} level. This is near to the 20% of initial of spawning biomass level at which recruitment in fisheries is often considered likely to decline if B^{sp} is reduced further (Clark *et al.* 1985).

As the population model "hard-wires" a recruitment step function, there is no mechanism for the stock to rebuild to the pristine level under this function. This is not thought to be an issue of immediate concern, as the current biomass levels are so small that one can't expect pristine recruitment levels to be able to be achieved in the near future.

8.2. Sensitivity tests

The Base Case model estimation procedure was subjected to a number of tests, to investigate the sensitivity of the resultant estimates of model parameters and variables to a number of changes to some of the underlying assumptions of the model. The sensitivity tests performed, together with the abbreviations used to identify them were:

Annual natural survivorship (male) (Base Case $S^m = 0.90$)

sm1: $S^m = 0.85$

sm2: $S^m = 0.95$

Discard mortality (Base Case $d = 10\%$)

d1: $d = 0\%$

d2: $d = 5\%$

d3: $d = 15\%$

Gear Selectivity: Traps (see Appendix 1, Figures A1.2a and A1.2b)

s1: $l^0 = 60$mm (Base Case $l^0 = 50$mm)

s2: $l^* = 90$mm (Base Case $l^* = 100$mm)

Somatic Growth

sg1: annual female somatic growth is at all times 0.25 mm more than thought

sg2: annual female somatic growth is at all times 0.25mm less than thought

sg3: the historic annual growth rate is taken to be as the 1985-1987 average, instead of the higher 1969-1988 average.

The results of these sensitivity tests are reported in Table 8.3. Values are reported for statistics of all the model parameters of Table 8.1, as well as for the quantities $B_{75}(1996)$, $B^{sp}(1996)$, $B_{75}(1996)$ as % pristine, and B^{sp} (1996) as % pristine (note B_{75} refers to male and females combined).

As might have been expected, the model estimates are sensitive to the value input for male annual natural survivorship. A surprising result found however, is that for both

robustness tests (S^m= 0.85 and S^m = 0.95) the model estimates for B_{75}(1996) are larger (37.9 `000 MT and 32.0 `000 MT respectively) than that for the Base Case (20.3 `000 MT), i.e. the dependence of the current biomass estimate on S^m is not monotonic. This result is unusual as one might have expected the model biomass estimate to increase with a larger S^m value and to decrease with a smaller S^m value. In the S^m = 0.85 test, the model fit reacts by increasing the estimate for S^f (female natural survivorship) to be equal to 0.95 (the upper bound applied for S^m and S^f). For the S^m = 0.95 test, the fit responds by reducing the pristine recruitment level and the year in which recruitment starts to decline. The model however **also** increases the estimate of female annual natural survivorship to 0.89. The goodness-of-fit to the data is reduced for both tests, particularly for the S^m = 0.95 case. Nearly all the σ values for the residuals are larger for both S^m sensitivity tests, which is indicative of much worse fits. Thus the S^m = 0.90 Base Case assumption produces the best fit to the data amongst the three value of S^m examined.

The model estimates are only slightly sensitive to the value assumed for discard mortality over the range tested (Table 8.3a). The d = 0% test does produce better fits to the CPUE data, but the overall likelihood value is smaller than that for the Base Case.

The tests **s1** and **s2** (Table 8.3b) show little sensitivity to assumptions concerning values of the parameters of the trap gear selectivity function. The B^{sp}(1996) estimate for test **s1** increases to 28.5 `000 MT compared to the 17.9 `000 MT estimated for the Base Case

model, although the B^{sp} (1996) as a proportion of the pristine value (0.22) remains close to the Base Case value (0.21).

The tests concerning the somatic growth rate of lobsters are important as there has been much controversy in the SFRI RLWG surrounding the development of the growth model and the various assumptions it makes. What is evident from Table 8.3b is that test **sg1** (female growth 0.25mm more) there are only moderate changes to current biomass estimates. The changes to these biomass estimates are somewhat more pronounced for the **sg2** test (female growth 0.25mm less) where the B_{75}(1996) estimate is increased to 28.9 `000 MT (a 42 % increase over the Base Case estimate).

The sensitivity to the assumption regarding the historic growth rate is tested in **sg3**. The results indicate that by using a shorter and more contemporary series of growth data to provide an average value for the historic series, the model biomass estimates are increased substantially. The B_{75}(1996) estimate is increased to 46.1 `000 MT, and the B_{75}(1996) estimate as a proportion of the pristine value increases to from 0.06 to 0.14.

8.3 Bootstrap estimates of variance

A parametric bootstrapping procedure (Efron 1982; 1985) was used to obtain estimates of variance for the model parameter estimates, as well as for estimates of recent biomass.
This procedure involves generating a number (100 used here) of bootstrap samples of "pseudo-data". These "pseudo-data" are randomly generated from parametric

distributions for the residuals about the original estimated values obtained from fitting the model to the actual data. The parametric distributions have variances equal to the variances of the residuals for the initial model fit to true data. The parametric bootstrap procedure is described in detail in Appendix 6.

The results are presented in Table 8.4. The median value, the 5^{th} and 96^{th} values in an ordered set, as well as the CVs (as %) are given. The highest CV reported is for the σ_{FIMS} (the FIMS CPUE σ value) for which the CV is 46%. The results suggest that many of the estimates reported are very precise, with CVs less than 3%. This high degree of precision is due to the fact that the model is being fitted to a very large amount of data. These indications of very high precision are probably unrealistic as they assume independence of the input data values, whereas many of the residuals for the fits to the actual data indicate systematic trends which could be interpreted as positive correlation. Taking such correlation into account in the bootstrap process would certainly reduce the level of precision indicated. The low cv's may also be due to some of the other parameters (male natural mortality and selectivity) being fixed.

Table 8.1: Parameter estimates for the Base Case model fit to the data.

Parameter	Explanation	Estimated value
σ_{trap}	σ for trap CPUE data	0.341
σ_{hoop}	σ for hoopnet CPUE data	0.310
σ_{FIMS}	σ for FIMS CPUE data	0.189
$\sigma_{size\text{-}trap}$	σ for trap catch-at-size data	9.655
$\sigma_{size\text{-}FIMS}$	σ for FIMS catch-at-size data	6.155
$\sigma_{F\%\text{-}trap}$	σ for trap percentage females in catch	0.574
$\sigma_{F\%\text{-}FIMS}$	σ for FIMS percentage females in catch	0.639
$-lnL$	negative ln likelihood value	827.70
R_1	pristine recruitment	3.065×10^8
R_2*	current recruitment as a proportion of R_1	0.345
y*	year at which R_1 decline commences	1932
P_1	female trap selectivity parameter - length axis - intercept value	110 mm
P_2	female trap selectivity parameter - scaling factor	0.781
S^f	female annual natural survivorship	0.866

Table 8.2: Biomass estimates ('000 MT) from the Base Case model fit to the data for B_{75} (male and female), B_{75}^{m}(male only), B_{75}^{f} (female only) and B^{sp} - the female spawning biomass (> 65mm). Values in brackets are the ratios of the biomass in question to the corresponding pristine level.

Year	B_{75}	B_{75}^{m}	B_{75}^{f}	B^{sp}
1950	207.4 (0.58)	170.8 (0.54)	36.7 (0.90)	66.6 (0.78)
1960	108.5 (0.30)	82.8 (0.26)	25.7 (0.63)	41.9 (0.49)
1970	48.4 (0.13)	33.1 (0.10)	15.3 (0.38)	30.4 (0.35)
1980	35.7 (0.10)	24.5 (0.08)	11.2 (0.28)	26.1 (0.30)
1990	24.6 (0.07)	18.5 (0.06)	6.0 (0.15)	21.2 (0.25)
1996	20.3 (0.06)	18.4 (0.06)	1.8 (0.05)	17.9 (0.21)

Table 8.3a: The sensitivity of parameter estimates to variations in the Base Case model specifications (tests **sm1-d3**). Biomass estimates are given in `000 MT.

	Base Case	**sm1** * $S^m = 0.85$	**sm2** * $S^m = 0.95$	**d1** + $d = 0\%$	**d2** + $d = 5\%$	**d3** + $d = 15\%$
R_1	3.065×10^8	3.054×10^8	3.01×10^8	3.089×10^8	3.058×10^8	3.517×10^8
R_2*	0.345	0.344	0.415	0.340	0.345	0.340
y*	1932	1924	1900	1929	1931	1917
P_1	110	110	107	110	110	110
P_2	0.781	0.779	0.787	0.794	0.785	0.791
S^f	0.866	0.950	0.892	0.857	0.860	0.858
-lnL	827.70	939.69	1463.16	895.09	856.82	860.20
σ_{trap}	0.341	0.508	0.303	0.269	0.296	0.282
σ_{hoop}	0.310	0.625	0.396	0.326	0.316	0.311
σ_{FIMS}	0.189	0.189	0.182	0.185	0.187	0.193
$\sigma_{size\text{-}trap}$	9.655	10.131	51.632	13.107	11.226	11.366
$\sigma_{size\text{-}FIMS}$	6.155	9.040	22.661	6.693	6.319	6.274
$\sigma_{F\%\text{-}trap}$	0.574	3.148	0.839	0.579	0.574	0.797
$\sigma_{F\%\text{-}FIMS}$	0.639	1.120	0.073	0.574	0.600	0.572
B_{75}(1996)	20.3	37.9	32.0	24.3	22.2	23.1
B_{75}(1996) as proportion of pristine	0.06	0.07	0.26	0.07	0.06	0.06
B^{sp}(1996)	17.9	71.3	38.2	17.3	17.3	17.6
B^{sp}(1996) as proportion of pristine	0.21	0.15	0.30	0.23	0.22	0.20

* Modify Base Case value for annual male natural survivorship S^m of 0.90

\+ Modify Base Case value for discard mortality rate of 10%

Table 8.3b: The sensitivity of parameter estimates to variations in the Base Case model specifications (tests **s1-sg3**). Biomass estimates are given in `000 MT.

	Base Case	**s1*** l^0=60	**s2*** l^*=90	**sg1$^+$** female growth 0.25 more	**sg2$^+$** female growth 0.25 less	**sg3$^+$** historic growth is 1985-87 ave growth
R_1	3.065 x 10^8	3.13 x 10^8	3.01 x 10^8	3.071 x 10^8	3.66 x 10^8	4.23 x 10^8
R_2*	0.345	0.361	0.403	0.348	0.348	0.344
y*	1932	1921	1924	1930	1906	1928
P_1	110	110	110	110	110	110
P_2	0.781	0.800	0.790	0.791	0.929	0.776
S^f	0.866	0.896	0.877	0.851	0.880	0.873
-lnL	827.70	863.02	845.06	840.20	951.54	1074.40
σ_{trap}	0.341	0.331	0.333	0.318	0.308	0.361
σ_{hoop}	0.310	0.418	0.399	0.313	0.362	0.371
σ_{FIMS}	0.189	0.192	0.193	0.189	0.191	0.189
$\sigma_{size\text{-}trap}$	9.655	10.803	10.462	9.943	16.277	19.610
$\sigma_{size\text{-}FIMS}$	6.155	5.574	6.534	6.425	6.681	9.487
$\sigma_{F\%\text{-}trap}$	0.574	0.952	0.533	0.814	1.477	0.865
$\sigma_{F\%\text{-}FIMS}$	0.639	0.778	0.674	0.579	0.630	0.582
B_{75}(1996)	20.3	25.6	25.3	21.3	28.9	46.1
B_{75}(1996) as proportion of pristine	0.06	0.07	0.06	0.06	0.07	0.14
B^{sp}(1996)	17.9	28.5	23.0	16.4	23.5	29.0
B^{sp}(1996) as proportion of pristine	0.21	0.22	0.21	0.21	0.22	0.29

* Changes to Base Case trap selectivity function

\+ Changes to Base Case assumptions regarding past somatic growth rates

Table 8.4: Bootstrap estimates of variance for the Base Case model estimates.

Estimate	Bootstrap results			
	Median	5th %ile	96th %ile	CV%
σ_{trap}	0.353	0.248	0.443	16.98
σ_{hoop}	0.310	0.178	0.468	28.87
σ_{FIMS}	0.143	0.045	0.279	45.89
$\sigma_{size\text{-}trap}$	11.64	10.88	11.94	3.08
$\sigma_{size\text{-}FIMS}$	6.349	6.282	6.397	0.50
$\sigma_{F\%\text{-}trap}$	0.571	0.351	0.828	23.43
$\sigma_{F\%\text{-}FIMS}$	0.589	0.313	0.981	32.76
-lnL	864.27	847.17	875.70	0.99
R_1	$3.05\ 10^8$	$3.00\ 10^8$	$3.07\ 10^8$	0.67
R_2*	0.346	0.343	0.348	0.93
y*	1930	1930	1932	0.04
P_1	110	110	110	0.47
P_2	0.784	0.780	0.790	0.38
S^f	0.866	0.856	0.873	0.73
B_{75}(1990)	24.9 `000	24.1 `000	25.9 `000	2.54
B_{75}(1996)	22.3 `000	21.7 `000	22.7 `000	1.67
B^{sp}(1996)	17.6 `000	16.1 `000	19.7 `000	7.73
B_{75}(1996) as proportion of pristine	0.051	0.050	0.052	2.05
B^{sp}(1996) as proportion of pristine	0.212	0.209	0.215	1.48

Figure 8.1a: Observed and Base Case model-estimated trap CPUE.

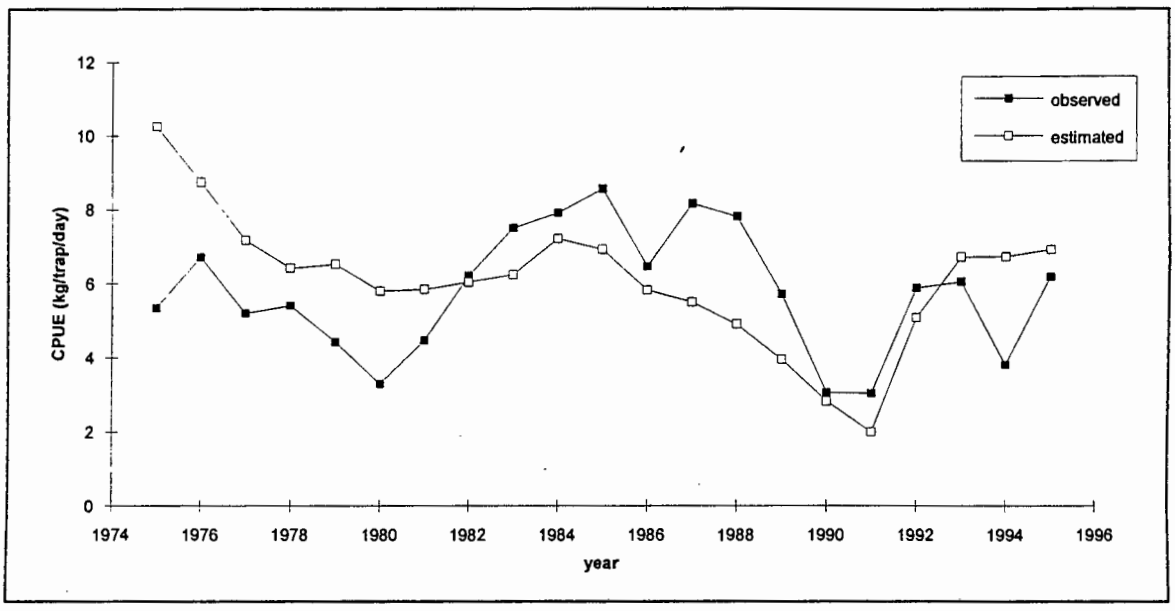


Figure 8.1b: Trap CPUE standardised residuals.

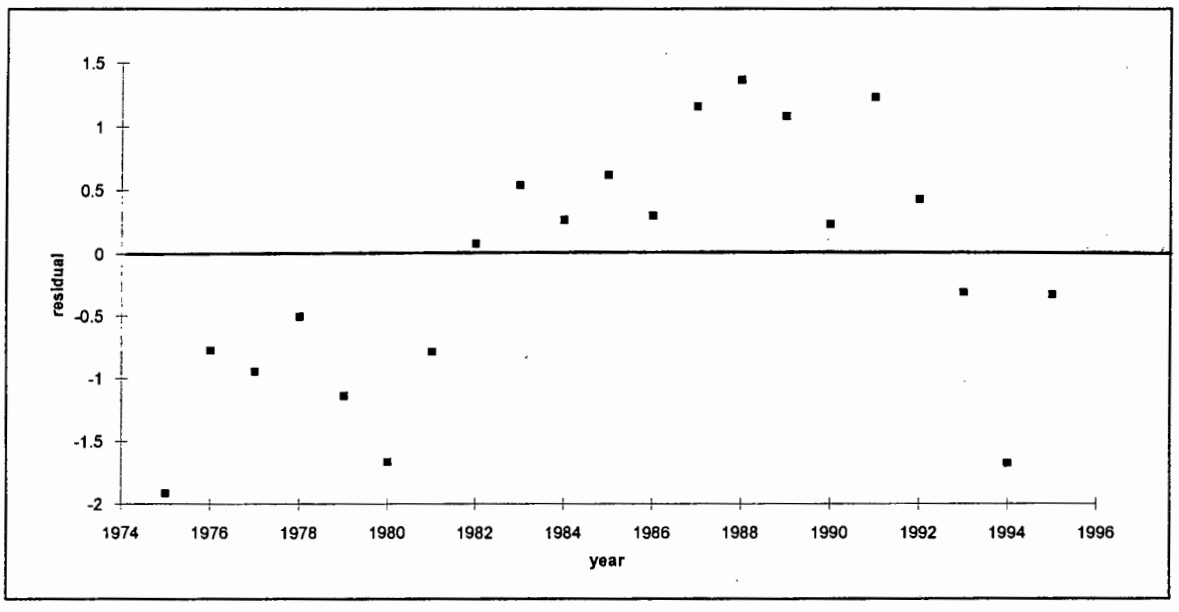


Figure 8.2a: Observed and Base Case model-estimated hoopnet CPUE.

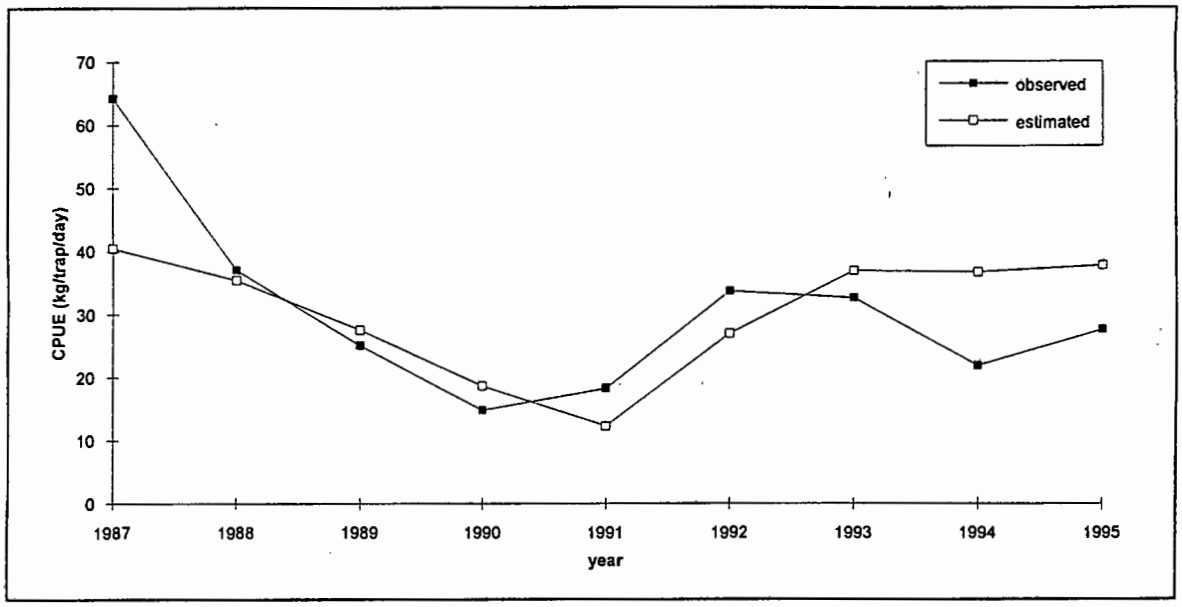


Figure 8.2b: Hoopnet CPUE standardised residuals.

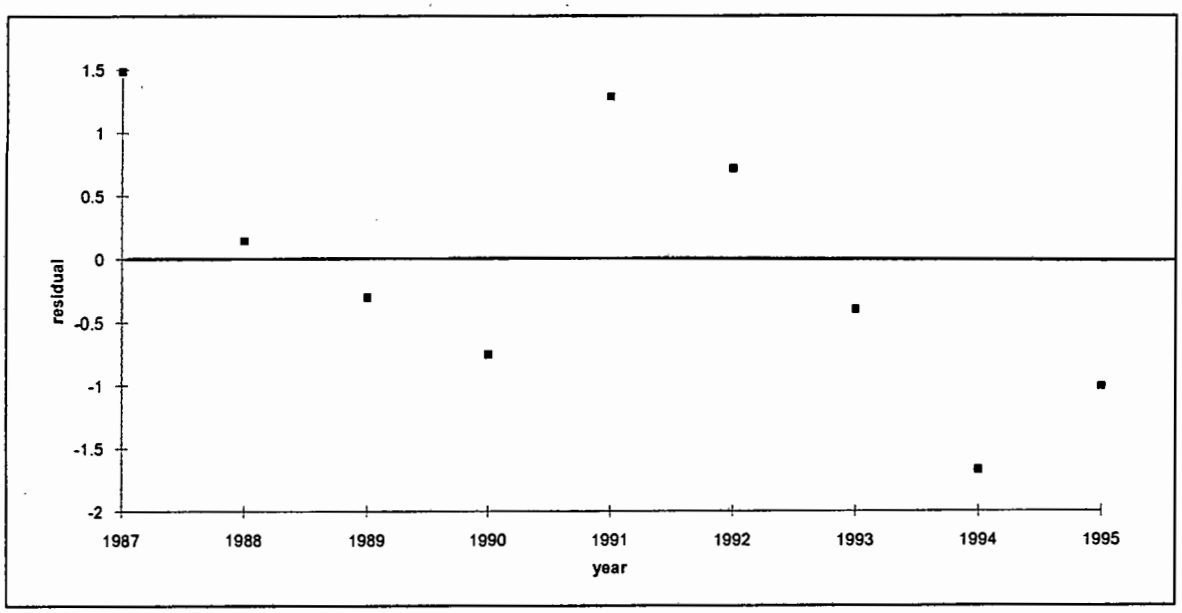


Figure 8.3: Observed and Base Case model-estimated FIMS CPUE.

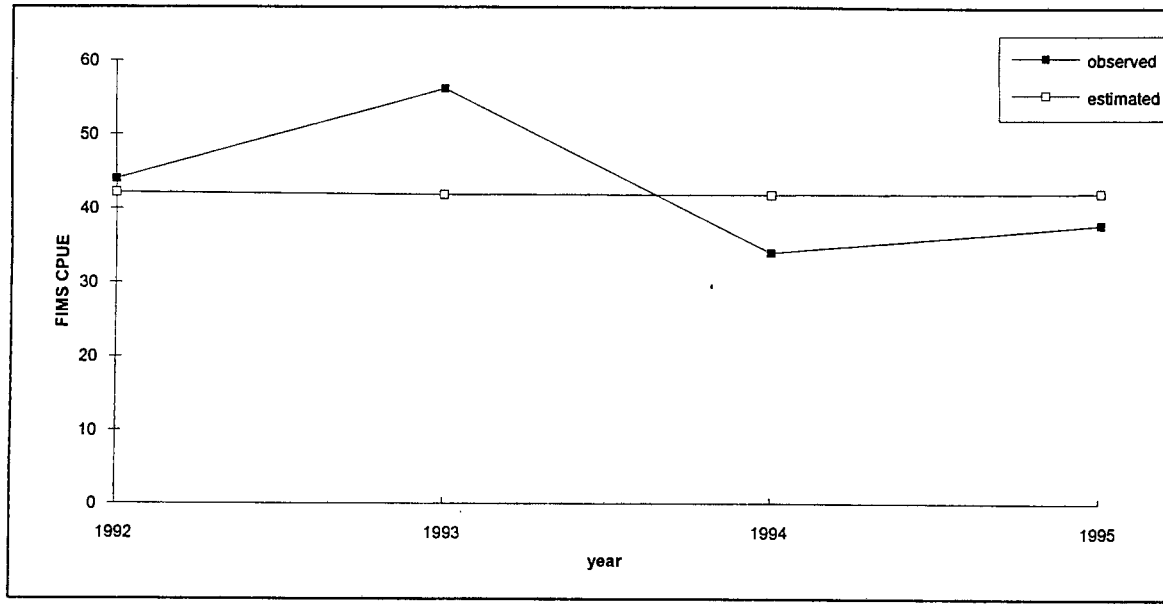


Figure 8.4a: Observed and Base Case model-estimated male trap catch-at-size - 1981.

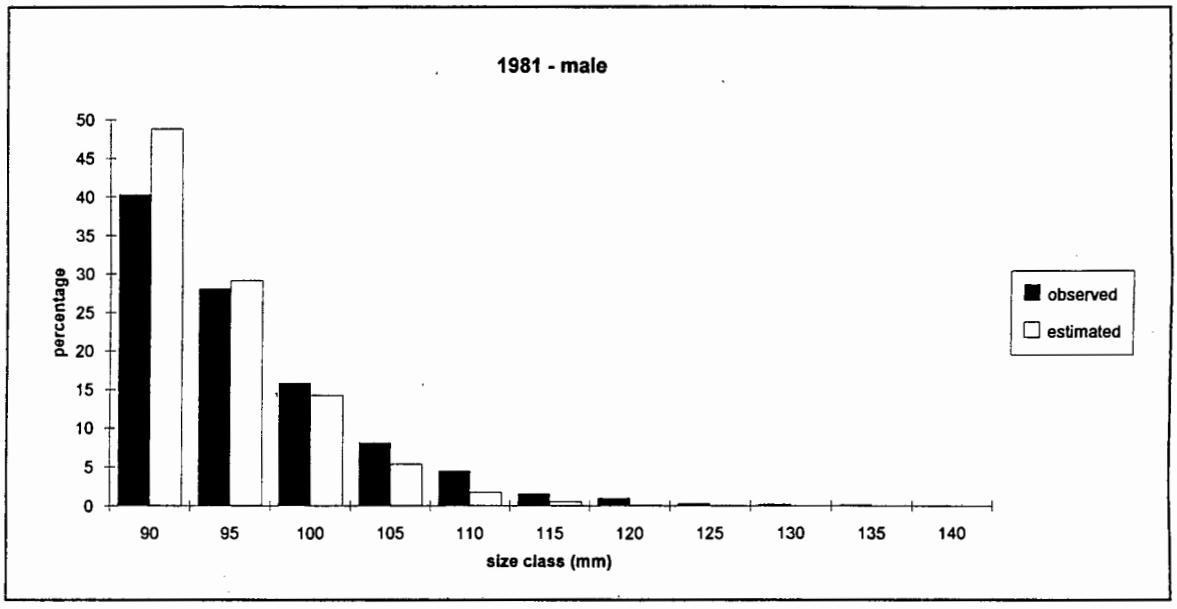


Figure 8.4b: Observed and Base Case model-estimated female trap catch-at-size - 1981.

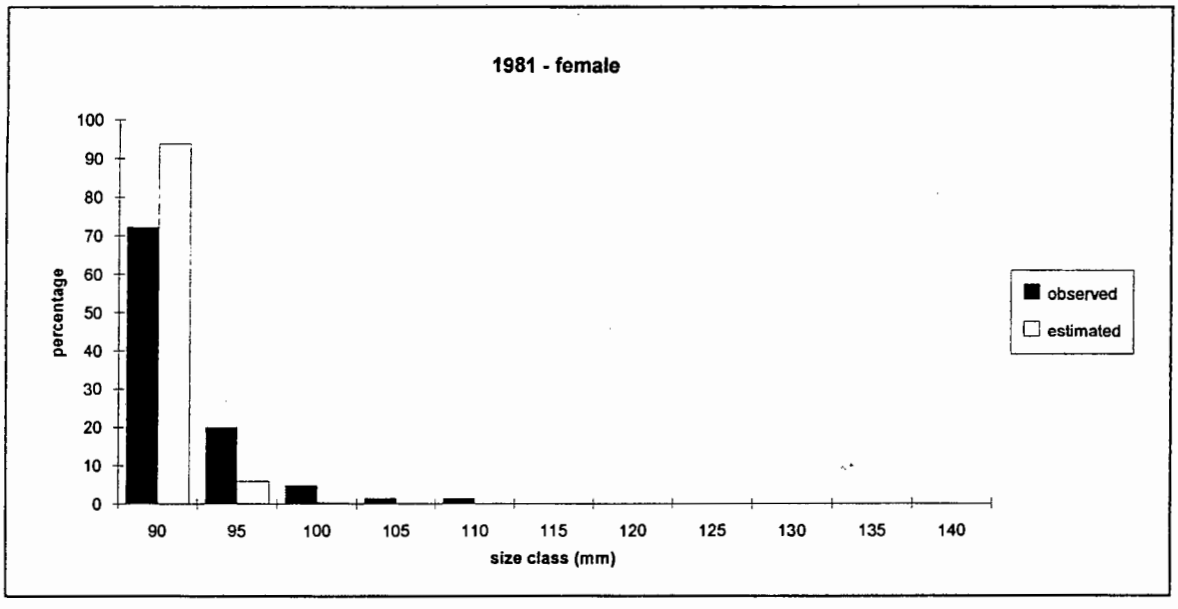


Figure 8.5a: Observed and Base Case model-estimated male trap catch-at-size - 1983.

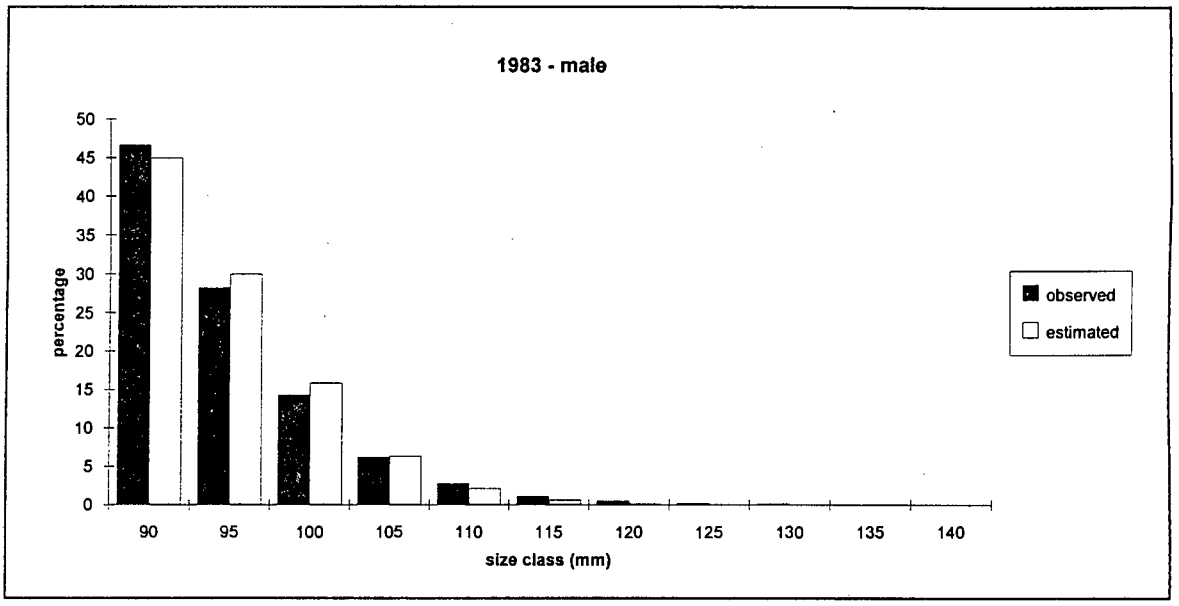


Figure 8.5b: Observed and Base Case model-estimated female trap catch-at-size - 1983.

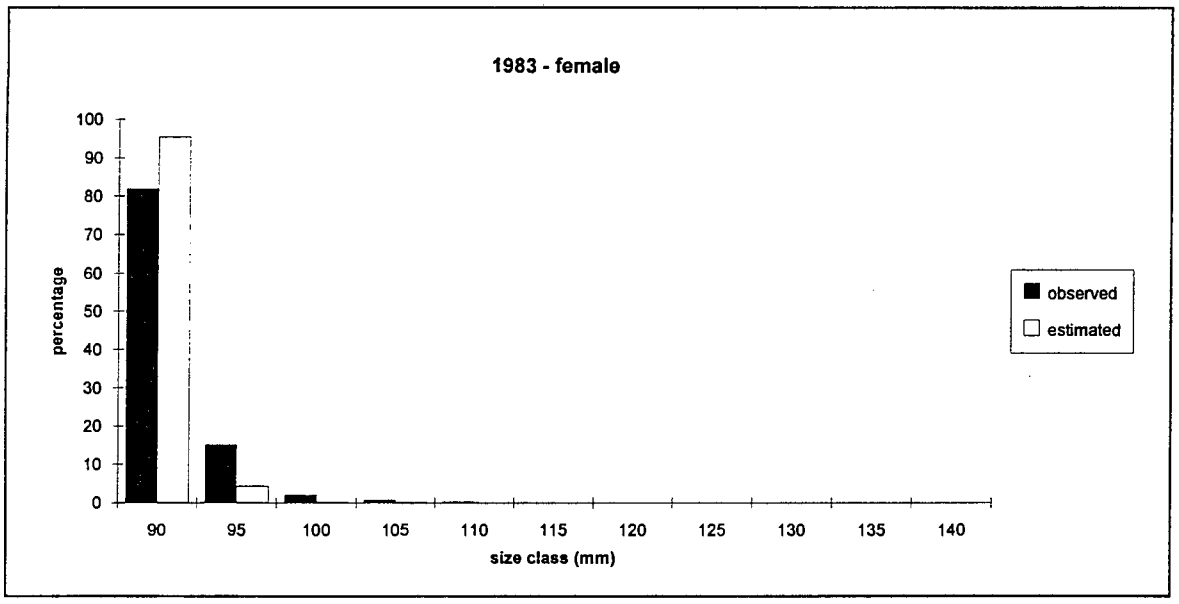


Figure 8.6a: Observed and Base Case model-estimated male trap catch-at-size - 1985.

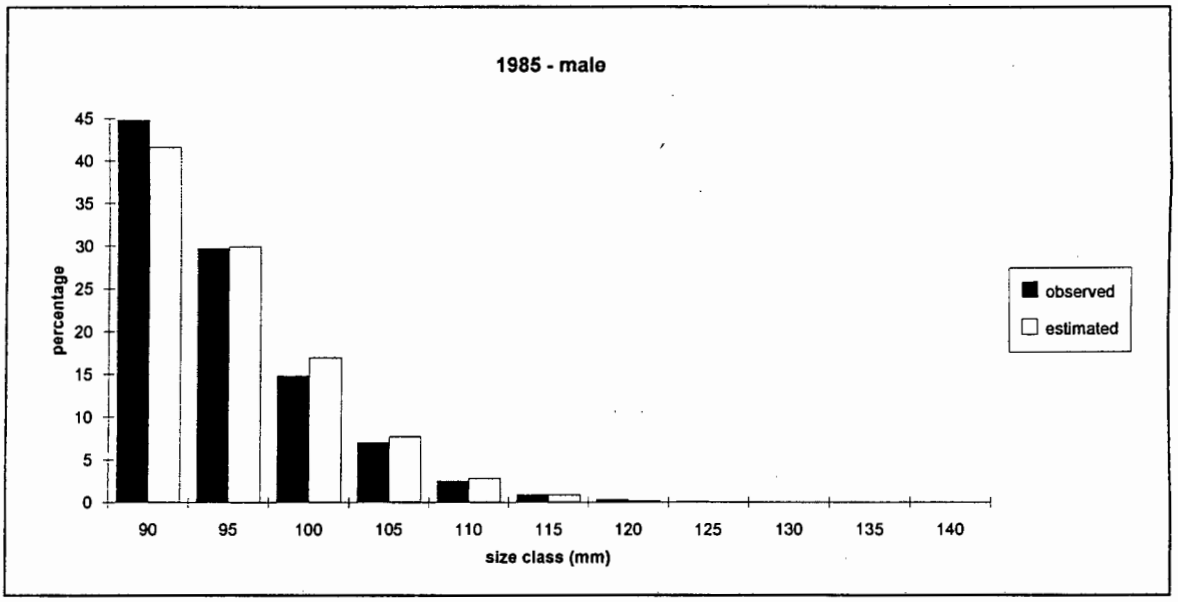


Figure 8.6b: Observed and Base Case model-estimated female trap catch-at-size - 1985.

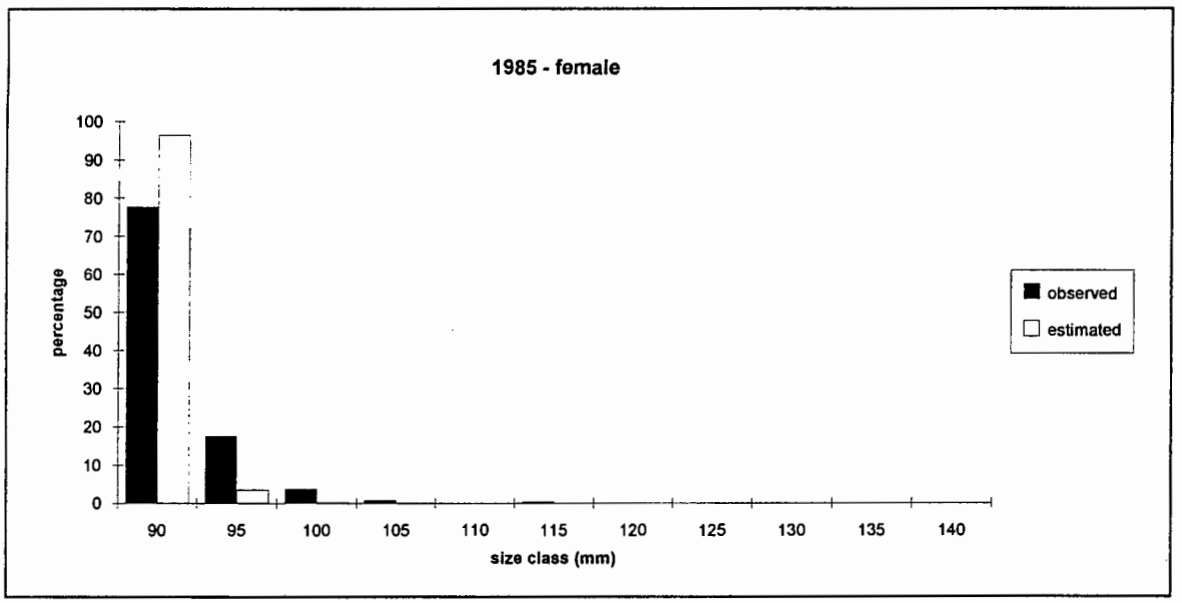


Figure 8.7a: Observed and Base Case model-estimated male trap catch-at-size - 1987.

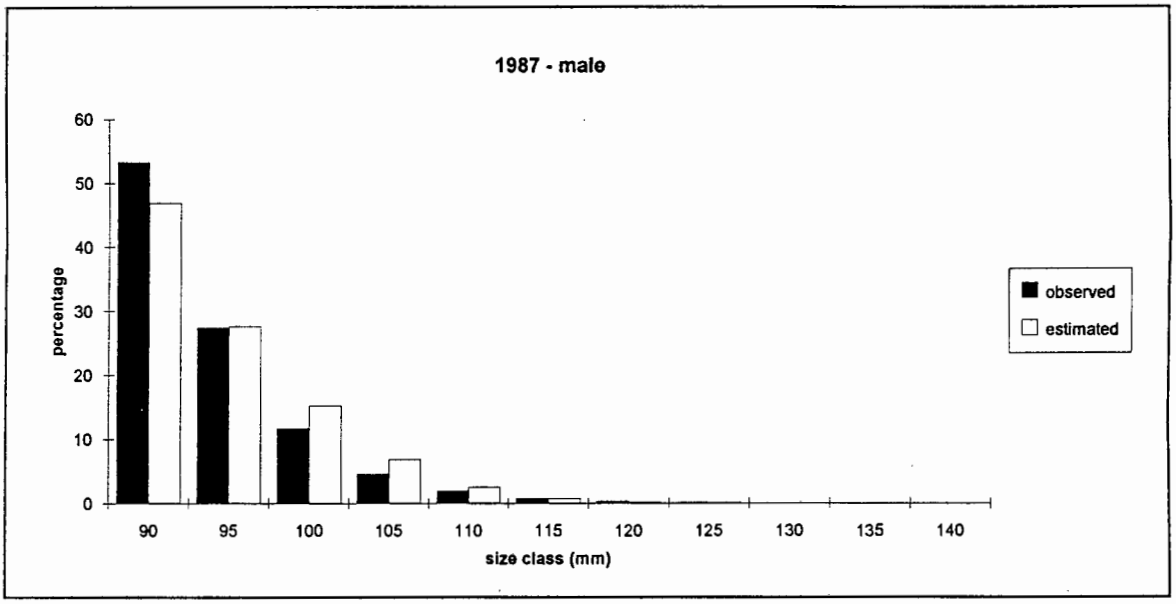


Figure 8.7b: Observed and Base Case model-estimated female trap catch-at-size - 1987.

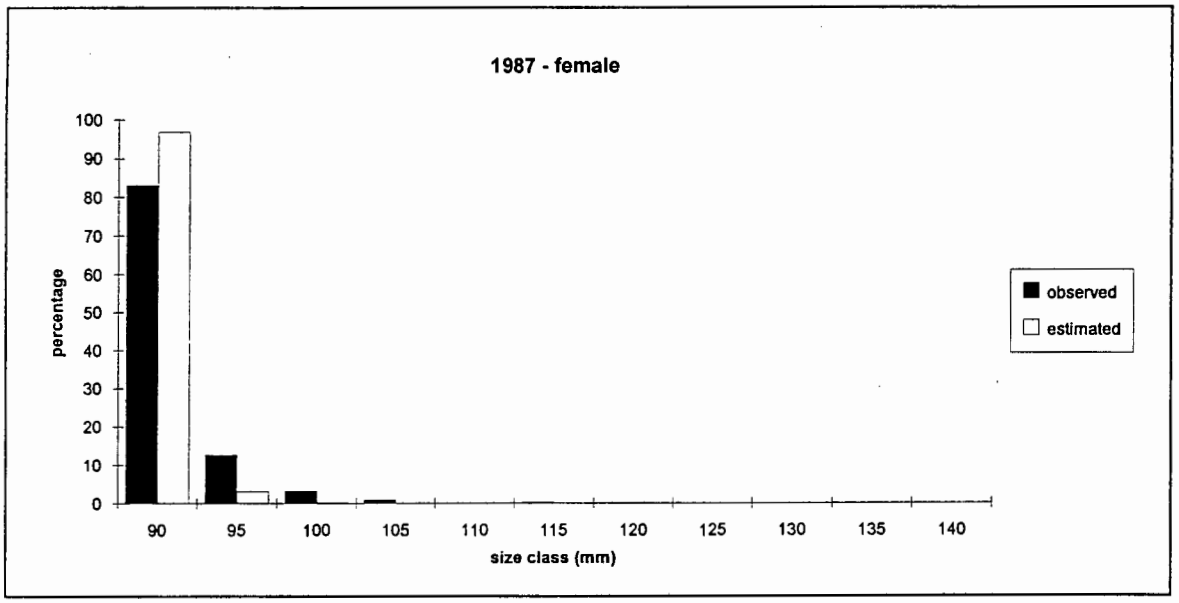


Figure 8.8a: Observed and Base Case model-estimated male trap catch-at-size - 1989.

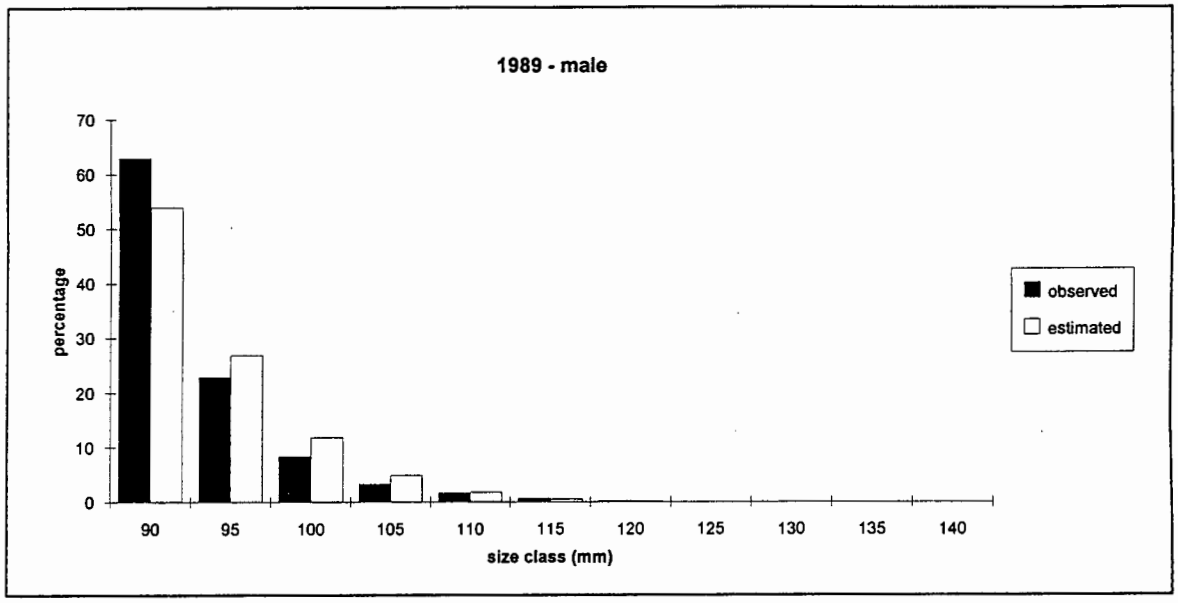


Figure 8.8b: Observed and Base Case model-estimated female trap catch-at-size - 1989.

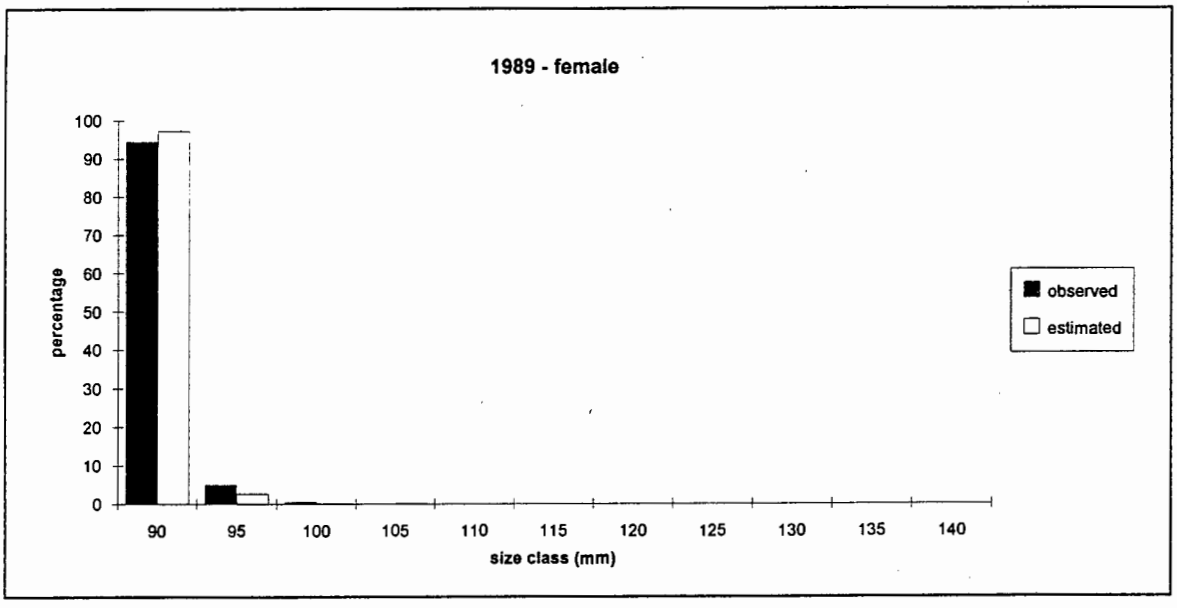


Figure 8.9a: Observed and Base Case model-estimated male trap catch-at-size - 1991.

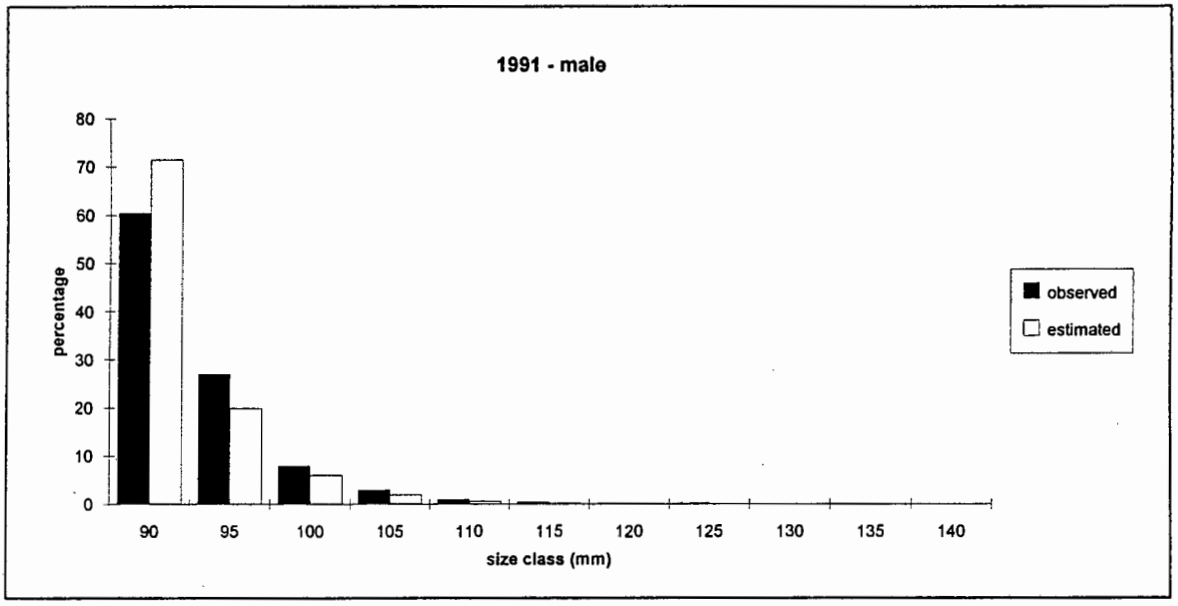


Figure 8.10a: Observed and Base Case model-estimated male trap catch-at-size - 1993.

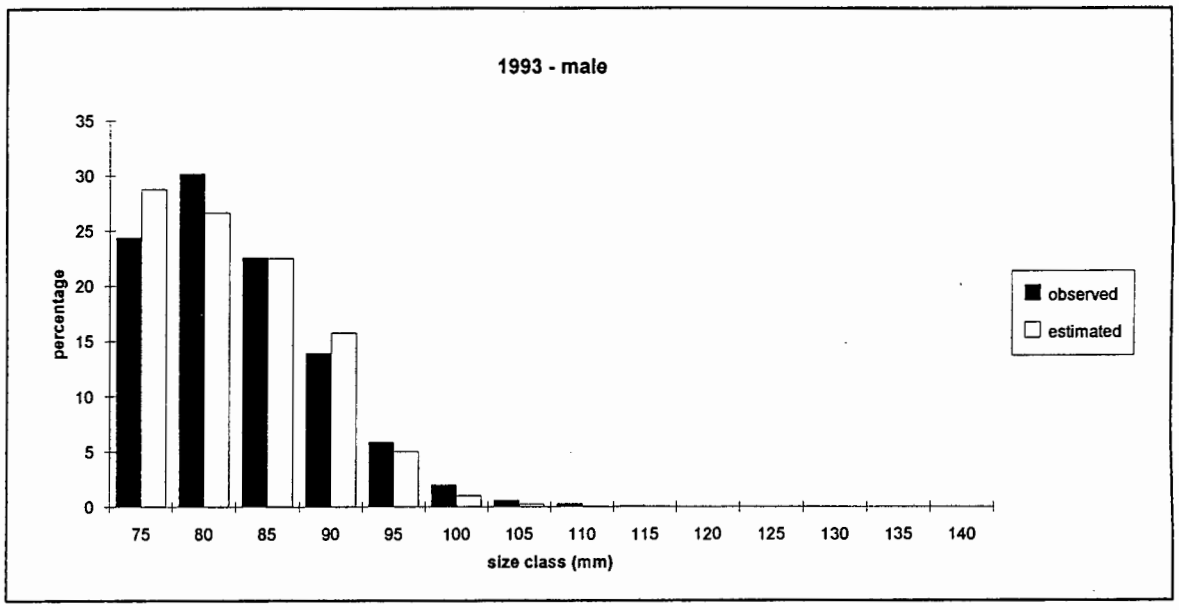


Figure 8.10b: Observed and Base Case model-estimated female trap catch-at-size - 1993.

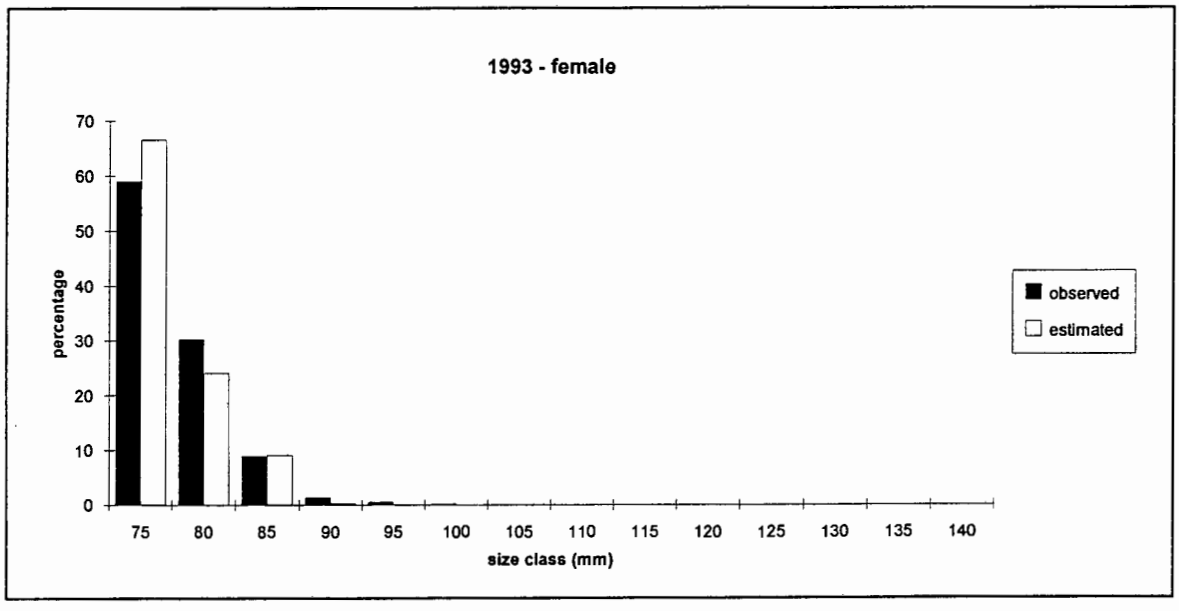


Figure 8.11a: Observed and Base Case model-estimated male trap catch-at-size - 1994.

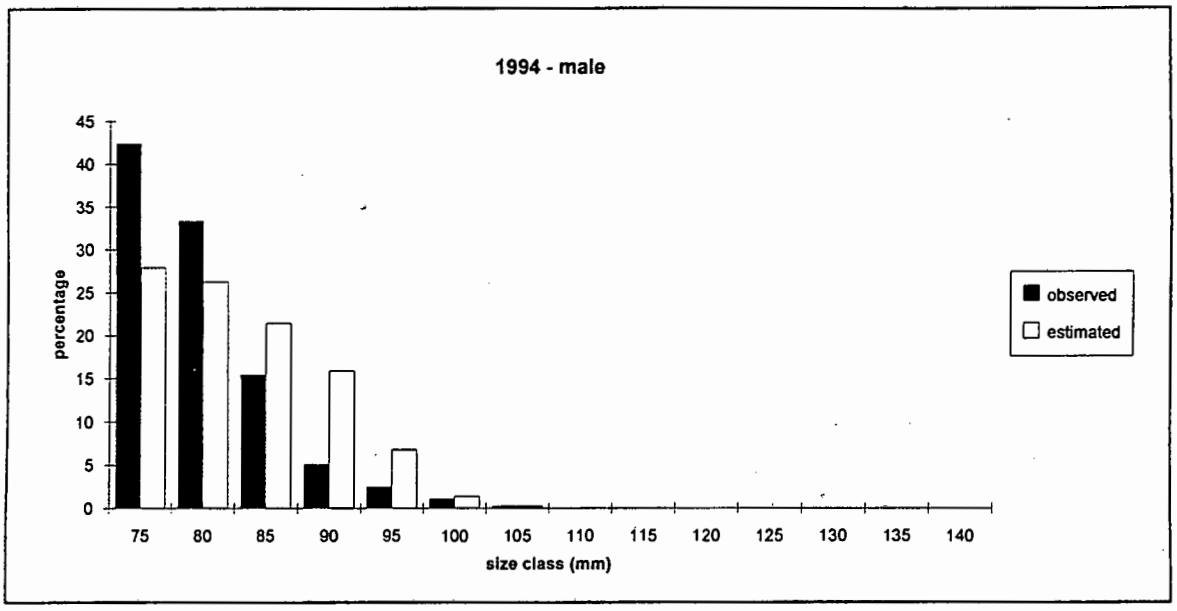


Figure 8.11b: Observed and Base Case model-estimated female trap catch-at-size - 1994.

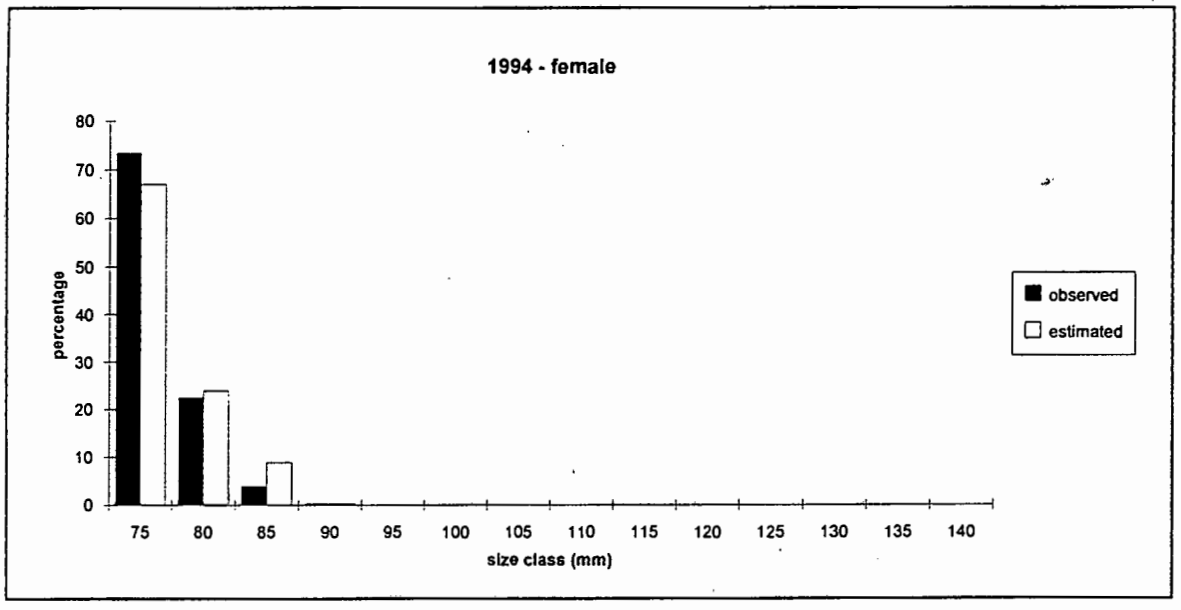


Figure 8.12a: Observed and Base Case model-estimated male trap catch-at-size - 1995.

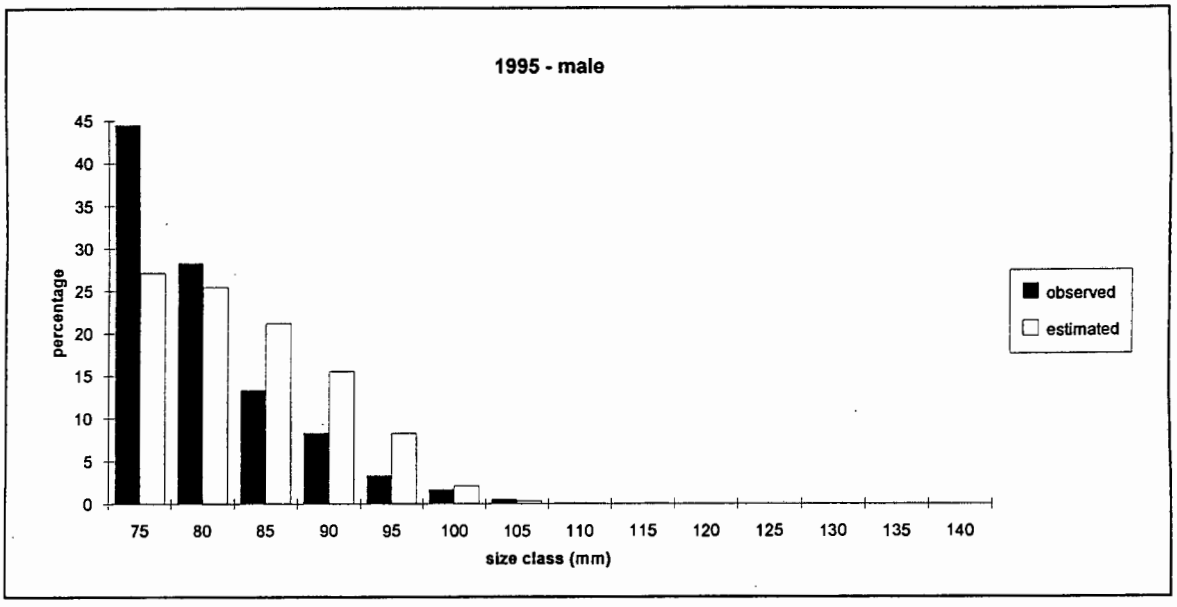


Figure 8.12b: Observed and Base Case model-estimated female trap catch-at-size - 1995.

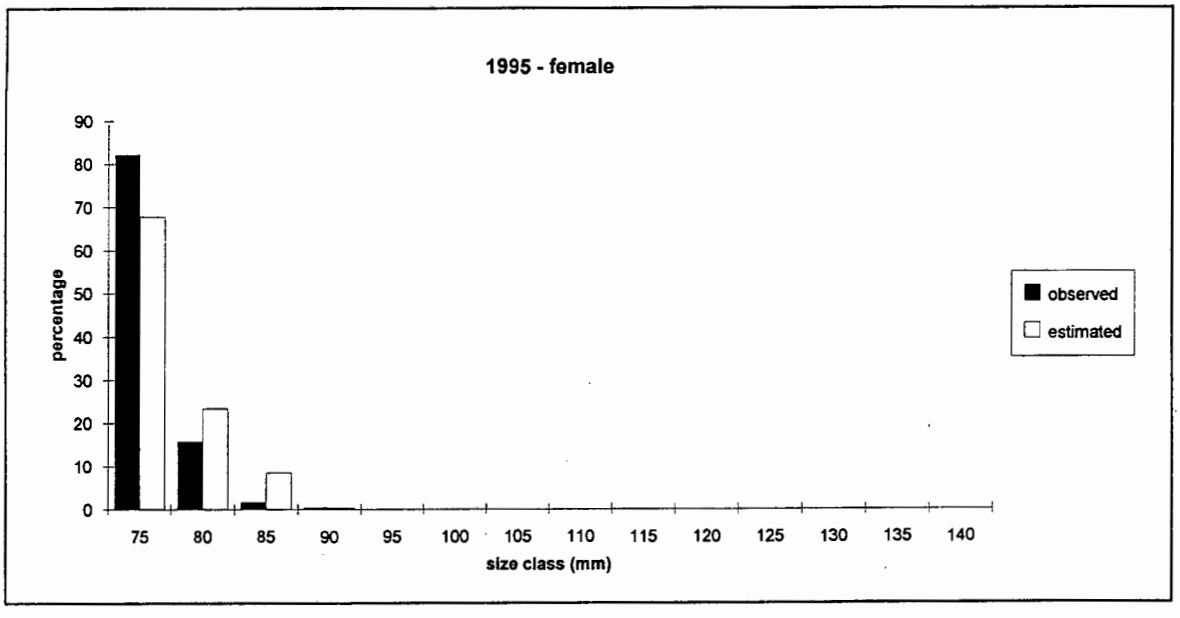


Figure 8.13: Trap catch-at-size weighted residuals plotted as root mean square errors (r.m.s.e's) for residual sets grouped to the nearest multiple of 10 in terms of the square root of the expected sample size ($\sqrt{n_e}$).

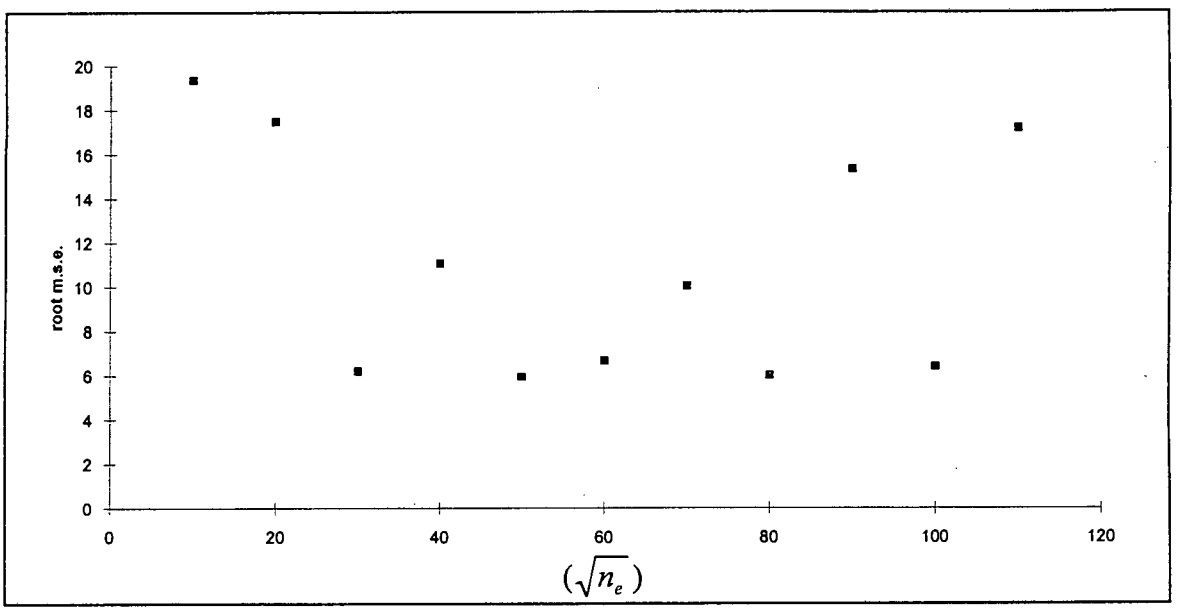


Figure 8.14a: Observed and Base Case model-estimated male FIMS catch-at-size - 1992.

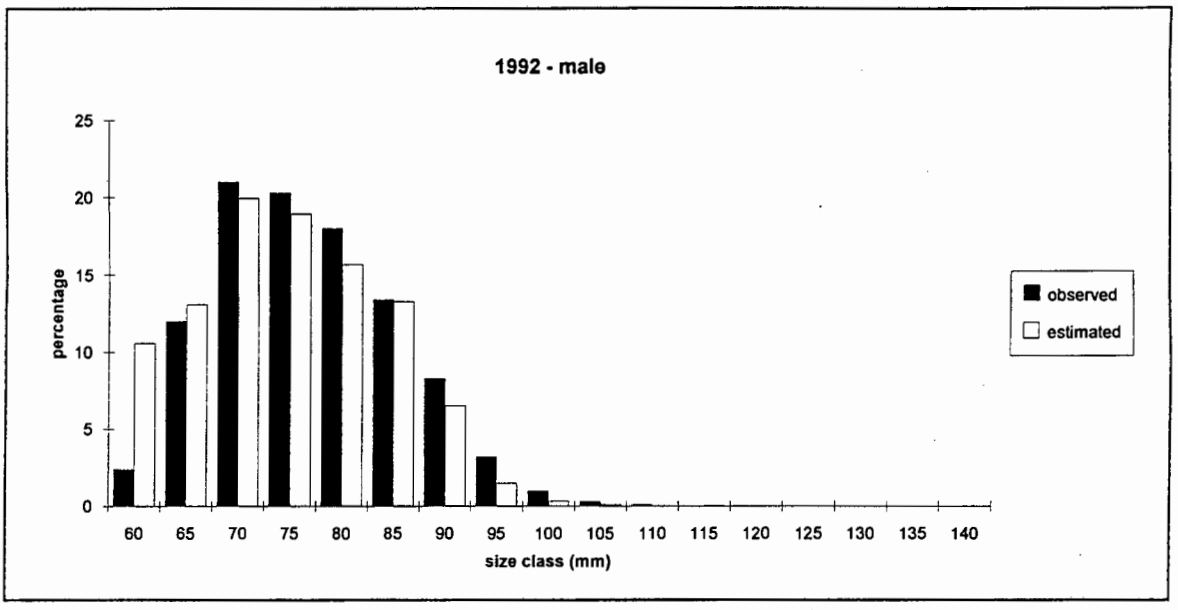


Figure 8.14b: Observed and Base Case model-estimated female FIMS catch-at-size - 1992.

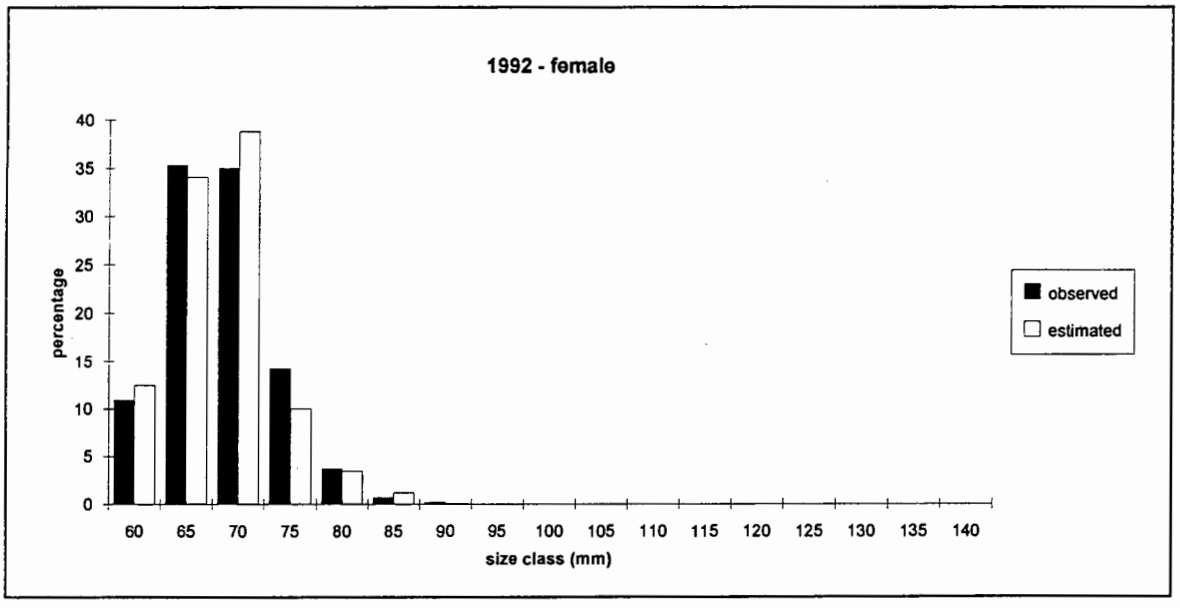


Figure 8.15a: Observed and Base Case model-estimated male FIMS catch-at-size - 1993.

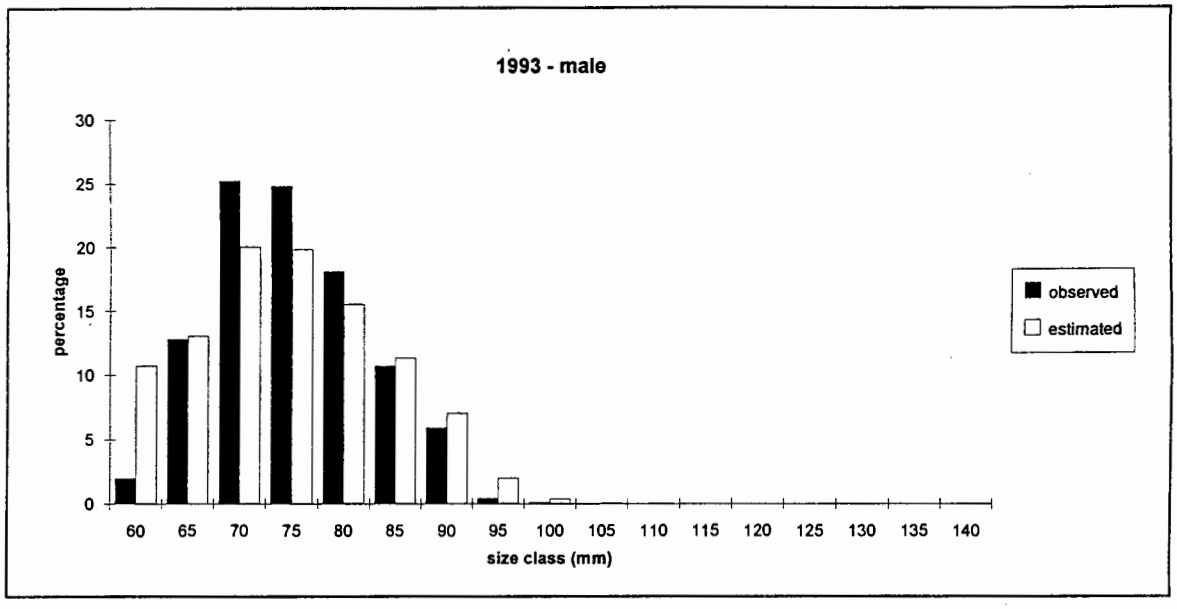


Figure 8.15b: Observed and Base Case model-estimated female FIMS catch-at-size - 1993.

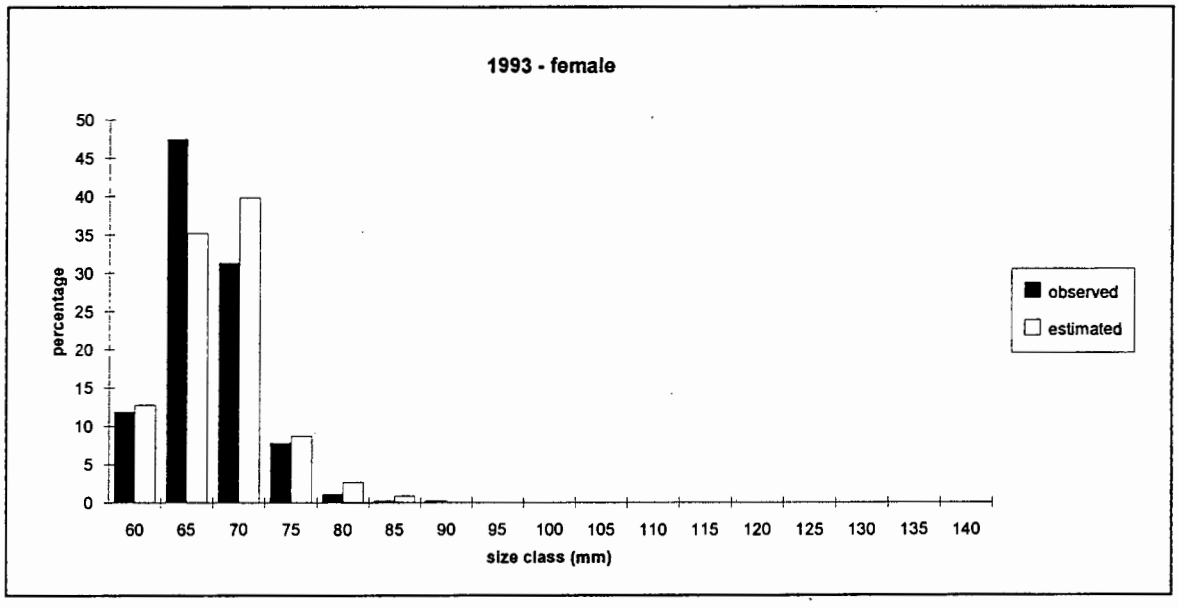


Figure 8.16a: Observed and Base Case model-estimated male FIMS catch-at-size - 1994.

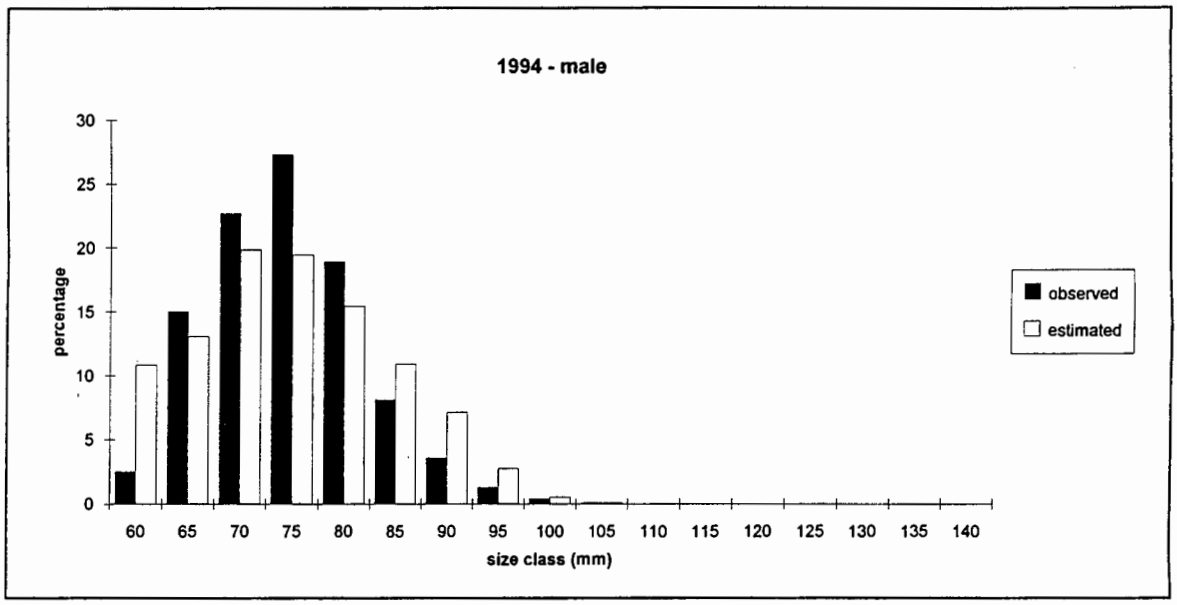


Figure 8.16b: Observed and Base Case model-estimated female FIMS catch-at-size - 1994.

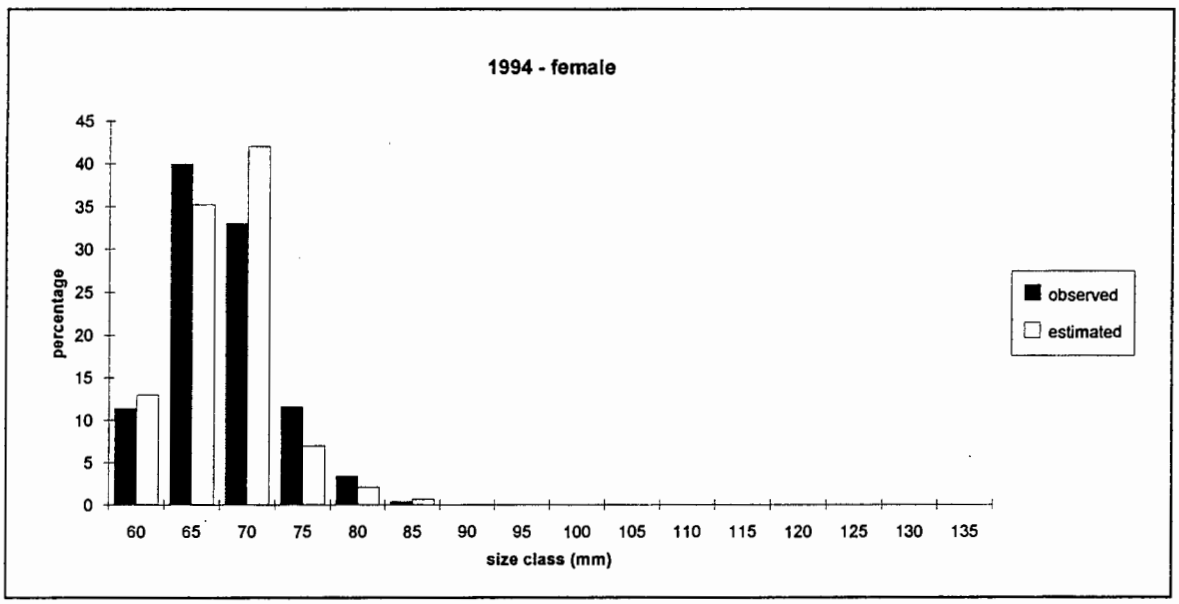


Figure 8.17a: Observed and Base Case model-estimated male FIMS catch-at-size - 1995.

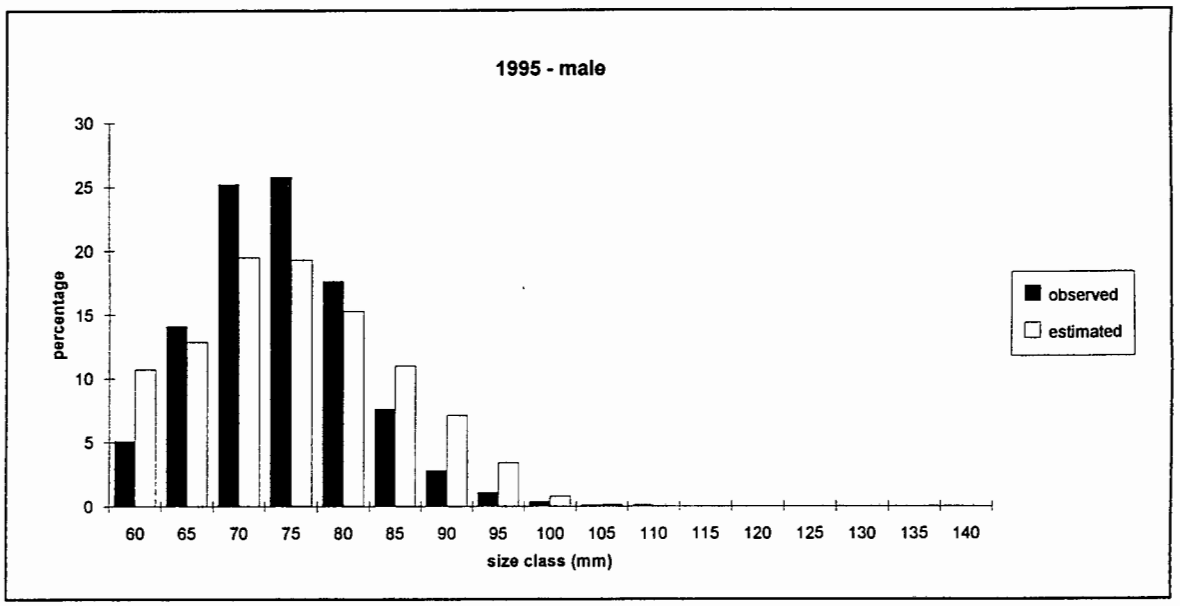


Figure 8.17b: Observed and Base Case model-estimated female FIMS catch-at-size - 1995.

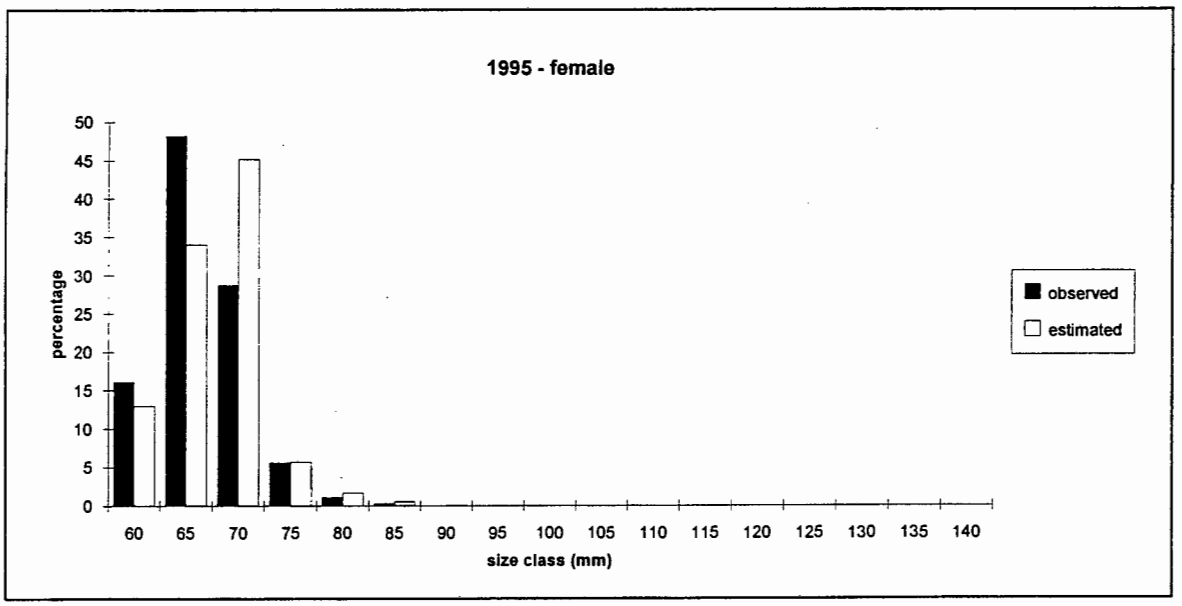


Figure 8.18: FIMS catch-at-size residuals plotted as root mean square errors (root m.s.e.) for residual sets grouped to the nearest multiple of 10 in terms of the square root of the expected sample size ($\sqrt{n_e}$).

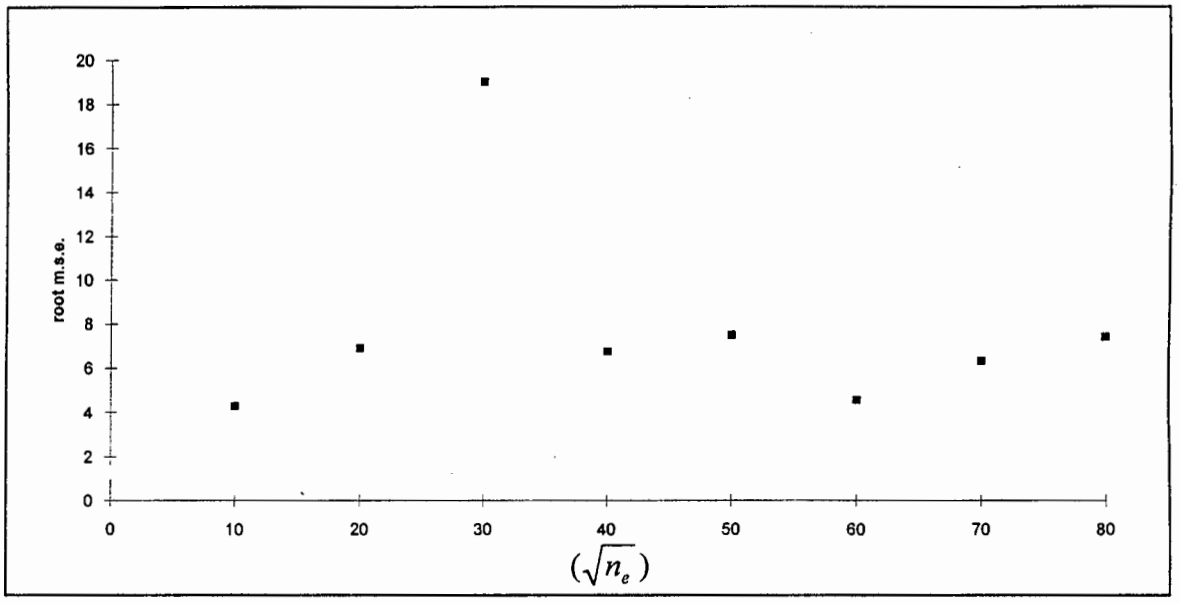


Figure 8.19a: $F^{\%}$ (percent females in catch) for trap catches: observed and Base Case model-estimated values.

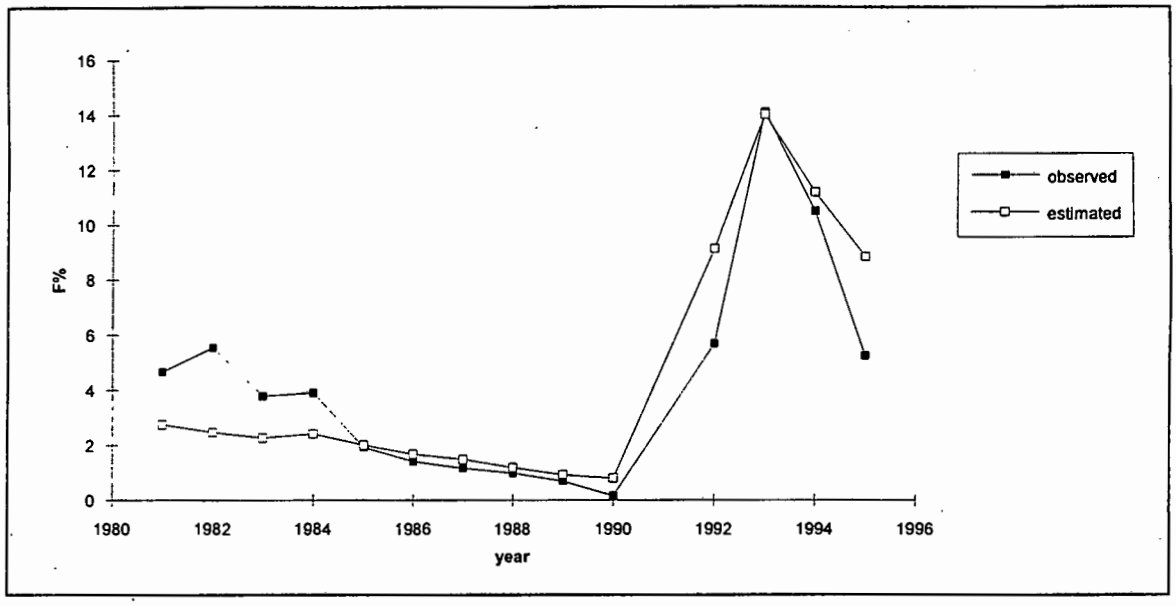


Figure 8.19b: $F^{\%}$ (percent females in catch) for trap catches: standardised residuals.

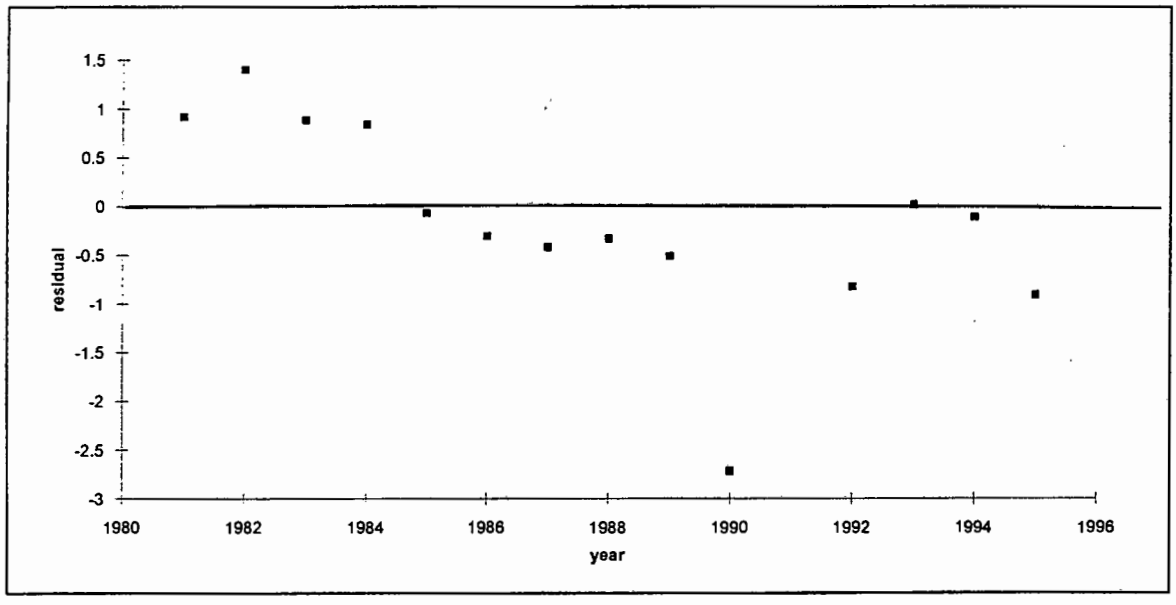


Figure 8.20: $\bar{F}^{\%}$ (percent females in catch) for FIMS catches: observed and Base Case model-estimated values.

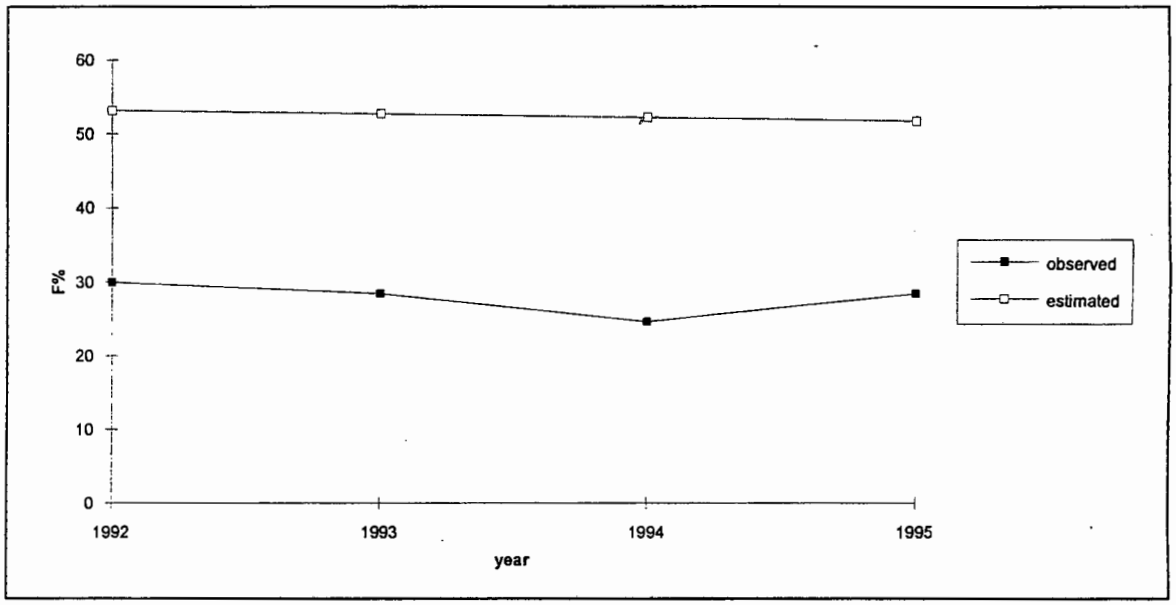


Figure 8.21a: Base Case model estimates for biomass above 75mm (B_{75}): historic trend for males and females combined.

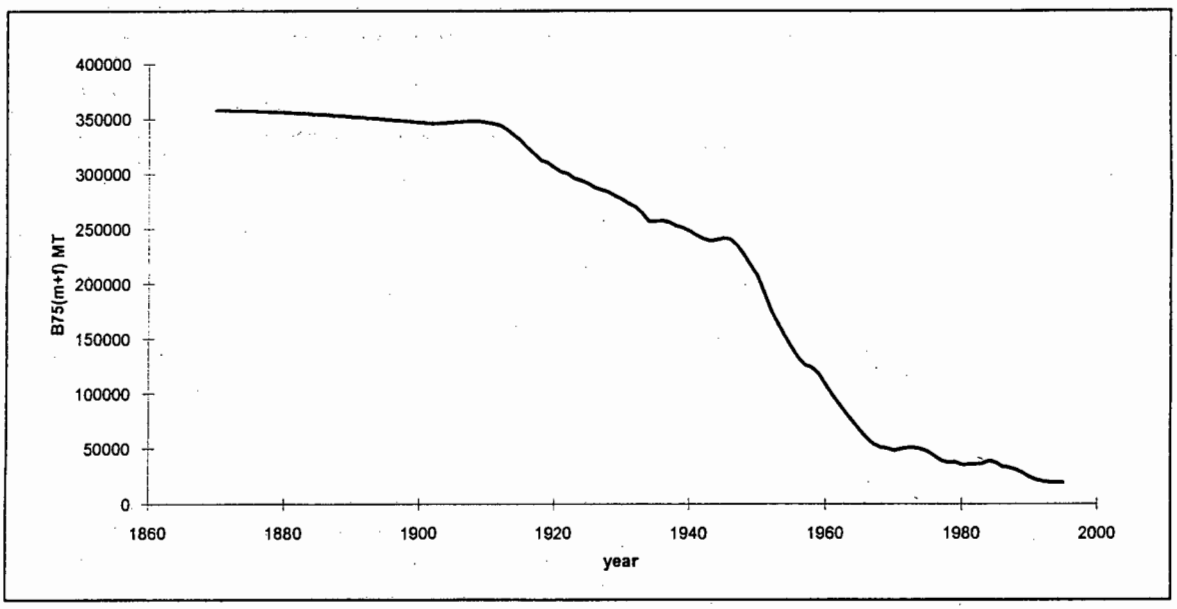


Figure 8.21b: Base Case model estimates for biomass above 75mm (B_{75}^{m}): historic trend for males only.

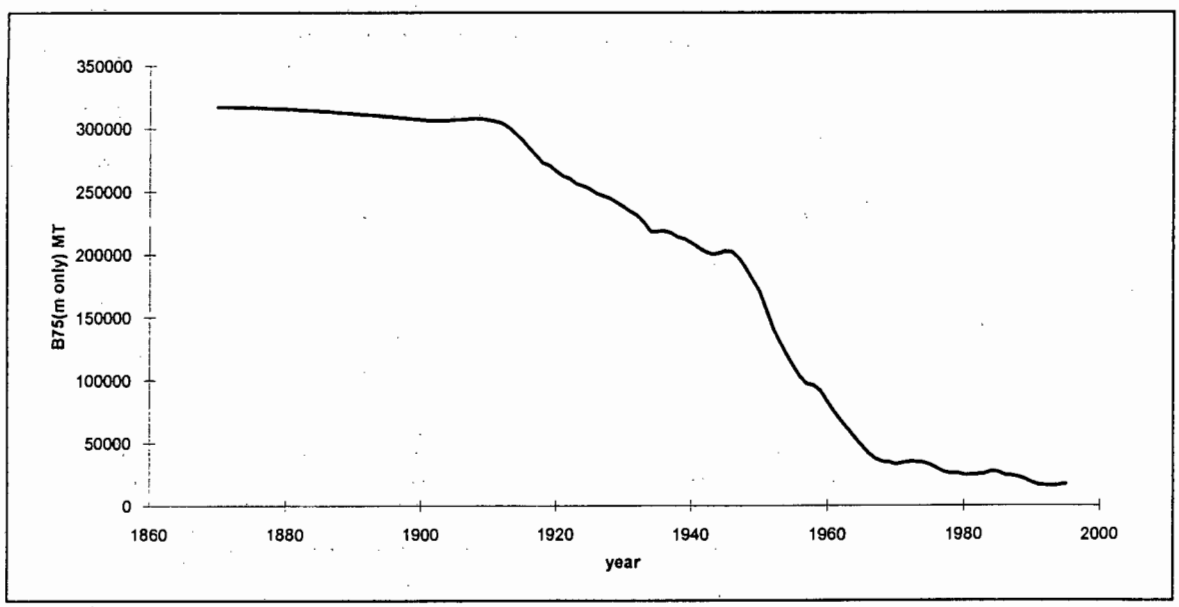


Figure 8.21c: Base Case model estimates for biomass above 75mm (B_{75}^{f}): historic trend for females only.

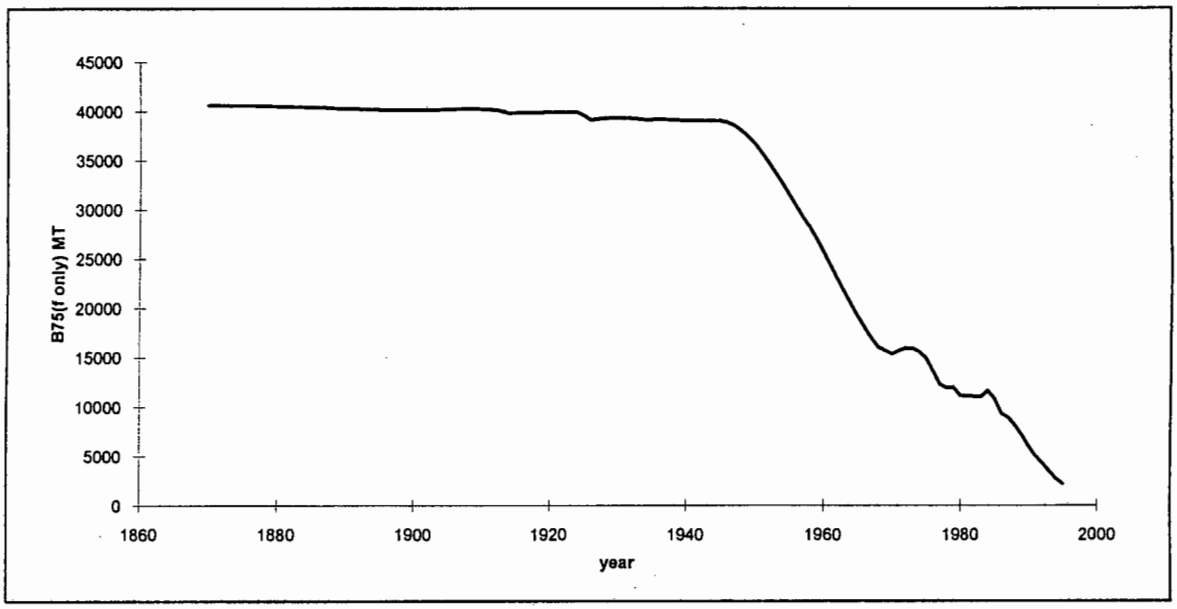
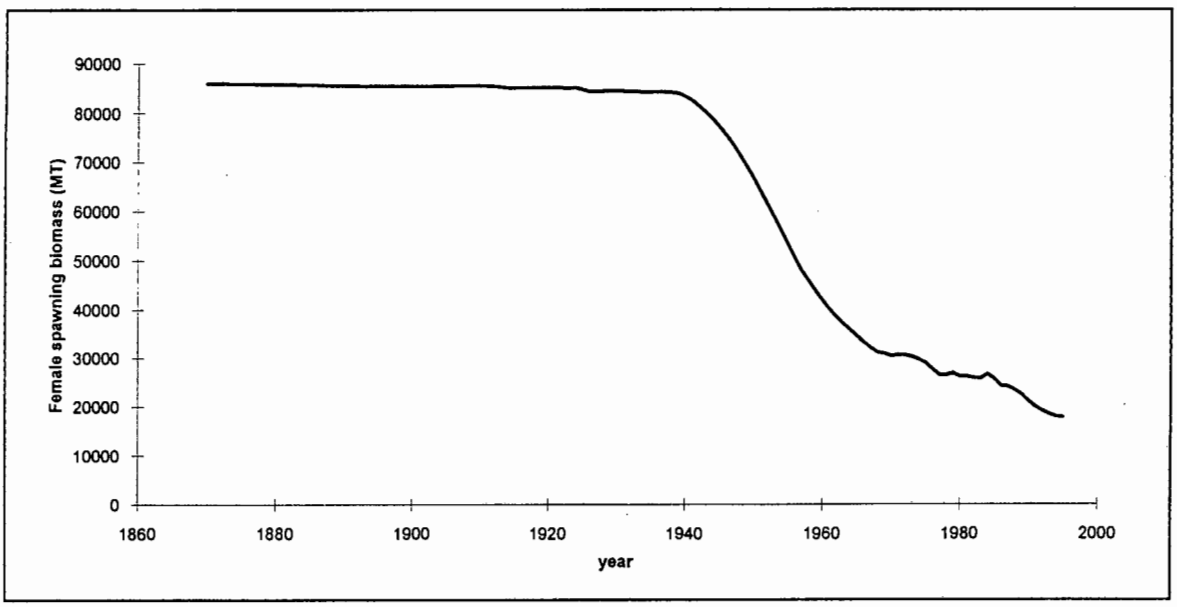


Figure 8.22: Base Case model estimated historic trend for female spawning biomass (B^{sp})



Chapter 9: Development of an Operational Management Procedure (OMP)

9.1 Management procedures

The present norm with regards to annual fisheries assessments (Butterworth *et al.* 1997) is summarised as follows: scientists assemble on an annual basis to debate and argue (usually at length) their current best assessment of the status of the resource concerned. Using this assessment, a TAC based upon some biological reference point is then recommended.

However, this procedure is both time consuming and costly to the government which is responsible for undertaking such a task. The question is - do these costs justify the benefits? Butterworth *et al.* (*op. cit.*) suggest not, and point out that for developed fisheries, the impact on parameter estimates of adding only one further data point to the many already available is likely to be small. These authors do not suggest that TACs be set at a fixed level a number of years ahead, as they realise annual adjustments are clearly needed, especially in fisheries for short-lived species (e.g. the South African anchovy *Engraulis capensis*) for which annual recruitment constitutes a large portion of the exploitable biomass. Butterworth *et al.* (*op. cit.*) also argue that, in the assessment process, too much of the fisheries scientists' time is focused on the short term, instead of the more important problems which can only be addressed over a longer period.

A management procedure is simply a set of rules which when given appropriate pre-defined data, can be used to provide a management recommendation. The basic underlying philosophy is that all parties (scientists, industry and managers) should agree upon clearly defined rules *before* the management game is played (Butterworth *op. cit.*). These rules specify exactly how the TAC is to be calculated each year, what data are to be collected for this purpose, and how these data are to be analysed for input into the rules. The basis for selection between alternative possible rules is the consideration of a number of outputs which are of direct interest to the industry and managers. These relate to the expected *performance* of the fishery and resource in the medium term (say 10-30 years for a longish-lived species such as the west coast rock lobster). Indeed, a management procedure should be evaluated as a feedback-control process implemented over a number of years, rather that be judged on the basis of anticipated performance over a single year (Butterworth and Bergh 1993), particularly because risk (especially for longer-lived species where annual catches are smaller proportions of the overall biomass) can be properly adjudged only over a longer time horizon. Such "performance" can be assessed in terms of three essentially conflicting objectives:

i) maximising the average catch (or profits);

ii) minimising the risk to the resource; and

iii) maximising stability in the interests of orderly industrial development - i.e. minimising inter-annual catch fluctuations.

Operational management procedures (OMPs) have formed the basis of the regulation of two of the three major fisheries of South Africa since 1990. These are:

i) the demersal hake (*Merluccius* spp.) trawl fishery; and

ii) the purse seine fishery for anchovy (*Engraulis capensis*) and sardine (*Sardinops sagax*).

Initiatives are currently in place to develop OMPs for other fisheries in South Africa.

A number of problems have to be addressed when developing an OMP. These include:

i) one can never be certain about the current status of the resource;

ii) it is very difficult to predict how the resource will behave in the future; and

iii) the fishing industry experiences constant changes in the economic and political climates.

To try to overcome these problems, one should aim towards an OMP that uses as much reliable and useful data as are available. A broad suite of candidate OMPs should be considered, and submitted to a wide range of robustness tests to assess their sensitivity to key uncertainties and assumptions. The aim is to seek an OMP whose anticipated performance is relatively insensitive to uncertainties such as indicated in i) - ii) above, and iii) also to the extent possible. It is also important to try and develop the OMP in collaboration with and with the co-operation of industry representatives, to facilitate its eventual acceptability.

9.2 Philosophy behind the development of an OMP for the west coast rock lobster

For the last four to five years, members of the SFRI RLWG have spent considerable time debating and re-examining issues such as new data, data analyses and population dynamics model specifications and assumptions. Little time was left to discuss the important issue of how the TAC itself should be determined on an annual basis. A consensus view as to how the TAC recommendation should be made did not exist - for example, industry scientists often argued for last minute adjustments to the TAC recommendation as new data or analyses became available late in the process.

This unsatisfactory procedure led to many important (and expensive) person hours being spent without ever reaching a satisfactory decision on how to recommend the TAC. A compromise *ad hoc* basis, which changed from year to year, was often adopted to recommend the TAC, with the aim of keeping all parties reasonably happy.

Much scientific uncertainty exists about the rock lobster resource, as is typical of most marine resources around the world. In addition to this scientific uncertainty, there are many diverse political viewpoints regarding the fishery and its management. A number of different users (commercial fishers, recreational fishers, poachers etc.) have conflicting interests. To confound these problems, there is also a high degree of environmental variability (as reflected, for example, by the major change in somatic growth rate at the end of the 1980's). A management approach that can function effectively under such

diverse and difficult circumstances is clearly a much desired objective. For these reasons, there has been a strong desire within the SFRI (which is ultimately responsible for making TAC recommendations) to develop an OMP for the resource, which could be put into place for a period of at least three years, and hence essentially "automate" the process of TAC recommendations over that period, leaving more time to focus on research issues pertinent to longer-term management considerations.

Recent assessments (see Chapter 8) of the west coast rock lobster resource have indicated it to be heavily depleted. This situation has been worsened by the recent years of lower than average somatic growth rates. With analyses showing that the present female spawning biomass may be as low as some 20% of its pristine level, there is also the possibility that a reduction in recruitment has occurred. A decline in recruitment is difficult to detect immediately (no indices of, for example, puerulus settlement are available). Due to the slow somatic growth of the lobsters, there is about a seven year delay between larval settlement and entry into the population sampled by FIMS. An undetected recruitment decline could have severe implications for both the resource and the fishery. For this reason it is important to assess the long-term consequences of any basis for TAC recommendations over a wide range of scenarios, encompassing the present spectrum of uncertainty about the resource's current status and future dynamics.

The primary objective of the development of an OMP is to provide a management approach that will ensure robust behaviour in achieving management objectives (e.g. a rebuilding target) over a wide range of possible scenarios. The advantages of an OMP for the west coast rock lobster resource include that it will:

i) allow focus on longer term objectives such as the rebuilding of the resource;

ii) provide an improved basis for taking account of risk;

iii) make allowance for the various uncertainties associated with the data input to compute the TAC recommendation;

iv) take into account whether future data will prove adequate to provide timely adjustment to TAC levels (up or down) to correct for errors in current perceptions of resource status;

v) provide a more efficient framework for conducting scientific research and providing TAC recommendations; and

vi) allow the process of scientific TAC recommendations each year to become more transparent, thus enhancing credibility with the industry.

Some allowance should also be made for "freak" situations, where keeping to the basic OMP rules (which typically include provisions limiting the extent to which the TAC can be reduced from one year to the next - a 15% annual maximum downward increase applies in the OMP that was finally adopted) could damage the resource. These rules are aimed at modifying the basic OMP TAC for circumstances which are outside the boundaries of the various robustness tests for which the candidate OMPs were tested.

These "exceptional circumstances" provisions for the west coast rock lobster resource are discussed in Chapter 11, along with the associated meta-rules that are to be applied in the event of such "exceptional circumstances".

9.3 The components of an OMP

An OMP consists of essentially two main components:

i) *Input data and their analyses*

For each resource, various sets of data are collected, e.g. somatic growth data and CPUE. These raw data can then be analysed (usually on an annual basis) in a number of different ways to produce "indices" of resource/fishery status. These data are then used as input into some TAC setting algorithm (for a resource, such as the west coast rock lobster, for which the commercial fishery is managed on a catch limitation basis).

ii) *A TAC setting algorithm*

An algorithm is developed which uses a number of data sets as indices of the status of and trends in the fishery to produce an annual TAC recommendation. The algorithm can be very simple, or can incorporate many different data sets and be far more complicated. The algorithm is developed and refined in order to satisfy a number of specific management objectives, such as a certain extent of increase in biomass over a given period of time. Meta-rules that will be invoked under "exceptional circumstances" can also be defined.

9.4 Data available for the use in an OMP for west coast rock lobster

A fairly wide range of data are collected on an annual basis from the west coast rock lobster resource and its fishery. These include CPUE (commercial), FIMS CPUE, catch-at-size data (both commercial and FIMS), percentage females in the catch, and somatic growth data. In order to keep the OMP relatively simple, only commercial trap CPUE and FIMS CPUE, as well as somatic growth data are used as input data for the OMP for the rock lobster. Catch-at-size data and other data from the catch size-structure are excluded at present as these cannot be easily summarised into a single annual index. Data which can be so summarised, such as CPUE and somatic growth, are preferred. Part of the motivation for this were studies by Punt (1992) of candidate management procedures for the South African hake resource, which suggested that attempts to include catch-at-age data in the TAC-setting algorithm served primarily to increase inter-annual catch variability without providing other compensatory gains in anticipated performance.

9.5 Candidate OMPs

Initially, a number of candidate OMPs were developed, with the following characteristics.

i) *Input data and their analyses*

Each year the OMP requires the input of FIMS, CPUE and somatic growth data for the three most recent years. The details of how these data are collected, and their subsequent analyses to provide annual indices of resource status, are provided in Chapter 7 and Appendix 4.

iii) *The TAC setting algorithm*

A number of objectives were set for the candidate OMPs. They had to:

- aim to satisfy a specific management target, e.g. a 20% increase in biomass;
- aim to enable the management target to be reached within a given period e.g. 10 years;
- be self-correcting, i.e. incorporate a feedback control so that if the resource indices performed in an unexpected way, indicating that previous assumptions about the resource productivity and/or size were incorrect, the TAC would be adjusted to keep the resource biomass on track towards its target; and
- keep inter-annual TAC changes as small as possible, to ensure efficient utilisation of available fishing capacity, to prevent over-capitalisation, and to minimise social disruption.

One of the objectives set for the candidate OMPs was to keep the inter-annual TAC changes as small as possible. This objective may be problematic if major errors are found in the data or stock assessment models. This objective is however favoured by industry to avoid taking unnecessary action when stocks appear to be in trouble, but this reflects only noise in the data rather than real resource trend.

A number of different types of harvesting strategies (the basis for the TAC setting algorithm of an OMP) are possible, the simplest being a constant catch strategy. Although a constant catch strategy may perform well in reaching a given management target in a

situation where perfect information is available, the performance of this type of strategy deteriorates markedly once either noise is added to the data, or uncertainty about the resource and its dynamics are taken into account, because such an approach does not permit feedback from the further data that become available as time proceeds. Some results for a constant catch strategy are reported in Chapter 10 to illustrate these problems.

The SFAC was asked to consider a number of issues relating to the OMP and provide some feedback to facilitate the development of a final set of candidate OMPs. The SFAC chose to:

i) endorse a resource rebuilding strategy;

ii) suggest possible target biomass levels (in terms of B_{75}) which were 20%, 30%, 40% and 50% above the 1996 level - to be reached over a 10 year period i.e. by 2006;

iii) set the 1997 TAC level at either a 10% increase or 20% increase over the 1996 TAC value of 1700 MT; (a 3% increase option was added by the RLWG);

iv) accept a three year period for implementation of the OMP with its associated standardisation of the analyses of the resource monitoring data; and

v) consider deviations from the OMP only in the case of "exceptional circumstances", for which they requested specifications to be developed.

9.6 The rationale underlying the form of the candidate OMPs

As indicated above, a re-building strategy was selected by the SFAC as the long-term strategy for the resource. Factors leading to this decision include:

i) the present biomass level above 75mm carapace length, $B_{75}(1997)$, is estimated to be 21.7 '000 MT, which is only 6% of the corresponding pristine level;

ii) the estimated female spawning biomass level at present, $B^{sp}(1997) = 18.1$ '000 MT is only 21% of the corresponding pristine level - putting the resource at danger of a possible recruitment decline; and

iii) although the present biomass level is estimated to be close to B_{MSY} (in terms of the estimated recent recruitment level R_2), this assumes no stock-recruit effects at low biomass levels. If the present spawning biomass level corresponds to the descending limb of the stock-recruit relation, this would place the resource as at present on the left descending limb of the curve of sustainable yield versus biomass. Furthermore, the assessment (see section 8.1.1) does indicate much higher recruitment levels than R_2 for the resource in the first half of the century, when biomass levels were higher than at present, suggesting potential benefit in an increase.

Appendix 7 provides a detailed account of the OMP computations.

A sustainable yield curve can be calculated for the west coast rock lobster resource for any given somatic growth rate. In Figure 9.1, the sustainable yield curve for the ARMA 1997 somatic growth rate (see Appendix 3) is shown. The biomass (above 75mm) at the start of the 1996 season is indicated - $B_{75}(1996) = 21.7$ '000 MT. The straight line gives the TACs to be set under a constant fishing mortality strategy which will result in the biomass equilibrating at a target biomass level - a 50% increase over $B_{75}(1996)$ for this example. The target biomass must be reached by 10 years, so $B_{75}(2006)$ must therefore equal 32.6 '000 MT. (Figure 9.1 illustrates just one of the management targets considered - that is a 50% increase in biomass).

Note that, in terms of Figure 9.1, the assumption being made is that the somatic growth rate stays fixed and equal to its ARMA 1997 estimated value throughout the 10 year period considered.

Under these assumptions and choices, we can calculate the annual TAC for year t as follows (note that B refers to B_{75}):

$$TAC_t^* = B_t \tan\theta \qquad (9.1)$$

$$= \frac{B_t}{B_{1996}} B_{1996} \tan\theta$$

where $\tan\theta = \frac{Y^Q_{ARMA'97}}{QB_{1996}}$ (9.2)

$Y^Q_{ARMA'97}$ is the sustainable yield at the target QB_{1996}, for an ARMA '97 somatic growth scenario, where in Figure 9.1, Q, the target biomass increase factor, is 1.5 (reflecting a

50% increase). Note that *tan* θ is the exploitation rate required to arrive at biomass QB_{1996}.

General properties the algorithm should have include:

i) to stabilise the biomass at the target QB_{1996}. Note that this TAC prescription (described above) will, if the somatic growth rate remains as assumed, lead to the resource biomass eventually stabilising at the target QB_{1996}; and

ii) not to cause the TAC to vary too much from year to year.

To re-express equation (9.1), in terms of measured quantities, it is modified to incorporate the two indices assumed proportional to biomass - CPUE and FIMS.

$\frac{B_t}{B_{1996}}$ is thus indexed by $\left(\frac{CPUE_t}{CPUE_{1996}}\right)^{\alpha}\left(\frac{FIMS_t}{FIMS_{1996}}\right)^{1-\alpha}$

The α value reflects the weight given to the CPUE relative to the FIMS data - at the extremes, for $\alpha = 0$ CPUE data are ignored and for the $\alpha = 1$ the FIMS data are disregarded. A value of $\alpha = 0.5$ was selected (giving the CPUE and FIMS data equal weights) as these two data are thought to be of similar importance when regarding their representation of the biomass. In order to help stabilise the TAC over time, the recent data are averaged over the last three years. A three year averaging period was selected, as a longer time period may prevent action being taken fast enough if a sudden decline in biomass occurs. Thus equation (9.1) becomes:

$$TAC_t^* = \left(\frac{CPUE_{t-1,t-2,t-3}}{CPUE_{93,94,95}}\right)^{\alpha}\left(\frac{FIMS_{t-1,t-2,t-3}}{FIMS_{92,93,94,95}}\right)^{1-\alpha} B_{1996}\tan\theta$$

$$= \left(\frac{CPUE_{t-1,t-2,t-3}}{CPUE_{93,94,95}}\right)^{\alpha}\left(\frac{FIMS_{t-1,t-2,t-3}}{FIMS_{92,93,94,95}}\right)^{1-\alpha} \frac{Y^{Q}_{ARMA'97}}{Q} \qquad (9.3)$$

where $X_{t1..t2}$ = arithmetic average of $X_{t1}, X_{t1+1} \ldots X_{t2}$.

CPUE reflects biomass above the minimum legal size (which changed to 75mm at the start of the 1993 season). As the FIMS data are not affected by minimum size changes, the inclusion of the available 1992 value was thus allowed. FIMS reflects biomass above 60mm. (Strictly the proportion pertinent to biomass > 75mm should be used to be consistent with Figure 9.1, but this exactitude was sacrificed in favour of the greater precision of the FIMS index over a wider size range).

The TAC setting algorithm needs to take into account the possibility that the somatic growth rate in the future may well deviate from the ARMA'97 prediction. Figure 9.2 illustrates how the sustainable yield function is effected by a change in the somatic growth rate. In this Figure, sustainable yield curves for the "high" and "low" growth rate scenarios (see Appendix 3, section A3.6.2 for definitions) are compared. An adjustment factor must be built into the algorithm to make allowance for this each year. Equation (9.4) effects this as follows:

$$TAC_t{*'} = TAC_t * \frac{Y_g^Q}{Y_{ARMA'97}^Q} \qquad (9.4)$$

where Y_g^Q is the sustainable yield at the target biomass level calculated for somatic growth level g (where g refers to β_t^m), and is calculated as the arithmetic average over years *t-1, t-2* and *t-3*. Given this adjustment, eventual attainment of the target biomass QB_{1996} is achieved whatever final somatic growth scenario eventuates (as distinct from the situation for equation (9.2) where achieving this required somatic growth to remain as per the ARMA'97 prediction). The equation (9.4) as it stands gets the biomass to the required level eventually, but will take in excess of 20 years in most cases. In order to ensure that the target biomass level is reached within the 10 year period, equation (9.4) is modified to form equation (9.5).

In order to allow for flexibility in targets for the TAC in the short term (e.g. TAC(1997)), the level of recovery desired over the 10 year projection period, and a reasonably smooth

TAC trajectory over time, the algorithm is then modified to include a number of tuning parameters: w, h, k and γ. These tuning parameters act independently (or more or less so), so each can be set or tuned individually. These parameters were tuned in a rather *ad hoc* manner. The w value was selected as an intermediate value (0.5) which prevent the catches from varying too greatly from one year to the next, whilst still allowing the target level to be reached in the 10 year period. A γ value was selected to provide a smooth TAC trajectory for the BC scenario. The k parameter (which determines the 1997 TAC value) and the h parameter (which determines the level of biomass recovery in 10 years) were calculated to provide the required values for each of the 12 candidate OMPs.

The final algorithm considered thus had the form:

$$wTAC_{t-1} + (1-w)TAC_t^{*'}\left[1 - h(t-1997)^{\gamma}\right]k \qquad (9.5)$$

TAC_t = max

$0.85\ TAC_{t-1}$

w: this is the relative weight (between 0 and 1) given to the previous year's TAC (i.e. it controls how quickly the TAC can change from year to year). The higher the value of w, the more slowly the TAC will change from year to year.

h: a tuning parameter which can be adjusted to produce a given target biomass at the end of the 10 year period considered. The basic algorithm gets the biomass to the target only over a very long time period, so that this adjustment is needed to get it there quicker (in 10 years).

k: the k parameter is tuned to produce a specified expected 1997 TAC value. (This value is "expected" in the sense that it is the value that will result if CPUE, FIMS and growth rate for 1996 reflect exactly the values predicted by the Base Case model used for the simulation tests.)

γ: a parameter which determines the "shape" of the TAC trajectory.

A problem likely to be encountered in the implementation of the automated formulae of the OMP is that if indices reflect a deterioration in resource status, the acceptability of the lower TACs indicated by the procedure may be challenged by industry. For this reason, a maximum inter-annual TAC reduction constraint is imposed. Following earlier discussion with the industry and the SFAC, this value was set at 15%. This means that the TAC may

not drop by more than 15% from one year to the next, except in "exceptional circumstances" (see Chapter 11).

9.7 Parameter values chosen for the final set of candidate OMPs

A number of the parameter values for the final set of candidate OMPs were fixed. These were as follows.

i) The α value was set at a value of 0.50, i.e. CPUE and FIMS receive equal weighting.

ii) The w value was set at 0.50.

iii) The γ value was set at 0.50, which results in a sensibly steady increase in TAC over the 10 year projection period (for the Base Case scenario).

The remaining parameter values (h and k) were then varied to provide alternative possibilities for 10-year biomass recovery levels and immediate levels of increase in the TAC. A full description of the OMP candidates presented to the SFAC may be found in Appendix 7.

9.8 Projection of population in assessing the OMPs

i) The system state as at 1996 was determined by running the simulation deterministically from 1870 to 1996.

ii) The population vectors of male and female lobsters are projected forwards to 2006 using equations described in Appendix 1.

iii) The parameter estimates of the BC model (Table 8.1) or the alternative

parameter estimates obtained by fitting the model under assumptions **sm1**, **sm2**, **d1**, **d3**, **d3**, **sg1**, **sg2** or **sg3** are used in the simulation.

iv) The observed catches referred to in Appendix 1 are replaced by the OMP generated TAC values. The indices used to determine the TAC were assumed to be either

a) measured without error, or

b) measured with observation error (as described in section 9.11)

9.9 Summary performance statistics

A number of summary performance statistics are reported, as the basis to compare the performances of different candidate OMPs (see Appendix 7 for detailed formulae):

C_{ave}: the average annual catch over the 10 year projection period;

V: the average inter-annual change (as a percentage) in TAC over this 10 year period, and

B(06/96): the biomass above 75mm at the end of the projection period (2006) divided by that at the start (1996). Though the process of OMP development was finalised only in 1997, it started much earlier and 1996 was kept throughout as the standard year against which to report resource recovery statistics, in the interests of consistency.

9.10 Robustness tests

A wide range of robustness tests were defined, in order to test the robustness of the OMPs' performance to many of the assumptions made in the performance evaluation process. These tests fall into two categories.

Category (i): those that use the results of the Base Case assessment model as they stand, but alter one (or several) of the assumptions regarding the status and productivity of the resource in the future, or the data used to monitor these.

Category (ii): those that change one of the assumptions of the underlying size structured model itself, or the data to which it was fitted, thus requiring the model to be re-fitted to the data used in the likelihood function.

Category (i) Robustness tests

Future somatic growth

The Base Case assumption is that future somatic growth will follow the ARMA growth predictions. The somatic growth rates that eventuate may however be somewhat different.

g1: Future somatic growth is 20% more than predicted by the ARMA model.

$g_t = g_{96} + (g_t(\text{ARMA}) - g_{96}) \times 1.2$

(g_t refers to the β_t^m values - see Appendix 3)

g2: Future somatic growth is 20% less than predicted by the ARMA model.

$g_t = g_{96} + (g_t(\text{ARMA}) - g_{96}) \times 0.8$

g3: Future somatic growth rate is at the "low" growth rate level ("low" refers to the average growth over 1989-1994, which was seen as a low growth period - see Appendix 3 for details).

g4: Future somatic growth is at the "high" level ("high" refers to the average somatic growth over 1969-1994 - see Appendix 3 for details).

g6: ARMA growth for the first 5 years, then a sudden drop to the "low" growth rate.

Future stock size

i) The effect of the 1989 recruitment on animals of a size monitored by commercial or FIMS CPUE have not yet been observed, so it is not known what this effect is and hence whether the biomass might decline because of lower recruitment as a consequence of the decreased spawning biomass in the early 1990's (see Figure 8.22).

ii) Other estimates of absolute abundance (i.e. 1996 numbers-at-size) could be wrong, as the assessment model used involves considerable aggregation and many assumptions, so could be giving an inaccurate picture of current resource size in absolute terms.

r1: Recruitment from 1989 onwards is half the current recruitment estimate for recent decades - R_2 (see equation A1.33 in Appendix 1).

r2: Recruitment from 1989 onwards is double the current recruitment estimate (R_2).

r3: Recruitment from 1989 onwards is half of the current recruitment estimate and the numbers-at-size in 1996 are half current estimates.

r4: Recruitment from 1989 onwards is double the current recruitment estimate, and the numbers-at-size in 1996 are double current estimates.

r5: Recruitment is related to the female spawning biomass as follows for the period following 1990:

$$R_t = R_2 \qquad \text{for } B^{sp}(t) \geq B^{sp}(1990) \tag{9.6}$$

$$R_t = R_2\left(\frac{B^{sp}(t)}{B^{sp}(1990)}\right) \qquad \text{for } B^{sp}(t) < B^{sp}(1990)$$

where

R_t = recruitment level for year t

R_2 = recruitment level for the 1950-1990 period

$B^{sp}(t)$ = the female spawning biomass in year t.

This stock-recruit relationship is shown in Figure 9.3. The value of $B^{sp}(1990) = 20.2$ '000 MT.

r6: Assume that recruitment from 1989 is half the current recruitment estimate. Use the stock-recruit relationship defined in equation (9.6) from 1990 onwards.

Doubling and halving recruitment and current numbers-at-size estimates might seem overly severe given the relatively small bootstrap CVs indicated for many model parameters in Table 8.4. However, as discussed in section 8.3, systematic deviations in the fits to certain data, and the likelihood of correlation between residuals, means that these small CVs give an over-optimistic indication of the confidence to be placed in these parameter estimates.

Simulation of an environmental catastrophe

A number of environmental catastrophes could occur, affecting both recruitment and numbers-at-size.

e1: For year t (chosen at random within 1989 - 2000), recruitment drops by 50% for three years, and then recovers to its original level.

e2: In year t (chosen at random within 1997 - 2006), 50% of all lobsters die.

Poaching

Although poaching is known to occur on a fairly large scale, the exact extent of the poaching is unknown.

p1: Poaching increases by 100% over the next 5 years, but this is not realised.

p2: Poaching decreases by 100% over the next 5 years, but this is not realised (i.e. no more poaching after five years).

Bias in indices

The assumption that CPUE is proportional to the biomass may be incorrect.

b1: CPUE from 1994 onwards stays constant (in expectation) irrespective of stock trends.

b2: There is a 2.5% per annum increase in trap efficiency, but this is not realised.

b3: There is a 1% per annum decrease in trap efficiency (due to new entrants), but this is not realised.

Given a TAC formula, the industry may attempt to change their operational patterns to increase CPUE.

b4: An immediate 30% increase in efficiency in CPUE occurs, but no further increases thereafter.

Field measurements of somatic growth may be biased.

b5: For future years, somatic growth is 0.5mm more than thought.

b6: For future years, somatic growth is 0.5mm less than thought.

Fishing selectivity

Access rights to the resource may change, resulting in different users of the resource using different fishing practices.

f1: From 1997 onwards, all commercial catches are made using hoopnets.

Walkouts

During the 1997 season a large mass of lobsters "walked out" of the sea on to the beach at Elands Bay (Van Zyl and Schoeman 1997). The "walk-out" was caused by very low oxygen levels in the water (as a result of large red-tide blooms in the area). It is estimated that over 2000 tons of lobsters died as a result, with a large proportion of these being female lobsters. This "walk-out" phenomenon has occurred in previous years, but never to this large an extent.

w1: In 1997 2000 MT females "walked out" i.e. died.

Category (ii) Robustness tests

Natural survivorship (male) (Base Case $S^m = 0.90$)

The Base Case value of 0.90 is based upon estimates derived in Johnston (1991) where a size-based modelling approach was used to obtain natural survivorship estimates for the west coast rock lobster, but this estimate could be biased for a number of reasons as discussed in that paper.

sm1: $S^m = 0.85$

sm2: $S^m = 0.95$.

Discard mortality (Base Case $d = 10\%$)

The Base Case value of $d = 10\%$ is really little more than a guess, although this value is within the range found in the literature for estimates for other lobster fisheries (Brown and Caputi 1983).

d1: $d = 0\%$

d2: $d = 5\%$

d3: $d = 15\%$.

Somatic Growth

Questions have been raised about the reliability of some of the historic somatic growth data, particularly that for females (as the data are scarce) and for the early tag data.

sg1: Historic adult female somatic growth is 0.25 mm more than thought.

sg2: Historic adult female somatic growth is 0.25mm less than thought.

sg3: The historic somatic growth rate is calculated from the (lesser) 1985-1987 average rather than the 1969 - 1988 average.

9.11 Stochastic analyses

The performances of various candidate OMPs were initially assessed by examining the summary statistics for a deterministic situation, i.e. all future indices of stock status used in the OMP formula (CPUE, FIMS, Growth rate) are exact, without observation error. Stochastic simulations for the most promising OMPs were then run, by repeating projections for different sets of random errors S, where $S = 1, 2, \ldots S_{max}$, for observations of these indices in the future. "Promising" OMPs were those for which adequate robustness was achieved in the deterministic runs. The Base Case scenario as well a number of robustness tests were used to explore the sensitivity of the results when noise is added to the data. The robustness tests that were applied using stochastic simulations were:

g3: Future somatic growth rate is at the "low" growth rate level.

g4: Future somatic growth is at the "high" level.

g6: ARMA growth for the first 5 years, then a sudden drop to the "low" growth rate.

r3: Recruitment from 1989 onwards is half the current recruitment estimate and the numbers-at-size in 1996 are half current estimates.

r4: Recruitment from 1989 onwards is double the current recruitment estimate, and the numbers-at-size in 1996 are double current estimates.

These tests **g3 - r4** were found to give the greatest differences in performance from the Base Case scenario when run deterministically, and were therefore chosen for the stochastic runs. It was not possible to perform every test stochastically as the computation time requirements are very high.

All errors in future indices were assumed to be log-normally distributed. Thus for CPUE as an example:

$$CPUE_t^S = CPUE_t e^{\varepsilon_t} \qquad \varepsilon_t \sim N(0,\sigma^2)$$

The σ values (roughly the CVs) used were:

CPUE: $\sigma = 0.30$ (slightly smaller value than that obtained from fits to past trap CPUE data - see Table 8.1 in Chapter 8)

FIMS: $\sigma = 0.30$ (Scott and Stewart 1997).

Somatic growth (in terms of the β_t^m values): $\sigma = 0.10$ (Brown 1997).

Fifty simulations were run. The median values, the 4th and 47th values after ordering, as well as the CVs are reported for each performance statistic. The 4th and 47th values correspond roughly to a 90% probability interval.

9.12 New data to be used in conjunction with the candidate OMPs

By the time the SFAC had selected an OMP from the suite of candidate OMPs, updated analyses on somatic growth data, commercial CPUE and FIMS CPUE data had been performed (see section 5.2.4). These "new" data values were used as the input data into the selected OMP in order to calculate the 1997 TAC.

Figure 9.1: Sustainable yield curve (assuming recruitment independent of spawning biomass) for west coast rock lobster under the assumption of the ARMA'97 somatic growth rate.

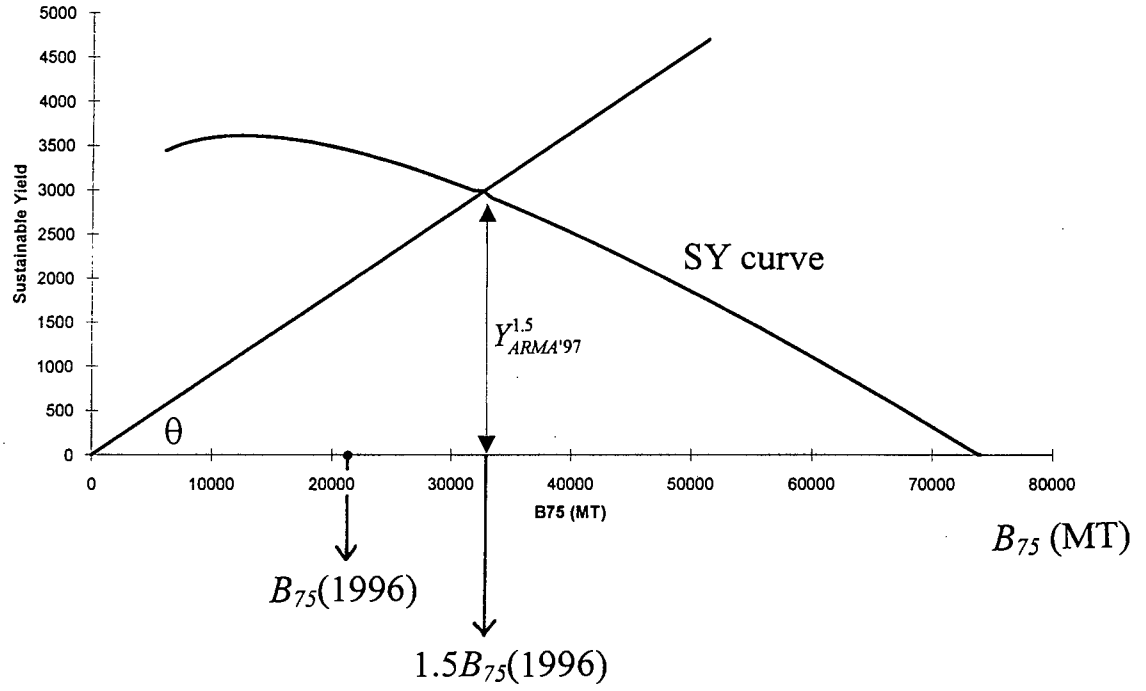


Figure 9.2: Sustainable yield curves for different somatic growth rates.

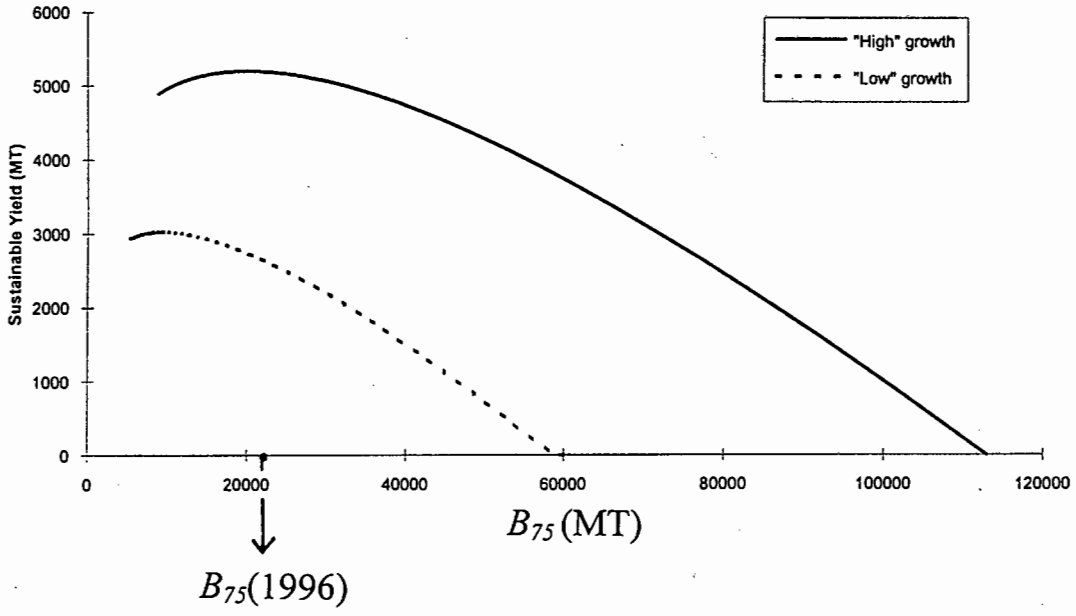
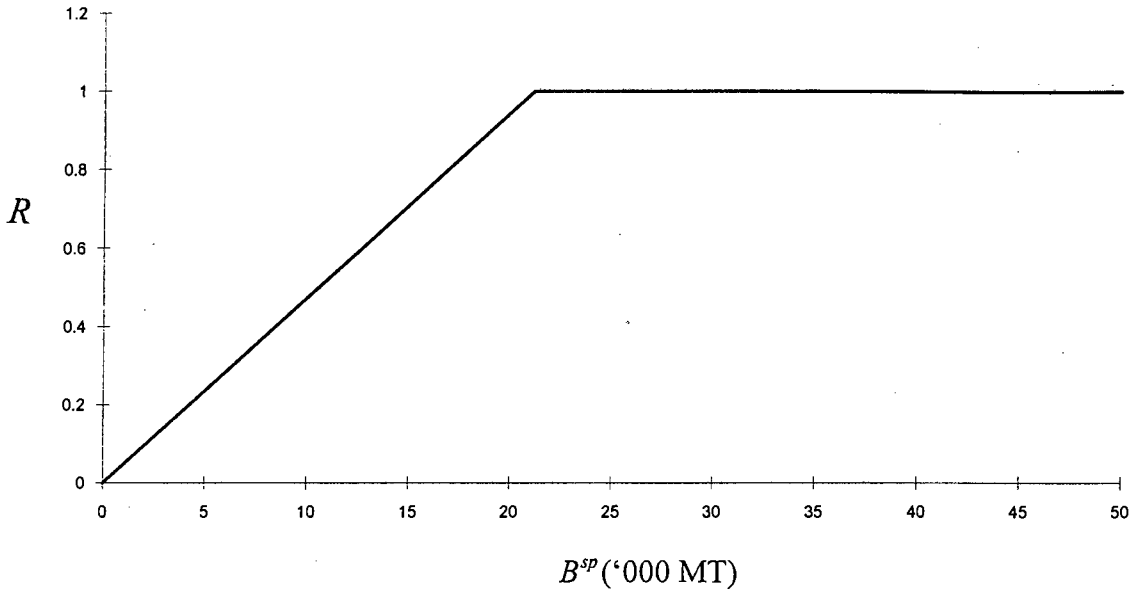


Figure 9.3: The stock-recruit relationship for the **r5** and **r6** robustness tests, where recruitment is expressed as a multiple of R_2 (see equation (9.6)).



Chapter 10: Results of tests of OMP candidates and the final selection

10.1 Introduction

The RLWG made a request to the SFAC to narrow the range of objectives for candidate OMPs for the west coast rock lobster resource. The SFAC responded by requesting results be produced for the following management scenarios:

i) two options of immediate TAC increase, either a 10% increase (on the 1996 TAC of 1700 MT) to 1870 MT; or a 20% increase to 2040 MT; the RLWG thought a third lower option of a 3% increase to 1750 MT might provide additional helpful contrasts; and

ii) the levels of biomass (in terms of B_{75}) recovery over the 10 year projection period of 20%, 30%, 40% and 50%.

The TAC for 1997 was separated from that determined in other years as it was felt that the starting point of the trajectory should fall within some pre-defined acceptable range, in order to facilitate acceptance of the OMP by industry.

These options combined to form the 12 candidate OMPs for west coast rock lobster. The anticipated performance statistics for each of these candidate OMPs were to be used by the SFAC in selecting an OMP for the resource to be implemented for a three year period.

This Chapter presents Base Case deterministic results for all 12 candidate OMPs. Deterministic robustness test results are presented for the full range of tests for the 20% biomass recovery - TAC'97 = 20% increase OMP. Selected robustness test results are also provided for the other candidate OMPs for comparison. Tests **g3**, **g4**, **g6**, **r3** and **r4** were found to perform "worst" deterministically, i.e. gave performance statistics that differed most from those from the Base Case, and were thus chosen for stochastic analyses - the associated results are produced for the 20% and 50% biomass recovery set of candidate OMPs only, to span the overall range.

10.2 Base case deterministic results

The summary statistics for the 12 candidate OMPs are reported in Tables 10.1a-c. By design, the 1997 TAC is the same across all levels of intended biomass recovery. The effects of the different biomass recovery levels on TAC estimates are evident only from the second year (1998).

10.2.1 Average annual catches (C_{ave})

The average catch over the 10 year period (C_{ave}) does not vary much between the different TAC'97 options for the same biomass target recovery level. For example, the 50% biomass recovery option has C_{ave} values of 1972 MT (TAC'97 = 3% increase OMP), 1958 MT (TAC'97 = 10% increase OMP) and 1927 MT (TAC'97 = 20% increase OMP). A greater difference of (about 40%) exists between the C_{ave} values across the range of biomass recovery options. Thus for any TAC'97 option, the 50% biomass recovery

candidate OMPs will produce about 40% less C_{ave} than the corresponding 20% biomass recovery candidates.

10.2.2 TAC variability (V)

The average inter-annual catch variation (V) ranges from between 2.2% (50% biomass recovery- TAC'97 = 3% increase candidate OMP) to 7.7% (20% biomass recovery - TAC'97 = 3% increase candidate OMP). These average values are therefore well below the 15% maximum interannual decrease constraint.

10.2.3 TAC trajectories

The TAC projections are reported in Tables 10.2a-c and illustrated in Figures 10.1a-c. Ideally, one would expect that the most desirable OMP should be associated with a steady increase in TAC over the 10 year projection period. For the TAC'97 = 3% increase candidate OMPs (Figure 10.1a), all four trajectories show a steady increase over the projection period. For the TAC'97 = 10% increase candidates (Figure 10.1b), all but one (the 50% biomass recovery option) show steady TAC increases. The TAC'97 = 20% increase candidates (Figure 10.1c) show two steady increasing TAC trends (20% and 30% biomass recovery levels), but both the 40% and 50% biomass recovery candidate OMPs have initial increases, which are followed by substantial decreases in TAC for the later part of the projection period. The TAC estimated for 2006 for the 50% biomass recovery - TAC'97 = 20% increase candidate is only 1547 MT. The decrease in TACs for the 40% and 50% biomass recovery scenarios is due to the fact that the starting point 1997 TAC

values are too high - requiring subsequent lower catches in order to allow the biomass to recover to these levels.

10.2.4 Biomass trajectories

The biomass (biomass > 75mm) trajectories for all 12 candidate OMPs are illustrated in Figures 10.2a-c. One must bear in mind that the 1996 B_{75} estimate of 20.3 '000 MT is only about 6% of the pristine level, and about 42% of the 1970 level. When asked for guidance by the RLWG, the SFAC strongly supported the management rationale of biomass rebuilding.

10.2.5 Effort trajectories

The production of effort trajectories for the 12 candidate OMPs (illustrated in Figures 10.3a-c) allows one to assess qualitatively what the expected "costs" to the industry of these different options might be. Effort is calculated as the commercial catch (MT) divided by the trap CPUE value ($kg.trap^{-1}.day^{-1}$). During the discussions that initiated the OMP development process, a constant effort strategy was discussed. For a number of reasons (including monitoring problems), this strategy in itself was abandoned, although the possibility of a constant effort strategy at some time in the future was seen to have some merit. An OMP producing an increase in effort over time is likely to mean an increase in costs to the industry. On the other hand, a decrease in effort over time may result in job losses. Of the 12 effort trajectories illustrated, only six can be considered to lead to more or less "constant effort" over the 10 year projection period. These six are for:

i) 30% biomass recovery - TAC'97 = 3% increase OMP

ii) 40% biomass recovery - TAC'97 = 3% increase OMP

iii) 30% biomass recovery - TAC'97 = 10% increase OMP

iv) 40% biomass recovery - TAC'97 = 10% increase OMP

v) 20% biomass recovery - TAC'97 = 20% increase OMP

vi) 30% biomass recovery - TAC'97 = 20% increase OMP

10.3 Deterministic robustness tests results

It is important to determine the performance of the candidate OMPs for not only the Base Case situation (as reported in section 10.2 above), but also for a wide range of robustness tests. These robustness tests investigate performance sensitivity across variations of a wide variety of underlying assumptions made in the model, and have been described in Chapter 9. The summary statistics for all 31 robustness tests are calculated for the 20% biomass recovery - TAC'97 = 20% increase candidate OMP. These results are reported in Table 10.3. To illustrate the sensitivity of the two key summary statistics - C_{ave} and $B(06/96)$ - to changes in the model assumptions, graphic output is produced in Figures 10.4 a- f.

Robustness is tested for three other candidate OMPs:

i) 20% biomass increase; TAC'97=3% increase OMP;

ii) 50% biomass increase; TAC'97=3% increase OMP; and

iii) 50% biomass increase, TAC'97=20% increase OMP.

Results for the "more difficult" tests **g3**, **g4**, **g6**, **r3** and **r4** only are produced for these three candidate OMPs, and are reported in Tables 10.4, 10.5 and 10.6 respectively.

A "good" OMP candidate should be able to automatically make appropriate TAC adjustments in the light of future data when Base Case perceptions and assumptions are incorrect. If the stock situation turns out to be better than predicted under the Base Case, the OMP should adjust the TAC upwards; similarly, if this situation turns out to be worse than expected, the OMP should adjust the TAC downwards. The aim of the OMP is thus to produce the required level of biomass recovery at the end of the 10 year projection period, no matter what the actual current stock situation is and what happens (to the somatic growth rate, for example) in the future.

Thus, when assessing the robustness tests results (for the 20% biomass recovery - TAC'97 = 20% increase candidate OMP) one needs to check how closely the $B(06/96)$ value stays to the required 1.20. The more "robust" the OMP, the closer the OMP will be able to maintain the $B(06/96)$ value to 1.20 over a wide range of robustness tests. It should be mentioned that many of the robustness tests examined here are extreme. The **r3** test, for example, assumes that both recruitment and current numbers-at-size are half what they are currently estimated to be. This is clearly an extreme scenario, but the aim of these tests is to investigate the ability of the OMP to self-correct TACs given large errors in current perceptions about the resource.

10.3.1 Robustness tests results for the 20% biomass recovery - TAC'97 = 20% increase candidate OMP

The performance of this candidate OMP is particularly robust to future somatic growth rate assumptions (Table 10.3 and Figure 10.4a). Robustness is worst for **g6** (ARMA for 5 years then low somatic growth rate) - here $B(06/96)$ is 0.96 instead of the target 1.20. For **g4** ("high" somatic growth in the future instead of ARMA), the OMP reacts by increasing the C_{ave} to 4153 MT and the resultant $B(06/96)$ is 1.29. On the other hand, for **g3** ("low" somatic growth instead of ARMA), the OMP reduces the C_{ave} to only 1776 MT and the resulting $B(06/96)$ value is 1.07. The TAC'97 value is hardly impacted across these tests - the largest change is for **g3** where TAC'97 is reduced to 1926 MT. [Note that the TAC'97 = 20% is as would be expected to result if the Base Case is correct; for the other scenarios reflected by the robustness tests, the most recent data used in the TAC'97 evaluation are likely to adjust it away from the 20% increase expected - see also section 10.5.1.]

It is particularly encouraging that this OMP is robust to assumptions regarding the future somatic growth rate, as this had been one of the most debated and controversial issues in the RLWG when previously formulating TAC recommendations. On one hand, some considered that the somatic growth rate is (and will continue to be) higher than the estimated ARMA growth. The **g4** robustness test is representative of such a scenario. On the other hand, others believed that the recent low somatic growth rate phenomenon could easily re-occur in the near future - robustness tests **g3** and **g6** cover this eventuality.

The second set of robustness tests deals with uncertainties regarding the future stock size and productivity: tests **r1** - **r6** (Figure 10.4b). The OMP has some difficulty in adjusting quickly enough if recruitment or current stock size is rather different from current perceptions. Although the B(06/96) values are not very close to the target 1.20 value, a number of factors must be highlighted:

i) as mentioned previously, these robustness tests are *extreme;* and

ii) the OMP does manage to increase (or decrease) the TAC fairly substantially in an attempt to self-correct - i.e. the OMP does recognise the problem, though it does not react either fast enough or to a large enough extent to correct fully.

These results are in fact very encouraging. Even under the very extreme **r3** scenario, this OMP will "turn the biomass decline around" before the end of the 10 year period. This is illustrated in Figure 10.5. The OMP is thus able to arrest a severe biomass decline even for this extreme scenario. The B(06/96) value for the **r3** test is 0.53. The TAC is reduced to a value of 652 MT by the year 2006. The V statistic is 10.33, indicating that the 15% maximum downward interannual TAC constraint that is in place for all these tests (as well as the Base Case) is unlikely to be preventing greatly improved performance. If one were to enforce a zero TAC on the fishery throughout the next 10 years for this scenario, the B(06/96) value would be 1.43 - this indicates the greatest level of recovery possible for the **r3** scenario.

For both the **e1** and **e2** scenarios twenty simulations were run, and the median values are reported. (Note that since this test involves random future events, it cannot be run in a

totally deterministic manner.) This OMP performs well with regards to robustness test **e1** - which assumes recruitment drops by 50% for three years (chosen at random within the 10 year projection period for each simulation) and then recovers. With the current biomass at such low levels (female spawning biomass is about 20% of pristine), this may in fact be a fairly likely scenario, and it is encouraging to observe (Figure 10.4c) that this OMP can handle it with only a fairly small drop in the biomass recovery level - median $B(06/96) = 1.07$ compared to the 1.20 target. This OMP candidate has greater difficulty in achieving self-correction in the event that 50% of all lobsters die in any one year (chosen at random) - robustness test **e2**. The median $B(06/96)$ value is 0.49 in this case (the 3rd value = 0.34 and the 18th value = 1.20). A problem here is that the decrease in biomass often occurs too late in the 10 year projection period for the OMP to correct sufficiently for the "damage" done to the biomass levels. The earlier the biomass decline, the better the OMP is able to self-correct.

The OMP shows robust performance to tests **p1** and **p2** (concerning an undetected increase or decrease in poaching), to **f1** (concerning a change of gear to hoopnets) and to **w1** (concerning the walkout of female lobsters in 1997). This is evident from the results shown in Figure 10.4c.

This OMP performance is robust to the range considered of changes in fishery efficiency, with biased CPUE trends as indices of abundance (tests **b1**, **b2**, **b3** and **b4**); this is illustrated in Figure 10.4d. Performance is, however, less robust for the **b5** robustness test

which assumes that future somatic growth is 0.5mm more than thought. Here the B(06/96) value is 1.62 (Figure 10.4d), i.e. the self-correction properties of the OMP are insufficient to increase the catch enough to take full advantage of this better growth. Nevertheless C_{ave} does increase by about 25% over the Base Case prediction, and in such circumstances using some of the bonus of this additional somatic growth to increase the biomass level of a very depleted resource would be quite desirable and defensible. The OMP performs better for the converse test **b6** (future somatic growth is 0.5mm less), with the B(06/96) value dropping only slightly below the 1.20 target level to 1.10.

Robustness to assumptions regarding the level of male natural survivorship (**sm1** and **sm2**) is satisfactory - although a perhaps surprising result is that the B(06/96) value declines for both **sm1** (S^m= 0.85) and **sm2** (S^m = 0.95) - Figure 10.4e. This follows from the result reported in Chapter 8 (Table 8.3a) where it is shown that for both **sm1** and **sm2** there is an increase in the estimated B_{75}(1996) estimate - if biomass is higher, more of the surplus production has to be left unharvested to achieve the same proportional increase in biomass. In these cases, not only is the biomass higher, but the surplus production is lower than in the Base Case, which is why the application of this OMP candidate leads to a slight biomass decline. The higher biomass levels involved do, however, mean that this is not catastrophic for the resource.

The OMP performance is very robust to mis-assumptions about the level of discard mortality, although the B(06/96) value **decreases** with reduced d values, and **increases**

with an increased d value (Table 10.3). This is a surprising result as one would expect future biomasses to decrease if the discard mortality increases. In Table 8.3a we see that when re-fitting the operating model using a d = 15%, the recruitment estimates are increased (presumably to compensate for an increase in d). This increase in recruitment is thus responsible for the future biomasses to increase under the high d scenario.

A number of concerns have been raised in discussions in the RLWG concerning both the female somatic growth and the historic somatic growth rate assumptions used in the Base Case model of the resource dynamics. In Figure 10.4f, we see that this OMP performance is robust to both these uncertainties. Although in Chapter 8 it was shown that the $B_{75}(1996)$ estimate is increased substantially for the **sg3** test, the effect that this has on the OMP performance is clearly negligible compared to changes for many other tests. The $B(06/96)$ value for **sg3** (historic growth rate = 1985-87 average) is 1.21 - virtually identical to the target level.

10.3.2 Robustness tests results for other candidate OMPs

Robustness tests results for five of the most "extreme" tests, i.e. those for which performance statistics showed the greatest sensitivity compared to the Base Case (**g3**, **g4**, **g6**, **r3** and **r4**) are reported for three other candidate OMPs. These results are presented in Table 10.4 (20% biomass recovery - TAC'97 = 3% increase OMP), Table 10.5 (50% biomass recovery - TAC'97 = 3% increase OMP) and Table 10.6 (50% biomass recovery - TAC'97 = 20% increase OMP). Note that these other three candidates bound the range

of OMPs investigated, which cover target biomass increases from 20% to 50% over the next 10 years, and immediate TAC increases of 3% to 20%. These results all show similar trends to those for the 20% biomass recovery - TAC'97 = 20% increase OMP already discussed.

The relatively low V estimates (generally below 10%) for the Base Case, and most of the robustness tests examined, reveal that the OMP reflects an inbuilt "inertia". This "inertia" prevents the OMP from over-reacting to what is actually only noise in the data. The "inertia" results from the following:

i) the $w = 0.50$ parameter value in the TAC setting algorithm (see equation (9.5));

ii) the constraint of 15% on the maximum extent to which the TAC can be reduced from one year to the next; and

iii) the three year averaging of the indices input to the algorithm (see equation (9.3)).

These controls result in the TAC changing in a steady pattern over time.

10.3.3 Comparisons to a constant catch strategy

The relatively good performance of these candidate OMPs and their associated advantages (particularly their feedback properties) can be seen more clearly if one examines the results presented in Table 10.7. Here the $B(06/96)$ values for a range of constant catch (CC) strategies (which effectively ignore future information on resource

behaviour) are reported. Results are shown for four different CC levels, and reported for the Base Case as well as for the **g3**, **g4**, **g6**, **r3** and **r4** robustness tests. A CC of 2000 MT produces a biomass recovery of $B(06/96) = 1.48$ for the Base Case scenario. This constant catch strategy is therefore closely comparable to a 50% biomass recovery OMP in terms of resource recovery (here the 50% biomass recovery - TAC'97 = 20% increase candidate OMP is used for comparison).

The OMP results are shown in brackets in the first column of Table 10.7, and it is clear that the OMP outperforms the CC strategy for all five robustness tests. The most important result is that for the **r3** robustness test. The 2000 MT CC strategy will result in the biomass to decline to 13% of the 1996 level, whereas the OMP is able to self-correct by altering the TAC values downwards and hence produce a higher $B(06/96)$ value of 0.62. For CC strategies larger than 2000 MT, results for the **r3** test are even worse. For a CC of 3000 MT or more, the resource will be rendered commercially extinct!

10.4 Stochastic analyses

The results presented so far have been for the deterministic situation - i.e. it has been assumed that values of the CPUE, FIMS and somatic growth data observed for each future year reflect resource behaviour exactly. This is unlikely to be the case in reality, and stochastic analyses that incorporate noise into these data are important, so as to assess the variability of the summary statistics for various candidate OMPs. A candidate which is not so good at achieving the target recovery level in deterministic tests may

nevertheless ultimately be preferred if it shows less variability in performance once the presence of noise in the data inputs is taken into account. (Essentially this is analogous to the "bias-variance" trade-off in statistical model selection.) Stochastic analyses (50 simulations for each test) are performed for the 20% and 50% biomass recovery OMP candidates. Results are presented for the Base Case (Tables 10.8a and b), the **g6** robustness test (Tables 10.9a and b), the **r3** robustness test (Tables 10.10a and b) and for the **r4** robustness test (Tables 10.11a and b). (The **g3** and **g4** tests were omitted at this level, because previous results showed greater sensitivities for **g6**.) Comparative performance of the various robustness tests are illustrated in Figures 10.6 - 10.7 (only the C_{ave}, V and $B(06/96)$ statistics are shown).

10.4.1 Base case: stochastic results

Stochastic results for the Base Case scenarios are reported in Table 10.8a (for 20% biomass recovery scenarios) and 10.8b (50% biomass recovery scenarios). These show that the median $B(06/96)$ values for all OMP candidates are slightly larger than the deterministic 1.20 and 1.50 values. The CV's for $B(06/96)$ range from 14.2% to 19.2%. CV's for other summary performance statistics are lower. The TAC'97 estimates are the most precise, with CV's ranging from 4.9% to 6.8%. This is not surprising as the expected values of TAC'97 (conditioned on the Base Case scenario) are fixed in the candidate OMPs by construction. Thus slight differences arise only because of deviations of 1997 input values from those expected under the assumptions of the Base Case scenario.

10.4.2 Robustness tests: stochastic results

The robustness tests stochastic results are presented in Table 10.9-10.11. These results are compared graphically to one another in Figure 10.6-10.9 for four different candidate OMPs. In these Figures, each "bar" plots the median (the central point) and the 4th and 47th values (the end points) - these correspond very roughly to the 90% probability intervals.

By comparing Figures 10.6 with 10.7, and 10.8 with 10.9, little difference is evident when varying the immediate TAC increase.

Examining across the various robustness tests, it is clear that C_{ave} is much more variable under **r4** and much less under **r3**. The V statistic is a bit less variable under **r3**, and a bit more under **g6**. The B(06/96) statistics show similar variability across all tests.

The difference between the 20% and 50% target recovery levels can be seen by comparing Figures 10.6 with 10.8, and 10.7 with 10.9. Here it is evident that variability is a bit greater for the 20% target level for both V and B(06/96).

Note that these variability statistics do not reflect the precision with which the simulations have estimated, say, median performance. Rather, they measure the extent to which the actual performance may deviate for the (deterministic) projection as a result of noise in the indices.

10.5 The OMP selected

The 12 candidate OMPs were presented to the SFAC in August 1997. After examination of their results (in the form of a condensed set of the results of this section, which concentrated particularly on the Base Case deterministic results), the SFAC chose the 20% biomass recovery - TAC'97 = 20% increase OMP to be implemented for the forthcoming year, and for the following two years. This OMP is essentially the least conservative of the 12 candidates, providing the maximum immediate TAC gain. The probable rationale behind this decision is discussed by De Oliveira, Butterworth and Johnston (1998) and in summary is as follows:

i) The changing political circumstances in South Africa, with the redistribution of wealth and opportunity being stressed in the White paper on marine fisheries policy (Anon. 1997) , has caused existing quota holders in the fishery to be unsure about their immediate and medium-term futures, especially since there has been much talk about "restructuring" of (i.e. introduction of new entrants) to the industry. These existing quota holders see their interests best served, given the present recovery trend in the resource following TAC cutbacks during the period of low somatic growth, by a rapid increase in TAC giving them a better chance of securing larger rights in the long term; in contrast, they see the risk of the slow TAC increases associated with the higher biomass recovery targets as likely to lead to all of the consequent lesser TAC increases being allocated to new entrants. Furthermore, why sacrifice TAC increases now for greater levels of future biomass, when they will not be the ones to benefit from these sacrifices in the future ?

ii) The SFAC includes members of the fishing industry, although these people are appointed in their personal rather than in a representative capacity. Because all 12 candidate OMPs were deemed "scientifically" acceptable in terms of risk to the resource, differing only in the level of biomass recovery and the amount of immediate TAC increase, non-industry members probably had no strong basis on which to object to any of the 12 candidates. Opinion within the SFAC was thus likely to have been driven largely by members of the industry, given the considerations discussed above.

The selected OMP is associated with a near constant effort trajectory as shown in Figure 10.3c - a further advantage.

10.5.1 TAC for 1997

The OMP evaluations were based on data available up to 1995, and essentially assumed model-predicted values for 1996. However, by the time the TAC advice had to be given, the 1996 data were available. These data are presented in Table 10.12, alongside the model-predicted values, upon which the OMP developments were based. The observed values differ somewhat from the model predictions - especially with regards to the β_t^m (the index of somatic growth used in the OMP formula). The observed value for 1996 is 9.75mm which is somewhat higher than the ARMA prediction of 9.52mm. The observed value for the 1996 trap CPUE is slightly higher (1.106) than the model predicted value of 1.068, and the observed value for 1996 FIMS (0.991) lower than the model prediction of 1.029. These differences resulted in the OMP providing a 1997 TAC of **1920** MT - a

lower figure to the projected value of 2040 MT (the 20% increase above the 1996 TAC) upon which the OMP tests had been based. The 2040 MT estimate was based upon the model's prediction of a certain amount of biomass increase. When the 1997 TAC value was calculated, observed data collected from the fishery itself were used (not model predicted data). These observed data produced the lower TAC value of 1920 MT, reflecting that the resource status had not improved as much as predicted by the model for 1997, and appropriately and in consequence, the OMP yielded a lower TAC than the full 20% increase.

Table 10.1a: Base Case deterministic summary performance statistics for the TAC'97 = 3% increase candidate OMPs.

	20% biomass recovery	**30% biomass recovery**	**40% biomass recovery**	**50% biomass recovery**
C_{ave} **(MT)**	2760	2489	2231	1972
V	7.66	6.12	4.37	2.23
B**(06/96)**	1.20	1.30	1.40	1.50
TAC '97 (MT)	1750	1750	1750	1750
TAC '06 (MT)	3532	3062	2604	2105

Table 10.1b: Base Case deterministic summary performance statistics for the TAC'97 = 10% increase candidate OMPs.

	20% biomass recovery	**30% biomass recovery**	**40% biomass recovery**	**50% biomass recovery**
C_{ave} **(MT)**	2744	2481	2205	1958
V	6.99	5.42	3.47	2.55
B**(06/96)**	1.20	1.30	1.40	1.50
TAC '97 (MT)	1870	1870	1870	1870
TAC '06 (MT)	3322	2871	2368	1882

Table 10.1c: Base Case deterministic summary performance statistics for the TAC'97 = 20% increase candidate OMPs.

	20% biomass recovery	**30% biomass recovery**	**40% biomass recovery**	**50% biomass recovery**
C_{ave} **(MT)**	2717	2458	2191	1927
V	6.11	4.73	4.12	5.32
B**(06/96)**	1.20	1.30	1.40	1.50
TAC '97 (MT)	2040	2040	2040	2040
TAC '06 (MT)	3026	2573	2078	1547

Table 10.2a: Base Case deterministic TAC trajectories (MT) for the TAC'97 = 3% increase candidate OMPs.

year	20% biomass recovery	30% biomass recovery	40% biomass recovery	50% biomass recovery
1997	1750	1750	1750	1750
1998	1951	1886	1827	1772
1999	2212	2076	1954	1839
2000	2486	2280	2094	1919
2001	2745	2474	2226	1989
2002	2977	2646	2341	2045
2003	3173	2792	2436	2083
2004	3330	2910	2510	2105
2005	3449	3002	2566	2112
2006	3532	3062	2604	2105

Table 10.2b: Base Case deterministic TAC trajectories (MT) for the TAC'97 = 10% increase candidate OMPs.

year	20% biomass recovery	30% biomass recovery	40% biomass recovery	50% biomass recovery
1997	1870	1870	1870	1870
1998	2081	2018	1955	1903
1999	2321	2190	2059	1952
2000	2558	2360	2161	1996
2001	2770	2508	2244	2021
2002	2949	2631	2305	2026
2003	3092	2726	2347	2012
2004	3199	2796	2368	1981
2005	3275	2843	2375	1937
2006	3322	2871	2368	1882

Table 10.2c: Base case deterministic TAC trajectories (MT) for the TAC'97 = 20% increase candidate OMPs.

year	20% biomass recovery	30% biomass recovery	40% biomass recovery	50% biomass recovery
1997	2040	2040	2040	2040
1998	2262	2200	2139	2087
1999	2471	2343	2216	2106
2000	2655	2460	2268	2097
2001	2799	2543	2288	2055
2002	2904	2593	2280	1986
2003	2973	2616	2250	1896
2004	3013	2616	2204	1790
2005	3028	2601	2145	1674
2006	3026	2573	2078	1547

Table 10.3: Deterministic robustness test results for the 20% biomass recovery - TAC'97 = 20% increase candidate OMP.

Test	Description	C_{ave} (MT)	V	B(06/96)	TAC '97 (MT)	TAC '06 (MT)
BC	Base Case	2717	6.11	1.20	2040	3026
g1	future growth increases 20%	2799	6.64	1.23	2040	3189
g2	future growth decreases 20%	2636	5.61	1.18	2040	2866
g3	low growth in future	1776	3.30	1.07	1926	1621
g4	high growth in future	4153	12.31	1.29	2348	4480
g6	ARMA 5yrs then low growth	2302	9.93	0.96	2040	1716
r1	R half of estimate	2159	6.07	0.58	2016	1820
r2	R double estimate	3806	12.38	2.43	2085	5408
r3	R and #'s half of estimates	1104	10.33	0.53	1819	652
r4	R and #'s double estimates	7428	21.14	2.09	2534	10576
r5	Stock-recruit relationship	2636	5.85	1.05	2040	2785
r6	R decreases 50%; S-R rel.	2114	6.77	0.48	2016	1677
e1	R drops at random for 3 yrs	2660	6.13	1.07	2040	2768
e2	50% lobsters die at random	2523	8.91	0.49	2040	2007
p1	poaching increases 100%	2677	5.93	1.11	2040	2898
p2	poaching decreases 100%	2756	6.51	1.30	2040	3151

Table 10.3 cont.

Test	Description	C_{ave} (MT)	V	B(06/96)	TAC '97 (MT)	TAC '06 (MT)
BC	Base Case	2717	6.11	1.20	2040	3026
b1	CPUE constant	2437	1.31	1.31	2015	2582
b2	2.5% p.a. ↑ in efficiency	2825	1.16	1.16	2040	3272
b3	1% p.a. ↓ efficiency	2676	1.22	1.22	2040	2932
b4	30% ↑ efficiency	2970	1.10	1.10	2040	3307
b5	growth 0.5mm more	3484	1.62	1.62	2040	4269
b6	growth 0.5mm less	2119	1.10	1.10	2040	2164
f1	1997+ all catches hoopnets	2721	1.24	1.24	2040	3047
w1	walkout	2684	1.20	1.20	2040	2990
sm1	$S^m = 0.85$	2216	3.57	0.84	1986	2207
sm2	$S^m = 0.95$	2161	3.29	0.92	1981	2131
d1	d = 0%	2607	5.50	1.16	2028	2856
d2	d = 5%	2667	5.83	1.18	2035	2948
d3	d = 15%	2829	6.81	1.30	2054	3236
sg1	female growth 0.25mm more	2758	6.42	1.32	2043	3123
sg2	female growth 0.25mm less	2763	6.48	1.26	2050	3141
sg3	historic growth = 1985-87 ave	2584	5.52	1.21	2026	2875

Table 10.4: Deterministic robustness test results for the 20% biomass recovery-TAC '97 = 3% increase candidate OMP.

Test	Description	C_{ave} (MT)	V	B(06/96)	TAC '97 (MT)	TAC '06 (MT)
BC	Base Case	2760	7.66	1.20	1750	3532
g3	low growth in future	1765	1.55	1.08	1664	1888
g4	high growth in future	4247	12.61	1.28	1982	5256
g6	ARMA 5yrs then low growth	2287	8.18	0.97	1750	1996
r3	R and #'s half estimates	1083	6.99	0.56	1582	818
r4	R and #'s double estimates	7693	22.59	2.06	2123	12190

Table 10.5: Deterministic robustness test results for the 50% biomass recovery-TAC '97 = 3% increase candidate OMP.

Test	Description	C_{ave} (MT)	V	B(06/96)	TAC '97 (MT)	TAC '06 (MT)
BC	Base Case	1972	2.23	1.50	1750	2105
g3	low growth in future	1194	5.43	1.30	1639	968
g4	high growth in future	3183	8.75	1.65	2051	3338
g6	ARMA 5yrs then low growth	1643	7.39	1.20	1750	1071
r3	R and #'s half estimates	880	11.22	0.73	1583	510
r4	R and #'s double estimates	5184	15.90	2.51	2123	7111

Table 10.6: Deterministic robustness test results for the 50% biomass recovery-TAC '97 = 20% increase candidate OMP.

Test	Description	C_{ave} (MT)	V	B(06/96)	TAC '97 (MT)	TAC '06 (MT)
BC	Base Case	1927	5.32	1.50	2040	1547
g3	low growth in future	1212	10.33	1.28	1893	717
g4	high growth in future	3089	12.57	1.66	2437	2441
g6	ARMA 5yrs then low growth	1715	9.68	1.17	2040	953
r3	R and #'s half estimates	985	14.07	0.62	1819	427
r4	R and #'s double estimates	4887	15.41	2.54	2533	5279

Table 10.7: *B*(06/96) values for a few constant catch (CC) strategies - Base Case and robustness test results. (The values in brackets in the first column give comparative values for the 50% biomass recovery - TAC'97 = 20% increase candidate OMP.)

Test	**Description**	**CC 2000 MT**	**CC 2500 MT**	**CC 3000 MT**	**CC 3500 MT**
BC	Base Case	1.48 (*1.50*)	1.29	1.08	0.88
g3	low growth in future	0.99 (*1.28*)	0.80	0.60	0.39
g4	high growth in future	1.80 (*1.66*)	1.62	1.43	1.24
g6	ARMA 5yrs then low growth	1.13 (*1.17*)	0.95	0.77	0.58
r3	R and #'s half estimates	**0.13 (*0.62*)**	**0.10**	**0.0001**	-
r4	R and #'s double estimates	3.11 (*2.54*)	3.02	2.92	2.82

Table 10.8a: Stochastic results for the Base Case - 20% Biomass increase candidate OMPs.

Candidate OMP	Statistic	Deterministic result	Median	4th	47th	CV (%)
20% Biomass increase	C_{ave} **(MT)**	*2760*	2700	2457	2996	8.91
Tac'97=3% increase	V	*7.66*	8.84	7.07	10.80	14.92
	B**(06/96)**	*1.20*	1.28	0.98	1.60	19.17
	TAC'97 (MT)	*1750*	1728	1600	1890	5.95
	TAC'06 (MT)	*3532*	3539	3103	4156	11.47
20% Biomass increase	C_{ave} **(MT)**	*2744*	2673	2438	2981	8.84
Tac'97=10% increase	V	*6.99*	8.04	6.45	10.04	14.96
	B**(06/96)**	*1.20*	1.28	0.98	1.60	19.01
	TAC'97 (MT)	*1870*	1846	1700	2029	6.31
	TAC'06 (MT)	*3322*	3308	2915	3897	11.45
20% Biomass increase	C_{ave} **(MT)**	*2717*	2641	2409	3004	7.93
Tac'97=20% increase	V	*6.11*	7.18	5.97	8.62	13.97
	B**(06/96)**	*1.20*	1.26	1.01	1.52	16.44
	TAC'97 (MT)	*2040*	2037	1914	2171	4.87
	TAC'06 (MT)	*3026*	3041	2648	3640	11.11

Table 10.8b: Stochastic results for the Base case - 50% Biomass increase candidate OMPs.

Candidate OMP	Statistic	Deterministic result	Median	4th	47th	CV (%)
50% Biomass increase	C_{ave} **(MT)**	*1972*	1910	1744	2145	9.05
Tac'97=3% increase	V	*2.23*	4.87	3.90	7.04	26.29
	B**(06/96)**	*1.50*	1.57	1.29	1.86	14.24
	TAC'97 (MT)	*1750*	1728	1600	1860	5.95
	TAC'06 (MT)	*2105*	2063	1847	2340	11.47
50% Biomass increase	C_{ave} **(MT)**	*1958*	1897	1731	2140	9.01
Tac'97=10% increase	V	*2.55*	5.07	3.62	7.27	26.30
	B**(06/96)**	*1.50*	1.58	1.29	1.86	14.23
	TAC'97 (MT)	*1870*	1846	1700	2029	6.31
	TAC'06 (MT)	*1882*	1847	1655	2175	11.38
50% Biomass increase	C_{ave} **(MT)**	*1927*	1871	1701	2100	9.03
Tac'97=20% increase	V	*5.32*	6.70	4.31	8.84	26.16
	B**(06/96)**	*1.50*	1.58	1.29	1.86	14.16
	TAC'97 (MT)	*2040*	2011	1842	2225	6.75
	TAC'06 (MT)	*1547*	1527	1376	1788	11.27

Table 10.9a: Stochastic results for the **g6** robustness test - 20% Biomass increase candidate OMPs.

Candidate OMP	Statistic	Deterministic result	Median	4th	47th	CV (%)
20% Biomass increase	C_{ave} **(MT)**	*2287*	2327	2072	2610	9.65
Tac'97=3% increase	V	*8.18*	9.87	6.85	12.38	20.20
	B**(06/96)**	*0.97*	1.05	0.77	1.28	18.93
	TAC'97 (MT)	*1750*	1728	1600	1890	5.94
	TAC'06 (MT)	*1996*	1955	1748	2309	10.53
20% Biomass increase	C_{ave} **(MT)**	*2428*	2343	2077	2606	9.66
Tac'97=10% increase	V	*9.36*	10.16	6.73	12.28	19.81
	B**(06/96)**	*0.95*	1.05	0.77	1.28	19.03
	TAC'97 (MT)	*1870*	1846	1700	2029	6.31
	TAC'06 (MT)	*2019*	1878	1641	2198	10.58
20% Biomass increase	C_{ave} **(MT)**	*2302*	1750	1522	1938	9.83
Tac'97=20% increase	V	*9.93*	9.56	7.94	11.41	15.38
	B**(06/96)**	*0.96*	1.25	1.02	1.47	14.32
	TAC'97 (MT)	*2040*	2011	1842	2226	6.75
	TAC'06 (MT)	*1716*	1068	883	1257	11.97

Table 10.9b: Stochastic results for the **g6** robustness test - 50% Biomass increase candidate OMPs.

Candidate OMP	Statistic	Deterministic result	Median	4th	47th	CV (%)
50% Biomass increase	C_{ave} **(MT)**	*1643*	1716	1516	1897	9.71
Tac'97=3% increase	*V*	*7.39*	7.73	5.61	9.28	18.80
	B(06/96)	*1.20*	1.28	1.03	1.48	14.07
	TAC'97 (MT)	*1750*	1729	1600	1890	5.95
	TAC'06 (MT)	*1071*	1221	1079	1408	11.13
50% Biomass increase	C_{ave} **(MT)**	*1764*	1736	1522	1914	9.74
Tac'97=10% increase	*V*	*7.22*	8.82	6.13	9.86	16.37
	B(06/96)	*1.20*	1.27	1.02	1.47	14.19
	TAC'97 (MT)	*1870*	1846	1700	2029	6.31
	TAC'06 (MT)	*1132*	1152	1013	1333	11.32
50% Biomass increase	C_{ave} **(MT)**	*1715*	1075	996	1149	6.06
Tac'97=20% increase	*V*	*9.68*	8.06	6.67	9.75	16.65
	B(06/96)	*1.17*	0.61	0.31	0.85	30.86
	TAC'97 (MT)	*2040*	1577	1469	1686	4.58
	TAC'06 (MT)	*953*	819	667	990	14.29

Table 10.10a: Stochastic results for the **r3** robustness test - 20% Biomass increase candidate OMPs.

Candidate OMP	Statistic	Deterministic result	Median	4th	47th	CV (%)
20% Biomass increase	C_{ave} **(MT)**	*1083*	1075	996	1149	6.06
Tac'97=3% increase	*V*	*6.99*	8.06	6.67	9.75	16.65
	B(06/96)	*0.56*	0.61	0.31	0.85	30.86
	TAC'97 (MT)	*1582*	1577	1469	1686	4.58
	TAC'06 (MT)	*818*	819	667	990	14.29
20% Biomass increase	C_{ave} **(MT)**	*1091*	1085	1011	1150	5.99
Tac'97=10% increase	*V*	*7.78*	8.76	7.40	10.25	15.12
	B(06/96)	*0.55*	0.60	0.36	0.83	31.79
	TAC'97 (MT)	*1681*	1674	1552	1797	5.05
	TAC'06 (MT)	*749*	739	607	901	14.61
20% Biomass increase	C_{ave} **(MT)**	*1104*	1102	1021	1171	6.09
Tac'97=20% increase	*V*	*10.33*	10.95	8.41	13.03	14.92
	B(06/96)	*0.53*	0.57	0.33	0.80	34.18
	TAC'97 (MT)	*1819*	1812	669	1955	5.44
	TAC'06 (MT)	*652*	631	536	780	14.16

Table 10.10b: Stochastic results for the **r3** robustness test - 50% Biomass increase candidate OMPs.

Candidate OMP	Statistic	Deterministic result	Median	4th	47th	CV (%)
50% Biomass increase	C_{ave} **(MT)**	*880*	887	835	944	5.02
Tac'97=3% increase	***V***	*11.22*	11.62	10.38	12.56	8.35
	***B*(06/96)**	*0.73*	0.76	0.56	0.98	21.95
	TAC'97 (MT)	*1583*	1577	1470	1686	4.58
	TAC'06 (MT)	*510*	497	441	613	11.34
50% Biomass increase	C_{ave} **(MT)**	*912*	921	863	984	5.70
Tac'97=10% increase	***V***	*12.42*	12.75	11.48	13.54	6.83
	***B*(06/96)**	*0.69*	0.73	0.51	0.95	23.58
	TAC'97 (MT)	*1680*	1674	1552	1797	5.04
	TAC'06 (MT)	*1439*	446	400	532	9.48
50% Biomass increase	C_{ave} **(MT)**	*985*	979	900	1072	6.71
Tac'97=20% increase	***V***	*14.07*	13.91	13.21	14.97	4.42
	***B*(06/96)**	*0.62*	0.66	0.43	0.91	27.26
	TAC'97 (MT)	*1819*	1812	1669	1956	5.44
	TAC'06 (MT)	*427*	434	405	470	6.17

Table 10.11a: Stochastic results for the **r4** robustness test - 20% Biomass increase candidate OMPs.

Candidate OMP	Statistic	Deterministic result	Median	4th	47th	CV (%)
20% Biomass increase	C_{ave} **(MT)**	*7693*	7572	6717	8419	10.43
Tac'97=3% increase	*V*	*22.59*	22.94	21.51	25.18	6.55
	***B*(06/96)**	*2.06*	2.19	1.75	2.60	15.31
	TAC'97 (MT)	*2123*	2093	1889	2341	8.84
	TAC'06 (MT)	*12190*	11994	10602	14081	11.98
20% Biomass increase	C_{ave} **(MT)**	*7588*	7447	6611	8269	10.38
Tac'97=10% increase	*V*	*21.96*	22.38	20.80	24.67	6.86
	***B*(06/96)**	*2.07*	2.20	1.76	2.60	15.15
	TAC'97 (MT)	*2293*	2259	2028	2540	9.27
	TAC'06 (MT)	*11528*	11293	9991	13238	11.93
20% Biomass increase	C_{ave} **(MT)**	*7428*	7255	6449	8095	10.33
Tac'97=20% increase	*V*	*21.14*	21.65	19.92	23.95	7.48
	***B*(06/96)**	*2.09*	2.22	1.78	2.62	14.89
	TAC'97 (MT)	*2534*	2494	2225	2821	9.80
	TAC'06 (MT)	*10576*	10267	9104	12020	11.86

Table 10.11b: Stochastic results for the **r4** robustness test - 50% Biomass increase candidate OMPs.

Candidate OMP	Statistic	Deterministic result	Median	4th	47th	CV (%)
50% Biomass increase	C_{ave} **(MT)**	*5184*	5048	4476	5739	10.64
Tac'97=3% increase	V	*15.90*	16.55	15.04	18.79	9.23
	B**(06/96)**	*2.51*	2.62	2.22	3.00	11.45
	TAC'97 (MT)	*2123*	2093	1889	2341	8.84
	TAC'06 (MT)	*7111*	6904	6144	8271	12.18
50% Biomass increase	C_{ave} **(MT)**	*5077*	4928	4355	5628	10.62
Tac'97=10% increase	V	*15.25*	16.23	14.12	18.31	10.40
	B**(06/96)**	*2.52*	2.63	2.23	3.01	11.37
	TAC'97 (MT)	*2293*	2259	2028	2540	9.28
	TAC'06 (MT)	*6386*	6198	5543	7413	12.10
50% Biomass increase	C_{ave} **(MT)**	*4887*	4727	4176	5377	10.64
Tac'97=20% increase	V	*15.41*	16.06	13.02	18.89	12.68
	B**(06/96)**	*2.54*	2.65	2.26	3.02	11.22
	TAC'97 (MT)	*2533*	2494	2224	2822	9.80
	TAC'06 (MT)	*5279*	5123	4617	6098	12.01

Table 10.12: Model-predicted values for trap CPUE, FIMS CPUE and β_t^m for 1996, compared to subsequent observations.

	Model-predicted	**Observed**
trap CPUE	1.068	1.106
FIMS CPUE	1.029	0.991
β_t^m **(mm)**	9.52	9.75

Figure 10.1a: Deterministic TAC (MT) trajectories for the TAC'97 = 3% increase candidate OMPs.

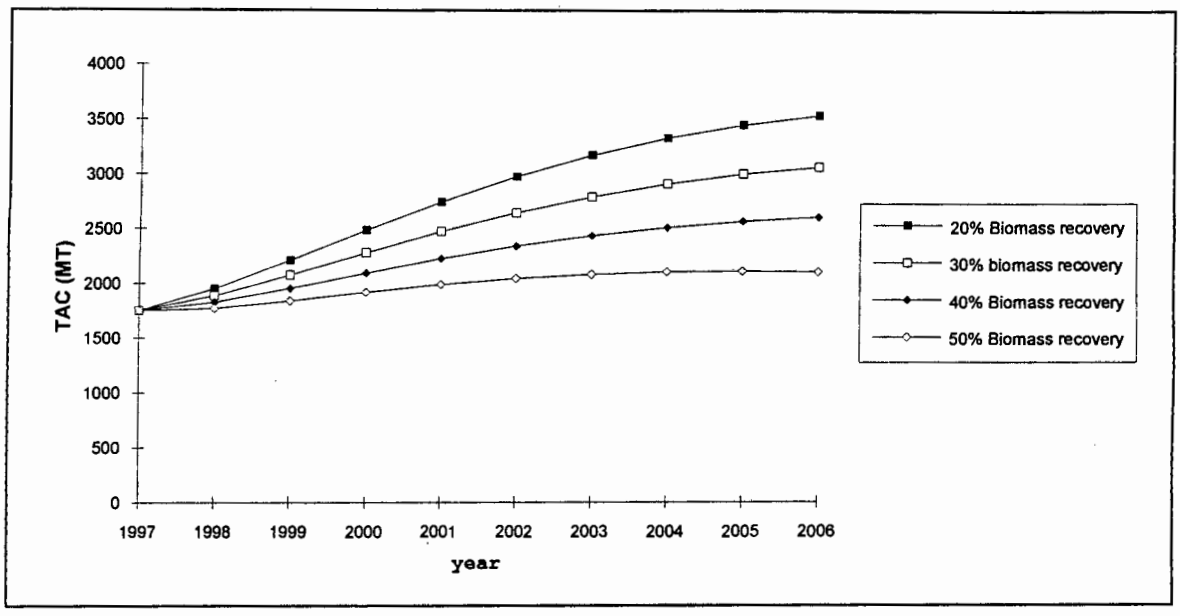


Figure 10.1b: Deterministic TAC (MT) trajectories for the TAC'97 = 10% increase candidate OMPs.

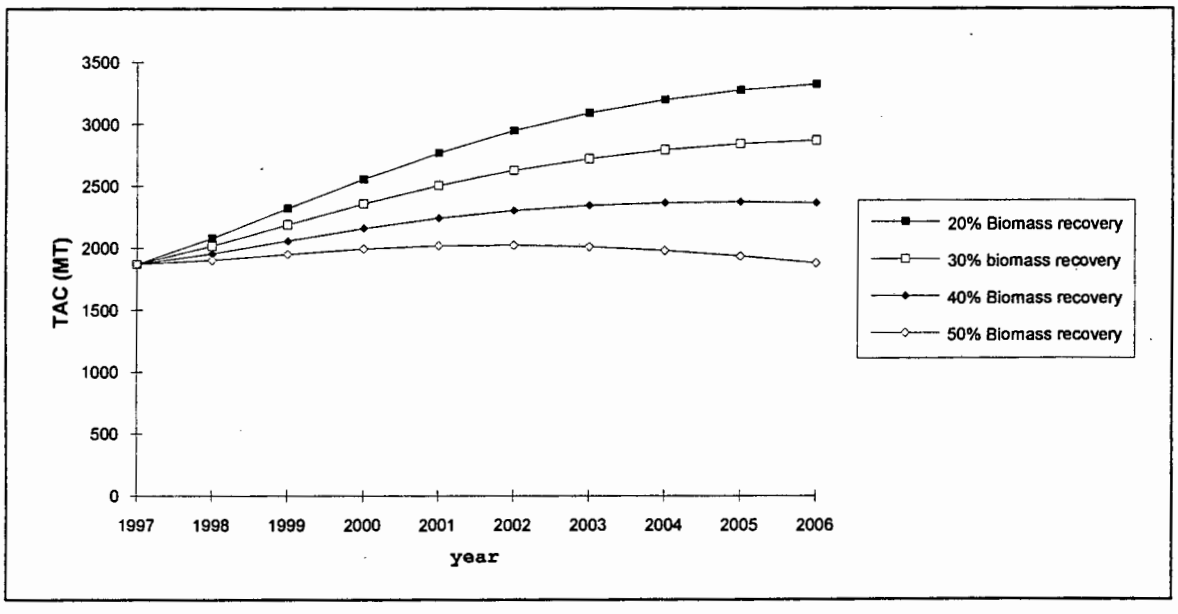


Figure 10.1c: Deterministic TAC (MT) trajectories for the TAC'97 = 20% increase candidate OMPs.

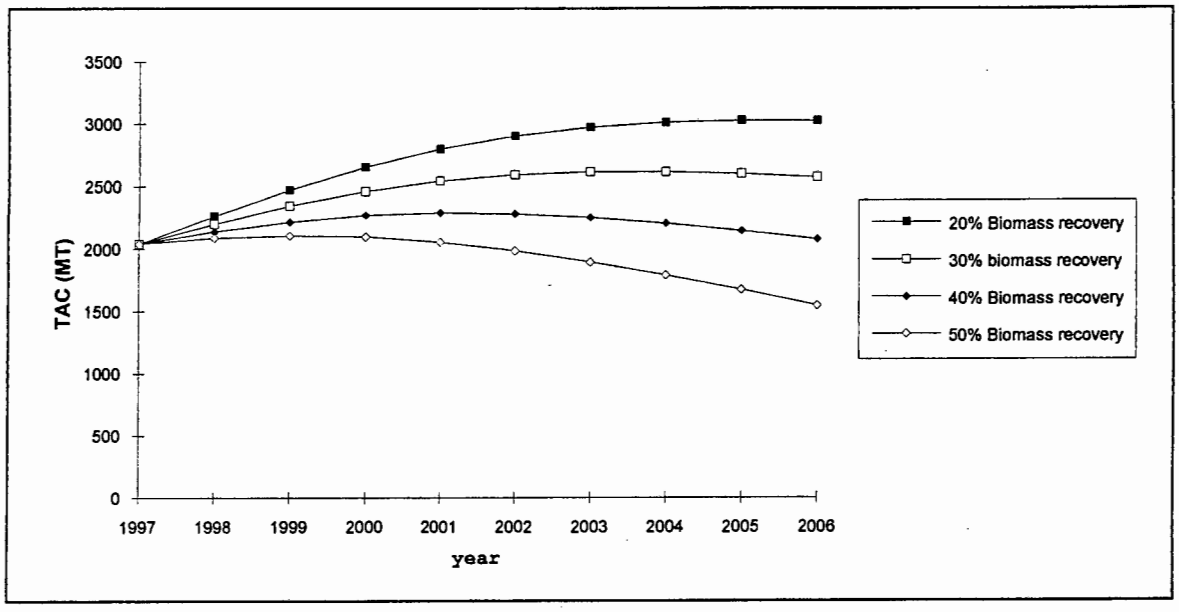


Figure 10.2a: Deterministic biomass (>75mm) trajectories (MT) for the TAC'97 = 3% increase candidate OMPs.

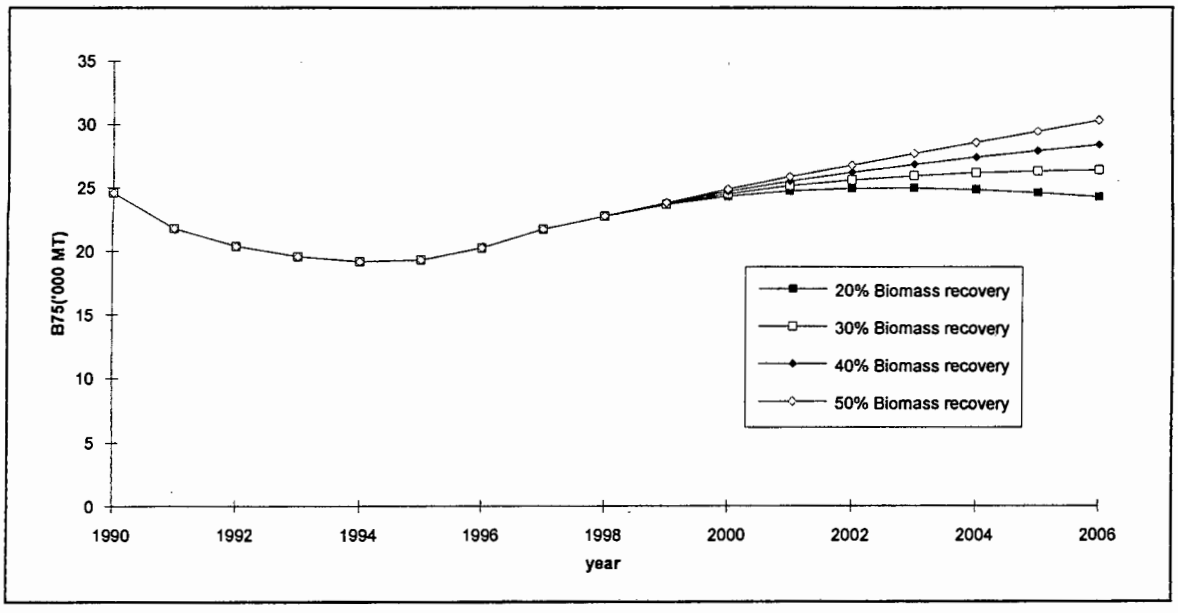


Figure 10.2b: Deterministic biomass (>75mm) trajectories (MT) for the TAC'97 = 10% increase candidate OMPs.

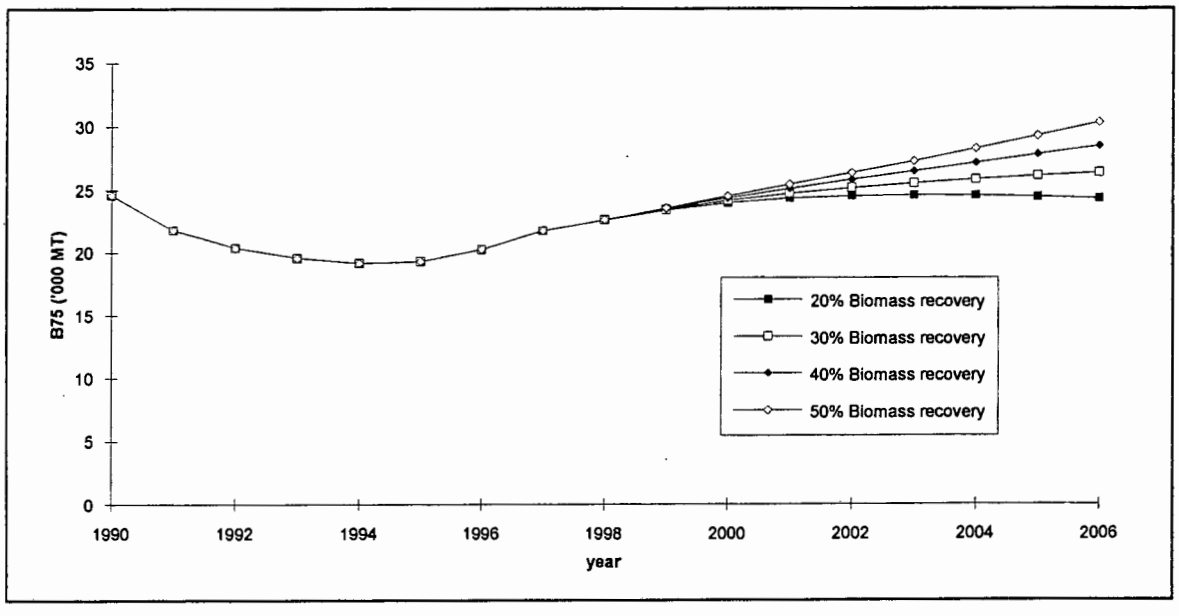


Figure 10.2c: Deterministic biomass (>75mm) trajectories (MT) for the TAC'97 = 20% increase candidate OMPs.

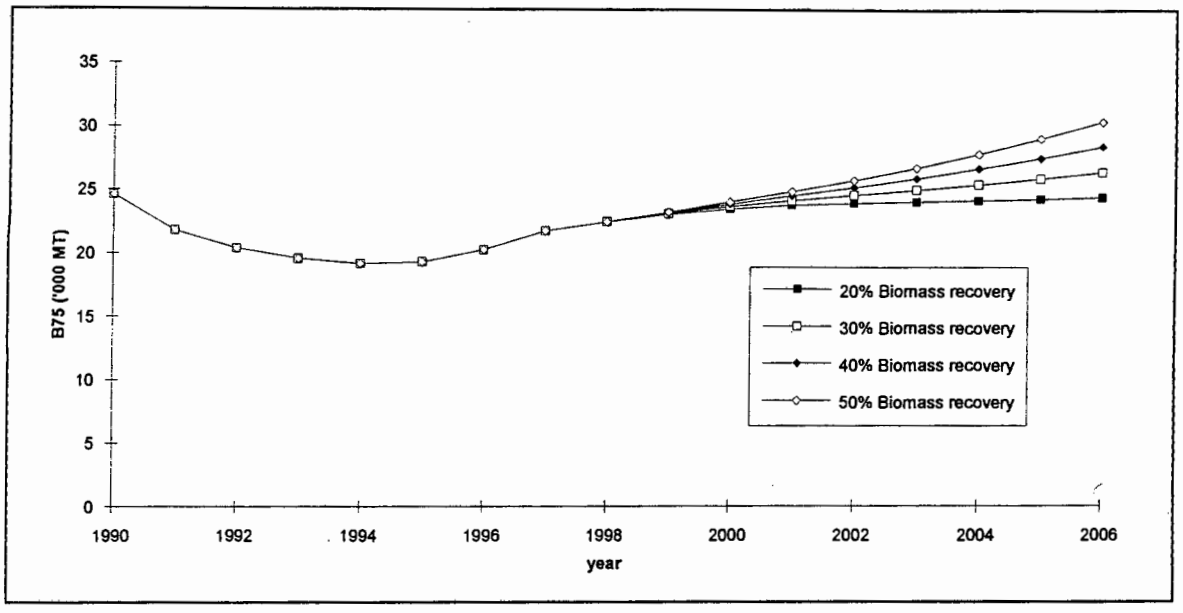


Figure 10.3a: Deterministic effort trajectories for the TAC'97 = 3% increase candidate OMPs.

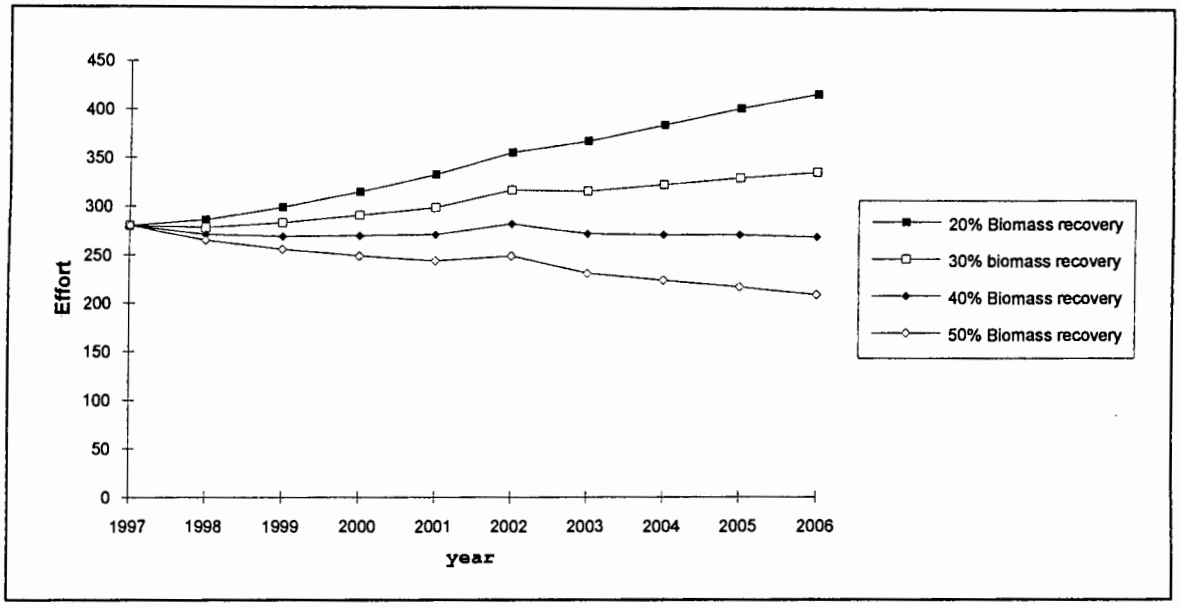


Figure 10.3b: Deterministic effort trajectories for the TAC'97 = 10% increase candidate OMPs.

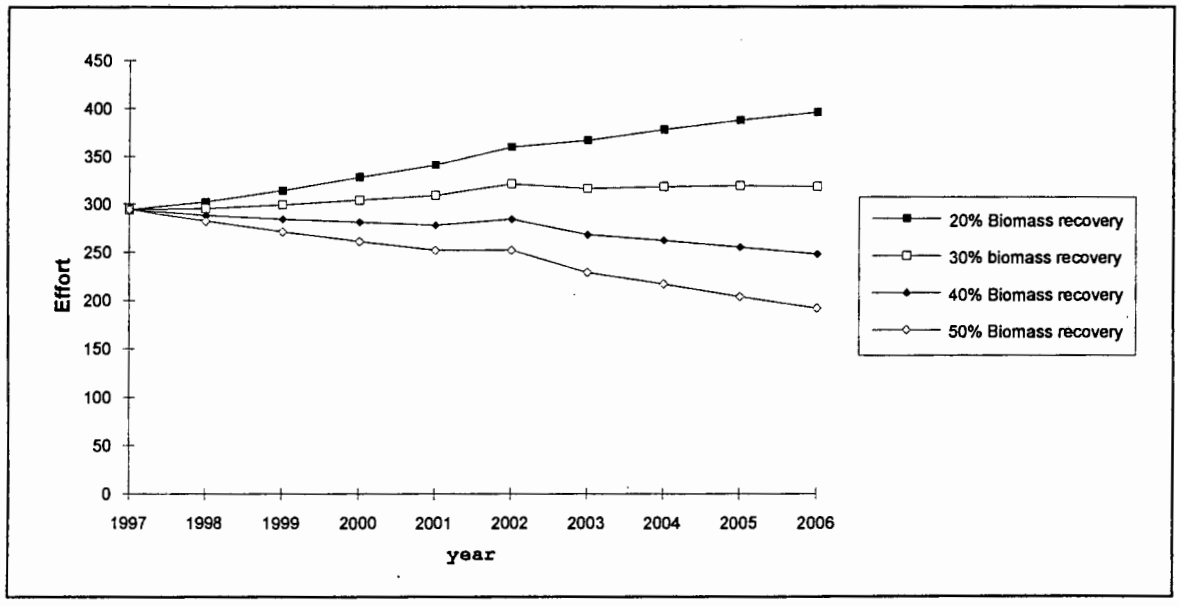


Figure 10.3c: Deterministic effort trajectories for the TAC'97 = 20% increase candidate OMPs.

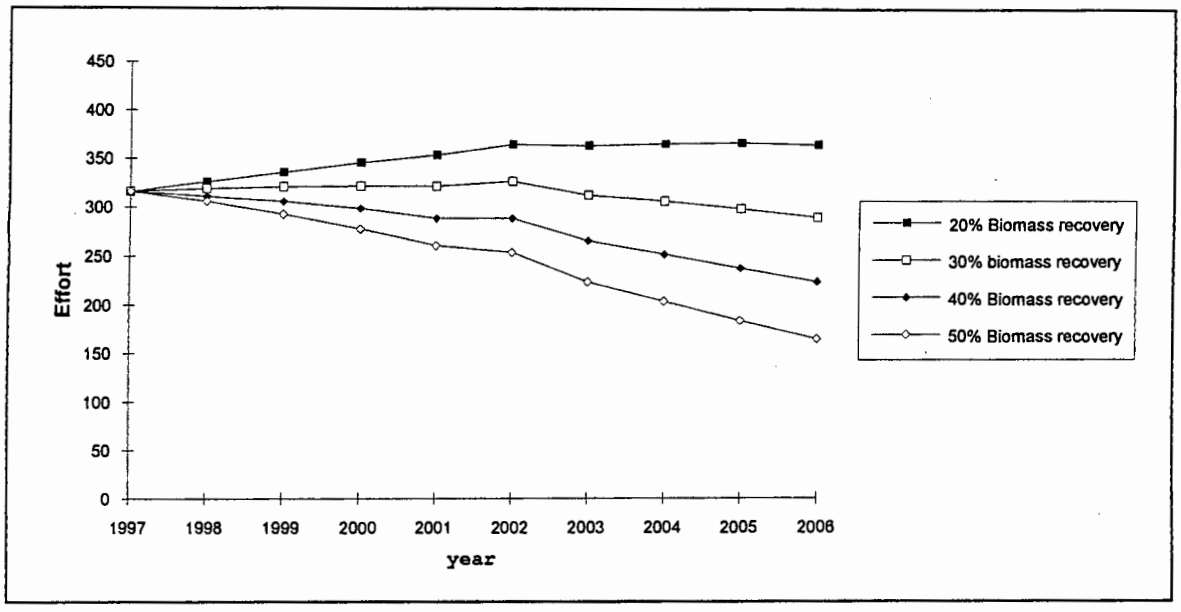
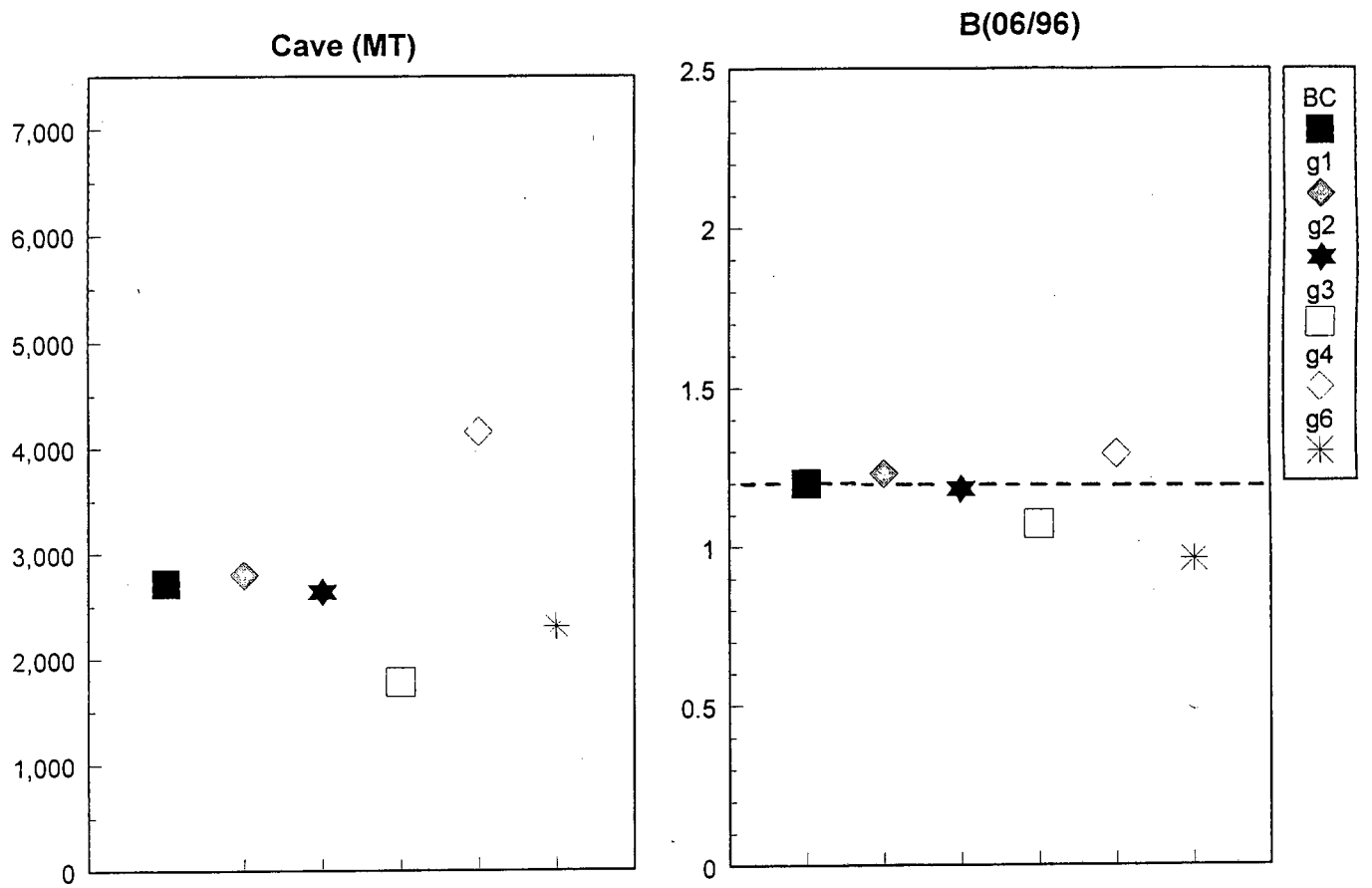


Figure 10.4a: C_{ave} (MT) and $B(06/96)$ values for deterministic robustness tests concerning future somatic growth assumptions (results are for the 20% biomass recovery - TAC'97 = 20% increase candidate OMP). The target recovery level is indicated by the dashed line.



g1: Future somatic growth is 20% more than predicted by the ARMA model.

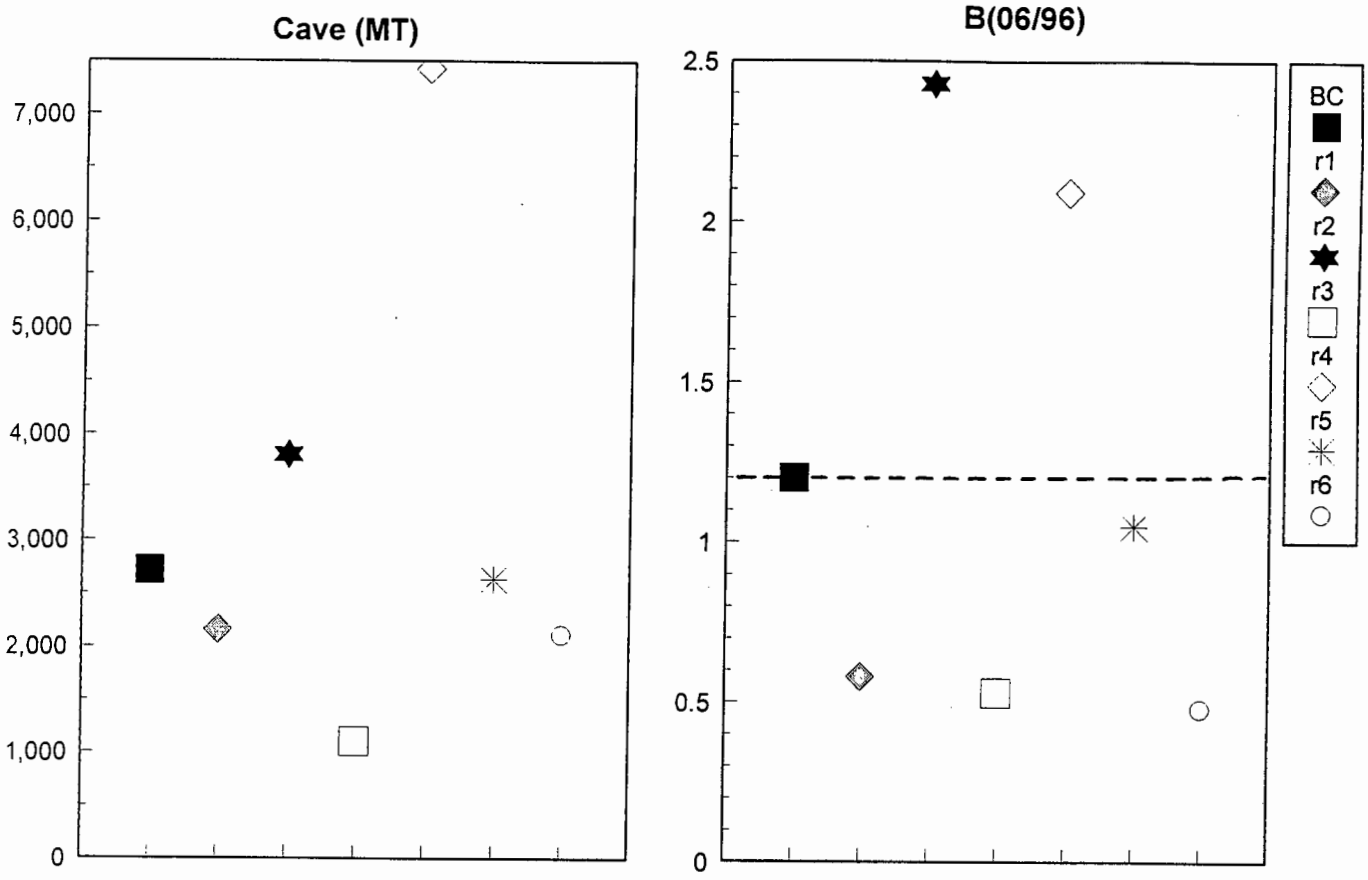
g2: Future somatic growth is 20% less than predicted by the ARMA model.

g3: Future somatic growth rate is at the "low" growth rate level.

g4: Future somatic growth is at the "high" level.

g6: ARMA growth for the first 5 years, then a sudden drop to the "low" growth rate.

Figure 10.4b: C_{ave} (MT) and $B(06/96)$ values for deterministic robustness tests concerning recruitment assumptions (results are for the 20% biomass recovery - TAC'97 = 20% increase candidate OMP). The target recovery level is indicated by the dashed line.



r1: Recruitment from 1989 onwards is half the current recruitment estimate for recent decades.

r2: Recruitment from 1989 onwards is double the current recruitment estimate (R_2).

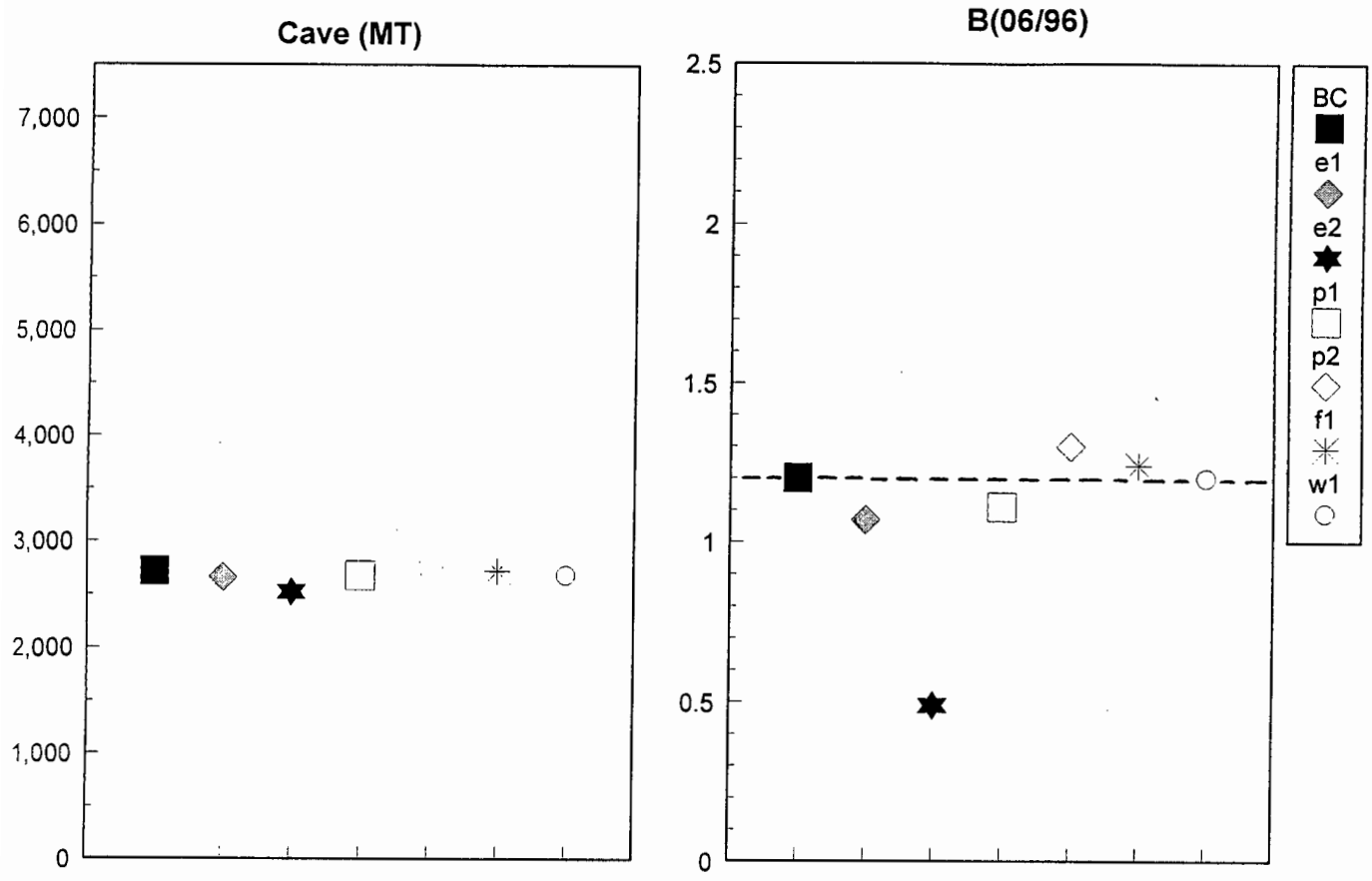
r3: Recruitment from 1989 onwards is half of the current recruitment estimate and the numbers-at-size in 1996 are half current estimates.

r4: Recruitment from 1989 onwards is double the current recruitment estimate, and the numbers-at-size in 1996 are double current estimates.

r5: Recruitment is related to the female spawning biomass for the period following 1990.

r6: Assume that recruitment from 1989 is half the current recruitment estimate. Use the stock-recruit relationship defined for **r5** from 1990 onwards.

Figure 10.4c: C_{ave} (MT) and $B(06/96)$ values for deterministic robustness tests concerning environmental perturbations, changes in poaching levels (unrealised by managers), selectivity changes and walkouts (results are for the 20% biomass recovery - TAC'97 = 20% increase candidate OMP). The target recovery level is indicated by the dashed line.



e1: For year *t* (chosen at random within 1989 - 2000), recruitment drops by 50% for three years, and then recovers to its original level.

e2: In year *t* (chosen at random within 1997 - 2006), 50% of all lobsters die.

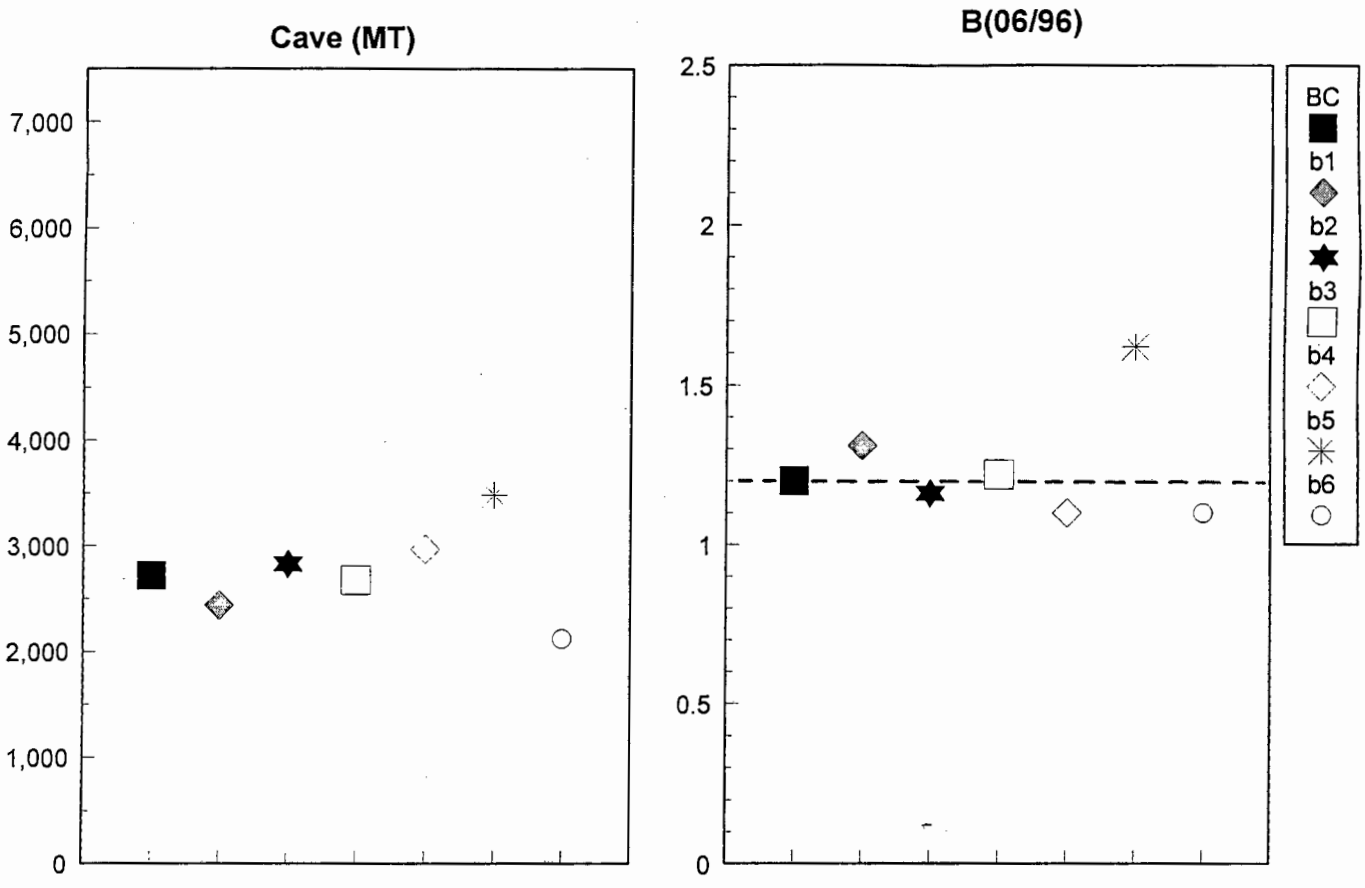
p1: Poaching increases by 100% over the next 5 years, but this is not realised.

p2: Poaching decreases by 100% over the next 5 years, but this is not realised (i.e. no more poaching after five years).

f1: From 1997 onwards, all commercial catches are made using hoopnets.

w1: In 1997 2000 MT females "walked out" i.e. died.

Figure 10.4d: C_{ave} (MT) and $B(06/96)$ values for deterministic robustness tests concerning bias in CPUE indices and future somatic growth measures (results are for the 20% biomass recovery - TAC'97 = 20% increase candidate OMP). The target recovery level is indicated by the dashed line.



b1: CPUE from 1994 onwards stays constant (in expectation) irrespective of stock trends.

b2: There is a 2.5% per annum increase in trap efficiency, but this is not realised.

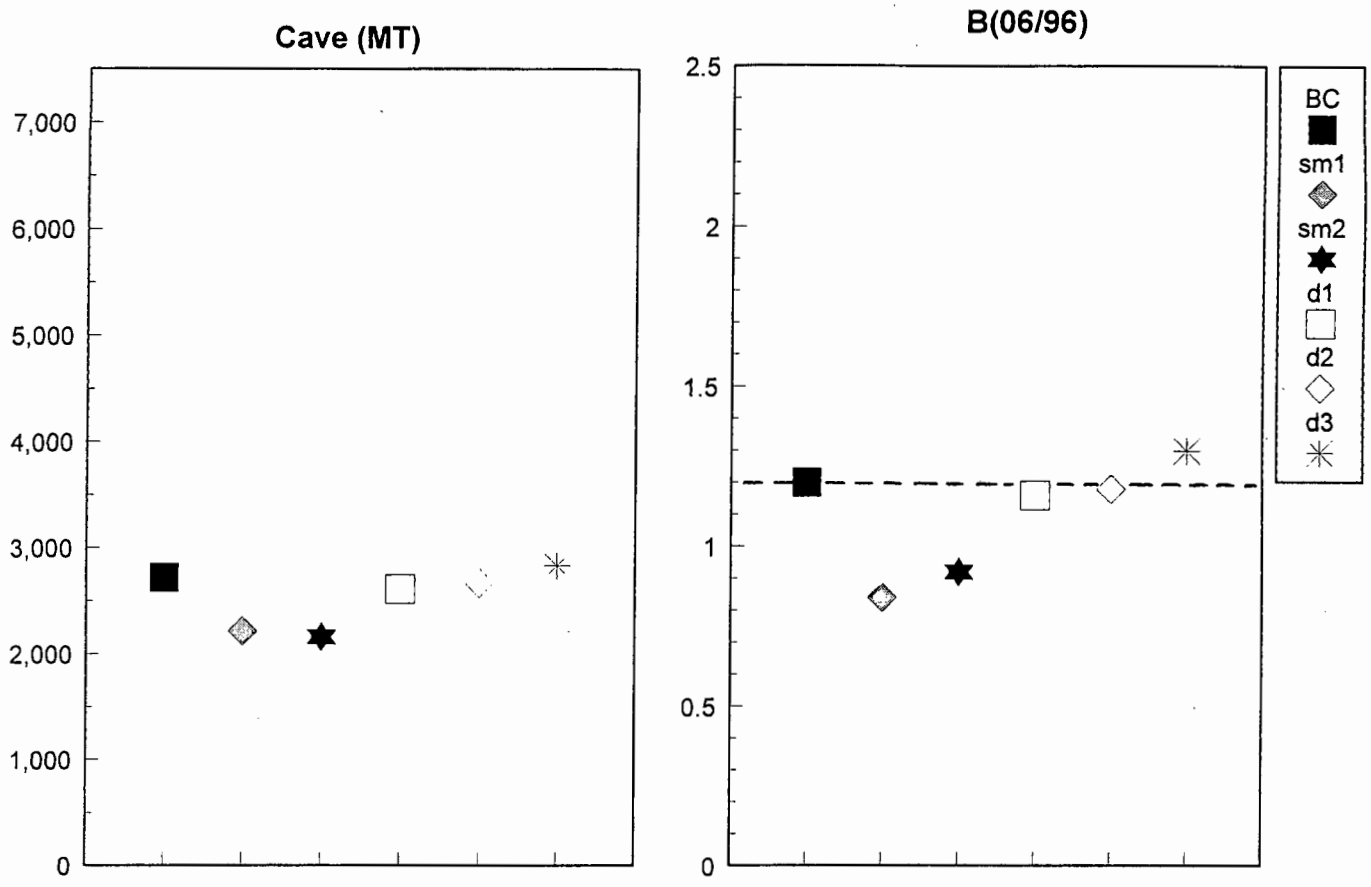
b3: There is a 1% per annum decrease in trap efficiency (due to new entrants), but this is not realised.

b4: An immediate 30% increase in efficiency in CPUE occurs, but no further increases thereafter.

b5: For future years, somatic growth is 0.5mm more than thought.

b6: For future years, somatic growth is 0.5mm less than thought.

Figure 10.4e: C_{ave} (MT) and B(06/96) values for deterministic robustness tests concerning natural survivorship and discard mortality assumptions (results are for the 20% biomass recovery - TAC'97 = 20% increase candidate OMP). The target recovery level is indicated by the dashed line.



sm1: $S^m = 0.85$

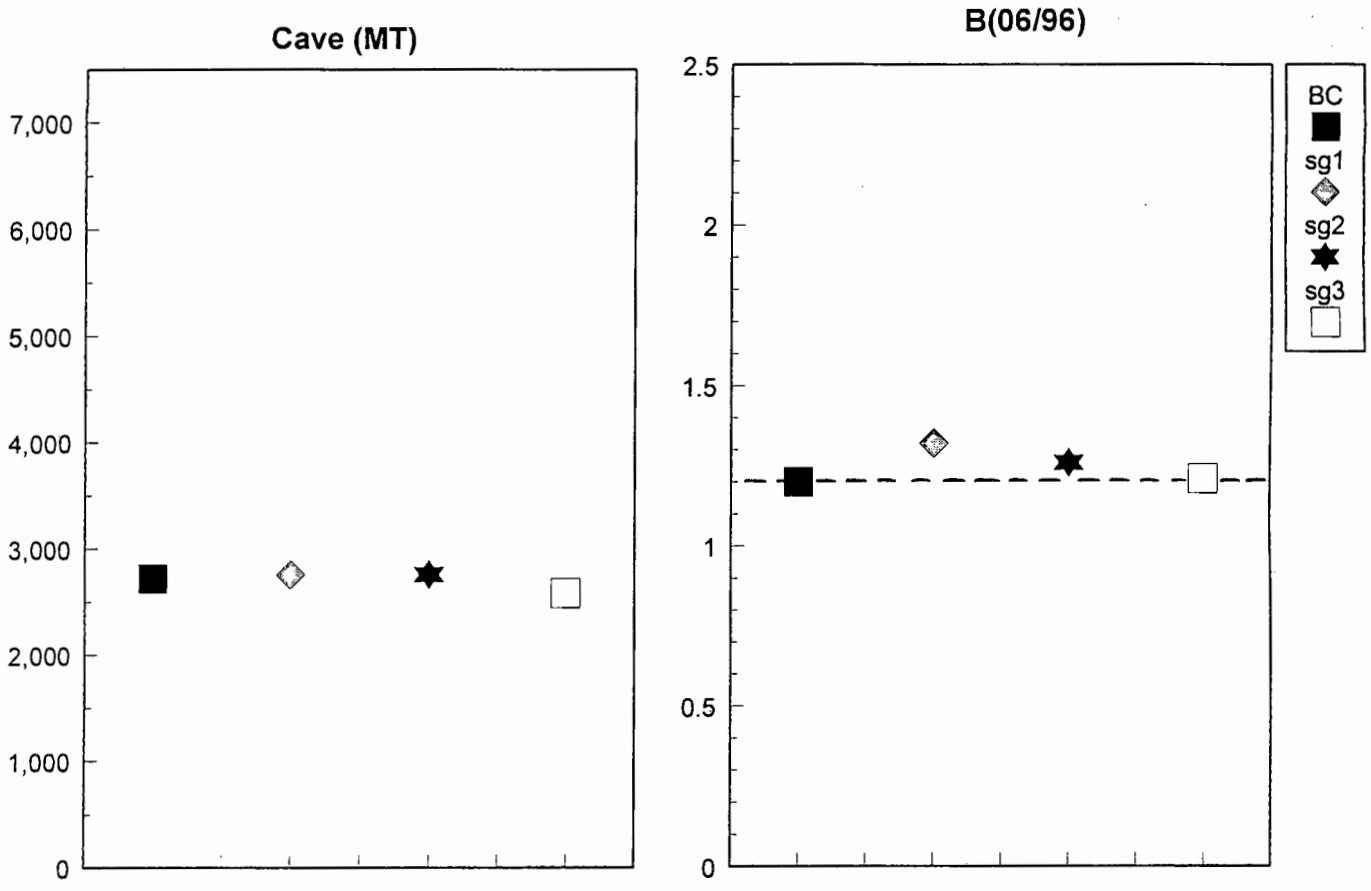
sm2: $S^m = 0.95$.

d1: $d = 0\%$

d2: $d = 5\%$

d3: $d = 15\%$.

Figure 10.4f: C_{ave} (MT) and $B(06/96)$ values for deterministic robustness tests concerning historic somatic growth assumptions (results are for the 20% biomass recovery - TAC'97 = 20% increase candidate OMP). The target recovery level is indicated by the dashed line.



sg1: Historic female somatic growth is 0.25 mm more than thought.

sg2: Historic female somatic growth is 0.25mm less than thought.

sg3: The historic somatic growth rate is calculated from the (lesser) 1985-1987 average rather than the 1969 - 1988 average.

Figure 10.5: Deterministic biomass (MT) trajectory for the **r3** robustness test (20% biomass recovery and TAC'97 = 20% increase candidate OMP).

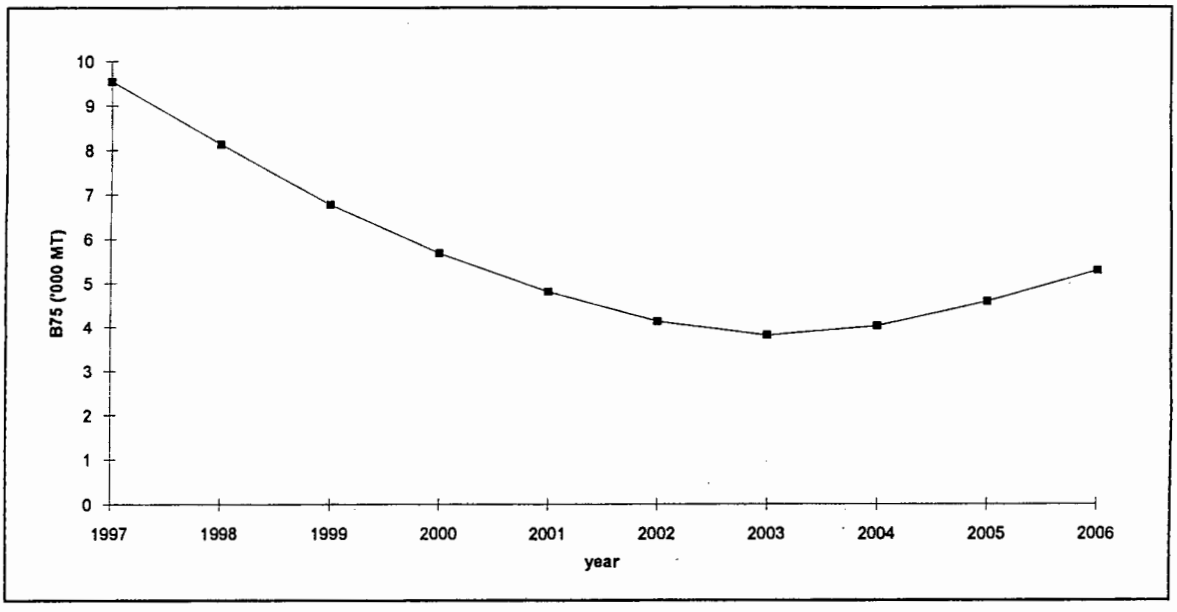
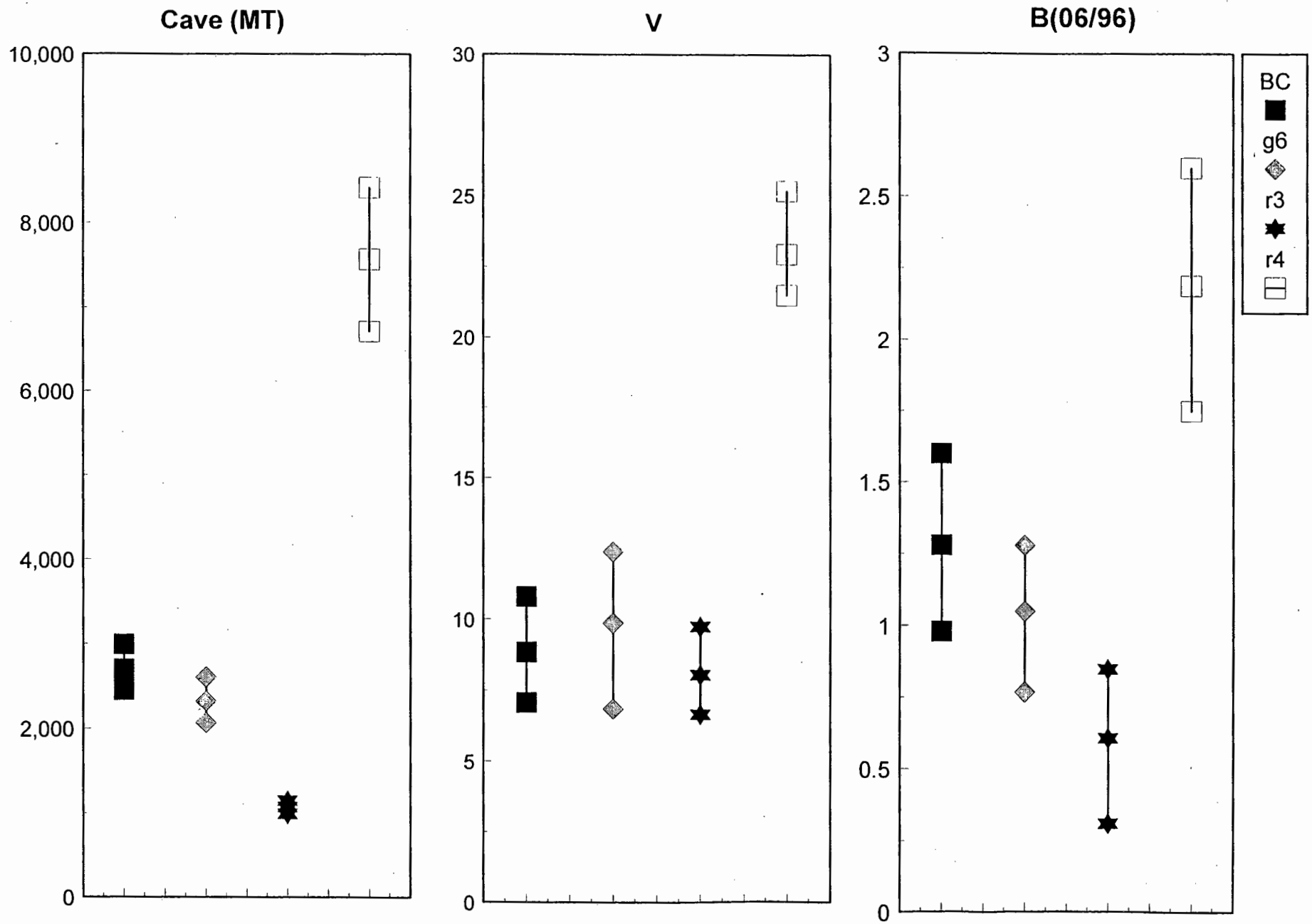


Figure 10.6: Stochastic results: 20% Biomass recovery - TAC'97 = 3% increase OMP.



g6: ARMA growth for the first 5 years, then a sudden drop to the "low" growth rate.

r3: Recruitment from 1989 onwards is half of the current recruitment estimate and the numbers-at-size in 1996 are half current estimates.

r4: Recruitment from 1989 onwards is double the current recruitment estimate, and the numbers-at-size in 1996 are double current estimates.

Figure 10.7: Stochastic results: 20% Biomass recovery - TAC'97 = 20% increase OMP.

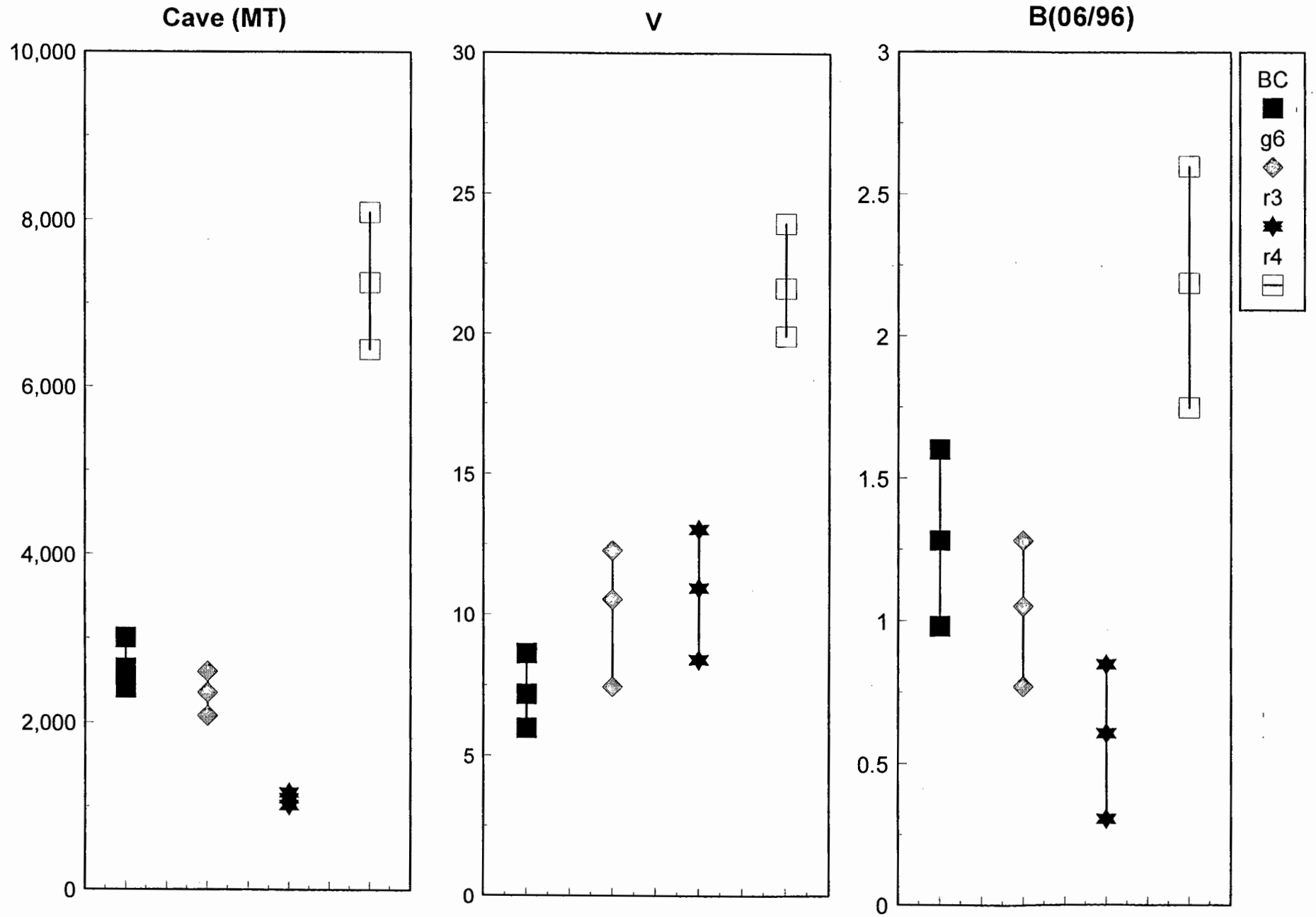


Figure 10.8: Stochastic results: 50% Biomass recovery - TAC'97 = 3% increase OMP.

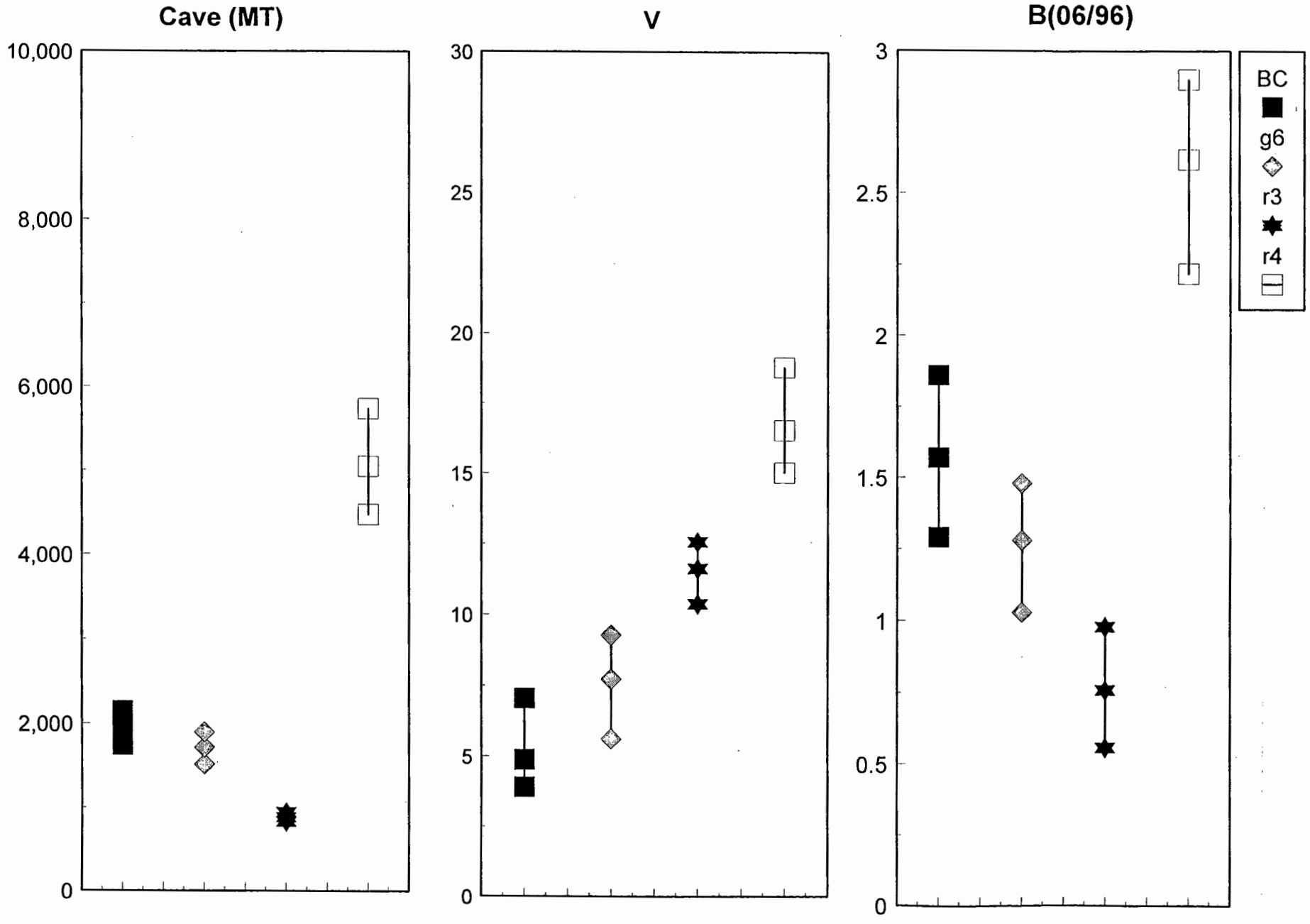
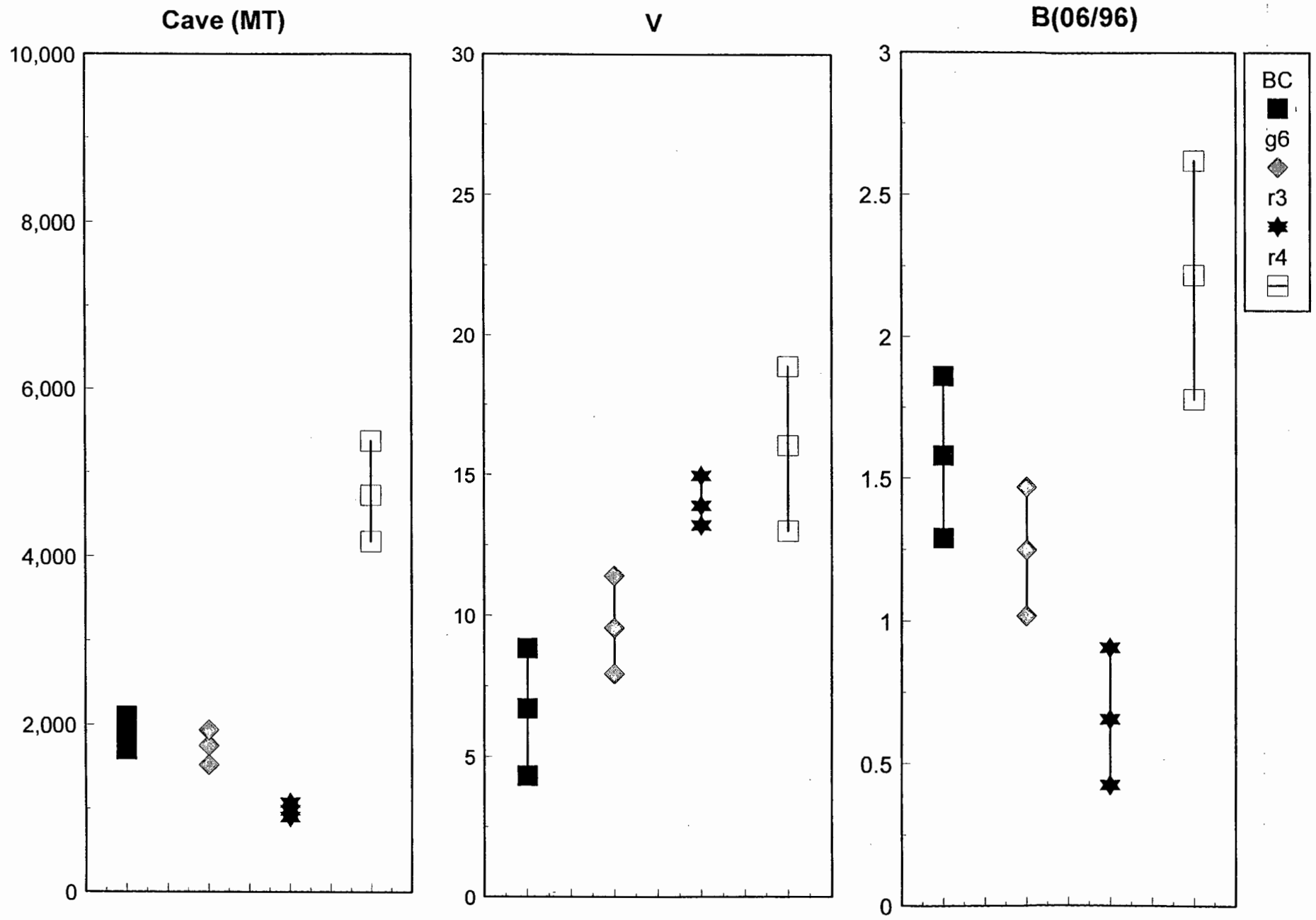


Figure 10.9: Stochastic results: 50% Biomass recovery - TAC'97 = 20% increase OMP.



Chapter 11: "Exceptional circumstances"

11.1 Introduction

The OMP selected by the SFAC for west coast rock lobster is the "20% biomass recovery- TAC'97 20% increase" candidate. This rule will be applied to provide scientific recommendations for the commercial TAC for the resource for the next three years (commencing 1997). This Chapter deals with what are termed "exceptional circumstances" for which some allowance needs to be made for freak situations, where keeping to the OMP rules could damage the resource. The idea is that under a pre-defined "exceptional circumstance" (EC), the OMP rule may be over-ridden or adjusted in order to prevent a "bad event" from happening, or if it has happened already, to ameliorate the effect. The SFAC requested that this provision be added, so that the OMP's 15% maximum annual TAC reduction constraint could (as it should) be over-ridden in such "exceptional circumstances".

EC rules to override maximum TAC reduction constraints in the face of indications of severely reduced resource abundance have been implemented in the TAC-setting formulation for the South African anchovy *Engraulis capensis* (De Oliveira 1995). Here, "exceptional circumstances" can be invoked by managers under the pre-agreed criterion of a hydoacoustic survey indication a spawning biomass below 0.5 million tons; furthermore, agreed meta-rules then prescribe the extent to which the TAC is recommended to be reduced. Criteria that are expected to amount to invoking EC rules no

more frequently than once every 10-15 years on average were used. Similar threshold levels have been developed for the South African pilchard *Sardinops sagax*, below which "exceptional circumstances" rules will be invoked (De Oliveira 1994, Anon. 1994). Clearly the SFAC had in mind putting something similar in place for the west coast rock lobster when it asked for the development of "exceptional circumstances" provisions.

11.2 The Exceptional Circumstance (EC) rule

The "bad event"

The first thing that had to be agreed upon by members of the SFRI RLWG, was what constituted a sufficiently "bad" event to warrant overriding the normal OMP TAC reduction constraint. It was decided that this "bad" event would be the biomass (above 75mm) $B_{75}(t)$ dropping below 0.75 $B_{75}(1997)$ in any one year of the 10 year projection period.

EC rules were developed for the "downside" only, as the candidate OMPs had been shown to respond reasonably to the more "optimistic" robustness tests (**r4** for example). If extremely good circumstances do occur (or current appraisals of stock status turn out to be overly pessimistic), it was seen by the RLWG to be in the interest of the fishery to use some of the larger associated surplus production for extra "resource re-building" (i.e. by more than the OMP's 20% target over the next 10 years), as the resource is currently at a very low level relative to its pristine state ($B_{75}(1996)$ is estimated to be some 6% of pristine - see Chapter 8).

The "flag" and EC rules

In order to indicate an EC (i.e. the likely occurrence of the "bad" event), there must be some sort of warning "flag" shown by the resource expressed in terms of measurable quantities. When this "flag" is shown, it will be assumed that we are dealing with an EC, and a precautionary "rule" will be applied to the TAC setting algorithm in an attempt to prevent the "bad" event from occurring, or ameliorating the effect if it has happened already. The measure which was chosen to determine whether the "flag" was shown and the rule invoked is based on a composite index of commercial and FIMS cpue data, which was compared to the base line values recorded in 1996. A three year averaging of the CPUE and FIMS data is used in an attempt to smooth the implementation of the rule, and particularly to prevent the data from a single anomalous year leading to the rule being perhaps unnecessarily invoked, thus:

$CPUE_{t,t-1,t-2}$ = the arithmetic average CPUE over *t, t-1* and *t-2*,

$FIMS_{t,t-1,t-2}$= is the arithmetic average FIMS over *t, t-1* and *t-2*, and

the measure used is $CPUE^{\alpha}_{t,t-1,t-2}.FIMS^{1-\alpha}_{t,t-1,t-2}$

Originally, a flag "on" or "off" scenario was used, where the flag which will invoke the rule was simply:

"if $CPUE^{\alpha}_{t,t-1,t-2}.FIMS^{1-\alpha}_{t,t-1,t-2} < \delta_1[CPUE^{\alpha}_{1996}FIMS^{1-\alpha}_{1996}]$ then invoke rule fully, else make no change to the TAC."

This implied a knife-edge transition between a value of the measure which will invoke the EC rule, and a value which will not. In practice, this would be likely to lead to considerable debate over the input data values if these values are close to this transition point, for example, simply the inclusion or exclusion of one arguably outlying data point could then make the difference as to whether or not the flag is shown. In order to alleviate this problem, a smoothing of the manner in which the EC rule will be invoked is proposed instead. In place of only one parameter value (δ), we use two - a central $\bar{\gamma}$ is defined, around which an interval Δ is set so that the full extent of reduction in TAC is introduced only gradually for successively lower values of the measure.

Figure 11.1 illustrates how this measure is used to invoke the EC rules. The extreme case of $\Delta = 0$ corresponds to the knife-edge function, as was initially defined above. Note that as in the OMP algorithm, the weighting factor α is set equal to 0.50 (giving equal weight to both CPUE and FIMS data).

The EC rules are thus as follows:

if $CPUE^{\alpha}_{t,t-1,t-2}.FIMS^{1-\alpha}_{t,t-1,t-2} > \left(\bar{\gamma}+\frac{\Delta}{2}\right)[CPUE^{\alpha}_{1996}FIMS^{1-\alpha}_{1996}]$

then

$$TAC_t = TAC^*_t \tag{11.1}$$

(i.e. no change to the OMP TAC is made)

if $CPUE^{\alpha}_{t,t-1,t-2}.FIMS^{1-\alpha}_{t,t-1,t-2} < \left(\bar{\gamma}-\frac{\Delta}{2}\right)[CPUE^{\alpha}_{1996}FIMS^{1-\alpha}_{1996}]$

then

$$TAC_t = (1\text{-}X)TAC^*_t \tag{11.2}$$

if $\left(\bar{\gamma}-\frac{\Delta}{2}\right)[CPUE^{\alpha}_{1996}FIMS^{1-\alpha}_{1996}] \leq CPUE^{\alpha}_{t,t-1,t-2}.FIMS^{1-\alpha}_{t,t-1,t-2} \leq \left(\bar{\gamma}+\frac{\Delta}{2}\right)[CPUE^{\alpha}_{1996}FIMS^{1-\alpha}_{1996}]$

then

$$TAC_t = \beta\, CPUE^{\alpha}_{t,t-1,t-2}.FIMS^{1-\alpha}_{t,t-1,t-2} + c \tag{11.3}$$

where $\beta = \dfrac{X.TAC^*_t}{\Delta B_{rel,1996}}$, and

$$c = TAC^*_t - \left(\bar{\gamma}+\frac{\Delta}{2}B_{rel,1996}\right)\beta$$

where $B_{rel,1996} = CPUE^{\alpha}_{1996}FIMS^{1-\alpha}_{1996}$

and where

TAC^*_t is the OMP TAC value, and X is the proportion by which TAC^*_t must be reduced.

11.3 Results

Results were computed for the **r3** robustness test, the most severe (in a pessimistic sense) of the robustness tests considered in testing the OMP (it assumes that recruitment from 1989 is half the current estimated value, and the numbers-at-size in 1996 are half the estimated values). Results are also presented below for the Base Case scenario and the **g3** robustness test for a selected EC rule, for comparison.

It is assumed that the 1997 TAC value of 1920 tons is taken by the commercial fishery - the model is thus projected ahead for a nine year period (1998-2006), with noise added to the projected CPUE, FIMS and somatic growth model values from 1997 onwards. The σ values (reflecting the level of this noise) used are the same as for previous stochastic analyses (see section 9.10). Fifty simulations were run. The median, 4^{th} and 47^{th} values are reported for C_{ave}, V, $B(06/96)$, TAC'98 and TAC'06 (see section 9.8 for definitions of these performance statistics). A number of $\overline{\gamma} : \Delta : X$ combinations were tested.

A new summary statistic which is reported is as follows:

N_{bad} = the proportion of occasions over all 9x50 (450) simulated years that the "bad" event does occur. Clearly, one would want to have this value as small as possible.

Other new statistics are:

t1 = proportion of occasions the rule was needed (i.e. actual underlying value of B_{75} did drop below 75% of its 1997 value), and the rule was applied,

t2 = proportion of occasions the rule was needed, but the rule was not applied,

t3 = a measure of the extent of unnecessary catch reduction - each time the rule was not needed, but was applied, is weighted by the proportion by which the TAC was (unnecessarily) reduced, for example, *t3* = 0.10 means that on average, there will be a 10% unnecessary catch reduction, and

t4 = proportion of occasions the rule was not needed, but the rule was not applied.

Results are presented in Tables 11.1 - 11.6.

11.4 Discussion

Tables 11.1 (N_{bad}) and 11.2 (median B(06/96, *t2* and *t3*) report EC trial results for a wide range of X, $\bar{\gamma}$ and Δ combinations, some of which are summarised in Table 11.3. Note that ideally one wants N_{bad}, *t2* and *t3* to all be as small as possible, but these are conflicting objectives, e.g. a higher choice for $\bar{\gamma}$ means a lower N_{bad} but a higher *t3*, so that trade-off choices are required. After preliminary discussions in the RLWG, it was decided to narrow the set of X, $\bar{\gamma}$ and Δ values for which more detailed results would be considered. The following initial decisions were made:

i) To restrict the maximum EC TAC reduction to 50%, i.e. $X = 0.50$. Larger values of X are able to produce smaller N_{bad} values (Table 11.1) and larger

range. The RLWG concentrated their deliberations on the EC rule choice to be preferred by examining the trade-offs reported in these Tables. More detailed stochastic analysis results for the $X = 0.50$, $\bar{\gamma} = 0.40$ range of options are reported in Table 11.5.

The RLWG finally selected the $X = 0.50$, $\bar{\gamma} = 0.40$, $\Delta = 0.30$ scenario to recommend to the SFAC for implementation in conjunction with the OMP for the west coast rock lobster. (The SFAC is due to consider this recommendation in August 1998 after this thesis had to be completed.) The rationale for this decision was as follows.

i) The value $X = 0.50$ is the maximum TAC reduction likely to be acceptable to the industry.

ii) There appears not to be very much difference between the $\bar{\gamma} = 0.50$ and 0.40 options with respect to the N_{bad} and median $B(06/96)$ values. A substantial improvement in the *t3* statistic is obtained, however, for the more conservative $\bar{\gamma} = 0.40$ set of scenarios. The value of *t3* for the $\bar{\gamma} = 0.40$ range of scenarios is about 5% (for $\Delta = 0$ to 0.4, compared to about 13% for the comparative $\bar{\gamma} = 0.50$ scenarios).

iii) There is not much difference between the results presented in Table 11.3 for Δ values in the range of 0 to 0.30. However, a fairly large increase in the *t3* statistic occurs for Δ values greater than 0.30. A further trend associated with increasing values of Δ is shown in Tables 11.5, where the CV of the *V* statistic is reduced from 29.3% (for $\Delta = 0$) to 14.8% (for $\Delta = 0.40$). A reduction in the extent to which TACs are likely to vary from one

year to the next is clearly an advantage to the industry. The RLWG therefore suggested the $\Delta = 0.30$ option be selected, for the perceived best trade-off between low values for both *t3* and *V*.

For comparative purposes, the **r3** stochastic results for which no EC rule is incorporated into the OMP algorithm are also shown (Table 11.5a).

The results discussed thus far all refer to the pessimistic **r3** scenario. Stochastic results for the Base Case scenario using the selected $X = 0.50$, $\bar{\gamma} = 0.40$, $\Delta = 0.30$ EC rule are shown in Table 11.6. These results turn out to be identical to those for which no EC rules were implemented - i.e., in terms of the Base Case scenario, it is expected that the selected EC rule will not be implemented in the next nine years. Similarly, stochastic results for the **g3** robustness test (which assumes "low" growth in future), when incorporating the selected $X = 0.50$, $\bar{\gamma} = 0.40$, $\Delta = 0.30$ EC rule, are also evaluated and found to be identical to those for which no EC rule is incorporated into the OMP algorithm. Thus the EC rule proposed would come into operation only if the present assessment of the status and productivity of the resource turns out to be substantially overoptimistic.

Table 11.1: N_{bad} values (= proportion of years out of 450 in which $B_{75}(t) < 0.75\ B_{75}(1997)$) for the **r3** trial. (Note with no EC rules, N_{bad} for **r3** = 0.84).

$\bar{\gamma}$	Δ	$X = 0.70$	$X = 0.60$	$X = 0.50$	$X = 0.40$	$X = 0.30$
0.35	**0.1**	0.71	0.74	0.78		0.78
0.40	**0**			0.70	0.72	
0.40	**0.1**			0.70		
0.40	**0.2**			0.71		
0.40	**0.3**		0.71	0.71	0.71	0.71
0.40	**0.4**			0.54		
0.50	**0**			0.58		
0.50	**0.1**			0.58		
0.50	**0.2**			0.59		
0.50	**0.3**	0.56	0.58	0.59	0.63	0.65
0.50	**0.4**			0.28		
0.55	**0.1**	0.40	0.49	0.55	0.61	
0.60	**0.2**	0.32	0.40	0.50	0.56	
0.65	**0.1**	0.24	0.33	0.43	0.52	0.64
0.70	**0.1**	0.09	0.19	0.33	0.47	0.60

Table 11.2: Median $B(06/96)$, *t2* and *t3* values for the **r3** trial. (Note with no EC rules, median $B(06/96)$ for **r3** = 0.43).

		Median $B(06/96)$					***t2***	***t3***
$\bar{\gamma}$	Δ	$X = 0.70$	$X = 0.60$	$X = 0.50$	$X = 0.40$	$X = 0.30$	$X = 0.50$	$X = 0.50$
0.35	**0.1**	0.83	0.80	0.72		0.72	0.14	0.02
0.40	**0**		0.85	0.81	0.78		0.15	0.05
0.40	**0.1**			0.83			0.07	0.05
0.40	**0.2**			0.82			0.02	0.05
0.40	**0.3**		0.81	0.81	0.81	0.80	0	0.05
0.40	**0.4**			0.94			0	0.18
0.50	**0**			0.91			0.02	0.14
0.50	**0.1**			0.91			0	0.13
0.50	**0.2**			0.91			0	0.13
0.50	**0.3**	0.93	0.92	0.90	0.87	0.83	0	0.12
0.50	**0.4**			0.96			0	0.34
0.55	**0.1**	1.04	0.99	0.94	0.87		0	0.16
0.60	**0.2**	1.06	1.01	0.95	0.88		0	0.20
0.65	**0.1**	1.08	1.02	0.96	0.89	0.82	0	0.24
0.70	**0.1**	1.12	1.06	0.99	0.91	0.83	0	0.33

Table 11.3: Summary Table of N_{bad}, median $B(06/96)$ and *t3* values for the **r3** trial - results reported for the $X = 0.50$ scenario, and for two values of $\bar{\gamma}$ (0.50 and 0.40).

	N_{bad}		$B(06/96)$		*t3*	
Δ	$\bar{\gamma} = 0.50$	$\bar{\gamma} = 0.40$	$\bar{\gamma} = 0.50$	$\bar{\gamma} = 0.40$	$\bar{\gamma} = 0.50$	$\bar{\gamma} = 0.40$
0	0.58	0.70	0.91	0.81	0.14	0.05
0.1	0.58	0.70	0.91	0.83	0.13	0.05
0.2	0.59	0.71	0.91	0.82	0.13	0.05
0.3	0.59	0.71	0.90	0.81	0.12	0.05
0.4	0.28	0.54	0.96	0.94	0.34	0.18

Table 11.4: The *t1, t2, t3* and *t4* statistics for the **r3** trial - results reported for the $X = 0.50$ scenario, and for two values of $\bar{\gamma}$ (0.50 and 0.40).

	$\bar{\gamma} = 0.50$				$\bar{\gamma} = 0.40$			
Δ	*t1*	*t2*	*t3*	*t4*	*t1*	*t2*	*t3*	*t4*
0	0.56	0.02	0.14	0.14	0.56	0.15	0.05	0.19
0.1	0.58	0	0.13	0.12	0.63	0.07	0 05	0.15
0.2	0.59	0	0.13	0.11	0.69	0.02	0.05	0.13
0.3	0.59	0	0.12	0.08	0.71	0	0.05	0.12
0.4	0.28	0	0.34	0.08	0.54	0	0.18	0.11

Table 11.5a: Stochastic results for the **r3** robustness test - with **no EC** rule.

Statistic	Median	4th	47th	CV(%)
C_{ave}	1255	1224	1307	2.7
V	12.1	10.5	12.8	7.7
B(06/96)	0.43	0.25	0.63	32.8
TAC'98	1926	1879	1995	2.1
TAC'06	623	565	750	12.6
N_{bad}	0.84			

Table 11.5b: Stochastic results for the $\bar{\gamma} = 0.40$; $\Delta = 0$, $X = 0.50$ rule - for the r3 trial.

Statistic	Median	4th	47th	CV(%)
C_{ave}	863	792	994	8.8
V	20.4	17.1	36.0	31.8
B(06/96)	0.81	0.65	0.98	16.0
TAC'98	1926	1879	1999	2.1
TAC'06	279	204	827	60.7

Table 11.5c: Stochastic results for the $\bar{\gamma} = 0.40$; $\Delta = 0.1$, $X = 0.50$ rule - for the r3 trial.

Statistic	Median	4th	47th	CV(%)
C_{ave}	865	792	980	7.3
V	23.4	18.4	32.3	22.1
B(06/96)	0.83	0.65	1.01	15.7
TAC'98	1927	1880	1999	2.1
TAC'06	352	217	836	54.0

Table 11.5d: Stochastic results for the $\bar{\gamma} = 0.40$; $\Delta = 0.2$, $X = 0.50$ rule - for the r3 trial.

Statistic	Median	4th	47th	CV(%)
C_{ave}	876	811	980	6.6
V	22.5	18.9	29.6	17.9
B(06/96)	0.82	0.64	1.01	15.9
TAC'98	1926	1880	1999	2.1
TAC'06	368	213	804	47.9

Table 11.5e: Stochastic results for the $\bar{\gamma} = 0.40$; $\Delta = 0.3$, $X = 0.50$ rule - for the r3 trial.

Statistic	Median	4th	47th	CV(%)
C_{ave}	890	819	993	6.4
V	21.3	17.3	28.1	17.2
B(06/96)	0.81	0.64	1.00	15.8
TAC'98	1927	1879	1999	2.1
TAC'06	406	229	729	41.1

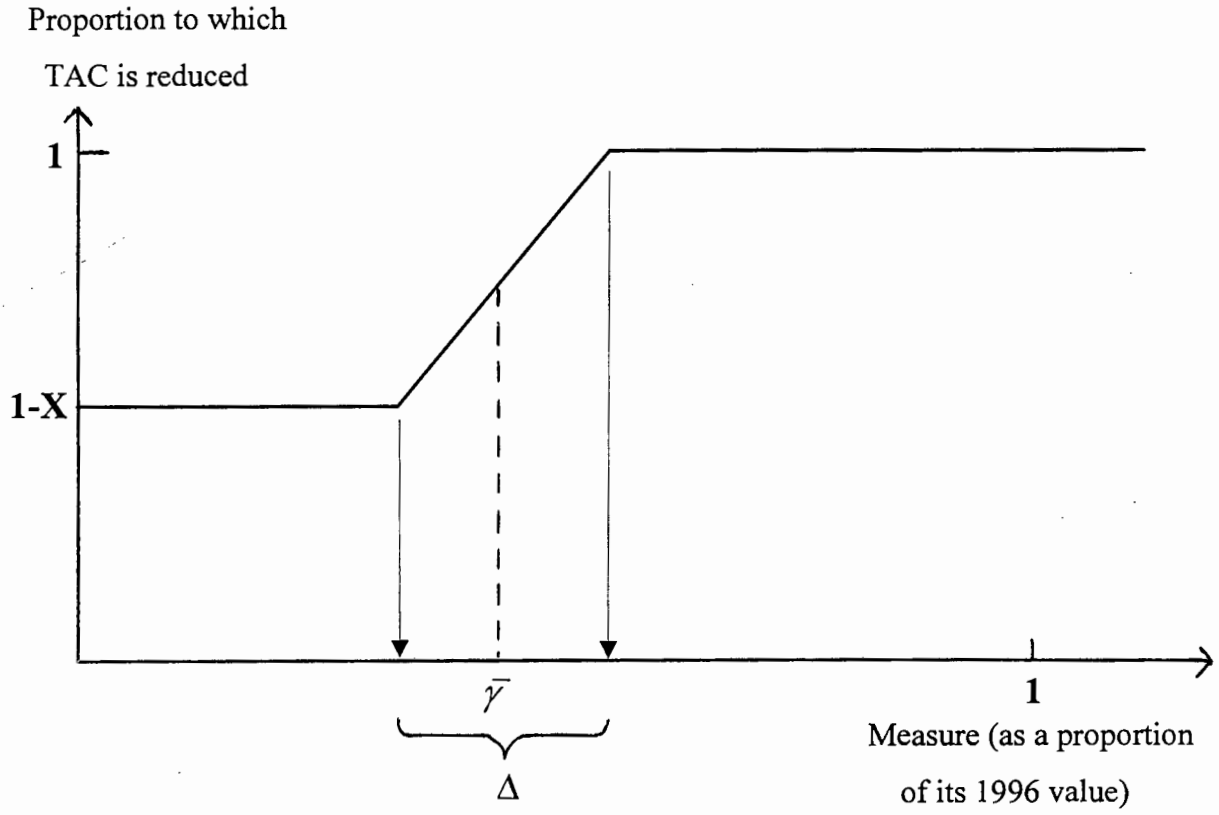
Table 11.5f: Stochastic results for the $\bar{\gamma} = 0.40$; $\Delta = 0.4$, $X = 0.50$ rule - for the r3 trial.

Statistic	Median	4th	47th	CV(%)
C_{ave}	715	686	747	2.9
V	18.0	16.2	21.3	17.2
B(06/96)	0.94	0.77	1.16	14.5
TAC'98	1927	1879	1999	7.7
TAC'06	345	256	432	41.1

Table 11.6: Stochastic results for the $\bar{\gamma} = 0.40$; $\Delta = 0.3$, $X = 0.50$ rule - for the Base Case (note results are identical to those for which no EC rules are used).

Statistic	Median	4th	47th	CV(%)
C_{ave}	2706	2415	3027	9.4
V	8.2	6.4	9.7	16.2
B(06/96)	1.23	0.97	1.60	19.2
TAC'98	2208	2037	2473	7.6
TAC'06	3095	2625	3631	11.7

Figure 11.1: The EC TAC modification in relation to the flag.



Chapter 12: Discussion and conclusions

12.1 General discussion about the OMP developed

The OMP developed here is shown to achieve all its initial objectives (see Chapter 9 section 9.2). Primarily, a management approach has been developed which will ensure robust behaviour in achieving the desired management objectives over a wide range of possible scenarios. In other words, the OMP is shown to be adequately robust to most of the uncertainties considered, as the TAC will be adjusted appropriately by the OMP so as not to seriously compromise the attainment of the biomass recovery target set to 20% over the next 10 years. Performance is particularly good for uncertainties relating to the future somatic growth rate of the lobsters. This is an important achievement, as there is much uncertainty in the minds of both scientists and the industry about what the future somatic growth rate of the lobsters might be. Given the recent period of very low somatic growth rates (commencing in 1989) which resulted in large TAC reductions, the development of an OMP which can handle the possibility of a future such growth reduction in a robust fashion (as has been demonstrated) and without high levels of inter-annual TAC change, which might compromise industrial stability, has been an important achievement.

The development and subsequent choice and implementation of an OMP has allowed the process of scientific TAC recommendations each year to become more transparent and thus enhances the credibility of the scientific process with the industry. Improved focus

on longer term management objectives and research requirements may now also be achieved, as crucial hours previously spent on the annual TAC setting deliberations should all but fall away.

The development of the candidate OMPs was initially hampered by the close involvement of industry scientists. The industry argued that they wanted the "best" input into the OMP, and hence pushed for more time to be spent on the input data side of the OMP development phase. The viewpoint held by other scientists was that there would always be some uncertainty, and the OMP approach was specifically designed to address this. At that stage, much debate was spent on the specifics of data collection and analyses, as well as on the various underlying assumptions of the operating model of the resource to be used for OMP candidate testing. The first crucial step towards the development of these OMPs was the finalisation of this operating model. Several years had been spent on this stage, and members of the SFRI RLWG felt confident in the adequacy of the final model for the OMP development process, and pressed to move on to the more important task of evaluating various candidate OMPs. At this point, input from industry scientists was restricted to a "commenting"[1] basis only, enabling speedier progression towards the final goal of assessing various candidate OMPs. However, input from the industry was still used in defining the various performance statistics to be used for comparing the OMPs, as well as in developing the suite of tests to be run to investigate the robustness of the OMPs to various uncertainties.

[1] These industry scientists took the view at that time that they could not support moving to finalise the OMP according to the schedule set by the SFAC, and hence did not want to be party to any final recommendations made by the RLWG on the matter.

As satisfactory robustness was shown to be achieved for most of the tests considered, most of the discussion and comparisons between candidate OMPs focused on the performance of the two tests that showed least robustness - those being the **r3** test (which assumes recruitment is half the current estimate, and the biomass is half the current estimate) and the **r4** test (which assumes recruitment is double the current estimate, and the biomass is double the current estimate), with concentration on **r3** as this involved greater risks. The **r3** test was seen to be an extreme scenario, and working group members felt that if an OMP candidate could achieve reasonable performance for this test, then that OMP candidate should be seen to be sufficiently satisfactory to be put forward to the SFAC for consideration.

12.1.1 Strengths of the candidate OMPs

i) The candidate OMPs are robust to most of the important uncertainties considered, both those related to the current status of the resource, and those concerning future trends and errors in future data.

ii) The candidate OMPs allow flexibility to alter both the target biomass recovery level, as well as the immediate likely TAC level for 1997. This flexibility allowed the presentation of 12 different candidate OMPs to the SFAC. Each of the 12 OMPs were shown to have similar risks associated with them. The choice presented to the SFAC allowed for a compromise between the industry desires (an immediate TAC level as high as possible)

and environmental/biological concerns (some level of biomass recovery, with a low risk of depletion below present levels).

iii) The interannual TAC variation is demonstrated to be acceptably small.

12.1.2 Weaknesses of the candidate OMPs

i) While the candidate OMPs perform well for most of the robustness trials, they do not perform that well in some situations where there is uncertainty regarding the recruitment levels and productivity of the resource (e.g. the **r3** robustness test).

ii) A population model-based procedure would use more data and hence might be able to reduce variability and improve performance on tests such as **r3**.

12.2 The selection between the candidate OMPs

The twelve eventual candidate OMPs were presented to the SFAC, whose responsibility was to make a final choice among them. The selected OMP would be implemented for a period of three years.

The SFAC did not use any formal multi-criteria decision making (MCDM) algorithms to aid their decision making. The use of MCDM techniques in aiding such management decisions is not yet common in fisheries management. At the 1991 meeting of the IWC (IWC 1992) the Scientific Committee members had to select a single management

procedure from a choice of five. On the basis of previous studies in the MCDM field, they concentrated on reducing the number of key statistics to be considered to about seven - a number at which consistent appraisal by "human integration" inspection remains possible. This was because they had decided that they could not make use of formal MCDM algorithms to condense the great volume of performance statistics provided, because these tools effectively required the input on the relative importance of the three objectives for management. Given the short time eventually available to meet the SFAC's deadline for an agreed OMP, it was not possible to explore the possibility of using MCDM algorithms in interaction with the SFAC. Some preliminary work on the use of MCDM procedures for selecting amongst candidate OMPs has recently been initiated (Moloney 1998), and is discussed briefly below.

The OMP selected (20% biomass recovery - TAC'97 20% increase OMP) was the least conservative of the 12 candidate OMPs. As all twelve candidate OMPs were considered to have acceptable biological risks and adequately robust performance, it was essentially left to the industry to push for its preferred OMP out of the 12. The final choice made was therefore not surprising, as the industry were keen to obtain the maximum immediate TAC increase, and calculations of the level of biomass giving MSY suggested that this was not greatly above the present level under the assumption of constant recruitment, i.e. the future gains in catches promised by higher target recovery levels were not particularly substantial.

12. 3 Future research

12.3.1. Reassessment of the underlying operating model

The size-structured operating model provided by the assessment process is not set in stone. Since its development, new data have become available. Also, different techniques for analysing these data are now preferred. The operating model must therefore be re-fitted to these updated data sets. Certain of the assumptions made in the operating model must also be re-evaluated. Increasing proportions of the TAC are being caught with hoopnets, and this must be reflected in the model. Assumptions regarding trends in recruitment over time should also be re-examined. Of particular importance are the following:

i) The west coast rock lobster stock is found over a wide geographical area. In this thesis, it has been treated as a single stock. Alternative models of substock dynamics need to be investigated. Attempts to deal with this in the GLMs for both CPUE and growth data have been made. Further work on the spatial heterogeneity of the stock needs to be attempted further however. In particular, the growth GLM analysis should try to address this heterogeneity as far as possible, as growth rates are known to vary quite considerably from area to area.

ii) Attention needs to be paid to the different weights that are given to the various sensitivity tests. At present, there is no attempt to differentiate between tests that correspond to more or less likely scenarios. Some consideration should also perhaps be given to defining levels of "adequate robustness", so that prior to robustness testing, one knows how to categorise the robustness test results as being either adequate or

inadequate. Parhaps a more quantitative means by which to evaluate these results would be useful.

iii) An attempt could be made to expand the number of model fit parameters to include those for recruitment levels of more recent years. This may improve the fit to the increase in CPUE data from 1980-1985 (which the model does not presently fit very well).

iv) The operating model has the feature of a very large "cryptic" population of females which is not vulnerable to exploitation. The size of this cryptic female population is inferred mainly on the basis of the female somatic growth rates, which are poorly known. The magnitude of the "cryptic" population is important with respect to recruitment (forms a major part of the spawning biomass). Closer attention needs to be paid to assumptions which effect the size of this portion of the stock. These include assumptions regarding the declining right-hand limb of the selectivity curve, the somatic growth rate function, and the natural mortality rate.

v) An attempt could be made to model the population from some more contemporary period (1975 say). This will require either fitting another parameter (the F for initial year) or making an assumtion regarding the F. This approach will eliminate the requirement to hypothesize the shift in recruitment levels used in the current operating model, and the assumptions regarding the historic levels of growth.

vi) A selectivity function needs to be incorporated for the FIMS fishing. This should improve the fits to especially the FIMS $F^{\%}$ data.

12.3.2 Index of recruitment

Research into some mechanism for estimating puerulus settlement would be highly advantageous. Techniques have been developed in Western Australia for *Panulirus cygnus*, and in New Zealand for *Jasus edwardsii.* Settlement plates are set out at the time of puerulus settlement to obtain relative estimates of settlement densities. An estimate of the annual puerulus settlement would aid management, as weak year classes could be predicted in advance, and hence recruitment failure detected in time to make appropriate compensating adjustments to the TAC. This method assumes that it is possible to link the density of the puerulus settlement on some relative scale to recruitment into the fishery about seven years later. In some preliminary research, puerulus collectors for the west coast rock lobster have been tested and deployed, and this research will hopefully be continued. The OMP, when revised in three years time, could be modified to include an index of puerulus settlement as one of the inputs.

12.3.3 Multi-criteria decision making (MCDM) techniques

During the process of developing and evaluating alternative OMPs, many model runs were carried out. A number of summary statistics were identified with which to compare different candidate OMPs and the results of the various robustness tests. This often resulted in large amounts of information being presented to the SFRI RLWG for evaluation.

Choices among different options and the use of consistent criteria in making choices can be difficult to achieve when faced with such an abundance of data. These difficulties are compounded when there are conflicting objectives that need to be considered. The management of the west coast rock lobster has multiple conflicting objectives, which require trade-offs between, for example, the extent of biomass recovery targeted and immediate catch levels. In this thesis and in the presentation of results to the working group, a graphical presentation of the relevant trade-offs was made to aid comparisons. Another approach that could be employed in making such comparisons would be the use of MCDM techniques. Preliminary work in this regard has been initiated (Moloney 1998). In this initial study Moloney (*op. cit.*) found that the 20% biomass recovery - 20% TAC'97 OMP was the "best" or preferred OMP strategy, given the objectives and criteria selected in her study. Five objectives were defined by Moloney, defining a "good" OMP strategy. These were:

1) the population biomass (B) should recover over a 10-year period

2) the average catch (C_{ave}) over the 10-year period should be large

3) the variability in catch (V) should be small

4) the TAC in 1997 should be large

5) the TAC in 2006 should be large

She then developed these verbal objectives into explicit criteria, defined in quantitative terms. These were:

1) $B(06/96) \geq 1.1$

2) $C_{ave} \geq 2000$ MT

3) $V \leq 7$

4) TAC'97 $\geq$ 1750 MT

5) TAC'06 $\geq$ 2000 MT

Two structured decision-making methods were then applied, the first using a hierarchy of goals or "goal filtering" (Ralls and Starfield 1995), and the second being a "simple multi-attribute ranking technique" (SMART) (Von Winterfeldt and Edwards 1986; Goodwin and Wright 1991). Both these methods showed the 20% biomass recovery - 20% TAC'97 OMP to be the "preferred" OMP strategy out of the candidate OMPs considered. The OMP selected by the SFAC was thus consistent with this choice. With Moloney's method, four out of five management objectives considered relate to fishing performance. It is not surprising therefore that the decision-making procedure would favour the less consevative strategy. A weighting that emphasised conservation (objective number I) would favour another. The choice of management objectives thus needs to be carefully considered.

12.3.4 Improved estimates of abundance

A detailed study of options to improve current indices of abundance (CPUE, FIMS), such as an inshore component of FIMS should be carried out, before such might be formally incorporated into a revised OMP. The industry has argued that the FIMS survey, which uses traps and cannot access shallower waters, is therefore missing important abundance trend information. The possible role of the component of the biomass to the east of the commercial fishery (currently a reserve) also needs to be better understood and taken into account - in the first instance by estimating its abundance relative to that in the regions fished.

In Figure 8.20, it is clear that the model does not currently fit the FIMS $F^{\%}$ data. The observed values are much lower that the model estimated values. It is thought that perhaps the FIMS samples are missing large numbers of females. An "inshore" component of FIMS is proposed, in order to sample the population more fully. It is known that for much of the year, females tend to aggregate inshore, so that the current FIMS may simply be "missing" these females.

The weighting of the FIMS data by area must be reconsidered. Effort weighting is perhaps more appropriate than area weighting.

12.3.5 Future improved OMPs

The present OMP is very simply constructed, being based primarily on the trend in abundance shown by commercial CPUE and FIMS data. Investigation of the performance of a population-model-fitting based procedure (as is the case for the OMP used for South African hake, Punt 1992) needs to be pursued, though it may be difficult to develop a sufficiently simple model to use in this fashion given the complications of changing minimum sizes and somatic growth rates shown by this resource.

12.3.6 Growth data

More research into negative growth is required. This is important with regard to the high shrinkage values that are currently assumed for femlaes under the lower growth rate scenarios. We currently assume that upto -3σ is possible - is this valid ?

12.4 Final conclusions

An OMP has been developed to set the annual commercial TAC for South African west coast rock lobster. This has provided a substantial aid to management. The candidate OMPs from which this final OMP was selected have been shown to achieve the desired management objectives reasonably closely over a wide range of uncertainties, especially those regarding the future somatic growth rates of the lobsters. The development of "meta-rules" to be implemented under pre-defined "exceptional circumstances" provides further safeguards for the resource. The selected OMP was implemented in 1997 for the first time to set the TAC for the resource, and will be used for the following two years.

The implementation of this OMP will drastically reduce the time spent by scientists, managers and industry in long deliberations on exactly what information should be considered and exactly how the TAC should be set, that had been the practice in recent years. The implementation of the OMP will also provide some security for the industry and aid in planning, as the likely TAC levels for the next few years can be produced in terms of the "Base Case" scenario.

Appendix 1: Model specifications and assumptions

The model of the west coast rock lobster dynamics described is a size-structured model which operates at a 1mm interval scale, from l = 1mm to $l = l_{max}$, where l refers to the carapace length (which for brevity will also be referred to as "size") in mm. The largest size class in the model, l_{max}, is equal to 180mm. Male and female lobsters are modelled separately, with ***m*** referring to males and ***f*** referring to females. In this Appendix, the superscript ***s*** refers to either male or female sex where the two sexes are treated separately but identically. Although the fishing season starts towards the end of year t and runs into year t+1, it is denoted only as year t (unless otherwise specified).

The basic model in vector-matrix notation is:

$$N^s(t+1) = N^s(t)H^s(t)S^sA^s(t) + R(t+1) \qquad \text{(A.1.1)}$$

where

$N^s(t) =$ the (1 x 180) vector of number of males/females in each of the 1mm size classes at the start of year t,

$N^s(t+1) =$ the (1 x 180) vector of number of males/females in each of the size classes at the start of year $t+1$,

$A^s(t) =$ the (180 x 180) somatic growth matrix for males/females over year t (models the proportion of lobsters moving from one size class to the next as a result of somatic growth),

$H^s(t) =$ the (180 x 180) fishing survivorship matrix for males/females over year t,

$S^s =$ the (180 x 180) diagonal natural survivorship matrix for males/females (constant over time), and

$R(t+1) =$ the (1 x 180) recruitment vector for year t+1 (equivalent for males and females).

Note that the structure of this discrete model is such that harvest is followed by natural mortality and then by somatic growth, i.e. fishing is approximated by a pulse at the start of the season.

A1.1 Length-weight conversions

The model thus operates on a numbers basis, but the number of lobsters in each size class is easily converted to biomass using the length-weight conversion equations given by Heydorn (1969c):

$$w_l^m = 0.6518 l^{2.8990} \text{ for males, and} \quad \text{(A.1.2)}$$

$$w_l^f = 0.5869 l^{2.9729} \text{ for females} \quad \text{(A.1.3)}$$

where the total body weight, w, is in grams, and length l, is the carapace length in centimetres. Heydorn's (1969c) data are based on 371 male and 310 female lobsters. None of these lobsters had lost appendages and females were not in berry. Heydorn fitted a power model to the data separately for males and females. Female rock lobsters were shown to have a notably higher tail weight than males of the same carapace length.

A1.2 Equilibrium conditions

Assuming no harvesting (pristine conditions) the equilibrium populations numbers are calculated as follows:

$$N^{s*} = N^{s*}S^s A^s + R \tag{A.1.4}$$

and therefore

$$N^{s*} = R(I - S^s A^s)^{-1} \tag{A.1.5}$$

where N^{s*} represents the male/female equilibrium population vector, and I is the unit matrix.

Equation (A.1.5) is used to set up the initial pristine population size-structure in 1870, when catches are assumed to have commenced.

A1.3 Natural survivorship matrix S

The natural survivorship matrix S^s models the proportion of lobsters in each size class at the beginning of the year which survive to the beginning of the next year in the absence of fishing. The matrix consists of zero entries except for the diagonal entries which contain the S_l^s values for size class l. The natural survivorship is assumed to be independent of size for lobsters greater than or equal to 60mm. However, the demography of immature lobsters is likely to be somewhat different from that of mature lobsters, so that smaller lobsters are assumed to have reduced survivorship. A linear increase in survivorship from 0.1 at size l = 1mm (a fictional size used purely for definition convenience) to S^m (males) and S^f (females) at size 60mm is assumed. The maximum male annual natural

survivorship, S^m, is set at 0.90. This is for two reasons. Firstly, a fair amount of work on the estimates of S^m has been conducted (and produced the value of around 0.90), and secondly, fixing S^m reduces the number of estimable paramters. The maximum female natural survivorship, S^f, is an estimable parameter of the model (i.e. the value is estimated in fitting the model to the data). Natural survivorship is assumed to be constant over time. The specific entries on the diagonal of the natural survivorship matrix are calculated as follows.

Males:

$$S_l^m = (l-1)\left(\frac{S^m - 0.1}{59}\right) + 0.1 \qquad \text{for } 1 \le l < 60\,\text{mm} \qquad \text{(A.1.6)}$$

$$S_l^m = S^m = 0.90 \qquad \text{for } l \ge 60\,\text{mm}$$

Figure A1.1 illustrates this natural survivorship relationship with carapace length for male lobsters.

Females:

$$S_l^f = (l-1)\left(\frac{S^f - 0.1}{59}\right) + 0.1 \qquad \text{for } 1 \le l < 60\,\text{mm} \qquad \text{(A.1.7)}$$

$$S_l^f = S^f \qquad \text{for } l \ge 60\,\text{mm}$$

A1.4 Gear selectivity

Different sized lobsters have different probabilities of being caught by various fishing gear, and each gear type operates in different parts of the overall resource area of distribution where different sizes or sexes may aggregate. The fishing selectivity functions model these different probabilities of being caught by the gear. In this study, selectivity is thus really a combination of the physical gear selectivity as well as availability. In the early period of the fishery, lobsters were caught using hoopnets which were set fairly close inshore in shallow waters. It is well known that for much of the year females inhabit these shallower waters, as well as the larger lobsters in the population (Pollock 1982). In 1970, fishers started using traps which were deployed in deeper waters where fewer females are to be found and where predominantly smaller lobsters live. By 1981, the vast majority of fishing was conducted using trap gear.

The model takes into account not only the difference between hoopnets and traps, and between male and female selectivity, but also takes account of the transition from hoops to traps. The model assumes that 100 % of the catch was taken using hoopnet gear from 1870-1969, and 100 % of the catch was taken using trap gear from 1981 onwards. A linear transition for the period 1970-1981 is assumed.

Trap Selectivity

The parameter $b_l^{m,trap}$ denotes the trap selectivity of male lobsters at size l. Below a certain size, l_0, it is assumed that no lobsters are retained by the trap.

Males: Selectivity increases linearly from length l_0 to l^* . Above length l^* selectivity is assumed to be constant, thus:

$$b_l^{m,trap} = \left(\frac{l - l_0}{l^* - l_0}\right) \qquad \text{for } l_0 \le l < l^* \qquad \text{(A.1.8)}$$

$$b_l^{m,trap} = 1 \qquad \text{for } l \ge l^*$$

The Base Case model assumes l_0 = 50mm, and l^* = 100mm. The trap gear does not retain lobsters smaller than 50mm (smaller lobsters escape through the net). It has also been observed in the field that lobsters of about 100mm and larger will all be fully retained by the gear, i.e. none escape. This function used for calculating male trap selectivity is shown in Figure A1.2a. The male trap selectivity function is fixed as it can be based upon experimental work which has produced estimates for l_0 and l^*.

Females: The selectivity for females includes two estimable parameters: P_1 and P_2.

$$b_l^{f,trap} = P_2\left(\frac{l - l_0}{l^* - l_0}\right) \qquad \text{for } l_0 \le l < l^* \qquad \text{(A.1.9)}$$

$$b_l^{f,trap} = P_2\left(\frac{l - P_1}{l^* - P_1}\right) \qquad \text{for } l^* \le l < P_1$$

$$b_l^{f,trap} = 0 \qquad \text{for } l \ge P_1$$

This function used for calculating female trap selectivity is shown in Figure A1.2b.

P_1 is thus the size at which selectivity for large sized females lobsters declines to zero, and P_2 is a factor which scales the female selectivity relative to male selectivity over the size range $[l_0, l^*]$.

Hoopnet selectivity

Insufficient catch-at-size data exist to estimate hoopnet selectivity functions in the overall fit of the model to data. These functions are thus calculated by multiplying the trap selectivity functions by fixed scaling functions which are input. These scaling functions have been calculated by contrasting comparable (i.e. same location) hoopnet and trap catch-at-size data. The details of these calculations are reported in Appendix 5.

The relative hoopnet scaling factors for each sex and size class are denoted by:

X_l^m for males at length l, and

X_l^f for females at length l,

so that to calculate the hoopnet selectivities, we use the following equations:

$$b_l^{m,hoop} = X_l^m b_l^{m,trap} \quad \text{for males, and} \qquad \text{(A1.10)}$$

$$b_l^{f,hoop} = X_l^f b_l^{f,trap} \quad \text{for females.}$$

Note that these gear selectivities were defined to take into account both the gear selectivity as well as availability.

A1.5 Fishing survivorship matrix *H*

The fishing survivorship matrix consists of diagonal entries $(1-p_l^s(t))$ with zeros everywhere else, where the $p_l^s(t)$ terms, the proportion of lobsters in size class l caught during year t, are calculated as follows.

$$p_l^s(t) = b_l^{s,sel}(t) d_l(t) F(t) \qquad \text{(A.1.11)}$$

where

$$b_l^{s,sel}(t) = b_l^{s,hoop} \qquad \text{for } t \le 1969$$

$$b_l^{s,sel}(t) = b_l^{s,trap} \qquad \text{for } t \ge 1981$$

$$b_l^{s,sel}(t) = b_l^{s,hoop} + \left(b_l^{s,trap} - b_l^{s,hoop}\right)\left(\frac{t-1969}{1981-1969}\right) \qquad \text{for } 1969 < t < 1981$$

and

$$d_l(t) = d \qquad \text{for } l < l_{\min}(t)$$

$$d_l(t) = 1 \qquad \text{for } l \ge l_{\min}(t)$$

where $l_{\min}(t)$ is the legal minimum size limit in year t (see Appendix 4.6). The parameter d refers to the **discard mortality**, and is the proportion of undersized lobsters that are caught and returned to the sea which subsequently die as a result of the original capture-and-return process. A value of $\boldsymbol{d = 0.10}$ is used in the Base Case model. This value is somewhat arbitrary, as detailed field experiments have not been conducted for *J.lalandii*, but $d = 0.10$ falls within the range found for other lobster fisheries (Brown and Caputi 1983).

The factor $F(t)$ in equation A.1.11 is the fishing mortality for fully selected animals which links the model-generated catches to the observed catches by weight (catches are only recorded by weight, not number), and is calculated as follows.

$$F(t) = \frac{C_t^{obs}}{\sum_{l \geq l_{\min}(t)} \left[N_l^m(t) b_l^{m,sel}(t) w_l^m + N_l^f(t) b_l^{f,sel}(t) w_l^f \right]}, \qquad \text{(A.1.12)}$$

where

C_t^{obs} is the total observed catch by weight in year t, and

$N_l^m(t)$ and $N_l^f(t)$ are the numbers-at-length for year t.

A1.6 The 1991 fishing season

The 1991 season (strictly the split-year 1991/92 season) in the model receives special treatment as the minimum size was altered during this season and only males were harvested. Both males and females were however subject to discard mortality. The model thus calculates $p_l^m(1991)$ and $p_l^f(1991)$ in two steps. The first step refers to the first part of the season when the minimum size limit was 89mm (denoted by superscript 89), while the second step refers to the second part when the minimum size limit was 75mm (denoted by superscript 75). Therefore, for the first half:

$$p_l^{m,89} = b_l^{m,sel}(1991) d_l^{89}(1991) F^{89}(1991) \qquad \text{(A.1.13)}$$

where

$d_l^{89}(1991) = d$ for $l < 89$mm

$d_l^{89}(1991) = 1$ for $l \geq 89$mm

and

$$p_l^{f,89} = b_l^{f,sel}(1991)d_l^{89}(1991)F^{89}(1991)$$

The fully-selected fishing mortality $F^{89}(1991)$ above is calculated as follows:

$$F^{89}(1991) = \frac{C_{1991}^{obs,89}}{\sum_{l \geq 89mm}\left[N_l^m(1991)b_l^{m,sel}(1991)w_l^m + N_l^f(1991)b_l^{f,sel}(1991)w_l^f\right]} \quad \text{(A.1.14)}$$

where $C_{1991}^{obs,89}$ refers to the catch (by weight) taken in the first part of the season when the minimum size limit was 89mm. Before proceeding with the calculations for the second part of the season, the numbers-at-size are updated to the end of the first part of the season taking into account the losses due to fishing mortality only, i.e.:

$$N_l^{m,89}(1991) = N_l^m(1991)\left(1 - p_l^{m,89}(1991)\right), \quad \text{and also therefore} \quad \text{(A.1.15)}$$

$$N_l^{f,89}(1991) = N_l^f(1991)\left(1 - p_l^{f,89}(1991)\right)$$

For the second part:

$$p_l^{m,75} = b_l^{m,sel}(1991)d_l^{75}(1991)F^{75}(1991) \quad \text{(A.1.16)}$$

where

$$d_l^{75}(1991) = d \qquad \text{for } l < 75\text{mm}$$

$$d_l^{75}(1991) = 1 \qquad \text{for } l \geq 75\text{mm}$$

and

$$p_l^{f,75} = b_l^{f,sel}(1991)d_l^{75}(1991)F^{75}(1991)$$

where, further:

$$F^{75}(1991) = \frac{C_{1991}^{obs,75}}{\sum_{l \geq 75mm}\left[N_l^{m,89}(1991)b_l^{m,sel}(1991)w_l^m + N_l^{f,89}(1991)b_l^{f,sel}(1991)w_l^f\right]} \quad \text{(A.1.17)}$$

and $C_{1991}^{obs,75}$ is the catch (by weight) taken in the second part of the season to which a minimum size limit of 75mm applied.

We therefore have $p_l^m(1991) = 1-(1-p_l^{m,89})(1-p_l^{m,75})$, and (A.1.18)

$$p_l^f(1991) = 1-(1-p_l^{f,89})(1-p_l^{f,75}).$$

From the preceding equations, it can be seen that the following will always apply:

$$p_l^s(t) \geq 0.$$

A1.7 Somatic growth matrix *A*

The somatic growth matrix models the proportion of lobsters in one size class that move into another size class as a result of somatic growth. The entry $a_t^s(i,j)$ represents the proportion of lobsters in size class *i* that move into size class *j* during the moult at the end of year *t*. Moult increments of lobsters have been shown to be highly variable. This variance in somatic growth is modelled using a normal probability distribution truncated at ± 3 standard deviations. In order to calculate the $a_t^s(i,j)$ values using this probability distribution, the mean annual moult increment value, $g_{l,t}^s$, must be known as well as an estimate of standard deviation around this mean moult increment, $\sigma_{l,t}^s$, for each length *l* and year *t*. The calculation of the $g_{l,t}^s$ and $\sigma_{l,t}^s$ values are reported in detail in Appendix 3. Note that this distribution allows for the possibility that lobsters shrink during the moult.

The calculation of the $a_t^s(i,j)$ values are described by the following steps for any given year t and sex s - the t and s indices have been omitted below for less cluttered notation.

[Note that because i represents the length class (i-1, i) mm, e.g. i = 75 means animals of size l where $74 < l \leq 75$ mm, it is convenient to use the midpoint i-0.5 of this interval in the following calculations.]

Step 1: For any given i, initialise $a(i,j)$ to zero for $j = 1, 2, ...180$, and calculate the mean length after moult (m_i) for length l_i (where $l_i = i - 0.5$):

$$m_i = l_i + g_i \qquad \text{(A1.19)}$$

where g_i is the mean moult increment for length i.

Step 2: Calculate the two endpoints of the growth distribution:

$$m_i(1) = m_i - 3\sigma_i \qquad \text{(lower point)} \qquad \text{(A1.20)}$$

$$m_i(2) = m_i + 3\sigma_i \qquad \text{(upper point)}$$

where σ_i is the standard deviation for the mean moult increment g_i.

If $\sigma_i = 0$, then set $a(i,j) = 1$ [where j is such that $j-1 < m_i \leq j$] and go back to step 1, incrementing i by 1.

Step 3: Find the midpoints $mp(1)$ and $mp(2)$ of the length classes into which $m_i(1)$ and $m_i(2)$ respectively fall.

Step 4: Define mp_j as the midpoint corresponding to length class (j-1, j); then for $mp_j = mp(1), mp(1)+1, ..., mp(2)$ do the following.

A: If $mp_j = mp(1)$, set $y(1) = m_i(1)$ (A.1.21)

set $y(2) = mp_j + 0.5$ (A.1.22)

If $mp_j = mp(2)$, set $y(1) = mp_j - 0.5$ (A.1.23)

set $y(2) = m_i(2)$ (A.1.24)

For all other cases, set $y(1) = mp_j - 0.5$ (A.1.25)

set $y(2) = mp_j + 0.5$ (A.1.26)

B: Calculate the z values for $y(1)$ and $y(2)$ (to convert to a normal distribution N(0;1)):

$$z(1) = \frac{y(1) - m_i}{\sigma_i} \quad \text{and} \tag{A.1.27}$$

$$z(2) = \frac{y(2) - m_i}{\sigma_i} \tag{A.1.28}$$

C: Calculate the area under the normal curve for each of these z values:

$A(1)$ = area from $z(1)$ to 0

$A(2)$ = area from $z(2)$ to 0

D: Calculate the proportion of lobsters moving from i to j (equal to the area under the normal curve from $z(1)$ to $z(2)$).

If $1 < mp_j < 179$, do the following:

$j = mp_j + 0.5$

$$a(i,j) = A(1) + A(2) \quad \text{if } y(1) < m_i < y(2) \tag{A.1.29}$$

otherwise

$$a(i,j) = |A(1) - A(2)|$$

If $mp_j < 1$, do the following:

$j = 1$

$$a(i,j) = |A(1) - A(2)| \tag{A.1.30}$$

If $mp_j > 179$, do the following:

$j = 180$

$$a(i,j) = |A(1) - A(2)| \tag{A.1.31}$$

Step 5: Normalise $a(i,j)$ so that $\sum_{j=1}^{180} a(i,j) = 1$

This is to correct for the fact that normal distributions are used at Step 4B, whereas Step 2 explicitly limits growth to ± three standard deviations from the mean.

Step 6: Go back to Step 1 incrementing i by 1.

A1.8 Recruitment *R*

Recruitment is assumed to occur into the first 15 size classes only. The value of recruitment for each of these size classes in year t is $R(t)$. Recruitment is assumed equal for male and female lobsters, and hence

$$R_l^m(t) = R_l^f(t) = R(t) \qquad \text{for } l \leq 15\text{mm} \qquad \text{(A.1.32)}$$

$$R_l^m(t) = R_l^f(t) = 0 \qquad \text{for } l > 15\text{mm}$$

$R(t)$ is assumed to have been constant at a level R_1 from inception of fishing (1870) to some year prior to 1950, y^*. At y^*, the biomass levels are assumed to have been sufficiently depleted to start having an impact on the pristine recruitment level. Recruitment is assumed to decline linearly from y^* to 1950, after which recruitment is assumed to remain constant once again, but at a new level R_2. Thus:

$$R(t) = R_1 \qquad \text{for } t \leq y^* \qquad \text{(A.1.33)}$$

$$R(t) = R_1 + (t - y^*)\left(\frac{R_2 - R_1}{1950 - y^*}\right) \qquad \text{for } y^* < t < 1950$$

$$R(t) = R_2 \qquad \text{for } t \geq 1950$$

More flexible forms than a constant recruitment form after 1950 provided little overall improvement in fits to the data, so that the constant form was retained.

A1.9 Commercial catch

The model is set up so that the model predicted catch $\hat{C}_t$ equals the "observed" catch C_t^{obs}. The "observed" catch consists of three contributions in each year t:

i) the recorded commercial catch, C_t^{comm},

ii) an estimate of poaching, C_t^{poach}, and

iii) an estimate of the public recreational catch, C_t^{rec}.

Thus:

$$C_t^{obs} = C_t^{comm} + C_t^{poach} + C_t^{rec} \tag{A.1.34}$$

The model predicted catch is calculated by:

$$\hat{C}_t = \sum_{l \geq l_{min}(t)} \left[F(t) b_l^{m,sel}(t) N_l^m(t) w_l^m + F(t) b_l^{f,sel}(t) N_l^f(t) w_l^t \right] \tag{A.1.35}$$

All catches reported have units metric tons (MT).

The commercial catch record available is from 1900 only, although various references (Pollock 1986, for example) indicate that commercial harvesting began around 1870. For this reason, it is assumed that the commercial catch was zero until 1870 and increased linearly thereafter to the recorded 1900 level, i.e.:

$$C_t^{comm} = \frac{C_{1900}^{comm}}{(1900-1870)}(t-1870) \quad \text{for } 1870 \leq t < 1900 \tag{A.1.36}$$

A1.10 Poaching and recreational catches

In addition to the recorded commercial catches, the model takes poaching and recreational catches into account (see A.1.34).

Poaching:

Poaching (at a non-negligible level) is assumed to start in 1951 and increase linearly to a value P_{max} in the year 1990 (these assumptions are based on anecdotal evidence from the industry). Poaching is assumed to remain at the P_{max} level after 1990. As about one third of poaching is estimated to occur east of Cape Hangklip (and hence is not assumed to affect the west coast rock lobster resource), the model incorporates 67% of the total poaching estimate each year. The estimates of C_t^{poach} used in the model are thus:

$$C_t^{poach} = 0 \qquad \text{for } t < 1950 \qquad \text{(A.1.37)}$$

$$C_t^{poach} = 0.67 P_{\max}\left(\frac{t-1950}{1990-1950}\right) \qquad \text{for } 1950 \le t \le 1990$$

$$C_t^{poach} = 0.67(P_{\max}) \qquad \text{for } t > 1990$$

The Base Case model assumes P_{max} = 500 MT

Recreational Catch:

Recreational catches (at a non-negligible level) are assumed to have started in 1959 (this assumption was based on discussions held by the RLWG in conjunction with the industry). From 1959 to 1992 the recreational catches are assumed to have increased linearly from zero to 469 MT. The recreational catch dropped to 391 MT for 1993 and is

assumed to remain at this level. As about half of the recreational catch is estimated to be taken east of Cape Hangklip, the model incorporates 50% of these estimates. The estimates of C_t^{rec} (in tons) used in the model are thus:

$$C_t^{rec} = 0 \qquad \text{for } t < 1959 \qquad \text{(A.1.38)}$$

$$C_t^{rec} = 0.50(469)\left(\frac{t-1959}{1992-1959}\right) \qquad \text{for } 1959 \le t \le 1992$$

$$C_t^{rec} = 0.50\ (391) \qquad \text{for } t > 1992$$

For projections into the future, both poaching and recreational levels are assumed to remain at present levels, i.e.:

$C_t^{poach} = 0.50\ (P_{\max}) = 0.50\ (500) = 335$ MT, and

$C_t^{rec} = 0.50\ (391) = 195.5$ MT

The assumptions made here with regards to poaching and recreational catches are "guestimates" - for this reason, a simple linear increase in recreational catch for example is used, as a more complicated function cannot be justified.

A1.11 Biomass

Since the model maintains information on numbers-at-size by sex, the biomass of any desired component of the resource is readily computed. These biomass estimates can refer to the male portion of the stock, B^m, the female portion of the stock, B^f, or to the combined total of males and females B. Furthermore, a biomass estimate can be

calculated for any given size range. For example, the biomass estimate for male and female lobsters above size l = 75mm in year t is calculated as follows:

$$B_{75}(t) = \sum_{l \geq 75} (N_l^m(t) w_l^m + N_l^f(t) w_l^f) \tag{A.1.39}$$

All biomass estimates have units metric tons (MT) or '000 MT.

A1.12 MSY Calculations

The maximum sustainable yield (MSY) can be calculated for a number of scenarios. The following must be defined:

i) somatic growth rate,

ii) recruitment level,

iii) gear selectivity, and

iv) minimum legal size.

Equations A.1.4 and A.1.5 are modified to include the fishing survivorship matrix, so that an equilibrium size structure can be calculated for any level of harvesting. For a fishing mortality level F, we have:

$$N^{s*}(F) = N^{s*}(F) H^s S^s A^s + R \tag{A.1.40}$$

so that

$$N^{s*}(F) = R(I - H^s S^s A^s)^{-1} \tag{A.1.41}$$

The sustainable yield for any F can be calculated as follows:

$$\mathrm{SY}(F) = \sum_{l \geq \min} (b_l^{s,sel} d_l F (n_l^{m*}(F) w_l^m + n_l^{f*}(F) w_l^f)) \tag{A.1.42}$$

where the $n_l^{m*}(F)$ are the number of male lobsters in the equilibrium population at size l and at fishing mortality level F, and $n_l^{m*}(F)$ are the corresponding number of female lobsters. At some level of fishing mortality, the sustainable yield reaches a maximum - the maximum sustainable yield (MSY). The F value corresponding to MSY is denoted F_{MSY}.

The biomass level (above the legal minimum size) at which MSY occurs, B_{MSY}, is calculated as follows.

$$B_{\text{MSY}} = \sum_{l \geq \min} (n_l^{m*}(F_{MSY}) w_l^m + n_l^{f*}(F_{MSY}) w_l^f) \qquad \text{(A.1.43)}$$

Figure A1.1: The natural survivorship relationship with carapace length ("size") for male lobsters.

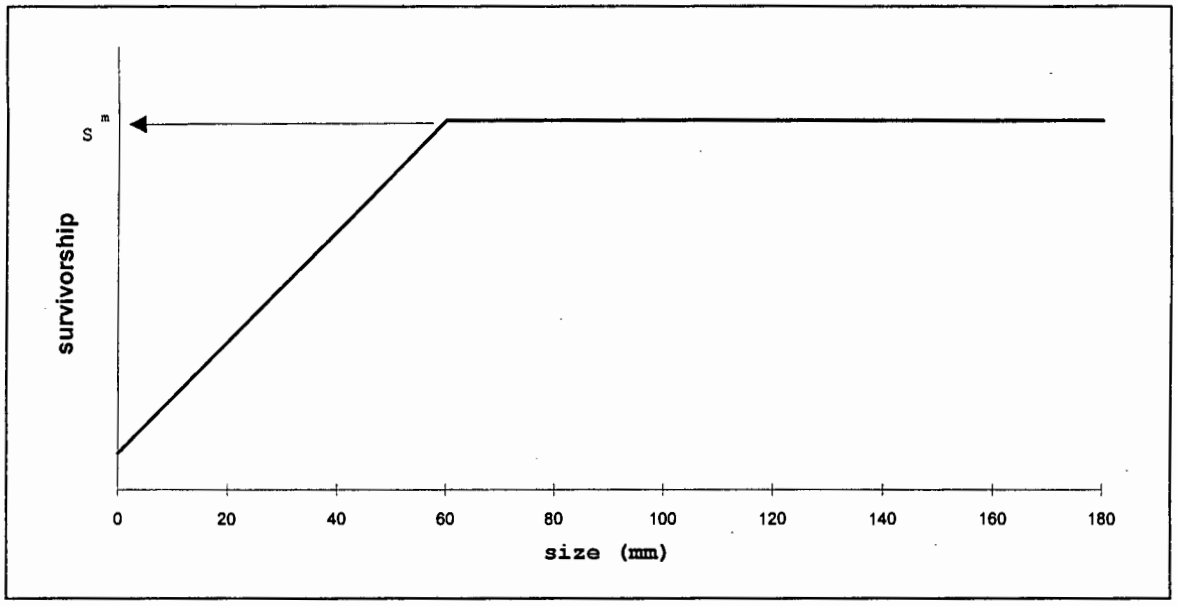


Figure A1.2a: Male trap selectivity function.

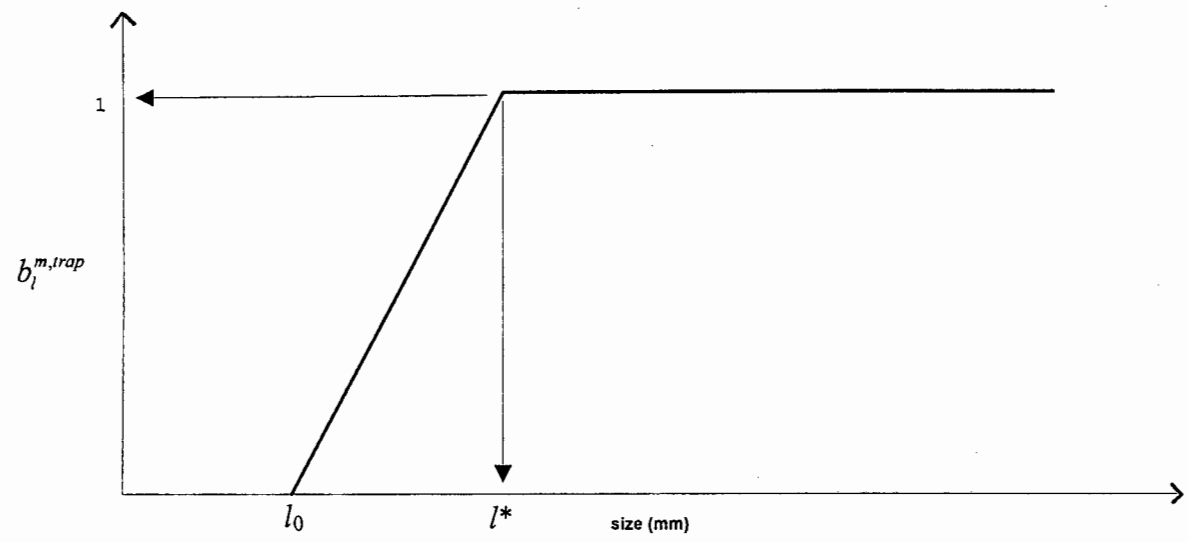
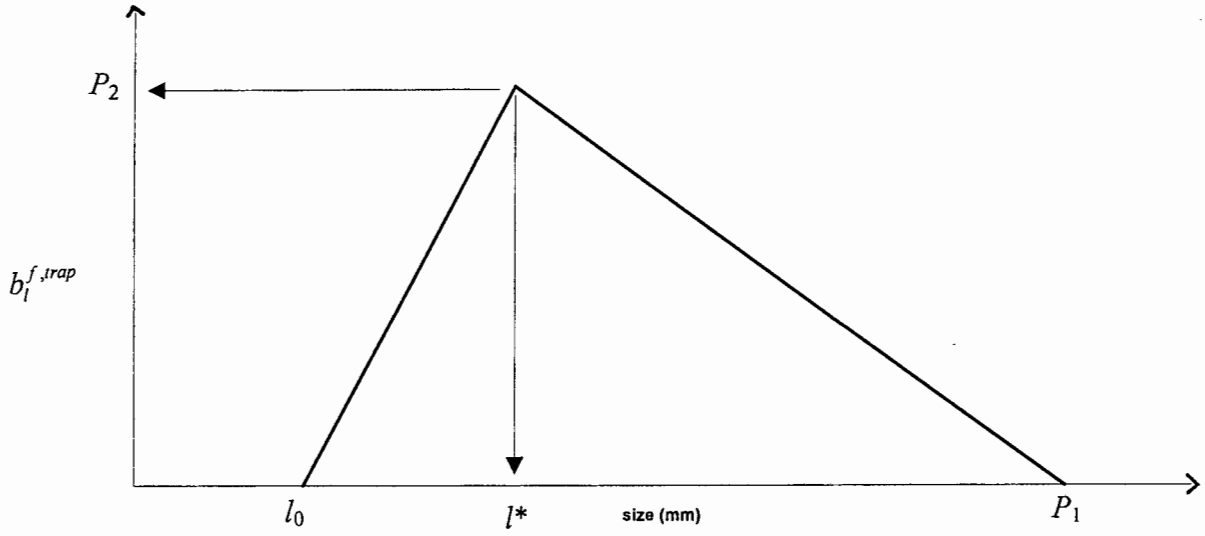


Figure A1.2b: Female trap selectivity function.



Appendix 2: Model fitting procedure

The estimable parameters of the "1870" size-structured model are estimated by fitting the model to a number of data series. This is achieved by minimising the negative of the log of the likelihood function for these data.

A2.1 Data

The negative log likelihood function incorporates three types of data.

i) **CPUE**

Three sources of CPUE data for the resource are used.

a) Commercial trap CPUE data for the 1975-1994 period.

b) Commercial hoopnet CPUE data for the 1987-1994 period.

c) FIMS CPUE data for the 1992-1995 period.

(Remember, 1995 refers to the 1995/96 season, for example.)

These CPUE values are assumed to be log-normally distributed.

ii) **Catch-at-size data**

Two sources of catch-at-size data are used.

a) Data obtained from commercial trap samples for 1981-1994.

b) Data obtained from the FIMS samples for 1992-1995.

Males and females are treated separately. Data are reported by 5mm size classes, i.e. the n^{th} size class incorporates lobsters of size n mm, n+1 mm ... n+4 mm. Data for size

classes equal or larger than the minimum legal size at the time are used from the commercial trap data, and data for 60mm+ are used from the FIMS data. When the minimum size is 89mm, the 89mm data are included in size class 90. Females are omitted for the year 1991 as there was a ban on catching females in that year.

iii) **Percent females in the catch ($F^{\%}$)**

Two sources of data are used.

a) Data from the commercial trap samples used for calculating catch-at-size data for 1981-1994.

b) Data from the FIMS samples for 1992-1995.

Percent females are the percentage by **number** of females in the samples. Once again the year 1991 is omitted as there was a ban on catching females then.

All data used in the likelihood are reported in Appendix 4. For 1995, only the FIMS 1995 data are included in the likelihood - at the time of the likelihood estimation, these were the only data available for that year.

For the commercial trap catch-at-size and $F^{\%}$ data, only the years 1981 - 1994 are used in the minimisation. This is because the model assumes the conversion from hoopnets to traps to have only been completed by 1981, and thus 1981+ model estimates of the catches-at-size are calculated using trap selectivity functions only.

A2.2 The Likelihood function

The superscript s is sometimes used below. It refers to either of the two sexes, where males and females are treated separately but identically. In order to give more recent data greater weight in the likelihood, a weighting scheme is used in the likelihood function, where the annual weighting factor w_t is:

$w_t = e^{-\lambda(1994-t)}$ where $\lambda = 0.05$, and t is the year to which the data refers. This choice is somewhat arbitrary and corresponds to downweighting the earliest data used by about 60% compared to those used finally. The reason for weighting in this manner is that the primary purpose of this model fitting exercise is to provide estimates of **current** (1995) numbers-at-size by sex for forward projection under future catches when testing candidate OMPs. In the possible event of model misspecification therefore, in which case not all the data would be well fitted, it is more important that recent rather than historic data be consistent with the model.After removal of constants from the negative log likelihood[1] , the function to be minimised is:

$$-\ln L = \sum_{A=1,2,3}\left(n^A_{cpue}\ln\sigma^A_{cpue} + \frac{1}{2\sigma^{A\ 2}_{cpue}}\sum_t w_t\left\{\ln CPUE^A_t - \ln \hat{CPUE}^A_t\right\}^2\right) + \qquad \text{(A.2.1)}$$

$$\sum_{A=1,2}\left(n^A_{size}\ln\sigma^A_{size} + \frac{1}{2\sigma^{A\ 2}_{size}}\sum_{t,l,s} w_t\left\{\sqrt{N^{A,s}_t p^{A,s}_{t,l}} - \sqrt{N^{A,s}_t \hat{p}^{A,s}_{t,l}}\right\}^2\right) +$$

$$\sum_{A=1,2}\left(n^A_{F\%}\ln\sigma^A_{F\%} + \frac{1}{2\sigma^{A\ 2}_{F\%}}\sum_t w_t\left\{\ln F^{\%,A}_t - \ln \hat{F}^{\%,A}_t\right\}^2\right)$$

---

[1] The $n\ln\sigma$ terms below originally have the form $\sum_t \ln\left(\frac{\sigma}{\sqrt{w_t}}\right) = n\ln\sigma - \frac{1}{2}\sum_t \ln w_t$. Since w_t is fixed (i.e. independent of the values of estimable parameters), the second term becomes one of the removable constants.

where

A = data series identifier:

A = 1 refers to the commercial trap data

A = 2 refers to the FIMS data

A = 3 refers to the commercial hoopnet data

w_t = the weight given to the data point for year t

t = year in question where:

t = 1975-1994 for commercial trap CPUE data

t = 1987-1994 for commercial hoopnet CPUE data

t = 1992-1995 for FIMS CPUE, catch-at-size and $F^{\%}$ data

t = 1981-1994 for commercial trap catch-at-size and $F^{\%}$ data (although no data for females available for 1991)

l = length class in 5 mm intervals:	l = 90, 95, ... 140	for 1981-1991
	l = 80, 85, ... 140	for 1992
	l = 75, 80, ... 140	for 1993 +

n_{cpue}^{A} = numbers of years of CPUE data for series A

= 20 for $A = 1$

= 4 for $A = 2$

= 8 for $A = 3$

n_{size}^{A} = number of catch size proportions that are used in the likelihood for series A

$n_{F^{\%}}^{A}$ = number of years of $F^{\%}$ data used in the likelihood for series A

= 13 for $A = 1$

= 4 for $A = 2$

$CPUE_t^A$ = observed CPUE value in year t for series A

$\widehat{CPUE}_t^A$ = model-estimated CPUE value in year t for series A

$N_t^{A,s}$ = catch-at-size sample size for sex s in year t for series A

$p_{t,l}^{A,s}$ = observed catch-at-size proportion for male/female lobsters of size l in year t for series A.

$\hat{p}_{t,l}^{A,s}$ = model-estimated catch-at-size proportion for male/female lobsters of size l in year t for series A

$F_t^{\%,A}$ = observed percentage females in the catch in year t for series A

$\hat{F}_t^{\%,A}$ = model-estimated percentage females in the catch in year t for series A

Also:

$$\hat{F}_t^{\%,A} = \frac{\sum_{l \geq l_{\min}} (b_l^{f,sel}(t) N_l^f(t))}{\sum_{l \geq l_{\min}} (b_l^{m,sel}(t) N_l^m(t) + b_l^{f,sel}(t) N_l^f(t))} .100 \qquad \text{(A.2.2)}$$

$$\hat{p}_{t,l}^{A,s} = \frac{b_l^{s,sel}(t) N_l^s(t)}{\sum_{l \geq l_{\min}} (b_l^{s,sel}(t) N_l^s(t))} \qquad \text{(A.2.3)}$$

$$\sigma_{cpue}^A = \sqrt{\frac{1}{n_{cpue}^A} \sum_t w_t (\ln CPUE_t^A - \ln \widehat{CPUE}_t^A)^2} \qquad \text{(A.2.4)}$$

$$\sigma_{size}^A = \sqrt{\frac{1}{n_{size}^A} \sum_{t,l,s} w_t \{\sqrt{N_t^{A,s} p_{t,l}^{A,s}} - \sqrt{N_t^{A,s} \hat{p}_{t,l}^{A,s}}\}^2} \qquad \text{(A.2.5)}$$

$$\sigma_{F^{\%}}^A = \sqrt{\frac{1}{n_{F^{\%}}^A} \sum_t w_t \{\ln F_t^{\%,A} - \ln \hat{F}_t^{\%,A}\}^2} \qquad \text{(A.2.6)}$$

For series $A = 1$ and $A = 3$: (trap and hoopnet data)

$$\ln q^A = \frac{1}{\sum w_t} \sum_t w_t \left(\ln CPUE_t^A - \ln \{ \sum_{l \geq l_{\min}} w_l^m b_l^{m,sel}(t) N_l^m(t) + w_l^f b_l^{f,sel}(t) N_l^f(t) \} \right)$$

(A.2.7)

$$\widehat{CPUE}_t^A = q^A \sum_{l \geq l_{\min}} (w_l^m b_l^{m,sel}(t) N_l^m(t) + w_l^f b_l^{f,sel}(t) N_l^f(t)) \qquad \text{(A.2.8)}$$

For series $A = 2$: (FIMS data)

$$\ln q^A = \frac{1}{\sum w_t} \sum_t w_t \left(\ln CPUE_t^A - \ln\{\sum_{l \geq 60} N_l^m(t) + N_l^f(t)\} \right) \quad \text{(A.2.9)}$$

$$\hat{CPUE}_t^A = q^A \sum_{l \geq 60} (N_l^m(t) + N_l^f(t)) \quad \text{(A.2.10)}$$

($b_l^{m,sel}(t)$ refers to the relevant male selectivity value; and $N_l^m(t)$ the number of male lobsters in size class l at time t; w_l^m is the weight of a male of length l).

The component of the -ln$L$ function which involves the catches-at-size ignores length classes for which both the observed and estimated numbers-at-size are zero. From equations (2.4)-(2.6) it is clear that a number of variances are estimated in this fitting procedure, that is effectively "iterative reweighting" is applied. This procedure can be problematic if there are data conflicts, and these lead to multiple maxima in the likelihood function. However, fits starting from different parameter values reached the same end point, suggesting no problems of this nature.

The weighting function used to obtain homoscedasticity

The square root transformation was applied to the catch-at-size numbers in equation A.2.1 in the expectation that sampling error dominates (i.e. a Poisson-like error distribution with variance proportional to the mean), so that this transformation should lead to homoscedastic residuals. However, the catch-at-size residuals for $A = 1$ (trap data) were found not to be homoscedastic, i.e. the variances of the residuals were not equal for

all expected values (as transformed). The variances (expressed as root mean square errors (r.m.s.e.'s) for smaller expected values were found to be less than those associated with larger expected values (Figure A2.1a). Weighting was therefore applied to restore homoscedasticity as follows. Denote the expected values:

$$\sqrt{n_e} = \sqrt{N_t^{A,s} \hat{p}_{t,l}^{A,s}} \tag{A.2.11}$$

and the observed values:

$$\sqrt{n_o} = \sqrt{N_t^{A,s} p_{t,l}^{A,s}} \tag{A.2.12}$$

The weighting of the residuals for the commercial trap catch-at-size data (A = 1) is then related to the quantity W_e (given by solid line in Figure A2.1a re-normalised to a maximum of 1) where:

$$W_e = \frac{3.3 + \sqrt{n_e} / 11.54}{8.5}, \qquad \text{for } \sqrt{n_e} \le 60, \text{ and} \tag{A.2.13}$$

$$W_e = 1 \qquad \text{for } \sqrt{n_e} > 60.$$

The line for $\sqrt{n_e} \le 60$ was fixed by eye rather than by regression. This was to ensure that values did not drop too low for small $\sqrt{n_e}$, and hence give such data very little weight in the fit. The dependence of the root m.s.e. on $\sqrt{n_e}$ effectively disappears after adjustment by W_e (Figure A1.2b).

The function to be minimised hence becomes:

$$-\ln L = \sum_{A=1,2,3}(n^A_{cpue}\ln\sigma^A_{cpue} + \frac{1}{2\sigma^{A\ 2}_{cpue}}\sum_t w_t\left\{\ln CPUE^A_t - \ln\widehat{CPUE}^A_t\right\}^2) + \qquad \text{(A.2.14)}$$

$$\sum_{A=1}(n^A_{size}\ln\sigma^A_{size} + \sum_{\sqrt{n_e}\le 60}\ln\{W_e\} + \frac{1}{2\sigma^{A\ 2}_{size}}\sum_{t,l,s} w_t\left\{\frac{\left(\sqrt{n_o}-\sqrt{n_e}\right)^2}{W_e^2}\right\}) +$$

$$\sum_{A=2}(n^A_{size}\ln\sigma^A_{size} + \frac{1}{2\sigma^{A\ 2}_{size}}\sum_{t,l,s} w_t\left\{\sqrt{N^{A,s}_t p^{A,s}_{t,l}} - \sqrt{N^{A,s}_t \hat{p}^{A,s}_{t,l}}\right\}^2) +$$

$$\sum_{A=1,2}(n^A_{F^{\%}}\ln\sigma^A_{F^{\%}} + \frac{1}{2\sigma^{A\ 2}_{F^{\%}}}\sum_t w_t\left\{\ln F^{\%,A}_t - \ln\hat{F}^{\%,A}_t\right\}^2)$$

The FIMS catch-at-size residuals were found to be homoscedastic, thus no weighting of these residuals was necessary.

Note that now for $A = 1$, $\sigma^A_{size} = \sqrt{\frac{1}{n^A_{size}}\sum_{t,l,s}\frac{\left(\sqrt{n_o}-\sqrt{n_e}\right)^2}{W_e^2}}$ (A.2.15)

A2.3 Estimable parameters

The Base Case model has a number of estimable parameters to be estimated from the data. Aside from $q^A, \sigma^A_{cpue}, \sigma^A_{size}$ and $\sigma^A_{F^{\%}}$ for which closed form expressions are available (see equations A2.4 to A2.10), these are:

R_1 (pristine recruitment)

R_2 (reduced current level of recruitment)

y^* (year at which recruitment starts to decline)

P_1 (female trap selectivity parameter - value of carapace length l where this drops to zero)

P_2 (female trap selectivity parameter - scaling factor)

S^f (female maximum natural survivorship).

Constraints are placed on these parameters during the estimation process to ensure that estimates remain sensible. These are:

$R_1 \geq 0$

$R_2 \geq 0$

$1900 \leq y^* < 1950$

$l^* < P_1 \leq 169$

$P_2 > 0$

$0.85 \leq S^f \leq 0.95$

Figure A2.1a: Trap catch-at-size residuals plotted as root mean square errors (r.m.s.e.'s) for residual sets grouped to the nearest multiple of 10 in terms of the square root of the expected sample size ($\sqrt{n_e}$) **prior to weighting**.

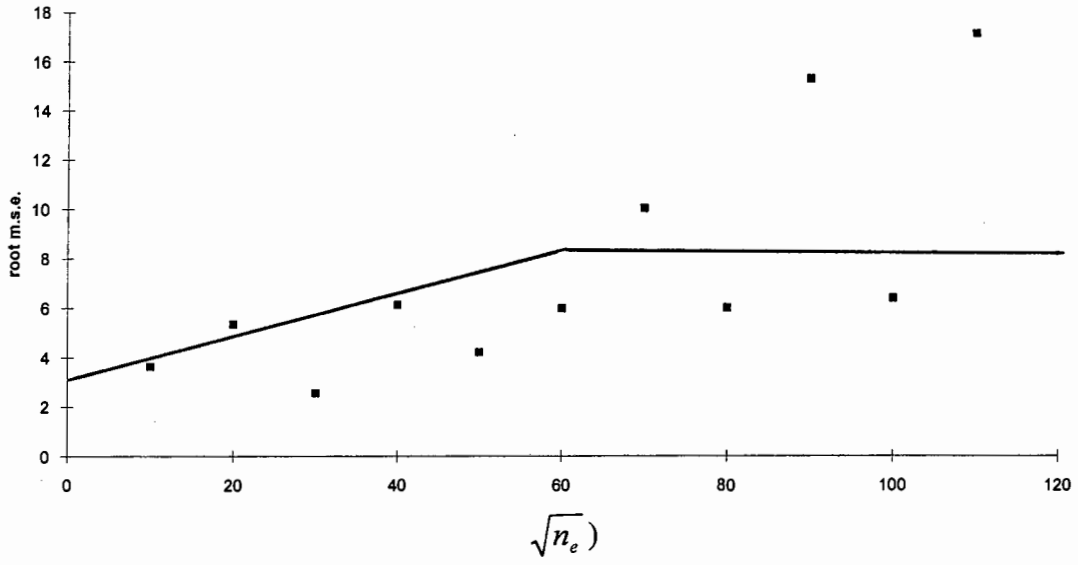
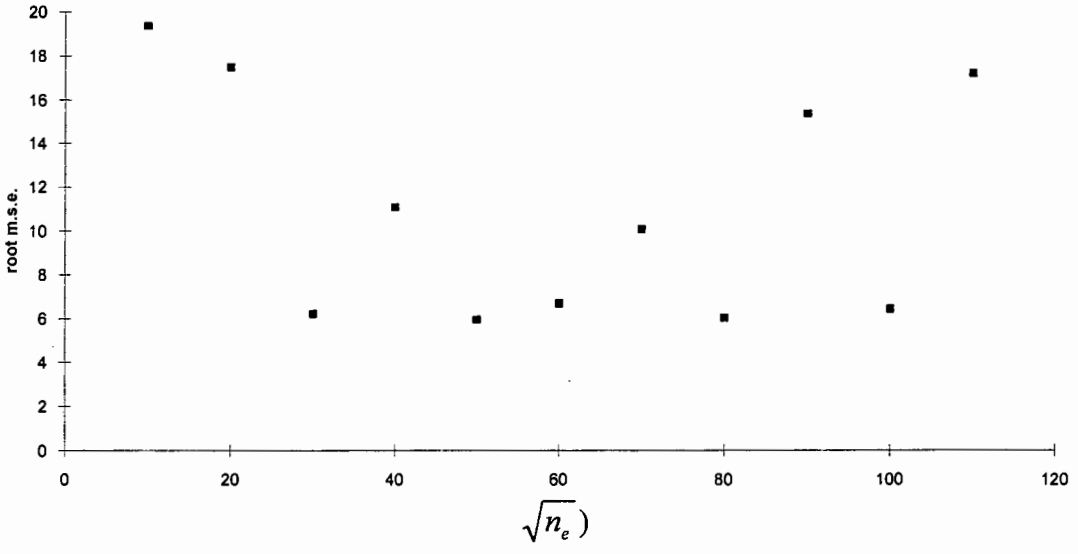


Figure A2.1b: Trap catch-at-size **weighted** residuals plotted as root mean square errors (r.m.s.e.'s) for residual sets grouped to the nearest multiple of 10 in terms of the square root of the expected sample size ($\sqrt{n_e}$) **after weighting**.



Appendix 3: Somatic growth function

A3.1 Introduction

In order to compute the entries of the projection matrix, one needs to calculate the mean annual growth (moult) increment values for each size class. Values are calculated separately for males ($g^m_{l,t}$) and females ($g^f_{l,t}$). Adult lobsters (70mm carapace length and larger) are assumed to moult once a year. Juveniles are known to moult several times a year, so that both the moult increment and moult frequency need to be taken into account when calculating the annual moult increment values for juveniles.

Moult increment data over a period of time (1969-1996) for mature males have been collected and documented by a number of authors and are summarised by Goosen and Cockcroft (1995). However, moult increment data for females are scarce, and are available for 1969-72 (Newman and Pollock 1997) and 1992 (SFRI data, unpublished) only. These growth data (for both males and females) have been collected from a number of different fishing locations along the west coast, but the locations sampled have varied from year to year and growth rate changes with location. General linear modelling techniques (GLMs) have thus had to be used to extract seasonal growth rate trends for west coast rock lobsters, where the GLMs used allow for both seasonal and spatial variation in the growth.

Two different GLM formulations have been used, and produce two slightly different growth rate trends over time. At the time of the 1870 size-structured model parameter estimation, growth data up to and including 1995 only were available. Cruywagen (1995b) fitted a GLM to the data up to 1994, and Brown (1996a) extended this analysis to include moult increment data for 1995. This last GLM is termed **GLM'95**, and its results are used as input to the population model of Appendix 1, and for simulated projections into the future using this model.

After the operational management procedure (OMP) analyses had been completed, growth data for 1996 became available. Another GLM (with slightly different assumptions) was then fitted to the full 1969-1996 data series. This GLM is termed **GLM'96**. Results from **GLM'96** are used in calculating the 1997 TAC corresponding to the selected OMP (see Chapter 10). These two different GLM's are described below.

A3.2 GLM'95

A3.2.1 Mature males

An initial GLM model (Cruywagen 1995b) was fitted to moult increment data for mature male lobsters (70mm+) from eight different Areas (Areas 1-8, see Figure 2.1) and for 24 years (1968-1994: excluding 1972-1974 during which data were not collected). The data are reported in Beyers and Goosen (1987), Melville-Smith *et al.* (1995) and Goosen and Cockcroft (1995). Prior to 1992 all recorded negative growth increments were attributed to measurement error and therefore adjusted to zero. Laboratory research has indicated,

however, that shrinkage in *Jasus lalandii* does actually occur, and as a result the data set has been corrected to annul the earlier adjustment and hence to reflect some negative increments (Cockcroft and Goosen 1995). Brown (1996a) extended Cruywagen's analysis to include moult increment data for 1995 - this analysis constitutes **GLM'95.**

The **GLM'95** model may be expressed as follows.

The annual moult increment for a male lobster length l for year t and in Area a, $g^m_{l,t,a}$, is:

$$g^m_{l,t,a} = \beta^m_{t,a} + \rho l + \varepsilon \qquad \text{(A.3.1)}$$

where

$$\beta^m_{t,a} = \beta^m_0 + \gamma^m_t + \delta^m_a \qquad \text{(A.3.2)}$$

ε is an error term assumed to be normally distributed, γ^m_t is the year effect, δ^m_a is the Area effect, and β^m_0 is a constant. The slope parameter ρ is estimated to be - 0.080. The GLM assumes that the slope parameter (ρ) remains constant over time and that all growth variation can be modelled by moving the growth versus length line up or down each year, thus changing the growth axis-intercept value β. Due to gaps in the data, area-year interaction could not be considered.

A multiple correlation coefficient $R^2 = 0.310$ was obtained. All but one of the year effect parameters were significant at the 5% level, while only two out of the eight parameters for Area effects were not significant at this level. The results used for input to the population model are standardised to the Dassen Island Area (Area 7).

Data are missing for the 1972, 1973 and 1974 moults. The β_t^m values for these three years are calculated by interpolating linearly between the 1971 and 1975 values.

The resultant β_t^m, $g_{70,t}^m$ (moult increment of a 70mm male lobster) and the $l_{\infty,t}^m$ values are reported in Appendix 4, Table 1a. [Note that $l_{\infty,t}^m = -\frac{\beta_t^m}{\rho}$.]

A3.2.2 Mature females

Moult increment data for female lobsters are scarce, and limited to two periods only: 1969-1971 (Newman and Pollock 1977) and 1992 (SFRI data, unpublished). For 1969, data are available from Dassen Island, Cape Point and Robben Island. For 1992, data are available for Cape Point and Hout Bay. As for males, a GLM approach is used to calculate a β_t^f value for each of the two data periods. The slope parameter is estimated to be ρ = - 0.0206. As with males:

$$g_{l,t,a}^f = \beta_{t,a}^f + \rho l + \varepsilon \qquad \text{(A.3.3)}$$

where

$$\beta_{t,a}^f = \beta_0^f + \gamma_t^f + \delta_a^f \qquad \text{(A.3.5)}$$

The results used for input to the population model are again standardised to the Dassen Island Area.

In order to calculate the β_t^f values for the years for which no data are available, linear interpolation is used where the female β_t^f values are assumed to follow the same

interannual fluctuating pattern as calculated for the male β_t^m values. Figure A3.1 indicates how this interpolation is performed. The equation of the line used to calculate the β_t^f values each year is:

$$\beta_t^f = 0.4357\beta_t^m - 2.25 \text{ (units mm)} \qquad \text{(A3.5)}$$

The β_t^f, $g_{70,t}^f$ and $l_{\infty,t}^f$ values are reported in Appendix 4, Table 1b.

(The mature female GLM analyses were performed by Helena Geromont, UCT.)

A3.3 GLM'96

The **GLM'95** model was updated to include the 1996 data to form **GLM'96** (Brown 1997a). This GLM is slightly different to the **GLM'95** model as the **Area** effect is replaced by a **location** effect - that is a finer spatial scale is used. There are 29 locations compared to 8 Areas. Data for Robben Island over the period 1973-1976 are omitted from the analysis as these data were not collected in a consistent manner. Negative growth increments are included in the analysis. The **GLM'96** model is the same as the **GLM'95** model (A3.1) except for the δ_a^m terms which now refer to the location effect.

A multiple correlation coefficient R^2 = 0.322 was obtained. All but two of the seasonal effect parameters were significant at the 5% level, while 11 of the 29 parameters for locations were not significant at this level. The results are standardised to the Dassen Island location.

The results of the **GLM'96** are reported in Table A4.1d in Appendix 4; these results are used only in applying the selected OMP to the observed data when calculating the 1997 TAC value.

GLM'96 produces updated moult increment values for males. Updated female moult increments are calculated as described in sub-section A3.2.2 using the new male moult increments. The juvenile-adult interpolation process (see sub-section 3.4.3) is the same for both the **GLM'95** and **GLM'96**.

A3.4 Juveniles

Juvenile annual moult increments refer to lobsters smaller than 60mm. Male and female lobsters are assumed to have equal juvenile moult increments. Unlike mature lobsters which are assumed to moult only once a year, juvenile lobsters moult several times a year, with the moult frequency gradually declining with increasing size. The annual moult increment calculation for a juvenile lobster must therefore take into the moult frequency or inter-moult period, as well as the inter-moult growth increment, into account. Linear interpolation is used for lobsters between 60mm and 70mm (see section A3.4.3).

A3.4.1 Inter-moult period

Juvenile moult frequency data is limited and has been reported by Pollock (1973).

A linear model was fitted to Pollock's (1973) data:

$$p_l = \alpha + \beta l \qquad \text{(A.3.6)}$$

where p_l is the inter-moult period in days for length l (mm).

$\alpha = 73.70$ days, and

$\beta = 1.36$ days.mm^{-1}.

A3.4.2 Moult growth increment

Juvenile moult growth increment data are available for two periods: 1969-1971 and for 1994 (Pollock 1973; P Goosen and M. Nofke , SFRI pers. commn). A quadratic function was fitted to these data simultaneously (Cruywagen, unpublished) to calculate $g_{l,t}^{juv}$ - the mean inter-moult growth increment for a juvenile lobster of length l in year t. The distribution of observation errors is specified in section A3.5.3. For the 1969-1971 data (for which growth is assumed to be "normal", i.e. equivalent to the historic average) the inter-moult growth increment $\Delta g_{l,t}^{juv}$ is given by:

$$\Delta g_{l,1970}^{juv} = \alpha + \beta l + \gamma l^2 \qquad \text{(A.3.7)}$$

The mid-point of the data period, 1970, is used for the subscript. It is assumed that smaller lobsters are less susceptible to growth fluctuations, and that lobsters smaller than 16mm are not affected by growth perturbations at all. Lobsters between 16mm and 30mm are assumed to be affected by growth perturbations to a slightly lesser degree than lobsters between 30mm and 60mm. For the 1994 data (when growth rates of mature lobsters are known to have been low) we have:

$$\Delta g_{l,1994}^{juv} = \delta_1(\alpha + \beta l + \gamma l^2) \qquad \text{for } 16\text{mm} \le l \le 30\text{mm} \qquad \text{(A.3.8)}$$

$$\Delta g_{l,1994}^{juv} = \delta_2(\alpha + \beta l + \gamma l^2) \qquad \text{for } 30\text{mm} < l \le 60\text{mm} \qquad \text{(A.3.9)}$$

where

α = -0.937

β = 0.248

γ = -0.003

δ_1 = 0.880

δ_2 = 0.760.

The net **annual** growth for juvenile lobsters is thus:

$$g_{l,t}^{juv} = \frac{\Delta g_{l,t}^{juv} .365}{p_l} \qquad \text{for } 5\text{mm} < l \leq 60\text{mm} \qquad \text{(A.3.10)}$$

Further, to avoid negative growth for very small lobsters, we assume $g_{l,1970}^{juv} = g_{l,1994}^{juv}$ for $l \leq 5$mm.

To calculate the annual moult increment values for juveniles in years other than 1970 and 1994 (those for which data are available), we assume a similar but damped year to year trend to that calculated for a 70mm male lobster in these other years. Comparable moult increments between juveniles and 70mm male lobsters are available for two periods: 1970 and 1994. Linear interpolation can therefore be carried out as follows:

$$g_{l,t}^{juv} = \tau_{l,t}^{juv} g_{l,1970}^{juv} \qquad \text{(A.3.11)}$$

where

$$\tau_{l,t}^{juv} = 1 \qquad \text{for } l \leq 15\text{mm} \qquad \text{(A.3.12)}$$

$$\tau_{l,t}^{juv} = 1 + (\delta_1 - 1)\left(\frac{1 - \tau_{70,t}^{m}}{1 - \tau_{70,1994}^{m}}\right) \qquad \text{for } 15\text{mm} < l \leq 30\text{mm}$$

and

$$\tau^{m}_{70,t} = \frac{g^{m}_{70,t}}{g^{m}_{70,1970}} \qquad \text{(A.3.13)}$$

where $\delta = \delta_1$ for $15\text{mm} < l \leq 30\text{mm}$

$\delta = \delta_2$ for $30\text{mm} < l \leq 60\text{mm}$.

Figure A3.2 illustrates how the $\tau^{juv}_{l,t}$ values are calculated for each year t.

A3.4.3 Juvenile-adult interpolation

Linear interpolation is used to calculate the annual moult increment values for male lobsters between length 60mm (juvenile) and 70mm (mature). For females, this interpolation is between 50mm (juvenile) and 70mm (mature).

The juvenile moult increments used in **GLM'96** are identical to those described above.

A3.5 Moult increment variance estimates

The projection matrix calculation requires not only estimates of the mean annual moult increment for each length, but also an estimate of the associated variance around this value. Standard deviations for moult increments have been calculated from the moult increment data. Moult increment variance models for male, female and juvenile lobsters are as follows.

A3.5.1 Mature males

Standard deviations for length l, σ_l^m, are calculated from tagging data (SFRI data, unpublished), and illustrated in Figure A3.3. The assumed relationship between σ_l^m and l used in the model is shown as a solid line in this figure. This relationship is defined as follows:

$\sigma_l^m = 1.8$ mm 70mm $\leq l <$ 110mm

$\sigma_l^m = -0.04l + 6.2$ mm 110mm $\leq l <$ 130mm

$\sigma_l^m = 1$mm 130mm $\leq l <$ 150mm

$\sigma_l^m = -0.1l + 16$ mm 150mm $\leq l <$ 160mm

$\sigma_l^m = 0$ mm $l \geq$ 160mm

There are no data for $l >$ 130mm, so that the σ_l^m was kept at the value extrapolated for l = 130mm for larger sizes. However, σ_l^m is reduced to zero for very large sizes for computational convenience (to avoid lobsters growing to sizes outside the range considered in the computations) - there are in any case very few lobsters that grow to such sizes, so these assumptions have minimal impact on results.

σ_l

A3.5.2 Mature females

The σ_l^f for all $l \geq$ 70mm is estimated to be 0.351. This value was calsulated from SFRI unpublished tagging data by Helena Geromont (UCT).

These fixed standard deviations are used regardless of the change in growth rate over the years. For very low levels of growth, it is acknowledged that this results in a fairly

substantial amount of shrinkage (especially for females), but this was felt by working group members not to be unreasonable given the number of negative growth increments observed in the more recent tagging data.

A3.5.3 Juveniles

There is a standard deviation associated with

i) the inter-moult period *SD(p)*, and

ii) with the inter-moult growth increment *SD(Δg)*.

The $SD(p) = \sigma_p$ (a constant), was estimated from the linear model fit to Pollock's (1973) data (see section A3.4.1). The $SD(\Delta g) = \sigma_0 e^{\mu l}$ was estimated in the process of fitting the quadratic function to the data (see section A3.4.2). The estimated values (SFRI data, unpublished) are as follows:

$\sigma_p = 7.78$ days

$\sigma_0 = 0.74$

$\mu = 0.004$.

If one re-writes equation A.3.12 with simplified notation as follows:

$$g = \frac{\Delta g.365}{p}$$

then, using a delta method of approximation (Seber 1973), the coefficient of variation (CV) of g becomes:

$$CV(g) = \sqrt{CV^2(\Delta g) + CV^2(p)} \tag{A3.14}$$

where

$$CV(\Delta g) = \frac{SD(\Delta g)}{\Delta g}$$

and

$$CV(p) = \frac{SD(p)}{p}$$

so that

$$\sigma_g = gCV(g) = \frac{\Delta g.365}{p}\sqrt{\left(\frac{\sigma_0 e^{\mu l}}{\Delta g}\right)^2 + \left(\frac{\sigma_p}{p}\right)^2} \tag{A.3.15}$$

Note: Unlike the variance for adult lobster growth, the juvenile variance is time-dependent (as Δg is time-dependent). Variance estimates for the historic average growth for juvenile lobsters are reported in the Table A3.1 (values for every 5th mm are given).

A3.5.4 Interpolation between juveniles and adults

As with the annual moult increment values, linear interpolation is used to provide the standard deviation estimates between 60mm (juvenile) and 70mm (adult) for male lobsters, and between 50mm (juvenile) and 70mm (adult) for females.

A3.6 Growth data for pre-data and post-data periods

The sections above have described how the mean moult increment values and their associated variance estimates are calculated for the period 1969-1995 (GLM'95). Assumptions made regarding the growth prior to 1969 and post 1995 are as follows.

A3.6.1 Pre - data period

An average of the GLM'95 β_t^m and β_t^f values for 1969-1988 are used for the 1870-1968 period. These values are assumed to represent the historic average growth of the resource.

A3.6.2 Post - data period

A number of growth scenarios for projecting the resource into the future can be postulated. Three future growth scenarios were identified by the RLWG for use for resource projection purposes:

i) **LOW** growth scenario- the growth rate is assumed to remain low at the 1989-1994 average level;

ii) **HIGH** growth scenario - the growth rate is assumed to recover immediately to the 1969-1994 average level (note that this level is lower than for the 1969-1988 average which is assumed to apply to the 1870-1968 period);

iii) **ARMA** scenario - this scenario assumes there is a gradual recovery of the growth to the 1969-1994 average level over the next 20 years, according to an AR(1) time series model fit to past data.

The β_t^m and β_t^f values for all three of these future growth scenarios (for the period 1996-2006) are reported in Table A4.1c in Appendix 4.

A3.6.3. ARMA growth scenario

The ARMA growth analysis is reported in Clarke *et al.* (1996). This ARMA analysis suggests that the growth be modelled by a first order auto-regressive process (AR(1)), which is defined by:

$$X_y = C + \varepsilon_y = C + \alpha\varepsilon_{y-1} + \eta_y \qquad \text{(A3.16)}$$

where C is a constant and the η_y are independent random deviates with zero mean and variance σ_η^2. The above process was fitted to the time series β_y^m for y = 1975-1995, yielding estimates

C = 10.042;

α = 0.757; and

σ_η = 0.681.

Table A3.1 : Standard deviation estimates for the historic (1870-1968) average growth for juvenile lobsters.

Length (l) (mm)	σ_l^J (mm)
5	3.42
10	3.25
15	3.13
20	3.02
25	2.92
30	2.82
35	2.70
40	2.62
45	2.54
50	2.46
55	2.38
60	2.31

Figure A3.1: Interpolation of the β_t^f values from the β_t^m values (see equation A.3.5).

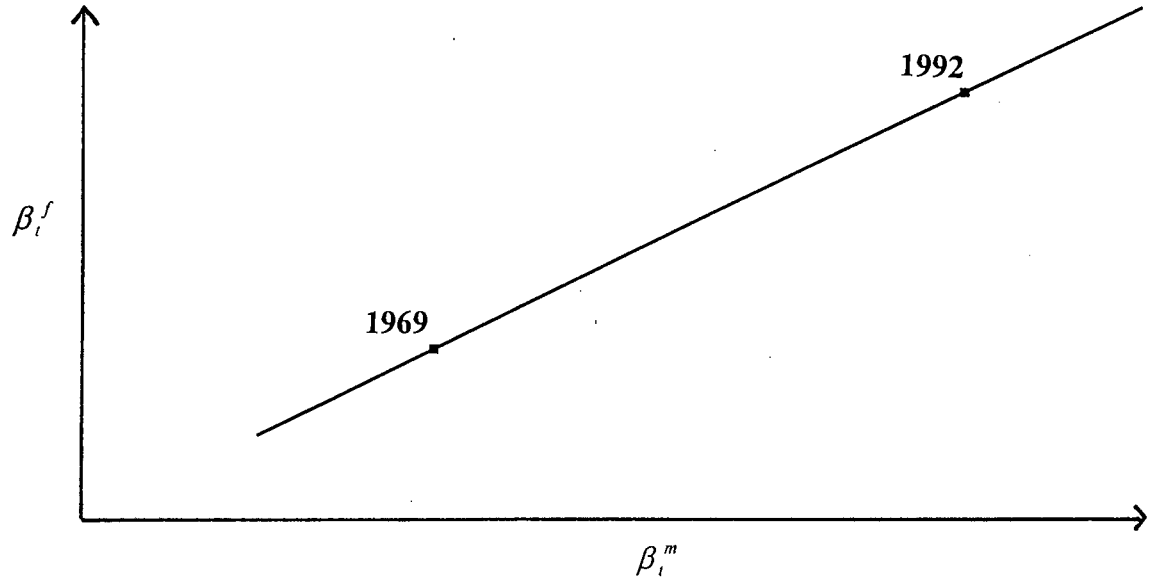


Figure A3.2: The calculation of the $\tau_{l,t}^{juv}$ values for each year (see equation A.3.12).

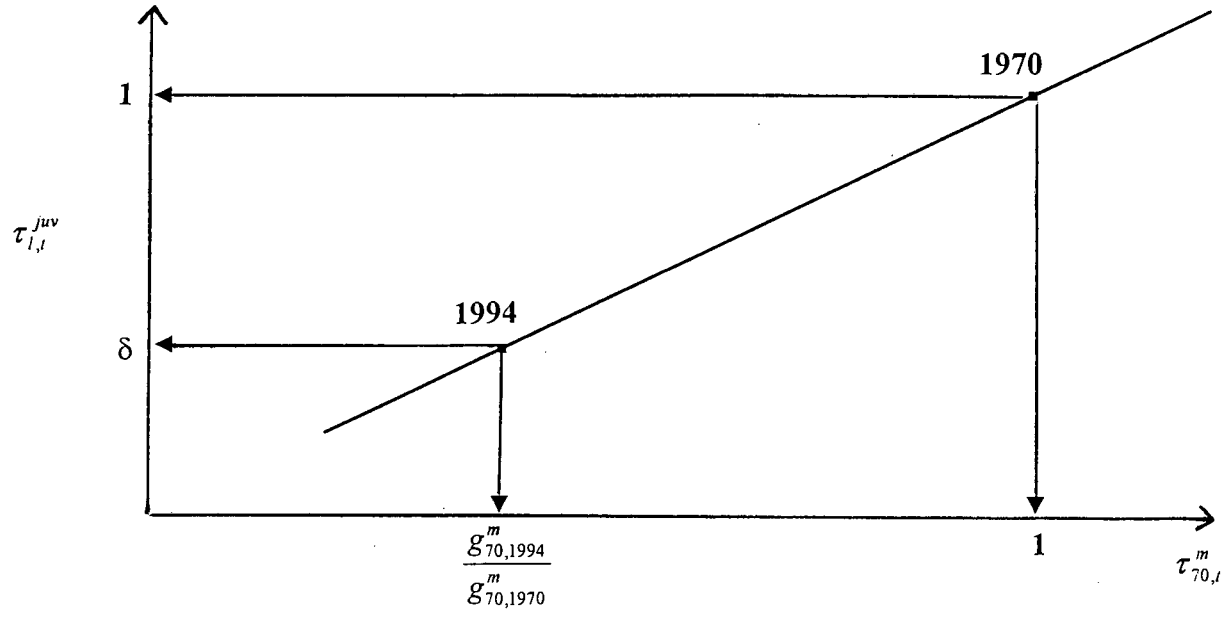
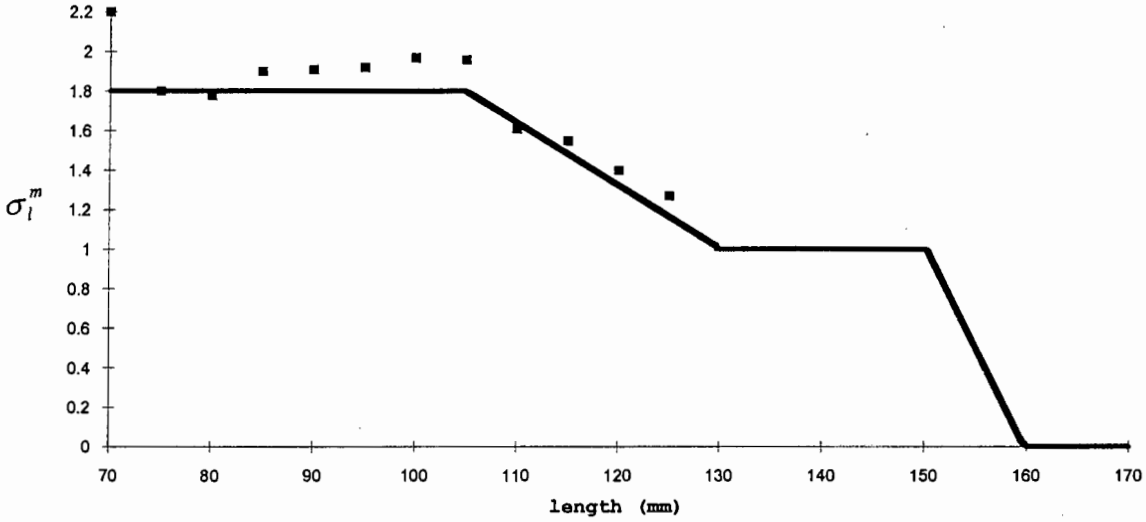


Figure A3.3: The standard deviation σ_l^m (in mm) as a function of carapace length l for mature males.



Appendix 4: Data used in the size structured model and OMP

A4.1 Somatic growth data

As described in Appendix 3, two sets of results from growth analyses are used. **GLM'95** is used for the population model parameter estimation, as well as for simulated projections into the future. **GLM'96** results are used in conjunction with the selected OMP to calculate the 1997 (and future) TAC values.

A4.1.1 Mature males

Mature male mean moult increment values, $g^m_{l,t}$, are calculated using the following equation:

$$g^m_{l,t} = \beta^m_t + \rho l$$

where the slope ρ =-0.080.

The β^m_t, $g^m_{70,t}$ (moult increments for a 70mm lobster) and $l^m_{\infty,t}$ (length at which moult increment becomes zero) values for GLM'95 are reported in Table A4.1a. The β^m_t values resulting from the GLM'96 are reported in Table A4.1d. Results have been standardised to the Dassen Island Area.

A4.1.2 Mature females

Mature female mean moult increment values, $g^f_{l,t}$, are calculated using the following equation:

$$g^f_{l,t} = \beta^f_t + \rho l$$

where the slope ρ =-0.0206.

The β^f_t, $g^f_{70,t}$ (moult increments for a 70mm lobster) and $l^f_{\infty,t}$ (size at which moult increment becomes zero) values are reported in Table A4.1b.

A4.1.3 Historic growth data series and future growth scenarios

The historic average growth that is used in the model for the 1870-1968 period, is calculated as the average for the 1969-1988 period. The β^m_t and β^f_t values for this average are as follows:

β^m_t = 11.15 mm

β^f_t = 2.34 mm.

The future growth scenarios considered have been defined in Appendix 3. The β^m_t and β^f_t values for these are reported in Table A4.1c.

A4.2 CPUE data

Three different CPUE data series are used in the likelihood - trap CPUE, hoopnet CPUE and FIMS CPUE. For both the trap CPUE and FIMS CPUE, updates to the original data analyses have been made recently. These are discussed in section A4.2.4. The analyses below describe how the CPUE data are calculated for use in the likelihood for the population model fit to the data (see equation A2.1)

A4.2.1 Commercial trap CPUE data

These data have been collected by the SFRI from each of the commercial fishing areas of the west coast rock lobster fishery. An area-weighted CPUE estimate has been calculated for each year (Cruywagen 1995a), to produce CPUE estimates which are representative of the resource as a whole. These estimates are reported in Table A4.2a. The minimum size was altered during the 1991 season from 89mm to 75mm. The CPUE for the 1991 season reported in Table A4.2a corresponds to that for the first part of the season (min = 89mm). Data are available for the 1975-1995 seasons. These data are used in calculating the likelihood for the population model fit to the data.

A4.2.2. Commercial hoopnet CPUE

The commercial hoopnet CPUE data are collected in the same manner as the commercial trap data. Two types of hoopnet data are available (hoopnets and bakkies). A GLM analysis was conducted to combine these two hoopnet data sources and to deal with missing values (Brown 1996b). In this GLM, only data from Areas 3-8 (to which the

current stock assessment is taken to apply) are considered. The hoopnet data are presented in Table A4.2b.

A4.2.3 FIMS CPUE

The fisheries independent monitoring survey (FIMS) for west coast rock lobster is described in full in Scott and Stewart (1996). The main aim of FIMS is to monitor the abundance of the west coast rock lobster by providing annual relative abundance indices. The four regions sampled cover the Areas 3-8 because they account for a greater proportion of the overall abundance. Each region is stratified into shallow and deep zones, with the shallow zones sampled four times as heavily. The surveys are conducted over two two-week periods in each region. The FIMS data are obtained using traps, but with a 60mm mesh size to ensure full selectivity for sizes 60mm and larger. FIMS CPUE data are in terms of numbers of lobsters (not biomass) for the 60mm+ portion of the resource. Data are available from 1992 only. The four FIMS estimates by region are area-weighted to produce an overall mean FIMS CPUE value for each season. These values are presented in Table A4.2c.

A4.2.4 New commercial CPUE and FIMS CPUE data analyses

Since the original analyses described above and used as input to the population model fitting process were conducted, new data have become available. This has allowed the analyses to be updated. The data from these "new" analyses are used in conjunction with the selected OMP to calculate the 1997 TAC value.

A new form of commercial CPUE analysis, based on a GLM analysis, is now preferred. This GLM is described in Brown (1997b). Data from the three methods used to catch west coast rock lobster, namely traps, hoops and bakkies, have been used together in a GLM context to derive a combined index of abundance. A number of different GLM models were originally fitted to the data. The selected model includes both Year*Area and Month*Area interactions. The resultant "new" commercial CPUE data are reported in Table A4.2d.

A new method is also now used for calculating the annual FIMS indices (Brown 1997a). This method area-weights data from Areas 5, 6 and 7, and then links these with Area 8 by a GLM - this is to make allowance for different catchabilities in these different regions at the time FIMS is conducted, thus avoiding the over-weighting of Area 8 results in earlier analyses.

A4.3 Catch-at-size data

Two sources of catch-at-size data are available: commercial trap data and FIMS data.

A4.3.1 Commercial trap catch-at-size data

The catch-at-size data series used in fitting the regression covers the period 1981-1995. These data have been collected from trap samples by the SFRI for each Area in each year. A pseudo-weighting technique was used to weight the data from each Area to produce a catch-at-size frequency for each year. The aim of this weighting scheme was to maintain the total sample size for each year, but weight the individual Area data according to each Area's commercial catch contribution in that year, for results more representative of the overall catch composition. The $p^s_{l,t}$ values (effectively catch-at-size proportion for length l, in year t for either sex s) are calculated as follows:

$$p^s_{l,t} = \frac{\sum_a \left(n^s_{l,a,t} \frac{C_{a,t}}{\sum_a C_{a,t}} \right)}{\sum_{a,l} \left(n^s_{l,a,t} \frac{C_{a,t}}{\sum_a C_{a,t}} \right)} \qquad \text{(A4.1)}$$

where

a - refers to the Area,

$C_{a,t}$ - refers to the catch in Area a in year t,

$n^s_{l,a,t}$ - is the sample catch-at-size number for length l in year t in Area a (for sex s), and

$p^s_{l,t}$ - is the catch-at-size proportion for length l and time t for sex s.

The $p^s_{l,t}$ values for each year are reported in Table A4.3a-c.

The total sample sizes for each year, $N_t^{m/f}$, are reported in Table A4.3d.

A4.3.2 FIMS catch-at-size data

These data are available for 1992-1995 only. Data are for size classes ranging from 60mm+ in 5mm categories. The data as reported are area-weighted. The FIMS catch-at-size proportions are reported in Table A4.4a. The FIMS catch-at-size sample sizes are reported in Table A4.4b.

A4.4 Percent females in catch ($F^{\%}$)

Two sources of $F\%$ are available: from the commercial trap samples and from FIMS.

A4.4.1 Commercial trap sample data

The data series consists of catch-weighted $F^{\%}$ for 1981-1995 and are reported in Table A4.5a. Note that the percentages reflect the percent by **number** of females in the catch. No females were caught during the 1991 season - due to a ban on harvesting females. Thereafter this percentage rises as a result of the lower size limit introduced.

A4.4.2 FIMS $F\%$ data

FIMS $F\%$ data are available for the 1992-1995 seasons only. These $F\%$ data represent the percentage females (by number) caught in the FIMS samples for the size range 60mm+. These data are presented in Table A4.5b.

A4.5 Historic catch record

The historic commercial catch record is reported in Table A4.6. A linear increase in catch from zero in 1870 to 1434.91 tons in 1900 is assumed for population modelling purposes, owing to lack of pre-1990 catch data. The early data from 1900-1968 are obtained from annual lobster export records (SFRI, unpublished data). The 1969-1995 data were provided by the SFRI. The data reported in Table A4.6 reflect commercial catches only and exclude poaching and recreational catches. Catch data are available for two parts of the 1991 season (the legal minimum size changed during this season). Catches from both parts are taken into account in the dynamic equations (see equations A1.14 and A1.17) when catches at length are removed.

A4.6 Minimum legal size limits.

A minimum legal size limit (min) has been imposed on the west coast rock lobster fishery since the late 1800's. A number of changes to this minimum size have been made. These minimum size limits are reported in Table A4.7.

Table A4.1a: The β_t^m, $g_{70,t}^m$ and $l_{\infty,t}^m$ values for mature male rock lobsters (**GLM'95**).

Year	β_t^m (mm^{-1})	$g_{70,t}^m$ (mm)	$l_{\infty,t}^m$ (mm)
1968	11.03	5.43	138
1969	11.64	6.04	145
1970	11.69	6.09	146
1971	12.20	6.60	153
1972	11.95	6.35	149
1973	11.69	6.09	146
1974	11.43	5.83	143
1975	11.16	5.56	140
1976	10.53	4.93	132
1977	10.43	4.83	130
1978	11.50	5.90	144
1979	11.95	6.35	149
1980	10.78	5.18	135
1981	11.32	5.72	142
1982	11.02	5.42	138
1983	11.05	5.45	138
1984	12.01	6.41	150
1985	10.39	4.79	130
1986	9.38	3.78	117
1987	10.63	5.03	132
1988	10.17	4.57	127
1989	9.72	4.12	122
1990	8.89	3.29	111
1991	8.96	3.36	112
1992	8.75	3.15	109
1993	9.03	3.43	113
1994	9.15	3.55	114
1995	9.35	3.75	116

Table A4.1b: The β_t^f, $g_{70,t}^f$ and $l_{\infty,t}^f$ values for mature female rock lobsters (**GLM'95**).

Year	β_t^f (mm^{-1})	$g_{70,t}^f$ (mm)	$l_{\infty,t}^f$ (mm)
1968	2.30	0.86	111
1969	2.55	1.11	123
1970	2.57	1.13	125
1971	2.79	1.34	135
1972	2.68	1.24	130
1973	2.57	1.13	125
1974	2.46	1.02	120
1975	2.35	0.91	114
1976	2.08	0.64	101
1977	2.04	0.60	99
1978	2.49	1.05	121
1979	2.68	1.24	130
1980	2.19	0.75	106
1981	2.42	0.98	117
1982	2.29	0.85	111
1983	2.30	0.86	112
1984	2.71	1.27	131
1985	2.03	0.59	98
1986	1.60	0.16	78
1987	2.13	0.69	103
1988	1.93	0.49	94
1989	1.74	0.30	85
1990	1.39	0	68
1991	1.42	0	69
1992	1.33	0	65
1993	1.45	0	70
1994	1.50	0.06	73
1995	1.58	0.14	77

Table A4.1c. The β_t^m and β_t^f values (in mm) for three future growth scenarios: values given for 1996-2006.

Year	High growth scenario		LOW growth scenario		ARMA growth scenario	
	β_t^m	β_t^f	β_t^f	β_t^m	β_t^m	β_t^f
1996	10.67	2.14	9.08	1.47	9.52	1.66
1997	10.67	2.14	9.08	1.47	9.64	1.71
1998	10.67	2.14	9.08	1.47	9.74	1.75
1999	10.67	2.14	9.08	1.47	9.81	1.78
2000	10.67	2.14	9.08	1.47	9.87	1.81
2001	10.67	2.14	9.08	1.47	9.91	1.82
2002	10.67	2.14	9.08	1.47	9.94	1.83
2003	10.67	2.14	9.08	1.47	9.97	1.85
2004	10.67	2.14	9.08	1.47	9.99	1.86
2005	10.67	2.14	9.08	1.47	10.00	1.86
2006	10.67	2.14	9.08	1.47	10.01	1.86

Table A4.1d: The β_t^m values (in mm) for the GLM'96 analysis (only the last three years' data are required by the OMP for calculating the 1997 TAC).

Year	β_t^m
1994	9.09
1995	9.26
1996	9.75

Table A4.2a: Area-weighted commercial trap CPUE data values.

Year	CPUE (kg/trap/day)
1975	5.34
1976	6.72
1977	5.20
1978	5.41
1979	4.43
1980	3.29
1981	4.47
1982	6.21
1983	7.51
1984	7.92
1985	8.57
1986	6.46
1987	8.17
1988	7.82
1989	5.72
1990	3.06
1991	3.04
1992	5.89
1993	6.06
1994	3.81
1995	6.20

Table A4.2b: Commercial hoopnet CPUE data.

Year	Hoopnet CPUE (kg/hoop/day)
1987	64.21
1988	37.05
1989	25.06
1990	14.77
1991	18.25
1992	33.62
1993	32.58
1994	21.88
1995	27.61

Table A4.2c: FIMS CPUE data.

Year	FIMS CPUE
1992	44.0
1993	56.2
1994	34.0
1995	37.9

Table A4.d: "New" commercial CPUE (from GLM) and FIMS CPUE data (data have been normalised to an average of 1).

Year	commercial CPUE	FIMS CPUE
1992	-	1.361
1993	1.010	1.255
1994	0.878	0.671
1995	1.006	0.721
1996	1.106	0.991

Table A4.3a: Pseudo-weighted trap catch-at-size proportions ($p^s_{l,t}$) for west coast rock lobster for 1981-1985.

	1981	1981	1982	1982	1983	1983	1984	1984	1985	1985
size (mm)	male	female	male	female	male	female	male	female	male	female
90	0.403	0.723	0.521	0.841	0.466	0.819	0.407	0.834	0.448	0.777
95	0.281	0.200	0.279	0.134	0.282	0.151	0.283	0.142	0.297	0.176
100	0.159	0.048	0.107	0.022	0.143	0.021	0.148	0.019	0.148	0.037
105	0.081	0.014	0.050	0.003	0.062	0.007	0.083	0.003	0.070	0.007
110	0.045	0.014	0.023	0	0.028	0.002	0.042	0.001	0.025	0
115	0.016	0	0.011	0	0.011	0.001	0.009	0.003	0.013	0
120	0.010	0	0.006	0	0.005	0	0.011	0	0.003	0
125	0.003	0	0.003	0	0.002	0	0.004	0	0.001	0
130	0.002	0	0.001	0	0.001	0	0.001	0	0	0
135	0.001	0	0	0	0	0	0	0	0	0
140	0.	0	0	0	0	0	0	0	0	0

Table A4.3b: Pseudo-weighted trap catch-at-size proportions ($p^s_{l,t}$) for west coast rock lobster for 1986-1991.

	1986	1986	1987	1987	1988	1988	1989	1989	1990	1990	1991
	male	female	male	female	male	female	male	female	male	female	male
90	0.547	0.836	0.533	0.831	0.540	0.872	0.630	0.945	0.616	0.919	0.604
95	0.273	0.129	0.274	0.127	0.249	0.104	0.229	0.050	0.262	0.074	0.270
100	0.180	0.027	0.117	0.032	0.123	0.015	0.084	0.005	0.068	0.008	0.079
105	0.041	0.008	0.046	0.009	0.053	0.005	0.033	0	0.033	0	0.030
110	0.015	0	0.020	0	0.025	0	0.017	0	0.015	0	0.010
115	0.005	0	0.008	0.002	0.008	0	0.007	0	0.005	0	0.004
120	0.001	0	0.003	0	0.003	0.004	0.002	0	0.001	0	0.001
125	0	0	0.001	0	0	0	0	0	0	0	0.001
130	0	0	0	0	0	0	0	0	0	0	0
135	0	0	0	0	0	0	0	0	0	0	0
140	0	0	0	0	0	0	0	0	0	0	0

Table A4.3c: Pseudo-weighted trap catch-at-size proportions ($p^s_{l,t}$) for west coast rock lobster for 1992-1994.

	1992	1992	1993	1993	1994	1994	1995	1995
	male	female	male	female	male	female	male	female
75	-	-	0.244	0.590	0.424	0.734	0.445	0.822
80	0.482	0.651	0.302	0.302	0.333	0.225	0.283	0.158
85	0.341	0.274	0.226	0.089	0.154	0.039	0.133	0.017
90	0.129	0.061	0.139	0.014	0.051	0.002	0.083	0.004
95	0.038	0.013	0.059	0.005	0.025	0	0.033	0
100	0.006	0	0.020	0.001	0.011	0	0.017	0
105	0.002	0	0.006	0	0.002	0	0.005	0
110	0.001	0.001	0.003	0	0	0	0.001	0
115	0	0	0.001	0	0	0	0	0
120	0	0	0	0	0	0	0	0
125	0	0	0	0	0	0	0	0
130	0	0	0	0	0	0	0	0
135	0	0	0	0	0	0	0	0
140	0	0	0	0	0	0	0	0

Table A4.3d: Trap catch-at-size sample sizes (N_t^s) for male and female lobsters.

Year	male	female
1981	17 243	1 318
1982	43 478	2 433
1983	36 107	1 583
1984	39 308	1 852
1985	42 078	597
1986	59 694	848
1987	40 530	575
1988	63 054	830
1989	54 839	501
1990	79 790	240
1991	56 774	6 238
1992	9 613	1 261
1993	30 702	3 134
1994	105 933	14 969
1995	50 484	4980

Table A4.4a: FIMS catch-at-size proportions.

Size class (mm)	1992		1993		1994		1995	
	male	female	male	female	male	female	male	female
60	0.024	0.109	0.020	0.119	0.025	0.114	0.051	0.161
65	0.120	0.353	0.128	0.475	0.150	0.400	0.141	0.482
70	0.210	0.350	0.252	0.313	0.227	0.330	0.252	0.287
75	0.203	0.142	0.248	0.078	0.273	0.116	0.258	0.056
80	0.180	0.037	0.181	0.011	0.189	0.034	0.176	0.011
85	0.134	0.007	0.107	0.002	0.081	0.004	0.076	0.003
90	0.083	0.002	0.059	0.002	0.036	0	0.028	0
95	0.032	0	0.004	0	0.013	0	0.011	0
100	0.010	0	0.001	0	0.004	0	0.004	0
105	0.003	0	0	0	0.001	0	0.001	0
110	0.001	0	0	0	0	0	0.001	0
115	0	0	0	0	0	0	0	0
120	0	0	0	0	0	0	0	0

Table A4.4b: FIMS catch-at-size sample sizes.

Year	male	female
1992	29129	12089
1993	24905	9687
1994	28233	9286
1995	17572	7574

Table A4.5a: Percent females ($F^{\%}$) in the commercial trap catch.

Year	$F^{\%}$
1981	4.67
1982	5.55
1983	3.79
1984	3.91
1985	1.94
1986	1.41
1987	1.17
1988	0.99
1989	0.70
1990	0.17
1991	0.00
1992	5.69
1993	14.14
1994	10.51
1995	5.25

Table A4.5b: FIMS *F*% data.

Year	*F*%
1992	29.97
1993	28.43
1994	24.61
1995	28.43

Table A4.6: Commercial catch record for west coast rock lobster.

Year	Catch (MT)	Year	Catch (MT)	Year	Catch (MT)
1900	1434.910	**1933**	15069.512	**1966**	9188.454
1901	1268.130	**1934**	7609.377	**1967**	7079.628
1902	922.183	**1935**	7510.018	**1968**	6175.846
1903	531.378	**1936**	9493.712	**1969**	7556.934
1904	396.131	**1937**	11436.398	**1970**	5600.000
1905	718.299	**1938**	9942.930	**1971**	5290.000
1906	249.047	**1939**	11148.713	**1972**	5541.000
1907	610.012	**1940**	11567.33	**1973**	5722.000
1908	1142.105	**1941**	10860.976	**1974**	6288.000
1909	1993.303	**1942**	9239.794	**1975**	6297.000
1910	1880.813	**1943**	5555.824	**1976**	6297.000
1911	2731.426	**1944**	4057.856	**1977**	6297.000
1912	5177.476	**1945**	5742.694	**1978**	5352.000
1913	6718.648	**1946**	9634.026	**1979**	5352.000
1914	6864.268	**1947**	12301.077	**1980**	4548.000
1915	8879.652	**1948**	13022.801	**1981**	3700.000
1916	8596.338	**1949**	12578.312	**1982**	3700.000
1917	9511.503	**1950**	18317.69	**1983**	3730.000
1918	5504.349	**1951**	18926.346	**1984**	3730.000
1919	8705.144	**1952**	14582.537	**1985**	3805.000
1920	8206.635	**1953**	13679.449	**1986**	3965.000
1921	6485.792	**1954**	12337.899	**1987**	3834.000
1922	9097.975	**1955**	11702.091	**1988**	4000.000
1923	6849.515	**1956**	8445.569	**1989**	3491.000
1924	8148.065	**1957**	3542.381	**1990**	2996.000
1925	9803.356	**1958**	6856.249	**1991**	1526.000
1926	7480.653	**1959**	11224.531	**1991**	863.000
1927	7794.046	**1960**	11224.531	**1992**	2125.000
1928	9492.865	**1961**	10471.379	**1993**	2155.000
1929	9643.231	**1962**	10320.748	**1994**	2000.000
1930	10621.084	**1963**	10622.009	**1995**	1500.000
1931	9931.129	**1964**	10622.009		
1932	13180.169	**1965**	10622.009		

Table A4.6: Minimum legal size limits for the west coast rock lobster fishery.

Period	Minimum legal size limit
1870-1892	55 mm (2 inches)
1893-1913	76 mm (3 inches)
1914-1923	102 mm (4 inches)
1924-1925	76 mm
1926-1928	102 mm
1929-1990	89 mm (3.5 inches)
1991 first part of season	89 mm
1991 second part of season	75 mm
1992	80 mm
1993+	75 mm

Appendix 5: Calculation of hoopnet selectivity scaling functions

The hoopnet selectivity functions are calculated by multiplying the trap selectivity functions by hoopnet scaling functions. These scaling functions have been calculated by comparing hoopnet and trap gear catch-at-size data. Data on catch-at-size from commercial samples are available for both trap and hoopnet gear for Areas 3-8 over a period of time. In this study only comparable data sets are used - i.e. both the trap and hoopnet sample must have been caught from the same Area in the same year. Comparable data sets are available for seasons ranging from 1968 to 1993. The number of comparable data sets for each Area are as follows:

Area 3 - 16

Area 4 - 15

Area 5 - 19

Area 6 - 23

Area 7 - 4

Area 8 - 10

Total number of samples: $n = 87$

The hoopnet and trap catch size frequencies for males and females are normalised over size 90mm, 95mm ... 140mm for each year to provide proportions which sum to 1.00 for each year and for each sex.

A scaling factor for each sex and size class (X_l^m or X_l^f) which multiplies the estimated/defined trap selectivity value to give a hoopnet selectivity value is calculated as follows for males (females similarly):

$$x_{l,a,t}^m = \frac{c_{l,a,t}^{h,m}}{c_{l,a,t}^{t,m}} \tag{A.5.1}$$

where

$c_{l,a,t}^{h,m}$ = hoopnet catch size proportion for length l in Area a in year t

$c_{l,a,t}^{t,m}$ = trap catch size frequency for length l in Area a in year t

$x_{l,a,t}^m$ = the scaling factor for length l in Area a in year t.

The results were initially averaged on an Area basis to determine if any major differences between Areas were evident, but none were detected. The results were then averaged over all Areas and years (where data were available) to give:

$$X_l^m = \frac{\sum_{a,t} x_{l,a,t}^m}{n} \tag{A.5.2}$$

where n refers to the number of comparative values available.

The mean X_l^m and X_l^f values are reported in Table A5.1. These values are plotted and illustrated in Figure A5.1a (males) and A5.1b (females) - shown as "data".

Scaling functions

Males: The X_l^m values appear to be fairly constant and equal to about 1.00 for sizes 75mm - 90mm. A straight line was fitted to the X_l^m points for size 95mm - 145mm. The slope of this line is 0.0758 and the intercept is -5.562. Linear interpolation is used for sizes 90-95mm.

Females: A straight line was fitted to all the female X_l^f values and is shown in Figure A5.1b. The slope of this line is -0.029 and the intercept is 4.642.

The fitted scaling functions shown in Figure A5.1a and A5.1b are used in the size-structured model to calculate the hoopnet selectivity functions (see equations A1.10).

Table A5.1: Mean X_l^m and X_l^f values.

Size class (mm)	X_l^m	X_l^f
75	1.00	2.79
80	0.82	2.40
85	0.82	2.39
90	0.84	1.71
95	1.00	1.77
100	1.34	1.49
105	1.91	1.39
110	2.57	1.81
115	2.81	1.37
120	3.60	1.43
125	4.16	
130	3.93	
135	3.78	
140	5.22	
145	4.30	

Figure A5.1a: Mean X_l^m values and the fitted scaling function.

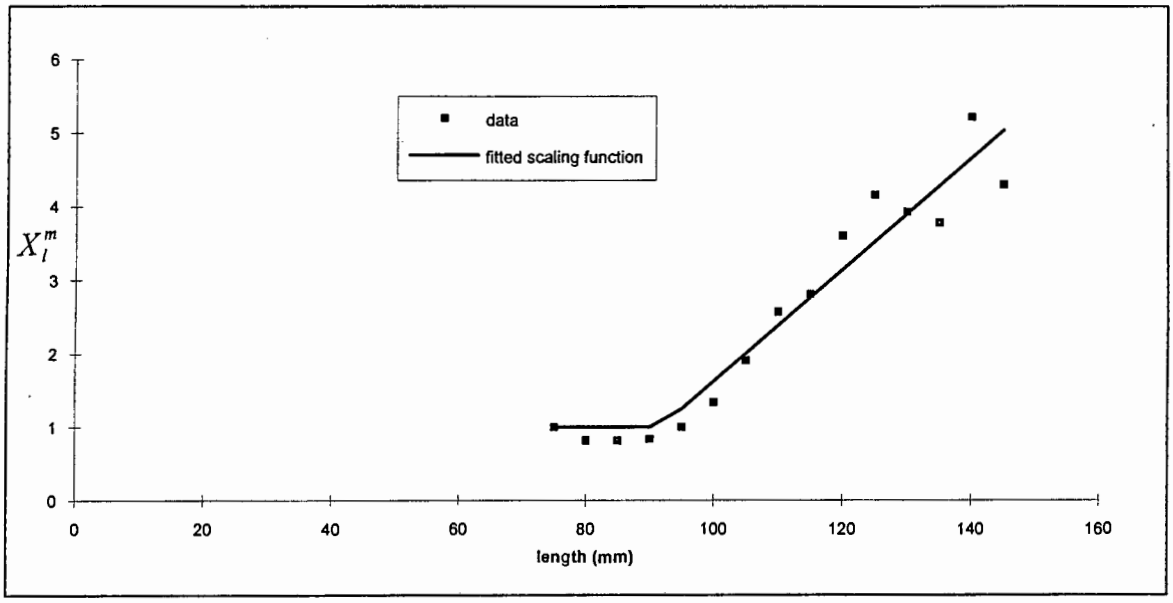
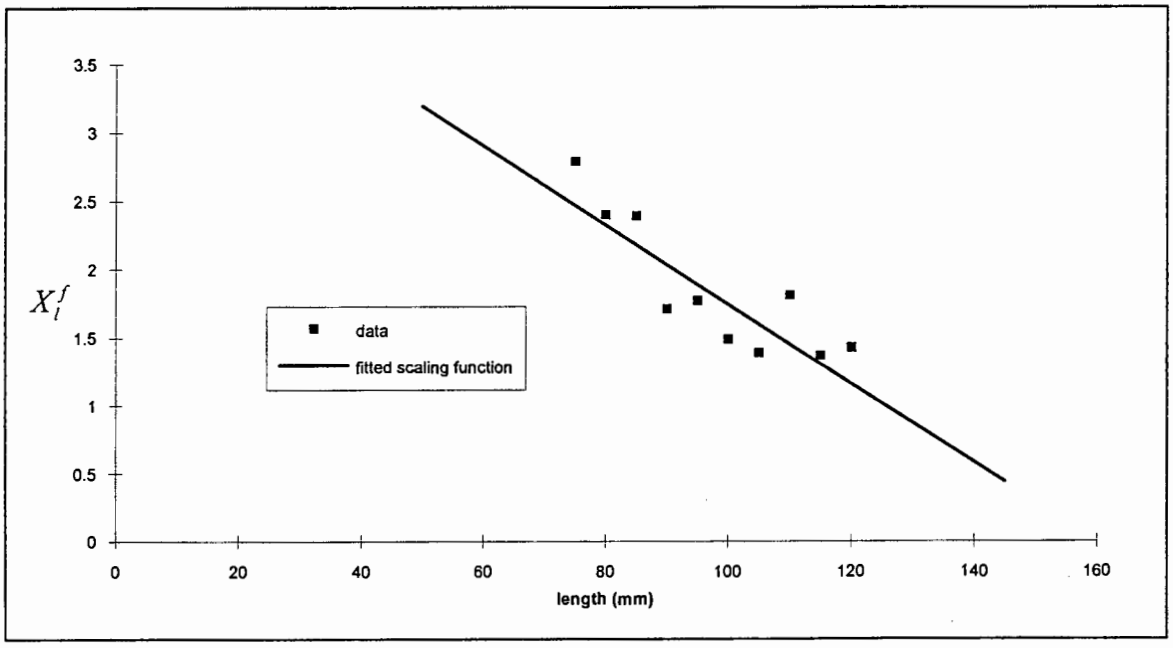


Figure A5.1b: Mean X_l^f values and the fitted scaling function.



Appendix 6: Bootstrap method for variance estimation

The parametric bootstrap procedure (Efron 1982, 1985) involves generating a number of bootstrap samples, B (B = 100 here), of pseudo-data. These pseudo-data are created by generating random errors from a parametric distribution, and adding these to the original model-estimated values obtained from fitting the model to true data. The parametric distribution has a variance equal to that of the residuals for the initial fit to true data.

The CPUE, catch-at-size and $F^{\%}$ data are treated separately.

A6.1 CPUE

The three CPUE data series (trap, hoopnet and FIMS) are treated in the same manner, except for the use of different standard deviation (σ) values:

$$CPUE_t^B = \widehat{CPUE}_t \, e^{\varepsilon_t} \qquad \varepsilon_t \sim \mathrm{N}(0;\sigma^2) \tag{A.6.1}$$

where

$CPUE_t^B$ is the pseudo CPUE value generated for year t and for bootstrap sample B,

$\widehat{CPUE}_t$ is the model-estimated CPUE value for year t obtained from the fit to observed data, and σ^2 is the variance of the CPUE residuals from the fit to observed data. The ε_t for each of the three series in any one year are assumed to be uncorrelated.

A6.2. Catch-at-size data

$$\left(n_{t,l}^{s}\right)^{B} = N_t^s \hat{p}_{t,l}^{s} + \varepsilon_t \qquad \varepsilon_t \sim \mathrm{N}(0;\, \sigma^2) \tag{A.6.2}$$

where

$\left(n_{t,l}^{s}\right)^{B}$ is the pseudo value of the number of lobsters of sex s in size class l in year t, for bootstrap sample B,

N_t^s is the sample size in year t for lobsters of sex s, and

$\hat{p}_{t,l}^{s}$ is the model-estimated catch size proportion (from the model fit to the observed data) for either lobsters of sex s.

σ^2 is the variance of the catch-at-size residuals from the fit to the observed data.

A6.3 Percentage females in the catch ($F^{\%}$) data

$$\left(F_t^{\%}\right)^{B} = \hat{F}_t^{\%} e^{\varepsilon_t} \qquad \varepsilon_t \sim \mathrm{N}(0;\sigma^2) \tag{A.6.3}$$

where

$\left(F_t^{\%}\right)^{B}$ is the pseudo $F^{\%}$ value generated for year t and for bootstrap sample B,

$\hat{F}_t^{\%}$ is the model-estimated $F^{\%}$ value for year t obtained from the fit to the observed data, and

σ^2 is the variance of the $F^{\%}$ residuals from the fit to the observed data.

Strictly, it could be argued that the downweighting of the earlier data points in equation A2.14 implies that the standard deviation associated with the residuals for these points should be increased. However, since this downweighting was *ad hoc* rather than

reflective of genuine lesser precision, this option was not pursued in the bootstrapping here, as the bootstrap results were in any case not considered realistic and hence not taken further. A more realistic bootstrap evaluation would need to take the serial correlation evident in the residuals into account.

Appendix 7: The candidate Operational Management Procedures

A7.1 The OMP computations

Refer to Figure 9.1 Chapter 9, where:

$$TAC_t^* = B_t \tan\theta \qquad \text{(A.7.1)}$$

$$= \frac{B_t}{B_{1996}} B_{1996} \tan\theta$$

where $\tan\theta = \frac{Y^Q_{ARMA'97}}{QB_{1996}}$. (A.7.2)

$Y^Q_{ARMA'97}$ is the sustainable yield at the target QB_{1996}, for an ARMA '97 somatic growth scenario, where, in this example, the target biomass increase factor Q, is 1.5 (reflecting a 50% increase).

To re-express in terms of measured quantities, Equation (A7.1) is modified to incorporate the two indices assumed proportional to biomass - CPUE and FIMS.

$\frac{B_t}{B_{1996}}$ is thus indexed by $\left(\frac{CPUE}{CPUE_{1996}}\right)^{\alpha}\left(\frac{FIMS}{FIMS_{1996}}\right)^{1-\alpha}$

The α value refers to the weight given to the CPUE relative to the FIMS data, and is set at a value of 0.50 in these OMP candidates. In order to help stabilise the TAC over time, the recent data is averaged over the last three years. Thus equation A.7.1 becomes:

$$TAC_t^* = \left(\frac{CPUE_{t-1,t-2,t-3}}{CPUE_{93,94,95}}\right)^{\alpha}\left(\frac{FIMS_{t-1,t-2,t-3}}{FIMS_{92,93,94,95}}\right)^{1-\alpha} B_{1996}\tan\theta$$

$$= \left(\frac{CPUE_{t-1,t-2,t-3}}{CPUE_{93,94,95}}\right)^{\alpha}\left(\frac{FIMS_{t-1,t-2,t-3}}{FIMS_{92,93,94,95}}\right)^{1-\alpha} \frac{Y^{Q}_{ARMA'97}}{Q} \qquad \text{(A.7.3)}$$

where $X_{t1..t2}$ is the arithmetic average of $X_{t1}, X_{t1+1} \ldots X_{t2}$.

CPUE reflects biomass above the minimum legal size (which changed to 75mm at the start of the 1993 season), hence the omission of the 1992 CPUE value from the average above as a higher minimum size applied that year. FIMS reflects biomass above 60mm. (Strictly the proportion pertinent to biomass > 75mm should be used to be consistent with Figure 9.1 (Chapter 9), but this exactitude was sacrificed in favour of the greater precision of the FIMS index over a wider size range.)

The algorithm needs to take into account the fact that the somatic growth rate in future may well deviate from the ARMA'97 (i.e. the value predicted for 1997 by the ARMA model for future somatic growth). Figure 9.2 (Chapter 9) illustrates how the sustainable yield function is effected by a change in the somatic growth rate. In Figure 9.2, sustainable yield curves for the "high" and "low" growth rate scenarios (see Appendix 3, section A3.6.2 for definitions) are compared. A correction factor must be built into the algorithm to make allowance for this each year. Equation (A.7.4) thus takes this allowance into account.

$$TAC_t^{*'} = TAC_t * \frac{Y_g^Q}{Y_{ARMA'97}^Q} \qquad \text{(A.7.4)}$$

where Y_g^Q is the sustainable yield at the target biomass level calculated for growth g, and is calculated as the arithmetic average over seasons t-1, t-2 and t-3. Given this adjustment, eventual attainment of the target biomass QB_{1996} is achieved whatever final somatic growth scenario eventuates (as distinct from the situation for equation (A.7.2) where this required growth remaining at the ARMA'97 prediction).

In order to allow flexibility in targets for the TAC in the short term (e.g. TAC(1997) and the level of recovery desired over the 10 year projection period), the algorithm is modified to include a number of tuning parameters: w, h and k.

The final algorithm is thus:

$$TAC_t = \max \begin{cases} wTAC_{t-1} + (1-w)TAC_t^{*'}\left[1 - h(t-1997)^{\gamma}\right]k \\ 0.85\ TAC_{t-1} \end{cases} \qquad \text{(A.7.5)}$$

The role played by these tuning parameters is as follows.

w: the weight given to the previous year's TAC (i.e. in relation to the updated calculation of equation A.7.4. The higher the value of w, the more slowly the TAC will change from year to year. The w value in these OMP candidates is 0.50.

h: a parameter which can be tuned to produce a given target biomass at the end of a 10 year period. The basic algorithm gets to the target only eventually, so that this adjustment is needed to get it there more quickly (in 10 years).

k: the parameter tuned to produce a specified expected 1997 TAC value. (This value is "expected" in the sense that it is the value that will result if CPUE, FIMS and somatic growth rate for the 1996 season reflect exactly the values predicted by the Base Case model used for the simulation tests.)

γ: a parameter which determines the "shape" of the TAC trajectory. A value of 0.5 was found to lead to smooth and usually monotonic trends.

A problem which may be encountered upon the implementation of the automated formulae of the OMP is that if indices reflect a deterioration in resource status, will the lower TACs indicated by the procedure be acceptable? For this reason, a maximum interannual TAC reduction constraint is imposed. Following earlier discussion with the industry and the SFAC, this value was set at 15%. This means that the TAC may not drop by more than 15% from one season to the next, except in "exceptional circumstances" (see Chapter 11).

For each target biomass increase and initial TAC value, the k and h values are tuned to produce these required results. The k and h values for the options considered for the OMP selection process by the SFAC in 1997 are listed in Table A7.1

For all these candidates then:

$\alpha = 0.5$

$w = 0.5$

$\gamma = 0.5$.

The $Y^{Q}_{ARMA'97}$ values (Equation A7.4) vary depending on the target level for biomass recovery, and for the candidates considered are:

$Y^{Q}_{ARMA'97}$ (for $Q = 1.2$) = 3292 MT

$Y^{Q}_{ARMA'97}$ (for $Q = 1.3$) = 3198 MT

$Y^{Q}_{ARMA'97}$ (for $Q = 1.4$) = 3092 MT

$Y^{Q}_{ARMA'97}$ (for $Q = 1.5$) = 2984 MT.

For each biomass recovery scenario, there is a different formula used for converting the observed growth rate in any year ($g = \beta_t^m$ - see Appendix 3) into the Y^{Q}_{g} value (the sustainable yield value for any growth g and for biomass recovery of Q). These formulae (for Y in '000 MT) are:

$$Y^{Q}_{g} = \beta_t^m 1.62 - 12.3 \qquad \text{for } Q = 1.2 \qquad \text{(A.7.6)}$$

$$Y^{Q}_{g} = \beta_t^m 1.69 - 13.0 \qquad \text{for } Q = 1.3 \qquad \text{(A.7.7)}$$

$$Y^{Q}_{g} = \beta_t^m 1.75 - 13.7 \qquad \text{for } Q = 1.4 \qquad \text{(A.7.8)}$$

$$Y^{Q}_{g} = \beta_t^m 1.91 - 15.4 \qquad \text{for } Q = 1.5 \qquad \text{(A.7.9)}$$

These formulae were defined by fitting a linear regression to sets of values of sustainable yields (at a cetain biomass level QB_{1996}) for a number of different somatic growth

levels (β_t^m).

A7.2 Summary performance statistics

The following summary statistics require some detailed definition.

i) C_{ave} - the average annual TAC over the 10 year projection period

$$C_{ave} = \frac{\sum_{t=1997}^{t=2006} C_t}{10}$$

ii) V - the average interannual catch variation

$$V = \frac{\sum_{t=1997}^{t=2006} \frac{|C_t - C_{t-1}|}{C_{t-1}}}{10}$$

where C_t is the TAC in year t.

Table A7.1: The k and h paramter values for a range of candidate OMPs.

Biomass increase over 10 years	**TAC'97=3% increase option**	**TAC'97=10% increase option**	**TAC'97=20% increase option**
20%	$k = 0.761$ $h = -0.043$	$k = 0.863$ $h = 0.021$	$k = 1.0066$ $h = 0.09$
30%	$k = 0.839$ $h = 0.026$	$k = 0.951$ $h = 0.08$	$k = 1.109$ $h = 0.140$
40%	$k = 0.945$ $h = 0.090$	$k = 1.071$ $h = 0.140$	$k = 1.248$ $h = 0.190$
50%	$k = 1.068$ $h = 0.155$	$k = 1.210$ $h = 0.195$	$k = 1.412$ $h = 0.240$

Glossary

Acronyms

ARMA	Autoregressive moving average model - used for calculating a future somatic growth rate scenario
ARMA'97	the somatic growth rate predicted by the ARMA model for 1997
CC	Constant Catch
CV	Coefficient of Variation
CPUE	Catch-Per-Unit-Effort
EC	Exceptional Circumstances
FIMS	Fisheries Independent Monitoring Survey
GLM	General Linear Model
GLM'95	GLM used to provide the somatic growth trend calculated in 1995
GLM'96	GLM used to provide the somatic growth trend calculated in 1996
MAC	Maximum Allowable Catch
MCDM	Multi Criteria Decision Making
MSY	Maximum Sustainable Yield
MT	Metric Ton
OMP	Operational Management Procedure
RLWG	Rock Lobster Working Group
SFAC	Sea Fisheries Advisory Council
SFRI	Sea Fisheries Research Institute
SY	Sustainable Yield
TAC	Total Allowable Catch

Symbols

A	identifies type of the data series used in the likelihood function
$A^s(t)$	the somatic growth matrix for lobsters of sex s over year t
B	the number of bootstrap samples
$B(06/96)$	the biomass (>75mm) at the start of 2006 divided by that at the start of 1996
B_t; $B_{75}(t)$	the biomass of male and female lobsters of length 75mm and larger in year t
$B_{75}^s(t)$	the biomass of lobsters of sex s and of length 75mm and larger in year t
$B^{sp}(t)$	the spawning biomass in year t
B^{MSY}	the biomass level at which MSY occurs
C_{ave}	the average annual catch over the 10 year projection period
$C_{a,t}$	the commercial catch in Area a in year t
C_t^{obs}	the total observed catch by weight in year t
C_t^{poach}	the level of poaching in year t
C_t^{rec}	the level of recreational catch in year t
$CPUE_t^A$	observed CPUE value for year t and series A
$\widehat{CPUE}_t^A$	model-estimated CPUE value for year t and series A
$CPUE_t^B$	the pseudo CPUE value generated for year t and for bootstrap sample B
$F^{\%}$	the percent females in the commercial catch (by number)
$F_t^{\%,A}$	observed percentage of females in the catch in year t and series A

$\hat{F}_t^{\%,A}$	model-estimated percentage of females in the catch in year t for data series A
$(F_t^{\%})^B$	the pseudo $F^{\%}$ value generated for year t and for bootstrap sample B
$F(t)$	the fishing mortality for fully selected lobsters in year t, which links the model-generated catches to the observed catches
F_{MSY}	the fishing mortality level at which MSY occurs
$H^s(t)$	the fishing survivorship matrix for lobsters of sex s over year t
I	the unit matrix (used in calculating equilibrium population structure)
$-\ln L$	the negative of the log of the likelihood function
N_{bad}	the proportion of years a "bad event" is estimated to occur
$N^s(t)$	vector of numbers-at-size of lobsters of sex s at the start of year t
$N_l^s(t)$	the number of lobsters of sex s and length l at the start of year t
N^{s*}	the vector of numbers-at-size of lobsters of sex s at equilibrium
$N_t^{A,s}$	catch-at-size sample size for sex s in year t and data series A
P_{max}	the maximum level of poaching (assumed to be reached in 1990)
P_1	female trap selectivity parameter corresponding to the length l where selectivity drops to zero
P_2	female trap selectivity parameter - scaling factor
Q	the target biomass increase factor
$R(t+1)$	the recruitment vector for year t+1
R_1	initial (pristine) recruitment level
R_2	current recruitment level for the 1950+ period
R_2*	current recruitment as a proportion of R_1
$R_l^s(t)$	recruitment of lobsters of sex s to length l in year t

S^s	the diagonal annual natural survivorship matrix for lobsters of sex s
S_l^s	the annual natural survivorship of lobsters of sex s and of length l
S^m	the maximum male annual natural survivorship
S^f	the maximum female annual natural survivorship
SD(p)	the standard deviation of the inter-moult period for juveniles
SD(Δg)	the standard deviation of the inter-moult growth increment for juveniles
TAC'97	the OMP predicted TAC for 1997
TAC'98	the OMP predicted TAC for 1998
TAC'06	the OMP predicted TAC for 2006
TAC_t^*	the TAC in year t predicted by the OMP, prior to adjustment for somatic growth variation
$TAC_t^{*'}$	the TAC in year t predicted by the OMP, after adjusting for somatic growth
TAC_t	the final TAC prediction from the OMP for year t
V	the proportional average annual catch variation over the 10 year projection period
W_e	relates to the weighting applied to the catch-at-size data in the likelihood
X	the proportion the indicated OMP TAC predicted value must be decreased by for the EC rule
X_l^s	scaling factor for lobsters of sex s and for length l, which is used to multiply the trap selectivity to obtain the hoopnet selectivity

$Y^{Q}_{ARMA'97}$	the sustainable yield at the target QB_{1996} for an ARMA'97 somatic growth scenario
Y^{Q}_{g}	the sustainable yield at the target biomass level calculated for growth g
a	refers to one of the eight fishing Areas
$a^{s}_{t}(i, j)$	the proportion of lobsters (of either sex) in length class i that move into length class j during the moult at the end of year t
$b^{s,sel}_{l}$	denotes the form of selectivity of lobsters of sex s and length l
$b^{s,trap}_{l}$	the trap selectivity of lobsters of sex s and length l
$b^{s,hoop}_{l}$	the hoopnet selectivity of lobsters of sex s and length l
$c^{h,s}_{l,a,t}$	the hoopnet catch size proportion for length l in Area a in year t for lobsters of sex s
$c^{t,s}_{l,a,t}$	the trap catch size proportion for length l in Area a in year t for lobsters of sex s
d	the discard mortality
$d_{l}(t)$	the discard mortality for lobsters of length l in year t
f	superscript/subscript referring to females
$g^{s}_{l,t}$	the mean annual moult increment for lobsters of sex s and length l in year t
$g^{s}_{l,t,a}$	the mean annual moult increment for lobsters of sex s and length l in year t and in Area a
$g^{juv}_{l,t}$	the mean inter-moult growth increment for a juvenile lobster of length l in year t

h	parameter of the OMP TAC setting equation A.7.5
k	parameter of the OMP TAC setting equation A.7.5
l	length in mm (usually used as a subscript)
l_{max}	largest length/size class in model (180mm)
$l_{\min}$	the minimum legal carapace length for harvesting
l_0	length below which gear selectivity is zero
l^*	length above which gear selectivity is assumed to be constant
$l^s_{\infty,t}$	the length at which growth becomes zero for male or female lobsters in year t
m	superscript/subscript referring to males
$n^s_{l,a,t}$	the sample catch-at-size number for length l in year t in Area a for sex s
$(n^s_{t,l})^B$	the pseudo value of the number of lobsters of sex s and length l in year t for bootstrap sample B
n^s_t	the catch-at-size sample size in year t for lobsters of sex s
n^{s*}_l	the number of lobsters of sex s and length l in the equilibrium population
n^A_{cpue}	numbers of years of CPUE data for series A
n^A_{size}	number of catch size proportions that are used in the likelihood for series A
$n^A_{F^{\%}}$	number of years of $F^{\%}$ data used in the likelihood for series A
$\sqrt{n_e}$	the expected value of the catch-at-size $\sqrt{N^{A,s}_t \hat{p}^{A,s}_{t,l}}$
$\sqrt{n_o}$	the observed value of the catch-at-size $\sqrt{N^{A,s}_t p^{A,s}_{t,l}}$

$p_{t,l}^{A,s}$	observed catch-at-size proportion for lobsters of sex s and size l in year t for data series A
$\hat{p}_{t,l}^{A,s}$	model-estimated catch-at-size proportion for lobsters of sex s and size l in year t for data series A
$p_l^s(t)$	the proportion of lobsters of sex s and caught during year t that have length l
p_l	the inter-moult period in days for juvenile lobsters of length l
q^A	the catchability coefficient estimated for CPUE series A
s	superscript referring to either sex (male or female)
t	refers to the year t (strictly the season starting in November of year t and ending typically in June of year t+1.
t1, t2, t3, t4	statistics relating to the performance of the EC rule
w	parameter of the OMP TAC setting equation A.7.5
w_l^s	the body weight (in grams) of lobsters of sex s and length l (in cm)
w_t	the annual weighting factor used in the likelihood function
$x_{l,a,t}^s$	the scaling factor for calculating hoopnet selectivities for lobsters of length l and sex s in Area a in year t
y^*	the year at which recruitment starts to decline
$\beta_{t,a}^s$	the mean moult increment of a 1mm male or female lobster in year t and in Area a
β_t^s	the mean moult increment of a 1mm male or female lobster in year t
β_0^s	a constant in the equation for calculating $g_{l,t,a}^s$

γ_t^s	the year effect in the equation for calculating $g_{l,t,a}^s$
δ_a^s	the Area effect in the equation for calculating $g_{l,t,a}^s$
γ	a parameter of the OMP TAC setting equation A.7.5
$\bar{\gamma}$	a parameter used in defining the function for the EC rule
Δ	a parameter used in defining the function for the EC rule
$\Delta g_{l,t}^{juv}$	the inter-moult growth increment of a juvenile lobster of length l in year t
$\tau_{l,t}^{juv}$	the scaling factor used for length l in year t to calculated the juvenile growth moult increment from that of a male lobster in year t
σ_l^s	the standard deviation of the moult increment for lobsters of sex s and length l
σ_p	the standard deviation of the inter-moult period for juveniles
σ_{cpue}^A	the σ estimated for the CPUE residuals for CPUE series A
σ_{size}^A	the σ estimated for the catch-at-size residuals for data series A
$\sigma_{F^{\%}}^A$	the σ estimated for the $F^{\%}$ residuals for data series A

References

Acheson, J.M. and R. Reidman. 1982. Biological and economic effects of increasing the minimum legal size of American lobster in Maine. *Trans. Am. Fish. Soc.* 3(1): 1-12.

Addison, J.T. 1986. Density-dependent mortality and the relationship between size composition and fishing effort in lobster populations. *Can. J. Fish. Aquat. Sci.* 43: 2360-2367.

Aiken, D.E. and S.L. Waddy. 1986. Environmental influence on recruitment of the American lobster, *Homarus americanus*: a perspective. *Can. J. Fish. Aquat. Sci.* 43: 2258-2270.

Annala, J.H. 1983. New Zealand Rock lobsters: Biology and fishery. Fisheries research division, New Zealand, Occasional Publication No. 42., 36pp.

Annala, J.H. and P.A. Breen. 1989. Yield- and egg-per-recruit analyses for the New Zealand rock lobster, *Jasus edwardsii. N. Z. J. Mar. Freshwat. Res.* 23: 93-105.

Annala, J.H. and D.B. Esterman. 1986. Yield estimates for the New Zealand rock lobster fishery. In Jamieson, G.S. and N. Bourne (eds): North Pacific workshop on stock assessment and management of invertebrates. *Can. Spec. Publ. Fish. Aquat. Sci.* 92: 347-358.

Annala, J.H. and. K.J. Sullivan. 1997. Management strategies in lobster fisheries:report from a workshop. *Mar. Freshwater Res.* 48: 1081-1083.

Anon. 1994. Updates to the management procedures for South African anchovy and pilchard. Sea Fisheries Research Institute (Cape Town) document WG/JAN94/PEL/3: 9pp.

Anon. 1997. White Paper. A marine fisheries policy for South Africa. Unpublished Report, Sea Fisheries, South Africa, 46pp.

Baranov, F.I. 1918. On the question of the biological basis of fisheries. Nauch Issled. Ikhtiol Inst. Izv. 1(1): 81-128. (In Russian)

Bannister, R.C.A. 1986. Assessment and population dynamics of commercially exploited shellfish in England and Wales. In G.S. Jamieson and N.Bourne (eds): North Pacific Workshop on stock assessment and management of invertebrates. *Can. Spec. Publ. Fish. Aquat. Sci.* 92: 182-194

Bannister, R.C.A. and. J.J. Addison. 1984. The effect on yield and biomass per recruit of changes in fishing mortality and size at first capture in the fisheries for lobster, *Hommarus gammarus* L., in England and Wales. ICES C.M. 1984/K:10. (Mimeo)

Bannister, R.C.A. and J.J. Addison. 1986. Effect of assumptions about the stock-recruitment relationship on a lobster (*Homarus gammarus*) stock assessment. *Can. J. Fish. Aquat. Sci.* 43(11): 2353-2359.

Barkai, A. and M.O. Bergh. 1990. Final report of the Zone A 30 MT diving experiment. Sea Fisheries Research Institute (Cape Town) document WG/06/90/WCL1. 75pp.

Barkai, A. and M.O. Bergh. 1992. A new management strategy for optimal utilisation of the South African Cape rock lobster (*Jasus lalandii*) resource. Sea Fisheries Research Institute (Cape Town) document WG/01/92 WCL1. 89pp.

Bergh, M.O. 1990. Consideration of a bioeconomically sensible minimum carapace length for the West Coast rock lobster resource. Sea Fisheries Research Institute (Cape Town) document WG/11/90/WCL1. 37pp.

Bergh, M.O. 1991. Rock lobster natural mortality estimates obtained from the Saldanha Bay and Robben Island sanctuary population size frequency distributions. Sea Fisheries Research Institute (Cape Town) document WG/06/91/WCL1. 31pp.

Bergh, M.O. and S.J. Johnston. 1991. Lobster resource projections at Dassen Island at different moult increment and catch levels. Sea Fisheries Research Institute (Cape Town) document WG/07/91/WCL1. 40pp.

Bergh, M.O. and S.J. Johnston. 1992. A size-structured model for renewable resource management with application to rock lobster resources in the Southeast Atlantic. *S. Afr. J. mar. Sci.* 12:1005 - 1016.

Bergh, M.O. and A. Barkai. 1991. Further aspects of the proposed revision of the minimum size and TAC for west coast rock lobster raised in WG/09/91/WCL2. Sea Fisheries Research Institute (Cape Town) document WG/09/91/WCL3. 3pp.

Bergh, M.O. and A. Barkai. 1992. Investigations into possible implications of minimum size relief measures in the 1991/92 fishing season for future harvesting options for the west coast rock lobster resource. Sea Fisheries Research Institute (Cape Town) document WG/02/92/WCL1. 16pp.

Bergh, M.O. and A. Barkai. 1994. The status and productivity of the west coast rock lobster resource and bioeconomic scenarios under different harvesting policies for the 1994/95 fishing season. Sea Fisheries Research Institute (Cape Town) document WG/06/94/WCL1. 65pp.

Bergh, M.O. and A. Barkai. 1995. Use of a modified Fox model to compare the performance of the west coast rock lobster resource under either a step-wise TAC reduction scheme or a constant catch level over the next 5 years. Sea Fisheries Research Institute (Cape Town) document WG/10/95/WCL3. 16pp.

Berry, P.F. 1971. The biology of the spiny lobster *Panulirus homarus* (Linnaeus) off the east coast of southern Africa. *Investl Rep. Sea Fish. Brch S. Afr.* 117:26pp.

Beverton, R.J.H. and S.J. Holt. 1957. On the dynamics of exploited fish populations. *Fish. Invest.* (London) 19: 1-533.

Beyers, C.J. de B. and P.C. Goosen. 1987. Variations in fecundity and size at sexual maturity of female rock lobster *Jasus lalandii* in the Benguela ecosystem. *S. Afr. J. mar. Sci.* 5: 513-521.

Beyers, C.J. de B. and C.G. Wilke. 1990. The biology, availability and exploitation of rock lobster *Jasus lalandii* off South West Africa/Namibia 1970-1980. *Rep. Sea Fish. Res. inst. S. Afr.* 133: 1-56

Booth, J.D. and P.A. Breen. The New Zealand fishery for *Jasus edwardsii* and *Jasus verreauxi*. In Phillips, B.F., Cobb, J.S. and J. Kittaka (eds): Spiny Lobster Management, pp 64-75. Blackwell Scientific,Oxford.

Botsford, L.W. 1984. Effect of individual growth rates on expected behaviour of the Northern Dungeness crab (*Cancer magister*) fishery. *Can. J. Fish. Aquat. Sci.* 41: 99-107.

Bosford, L.W. 1986. Effects of environmental forcing on age-structured populations: northern California Dungeness crab (*Cancer magister*) as an example. *Can. J. Fish. Aqaut. Sci.* 43(11): 2345-2352.

Botsford, L.W. and. D.E. Wickam. 1978. Behaviour of age-specific, density dependent models and the northern California Dungeness crab (*Cancer magister*) fishery. *J. Fish. Res. Bd Can.* 35: 833-834.

Brander, K.M. and D.B. Bennett. 1989. Norway lobster in the Irish Sea: Modelling one component of a multispecies resource. In Caddy, J.F. (ed.): Marine Invertebrate Fisheries: Their assessment and Management. Ch.8.

Branford, J.R. 1979. Locomotor activity and food consumption by the lobster *Homarus gammarus*. *Marine Behaviour and Physiology* 6: 13-24.

Breen, P.A. and T.H. Kendrick. 1997. Production analyses for two substocks of the New Zealand red rock lobster (*Jasus edwardsii*) fishery. New Zealand Fisheries Assessment Research Document No. 97/4. 21 pp.

Brown, J. 1996a. Growth analysis of the west coast rock lobster. Sea Fisheries Research Institute (Cape Town) document WG/05/96/WCL10. 14pp.

Brown, J. 1996b. Updated GLM analysis applied to the west coast bakkie and hoopnet data to determine a combined index of abundance. Sea Fisheries Research Institute (Cape Town) document WG/07/96/WCL22. 2pp.

Brown, J. 1997a. Updated growth analysis of the west coast rock lobster. Sea Fisheries Research Institute (Cape Town) document WG/06/97/WCL20. 6pp.

Brown, J. 1997b. A combined index of abundance for the west coast rock lobster resource derived from a GLM analysis of trap, bakkie and deckboat CPUE data. Sea Fisheries Research Institute (Cape Town) document WG/05/97/WCL15. 8pp.

Brown, J. 1997c. Data used in the 1997/98 West Coast Rock Lobster assessment. Sea Fisheries Research Institute (Cape Town) document WG/07/97/WCL28. 3pp.

Brown, R.S. and N. Caputi. 1983. Factors affecting the recapture of undersize western rock lobster *Panulirus cygnus* George returned by fishermen to the sea. *Fish. Res.* 2: 103-128.

Brown, R.S. and N. Caputi. 1985. Factors affecting the growth of undersize western rock lobster, *Panulirus cygnus* George, returned by fishermen to the sea. *Fishery Bull.*, Wash. 83(4): 567-574.

Brown, R.S. and N. Caputi. 1986. Conservation of recruitment of the western rock lobster (*Panulirus cygnus*) by improving survival and growth of undersize rock lobsters captured and returned to the sea. *Can. J. Fish. Aquat. Sci.* 43(11): 2236-2242.

Butterworth, D.S. and M.O. Bergh. 1993. The development of a management procedure for the South African anchovy resource. In Smith, S.J., J.J. Hunt and D. Rivard. (eds): Risk Evaluation and Biological Reference Points for Fisheries Management. *Can. Spec. Publ. Fish. Aquat. Sci.* 120: 83-99.

Butterworth, D.S., Cochrane, K.L. and J.A.A. De Oliveira. 1997. Management procedures: a better way to manage fisheries? The South African experience. In Global trends: Fisheries management. Pikitch, E.K., Huppert, D.D. and M.P. Sissenwine (eds): American Fisheries Society Symposium 20, Bethesda, Maryland: 83-90.

Caddy, J.F. 1977. Approaches to a simplified yield-per-recruit model for Crustacea, with particular reference to the American lobster, *Homarus americanus*. *Fish. Mar. Serv. Ms. Rep.* 1445: 14pp.

Caddy, J.F. 1979. Notes on a more generalised yield-per-recruit analysis for crustaceans using size-specific inputs. *Fish. Mar. Serv. Ms. Rep.* 1525: 10pp.

Caddy, J.F. 1986. Modelling stock-recruitment processes in Crustacea: some practical and theoretical perspectives. *Can. J. Fish. Aquat. Sci.* 43: 2330-2344.

Caddy, J.F. 1987. Size-frequency analysis for Crustacea: moult increment and frequency models for stock assessment. *Kuwait Bull. Mar. Sci.* 9: 43-61.

Campbell, A. 1980. Application of a yield and egg-per-recruit model of the lobster fishery in the Bay of Fundy. *N. Am. Fish. Manage.* 5: 91-104.

Campbell, A. 1985. Application of a yield and egg-per-recruit model to the lobster fishery in the Bay of Fundy. *N. Amer. J. Fish. Manage.* 5: 91-194.

Campbell, A. 1989. The lobster fishery of South-western Nova Scotia and the Bay of Fundy. In J.F. Caddy (ed.): Marine Invertebrate Fisheries: Their assessments and management, John Wiley and Sons. pp 141-158.

Campbell, A., Noakes, D.J. and R.W. Elner. 1991. Temperature and lobster, *Homarus americanus*, yield relationships. *Can. J. Fish. Aquat. Sci.* 48: 2073-2082.

Caputi, N and Brown, R.S. 1993. The effect of environment on puerulus settlement of the western rock lobster (*Panulirus cygnus*) in Australia. *Fisheries and Oceanography* 2: 1-10.

Caputi, N, Chubb, C.F. and Brown, R.S. 1995. Relationship between spawning stock, environment, recruitment and fishing effort for the western rock lobster, *Panulirus cygnus*, fishery in Western Australis. *Crustaceana* 68: 213-226.

Caputi, N. and R.S. Brown. 1986. Relationship between indices of juvenile abundance and recruitment in the western rock lobster (*Panulirus cygnus*) fishery. *Can. J. Fish. Aquat. Sci.* 43: 2131-2139.

Chittleborough, R.G. 1970. Studies on recruitment in the western Australian rock lobster *Panulirus longipes cygnus* George: density and natural mortality of juveniles. *Aust. J. mar. Freshwat. Res.* 21: 131-148.

Chittleborough, R.G. 1975. Environmental factors affecting growth and survival of juvenile western rock lobsters *Panulirus longipes* (Milne-Edwards). *Aust. J. mar. Freshwat. Res.* 26: 177-196.

Clarke, E.D., Butterworth, D.S. and S.J. Johnston. 1996. ARMA Estimation and Projection. Sea Fisheries Research Institute (Cape Town) document WG/07/96/WCL25. 5pp.

Cochrane, K.L., Butterworth, D.S. and A.I.L. Payne. 1997. South Africa's offshore living marine resources: the scientific basis for management of the fisheries. *Proc. Roy. Soc. Sth. Afr.* 52(1): 149-176.

Cochrane, K.L., Butterworth, D.S., De Oliveira, J.A.A. and B.A. Roel. 1998. Management procedures in a fishery based on highly variable stocks and with conflicting objectives: experiences in the South African pelagic fishery. *Rev. Fish. Biol. and Fisheries* 8: 177-214.

Cockcroft, A.C. and P.C. Goosen. 1995. Shrinkage at moulting in the spiny lobster *Jasus lalandii* and associated changes in reproductive parameters. *S. Afr. J. mar. Sci.* 16:195-203.

Cockcroft, A.C. 1997. Biochemical composition as a growth predictor in male west coast rock lobster (*Jasus lalandii*). *Mar. Freshwater Res.* 48:845-856.

Cobb, J.S. and J.F. Caddy. 1989. The population biology of decapods. In J.F. Caddy (ed.): Marine invertebrate fisheries: Their assessment and management. pp 327-374.

Cruywagen, G.C. 1995a. West coast rock lobster CPUE series. Sea Fisheries Research Institute (Cape Town) document WG/04/95/WCL2. 5pp.

Cruywagen, G.C. 1995b. Modelling seasonal and spatial variation of growth in size. Sea Fisheries Research Institute (Cape Town) document WG/06/95/WCL1b. 23pp.

Cruywagen, G.C. and K.L Cochrane. 1994. Calculating the pristine biomass and the 1994/95 replacement yields for the west coast rock lobster. Sea Fisheries Research Institute (Cape Town) document WG/06/94/WCL1a. 15pp.

Davies, N.M. 1992. A comparison of the performance of size-structured and surplus-production estimates for the assessment of the South African west coast rock lobster resource. M.Sc. thesis, Department of Zoology, University of Cape Town. 101pp.

Davis, G.E. 1980. Effects of injuries on spiny lobster, *Panulirus argus*, and implications for fishery management. *Fishery Bull., Wash.* 78(4): 979-984.

Davis, G.E. 1981. Effects of injuries on spiny lobster, *Panulirus argus*, and implications for fishery management. *Fish. Bull.* 78(4): 979-984.

Davis, G.E. and J.W. Dodrill. 1980. Marine parks and sanctuaries for spiny lobster fisheries management. *Proc. Gulf. Caribb. Fish. Inst.* 32: 194-207.

De Oliveira, J.A.A. 1994. Background: Exceptional Circumstances. Sea Fisheries Research Institute (Cape Town) document WG/JAN94/PEL/4. 9pp.

De Oliveira, J.A.A. 1995. Assessment and management of the South African anchovy resource. M.Sc. thesis, Department of Applied Mathematics, University of Cape Town.

De Oliveira, J.A.A., Butterworth, D.S. and S.J. Johnston. 1998. Progress and problems in the application of management procedures to South Africa's major fisheries. (in press).

Dow, R.L. 1969. Cyclic and geographic trends in seawater temperature and abundance of American lobster. *Science* 164: 1060-1063.

Dow, R.L. 1977. Relationship of sea surface temperature to American and European lobster landings. *J. Cons. Int. Explor. Mer.* 36: 186-191.

Eekhout, A., Raubenheimer, C.M., Branch, G.M., Bosman, A.L. and M.O. Bergh. 1992. A holistic approach to the exploitation of intertidal stocks: limpets as a case study. In Benguela Trophic Functioning. Payne, A.I.L., Brink, K.H., Mann, K.H. and R. Hilborn (eds): *S. Afr. J. mar. Sci.* 12: 1017-1029.

Efron, B. 1982. The jacknife, the bootstrap and other resampling plans. Society of Industrial and Applied Mathematics, Philadelphia. 92pp.

Efron, B. 1985. Bootstrap confidence intervals for a class of parametric problems. *Biometrika* 72(1): 45-48.

Ennis, G.P. 1978. Growth curves for Newfoundland lobsters from data on moult increment and proportion moulting. Canadian Atlantic Fisheries Scientific Advisory Committee, Research Document 78/29/ Dartmouth, Nova Scotia.

Ennis, G.P. 1985. An assessment of the impact of size limit and exploitation rate changes on egg production in a Newfoundland lobster population. *N. Amer. J. Fish. Manage.* 5: 86-90.

Ennis, G.P. 1986. Stock definition, recruitment variability, and larval recruitment processes in the American lobster, *Homarus americanus*: A review. *Can. J. Fish. Aquat. Sci.* 43: 2072-2084.

Ennis, G.P. 1980. Canadian efforts to assess yield per recruit in lobsters. *Can. Tech. Rep. Fish. Aquat. Sci.* 932: 45-48.

Ennis, G.P. and M.J. Fogarty. 1997. Recruitment overfishing reference point for the Amercian lobster, *Homarus americanus*. Mar. Freshwater Res. 48: 1029-1034.

FAO. 1995. Code of conduct for responsible fisheries. FAO, Rome. 41 pp.

Flowers, J.M. and S.B. Saila. 1972. An analysis of temperature effects on the inshore lobster fishery. *J. Fish. Res. Board Can.* 29: 1221-1225.

Fogarty, M.J. 1980. Assessment of yield-per-recruit for the American lobster (*Homarus americanus*). *Can. Tech. Rep. Fish. Aquat. Sci.* 932: 37-44.

Fogarty, M.J. 1988. Time series of the Maine lobster fishery: the effect of temperature. *Can. J. Fish. Aquat. Sci.* 45: 1145-1153.

Fogarty, M.J. 1995. Populations, fisheries and management. In J.R. Factor (ed.). Biology of the American lobster (*Homarus americanus*). pp 111-137. Academic press, New York.

Fogarty, M.J. and J.S. Idoine. 1986. Recruitment dynamics in an American lobster (*Homarus americanus*) population. *Can. J. Fish. Aquat. Sci.* 43: 2263-2376.

Fogarty, M.J. and J.S. Idoine. 1988. Application of a yield and egg production model based on size to an offshore American lobster population. *Trans. Am. Fish. Soc.* 117: 350-362.

Fogarty, M.J. and S.A. Murawski. 1986. Population dynamics and assessment of exploited invertebrate stocks. In Jamieson, G.S. and N. Bourne. (eds): North Pacific Workshop on stock assessment and management of invertebrates. *Can. Spec. Publ. Fish. Aquat. Sci.* 92: 228-244.

Fournier, D.A. and P.A. Breen. 1983. Estimation of abalone mortality rates with growth analysis. *Trans. Amer. Fish. Soc.* 112: 403-411.

Frusher, S.D. 1996. The 1995/96 rock lobster season: a temporary reprieve or signs of recovery ? *Fishing Today* 9: 27-29.

Garcia, S.M. and C. Newton. 1997. Current situation, trends, and prospects in world capture fisheries. In E.K. Pikith, D.D. Huppert and M.P. Sissenwine (eds): Global Trends: Fisheries Management. American Fisheries Society Symposium 20, Bethesda, Maryland. pp 2-27.

Goodwin, P. and G. Wright. 1991. Decision analysis for management judgement. John Wiley & Sons, Chichester.

Gregory, D.R., Labisky, R.F. and C.L.Coombs. 1982. Reproductive dynamics of the spiny lobster *Panulirus argus* in South Florida. *Trans. Am. Fish. Soc.* 3(5): 575-584.

Griffiths, C.L. and J.L. Seiderer. 1980. Rock-lobsters and mussels - limitations and preferences in a predator-prey interaction. *J. exp. mar. Biol. Ecol.* 44(1): 95-109.

Gilchrist, J.D.E. 1913. The Cape crawfish and crawfish industry. *Mar. Biol. Rep.* I: 1-42.

Gilchrist, J.D.E. 1914. The Cape crawfish and crawfish industry (continued). *Mar. Biol. Rep.* II: 36-74.

Gilchrist, J.D.E. 1918. Crawfish investigations including experimental hauls, artificial rearing and migratory movements of the Cape crawfish. *Mar. Biol. Rep.* IV: 1-44.

Goosen, P.C. and A.C. Cockcroft. 1995. Mean annual growth rates for male west coast rock lobster - a 25 year record (1969/80 - 1993/94) reviewed. *S. Afr. J. mar. Sci.* 16:377-386.

Gulland, J.A. 1987. Length-based methods in fisheries research: from theory to application. In Pauly, D. and G.R. Morgan (eds): Length-based methods in fisheries research. ICLARM Conference Proceedings 13, 468 p. International Center for Living Aquatic Resources Management, Manila, Philippines, and Kuwait Institute for Scientific Research, Safat, Kuwait.

Hall, N.G. 1997. Delay-difference model to estimate the catch of different categories of the western rock lobster (*Panulirus cygnus*) for the two stages of the annual fishing season. *Mar. Freshwater Res.* 48: 949-958.

Harding, G.C, Drinkwater, K.F. and W.P. Vass. 1983. Factors influencing the size of American lobster (*Homarus americanus*) stocks along the Atlantic coast of Nova Scotia, Gulf of St. Lawrence, and Gulf of Maine: A new synthesis. *Can J. Fish. Aquat. Sci.* 40: 168-184.

Hepper, B.T. 1972. The growth at moulting of lobsters, *Homarus vulgaris* Milne-Edwards, in the Menai Straits, North Wales. *J. Cons. int. Explor. Mer.* 34(2): 169-173.

Heydorn, A.E.F. 1965. The rock lobster of the South African West Coast, *Jasus lalandii*, (H. Milne-Edwards). 1: Notes on the reproductive biology and the determination of minimum size limits for commercial catches. *Invest. Rep. Div. Sea. Fish. S. Afr.* 53: 1-32.

Heydorn, A.E.F. 1968. The rock lobster of the South African West coast *Jasus lalandii* (H. Milne-Edwards). 2. Population studies, behaviour, reproduction, moulting, growth and migration. *Invest. Rep. Div. Sea. Fish. S. Afr.* 71: 52pp.

Heydorn, A.E.F. 1969a. The rock lobster of the South African west coast, *Jasus lalandii* (H. Milne-Edwards). *Invest. Rep. Div. Sea. Fish. S. Afr.* 71: 28-31.

Heydorn, A.E.F. 1969b. The South Atlantic rock-lobster *Jasus lalandii* at Vema Seamount, Gough Island and Tristan da Cunha. Invest. *Rep. Div. Sea. Fish. S. Afr.* 73: 20pp.

Heydorn, A.E.F. 1969c. Notes on the biology of *Panulirus homarus* and on length/weight relationships of *Jasus lalandii*. *Invest. Rep. Div. Sea. Fish. S. Afr.* 69: 1-27.

Hunt, J.H., Lyons, W.G. and F.S. Kennedy. 1986. Effects of exposure and confinement on spiny lobsters, *Panulirus argus*, used as attractants in the Florida trap fishery. *Fishery Bull, Wash.* 84(1): 69-76.

Hunt, J.H. and W.G. Lyons. 1986. Factors affecting growth and maturation of spiny lobsters, *Panulirus argus*, in the Florida Keys. *Can J. Fish. aquat. Sci.* 43(11): 2243-2247.

IWC. 1992. Report of the Scientific Committee, Reykjavik, May 1991. *Rep. int. Whal. Commn* 42: 51-79.

IWC. 1994. Report of the Sub-Committee on management procedures. *Rep. int. Whal. Commn* 44: 74-92.

Jensen, A.L. 1986. Assessment of the Maine lobster fishery with surplus production models. *N. Amer. J. Fisheries. Man.* 6: 63-68.

Johnston, S.J. 1991. Natural survivorship estimates for the west coast rock lobster *Jasus lalandii* obtained using a size-based modelling approach. M.Sc thesis, Department of Zoology, University of Cape Town. 68pp.

Johnston, S.J. 1995. Base case model: assumptions and data. Sea Fisheries Research Institute (Cape Town) document WG/10/95/WCL1. 23 pp.

Johnston, S.J. and M.O. Bergh. 1993. Size-based estimates of survivorship for the South African rock lobster *Jasus lalandii*. *Fish. Res.* 18: 277-304.

Johnston, S.J. and M.O. Bergh. 1992. Egg production analyses for the southern grounds of the *Jasus lalandii* fishery. Sea Fisheries Research Institute (Cape Town) document WG/06/92/WCL1. 47pp.

Johnston, S.J. and M.O. Bergh. 1994. Estimates of the sustainable yield and current status of sub-stocks of west coast rock lobster. Sea Fisheries Research Institute (Cape Town) document WG/06/94/WCL6. 41pp.

Jones, R. 1974. Assessing the long term effects of changes in fishing effort and mesh size from length composition data. ICES C.M. 1974/F:33. (Mimeo.)

Jones, R. 1979. An analysis of a Nephrops stock using length composition data. *Rapp. P.-V. Reun. Cons. Int. Explor. Mer.* 175: 259-269.

Jones, R. 1981. The use of length composition data in fish stock assessments (with notes on VPA and cohort analysis). *FAO Fish. Circ.* 734: 55p.

Jones, R. 1984. Assessing the effects of changes in exploitation pattern using length composition data (with notes on VPA and cohort analysis). *FAO Fish. Tech. Pap.* No. 256: 188pp.

Kirkwood, G.P. 1992. Background to the development of revised management procedures. *Rept. int. Whal. Commn* 42: 236-243.

Kirkwood, G.P. 1997. The revised management procedure of the international whaling committee. In E.K. Pikitch, D.D. Huppert and M.P. Sissenwine (eds): Global Trends: Fisheries management. American Fisheries Society Symposium 20, Bethesda, Maryland, pp 91-99.

Lai, H.L. and V.F. Gallucci. 1987. Effect of variability on estimates of cohort parameters using length-cohort analysis: with a guide to its use and mis-use. Fish. Stock Assess. Title XII CRSP Tech. Rep. 2: CQS, School of Fisheries, University of Washington, Seattle, WA. 70pp.

Lai, H.L. and V.F. Gallucci. 1988. Effects of parameter variability on length cohort analysis. *J. Cons. Int. Explor. Mer.* 45: 82-92.

Lefkovitch, L.P. 1965. The study of population growth in organisms grouped by stages. *Biometrics* 21: 1-18.

Leslie, P.H. 1945. The use of matrices in certain population mathematics. *Biometrics* 33: 188-212.

Leslie, P.H. 1948. Some further notes on the use of matrices in population mathematics. *Biometrika* 35: 213-245.

Lyons, W.G. 1986. Problems and perspectives regarding recruitment of Spiny lobsters, *Panulirus argus*, to the South Florida Fishery. *Can. J. Fish. Aquat. Sci.* 43: 2099-2106.

Lyons, W.G. and F.S. Kennedy. 1981. Effects of harvest techniques on sublegal spiny lobsters and on subsequent fishery yield. Proc. *Gulf Carib. Fish. Inst.* 33: 290-300.

Moloney, C.L. 1998. Preliminary use of decision analysis procedures to choose among OMPs. Sea Fisheries Research Institute (Cape Town) document WG/02/98/WCL3. 3 pp.

Marchessault, G.D., Saila, S.B. and W.J. Palm. 1976. Delayed recruitment models and their application to the American lobster (*Homarus americanus*) fishery. *J. Fish. Res. Board Can.* 33: 1779-1789.

Mayfield, S. 1998. Assessment of the diet of the west coast rock lobster (*Jasus lalandii*): relationships between growth rate, diet and benthic community composition, with implications for the survival of juvenile abalone (*Haliotis midae*). M.Sc. thesis, Department of Zoology, University of Cape Town.

McLeese, D.W. 1965. Survival of lobsters, *Homarus americanus*, out of water. *J. Fish. Res. Bd Can.* 22(2): 385-394.

McLeese, D.W. and D.G. Wilder. 1958. The activity and catchability of the lobster (*Homarus americanus*) in relation to temperature. *J. Fish. Res. Bd Can.* 15: 1345-1354.

McMahon, B.R., Butler, P.J. and E.W. Taylor. 1978. Acid base changes during recovery from disturbance and during long term hypoxic exposure in the lobster *Homarus vulgaris*. *J. Expl Zool.* 205: 361-370.

Melville-Smith, R. 1992. Considerations to be taken into account in any decision relating to a new minimum size for west coast rock lobster. Sea Fisheries Research Institute (Cape Town) document WG/06/92/WCL2. 9 pp.

Melville-Smith, R. 1993. The west coast rock lobster berry season: a proposed amendment. Sea Fisheries Research Institute (Cape Town) document WG/07/93/WCL1. 6 pp.

Melville-Smith, R. 1994. Where have all the lobsters gone? S.A. Shipping News and Fishing Industry Review. May/June.

Melville-Smith, R., Goosen, P.C., and T.J. Stewart. 1995. The spiny lobster *Jasus lalandii* (H. Milne-Edwards, 1837) off the South African coast: inter-annual variations in male growth and female fecundity. *Crustaceana* 68(2): 174-183.

Miller, R.J. and R.K. Mohn. 1993. Critique of the Leslie Method for estimating sizes of crab and lobster populations. *N. Amer. J. Fish. Manage.* 13: 676-685.

Morgan, G.R. 1972. Fecundity in the western rock lobster *Panulirus cygnus* (George) (Crustacea: Decapoda: Palinuridae). *Aust. J. mar. Freshwat Res.* 23: 133-141.

Morgan, G.R. 1974. Aspects of the populations dynamics of the western rock lobster, *Panulirus cygnus* George. II. Seasonal changes in the catchability coefficient. *Aust. J. mar. Freshwat. Res.* 25: 249-259.

Morgan, G.R. 1979. Trap response and the measurement of effort in the fishery for the western rock lobster. *Rapp. P.-V. Reun., Cons. Int. Explor. Mer.* 175: 197-203.

Morgan, G.R. 1980. Population dynamics and management of the western rock lobster fishery. *Mar. Policy,* Jan 1980: 52-60.

Morgan, G.R., Phillips, B.F. and L.M. Joll. 1982. Stock and recruitment relationships in *Panulirus cygnus*, the commercial rock (spiny) lobster of western Australia. *Fish. Bull.* 80(3): 475-486.

Nelder, J.A. and R.Mead. 1965. A simplex method for function minimisation. *Computer J.* 7: 308-313.

Newman. G.G. 1973. Assessment and management of some Marine Stocks in Southern Africa. Ph.D. thesis, University of Stellenbosch, South Africa.

Newman, G.G. and D.E. Pollock. 1969. The efficiency of rock lobster fishing gear. *S. Afr. Shipp. News Fish. Ind. Rev.* 24(6): 79-81.

Newman, G.G. and D.E. Pollock. 1971. Biology and migration of rock lobster *Jasus lalandii* and their effect on availability at Elands Bay, South Africa. *Investl Rep. Sea Fish. Branch S. Afr.* 94: 24pp.

Newman, G.G. and D.E. Pollock. 1974a. Growth of the rock lobster *Jasus lalandii* and its relationship to benthos. *Mar. Biol.* 24: 339-346.

Newman, G.G. and D.E. Pollock. 1974b. Biological cycles, maturity and availability of rock lobster *Jasus lalandii* on two South African fishing grounds. *Investl Rep. Sea Fish. Branch S. Afr.* 107: 16pp.

Newman, G.G. and D.E. Pollock. 1977. The population dynamics of rock lobster *Jasus lalandii* on two South African fishing grounds. *Colln. sci. Pap. int. Commn. SE. Atl. Fish.* 4: 175-187.

Patterson-Jones, C. 1993. Where have all the crayfish gone ? *Africa Environment and Wildlife* 1(2): 86-90.

Paulik, G.J. 1973. Studies of the possible form of the stock-recruit curve. *Rapp. P.-V. Reun., Cons. Int. Explor. Mer.* 164: 302-315.

Pauly, D. and N. David. 1981. ELEFAN 1, a basic program for the objective extraction of growth parameters from length frequency data. *Meeresforsch* 28: 205-211.

Payne, A.I.L. and A.E. Punt. 1995. Biology and fisheries of South African Cape hakes (*M. capensis* and *M.paradoxus*). In Alheit, J. and T.J. Pitcher (eds): Hake: Biology, Fisheries and Markets. London, Chapman and Hall, pp 15-47.

Phillips, B.E. 1986. Prediction of commercial catches of the western rock lobster *Panulirus cygnus. Can. J. Fish. Aquat. Sci.* 43: 2126-2130.

Phillips, B.F., Cruz, R., Brown, R.S. and N. Caputi. 1994. Predicting the catch of spiny lobster fisheries. In Phillips, B.F., Cobb, J.S. and J. Kittaka (eds): Spiny Lobster Management. Fishing News Books: Oxford, UK. pp 285-301.

Plaganyi, E. 1991. Assessing the dynamics of the Dassen Island rock lobster (*Jasus lalandii*) resource: A new approach using a surplus production model. Honours Project, Department of Zoology, University of Cape Town, Cape Town. 61pp.

Pollock, D.E. 1973. Growth of juvenile rock lobster *Jasus lalandii. Investl Rep. Sea Fish. Branch S.Afr.* 106: 1-16.

Pollock, D.E. 1978. Growth and Production rates of the rock lobster *Jasus lalandii* (H. Milne-Edwards). Ph.D thesis, University of the Witwatersrand. 226 pp.

Pollock, D.E. 1979. Predator-prey relationships between the rock lobster *Jasus lalandii* and the mussel *Aulacomyer ater* at Robben Island on the Cape West coast of Africa. *Mar. Biol.* 52: 347-356.

Pollock, D.E. 1982. The fishery for and population dynamics of west coast rock lobster related to the environment in the Lambert's Bay and Port Nolloth areas. *Invest. Rep. Sea. Fish. Inst. S.Afr.* 124: 1-57.

Pollock, D.E. 1986. Review of the fishery for and biology of the cape rock lobster *Jasus lalandii* with notes on larval recruitment. *Can. J. Fish. Aquat. Sci.* 43: 2107-2117.

Pollock, D.E. 1987. Simulation models of rock lobster populations from areas of widely divergent yields on the Cape west coast. *S. Afr. J. mar. Sci.* 5: 531-545.

Pollock, D.E. 1989. Spiny Lobster. In Oceans of Life off Southern Africa. Payne, A.I.L. and R.J.M. Crawford (eds) Cape Town, Vlaeberg. pp 70-80.

Pollock, D.E. 1990. Palaeoceanography and speciation in the spiny lobster genus *Jasus. Bull. mar. Sci.* 46(2): 387-405.

Pollock, D.E., Augustyn, C.J. and P.C. Goosen. 1982. The rock lobster *Jasus lalandii* and its environmental biology on the Saldanha-Columbine fishing ground off the Cape west coast, 1978-1981. *Invest. Rep. Sea Fish. Inst. S. Afr.* 125, 1-30.

Pollock, D.E. and L.V. Shannon. 1987. Response of rock lobster populations in the Benguela ecosystem to environmental change - a hypothesis. *S. Afr. J. mar. Sci* 5: 887-899.

Pollock, D.E. and Beyers, C.J. de. B. 1979. Trap selectivity and seasonal catchability of rock lobster *Jasus lalandii* at Robben Island sanctuary, near Cape Town. *Fish. Bull. S. Afr.* 12: 75-79.

Pollock, D.E. and R. Melville-Smith. 1993. Decapod life histories and reproductive dynamics in relation to oceanography of southern Africa. *S. Afr. J. mar. Sci.* 13: 205-212.

Press, W.H., Flannery, B.P., Teukolsky, S.A. and W.T. Vetterling. 1986. Numerical recipes: the art of scientific computing. Cambridge University Press.

Punt, A.E. 1992. Management procedures for Cape hake and baleen whale resources. Rep. Benguela Ecol. Progm. S. Afr. 23:[viii] + 689pp.

Punt, A.E. 1993. The comparative performance of production-model and ad hoc tuned VPA based feedback control management procedures for the stock of Cape hake off the west coast of South Africa. In Risk evaluation and biological reference points for fisheries management. Smith, S.J., J.J. Hunt and D. Rivard. (eds): *Can. Spec. Publ. Fish. Aquat. Sci.* 120: 83-99.

Punt, A.E. and R.B.Kennedy. 1997. Population modelling of Tasmanian rock lobster, *Jasus edwardsii*, resources. *Mar. Freshwater Res.* 48: 967-986.

Ralls, K. and A.M. Starfield. 1995. Choosing a management strategy: two structured decision-making methods for evaluating the predictions of stochastic simulation models. *Conservation Biology* 9:175-181.

Raubenheimer, C.M. 1991. Length-based simulation model for assessing the exploitation potential of the limpet *Patella granatina*. M.Sc. thesis, University of Cape Town: 58pp.

Rand, R.W. 1959. The Cape fur seal (*Arctocephalus pusillus*): distribution, abundance and feeding habits off the south western coast of the Cape Province. *Investl Rep. Div. Sea Fish. S. Afr.* 34: 1-75.

Ricker, W.E. 1954. Stock and recruitment. *J. Fish. Res. Board Can.* 11:559-623.

Ricker, W.E. 1975. Computation and interpretation of biological statistics of fish populations. *Bull. Fish. Res. Board Can.* 191: 1-382.

Rosenberg, A.A. and J.R. Beddington. 1980. Length-based methods of stock assessment. In Gulland, J.A. (ed.): Population Dynamics. Wiley and Sons.

Rosenberg, A.A. Beddington, J.R. and M. Basson. 1986. Growth and longevity of Antarctic krill during the first decade of pelagic whaling. *Nature* 324(6093): 152-154.

Rossenburg, A.A., Fogarty, M.J., Sissenwine, M.P., Beddington, J.R. and J.G. Shepherd. 1993. Achieving sustainable use of renewable resources. *Science* 262: 828-829.

Saila, S.B., Annala, J.B., McKoy, J.L. and J.D. Booth. 1979. Application of yield models to the New Zealand rock lobster fishery. *New Zealand J. Mar. Freshwat. Res.* 13: 1-11.

Sainsbury, K.J. 1982. Population dynamics and fishery management of the paua, *Halliotis iris*. 2. Dynamics and management as examined using a size class population model. *N.Z. J. mar. Freshwat. Res.* 16(2): 163-173.

Schnute, J. 1987. A general fishery model for a size-structured fish population. *Can. J. Fish. Aquat. Sci.* 44: 924-940.

Schnute, J. and D. Fournier. 1980. A new approach to length frequency analysis: growth structure. *J. Fish. Res. Bd Can.* 37(9): 1337-1351.

Schnute, J.T., Richards, L.J. and A.J. Cass. 1989a. Fish growth: investigations based on a size-structured model. *Can. J. Fish. Aquat. Sci.* 46: 730-742.

Schnute, J.T., Richards, L.J. and A.J. Cass. 1989b. Fish survival: investigations based on a size-structured model. *Can. J. Fish. Aquat. Sci.* 46: 743-769.

Scott, L. and T.J. Stewart. 1996. Fisheries Independent Lobster Monitoring Programme 1996. Sea Fisheries Research Institute (Cape Town) document, not numbered.

Scott, L. and T.J. Stewart. 1997. Estimation of variance of CPUE estimates. Sea Fisheries Research Institute (Cape Town) document WG/05/97/WCL16. 1 pp.

Seber, G.A.F. 1973. The estimation of animal abundance and related parameters. 2nd edition. Griffin and Co., London.

Shannon, L.V. 1985. The Benguela ecosystem. Part I. Evolution of the Benguela, physical features and processes. *Oceanogr. Mar. Biol. Ann. Rev.* 23: 105-182.

Shepherd, J.G. 1982. A versatile new stock-recruitment relationship for fisheries, and the construction of sustainable yield curves. *J. Cons. Int. Explor. Mer.* 40: 67-75.

Shepherd, J.G. 1987. Towards a method for short-term forecasting of catch rates based on length compositions. In Pauly, D. and G.R. Morgan (eds): Length-based methods in fisheries research. ICLARM Conference Proceedings 13. International Center for living Aquatic Resources Management, Manila, Philippines, and Kuwait Institute for Scientific Research, Safat, Kuwait. 468pp.

Shotton, R. 1989. A model for evaluation of management policy options for lobster or moult-type fisheries. *Can. tech. Rep. Fish. aqat. Sci.* 1696: 57pp.

Starr, P.J., Breen, P.A., Hilborn, R.H. and T.H. Kendrick. 1997. Evaluation of a management decision rule for a New Zealand rock lobster substock. *Mar. Freshwater Res.* 48: 1093-1101.

Sullivan, P.J., Lai, H-L., and V.F. Gallucci. 1990. A catch-at-length analysis that incorporates a stochastic model of growth. *Can. J. Fish. Aquat. Sci.* 47: 184-198.

Tang, Q. 1985. Modification of the Ricker stock recruitment model to account for environmentally induced variation in recruitment with particular reference to the blue crab fishery in Chesapeake Bay. *Fish. Res.* 3: 13-21.

Tasmanian Department of Primary Industry and Fisheries. 1997. Background paper for the legislative council select committee on the Tasmanian rock lobster fishery. Internal Document, Tasmanian Department of Primary Industry and Fisheries. 12 pp.

Usher, M.B. 1971. Developments in the Leslie matrix model. In Mathematical Models in Ecology. Jeffers, J.N.R. (ed.) London, Blackwell: 29-60.

Von Winterfelt, D. and W. Edwards. 1986. Decision analysis and behavioural research. Cambridge University Press, Cambridge.

Walters, C.J., Hall, N., Brown, R. and C. Chubb. 1993. Spatial model for the population dynamics and exploitation of the Western Australian rock lobster, *Panulirus cygnus. Can. J. Fish. Aquat. Sci.* 50: 1650-1652.

Waugh, G.T. 1981. Management of juvenile spiny lobster (*Panulirus argus*) based on estimated biological parameters from Grand Bahamas Island, Bahamas. *Proc. Gulf Caribb. Fish. Inst.* 33: 271-289.

Wickens, P.A. and J.G. Field. 1988. Rock lobsters *Jasus lalandii* and mussels *Aulacomyer ater*: demographic parameters and simulation models of their populations and interaction. *S. Afr. J. mar. Sci.* 7: 193-217.

Winstanly, R.H. (1973). Rock lobster fishing in Tasmania 1904-1972. *Tasmanian Fisheries Research*, Vol 7.

Van Zyl, D. and D. Schoeman. 1997. Preliminary summary of rock lobster walkouts during Autumn 1997. Sea Fisheries Research Institute (Cape Town) document WG/05/97/WCL12. 2 pp.

Zoutendyk, P. 1988. Consumptive rates of captive Cape rock lobster *Jasus lalandii. S. Afr. J. mar. Sci* 6: 267-271.

Zoutendyk, P. 1990. Gonad output in terms of carbon and nitrogen by the Cape Lobster *Jasus lalandii* (H. Milne Edwards, 1937) (Decapoda, Palinuridae). *Crustaceana*, 59(2): 180-192.