GROWTH AND SIMULATION MODELLING STUDIES OF ROCK-LOBSTER (*JASUS LALANDII*) AND MUSSEL (*AULACOMYA ATER*) POPULATIONS AND THEIR INTERACTIONS

BY

PATTI A. WICKENS

Submitted for the degree of Master of Science,
Faculty of Science, University of Cape Town

Supervisor : Professor J.G. Field

September 1985

CONTENTS

DECLARATION

The collection of all data was done by other researchers and includes both published and unpublished work. The compilation and manipulation of the data and /the formulation and program coding of the five models were done by myself. The selection and implementation of simulations and the interpretation thereof are my own.

ABSTRACT

ABSTRACT

The availability of the ribbed mussel, Aulacomya ater is thought to be the most important factor influencing the growth rate of the commercial rock-lobster, Jasus lalandii on the southern African west coast. A range of growth rates represented by von Bertalanffy growth curves is estimated for both A. ater and J. lalandii. Five models of differing complexity based on the age distributions of these populations are formulated with the main purpose of investigating optimal harvesting strategies for J. lalandii. Mussel and lobster single-species models are developed with constant recruitment, as is a lobster model incorporating a linear stock-recruitment relationship. Two models in which lobster growth is influenced by mussel availability are presented, one in which there is constant recruitment and the other having a linear stock-recruitment relationship for lobsters. Data are compiled for three areas of differing J. lalandii growth rates and A. ater biomass. Two are rock-lobster fishing grounds, the Cape Peninsula and Dassen Island at which there is a small and large benthic biomass and corresponding "slow" and "overall" estimates for rock-lobster growth, respectively. The third area is a rock-lobster sanctuary, Robben Island where there is a large benthic biomass and rock-lobsters grow at a "fast" rate. The mussel, lobster and lobster-mussel models assuming constant recruitment are used to examine the effects various parameters have on population size composition. Growth and predation have marked effects on the size structure of the prey population whereas the size composition of the predator population is greatly affected by growth and harvesting. The simplest of the four lobster models, the single-species constant recruitment model produced the most practical management information. The lobster model incorporating a stock-recruitment relationship is unstable while the lobster-mussel model with constant recruitment requires fine-tuning. Only simulations of the Cape Peninsula fishing ground produced valid results using the lobster-mussel model with a stock-recruitment relationship. Based on the results of the most reliable models, three main conclusions about rock-lobster harvesting strategies are made. An increase in fishing pressure is unlikely to be commercially beneficial because of the resulting decrease in catch per unit effort. If opened to fishing, the Robben Island sanctuary is likely to produce a sustainable yield of at least 340 tons annually with a small reduction (7 %) in the size of this population. Although results differ from area to area according to growth and harvesting rates, reducing the minimum catchable size from the present 89 mm carapace length to 70 mm or 80 mm is predicted to give a better overall harvest. The more conservative estimate of 80 mm minimum catchable size may cause the least change to the ecosystem, possibly produce a catch of more marketable size and may guard against "recruitment overfishing".

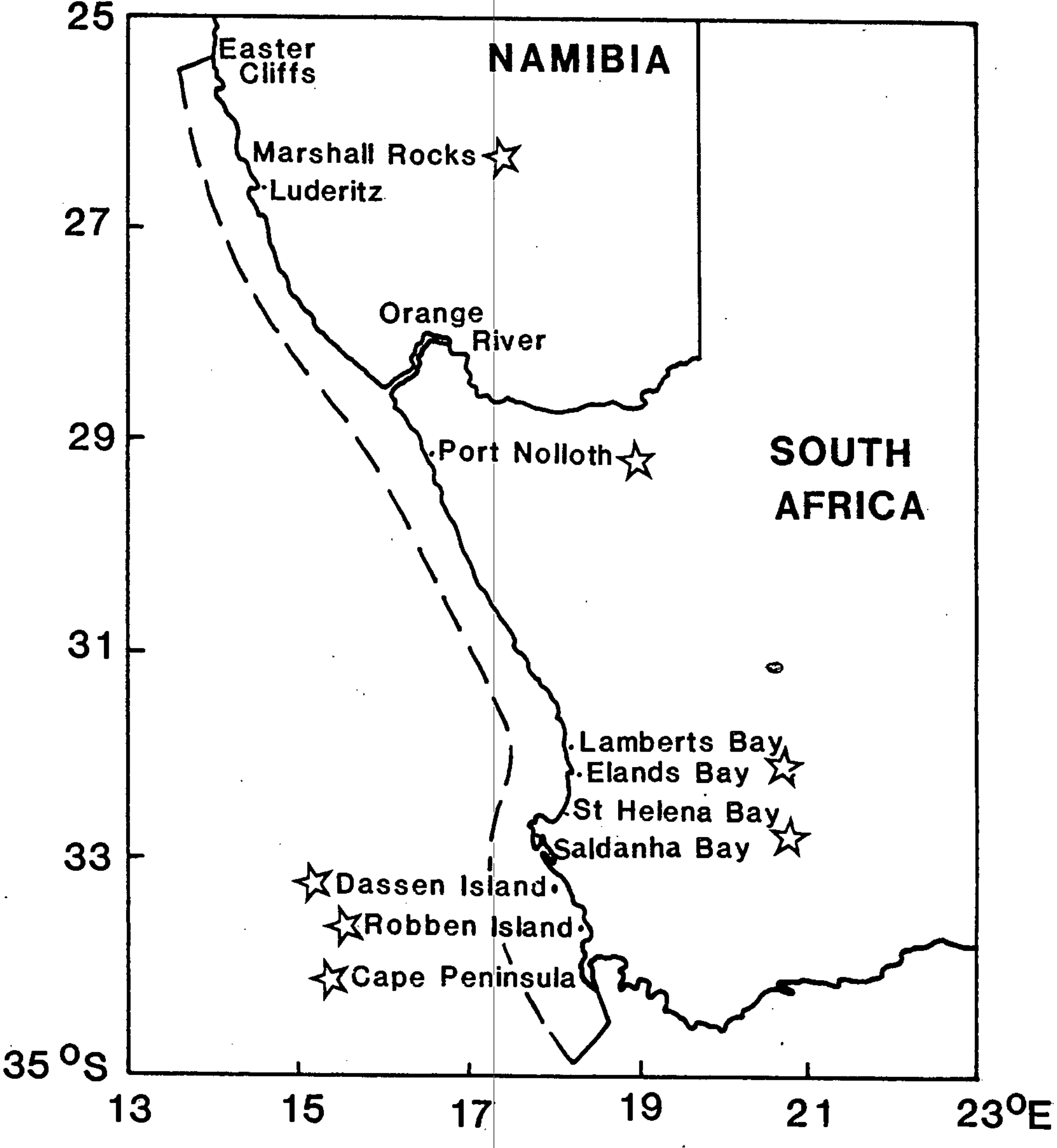
CHAPTER 1

Introduction

CHAPTER 1 : INTRODUCTION

Pollock and Beyers (1981) investigated the major environmental factors affecting growth of the commercially exploited rock-lobster, Jasus lalandii at six areas on the South African west coast and off Namibia over a period of nine years. They suggested that oxygen saturation may have an effect on rock-lobster growth as it does in juvenile Western Australian rock-lobster, Panulirus cygnus (Chittleborough, 1975) but this is not confirmed (Pollock and Beyers, 1981). Kurata (1962), Chittleborough (1975) and Smale (1978) have shown that the frequency of moulting increases with temperature in many spiny lobster species but its effect on the actual growth increment is not marked. Since J. lalandii only moults once a year (Heydorn, 1965, 1969b; Newman and Pollock, 1971, 1974a) and all areas on the South African west coast are subject to the cold Benguela current, temperature is believed to be an unimportant factor for growth of J. lalandii. Other influential factors on growth of spiny lobster species include amount of light/darkness (Kurata, 1962), and in juvenile P. cygnus, isolation and replacement of limbs (Chittleborough, 1975). Food availability was considered by Pollock and Beyers (1981) to be the most important factor influencing growth rates of J. lalandii. This food, often in the form of the ribbed mussel, Aulacomya ater, may be limiting even in areas of relatively large mussel biomass because specific sizes of mussel are required (Griffiths and Seiderer, 1980). Availability depends on prey size, accessibility in mussel beds and degree of exposure because J. lalandii can only feed in fairly calm conditions (Pollock, 1978). Similar limitations were found by Miller et al. (1971) for the lobster, Homarus americanus in areas of excess prey production, possibly because the available sizes and densities of prey could not be exploited or there was competition for food amongst the predators. Food availability has also been shown to be a dominant factor affecting growth in various spiny lobster species (Kurata, 1962; Witham et al., 1964; Chittleborough, 1975, 1976). Chittleborough

FIGURE 1.1 : Map of the southern African west coast showing areas in which the adult growth rate of the rock-lobster, Jasus lalandii has been measured (☆). The demarked area (Easter Cliffs, 25° 20' S to Cape Point, 34° 30' S) shows where J. lalandii is found in commercially exploitable densities (Pollock and Beyers, 1981).



(1975) showed that daily feeding was necessary to maintain maximum growth in juvenile P. cygnus, a decrease in food causing a longer intermoult period with severe shortage resulting in both a longer period and a decrease in increment at moult.

Fig. 1.1 shows areas on the southern African west coast in which the growth rate of adult rock-lobsters has been measured and the range over which this species is exploited. Geographic variation in growth rates of J. lalandii has been described for several areas on the west coast (Newman and Pollock, 1974a, 1977; Pollock, 1978; Pollock and Beyers, 1981) and considerable variation in growth has been observed within a single area such as Dassen Island (Newman, 1973). In most cases the variation is ascribed to differences in food availability (Pollock et al., 1982). Extensive larval dispersion confirms that the growth rate between locations is not genetic but environmentally induced (Newman and Pollock, 1974a). Smith (1950) has noted that knowledge of population parameters, growth rates, breeding seasons, size at sexual maturity and similar biological statistics are necessary for the successful control and management of a fishery. Fisheries biology is largely concerned with factors affecting rates of birth, growth and death, parameters which cannot often be directly observed (Burkenroad, 1951). Growth rate is very important in regulating catch (Pollock et al., 1982). Therefore the difference in growth rates between fishing grounds complicates the formulation of harvesting restrictions which have to be applied to the whole fishing area (Newman and Pollock, 1977). Morgan (1980) suggests that detailed studies of growth rates and their variation in lobsters are likely to become important in the development of yield models. Since growth of the commercially exploited rock-lobster, J. lalandii may be influenced by the abundance of the mussel, A. ater, the measurement of growth rates of these species is important if the interaction is to be investigated in a model.

Young (1950) defines growth as the addition of material to that which is already organised within a living system. This definition does not necessarily require an increase in size but recognises such features of the growth process as repair, regeneration and maintenance (Ford, 1977) and is therefore comprehensive for crustacean growth. Measurement of some increase in individual size with time, a fundamental parameter in studies of population dynamics, can take the form of increase in length, width, volume or mass. Mass and volume can be regarded as the most reliable and effective parameters for expressing growth rate (du Plessis, 1977). However, most parameters for J. lalandii and A. ater populations are measured as functions of length or partial length. Therefore in a modelling exercise which requires use of these parameters, length-based ageing is chosen.

There are various methods of measuring growth increments and they are specific to various classes of animals and they all differ in accuracy. Methods of measuring bivalve growth include the use of annual growth rings, tagging and analysis of population size-frequency distributions (Muus, 1973). Growth measurement of sessile animals does not have some of the drawbacks of motile individuals but they may be very slow growing, making measurement difficult. Growth in Crustacea is a discontinuous, stepped process, only taking place in the immediate post-moult period whereas during the intermoult period body size is constant. This, and the absence of such markings as growth rings makes growth measurement difficult. Burkenroad (1951) noted four methods of measuring crustacean growth, namely tagging, measurement of captive animals, analysis of size-frequency distributions and observation of moult frequency in nature combined with increment per moult of animals captured just prior to moult in the field. Tagging, a common method described by Hancock and Edwards (1967) has drawbacks in that returns are often small and it takes years to obtain a data set (Mauchline, 1977) so annual fluctuations in environmental factors cannot be used to account for changes in growth rate. Growth measured in captive animals does not allow for environmental fluctuations and generally excludes hazards which may affect growth in nature. Use of size-frequency distributions is inadequate since the annual increment is small, and there is often migration between or within areas (Mauchline, 1977). Moult frequency in nature may be well-defined in some species but the combination of this with laboratory-measured increments incorporates the problems of growth measurement in captive animals.

The harvesting of rock-lobster or "kreef" (J. lalandii) on the South African Cape coast is controlled by restrictions specified by the Marine Development Branch, "Control Measures on Rock-lobster", published in 1973. These control measures include a minimum catchable size (officially termed the "minimum catch size limit") of 8.89 cm in carapace length or if the tail has been severed from the body, the second tail segment must be no less than 2.38 cm in length; prohibition of landing rock-lobster which are in berry or in soft-shelled condition; prohibition of landing rock-lobster in five proclaimed sanctuaries in areas of Betty's Bay, False Bay, in the Cape Peninsula from Melkbos Point to Hout Bay, in Saldanha Bay and St Helena Bay; a closed season from July to October which was changed in 1984 to the period mid-May to October. For commercial harvesters additional restrictions include a total rock-lobster fishing quota set each year; no trawling of rock-lobster; capturing only from a licensed rock-lobster boat; catches only to be landed at proclaimed rock-lobster landing areas and sold to authorised rock-lobster packers or rock-lobster quota holders; Additional restrictions for sport harvesters include a maximum of 5 rock-lobster to be taken per person (in possession of a permit) per day by means of a scoop-net or diving without artificial breathing apparatus, only from the shore; a maximum of 20 rock-lobster may be transported per vehicle, accompanied by the catchers and these rock-lobster may not be sold.

To test the optimal choice of a minimum catchable size, a lobster-mussel model, based on the length distributions of J. lalandii and A. ater stocks was developed by Seiderer et al. (1982). The reasoning behind the formulation of their model was based on two findings. They showed that most of A. ater biomass is concentrated in the larger size classes. Griffiths and Seiderer (1980) showed that because of the prey size specificity in J. lalandii feeding, food restrictions are probably most severe for smaller rock-lobsters whose already limited food resources of small mussels are competed for by larger individuals. Therefore they suggest that it may not be detrimental to harvest rock-lobsters of smaller size because there may be less competition for the more limited resource, and the growth rate of the rock-lobster population may increase, thereby benefiting the fishery. However, there are logical problems in using length as opposed to age distributions in a population dynamics model such as that of Seiderer et al. (1982). Models based on population age structure such as those used in other types of fish stock management are not applicable because ageing of rock-lobsters is difficult. For this reason, Morgan (1980) suggests that further developments in length-related cohort analysis techniques such as that developed by Jones (1974) for crustacean species would be useful. Likewise, Hancock (1980) states that the formulation of a suitable crustacean growth model is clearly an area which continues to receive attention. Such techniques need to refer to a time base so it is necessary to be able to convert lengths to ages using appropriate growth equations.

The purpose of this work is firstly, to obtain sets of growth curves for different growth rates for both mussels and rock-lobsters (which will be referred to simply as "lobsters" throughout). Thereafter, to derive a method in which length-related data can be used in age-based population dynamics models and to construct separate simulation models for mussel and lobster populations using this length-related technique. The models can then be combined into an interacting one in which lobster growth is affected by mussel availability. Thereafter, to define an appropriate stock-recruitment relationship for lobsters and build this into both the single-species lobster model and the lobster-mussel interaction model. Data for areas of known different growth rates and differing mussel availability can then be compiled for use in the models. Use the single-species and two-species models, the following questions can be tested :

1) What effect do growth, natural mortality, fishing and/or predation have on lobster and mussel population size structure ?
2) What effect do different fishing strategies have on lobster harvest ?
3) What effect does mussel-dependent growth of lobsters have on optimal lobster harvesting strategies ?
4) How does recruitment pattern affect lobster harvesting ?

CHAPTER 2

Growth of mussels and lobsters

FIGURE 4.2 : Maps showing the chosen simulation areas in relation to each other (a) and the depth contours at each area (b - d).

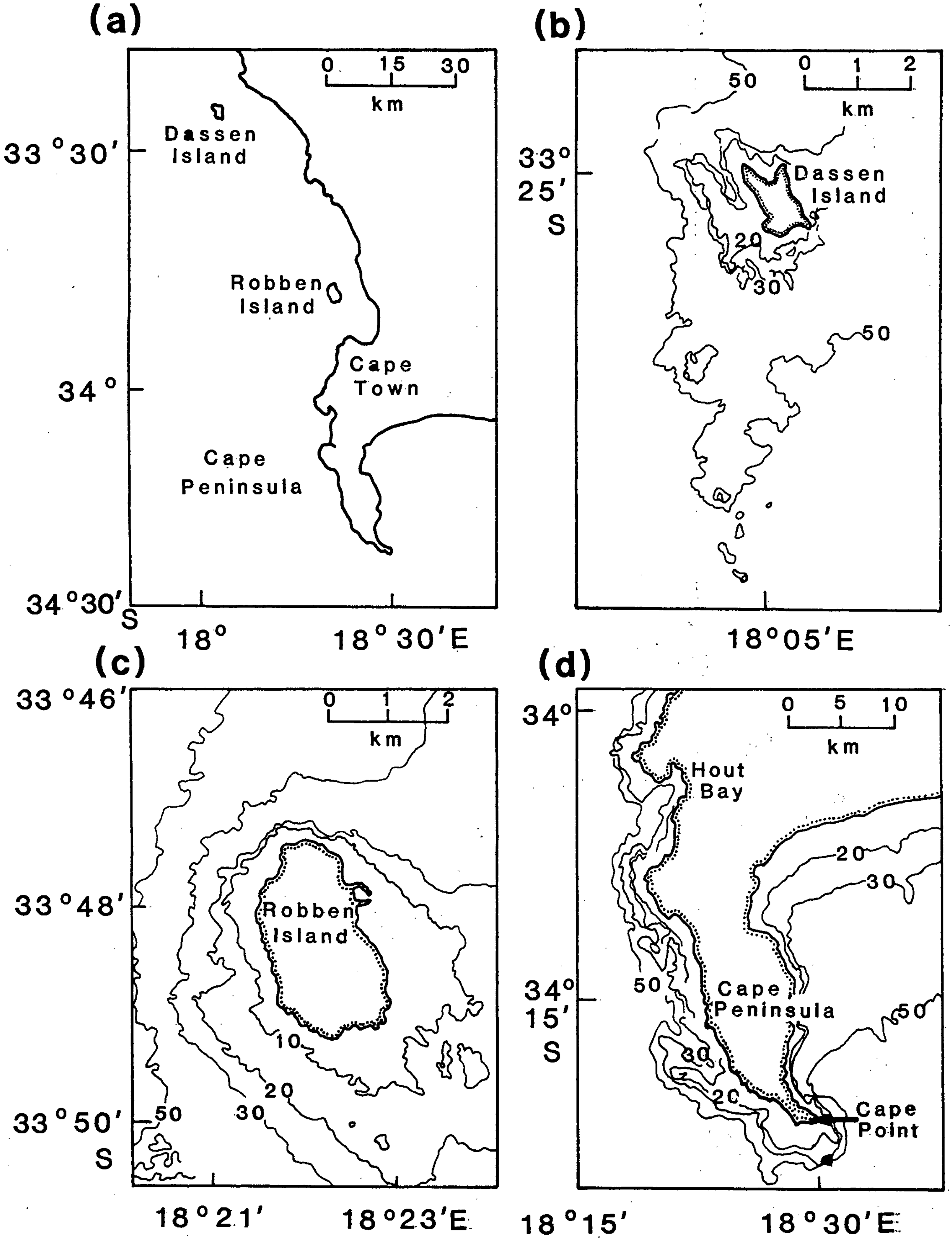


TABLE 4.2 : A. ater growth increments for different growth rates estimated from measurements taken on the South African west coast by A. Barkai and C.L. Griffiths, unpublished data and Pollock (1978) (see Chapter 2).

SIZE CLASS	GROWTH RATE (mm.month^{-1})		
	"OVERALL" ESTIMATE	"FAST"	"SLOW"
1	0.546	0.882	0.210
2	1.160	1.160	0.288
3	1.081	1.140	0.373
4	0.450	0.504	0.350
5	0.245	0.245	0.245
6	0.225	0.225	0.225
7	0.110	0.110	0.110
8	0.061	0.061	0.061

TABLE 4.3 : A. ater age-length distributions for different growth rates computed by the program "GROWTH" (see Chapter 2).

AGE (years)	LENGTH (mm)		
	"OVERALL" GROWTH ESTIMATE	"FAST" GROWTH	"SLOW" GROWTH
1	6.6	10.6	2.5
2	16.2	24.4	5.0
3	29.5	33.7	7.6
4	35.5	39.7	10.1
5	40.7	42.9	13.5
6	43.6	45.9	17.0
7	46.6	48.8	20.5
8	49.5	51.6	25.0
9	52.3	54.3	29.5
10	55.0	57.0	33.7
11	57.7	59.7	37.9
12	60.3	61.3	41.5
13	61.6	62.6	44.4
14	62.9	63.9	47.4
15	64.2	65.2	50.3
16	65.5	66.5	53.0
17	66.9	67.9	55.7
18	68.2	69.2	58.4
19	69.5	70.3	60.6
20	70.5	71.0	62.0
21	71.2	71.8	63.2
22	71.9	72.5	64.6
23	72.7	73.2	65.9
24	73.4	74.0	67.2
25	74.1	74.7	68.6
26	74.9	75.4	69.9
27	75.6	76.2	70.1
28	76.3	76.9	71.4
29	77.1	77.6	72.2
30	77.8	78.3	72.9
31	78.5	79.1	73.6
32	79.3	79.8	74.4
33	80.0		75.1
34			75.8
35			76.6
36			77.3
37			78.0
38			78.8
39			79.5

CHAPTER 2 : GROWTH OF MUSSELS AND LOBSTERS

Griffiths and King (1979b) constructed a growth curve for the mussel, *Aulacomya ater* but this was based on a small data set from Oudekraal, Cape Peninsula. Growth curves of male and female lobster, *Jasus lalandii*, based on growth increments in carapace length measured at Robben Island were computed by Pollock (1978). Since then more data have been collected, recording growth increments for both species at various areas on the South African west coast. The available literature and new sources of data were reviewed and an attempt was made to compile a set of realistic growth increments and curves for an "overall" (average) growth estimate, "fast" (upper limit) and "slow" (lower limit) growth for mussels and male and female lobster on the South African west coast.

DATA COMPILATION

Mussels

A. ater growth data was obtained from four sources and is not separate for males and females. On the islands of Marcus and Malgas, off Saldanha Bay, individuals of different sizes were tagged and their length at 0, 2, 4 and 6 months measured (A. Barkai, unpublished data). The individuals were separated into 10 mm-size classes according to their initial length. Each of the three sampling periods were treated as separate data sets, then combined and the mean monthly growth increment for each size class calculated. Some estimates of *A. ater* growth on Robben Island are given by Pollock (1978). One value was obtained by following the mean length of a spat settlement from 1.6 to 2.5 mm over a period of 4.4 months. Other values were estimated by measuring the change in mean length of a settlement of juveniles on five occasions over a period of two and a half years and noting the mean monthly growth as the population grew through different size ranges. Raw data from Griffiths and King (1979b) was used to

TABLE 2.1 : *A. ater* growth increments for different growth rates based on sets of data from different areas on the South African west coast (Pollock, 1978; A. Barkai and C.L. Griffiths, unpublished data). In the two sets of increments excluding Marcus Island data, an asterisk indicates use of a Marcus Island data point in length classes where no other data were available. Values in parentheses indicate estimates based on trends.

LENGTH (mm)	GROWTH RATE (mm.month^{-1})				
	MEAN	MINIMUM	MAXIMUM	MEAN EXCL. MARCUS ISL. DATA	MINIMUM EXCL. MARCUS ISL. DATA
1 - 10	0.546	0.210	0.882	0.546	0.210
11 - 20	0.724	0.288	1.160	1.160	0.288*
21 - 30	0.796	0.142	1.140	1.081	0.373
31 - 40	0.313	0.107	0.504	0.450	0.350
41 - 50	0.148	0.049	0.245	0.245	0.245
51 - 60	0.123	0.021	0.225	0.225	0.225
61 - 70	0.110	0.110	0.110	0.110*	0.110*
71 - 80	(0.061)	(0.061)	(0.061)	(0.061)	(0.061)

FIGURE 2.1 : Monthly growth increments of *A. ater* of different sizes recorded by various authors at different areas off the South African west coast.

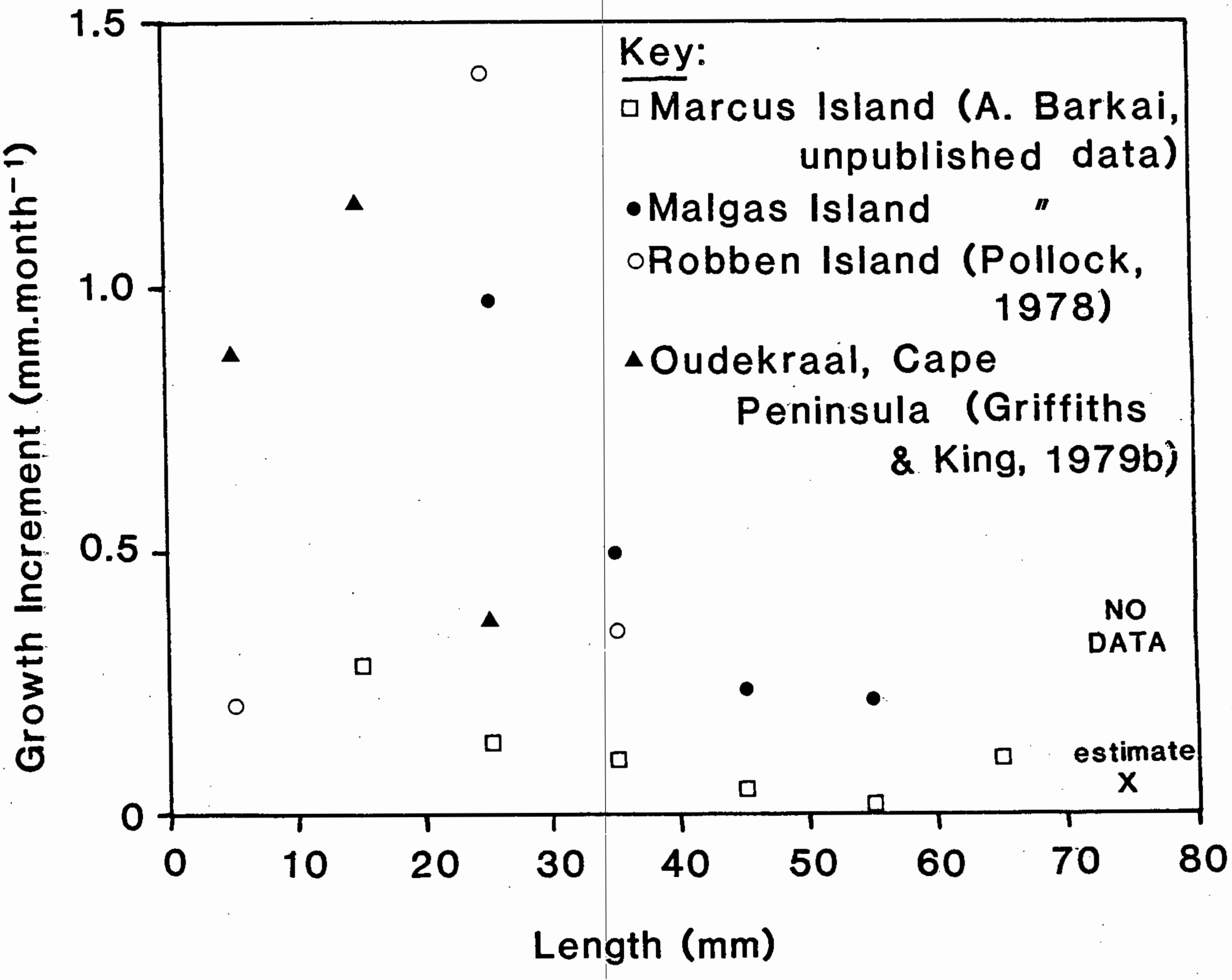
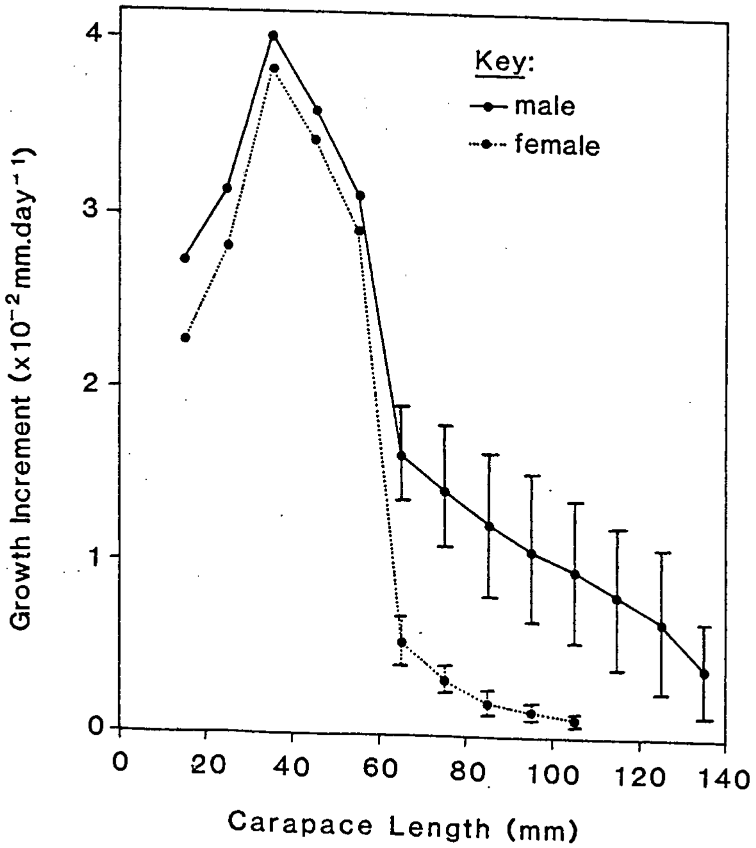


TABLE 2.2 : Increase in carapace length at different growth rates for male and female J. lalandii over their respective size ranges. Juvenile growth rate data are from Pollock (1973) and adult data are based on ranges given by D.E. Pollock (pers. comm.). For adult females, an additional set of growth increments believed to most representative of natural populations (D.E. Pollock) are given and are derived from mean and maximum rates.

CARAPACE LENGTH (mm)	GROWTH RATE (x10^{-2} mm.day^{-1})						
	MALES			FEMALES			
	MINIMUM	MEAN	MAXIMUM	MINIMUM	MEAN	MAXIMUM	MEAN or MAXIMUM
Juvenile Growth							
11 - 20		2.547			2.261		
21 - 30		3.292			2.817		
31 - 40		4.029			3.838		
41 - 50		3.700			3.442		
51 - 60		3.215			2.907		
Adult Growth							
61 - 70	0.370	1.644	1.918	0.411	0.548	0.685	0.548
71 - 80	1.096	1.439	1.781	0.274	0.343	0.411	0.343
81 - 90	0.822	1.233	1.644	0.137	0.206	0.274	0.274
91 - 100	0.685	1.096	1.507	0.110	0.151	0.192	0.192
101 - 110	0.548	0.959	1.370	0.082	0.110	0.137	0.137
111 - 120	0.411	0.822	1.233				
121 - 130	0.274	0.685	1.096				
131 - 140	0.137	0.411	0.685				

FIGURE 2.2 : Daily growth increments of male and female J. lalandii over their respective size ranges. Juvenile (< 60 mm) growth data was obtained from Pollock (1973). Adult growth data estimated from realistic ranges of growth increments given by D.E. Pollock (pers. comm.).



estimate monthly growth increments for *A. ater* from Oudekraal. These data were collected by selecting areas of mussel bed that appeared to comprise a single cohort and periodically sampling these areas to estimate mean cohort length. Data from two of these areas which were sampled over a period of 12 months were selected. Using the mean length of each sample and the inter-sampling period, monthly growth increments were calculated for the various size classes.

The data from these four areas were combined in order to give some estimates of mussel growth on the South African west coast. A maximum length of 80 mm was chosen since there are few mussels larger than this size and, for the purpose of the lobster-mussel model, lobsters have not been observed to eat individuals larger than this length (Griffiths and Seiderer, 1980). For the last size class (71 - 80 mm) no data were available; therefore an estimate was made, based on the trend evident from the other increments (Fig. 2.1). From these data, five sets of growth increments were compiled - the i) mean, ii) minimum and iii) maximum of all points for each size class, and a iv) mean and v) minimum excluding the Marcus Island data points (where other increments were available) since these increments appeared to be so much smaller than the rest (Table 2.1).

Lobsters

Lobster growth is measured in terms of carapace length which is the distance from the tip of the rostrum to the posterior edge of the cephalothorax. The daily increments for male and female juvenile *J. lalandii* of sizes ranging from 10 to 59 mm were estimated using mean moult increments and intermoult periods (Pollock, 1973). D.E. Pollock (pers. comm.) has suggested realistic ranges of annual growth increments for adult males and females of different size classes, based on tagging data from numerous sites on the South African west coast. These were converted to daily increments. D.E. Pollock (pers. comm.) suggests that maximum lengths

TABLE 2.4 : Parameters for von Bertalanffy growth equations fitted to *A. ater* growth data for different growth rates. Figures in parentheses give one standard deviation.

GROWTH RATE	$l\infty$	k
"OVERALL" ESTIMATE (forced $l\infty$)	80	0.113 (0.003)
"OVERALL" ESTIMATE (closest fit)	78.19 (0.83)	0.123 (0.005)
"SLOW" (closest fit)	92.12 (2.32)	0.055 (0.003)
"FAST" (closest fit)	77.47 (0.94)	0.132 (0.007)

FIGURE 2.3 : Algorithm for calculating size (S) at yearly intervals (A) given the times taken for an individual to reach specific sizes indicated by ● (see text).

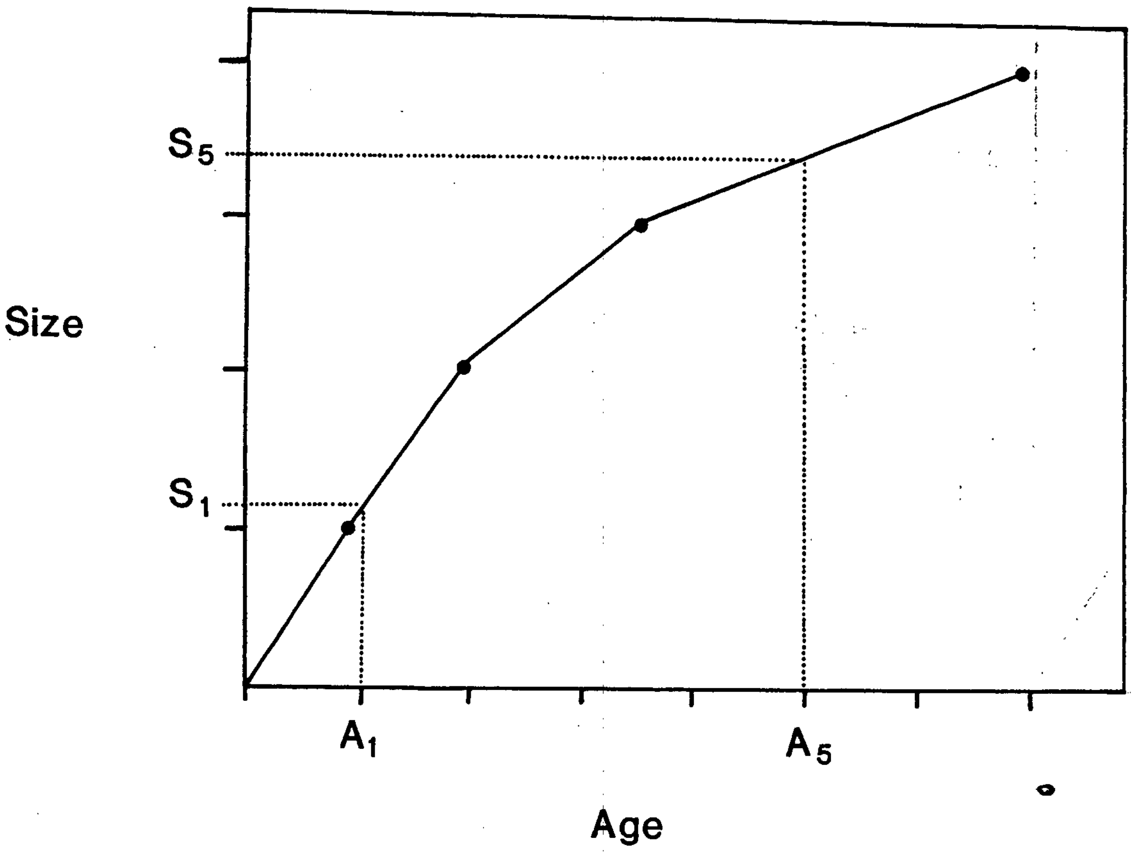


TABLE 2.3 : Calculated number of years taken by A. ater to reach various lengths at different growth rates. An asterisk indicates growth rates chosen as most realistic (C.L. Griffiths, pers. comm.).

GROWTH RATE	LENGTH (mm)							
	10	20	30	40	50	60	70	80
MEAN	1.4	2.8	3.9	6.6	12.0	18.8	26.5	40.0
* MEAN EXCL. MARCUS ISLAND	1.4	2.3	3.1	4.9	8.2	11.9	19.4	33.0
MINIMUM	4.0	6.9	12.7	20.6	37.6	77.0	84.7	98.2
* MINIMUM EXCL. MARCUS ISLAND	4.0	6.9	9.1	11.6	14.9	18.7	26.1	39.7
* MAXIMUM	0.9	1.7	2.6	4.1	7.4	11.2	18.7	32.3

of 140 mm and 110 mm for J. lalandii males and females respectively are reasonable. The sets of data for juvenile and adult lobster were combined (Table 2.2 and Fig. 2.2).

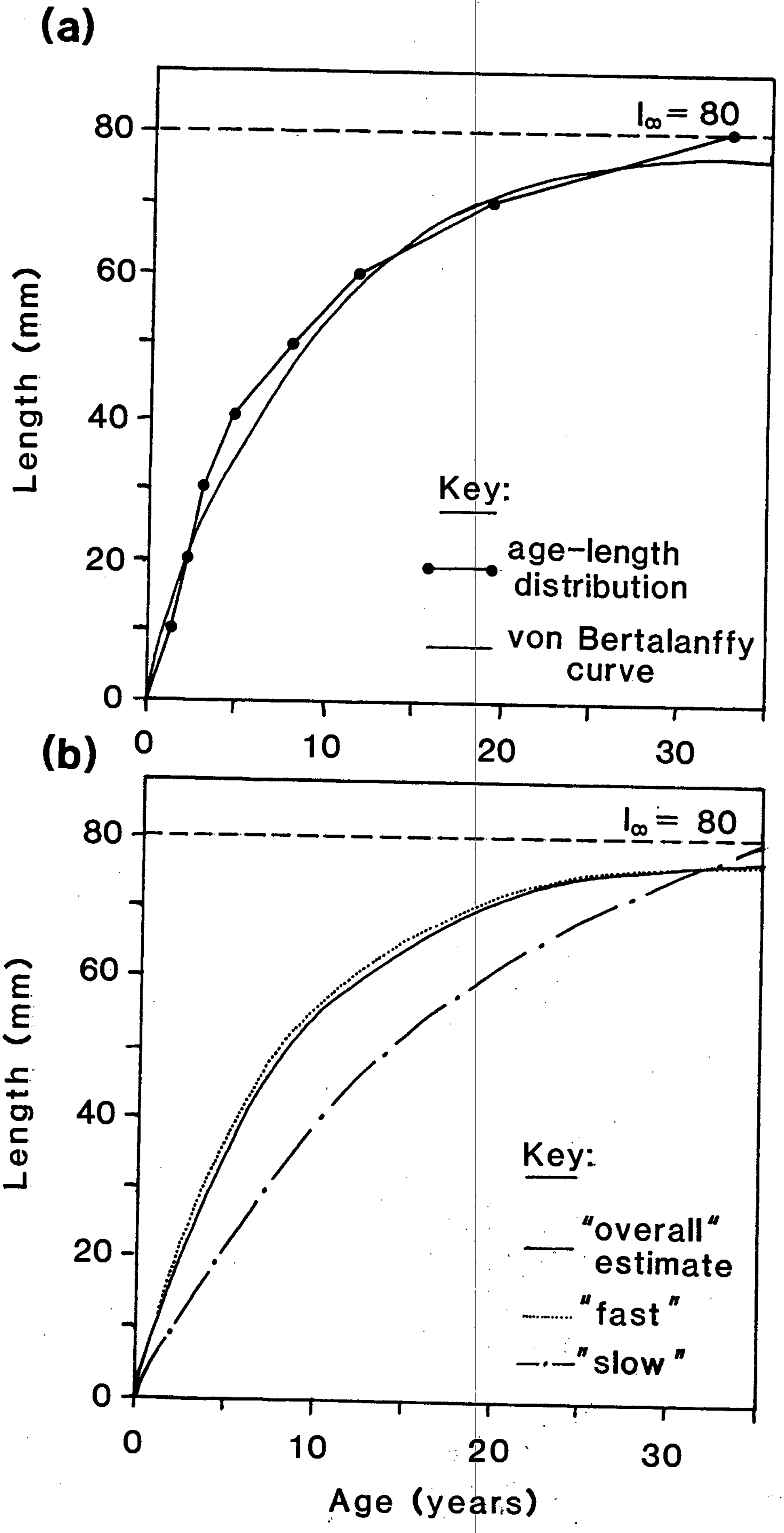
AGE-LENGTH RELATIONSHIP AND CURVE-FITTING

A computer program, "GROWTH" (Appendix A and B) was designed to use daily or monthly growth increments in order to calculate an age-length distribution. The time taken for an individual to "grow" through a size class is calculated from the number of growth increments, specific to that size range, needed to pass through the size class. Thus the time taken to grow through all the size classes is summed, giving evenly spaced length intervals with corresponding growth times. However, the length at each yearly interval is required. The algorithm for this calculation is based on the assumption that the data points are linked by straight lines (Fig. 2.3). Equations for each straight line are calculated and the length at each yearly interval (age) determined by substitution into the relevant equation, yielding an age-length distribution. A BMDP package (P3R of the 1983 version used on a SPERRY 1100/81) was used to fit von Bertalanffy, Gompertz and Logistic growth curves to the age-length data.

Mussels

Age-length distributions for different growth rates were computed using the program "GROWTH". From these, the number of years taken to reach various lengths was calculated (Table 2.3). C.L. Griffiths (pers. comm.) suggested that the data set using the mean excluding Marcus Island data produced the best "overall" growth estimate. The minimum growth rates were considered too unrealistic (approximately 100 years to reach 80 mm) and were disregarded. Thus the mean and minimum rates excluding Marcus Island data and the maximum rates were used as a realistic range of values from "slow" to "fast" growth. The von Bertalanffy curve appeared to give the best fit

FIGURE 2.4 : Comparison of a computed age-length distribution and its corresponding von Bertalanffy curve for the "overall" growth estimate of <u>A. ater</u> (a) and von Bertalanffy growth curves for the "overall" estimate, "slow" and "fast" growth (b).



to the three sets of data (Table 2.4 and Fig. 2.4).

Lobsters

Silberbauer (1971) gives the following time intervals (days) for the early stages of lobster development : spawning and incubation of eggs (92), hatching (1), naupliosoma larvae (1), 11 stages of phyllosoma larvae (231) and puerulus stage (25). This gives a total of 350 days, by which time the individuals are approximately 10 mm in carapace length. The growth increment data are used in the program, "GROWTH" with a starting length of 10 mm and an initial age of one year during which time a lobster egg passes through its larval stages and reaches 10 mm in length. The number of years taken to reach various lengths at different growth rates was calculated from the age-length distributions (Table 2.5). The different growth rates only involve differences in adult growth, the juvenile rates are kept constant (see Table 2.2). D.E. Pollock (pers. comm.) suggested that the mean growth rate for males gave the best "overall" estimate. However, for females, the mean growth rate up to 80 mm was realistic and thereafter maximum rates yielded a reasonable maximum age so this was taken as the "overall" estimate. The von Bertalanffy curve showed the best fit to the age-length distributions for "overall" growth estimate, "fast" and "slow" growth of both sexes (Figs 2.5, 2.6 and Table 2.6).

DISCUSSION

Mussels

The previous growth equation given for A. ater (Griffiths and King, 1979b) was a Gompertz curve with a specified maximum size of 90 mm, extrapolated from data for individuals of length 0 to 30 mm. Maximum size was reached after a period of 12 years using this equation. The von Bertalanffy curve given here is based on more data over a greater size range but the period of 33 years to reach 80 mm does appear to be unusually long. There are,

TABLE 2.5 : Calculated number of years taken by male and female J. lalandii to reach various lengths at different growth rates. For females an additional set of figures is given based on a set of mean and maximum growth increments. An asterisk indicates the growth rates believed to be most realistic of an "overall" growth estimate (D.E. Pollock, pers. comm.).

GROWTH RATE	LENGTH (mm)													
	10	20	30	40	50	60	70	80	90	100	110	120	130	140
							MALES							
MINIMUM	1.0	2.1	2.9	3.6	4.4	5.3	7.2	9.8	13.0	17.1	22.1	28.8	38.9	58.8
* MEAN	1.0	2.1	2.9	3.6	4.4	5.3	6.9	8.8	11.0	13.5	16.4	19.7	23.8	30.3
MAXIMUM	1.0	2.1	2.9	3.6	4.4	5.3	6.6	8.2	9.8	11.7	13.7	15.9	18.5	22.4
							FEMALES							
MINIMUM	1.0	2.2	3.1	3.9	4.7	5.9	12.4	22.5	42.4	67.4	100.8			
MEAN	1.0	2.2	3.1	3.9	4.7	5.9	10.6	18.6	32.0	50.2	75.1			
MAXIMUM	1.0	2.2	3.1	3.9	4.7	5.9	9.8	16.4	26.4	40.7	60.7			
* MEAN or MAXIMUM	1.0	2.2	3.1	3.9	4.7	5.9	10.7	18.7	28.7	43.0	63.0			

TABLE 2.6 : Parameters for von Bertalanffy growth equations fitted to male and female J. lalandii growth data for different growth rates. Figures in parentheses give one standard deviation.

GROWTH RATE	MALES		FEMALES	
	l∞	k	l∞	k
"OVERALL" ESTIMATE (Forced l∞)	140	0.104 (0.002)	110	0.078 (0.003)
"OVERALL" ESTIMATE (closest fit)	145.48 (1.75)	0.095 (0.003)	100.90 (1.18)	0.108 (0.006)
"SLOW" (closest fit)	130.09 (3.58)	0.106 (0.008)	95.79 (4.39)	0.150 (0.029)
"FAST" (closest fit)	159.00 (4.24)	0.093 (0.005)	99.22 (3.82)	0.148 (0.021)

FIGURE 2.5 : Comparison of a computed age-length distribution and its corresponding von Bertalanffy curve for the "overall" growth estimate of male *J. lalandii* (a) and von Bertalanffy growth curves for the "overall" estimate, "slow" and "fast" growth (b).

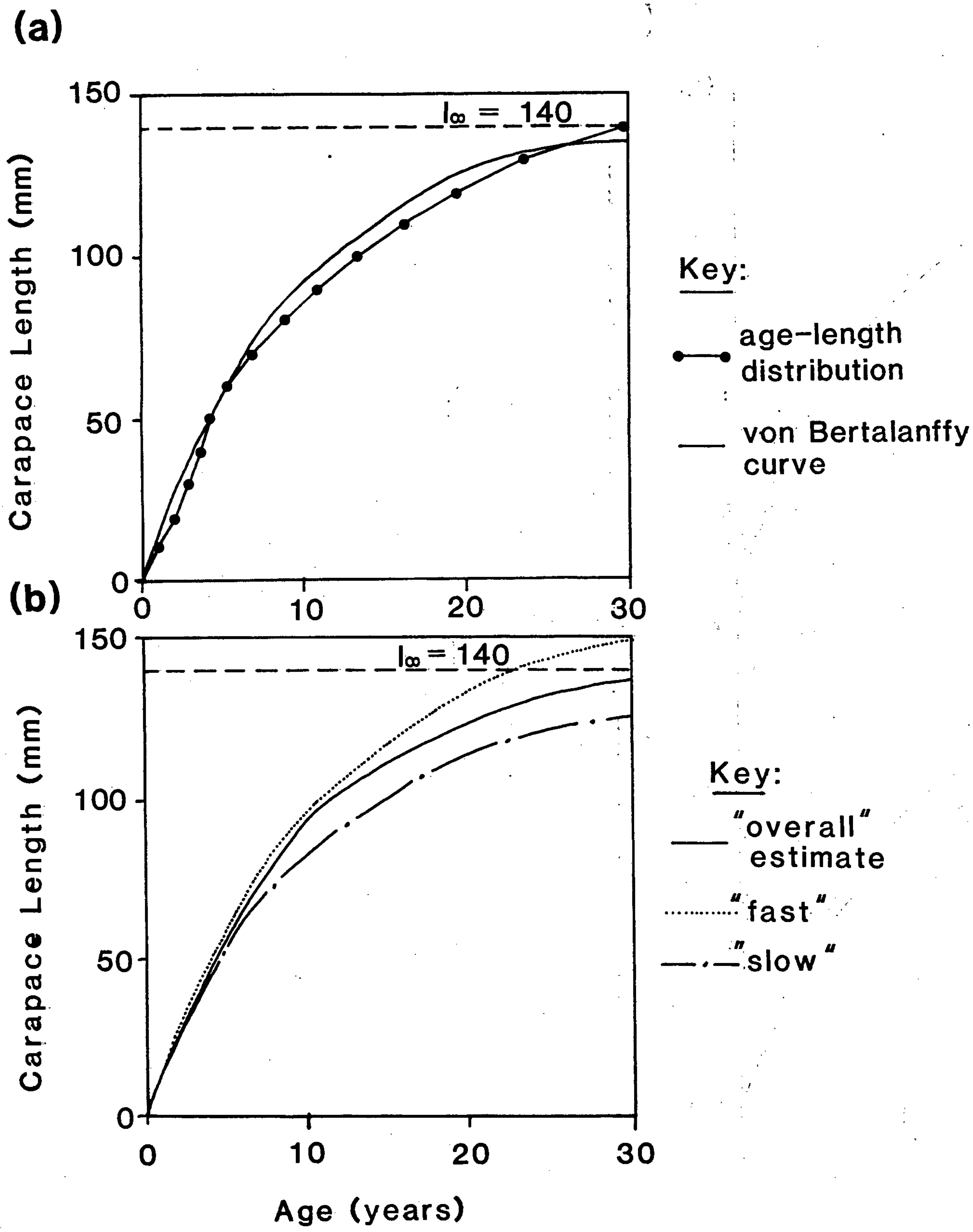
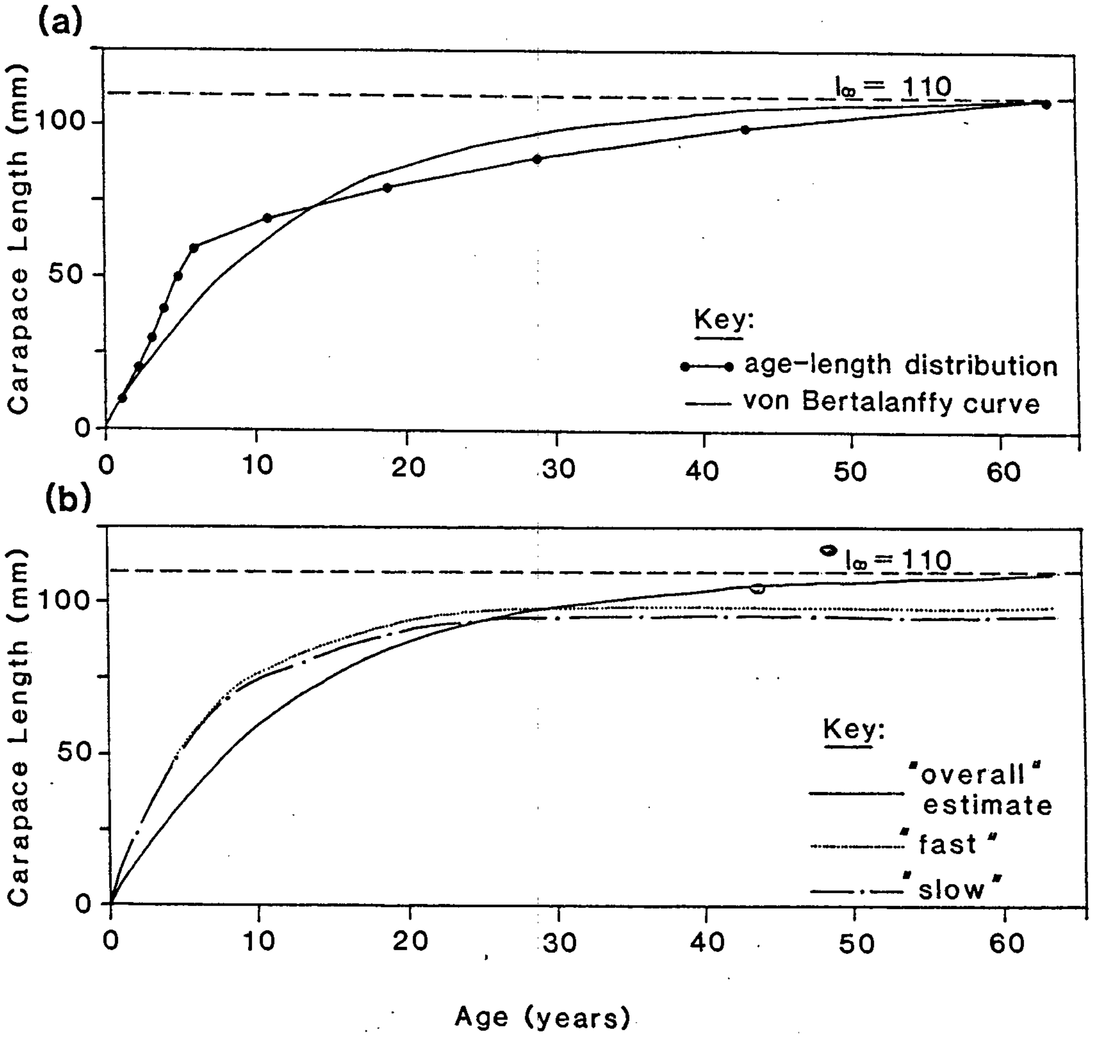


FIGURE 2.6 : Comparison of a computed age-length distribution and its corresponding von Bertalanffy curve for the "overall" growth estimate of female *J. lalandii* (a) and von Bertalanffy growth curves for the "overall" estimate, "slow" and "fast" growth (b).



however, problems with measuring growth in this particular mussel species. Firstly, at Marcus Island there are some cases of negative growth in length (A. Barkai, unpublished data) because mussels expand in the width. Secondly, A. ater form multilayer beds in which the individuals on the top are able to filter more efficiently and therefore possibly grow faster. Thus growth in one area is very variable, being highly density-dependent. Seed (1969) suggests that the slow growth rates of mussels are partly attributable to their sessile habit in that they are unable to move away from environmental conditions which may be unfavourable. Baird (1966) showed that Mytilus edulis which are subjected to greater exposure to the air by the tide show reduced growth rates which can be increased if they are moved experimentally to lower tidal levels. Similar observations of a decrease in growth rate at higher shore levels have been made for Choromytilus meridionalis (Griffiths, 1981) and for Mytilus edulis (Newcombe, 1935; Suchanek, 1978).

Table 2.7 gives estimates of time taken by some mussel species in different areas to reach various lengths and the corresponding time taken by A. ater using the "overall" growth estimate given here. A. ater appears to grow slowly in comparison to the other estimates apart from those presented for Choromytilus meridionalis in False Bay (S.A. south coast). Mossop (1922) gives estimates for Mytilus edulis growth as 16.0 mm (Nova Scotia), 10.8 - 14.8 mm (New Brunswick) and 8.4 mm (Hudson Bay) per growing season. du Plessis (1977) measured a 76 mm increase in 2 years of growth of Choromytilus meridionalis in Saldanha Bay (S.A. west coast). These estimates are much faster than the A. ater increments given here. Cook (1978) estimates an annual increment of 1 $mm.yr^{-1}$ for A. ater individuals 10 - 30 mm in length at Duinefontein on the S.A. west coast, kept at ambient temperature of between 9 and 14 °C. At temperatures 6 °C above ambient this growth was significantly slowed to 0.6 $mm.yr^{-1}$. These increments show extremely slow growth as do those suggested by Griffiths

TABLE 2.7 : Time taken for mussel species from different areas to reach various lengths. Figures in parentheses indicate approximate time in years taken by A. ater at the chosen "overall" growth rate to reach this length.

SPECIES	TIME (years)	LENGTH REACHED (mm)	AREA	SOURCE
Choromytilus meridionalis	1.5 (1.4)	8.3	False Bay (S.A. south coast)	A.H. Fricke, pers. comm.
	5 - 6 (10.1)	55	"	Griffiths, 1981
	1.5 (11.9)	60	Table Bay (S.A. west coast)	B. Currie, unpubl. data (quoted by Griffiths, 1981)
Perna perna	1.0 (11.9)	60	S.A. east coast	Berry, 1978
Mytilus edulis	18.0 (33.0)	80	Greenland	Theisen, 1973
	2.4 (1.9)	14 - 16	England	Seed, 1969
	1.5 - 4.0 (33.0)	70 - 90	Wales	Baird, 1966

and King (1979b) for _A. ater_ at less than 1 mm per month. Griffiths (1981) found that _Choromytilus meridionalis_ growth was best defined by the von Bertalanffy equation. Theisen (1973) working with the growth rings of _Mytilus edulis,_ fitted a Gompertz curve up to half of maximum size and a von Bertalanffy curve from 1/3 of maximum size up to the maximum size. The best curve for mussels is probably somewhere between these two as a Gompertz curve was originally fitted to _A. ater_ data (Griffiths and King, 1979b) and a von Bertalanffy curve gave the best fit in this study.

Lobsters

There are two sets of data for each sex, one for juveniles (< 60 mm carapace length) from aquarium measurements and a set for adults from field estimates. A sharp decline in growth is shown at the changeover from one set to the other (see Fig 2.2). Juvenile lobster growth does not always show the same trend as that of the adults because they inhabit different areas (Pollock _et al._, 1982). While this changeover may represent a true change as the juveniles become mature, it may simply be a reflection of the separate data sets. The decline is greater in females which is to be expected since more energy is put into reproduction and less into growth once they become sexually mature. This is also the reason for their smaller maximum size. Pollock (1973) suggests that _J. lalandii_ takes approximately 9 years to reach size at recruitment into the fishery (89 mm carapace length) and this is similar to the time taken assuming the "fast" growth rate presented for males (9.8 years). For comparison, the clawed lobster, _Homarus americanus_ takes approximately half the time to reach marketable size (5 years, Hughes and Matthiesen, 1962; Marchessault _et al._, 1976).

Table 2.8 shows there is considerable variation in mean annual increment of juvenile lobsters of different species at different areas but the values are notably larger than adult increments (see Tables 2.9 and 2.10). Growth

TABLE 2.8 : Annual growth increments for juveniles or "whites" of various spiny lobster species at different localities estimated by different authors using various methods of growth estimation. The mean is calculated from values given from all sample sites at the locality over all size classes weighted according to the number sampled in each size class.

SPECIES	CARAPACE LENGTH (mm)	ANNUAL GROWTH INCREMENT (mm.yr^{-1})		AREA	SOURCE
		RANGE	MEAN		
Jasus lalandii	15 - 60	8.3 - 14.8	12.0	S.A. west coast	Pollock, 1973
Panulirus homarus	20 - 55	22.7 - 45.1	32.5	"	Berry, 1971
Panulirus cygnus					
male	-	0.6 - 22.0	10.2	Western Australia	Chittleborough, 1976
	68 - 86	-	16.0	"	George, 1958
female		0.8 - 21.0	9.6	"	Chittleborough, 1976
	64 - 84	-	15.0	"	George, 1958
Panulirus versicolor	9 - 21	21.6 - 43.2	32.4	Vizinham Bay, India	Kuthalingham et al., 1980

of juvenile J. lalandii is similar to that of the other tabulated species except for Panulirus homarus (S. A. west coast) and Panulirus versicolor (India) which grow faster. Tables 2.9 and 2.10 show that in all spiny lobster species except for Panulirus interuptus from southern California, adult males tend to grow faster than the females. Within the adult J. lalandii measurements given in the literature from various areas off the S.A. west coast, there is variation in mean increments in carapace length (2.3 - 6.5 mm.yr^{-1} for males, 0.6 - 5.9 mm.yr^{-1} for females). Similarly, Cook (1978) gives annual increments of 2.9 ± 0.1 and 4.5 ± 0.1 for both sexes of J. lalandii in the size range 55 to 90 mm carapace length at Duinefontein on the S. A. west coast held at ambient (9 - 14℃) and 6℃ above ambient, respectively. An annual increment of 7.8 mm and increment range of 5 - 12+ mm for J. novaehollandiae (40 - 99 mm in carapace length) held in aquaria in South Australia was calculated from the data presented by Fielder (1964). This is a large increment compared to the estimates from South Africa. Peacock (1974) also gives fairly large increments of 5.6 - 8.6 mm for the tropical Panulirus argus of both sexes 50 - 100 mm in carapace length from Antigua and Barbuda in the West Indies. Mean growth increments for all the other species fall in the upper part and above the ranges given for J. lalandii, apart from Panulirus gilchristi, found on the east coast of South Africa which has very slow growth in both sexes. Panulirus interruptus from southern California appears to have rapid growth, well above the range for the other species at 17.0 mm (male) and 20.0 mm (female). Males of most spiny lobster species attain a greater maximum size than females (Kanciruk, 1980). It is interesting to note that female P. interruptus from southern California seem to have a faster growth rate than males and also reach a greater maximum size (data was calculated from size-frequency distributions). Thus all the evidence suggests that J. lalandii is a relatively slow growing species of spiny lobster.

Hiatt (1948) diagrams have been produced for many lobster species. These

TABLE 2.9 : Annual growth increments for adult males of various spiny lobster species at different localities calculated from measurements given by various workers using a variety of methods for growth estimation. The mean is calculated from values given from all sample sites at the locality over all size classes weighted according to the number sampled in each size class. Means in double parentheses are not weighted.

SPECIES	CARAPACE LENGTH (mm)	ANNUAL GROWTH INCREMENT (mm.yr^{-1})		AREA	SOURCE
		RANGE	MEAN		
Jasus lalandii	70 - 110	2.9 - 4.6	3.7	Cape Peninsula	Newman & Pollock, 1977
	80 - 130	2.2 - 3.7	3.5	Cape Peninsula - aquaria	P. Zoutendyk, unpubl. data
	65 - 150	2.8 - 8.2	6.5	Robben Island	Pollock & Beyers, 1981
	70 - 110	4.3 - 4.6	4.4	Dassen Island	Newman & Pollock, 1977
	80 - 120	3.0 - 4.4	4.4	St Helena Bay -Saldahna Bay	Pollock *et al.*, 1982
	80 - 110	2.8 - 4.8	4.4	Lamberts Bay -Elands Bay	Pollock, 1982
	60 - 110	1.0 - 2.8	2.3	Port Nolloth - aquaria	"
	60 - 110	3.0 - 5.0	3.0	Marshall Rocks (N of Luderitz)	Beyers, 1979
	70 - 140	1.5 - 6.0	((3.8))	"Overall" estimate, S.A. west coast	D.E. Pollock, pers. comm.
	70 - 140	0.5 - 5.0	((2.8))	"Slow" estimate, S.A. west coast	"
	70 - 140	2.5 - 7.0	((4.8))	"Fast" estimate, S.A west coast	"
	70 - 119	4.8 - 5.8	4.9	South western Cape - aquaria	Paterson, 1969
Jasus tristani	60 - 110	3.0 - 6.9	6.4	Nightingale Island	Pollock, 1981
	75 - 110	3.0 - 7.0	5.0	"	Pollock & Roscoe, 1977
	60 - 100	4.4 - 5.5	5.1	Tristan da Cunha	Pollock, 1981
	80 - 105	3.0 - 5.0	4.0	"	Pollock & Roscoe, 1977
	60 - 110	3.4 - 4.8	4.5	Inaccessible Island	Pollock, 1981
	70 - 110	5.7 - 7.3	6.4	Gough Island	"
Jasus edwardsii	85 - 90	1.0 - 5.0	-	New Zealand	Bradstock, 1950
	55 - 105	4.2 - 6.0	5.2	"	Street, 1969
Panulirus gilchristi	60 - 80	1.4 - 1.7	1.5	Port Alfred, S.A. east coast	Pollock & Augustyn, 1982
Panulirus cygnus	age 6-12 yrs	4.8 - 5.4	5.0	Aquaria (25°C)	Phillips *et al.*, 1983
	age 6-12 yrs	1.9 - 7.2	5.8	Aquaria (20°C)	"
	66 - 119	8.0 - 11.0	((10.0))	Western Australia	Sheard, 1962
Panulirus homarus	68 - 93	5.5 - 13.4	7.4	S. A. east coast	Berry, 1971
Panulirus interruptus	82 - 125		17.0	Southern California	Backus, 1960

are graphical representations showing two lines, one being some factor of growth per moult and the other, length of intermoult period, both over carapace length. This method which combines the above two factors produces a curve which closely approximates the von Bertalanffy-type curve (Morgan, 1980). The diagrams are designed for Crustacea and are analogous to Ford-Walford plots constructed for fish (Mauchline, 1976). However, in general, crustacean intermoult periods increase logarithmically with size whereas time between growth events in fish is linear. Similarly, Phillips et al. (1983) used ARGR (average relative growth rate) plotted against intermoult period. Adult J. lalandii moult once a year (Heydorn, 1965, 1969b; Newman and Pollock, 1971, 1974a) resulting in a constant intermoult period with increasing size so Hiatt diagrams and ARGR's are not applicable.

The best description of growth of several spiny lobster species is provided by the von Bertalanffy curve although the variation around the curve makes an accurate description difficult (Morgan, 1980). He suggests that variation is due to changes in moult increment and frequency, exhibited in response to environmental pressures such as food supply and temperature. Seiderer et al. (1982) calculated von Bertalanffy k values in the range of 0.06 to 0.10 for male J. lalandii, using growth rates observed by Newman and Pollock (1977) in different areas. The range calculated here for different adult growth rates estimated by D.E. Pollock (pers. comm.) yields similar values (see Table 2.6). For females, Seiderer et al. (1982) give a k of 0.196 while the value used here (Table 2.6) is somewhat lower, indicating slower rates. Although the age at maximum size appears very old, it is likely that at very slow rates, the individuals do not survive to reach the larger sizes. Von Bertalanffy curves have been fitted to growth data for Jasus novallandiae (Bradbury, 1977; Lewis, 1977), Panulirus homarus (Smale, 1978), Panulirus argus (Munro, 1974), Panulirus cygnus (Morgan, 1977) and juvenile Panulirus cygnus (Chittleborough, 1976). The adequacy of the von Bertalanffy function depends on the validity of several

TABLE 2.10 : Annual growth increments for adult females of various spiny lobster species at different localities calculated from measurements given by various workers using a variety of methods for growth estimation. The mean is calculated from values given from all sample sites at the locality over all size classes weighted according to the number sampled in each size class. Means in double parentheses are not weighted. Ranges given in parentheses are those determined from different sample sites of an area as no size class data are given.

SPECIES	CARAPACE LENGTH (mm)	ANNUAL GROWTH INCREMENT ($mm.yr^{-1}$)		AREA	SOURCE
		RANGE	MEAN		
Jasus lalandii	70 - 90	0.8 - 1.1	0.9	Cape Peninsula	Newman & Pollock, 1977
	60 - 110	0.3 - 2.5	-	Robben Island	D.E. Pollock, unpubl. data
	70 - 100	0.4 - 1.1	0.6	Dassen Island	Newman & Pollock, 1977
	-	(0.7 - 2.0)	0.9	St Helena Bay -Saldahna Bay	Pollock et al., 1982
	89 - 94	(0.0 - 2.8)	1.0	Lamberts Bay -Elands Bay	Pollock, 1982
	60 - 90	0.2 - 0.9	0.7	Marshall rocks (N of Luderitz)	Beyers, 1979
	70 - 110	0.5 - 2.0	((1.3))	"Overall" estimate, S.A. west coast	D.E. Pollock, pers. comm.
	70 - 110	0.3 - 1.5	((0.9))	"Slow" estimate, S.A. west coast	"
	70 - 110	0.5 - 2.5	((1.5))	"Fast" estimate, S.A. west coast	"
	20 - 109	3.7 - 11.5	5.9	Southern Cape	Paterson, 1969
Jasus tristani	60 - 110	0.0 - 2.7	1.9	Nightingale Island	Pollock, 1981
	60 - 100	0.5 - 2.7	1.5	Tristan da Cunha	"
	-	-	1.0	"	Pollock & Roscoe, 1977
	60 - 100	1.8 - 2.0	1.0	Inaccessible Island	Pollock, 1981
	70 - 90	1.9 - 2.0	1.9	Gough Island	"
Panulirus gilchristi	60 - 80	0.7 - 1.7	1.0	Port Alfred, S.A. east coast	Pollock & Augustyn, 1982
Panulirus cygnus	age 6-11 yrs	1.0 - 2.4	2.1	Aquaria (25 °C)	Phillips et al., 1983
	age 6-9 yrs	3.0 - 8.5	4.7	Aquaria (20 °C)	"
	68 - 91	6.0 - 10.0	((10.0))	Western Australia	Sheard, 1962
Panulirus homarus	65 - 97	3.4 - 12.4	7.1	S. A. east coast	Berry, 1971
Panulirus interruptus	84 - 142	-	20.0	Southern California	Backus, 1960

inherent assumptions. The most important of these is that the growth rate in one year is constant, having no within-season variations although this is not a true reflection of the natural situation (Morgan, 1980). When juveniles emigrate from the shallow water they are exposed to a new set of environmental pressures so Chittleborough (1976) suggests that growth is not well represented by a single von Bertalanffy curve. Therefore a modified form of the von Bertalanffy equation may provide the most realistic description of the growth process in panulirid populations, although the von Bertalanffy equation gives the best fit to this J. lalandii growth data.

CHAPTER 3

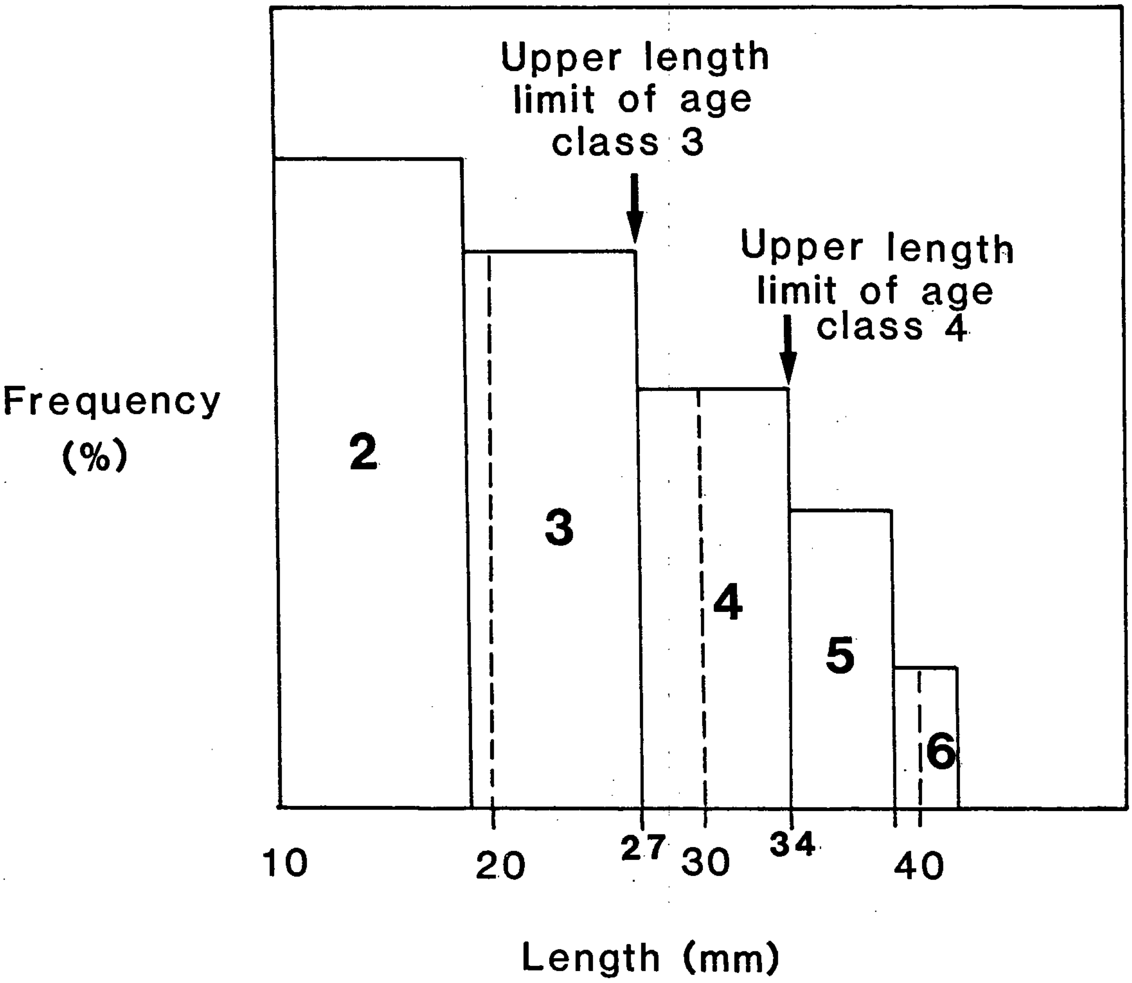
Concepts, assumptions and equations of the models

CHAPTER 3 : CONCEPTS, ASSUMPTIONS AND EQUATIONS OF THE MODELS

The models have been constructed in such a way that two single-species models of lobster and mussel populations may be used separately or they may be linked to form a lobster-mussel interaction model. Appendix C and D give the documentation and code for the computer program "LOBMUS" that was written to run the models. Since annual trends are being observed and considering the longevity of the animals, a discrete model with a time step of one month was considered appropriate. This made the implementation of details such as fishing season, annual moult in a particular month and the interaction between species practical. The whole area of habitation at a particular lobster ground and the entire life cycle of *Jasus lalandii* and *Aulacomya ater* individuals are modelled. It is naturally desirable for fisheries management to know if the lobster populations in different areas remain separate or whether they intermingle, since fishing operations in a given area may affect stocks in neighbouring areas if there is migration (Street, 1969). Longshore migrations over sandy bottoms occur regularly in the South African east coast rock lobster, *Panulirus homarus* (Pollock, 1978) and in the New Zealand lobster *Jasus edwardsii* (Street, 1969), causing a mixing of stocks. Heydorn (1969b) and Pollock (1978) observed that in *J. lalandii* there is little migration of exploited size classes between fishing grounds on the South African west coast where rocky shores are commonly separated by sand. This helps maintain discrete stocks in different areas so these migrations do not need to be modelled.

The upper length limit of one age class is the lower length limit of the following age class, and the number of individuals in an age class is evenly distributed between the its length limits (Fig. 3.1). . For mussels length is given as total length whereas for lobsters carapace length is used. Age classes incorporate one year class, and size classes have a range of 10 mm. In the equations, an "a" or "s" and similarly "ma", "la", "ms",

FIGURE 3.1 : Hypothetical example of a size-frequency distribution in which the bars represent the number in each age class. It indicates the size range of each age class and that the number of individuals is assumed to be evenly distributed between the length limits of the class.



or "ls" as a subscript indicates a mussel or lobster age or size class respectively. "SIZE", and "MSIZE", "LSIZE", "MAGE" or "LAGE" indicate the total number of mussel or lobster size and age classes respectively. No constraints are placed on any of the parameters.

AGE - SIZE CONVERSION

Data for a population parameter, collected in the field as well as experimentally in the laboratory, are usually separated according to the size of individuals. However, in a model simulating a population in which individuals are growing, individuals should be separated by age rather than by size. Therefore, in order to be able to use existing size class data (age class data are extremely difficult to obtain), variables need to be calculated to specify the fractions of each age class that fall into different size classes . In the example given in Fig. 3.1, 3/7 of the individuals in age class 4 fall into the size class 20 - 30 mm while the remaining 4/7 fall into the next size class. In order to calculate the fraction of a mussel or lobster age class (a) that falls into each size class, the upper (MAX) and lower (MIN) limits of an age class are computed as follows :

$$MIN = \left\{ \begin{array}{ll} LEN_{a-1} & (a \neq 1) \\ \left. \begin{array}{ll} JUVLEN & (MON = MOULT) \\ 0 & (MON \neq MOULT) \end{array} \right\} & (\text{lobsters, } a = 1) \\ \left. \begin{array}{ll} MON \times GRO_1 & (MON \neq 0) \\ 0 & (MON = 0) \end{array} \right\} & (\text{mussels, } a = 1) \end{array} \right.$$

$$MAX = LEN_a$$

LEN is the upper length limit of an age class; MON is the current month; JUVLEN is the upper length limit (10 mm carapace length) of the first age class (approximated from Silberbauer, 1971); GRO_1 is the monthly growth increment for mussels in size class 1 and MOULT is the month in which annual lobster moulting occurs. The month of lobster moulting is taken for simplicity as one month although moulting of a population usually extends over a period of 3 to 4 months (Heydorn, 1969b; Newman and Pollock, 1974a). Since the purpose of the model is to look at harvesting strategies, and males form the largest percentage of the catch, a single month, corresponding approximately to the male moult period was chosen. This annual event is modelled in October (month 10) although females usually moult earlier towards midyear (Heydorn, 1969b; Newman and Pollock, 1974a) and juveniles moult 2 to 4 times annually (Pollock, 1973). The separate equations for the first age class are merely a result of there being no "a - 1" class to give a lower limit to this age class.

For each age class (a), the fraction (FRAC) falling into each size class (s) is calculated for each of the seven possible cases by the following equations where SIZ is the upper length limit of a size class; MIN and MAX are the lower and upper limits of an age class respectively. Using these fractions, average parameter values can be computed for each age class from the relative proportions of size class values.

$$\text{For } s = 1,\text{SIZE} \quad \text{FRAC}_{s,a} = \begin{cases} 1 & \begin{pmatrix} \text{MIN} >= \text{SIZ}_{s-1} \\ \text{MAX} \quad \text{SIZ}_{s} \end{pmatrix} \\[2ex] 1 & (\text{MIN} = \text{MAX}) \\[2ex] \dfrac{\text{SIZ}_s - \text{MIN}}{\text{MAX} - \text{MIN}} & \begin{pmatrix} \text{MIN} <= \text{SIZ}_{s} \\ \text{MIN} >= \text{SIZ}_{s-1} \\ \text{MAX} >= \text{SIZ}_{s} \end{pmatrix} \\[2ex] \dfrac{\text{MAX} - \text{SIZ}_{s-1}}{\text{MAX} - \text{MIN}} & \begin{pmatrix} \text{MIN} <= \text{SIZ}_{s-1} \\ \text{MAX} <= \text{SIZ}_{s} \\ \text{MAX} >= \text{SIZ}_{s-1} \end{pmatrix} \\[2ex] \dfrac{\text{SIZ}_s - \text{SIZ}_{s-1}}{\text{MAX} - \text{MIN}} & \begin{pmatrix} \text{MIN} <= \text{SIZ}_{s-1} \\ \text{MAX} >= \text{SIZ}_{s} \end{pmatrix} \\[2ex] 0 & (\text{MAX} <= \text{SIZ}_{s-1}) \\[2ex] 0 & (\text{MIN} >= \text{SIZ}_{s}) \end{cases}$$

LOBSTER - MUSSEL INTERACTION

The following set of equations link the lobster and mussel populations for the lobster-mussel model. In order to calculate monthly mussel availability and lobster consumption requirements, the number of male and female lobsters and mussels in each of their respective size classes (FREQ) are determined by the sum of the fractions (FRAC) of the number (NUM) in each age class (a) that fall into a particular size class (s).

$$\mathrm{FREQ}_{s} = \sum_{a=1}^{AGE} \mathrm{FRAC}_{s,a} \times \mathrm{NUM}_{a}$$

Male and female lobsters are assumed to have the same requirements in terms of number and sizes of mussels consumed. The number of mussels eaten (NUMEAT) from a mussel size class (ms) by each lobster size class (ls) is the product of the optimal number of mussels required by one lobster (NUMOPTEAT) and the total number in the lobster size class (FREQ). The total number of mussels eaten from a mussel size class is the sum of the number of this size eaten by each lobster size class (TOTEAT).

For ms = 1,MSIZE $\mathrm{NUMEAT}_{ls,ms} = \mathrm{NUMOPTEAT}_{ls,ms} \times \mathrm{FREQ}_{ls}$

$$\mathrm{TOTEAT}_{ms} = \sum_{ls=1}^{LSIZE} \mathrm{NUMEAT}_{ls,ms}$$

A fraction (REM) of the mussel population is assumed to be unobtainable to the lobsters but the lobsters are assumed to be able to find and eat every remaining mussel in order to consume an optimal amount of energy. If the total number of mussels required (TOTEAT) from one size class (ms) is greater than the obtainable number of mussels in that size class (MUSFREQ x (1 - REM)) then the number eaten (NUMEAT) is altered by the ratio of mussel availability to total number of mussels required for consumption from that size class. The total number eaten by each lobster size class (ls) is reduced to the number available. In this way there is no discrimination between size classes of lobster, they are all given equal opportunity to consume similar size mussels.

For ls = 1,LSIZE $\mathrm{NUMEAT}_{ls,ms} = \mathrm{NUMEAT}_{ls,ms} \times \dfrac{\mathrm{MUSFREQ}_{ms} \times (1 - \mathrm{REM})}{\mathrm{TOTEAT}_{ms}}$

$$\mathrm{TOTEAT}_{ms} = \mathrm{MUSFREQ}_{ms} \times (1 - \mathrm{REM})$$

Lobsters show punctuated growth, in that increase in size only occurs in the period immediately after a moult and for the remaining time they eat merely to maintain growth of tissues. D.E. Pollock (pers. comm.) has suggested that immature lobsters may not be as dependent on mussels for food as the older individuals, thus the growth rate of lobsters smaller than 60 mm carapace length has been made independent of mussel availability. Adult J. lalandii generally moult once a year (Heydorn 1965, 1969b; Newman and Pollock, 1971, 1974a) so it is the growth increment not intermoult period that is probably affected by lack of food. It is assumed that there is sufficient food other than A. ater, such as other mussel species, polychaete worms, urchins, kelp, other crustaceans including lobsters (Heydorn, 1969b; Newman and Pollock, 1974b; Pollock, 1978, 1979) and barnacles (A. Barkai, unpublished data) for survival but the availability of this mussel species determines the increment at a moult. The species interaction is therefore one in which lobster growth is limited by the availability of mussels for their consumption. In the month before moulting only, the lobsters suffer a reduced growth rate if insufficient mussels of optimal size are available. The number of kilojoules consumed by each size class (ls) of male or female lobster (KJEAT) is the number eaten (NUMEAT) from a mussel size class (ms) multiplied by the energy value of a mussel that size (MUSKJ).

$$KJEAT_{ls} = \sum_{ms=1}^{MSIZE} NUMEAT_{ls,ms} \times MUSKJ_{ms}$$

The growth increment (GRO) of each male or female size class (ls) is altered by the ratio of kilojoules consumed (KJEAT) to the optimal number of kilojoules required by a size class, where KJOPTEAT is the optimal kilojoule requirement of one lobster and FREQ is the number of lobster per size class.

$$GRO_{ls} = GRO_{ls} \times \frac{KJEAT_{ls}}{(KJOPTEAT_{ls} \times FREQ_{ls})}$$

Therefore the growth rate of a size class may be reduced to a negligible increment if few mussels are available, in which case it is assumed that the lobsters have sufficient energy intake from other sources to subsist but not enough to grow.

MUSSEL DYNAMICS

The change in number (NUM) in each age class (ma) is an exponential function of average natural mortality (MOR) calculated from size class fractions (FRAC) for each age class. In the presence of lobsters, the number in each age class falling into a particular size class is first reduced by the ratio of mussels available (MUSFREQ) to mussels consumed (TOTEAT) from the size class (ms). In this way, equivalent percentages are removed from each age class in the size class. Thereafter only the remaining number are subject to the natural mortality parameter. Although R.J. Griffiths (1977) suggests two spawning periods per year by _A. ater_ at Bloubergstrand on the S.A. west coast, C.L. Griffiths and King (1979a) showed that in the years 1975 to 1977 at Oudekraal, Cape Peninsula, three spawnings by _A. ater_ per year were evident. Three spawning periods were modelled so the first year class of mussels incorporates individuals that are spawned at the end of months 4 (April), 8 (August) and 12 (December) of that year. Larval stages have been disregarded as the mussel trochophore and veliger larvae last for approximately one week before they metamorphose into adults (Branch and Branch, 1981). EGG is the number of eggs spawned each third of a year in particular months (MON) and EGGMOR is the mortality of these eggs. The number of mussels in each age class is given by :

$$
NUM_{ma} = \begin{cases} \left.\begin{array}{ll} \displaystyle\sum_{ms=1}^{MSIZE} FRAC_{ma,ms} \text{ x } NUM_{ma} \text{ x } e^{MOR}{}_{ms} & \text{(Lobsters absent)} \\ \displaystyle\sum_{ms=1}^{MSIZE} FRAC_{ma,ms} \text{ x } NUM_{ma} \text{ x}\left(1 - \frac{TOTEAT_{ms}}{MUSFREQ_{ms}}\right) \text{ x } e^{MOR}{}_{ms} & \text{(Lobsters present)} \end{array}\right\} & (ma > 1) \\ NUM_{1} + EGG \text{ x } e^{-EGGMOR} & (ma = 1,\ MON = 4 \text{ or } 8) \end{cases}
$$

Originally the increase in upper length limit of each age class was implemented using an average monthly growth increment for each age class, calculated using the fractions from each size class. However, this led to one age class overtaking the succeeding age class if it spanned two size classes, an artefact of using difference equations in a discrete model as opposed to differential equations in a continuous model. Therefore the growth increment is calculated in such a way that no overtaking can occur. The change in upper length limit (LEN) of each age class (ma) is simply the addition of a growth increment (GRO) for the class if the age class does not span two size classes. Alternatively, it is the upper length limit (SIZ) of the lower size class (ms) plus a fraction of the growth increment of the next size class, if the lower size class is not the largest class. Since the individuals of an age class in the larger size will grow one full increment, no overtaking can occur. Once a length limit that is greater than or equal to that of the largest size class (MSIZE) is reached, this age class is taken to be the oldest and its length limit is set to maximum size. Thus the upper length limit of mussels is given by :

$$LEN_{ma} = \begin{cases} \left.\begin{array}{ll} SIZ_{ms} + GRO_{ms+1} \times 1 - \dfrac{(SIZ_{ms} - LEN_{ma})}{GRO_{ms}} & \\ & (ms \neq MSIZE) \\ SIZ_{MSIZE} & (ms = MSIZE) \end{array}\right\} & \left(\dfrac{(SIZ_{ms} - LEN_{ma})}{GRO_{ms}} < 1\right) \\ LEN_{ma} + GRO_{ms} & \left(\dfrac{(SIZ_{ms} - LEN_{ma})}{GRO_{ms}} >= 1\right) \end{cases}$$

LOBSTER DYNAMICS

The fraction (LIMFRAC) of each age class (la) that exceeds the minimum catchable size (CATLIM) is calculated for each sex, as follows :

$$LIMFRAC_{la} = \begin{cases} 0 & (LEN_{la} <= CATLIM) \\ \dfrac{LEN_{la} - CATLIM}{LEN_{la} - LEN_{la-1}} & \begin{pmatrix} LEN_{la-1} < CATLIM \\ LEN_{la} > CATLIM \end{pmatrix} \\ 1 & (LEN_{la-1} >= CATLIM) \end{cases}$$

Males and females have equivalent equations calculating the change in number and upper length limit of each age class. The change in number (NUM) of individuals in an age class (la) is an exponential function of average mortality for that class calculated from the size class fractions (FRAC) for each age class. During the fishing season, this average mortality is equivalent to the natural mortality (MOR) of individuals below the minimum catchable size and for the harvestable-sized individuals, it is a combination of fishing (FIS) and natural mortality.

$$NUM_{la} = \sum_{ls=1}^{LSIZE} \begin{cases} FRAC_{la,ls} \times NUM_{la} \times e^{MOR}{}_{ls} & \text{(Out of fishing season)} \\ FRAC_{la,ls} \times NUM_{la} \times e^{MOR}{}_{ls} \times ((1 - LIMFRAC_{la}) + LIMFRAC_{la} \times e^{-FIS}{}_{ls}) & \text{(During fishing season)} \end{cases}$$

Increase in carapace length is implemented in month 10 (October) each year corresponding to the male moult period. The upper length limit (LEN) of each age class (la) is calculated as for mussels, except this is done annually.

$$LEN_{la} = \begin{cases} \left.\begin{matrix} SIZ_{ls} + GRO_{ls+1} \times 1 - \dfrac{(SIZ_{ls} - LEN_{la})}{GRO_{as}} & (ls \neq LSIZE) \\ SIZ_{LSIZE} & (ls = LSIZE) \end{matrix}\right\} & \left(\dfrac{(SIZ_{ls} - LEN_{la})}{GRO_{ls}} < 1\right) \\ LEN_{la} + GRO_{ls} & \left(\dfrac{(SIZ_{ls} - LEN_{la})}{GRO_{ls}} >= 1\right) \\ LEN_{la} & (GRO_{ls} = 0) \end{cases}$$

STOCK-RECRUITMENT RELATIONSHIPS

Specific areas are simulated, each inhabited by sub-populations of the S.A. west coast stocks of mussels and lobsters. C.L. Griffiths (pers. comm.) suggests that a mussel stock-recruitment relationship for a particular ground is meaningless as does D.E. Pollock (pers. comm.) for lobsters since the planktonic larval stages drift great distances. Although this is not entirely realistic, spawning in a specific area is not an indication of the number of recruits that may return to that site. Recruitment is a function of many biotic and abiotic factors during the wide dispersal phase of the larvae. Chittleborough and Phillips (1975) suggest that density-dependent mortality of juvenile *Panulirus cygnus* in Western Australia lobster results in similar numbers surviving to post-larval stages irrespective of wide differences in density at or soon after larval settlement, provided that the initial stocking rate is sufficiently large.

Although D.E. Pollock (pers. comm.) suggested that a stock-recruitment relationship for lobsters is not meaningful, theoretical simulations to test the effect of such a relationship on harvesting strategies were desirable. Morgan *et al.* (1982) have suggested that a Ricker (1958) stock-recruitment relationship fits data for puerulus settlement and a relative abundance of spawning stock of *Panulirus cygnus* in Western Australia. They suggest that there are stock-dependent effects during the planktonic stages which control the level of puerulus settlement and consequently the magnitude of recruitment to the fishery. Since there would be no basis for estimating density-dependent and -independent mortality for a stock-recruitment relationship such as that of Ricker (1958), a linear relationship of the following form was used :

$$EGG = \sum_{Is=MAT}^{LSIZE} FEC_{Is} \times FREQ_{Is}$$

EGG is the number of recruits to the population and is simply the sum of the fecundity (FEC) per females multiplied by the number of female lobster (FREQ) for each mature size class (Is, starting with MAT). Marchessault *et al.* (1976) used an equivalent linear stock-recruitment relationship in a model of a lobster population (*Homarus americanus*) at Rhode Island. They point out that such a relationship falls short of defining many factors but is a useful management tool that can easily be applied utilizing the available data. The justification for attempting such simulations is that there are different transportation currents to different areas, different settling potential for larval stages and differing habitable space for adults. Therefore, the number of adults living in an area may, to some degree, determine the number of larvae that are able to settle and inhabit the area.

MOVEMENT OF INDIVDUALS THROUGH AGE CLASSES

Mussels : At the end of each year the number of individuals (NUM) in each age class (ma) is moved up into the next age class. As described earlier, there are three spawnings annually, one of which is implemented at the end of each year. This brings one third of the annual number of eggs spawned (EGG), reduced by egg mortality (EGGMOR), into the first age class. Individuals reaching maximum age/size simply stay in this age class, therefore there is an accumulation in the last age class. The upper length (LEN) of each age class is moved up to the next age class at the end of the year and that of the first age class is set to twelve times the monthly growth increment of the first size class (GRO_1).

$$NUM_{ma} = \begin{cases} EGG \times e^{-EGGMOR} & (ma = 1) \\ NUM_{ma-1} & (ma \neq 1 \text{ and } ma \neq MAGE) \\ NUM_{ma} + NUM_{ma-1} & (ma = MAGE) \end{cases}$$

$$LEN_{ma} = \begin{cases} GRO_1 \times 12 & (ma = 1) \\ LEN_{ma-1} & (ma \neq 1) \end{cases}$$

Lobsters : Silberbauer (1971) gives a period of approximately one year from the time of spawning until development into juveniles (> 10 mm carapace length). Data from Heydorn (1969b) and Newman and Pollock (1974a) show that over a period of five years, although there was some fluctuation, June to October is the annual period during which J. lalandii females are in berry with early stage lobster larvae being most common in the plankton in October. Although all the females have spawned by October, the model implements the annual spawning in January of year 1 when the larvae are put into age class 1 which has a set upper length limit (JUVLEN) of 10 mm. It is in the January of year 2 that they become juveniles in age class 2, the upper length limit being set by their growth. At the end of each year, the number (NUM) in each age class is moved up into the next age class. Half of the total number of eggs (EGG) are brought into the first age class of each sex and there is an accumulation of individuals reaching maximum age/size in the last age class. The upper length limit (LEN) of each age class is moved up to the next age class at the end of the year and that of the first age class is set to 10 mm (JUVLEN). The growth rate may speed up if sufficient mussels are available, resulting in fewer age classes so the individuals in the older age classes may be lost. However, generally only one class will be lost at a time and there are very few individuals in the older ages so this is not significant. Equations for males and females are equivalent.

$$\mathrm{NUM}_{la} = \begin{cases} \dfrac{\mathrm{EGG}}{2} & (la = 1) \\ \mathrm{NUM}_{la-1} & (la \neq 1 \text{ and } la \neq \mathrm{LAGE}) \\ \mathrm{NUM}_{la} + \mathrm{NUM}_{la-1} & (la = \mathrm{LAGE}) \end{cases}$$

$$\mathrm{LEN}_{la} = \begin{cases} \mathrm{JUVLEN} & (la = 1) \\ \mathrm{LEN}_{la-1} & (la \neq 1) \end{cases}$$

CHAPTER 4

Data for the models

CHAPTER 4 : DATA FOR THE MODELS

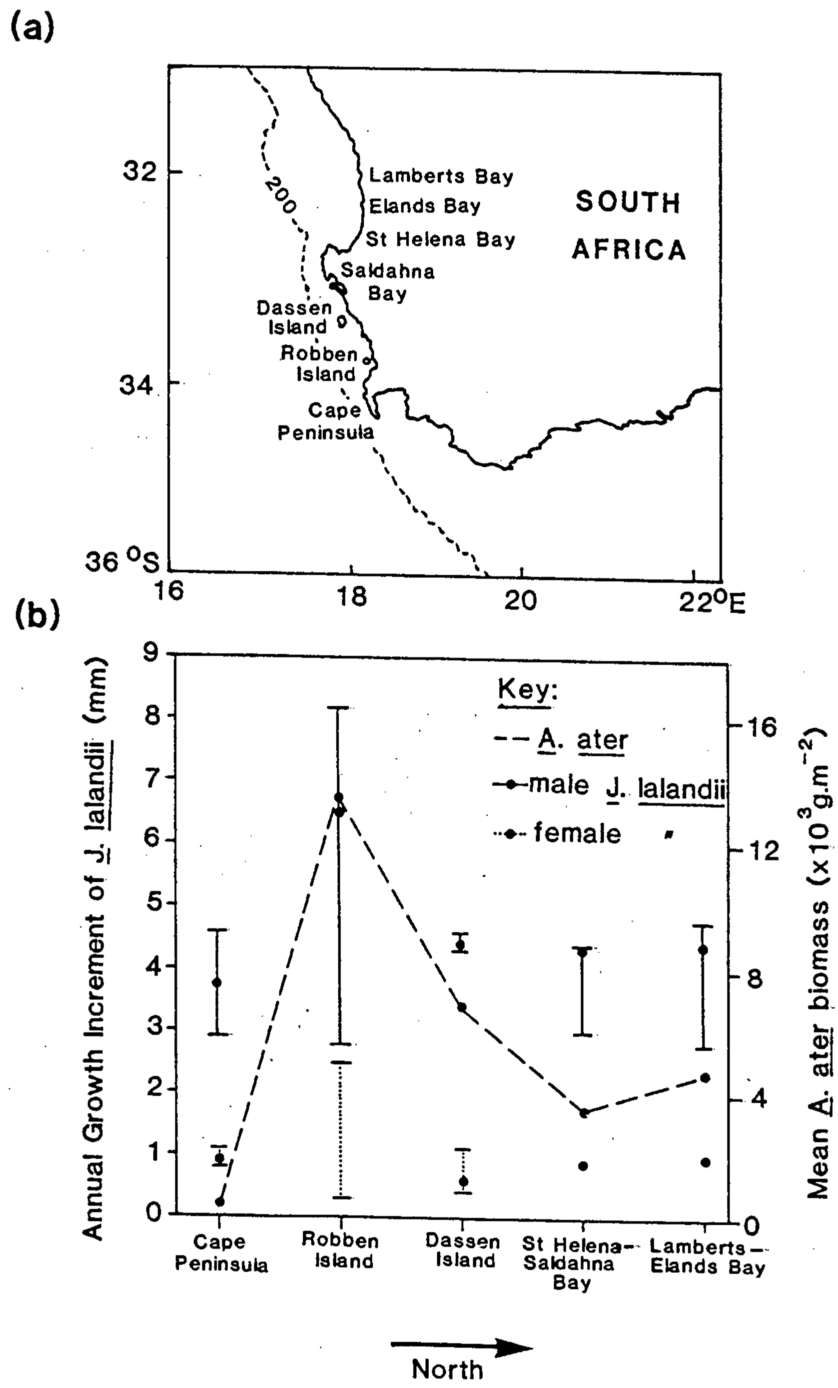
The choice of sites inhabited by Jasus lalandii populations would ideally be two fishing grounds and two sanctuaries (which could be used as controls for the two fishing grounds), one with small and one with large Aulacomya ater biomass. Lobster growth rates and the mean biomass of benthos averaged over all depths at five sites on the South African west coast were calculated from the literature (Fig. 4.1 and Table 4.1). Of the sites for which data were available there was only one sanctuary, Robben Island, where lobsters grow fast. It was proclaimed a sanctuary in 1964; previously it had been a productive fishing ground. The two fishing grounds chosen were the Cape Peninsula where lobsters grow slowly and Dassen Island where lobster growth is intermediate, with sparse and dense benthic biomass respectively (Fig. 4.2). According to commercial catch statistics (Sea Fisheries Research Institute, unpublished data), these two fishing grounds have yielded some 30 to 40 % of the annual J. lalandii harvest on the S.A. west coast in past years.

The number of a size class is given by the upper length limit of the size class in cm, ie : size class 81 - 90 mm is indicated by 9. Parameter values for the 10 mm size classes were calculated using the midpoint of the size class. All size measurements are in mm, rate measurements per month, and age in years. For lobsters, size is measured in terms of carapace length whereas total length is used for mussels. Maximum sizes of 140, 110 and 80 mm were estimated for male and female J. lalandii and A. ater respectively. Some parameters have been estimated with very little experimental and observational validation. These parameters were used in tuning the models by adjusting them until the output of a simulation was shown to approximate the "real" situation. The models were thus used to estimate these parameters by simulation.

TABLE 4.1 : Source of data for Fig. 4.1

AREA	A. ATER DENSITY	J. LALANDII GROWTH RATES	
		MALES	FEMALES
Cape Peninsula	Newman and Pollock, 1977	Newman and Pollock, 1977	Newman and Pollock, 1977
Robben Island	Pollock, 1978	Pollock and Beyers, 1981	Pollock, unpubl. data
Dassen Island	Newman and Pollock, 1974b	Newman and Pollock, 1977	Newman and Pollock, 1977
St Helena Bay - Saldanha Bay	Pollock *et al.*, 1982	Pollock *et al.*, 1982	Pollock *et al.*, 1982
Lamberts Bay - Elands Bay	Pollock, 1982	Pollock, 1982	Pollock, 1982

FIGURE 4.1 : Map (a) and diagram (b) showing areas in which growth of the lobster, *J. lalandii* and the standing stock of the mussel, *A. ater* has been measured. The sources of the data are given in Table 4.1.



MUSSEL DATA

Growth Increments (GRO$_{a,i}$)

Monthly growth increments are given in Table 4.2 for the "overall" growth estimate, "fast" and "slow" growth rates which were suggested as most realistic for *A. ater* (see Chapter 2).

Age - Length Distribution (LEN$_{a,i}$)

Table 4.3 shows the upper length limit of each *A. ater* age class for the range of growth rates computed using the three sets of growth increments in the program "GROWTH" (see Chapter 2).

Natural Mortality (MOR$_{a,i}$)

Griffiths (1981) gives values for the substrate carrying capacity of the black mussel, *Choromytilus meridionalis* of different sizes. The decline in numbers with increase in size is an indication of natural mortality resulting from intra-specific competition for space. She shows that *C. meridionalis* grows 37.4 mm in 3.5 years (approximately 5 mm in 0.5 years). Calculation of the percentage of individuals lost with growth through each 5 mm size class gives estimates of natural mortality in half a year for this mussel species. From this, annual mortality values were calculated and a regression line fitted to the mortality-size data ($r = 0.990$, $n = 9$). This equation was used to produce approximations of natural mortality for different-sized *A. ater* up to 70 mm and mortality in the last size class was made equal to the 7th (Table 4.4). The values are probably overestimates as *A. ater* form multilayer beds so are not entirely limited by substrate surface area. However, Wickens and Griffiths (1985) have suggested that *A. ater* may experience very high mortality rates due to predation, and they are able to absorb such losses because the juveniles have such a high P/B ratio.

TABLE 4.4 : *A. ater* natural mortality computed from natural mortality estimates calculated from Griffiths (1981) for *Choromytilus meridionalis*

SIZE CLASS	ANNUAL	MONTHLY
1	0.937	0.078
2	0.800	0.067
3	0.663	0.055
4	0.526	0.044
5	0.389	0.032
6	0.252	0.021
7	0.115	0.010
8	0.115	0.010

TABLE 4.5 : *A. ater* size-frequency distribution from Robben Island (D.E. Pollock, unpublished data).

SIZE CLASS	PERCENTAGE FREQUENCY
1	91.70
2	7.07
3	0.05
4	0.01
5	0.04
6	0.18
7	0.51
8	0.44

TABLE 4.6 : Population numbers of *A. ater* at three sites off the South African west coast calculated from biomass and area estimates from various sources (see text).

	CAPE PENINSULA	DASSEN ISLAND	ROBBEN ISLAND
MEAN BIOMASS (g.m^{-2})	387	6 833	13 575
TOTAL AREA OCCUPIED BY MUSSELS (km^{2})	134	50	23
TOTAL BIOMASS OF AREA (x 10^{6} g)	51 858	341 650	156 124
TOTAL NUMBER OF MUSSELS IN AREA (x 10^{6})	27 395	180 481	82 474

Age - Frequency Distribution (NUM$_{a}$)

One size-frequency distribution for *A. ater*, obtained from a series of monthly samples at Robben Island from December 1972 to October 1973 at depths of 45', 65' and 90' (D.E. Pollock, unpublished data) is used for all three areas (Table 4.5). A mean *A. ater* biomass (g.m^{-2}) was estimated from samples at various regions and depths off the Cape Peninsula (Newman and Pollock, 1977), Dassen Island (Newman and Pollock, 1977) and Robben Island (Pollock, 1978). Multiplication of these values by total area of each site (Cape Peninsula estimated by Newman and Pollock, 1977; Dassen Island and Robben Island estimated by D.E. Pollock, pers. comm.) yields the total biomass of mussels in each area. The size of an average mussel (6.5 mm) was calculated from the size-frequency distribution and converted to average mussel mass (1.893 g) using the *A. ater* mass-length equation derived under "Mussel Energy Content (MUSKJ)" (see p 41). For each area, the total mussel biomass was converted to total mussel number by dividing by the mass of an average size mussel (Table 4.6).

In order to compute age-frequency distributions for each area at the "overall" growth rate, the program "FREQ" (Appendix E and F) which does not require natural mortality rates, was used because the mussel natural mortality values calculated here are very approximate. The algorithm used in "FREQ" computes an age-frequency distribution from the size composition structure of the population. A cumulative size-frequency distribution is calculated from the percentage size-frequency distribution and total population number. It is assumed that straight lines link the data points corresponding to the cumulative number and upper length of each size class (as in Fig. 2.3, replacing size with cumulative numbers and age with size). Equations for each straight line are calculated and the cumulative number at the estimated upper length of each age class computed by substitution into the relevant equation. The cumulative frequencies are then reduced to absolute numbers per age class by simple subtraction, producing an age-

TABLE 4.7 : Reproductive output of *A. ater* calculated from various sources of data (see text).

SIZE CLASS	ENERGY OUTPUT OF GONAD ($kJ.ind^{-1}.yr^{-1}$)	MASS OUTPUT OF GONAD (dry $g.ind^{-1}.yr^{-1}$)	NUMBER EGGS SPAWNED ANNUALLY ($ind^{-1}.yr^{-1}$)	NUMBER EGGS PER SPAWNING ($ind^{-1}.1/3yr^{-1}$)
2	1.070	0.059	1 247 357	415 786
3	3.610	0.198	4 186 047	1 395 349
4	8.041	0.440	9 302 326	3 100 775
5	14.625	0.800	16 913 319	5 637 773
6	23.578	1.291	27 293 869	9 097 956
7	35.090	1.921	40 613 108	13 537 703
8	49.328	2.700	57 082 452	19 027 484

frequency distribution. The age-frequency distributions are believed to be unstable because the numbers do not decline with age. Nevertheless they are used as a starting point in the model.

Reproductive Output (EGG) and Egg Mortality (EGGMOR)

Estimates of reproductive output in terms of kilojoules per year for *A. ater* of size 15 - 90 mm are given by C.L. Griffiths (unpublished data). Non-linear regression of this data produced the following equation (r^2 = 0.992).

A. ater reproductive output (kJ.individual. yr^{-1}) = 0.0017 x Shell length $(mm)^{2.38}$

Energy output was converted to *A. ater* dry mass using the factor 18.27 $kJ.g^{-1}$ (Wickens and Griffiths, 1985). Thompson (1979) estimated that 10^6 freeze-dried *Mytilus edulis* eggs weigh 47.3 mg. Making the assumption that eggs of *M. edulis* and *A. ater* are comparable in weight, the reproductive output of different-sized *A. ater* was converted to number of eggs spawned per year. Since there are three spawnings per year (Griffiths and King, 1979a), the annual reproductive output was further divided by three to give the number of eggs per spawning (Table 4.7). Size-frequency distributions for the Cape Peninsula, Dassen Island and Robben Island mussel populations were calculated from the percentage size-frequency distribution (D.E. Pollock, unpublished data) and the population number in each area (see "Age Frequency Distribution ($NUM_{a,j}$)", p 31). The number of eggs spawned by different-sized mussels was multiplied by these distributions and the number of eggs produced by the female half of the population in each of these areas totalled. Mean (9.735 x 10^{15}), upper (18.148 x 10^{15}) and lower (2.762 x 10^{15}) estimates of egg production per spawning were calculated for these areas on the S.A. west coast.

Since no data were available for the mortality of mussel eggs, an estimate was made from the ratio of the number of eggs produced in one year to the

TABLE 4.8 : Annual increase in carapace length at different growth rates for male and female *J. lalandii* over their respective size ranges. The rate given for the first size class simply allows one year for larval stages up to a length of 10 mm. Juvenile growth rate data are from Pollock (1973) and adult data are based on ranges given by D.E. Pollock (pers. comm.) (see Chapter 2).

SIZE CLASS	GROWTH RATE (mm.year^{-1})					
	MALES			FEMALES		
Juvenile Growth						
1	10.00			10.00		
2	9.30			8.25		
3	12.02			10.28		
4	14.71			14.01		
5	13.51			12.56		
6	11.74			10.61		
Adult Growth						
	"OVERALL" ESTIMATE	"FAST"	"SLOW"	"OVERALL"	"FAST"	"SLOW"
7	6.00	7.00	5.00	2.00	2.50	1.50
8	5.25	6.50	4.00	1.25	1.50	1.00
9	4.50	6.00	3.00	1.00	1.00	0.50
10	4.00	5.50	2.50	0.70	0.70	0.40
11	3.50	5.00	2.00	0.50	0.50	0.30
12	3.00	4.50	1.50			
13	2.50	4.00	1.00			
14	1.50	2.50	0.50			

calculated number of one year olds. The annual mortality rate was assumed to be approximately in the region of M = 10.6 to 12.5.

LOBSTER DATA

Growth Increments ($GRO_{i,j}$)

Annual increments in carapace length for the "overall" growth estimate, "fast" and "slow" growth rates, for male and female J. lalandii were calculated from the daily values considered most realistic (see Chapter 2) and are given in Table 4.8. Fig. 4.1 indicates that the "overall" estimate, "slow" and "fast" growth rates are appropriate for the Dassen Island, Cape Peninsula and Robben Island lobster populations respectively (supported by D.E. Pollock, pers. comm.).

Age - Length Distributions ($LEN_{i,j}$ and JUVLEN)

Tables 4.9 and 4.10 show the upper length limits of each male and female age class ($LEN_{i,j}$) for the range of growth rates, computed using the three sets of growth increments as data in the program "GROWTH" (see Chapter 2). The upper length limit of the first age class (JUVLEN) was set to 10 mm (approximated from Silberbauer, 1971).

Natural Mortality ($MOR_{i,j}$)

D.E. Pollock (pers. comm.) believes that few eggs are lost from a berried J. lalandii female so that egg mortality may be taken to be negligible. Morgan (1972) has also shown for Panulirus cygnus that there is little egg loss during incubation and that infertile eggs comprise a very small percentage of the total carried (4.5 %). In the larval stages, prolific predation by fish such as the maasbanker, Trachurus trachurus, pilchard, Sardinops ocellata and the longfin tuna, Thunnus alalunga (Heydorn, 1969b) accounts for some mortality. The greatest cause of larval mortality,

TABLE 4.9 : Male _J. lalandii_ age-length distributions for different growth rates computed by the program "GROWTH" (see Chapter 2).

AGE (years)	CARAPACE LENGTH (mm)			AGE (years)	CARAPACE LENGTH (mm) (CONTINUED)
	"OVERALL" GROWTH	"FAST" GROWTH	"SLOW" GROWTH		"SLOW" GROWTH
1	10.0	10.0	10.0	31	122.3
2	19.3	19.3	19.3	32	123.3
3	31.3	31.3	31.3	33	124.3
4	45.5	45.5	45.5	34	125.3
5	57.8	57.8	57.8	35	126.3
6	64.9	65.7	64.1	36	127.3
7	70.7	72.5	69.0	37	128.3
8	76.0	79.0	73.2	38	129.3
9	81.1	85.0	77.2	39	130.1
10	85.5	90.9	80.9	40	130.6
11	90.0	96.4	83.9	41	131.1
12	94.0	101.7	86.9	42	131.6
13	98.0	106.7	89.9	43	132.1
14	101.8	111.5	92.4	44	132.6
15	105.3	116.0	94.9	45	133.1
16	108.7	120.5	97.4	46	133.6
17	111.9	124.5	99.9	47	134.1
18	114.9	128.5	101.9	48	134.6
19	117.9	131.5	103.9	49	135.1
20	120.8	134.0	105.9	50	135.6
21	123.2	136.5	107.9	51	136.1
22	125.7	139.0	109.9	52	136.6
23	128.2		111.4	53	137.1
24	130.4		112.9	54	137.6
25	131.9		114.4	55	138.1
26	133.4		115.9	56	138.6
27	134.9		117.4	57	139.1
28	136.4		118.9	58	139.6
29	137.9		120.3		
30	139.4		121.3		

TABLE 4.10 : Female *J. lalandii* age-length distributions for different growth rates computed using the program "GROWTH" (see Chapter 2).

AGE (years)	CARAPACE LENGTH (mm)			AGE (years)	CARAPACE LENGTH (mm) (CONTINUED)		
	"OVERALL" GROWTH	"FAST" GROWTH	"SLOW" GROWTH		"OVERALL" GROWTH	"FAST" GROWTH	"SLOW" GROWTH
1	10.0	10.0	10.0	51	104.0	105.2	93.5
2	18.2	18.2	18.2	52	104.5	105.7	93.9
3	28.1	28.1	28.1	53	105.0	106.2	94.3
4	41.2	41.2	41.2	54	105.5	106.7	94.7
5	53.2	53.2	53.2	55	106.0	107.2	95.1
6	60.7	60.9	60.5	56	106.5	107.7	95.5
7	62.7	63.4	62.0	57	107.0	108.2	95.9
8	64.7	65.9	63.5	58	107.5	108.7	96.3
9	66.7	68.4	65.0	59	108.0	109.2	96.7
10	68.7	70.5	66.5	60	108.5	109.7	97.1
11	70.4	72.0	68.0	61	109.0		97.5
12	71.7	73.5	69.5	62	109.5		97.9
13	72.9	75.0	70.7	63	110.0		98.3
14	74.2	76.5	71.7	64			98.7
15	75.4	78.0	72.7	65			99.1
16	76.7	79.5	73.7	66			99.5
17	77.9	80.7	74.7	67			99.9
18	79.2	81.7	75.7	68			100.2
19	80.4	82.7	76.7	69			100.5
20	81.3	83.7	77.7	70			100.8
21	82.3	84.7	78.7	71			101.1
22	83.3	85.7	79.7	72			101.4
23	84.3	86.7	80.3	73			101.7
24	85.3	87.7	80.8	74			102.0
25	86.3	88.7	81.3	75			102.3
26	87.3	89.7	81.8	76			102.6
27	88.3	90.5	82.3	77			102.9
28	89.3	91.2	82.8	78			103.2
29	90.2	91.9	83.3	79			103.5
30	90.9	92.6	83.8	80			103.8
31	91.6	93.3	84.3	81			104.1
32	92.3	94.0	84.8	82			104.4
33	93.0	94.7	85.3	83			104.7
34	93.7	95.5	85.8	84			105.0
35	94.4	96.1	86.3	85			105.3
36	95.1	96.8	86.8	86			105.6
37	95.8	97.5	87.3	87			105.9
38	96.5	98.2	87.8	88			106.2
39	97.2	98.9	88.3	89			106.5
40	97.9	99.6	88.8	90			106.8
41	98.6	100.2	89.3	91			107.1
42	99.3	100.7	89.8	92			107.4
43	100.0	101.2	90.3	93			107.7
44	100.5	101.7	90.7	94			108.0
45	101.0	102.2	91.1	95			108.3
46	101.5	102.7	91.5	96			108.6
47	102.0	103.2	91.9	97			108.9
48	102.5	103.7	92.3	98			109.2
49	103.0	104.2	92.7	99			109.5
50	103.5	104.7	93.1	100			109.8

TABLE 4.11 : Natural mortality for male and female *J. lalandii* estimated from monthly natural mortality values suggested by D.E. Pollock (pers. comm.).

SIZE CLASS	MALES		FEMALES	
	ANNUAL	MONTHLY	ANNUAL	MONTHLY
1	12.000	1.000	12.000	1.000
2	0.275	0.023	0.275	0.023
3	0.225	0.019	0.225	0.019
4	0.175	0.015	0.175	0.015
5	0.125	0.010	0.125	0.010
6	0.100	0.008	0.100	0.008
7	0.100	0.008	0.100	0.008
8	0.100	0.008	0.125	0.010
9	0.100	0.008	0.175	0.015
10	0.100	0.008	0.225	0.019
11	0.125	0.010	0.275	0.023
12	0.175	0.015		
13	0.225	0.019		
14	0.275	0.023		

however, is dispersal by currents to areas which are unsuitable for settling of the benthic larvae (Lazarus, 1967). J. lalandii larval counts from Lamberts Bay to Cape Infanta showed that 1012 first stage phyllosoma larvae were reduced to 4 last stage larvae (Lazarus, 1967). Exponential decline from 1012 to 4 over the 7.5 month phyllosoma stages (Silberbauer, 1971) indicates a monthly mortality rate of M = 0.738. To account for the natural mortality of hatching, naupliosoma larvae and the puerulus stage, a monthly mortality of M = 1.0 was estimated for the first year of life, by which time a length of 10 mm has been reached.

Predation on post-larval J. lalandii is fairly rare, occurring mainly when the animal is in soft-shelled condition and unable to defend itself. The predators include the Cape fur seal, Arctocephalus pusillus, hagfish, Heptatretus hexatrema, octopus and various dogsharks and rockfish (Heydorn, 1969b). J.H.M. David (unpublished data), however, has estimated that the first year pups of a seal colony at Kleinsee on the S.A. west coast may eat a large tonnage of lobster during the period July to December. Cannibalism may occur in adults (Pollock, 1978) but this generally only happens in crowded conditions (Paterson, 1969). Death resulting from mechanical damage in the immediate post-moult stage and complications during ecdysis are other forms of mortality (Paterson, 1969). Senility is possibly also a factor (Seed, 1969) and, in terms of the model, natural mortality may include poaching and emigration to more sheltered areas in larger animals (Pollock, 1978). Estimates of annual natural mortality of male and female J. lalandii over 10 mm were made by D.E. Pollock (pers. comm.) using observed sex ratios as a guideline. The range of values varied between M = 0.1 and 0.3 over the respective size ranges of each sex. The trend showed a higher juvenile mortality, decreasing towards maturity, stabilizing for some years and thereafter increasing with age. Juvenile size classes (2 - 6) were given linearly decreasing annual mortality rates in this range. An annual mortality rate of M = 0.1 was then estimated until each sex was

TABLE 4.12 : Whole wet mass of different size classes of *J. lalandii* males calculated from the size-mass relationship given by Heydorn (1969a).

SIZE CLASS	MASS (x 10^{-6} tons)
2	2.112
3	9.284
4	24.625
5	51.024
6	91.291
7	148.167
8	224.345
9	322.478
10	445.179
11	595.034
12	774.600
13	986.408
14	1232.968

approximately the size corresponding to 15 years of age whereafter the mortality increases linearly to the upper end of the range at the maximum sizes of each sex (Table 4.11).

Other workers on different spiny lobster species have calculated similar natural mortality values. Bowen and Chittleborough (1966) and Morgan (1977) have given annual values of 0.592 - 2.083 and 0.226 respectively for Panulirus cygnus. Chittleborough and Phillips (1975) have calculated annual natural mortality values for juvenile Panulirus cygnus over 3 years of age to be between 0.244 and 1.516, caused mostly by density-dependent factors. Annual natural mortality values of 0.2 - 1.04 for Jasus paulensis were estimated by Vranckx (1973). Munro (1974) calculated instantaneous mortality rates of 0.52 (unexploited stocks), 0.23 (moderately exploited) and 0.14 (heavily exploited) for Panulirus argus. Newman (1973) gives natural mortality rates of between 0.1 and 0.2 for the commercially-exploited stocks of J. lalandii at Dassen Island and the Cape Peninsula. Exploited stocks are likely to have lower natural mortality rates because densities are reduced by fishing. Thus the Robben Island stock may have a higher natural mortality than the other areas. This is confirmed by Pollock (1978) who calculated an annual mortality of 0.36 at Robben Island.

Whole Wet Mass

Heydorn (1969a) gives the following relationship between mean whole wet mass and carapace length of male J. lalandii from data collected from a number of different areas off the S.A. west coast.

J. lalandii whole wet mass (g) = 0.652 x Carapace length (cm)$^{2.899}$

From this equation, the mean mass of lobsters of different sizes could be estimated (Table 4.12). This parameter is used in the model to estimate catch in tons from the number of harvested. Although the equation only

Table 4.13 : Catch of *J. lalandii* in numbers calculated from the 1983/1984 commercial catch statistics (Sea Fisheries Research Institute, unpublished data) for the South African west coast and the size-mass relationship given by Heydorn (1969a).

AREA	MEAN SIZE OF CATCH (mm)	WHOLE WET MASS OF MEAN SIZE (g)	CATCH (tons)	CATCH (x 10^3 individuals)
CAPE PENINSULA	94	431.73	530	1227.62
DASSEN ISLAND	96	458.90	830	1808.67

TABLE 4.14 : Number of *J. lalandii* of different sizes caught, calculated from the 1983/1984 commercial catch size-frequency distribution (Sea Fisheries Research Institute, unpublished data) and the estimates given in Table 4.13.

CARAPACE LENGTH (mm)	CAPE PENINSULA				DASSEN ISLAND			
	MALES		FEMALES		MALES		FEMALES	
	%	NUMBER	%	NUMBER	%	NUMBER	%	NUMBER
89-90	1.00	12 276	-	-	2.10	37 989	0.03	543
91-95	53.10	651 866	0.08	982	45.80	828 522	2.2	39 798
96-100	26.30	322 864	-	-	28.10	508 329	0.3	5 427
101-105	13.70	168 184	-	-	12.00	217 080	0.02	362
106-110	4.60	56 471	-	-	5.30	95 877	-	-
111-115	0.96	11 785	-	-	2.60	47 034	-	-
116-120	0.18	2 210	-	-	0.80	14 472	-	-
121-125	0.06	737	-	-	0.50	9 045	-	-
126-130	0.02	246	-	-	0.20	3 618	-	-
131-135	-	-	-	-	0.05	904	-	-
TOTAL	99.92	1 226 639	0.08	982	97.45	1 762 870	2.55	46 130

applies to males, it is appropriate because commercial catch statistics (Sea Fisheries Research Institute, unpublished data) show that males form by far the greatest percentage of the catch (> 90 %).

Catchable Size (CATLIM), Fishing Mortality (FIS$_{i,j}$) and Fishing Seasons

The legal minimum catchable size for *J. lalandii* in South African waters was introduced in 1933 and is at present, 88.9 mm carapace length. For the purpose of the models this is taken as 89 mm.

The 1983/1984 commercial catch data (Sea Fisheries Research Institute, unpublished data) given as whole wet mass in metric tons for the Cape Peninsula and Dassen Island were converted to catch numbers using the mean size of individuals in the catch and the mean mass of this size lobster, calculated from the equation in "Whole Wet Mass" (see p 35) (Table 4.13). The number of lobster caught in each size class was calculated from the total catch in numbers and the percentage of males and females caught in each size class (Table 4.14). Calculation of fishing mortality was done graphically for males only as female catches are minimal. The actual catches of size classes 90 - 94, 95 - 99 and 100 - 104 mm were plotted on a catch-size plot and a curve through these points fitted by eye. An annual growth increment of 4 mm was assumed (corresponding to the 3.95 mm annual increment of size class 90 - 94 mm) and the catch corresponding to points 4 mm apart from 89 to 105 mm were read off. Assuming this catch-size distribution reflects the size-frequency distribution of the population, four estimates of total annual mortality (Z) were obtained from the proportions of age classes lost in one year. These were converted to instantaneous rates and an estimated instantaneous natural mortality value of 0.1 (D.E. Pollock, pers. comm.) was subtracted from the total instantaneous mortality values to give instantaneous fishing mortality. One monthly fishing mortality value per area was calculated from the mean of these four estimates. The mean monthly fishing mortality was converted to annual fishing mortality for males giving values of F = 0.342 for the Cape Peninsula and F = 0.399 for Dassen Island.

Using one figure for all lobster sizes over the minimum catchable size and all months of the fishing season is adequate although not strictly realistic. Heydorn (1969b) and Newman and Pollock (1974a) suggest that larger males are less active; if this applies to foraging, availability in traps may be size-dependent. Newman and Pollock (1974a) have also indicated that larger males may be less catchable because of increased wariness to enter traps and possibly a different feeding pattern. There is seasonal variation in catch per unit effort (Newman and Pollock, 1971, 1974a), the catches being dependent on migration, moulting, water conditions for the lobsters, and weather for the fishermen.

D.E. Pollock (pers. comm.) suggests that female fishing mortality is somewhat lower than that of males for various reasons. The most obvious is that there are fewer females over the minimum catchable size as they have a smaller maximum size, and they tend to stay in the shallower water therefore reducing their catchability (Pollock, 1978). At the beginning of the season the males have just completed moulting during which time they have not eaten, therefore they are feeding actively (Newman and Pollock, 1971, 1974a and Pollock and Beyers, 1981) and readily enter the traps. The female moulting period occurs later, towards the end of the fishing season. Therefore, for some of the season they are in the soft-shelled condition and may not be caught. In addition, during their period of maximal eating, most of the fishing quotas have been filled and there is a subsequent reduction in fishing effort. Legal-sized males are younger ($\approx$ 11 years) than females reaching the minimum catchable size ($\approx$ 28 years) and this probably also adds to the greater male catchability. An annual estimate of F = 0.3 for females at both fishing grounds was chosen as a starting value.

TABLE 4.15 : Population numbers of *J. lalandii*, estimates of the number over the minimum catchable size of 89 mm (in parentheses) and the percentage of the population over this size at three sites off the South African west coast estimated from the calculated age-frequency distributions.

AREA	MALES	FEMALES	TOTAL	PERCENTAGE OF POPULATION OF CATCHABLE SIZE
CAPE PENINSULA	31 078 956 (4 724 051)	35 372 042 (1 094 190)	66 450 998 (5 818 240)	8.8
DASSEN ISLAND	65 581 224 (7 683 839)	80 663 882 (1 470 228)	146 245 106 (9 154 067)	6.3
ROBBEN ISLAND	20 809 616 (6 136 351)	20 750 775 (413 772)	41 560 391 (6 550 123)	15.8

TABLE 4.16 : Sex ratios of mature *J. lalandii* of different sizes, given as percentage males as observed (O) in the field by D.E. Pollock (unpublished data) and from the calculated (C) size-frequency distributions. The codes [1] and [2] indicate 1 year sampling at 30 m depth and 3 stations, and 2 years of sampling at a depth of 12 - 33 m, respectively.

SIZE CLASS	CAPE PENINSULA		DASSEN ISLAND		ROBBEN ISLAND	
	O [1]	C	O [1]	C	O [2]	C
7	32	31	17	27	24	27
8	33	34	30	34	40	33
9	48	62	51	59	61	59
10	83	80	65	86	86	89
11	99	97	72	98	97	100
12	100	100	89	100	99	100
13	100	100	100	100	100	100
14	100	100	100	100	100	100

The open fishing season for J. lalandii off the South African west coast at the time of compilation of the data and programming of the models lasted for eight months from November to June inclusive. At present the season is from the beginning of November to mid-May, a period of six and a half months. Although the eight-month season was used, this makes negligible difference because the annual mortality remains the same. One eighth of the annual fishing mortalities gives monthly fishing mortalities averaged over this harvesting period. At the Cape Peninsula and Dassen Island, monthly F values of 0.043 and 0.050 respectively for males, and 0.038 for females were calculated for all individuals over the minimum catchable size.

Age - Frequency Distributions (NUM$_{i,j}$)

The numbers in the first J. lalandii age class, which comprises eggs and larvae, were calculated for each sex as half of the mean number of eggs spawned by the three populations from the three areas (calculated under "Reproductive Output (EGG)", see p 40). The older age classes of both males and females were separated into unequal length classes using the upper length limits of each age (LEN) for each area at the estimated "overall" growth rate since the natural mortality figures correspond approximately to this growth rate. The natural mortality of an age class spanning two size classes was calculated using the proportions of the age class in each size class. Catch numbers for size classes were split proportionally into numbers per age class. The method of calculation of Cape Peninsula and Dassen Island age-frequency distributions differed from that of Robben Island because the latter has no catch data. For the two fishing grounds the following equations were used for males and only the second one for females.

$$N = \frac{C \,.\, \frac{Z}{F}}{(1 - e^{-Z})}$$

$$N_1 = N_0 e^{-M}$$

In the first equation, N and C are the number and the catch in an age class respectively, Z is total annual mortality and F is annual fishing mortality of the class. This equation was used for the male age classes in which catches were made and the numbers in these age classes were calculated first. Thereafter, working from the age classes with catches towards the younger and older age classes, the second equation was used to complete the male age-frequency distribution. In this equation, M is annual natural mortality and N_1 and N_0 are the number of individuals in the present and preceding years respectively. Since catch data for females are unrepresentative of population numbers, juvenile females smaller than 60 mm carapace length were assumed to have the same number of individuals as the males since the natural mortality over these size classes is believed to be the same for the two sexes. The numbers in the older female age classes were extrapolated from the oldest juvenile class using the second equation.

Pollock (1979) estimates that the mean density of J. lalandii (over 55 mm carapace length) per metre squared at depths of 14 - 27 m off Robben Island is 0.81, and he suggests (pers. comm.) that an area of 23 km^2 is occupied by the lobsters. This yields a total of 1.863×10^7 mature (> 55 mm) lobsters in the area. Since there is no legal exploitation of lobster at Robben Island and juvenile lobster have equivalent growth and mortality rates, it is assumed that there are similar numbers (0.932×10^7) of each sex over 55 mm. It is not possible to obtain a total population size-frequency distribution for lobster as the juveniles live in crevices in the shallows and only migrate to deeper waters as they near maturity. Percentage size-frequency distributions for mature males and females at Robben Island (D.E. Pollock, unpublished data) (Fig. 4.3) were converted to total number distributions, the absence of juveniles causing it to show a normally-distributed population structure. The slope of the right-hand side of the distribution is assumed to reflect that of a distribution of the whole population. The number in size class 10 in the male population size-frequency distribution, was used as a starting point for calculations. Thereafter, older and younger age class numbers were calculated using the second equation (p 38). The female immature age classes were assumed to be equivalent to those of the males and the older age classes were calculated from these using the same equation.

The male distributions calculated using catch data have a bimodal age-frequency distribution in which some older age classes have more individuals than preceding classes. Although this is impossible in a stable state because numbers should decline with age, it is assumed that the population is not in steady state. The total number of each sex (excluding the larval stages of age class 1) and the number over the minimum catchable size is assumed to be approximately correct for each area (Table 4.15) and the calculated distributions are used as a starting point in the model. The sex ratio of lobsters varies among size classes because females have a smaller maximum carapace length (110 mm) than males (140 mm) (Table 4.16).

Reproductive Output (EGG)

In order to obtain a fecundity-size relationship, egg counts by Hickman (1945) were combined with those by Heydorn (1965) for J. lalandii females of various carapace lengths. Morgan (1972) showed that for the Western Australian spiny lobster, Panulirus cygnus, fecundity did not vary over the geographical range of the species, so the J. lalandii data is assumed to apply to all of the study sites. Regression of the data produced a linear relationship between number of eggs and carapace length ($r = 0.978$), predicting the number of eggs spawned annually as J. lalandii only spawns once a year (Heydorn, 1969b; Newman and Pollock, 1974a).

Number of J. lalandii eggs spawned = -345521 + 575 x Carapace length (mm)
(individual^{-1}.yr^{-1})

FIGURE 4.3 : Size-frequency distribution of adult *J. lalandii* at Robben Island (D.E. Pollock, unpublished data).

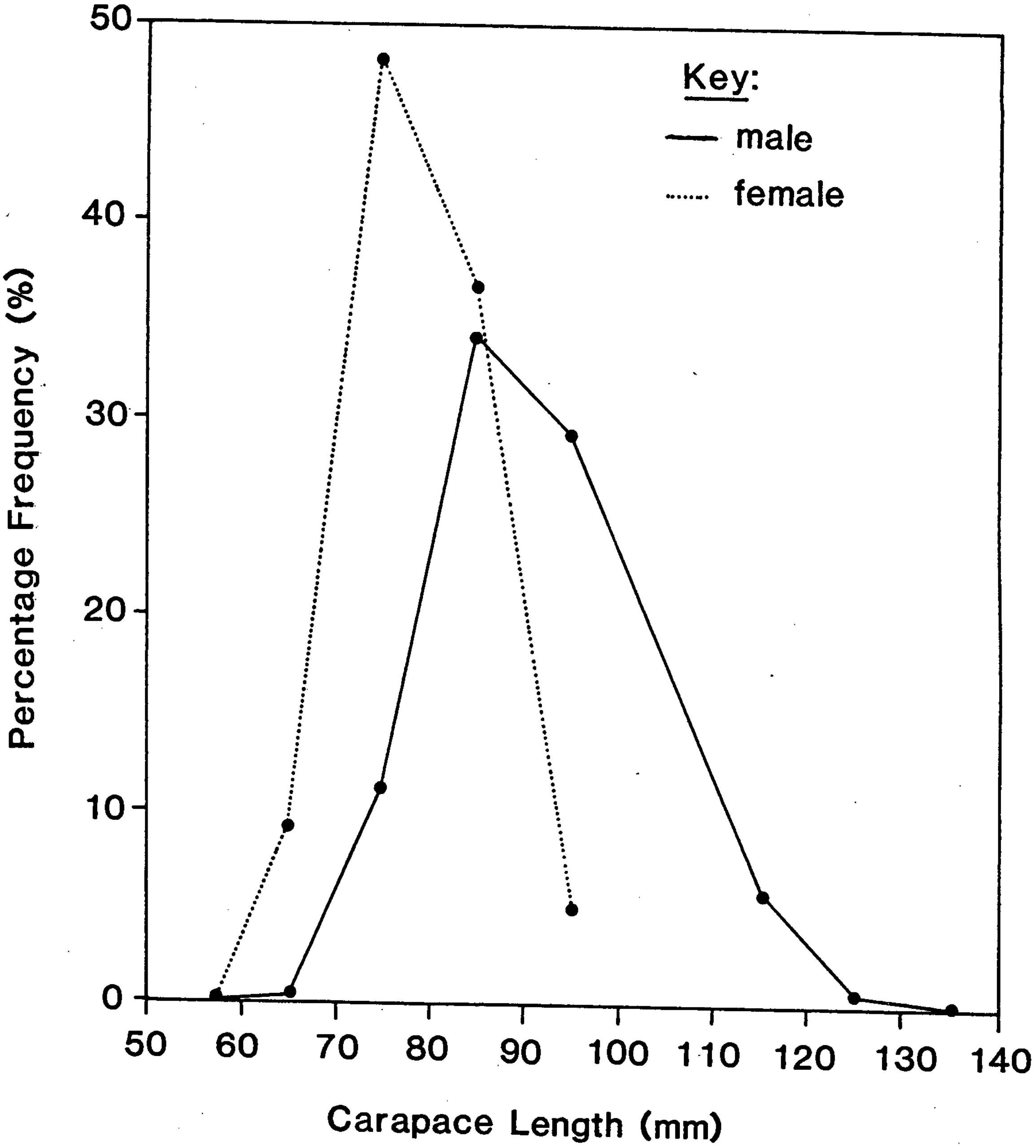


TABLE 4.17 : Reproductive output of female *J. lalandii* of different sizes calculated from the equation derived from the data of Hickman (1945) and Heydorn (1965).

SIZE CLASS	NUMBER OF EGGS PER FEMALE
8	85 729
9	143 229
10	200 729
11	258 229

TABLE 4.18 : Energy content of *A. ater* of different sizes calculated from the equation derived from data given by Griffiths and King (1979a) and Wickens and Griffiths (1985).

SIZE CLASS	FLESH (kJ)
1	0.017
2	0.321
3	1.249
4	3.057
5	5.967
6	10.179
7	15.876
8	23.234

Morgan (1972) suggests that the relationship between carapace length and the number of eggs carried by a female lobster is generally linear. The present data confirm this since both exponential and power curves gave a poorer fit (r^2) between fecundity and female size. Heydorn (1965) suggests that female J. lalandii populations as a whole can only be regarded as sexually mature from 70 mm so only size classes 8 to 11 have been considered as reproductive (Table 4.17). Morgan (1980) reviews fecundity in various species of spiny lobster of the genera Jasus and Panulirus and gives a range of approximately 87 to 460 thousand eggs per spawning for different-sized females although a figure of 2 million eggs is possible in J. verreauxi (Kensler, 1967). Morgan (1980) shows that Jasus sp. appear to be less fecund than Panulirus sp. and the values calculated for J. lalandii do appear to fall in the lower half of his range. The reproductive output of different-sized females was multiplied by the calculated population size-frequency distributions of each area and the total number of eggs spawned by the Cape Peninsula, Dassen Island and Robben Island populations calculated. This provided a mean (1.488×10^{12}), upper (2.579×10^{12}) and lower (0.688×10^{12}) estimates of annual J. lalandii egg producton per spawning for these areas on the S.A. west coast.

LOBSTER - MUSSEL INTERACTION DATA

Mussel Energy Content (MUSKJ)

Raw data on the mass of A. ater in the size ranges 5 - 25 mm and 25 - 85 mm were provided by Wickens and Griffiths (1985) and Griffiths and King (1979a), respectively. By combining these two sets of data, a regression was calculated correlating A. ater mass and size ($r^2 = 0.880$).

$$\text{A. ater dry mass (mg)} = 0.013 \times \text{Shell length (mm)}^{2.661}$$

The energy content of A. ater dry flesh is 18.27 kJ.g^{-1} (Wickens and Griffiths, 1985). These two relationships yielded a flesh energy content to

TABLE 4.19 : Monthly energy consumption of adult J. lalandii of different sizes, given for use in the model as 80 % of the requirement value estimated by the equation derived from data of Griffiths and Seiderer (1980).

SIZE CLASS	CONSUMPTION (kJ.month^{-1})
7	196.91
8	302.44
9	440.21
10	614.51
11	829.62
12	1089.85
13	1399.48
14	1762.80

size equation.

A. ater flesh (kJ) = $2.38 \times 10^{-4} \times$ Shell length $(mm)^{2.661}$

The energy content of an average size mussel from each mussel size class was calculated (Table 4.18). This equation was used as an average throughout the year although there is seasonal fluctuation such as an increased energy content when the mussels are reproducing.

Adult Lobster Energy Requirements (KJOPTEAT$_{i,j}$)

Although immature *J. lalandii* (< 60 mm carapace length) eat mussels, D.E. Pollock (pers. comm.) suggests that they may not be dependent on them as a source of food since other prey items have been found in stomachs of small lobster while they are still in the shallower waters. Using the raw data from Griffiths and Seiderer (1980) for the numbers and sizes of *A. ater* consumed per day by five adult *J. lalandii* of different sizes and the relationship between *A. ater* energy content and shell length derived under "Mussel Energy Content (MUSKJ)" (p 41), the daily energy consumption of these five lobsters was calculated. Conversion to monthly consumption and regression of the data produced the following relationship ($r^2 = 0.964$).

J. lalandii consumption ($kJ.month^{-1}$) = $0.0009 \times$ Carapace length $(mm)^{2.999}$

This equation is similar to that given by Griffiths and Seiderer (1980) for *J. lalandii* consumption but uses the *A. ater* energy content equation derived here. To confirm this equation, consumption rates calculated by P. Zoutendyk (unpublished data) from an aquarium experiment of one year duration involving six males 80 to 130 mm in carapace length, feeding on the mussel, *Choromytilus meridionalis*, show very similar monthly energy intake. In a laboratory experiment, specimens do not have to expend energy foraging as there may be an unlimited supply of food but they are not subjected to environmental hazards such as wave action, and the two factors may compensate. For the purpose of the model, consumption figures 80 % of

TABLE 4.20 : Numbers and sizes of *A. ater* consumed by one adult *J. lalandii* per month based on the data of Griffiths and Seiderer (1980). The figures are given for use in the model as 80 % of the requirement value estimated by the consumption equation derived from the same source.

		LOBSTER SIZE CLASS							
		7	8	9	10	11	12	13	14
MUSSEL SIZE CLASS	1	65	48	36	29	12	0	0	0
	2	166	182	199	223	110	60	36	0
	3	79	96	137	173	120	72	58	38
	4	14	31	53	72	84	96	84	60
	5	0	5	7	10	24	34	62	74
	6		0	0	5	24	48	60	77
	7				0	0	0	5	19
	8							0	0

the calculated amounts were used since, in reality *A. ater* is not the only source of food, although optimal lobster growth may depend upon this species (Table 4.19).

Numbers and Sizes of Mussels Consumed by Lobsters ($NUMOPTEAT_{i,s,j}$)

The raw data from Griffiths and Seiderer (1980) on numbers and sizes of *A. ater* consumed per day by five different-sized adult *J. lalandii* were converted to monthly consumption requirements. They were used in conjunction with the 80 % monthly energy consumption figures for *J. lalandii* of all sizes (calculated in "Adult Energy Requirements ($KJOPTEAT_{i,j}$)" from the same data (p 42)) in order to estimate numbers and sizes of *A. ater* eaten by the whole size spectrum of adult lobsters (> 60 mm carapace length) (Table 4.20).

Proportion of mussels unavailable to lobsters (REM)

A figure of 25 % of all *A. ater* was modelled as being unobtainable to lobsters and subject to natural mortality only. The reason for this is that some sizes of mussels occur in dense clumps that are not easily accessible to lobsters and if there is a low density of mussels, the lobsters are not likely to find all of them.

CHAPTER 5

Mussel model

CHAPTER 5 : MUSSEL MODEL

TUNING

Three mussel parameters (natural mortality, eggs spawned and egg mortality) and three forms of output (total population number at yearly intervals and age- and size-frequency distributions of the last simulated year) may have been used in tuning this model. However, the observed size-frequency distribution of D.E. Pollock (unpublished data) produced "unstable" age-frequency distributions (see Chapter 4); thus the output age/size-frequency distributions were not suitable for tuning the model and only the total number of mussels was used. There was therefore no basis for adjusting post-larval natural mortality of different mussel size classes leaving reproductive potential (calculated from the number of eggs spawned and the mortality of these eggs) as the only tuning tool.

The tuned output for the mussel model was stable after the simulation period of 100 years and varied by no more than a fraction of a percent from the calculated population values for each area (Appendix G). Reproductive output appeared to have been overestimated, resulting in large mussel populations so that the minimum estimate for the number of eggs per spawning was eventually used. The tuned values of the main tuning parameter, egg mortality, which was tuned to three significant places, are close to the calculated value (Table 5.1). The magnitude of the tuned mortality values are inversely proportional to the total population number at each area. Percentage size-frequency distributions for each area are identical since growth and natural mortality are the same. These "stable" size-frequency distributions are very different from the observed distribution at Robben Island (D.E. Pollock, unpublished data) showing little evidence of bimodality (Fig. 5.1 and Table 5.2). The age-frequency distribution (not illustrated) is representative of a "stable" state with numbers declining with age. In further simulations, the stable values from

TABLE 5.1 : Tuned values for parameters of the mussel model. Values in parentheses below each area name give the total number of mussels (in millions) found in the area.

PARAMETER	ORIGINAL VALUE	TUNED VALUE		
		CAPE PENINSULA (27 395)	DASSEN ISLAND (180 481)	ROBBEN ISLAND (82 474)
Eggs per spawning (EGG)	9.735×10^{15}	2.762×10^{15}	2.762×10^{15}	2.762×10^{15}
Egg mortality at spawning (EGGMOR)	11.550	13.084	11.199	11.982

TABLE 5.2 : Comparison of *A. ater* size-frequency distribution as observed by D.E. Pollock (unpublished data) at Robben Island and the tuned distribution from the mussel model.

SIZE CLASS	OBSERVED PERCENTAGE FREQUENCY	TUNED PERCENTAGE FREQUENCY
1	91.70	33.14
2	7.07	27.49
3	0.05	12.37
4	0.01	13.10
5	0.04	7.65
6	0.18	2.69
7	0.51	2.15
8	0.44	1.41

FIGURE 5.1 : Tuned size-frequency distribution of a mussel population as simulated by the mussel model for any area.

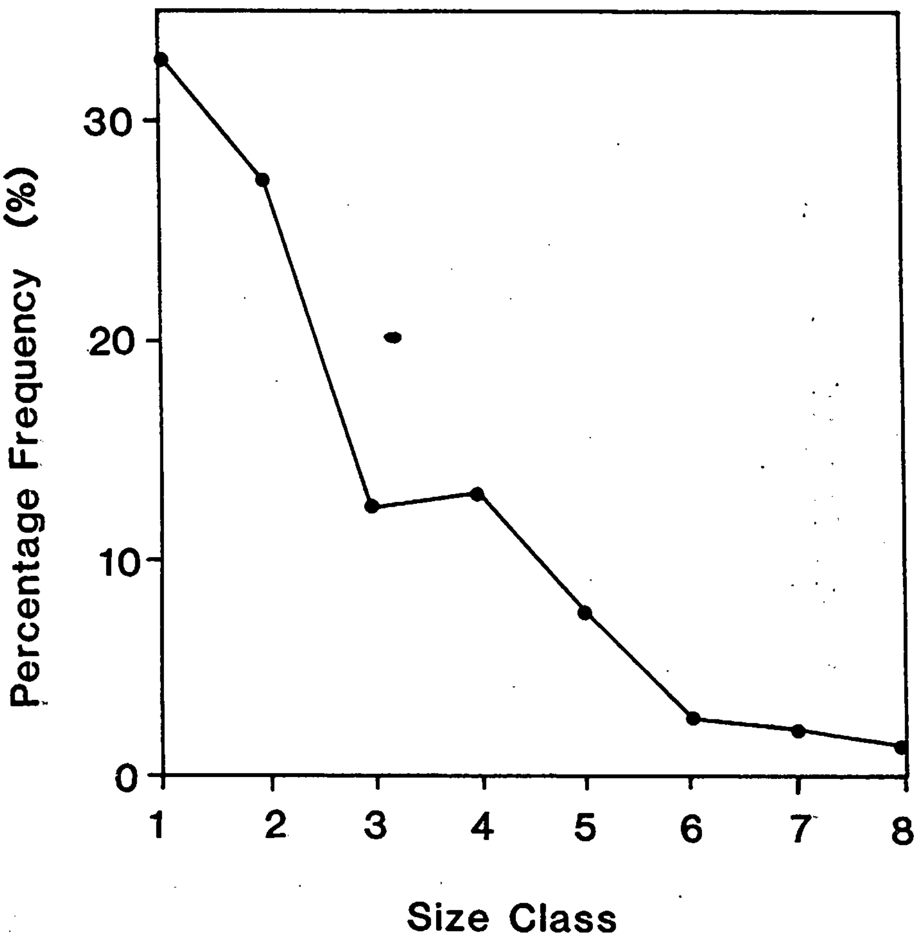


TABLE 5.3 : Results of the sensitivity analysis on the mussel model. Where a range of values occurs, the letter in parentheses indicates the area values (C = Cape Peninsula, D = Dassen Island, R = Robben Island).

SENSITIVITY PARAMETER		TOTAL POPULATION NUMBER (% OF TUNED VALUE)
Eggs	+20%	120
	-20%	80
Egg	+20%	(C)7 / 9(R) / 11(D)
mortality	-20%	(D)939 / 1098(R) / 1369(C)
Natural	+20%	80
mortality	-20%	135
"Slow" growth		(R+D)79 / 80(C)
"Fast" growth		114

the tuned runs and a simulation time of 100 years were used as input. Only the stable endpoint values are used for comparison between different simulations because the initial fluctuations in the trends are merely a result of the model "settling in" to the new parameters.

SENSITIVITY ANALYSIS

The sensitivity analysis involved testing all of the mussel parameters at approximately ± 20 % of their tuned values and in the case of growth rate, at "slow" and "fast" growth (Table 5.3). In terms of total numbers, only mussel egg mortality caused a disproportionately (> 20 %) large change from tuned numbers because this effect is implemented during each of the three spawnings each year and large numbers of eggs are involved. Change in growth rate can alter the total numbers to -21 % ("slow") or +14 % ("fast") due to the fact that with the "slow" growth rate, the individuals are subjected to the larger mortality of the small size classes for longer and *vice versa*.

EFFECTS OF VARIOUS PARAMETERS ON POPULATION SIZE STRUCTURE

Natural mortality rate :

A 20 % change in natural mortality of different size classes caused complete loss of bimodality (+ 20 % mortality) or an enhanced bimodality (-20 %) in the size distribution (Fig. 5.2).

Growth rate :

Growth rate has a marked effect on mussel population size composition (Fig. 5.3). The input values for "slow" growth are noticeably different from the growth increments of the "overall" estimate and "fast" growth. A slowing of the growth rate causes complete loss of bimodality and there appears to be an exponential decrease in number with increase in size.

FIGURE 5.2 : The effect of natural mortality rate on mussel population size composition as simulated by the mussel model.

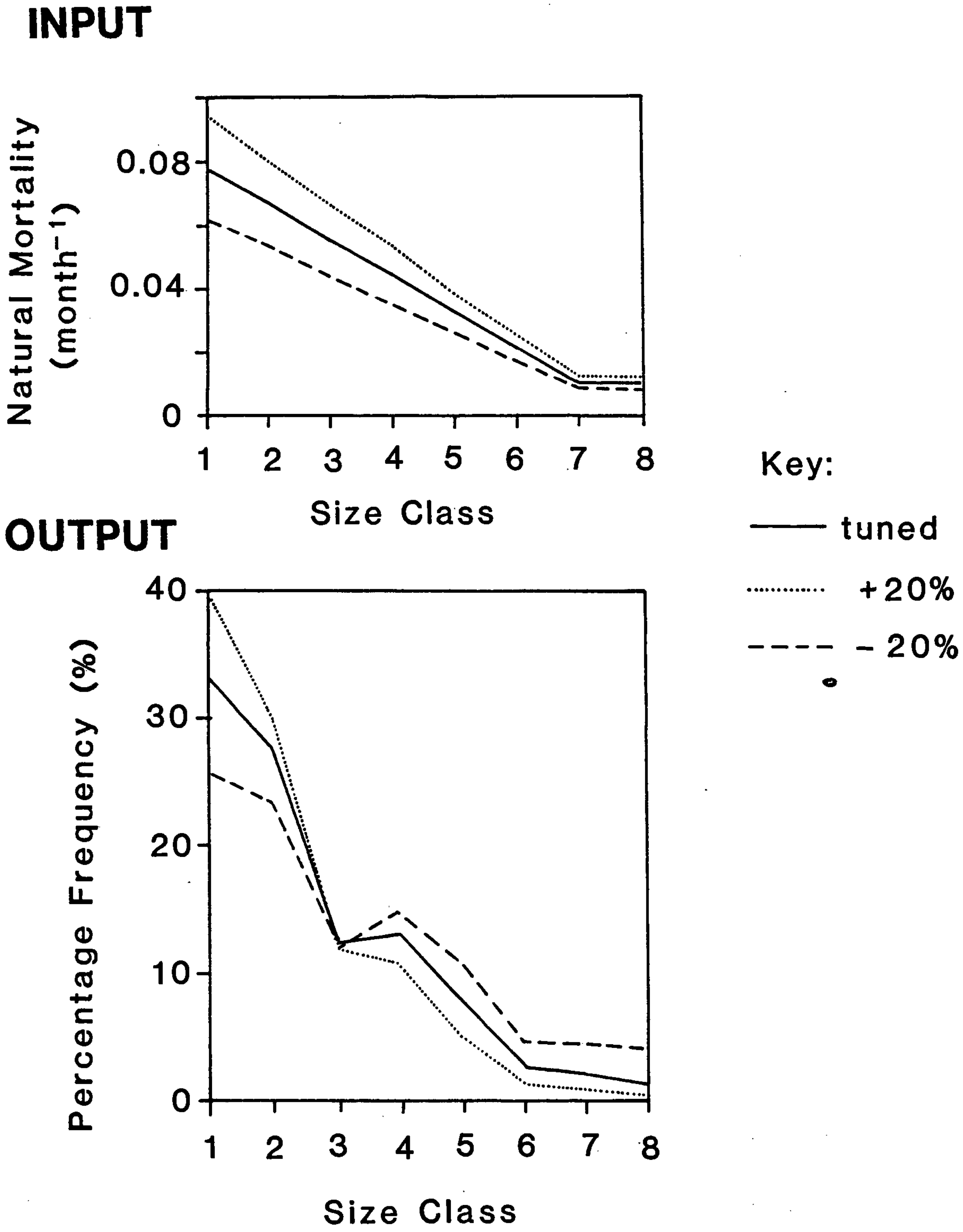


FIGURE 5.3 : The effect of growth rate on mussel population size composition as simulated by the mussel model.

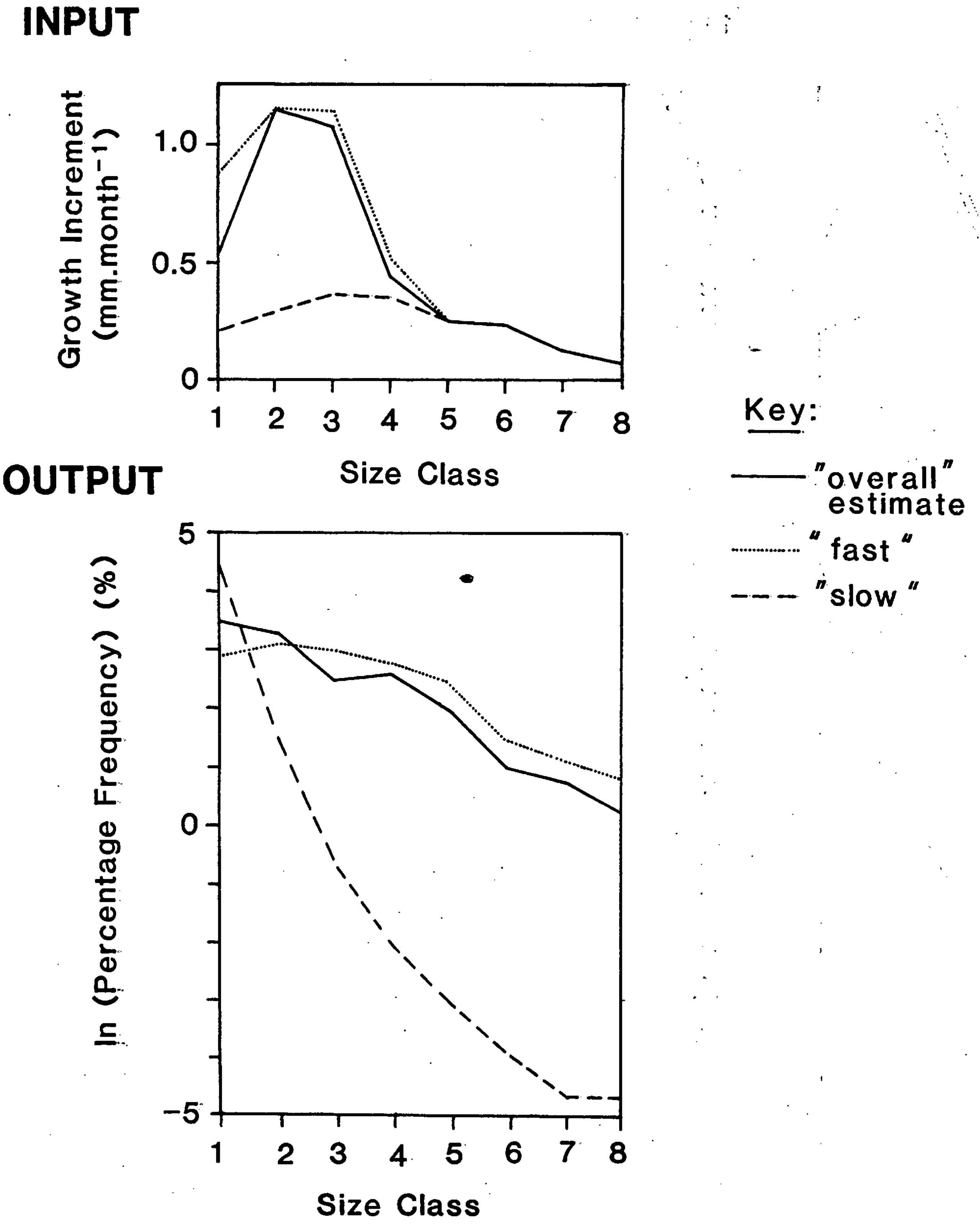
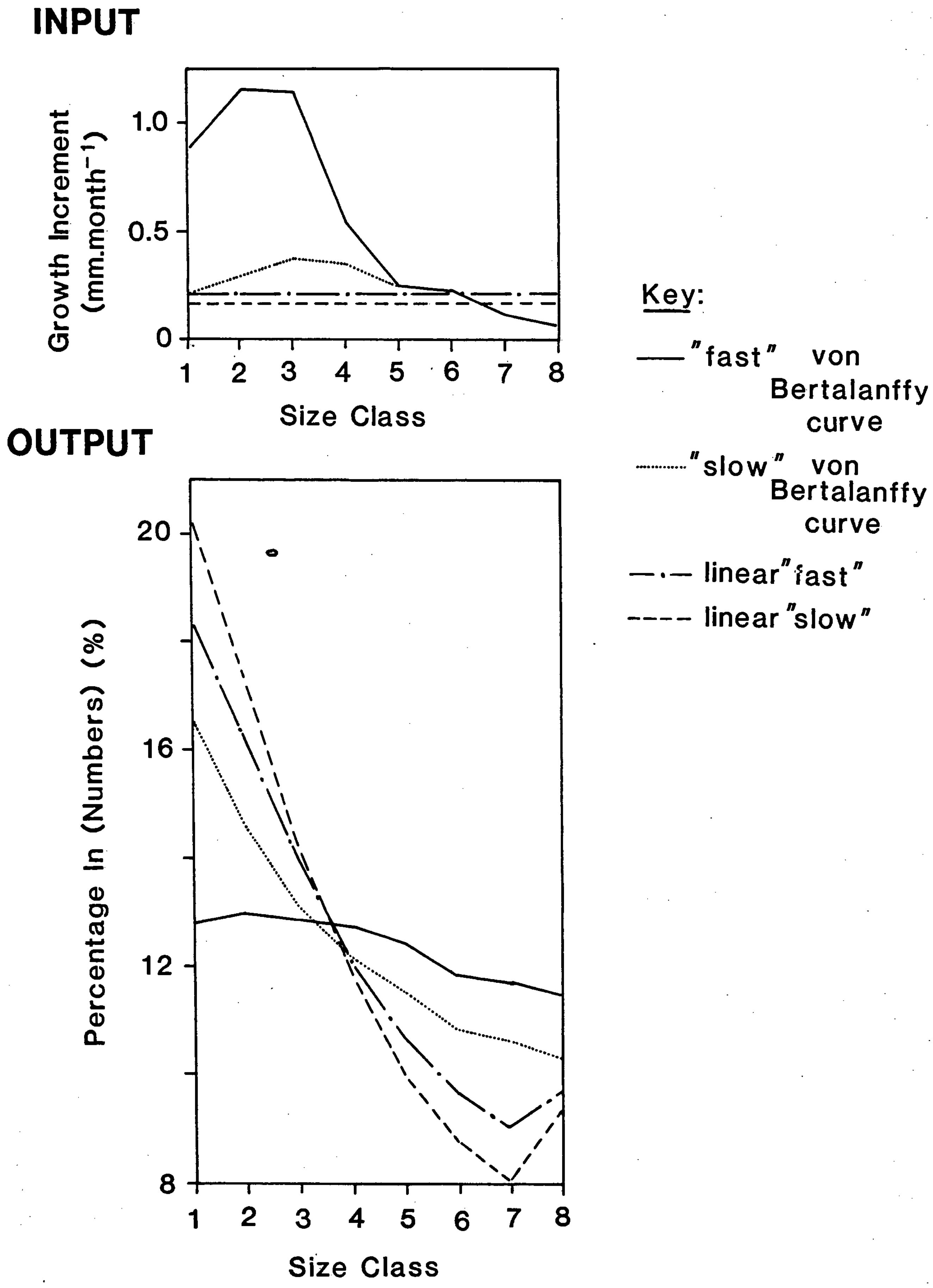


FIGURE 5.4 : The effect of the shape of a growth curve on mussel population size composition as simulated by the mussel model.



Growth curve :

The observed growth data indicate that mussels have a von Bertalanffy-like growth curve. The effect of linear growth "curves" in which there is no change in growth increment over size was tested to see whether the shape of the growth curve influences population size structure (Fig. 5.4). "Fast" and "slow" linear growth rates which yield the same maximum age at the given maximum size of 80 mm as in the equivalent von Bertalanffy curves were used. Such linear increments result in an exponentially decreasing size structure apart from the increase in the last age class which is caused by accumulation of individuals in this class. The "slow" von Bertalanffy curve is almost linear and therefore shows a unimodal, approximately exponential, decrease in size structure.

DISCUSSION

Since there was only one output value available for use in tuning, only one parameter was used to vary this and natural mortality values for different mussel size classes were not estimated through simulation. The mortality of mussel eggs, which is inversely proportional to the number of mussels occurring in each area, can be explained by two main features. Firstly, the number of eggs lost during their drift in the currents to each area differs and this is accounted for by the egg mortality. Secondly, the substrate at each area differs and the mortality of eggs in the model serves to reduce the numbers to the carrying capacity of the area suitable for habitation.

The effects that the natural mortality and growth parameters have on population size structure are substantial. If natural mortality is increased, fewer individuals survive to the larger size classes shifting the size-frequency distribution to the left and decreasing bimodality. Likewise, reduction of the mortality rate causes greater numbers to survive to the larger size classes, shifting the size distribution to the right and enhancing bimodality. "Slow" growth results in more individuals remaining in the smaller size classes for longer, and *vice versa*, thereby changing the size structure. From the results of using different growth curves it may be concluded that the shape of the von Bertalanffy growth curve, which is defined by the growth rate (k) and maximum length (l_{∞}) attained, is instrumental in causing large variations in the size distribution. A "slow" growth rate results in similar increments in the smaller and larger size classes. Thus the size-frequency distribution produced by "slow" growth following a von Bertalanffy growth curve looks similar to the distribution formed by a linear growth "curve". The more growth increments change with size, the less the distribution resembles an exponential curve which is caused by reduction in numbers from natural mortality as individuals grow through the size classes. Neither the observed (D.E. Pollock, unpublished data) nor the tuned mussel size-frequency distributions are biased towards particular cohorts as may occur when mussel beds comprise one or a few age classes. However, considering the variability in size distributions with parameter change, it is not unexpected that these two distributions are very different.

The practical use of this model is limited, but it can be used to show the great variability in mussel population size structure caused by a variety of factors, in particular the influence of growth. Natural mortality and growth rates vary considerably between and within habitats so that there will be no single distribution which can be considered representative of all shore zones and seasons at a study site.

CHAPTER 6

Lobster models

CHAPTER 6 : LOBSTER MODELS

The simulations have been divided into two sections; those in which recruitment is assumed to be constant and those in which a linear stock-recruitment relationship is used.

A. WITH CONSTANT RECRUITMENT

TUNING

Each area was simulated separately with its appropriate growth rate as input, so that parameters specific to each could be obtained. The "overall" estimate, "fast" and "slow" growth correspond to the growth rates for Dassen Island, Robben Island and the Cape Peninsula, respectively. There were four sets of lobster parameters (number of eggs per spawning, egg/larval mortality, lobster natural mortality [13 and 10 values for male and female size classes, respectively] and fishing mortality) and a number of forms of output (for each sex, total number of individuals excluding larval stages [size class 1], number of harvestable size, number harvested, mean size of individuals in the catch and size-frequency distributions; mass of lobster harvested and the sex ratios of different size classes of lobster) which may have been used in tuning this model for each of the chosen areas. Because the age-frequency distributions calculated were "unstable" (see Chapter 4), the output age/size-frequency distributions could not be used as indicators in tuning. The number of eggs per spawning and the egg/larval mortality of these eggs during the first year of life were used to tune the total number of individuals. Lobster smaller than 60 mm in carapace length occur as a separate stock from the adults and have similar growth increments, probably typical for most areas on the S.A. southwest coast (Pollock, 1973). Using the same reasoning, the calculated juvenile natural mortality values (up to the 6th size class) were kept the same for each area. The main tuning parameter was natural mortality of the

Table 6.1 : Tuned values of parameters in the lobster constant recruitment model. Values in parentheses below each area name give the total number of lobsters found in each area.

PARAMETER	ORIGINAL VALUE	TUNED VALUE		
		CAPE PENINSULA (66 450 240)	DASSEN ISLAND (146 245 106)	ROBBEN ISLAND (6 550 123)
Eggs per spawning (EGG)	1.488×10^{12}	0.688×10^{12}	0.688×10^{12}	0.688×10^{12}
Monthly egg/ larval mortality	1.000	1.076	0.978	1.109
Monthly natural mortality (male/female)				
7	0.008/0.008	0.006/0.006	0.011/0.010	0.006/0.008
8	0.008/0.010	0.005/0.008	0.014/0.012	0.008/0.011
9	0.008/0.015	0.005/0.010	0.015/0.013	0.011/0.016
10	0.008/0.019	0.006/0.011	0.016/0.014	0.015/0.021
11	0.010/0.023	0.006/0.012	0.017/0.015	0.018/0.024
12	0.015	0.007	0.018	0.020
13	0.019	0.007	0.019	0.022
14	0.023	0.008	0.020	0.024
Female monthly fishing mortality (FIS)	0.038	0.0002	0.007	-

different adult size classes. The number of harvestable size, catch mass, mean size of individuals in the catch and the observed sex ratios of each size class were tuned by altering the size composition of the catch with the natural mortality parameters from different size classes for each sex. Male fishing mortality was kept to the calculated values as there was some basis for the calculation of these figures. Female fishing mortality was used in conjunction with natural mortality to produce the correct number of females harvested. The parameters were tuned to three significant places (Table 6.1).

The tuned output stabilized during the 100-year simulation and differed by no more than four percent from the calculated population estimates (Appendix G). The minimum estimate of number of eggs shed per spawning was used because the mean estimate for reproductive output resulted in large population sizes. Egg/larval mortality for each area does not differ much from the calculated value and shows a trend in magnitude from area to area that is inversely proportional to population size. The main tuning parameter, natural mortality of different adult size classes, has tuned values that maintain the same trend as the calculated values, increasing in the larger size classes. The natural mortality values of the adults increase from the Cape Peninsula to Dassen Island to Robben Island. The difference in natural mortality between areas is probably an indication of the range of annual natural mortality values that may be expected for adult lobsters (M = 0.06 to 0.29). Tuned fishing mortality of females was found to be much lower than the estimated value. At Dassen Island females have a fishing mortality value one order of magnitude higher than at the Cape Peninsula fishing ground.

Fig. 6.1 shows the "stable" output size-frequency distributions which differ for each area. These cannot be compared to any observed distributions because counts for juveniles and adults which inhabit

FIGURE 6.1 : Size-frequency distributions of *J. lalandii* populations at the Cape Peninsula, Dassen Island and Robben Island as simulated by the lobster constant recruitment model. The vertical broken line indicates the present minimum catchable size (89 mm carapace length).

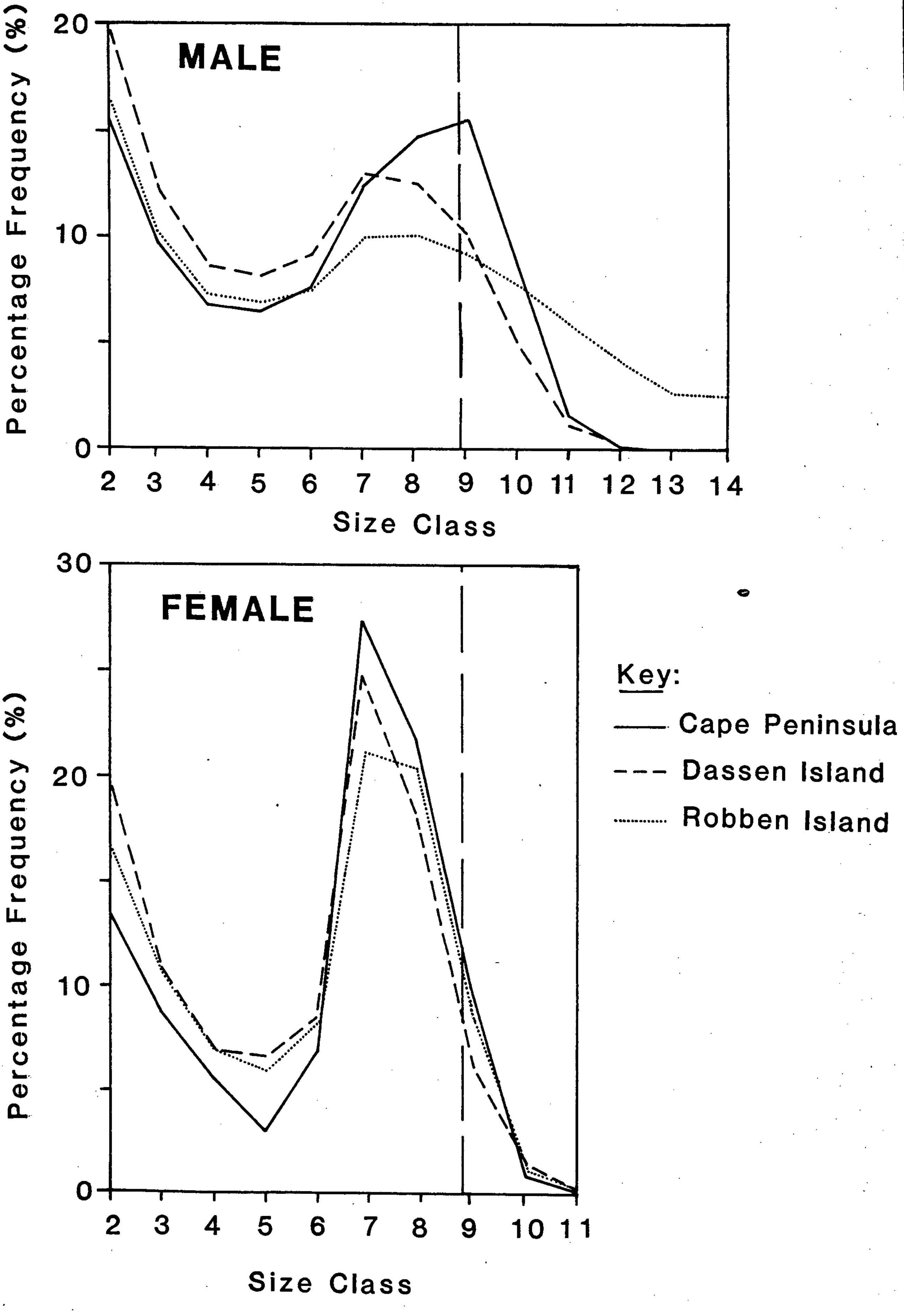


Table 6.2 : Sex ratios of mature *J. lalandii* of different sizes, given as percentage males as observed (O) in the field by D.E. Pollock (unpublished data), from calculated (C) size-frequency distributions and the tuned simulation runs of the lobster constant recruitment model (L). The codes [1] and [2] indicate 1 year sampling at 30 m depth and 3 stations, and 2 years of sampling at a depth of 12 - 33 m, respectively.

SIZE	CAPE PENINSULA			DASSEN ISLAND			ROBBEN ISLAND		
CLASS	O [1]	C	L	O [1]	C	L	O [2]	C	L
7	32	31	28	17	27	30	24	27	31
8	33	34	36	30	34	36	40	33	32
9	48	62	58	51	59	57	61	59	51
10	83	80	89	65	86	79	86	89	87
11	99	97	98	72	98	96	97	100	100
12	100	100	100	89	100	100	99	100	100
13	100	100	100	100	100	100	100	100	100
14	100	100	100	100	100	100	100	100	100

Table 6.3 : Percentage of *J. lalandii* males in the population, over the minimum catchable size and in the catch at the Cape Peninsula, Dassen Island and Robben Island as estimated from the calculated age-frequency distributions and as simulated by the lobster constant recruitment model.

	PERCENTAGE OF MALES	
	CALCULATED	SIMULATED
<u>IN POPULATION</u> :		
Cape Peninsula	46.8	45.5
Dassen Island	44.8	45.2
Robben Island	50.1	49.2
<u>OVER MINIMUM CATCHABLE SIZE</u> :		
Cape Peninsula	81.2	91.2
Dassen Island	83.9	84.6
Robben Island	93.7	93.7
<u>IN CATCH</u> :		
Cape Peninsula	99.9	99.9
Dassen Island	97.5	96.6
Robben Island	-	-

Table 6.4 : Results of the sensitivity analysis on the lobster constant recruitment model. The range of figures show male (M) and female (F) values.

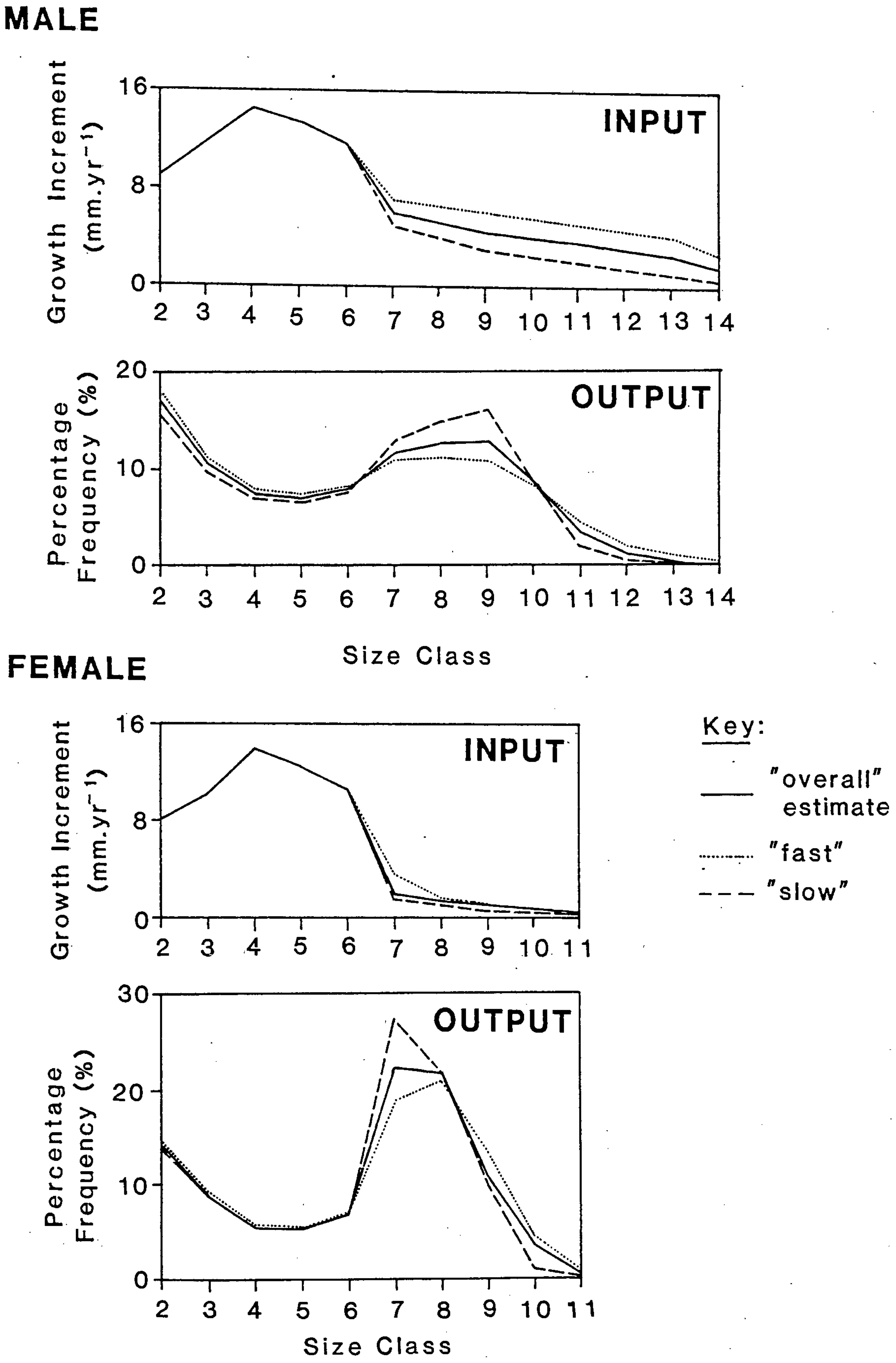
SENSITIVITY PARAMETER	OUTPUT (% OF TUNED VALUE)						
	TOTAL NUMBER		NUMBER OVER MINIMUM CATCHABLE SIZE		NUMBER HARVESTED		MASS HARVESTED
	M	F	M	F	M	F	
CAPE PENINSULA							
Natural +20%	9	9	8	4	8	4	8
mortality -20%	1072	1194	1203	2729	1216	2803	1223
Fishing +20%	98	100	90	100	103	120	101
mortality -20%	102	100	114	100	96	80	99
Eggs +20%	120	120	120	120	120	120	120
-20%	80	80	80	80	80	80	80
"Overall" growth	92	97	113	396	111	395	125
"Fast" growth	87	95	120	484	122	484	150
DASSEN ISLAND							
Natural +20%	12	11	9	5	9	5	9
mortality -20%	879	953	1078	1928	1115	2005	1158
Fishing +20%	99	100	93	97	106	110	104
mortality -20%	101	100	109	103	92	89	95
Eggs +20%	120	120	120	120	120	120	120
-20%	80	80	80	80	80	80	80
"Slow" growth	105	102	73	15	73	15	66
"Fast" growth	96	99	119	137	120	137	128
ROBBEN ISLAND							
Natural +20%	9	8	7	4	-	-	-
mortality -20%	1191	1213	1430	2300	-	-	-
Eggs +20%	120	120	120	120	-	-	-
-20%	80	80	80	80	-	-	-
"Overall" growth	104	102	92	76	-	-	-
"Slow" growth	109	105	78	9	-	-	-

different areas were not available. Both sexes show bimodal distributions, this being more marked in females. The two peaks in the distribution correspond to the younger juveniles and the newly-matured adults and differ in height from area to area. The age-frequency distributions stabilize so that the numbers decline with age, each area having a different number of age classes according to its growth rate. The stable percentage of males in each size class in each area shown by the model follows the trends shown by the observed (D.E. Pollock, unpublished data) and calculated sex ratios although the figures do vary from these possibly "unstable" representations (Table 6.2). Calculated and model percentage of males in the population, of legal catchable size and present in the catch agree in the three areas (Table 6.3). Fig. 6.1. and Table 6.3 show that Robben Island has a larger percentage of harvestable males than the two fishing grounds. In further simulations, the stable tuned values and a simulation time of 100 years were used as input. Only the stable endpoint values after this simulation time were used for comparison among simulations because initial fluctuations are a result of the model adjusting to new parameters.

SENSITIVITY ANALYSIS

Table 6.4 shows the results of the sensitivity analysis which included testing all lobster model parameters except for whole wet mass and the minimum catchable size. The parameters were tested at approximately ± 20 % of their tuned values and in the case of growth rate, to either the "overall" estimate, "slow" or "fast" growth depending on the area. Fishing mortality and the number of eggs per spawning show no disproportionate (> 20 %) differences in output. Changing natural mortality, which includes egg/larval mortality, has a cumulative effect, the mass harvested being altered to a maximum of 8 % to 1223 % with a 20 % increase and decrease in the parameter, respectively (Figures for the Cape Peninsula). Changing the growth rate causes individuals to be subjected to various mortality rates

FIGURE 6.2 : The effect of adult growth rate on male and female lobster population size structure as simulated by the lobster constant recruitment model.



for different periods of time. Therefore speeding up or slowing down the adult growth rate can make a substantial difference to numbers and mass harvested, especially in the case of females. A faster growth rate results in a substantially higher yield and vice versa.

EFFECTS OF VARIOUS PARAMETERS ON POPULATION SIZE STRUCTURE

The effects of natural mortality, growth and fishing on the population size composition of lobsters were tested using particular areas as examples.

Natural mortality :

The effects of a 20 % change in mortality rate in all size classes and of a change in the trend in natural mortality rate with increase in size make neglible difference to the Dassen Island population size distribution (not illustrated).

Growth rate :

Adult growth rate affects the intensity of bimodality of population size structure of male and female lobsters at the Cape Peninsula (Fig. 6.2). Reduced growth rate results in more individuals accumulating in the second peak of the distribution, enhancing the bimodality and vice versa. Adult female lobsters have a slower growth rate than males and this is reflected in the increased height of the second peak (Figs 6.1, 6.2).

Growth curve :

Data on observed growth rates indicate that lobsters have a von Bertalanffy-like growth curve. The effect of a "linear" growth curve in which there is no change in growth increment with size was tested to see whether the shape of this curve influences population size structure, using the Dassen Island population as an example. Such "linear" growth increments result in an approximately exponential curve as opposed to the bimodal structure that results from using a von Bertalanffy curve (Fig. 6.3).

FIGURE 6.3 : The effect of the shape of the growth curve on male and female lobster population size structure as simulated by the lobster ' constant recruitment model.

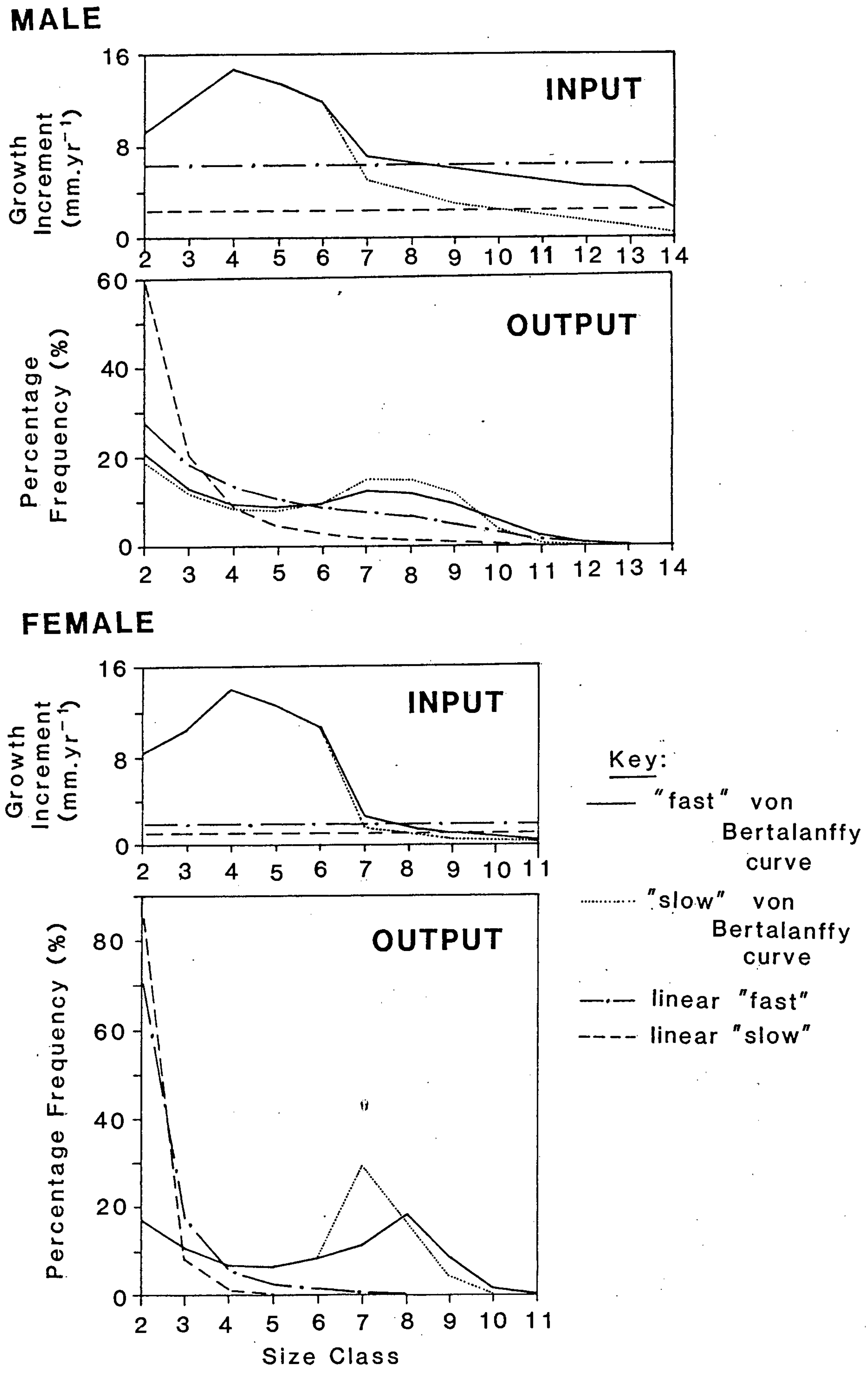


FIGURE 6.4 : The effect of ceasing lobster harvesting at two fishing grounds (the Cape Peninsula and Dassen Island) and of introducing fishing to a sanctuary (Robben Island) on male population size structure as simulated by the lobster constant recruitment model. The vertical broken line indicates the present minimum catchable size (89 mm carapace length).

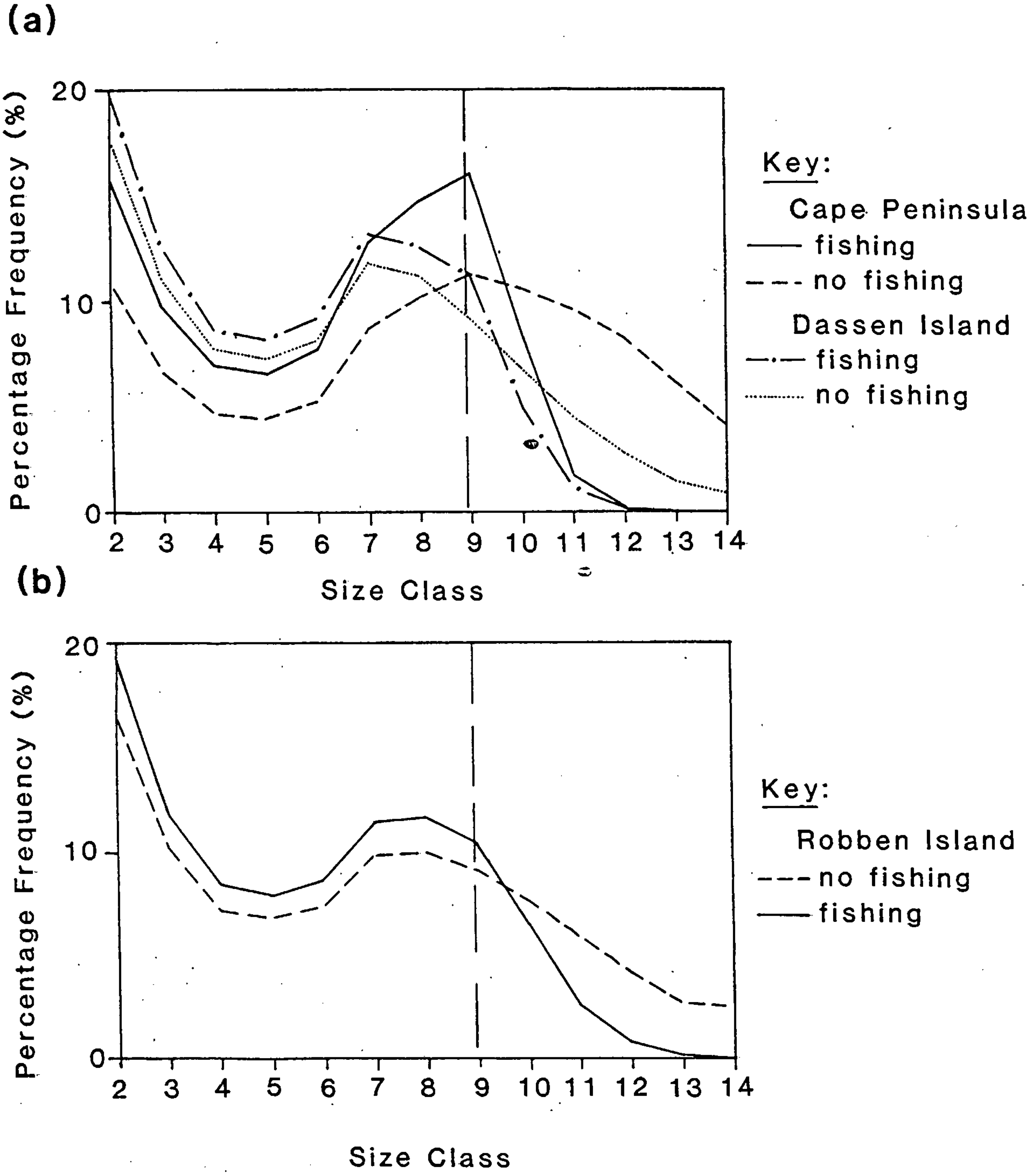
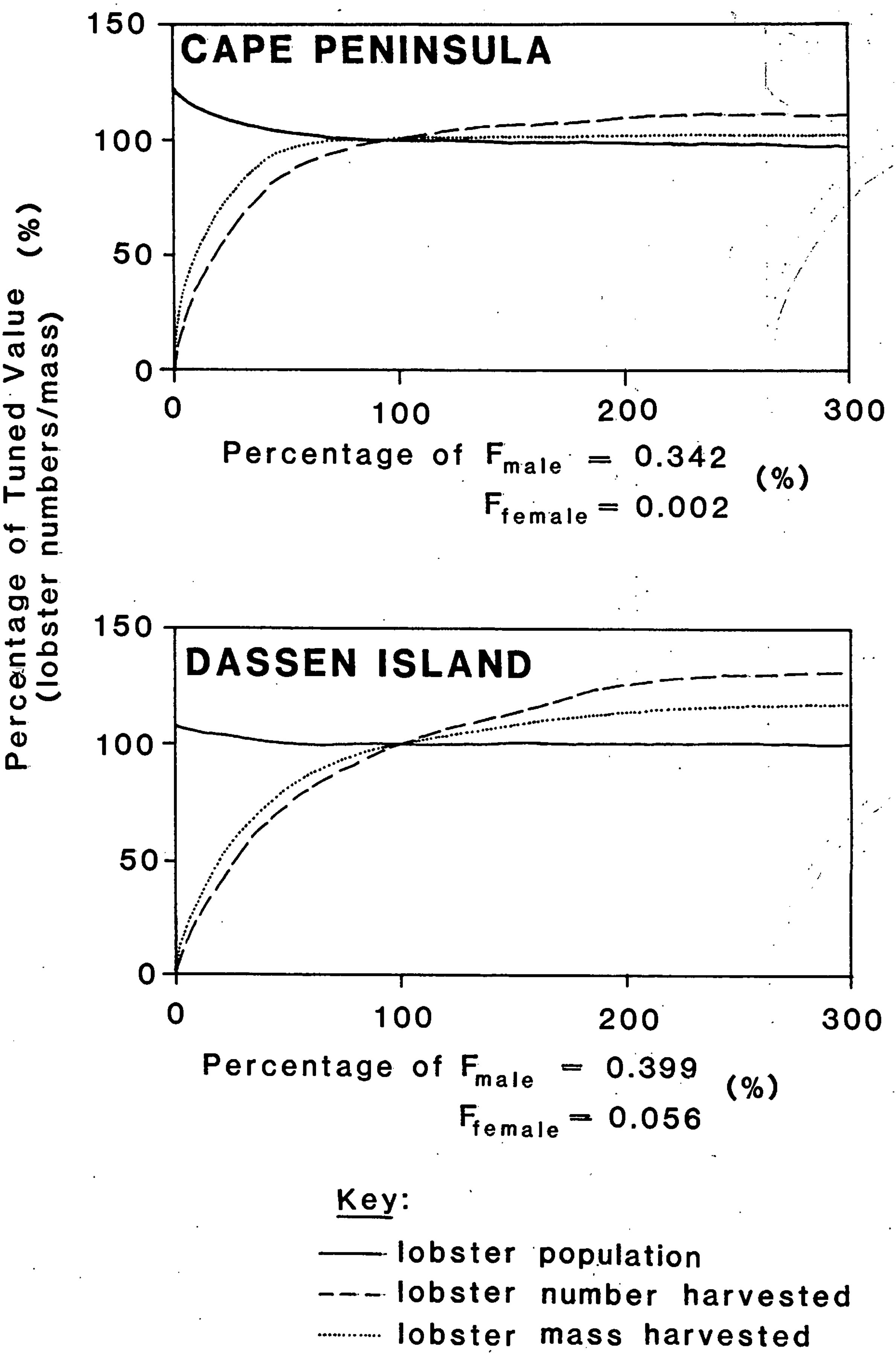


FIGURE 6.5 : The results of changing fishing pressure on *J. lalandii* at the two fishing grounds as simulated by the lobster constant recruitment model.



Fishing :

The simulated cessation of harvesting at two fishing grounds and the introduction of fishing to a sanctuary give three clear examples of the effect that fishing has on population size structure (Fig. 6.4). Only males are shown because the harvest of females is negligible. Lack of fishing results in a considerable increase in percentage of harvestable individuals (> 89 mm carapace length), resulting in a flattening of the entire distribution.

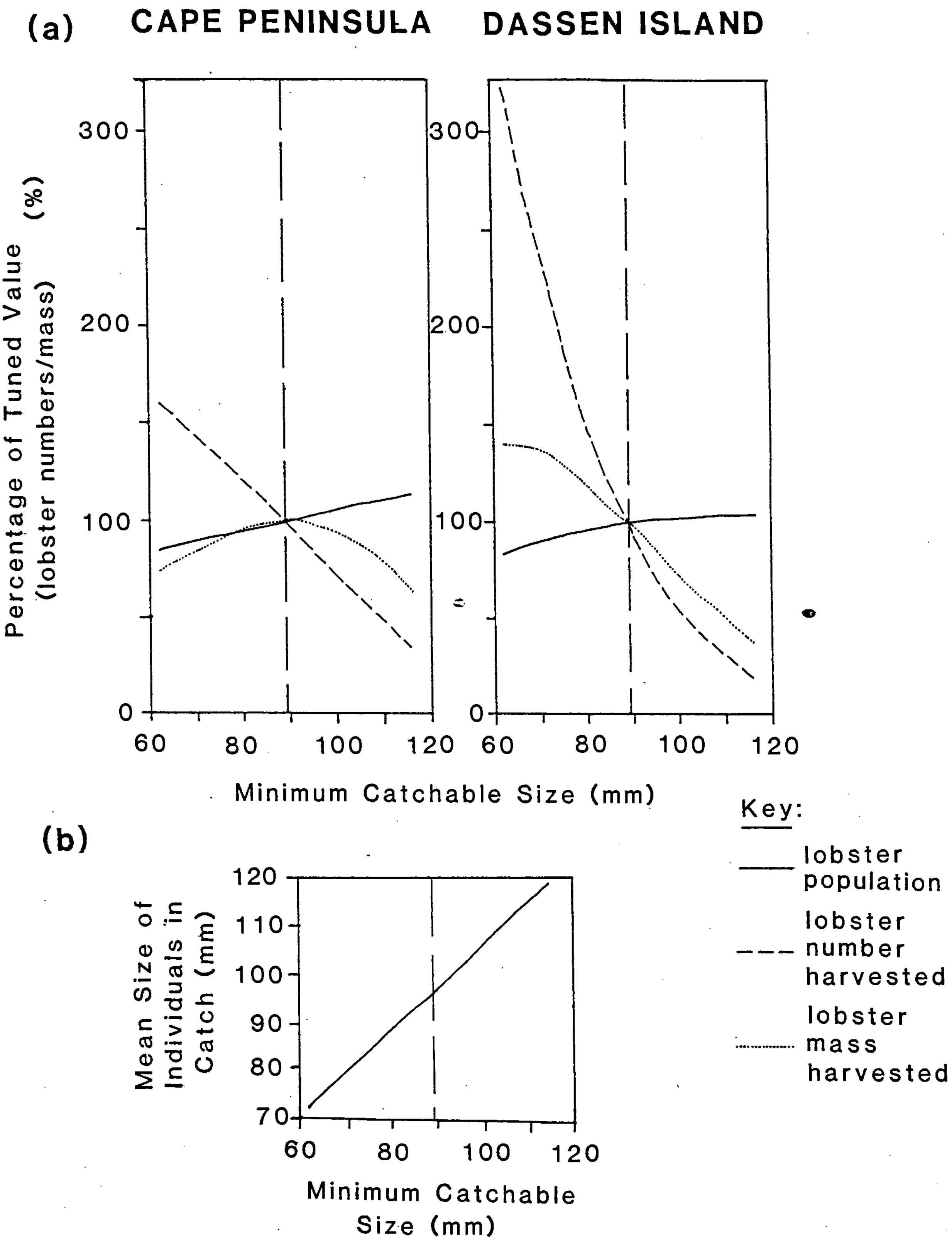
TESTING DIFFERENT LOBSTER HARVESTING STRATEGIES

Simulations were carried out to investigate change in harvesting strategies at both fishing grounds, the Cape Peninsula and Dassen Island, and the sanctuary, Robben Island. The three areas have different lobster growth rates and the fishing pressure at the two fishing grounds differs. The annual fishing mortality at the Cape Peninsula is smaller (F_{male} = 0.342, F_{female} = 0.002) than that at Dassen Island (F_{male} = 0.399, F_{female} = 0.056).

Change in fishing pressure :

Fig. 6.5. shows the results of simulations in which fishing pressure was increased to 300 % and decreased to 0 % from the present fishing mortalities at the fishing grounds. An increased number and mass of lobsters are harvested with increasing fishing mortality from zero to 100 % of the present rates above which the yield levels off. The population numbers are increased slightly with greatly reduced fishing pressure. At the Cape Peninsula, increased fishing makes negligible difference to the catch while at Dassen Island the harvest may be increased with a large increase in effort. In both areas, the mean size of individuals in the catch (not illustrated) is reduced slightly with increased fishing pressure.

FIGURE 6.6 : The results of changing the minimum catchable size of *J. lalandii* at the two fishing grounds as simulated by the lobster constant recruitment model. The vertical broken line shows the present minimum catchable size (89 mm carapace length).



Change in minimum catchable size :

Simulations were carried out in which the minimum catchable size was increased and decreased to plus and minus 30 % (62 mm - 116 mm) of the present limit (89 mm) at the two fishing grounds (Fig. 6.6a,b). Increased numbers are harvested with reduced minimum catchable size and *vice versa*. Population size has the opposite response, decreasing with a decrease in minimum catchable size. There is a marked difference in the results between the Cape Peninsula and Dassen Island (Fig. 6.6a). While both areas show decreasing harvested mass with increasing minimum catchable size, the Cape Peninsula shows a similar decrease with lowering of the minimum catchable size, indicating optimum minimum catchable size regulations at the Cape Peninsula ground. However, at Dassen Island the mass harvested increases with reduced minimum size, levelling off with a decrease of more than 20 % (< 71 mm). In both areas, the mean size of individuals in the catch alters considerably with minimum catchable size, having the lowest mean some 20 mm smaller than the present mean size at smallest minimum catchable size and *vice versa* (Fig. 6.6b).

Cessation of harvesting at fishing grounds :

The effect of ceasing harvesting at the two fishing grounds is an increase in population size and more individuals of harvestable size (Fig. 6.7). At the Cape Peninsula, the effect on female numbers is negligible because the fishing mortality of this sex is so low. At Dassen Island, the number of females of catchable size is greatly increased with cessation of harvesting.

Fishing in a sanctuary :

The effect of introducing fishing to the sanctuary at the harvesting rates of the Cape Peninsula (moderate fishing rate) and Dassen Island (heavy fishing rate) is in both cases a slight reduction (-7 %) in population size and number of harvestable size (-45 %) but with a reasonable catch of 339 -

FIGURE 6.7 : The results of ceasing harvesting of *J. lalandii* at the two fishing grounds as simulated by the lobster constant recruitment model.

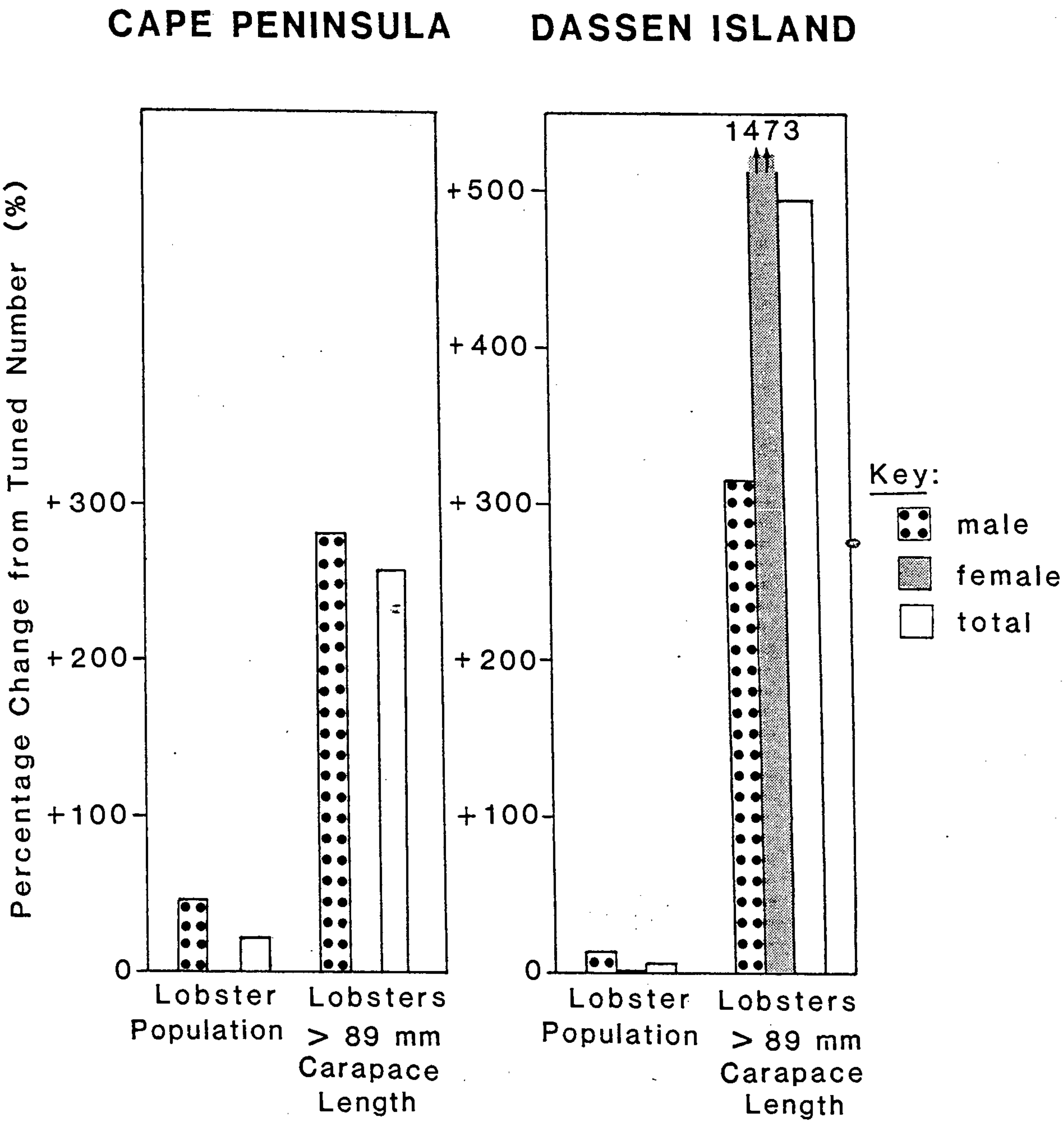


FIGURE 6.8 : The results of fishing *J. lalandii* at the sanctuary, Robben Island, using two different fishing pressures (F_{male}, F_{female}) as simulated by the lobster constant recruitment model.

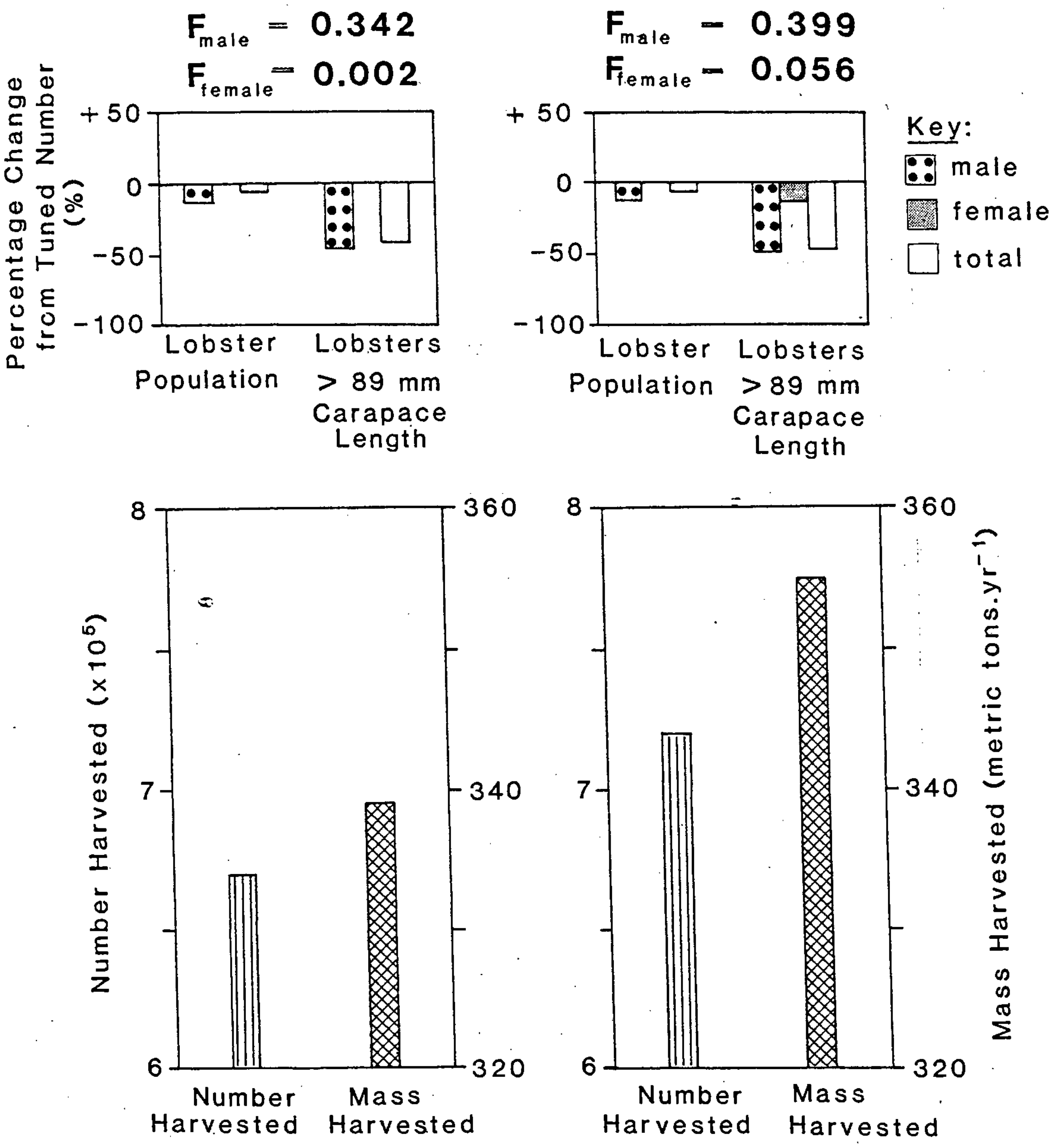


FIGURE 6.9 : The results of changing fishing pressure on J. lalandii from a "heavy" harvesting rate (F) at sanctuary, Robben Island as simulated by the lobster constant recruitment model.

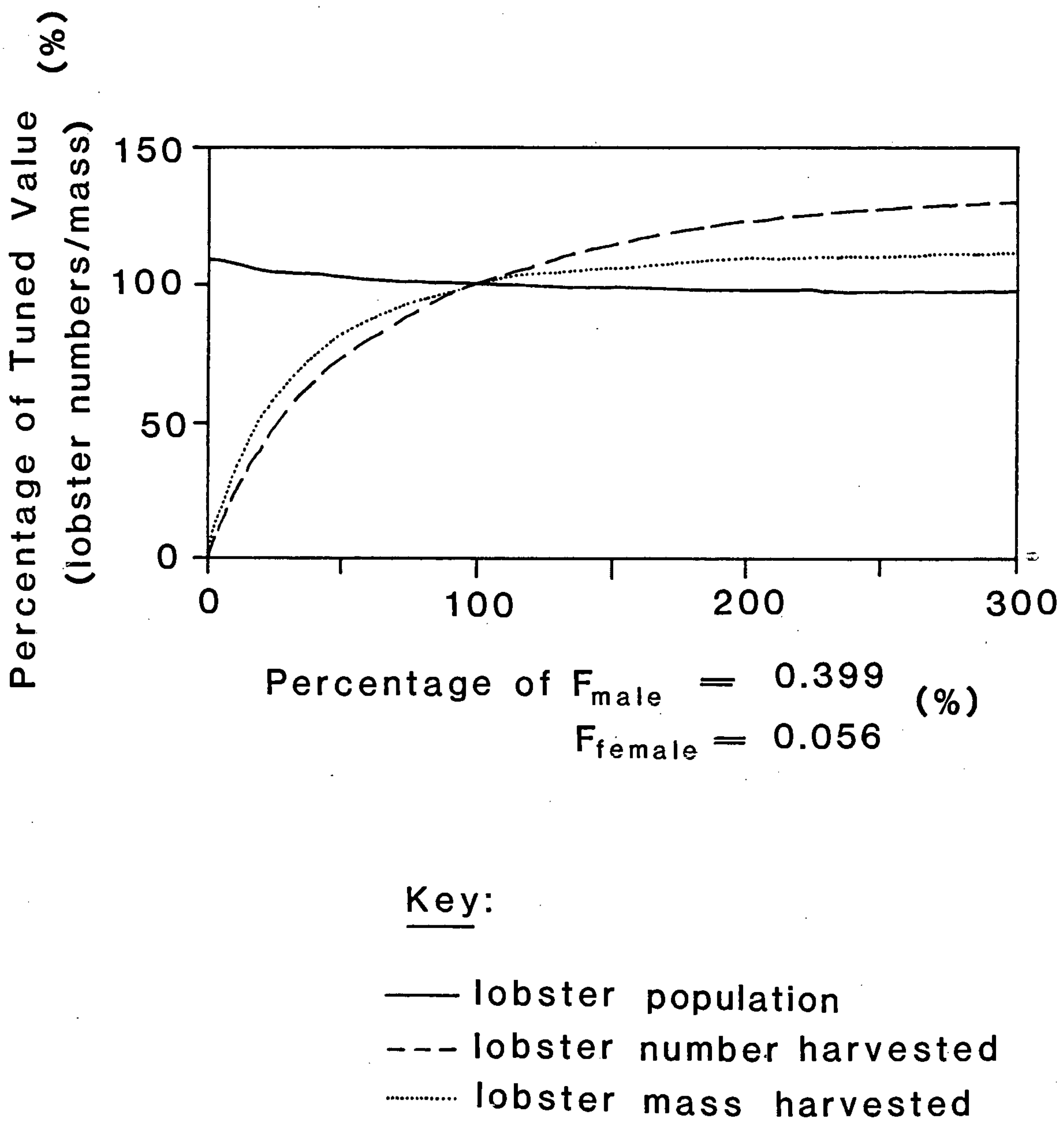


FIGURE 6.10 : The results of changing the minimum catchable size using "moderate" and "heavy" harvesting rates of J. lalandii at the sanctuary, Robben Island as simulated by the lobster constant recruitment model. The vertical broken line shows the present minimum catchable size (89 mm carapace length).

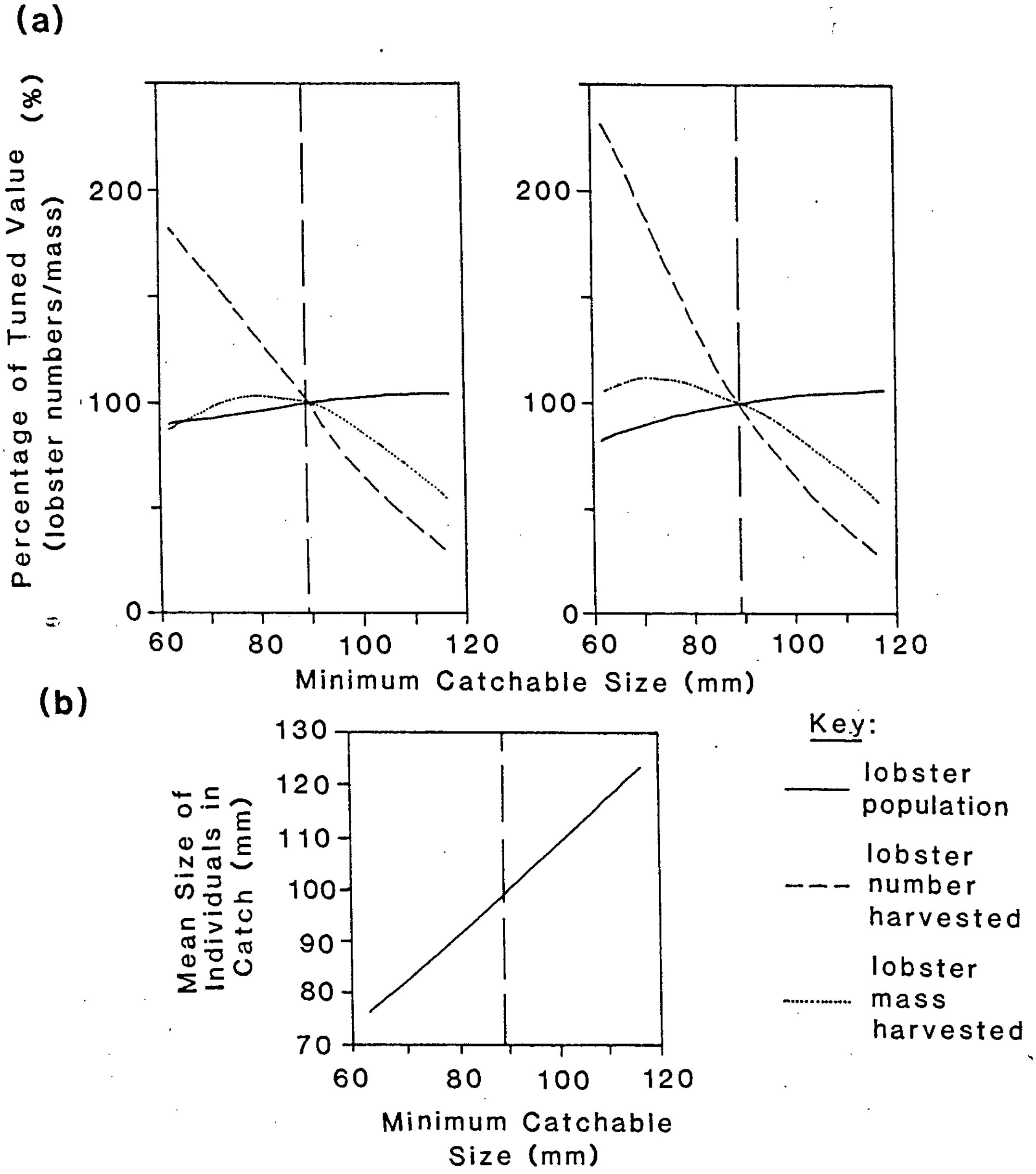


Table 6.5 : Tuned values of monthly *J. lalandii* egg/larval mortality from the lobster constant recruitment and stock-recruitment models

MODEL	CAPE PENINSULA	DASSEN ISLAND	ROBBEN ISLAND
Constant recruitment	1.076	0.978	1.109
Stock-recruitment relationship	1.135	1.089	1.110

355 tons per annum (Fig. 6.8). The effect of changing fishing effort from the heavy fishing pressure shows that the yield may increase with a large increase in harvesting rate (Fig. 6.9). Under heavy fishing pressures the mean size of individuals in the catch (not illustrated) is slightly reduced.

Changing the minimum catchable size has different results with different fishing mortalities (Fig. 6.10a). Under both fishing intensities the number harvested increases with a reduced minimum catchable size and decreases when the minimum size is increased. The trend in population numbers is opposite. Using the heavier fishing pressure (F_{male} = 0.399, F_{female} = 0.056) the harvested mass is greatest at a minimum catchable size of 70 mm whereas at moderate fishing intensity (F_{male} = 0.342, F_{female} = 0.002), the mass caught is largest at 80 mm minimum catchable size. Decreasing the minimum catchable size causes a drop of approximately 20 mm in mean size of individuals in the catch and <u>vice versa</u> (Fig. 6.10b).

B. <u>WITH A STOCK-RECRUITMENT RELATIONSHIP</u>

<u>TUNING</u>

The tuned parameter values and the stable age-frequency distributions from the constant recruitment model were used as input into this model which incorporates a linear stock-recruitment relationship. The only tuning parameter, lobster egg/larval mortality, was tuned to three significant figures for each area (Table 6.5). The Robben Island values are very similar in both models, whereas for the other areas the tuned values of the stock-recruitment model are somewhat higher and the trend from area to area does not follow that of the constant recruitment model. Complete steady state was not attained but simulations were run for 100 years. The output varied by no more than 4 % of the calculated values (Appendix G). The simulated size-frequency distributions are the same as in the constant recruitment model and therefore so are the sex ratios of different size

Table 6.6 : Results of the sensitivity analysis on the lobster stock-recuitment model. The range of figures show male (M) and female (F) lobster values. An arrow indicates the trend in numbers after 100 years of simulation, the magnitude of which ranges from negligible to a rapid increase/decrease.

SENSITIVITY PARAMETER	OUTPUT (% OF TUNED VALUE)							DIRECTION OF TREND
	TOTAL NUMBER		NUMBER OVER MINIMUM CATCHABLE SIZE		NUMBER HARVESTED		MASS HARVESTED	
	M	F	M	F	M	F		
CAPE PENINSULA								
Natural +20%	0	0	0	0	0	0	0	↓
mortality -20%	10^{9}	10^{9}	10^{8}	10^{7}	10^{8}	10^{7}	10^{8}	↑
Fishing +20%	98	100	90	100	103	120	101	↑
mortality -20%	102	100	114	100	96	80	99	↑
Eggs +20%	238	232	224	172	221	170	221	↑
-20%	36	37	38	53	39	54	39	↓
"Fast" growth	401	415	510	1547	500	1506	600	↑
"Overall" growth	234	238	270	790	266	776	292	↑
DASSEN ISLAND								
Natural +20%	0	0	0	0	0	0	0	↓
mortality -20%	10^{10}	10^{10}	10^{10}	10^{8}	10^{9}	10^{8}	10^{10}	↑
Fishing +20%	97	98	92	96	104	109	102	↓
mortality -20%	103	102	111	104	94	90	97	↑
Eggs +20%	296	289	277	227	273	223	271	↑
-20%	27	28	30	38	30	39	31	↓
"Fast" growth	243	244	286	279	283	275	299	↑
"Slow" growth	31	31	24	7	24	7	22	↓
ROBBEN ISLAND								
Natural +20%	0	0	0	0	-	-	-	↓
mortality -20%	10^{11}	10^{10}	10^{10}	10^{9}	-	-	-	↑
Eggs +20%	322	318	300	251	-	-	-	↑
-20%	25	25	27	33	-	-	-	↓
"Overall" growth	55	54	51	46	-	-	-	↓
"Slow" growth	24	23	19	3	-	-	-	↓

classes and the sex ratio in the population as a whole, of harvestable individuals and in the catch. The stable tuned output after 100 years was used as input in all further simulations, and the tuned output was also used for comparison with the endpoint values of further 100-year simulations.

SENSITIVITY ANALYSIS

Sensitivity of the model was tested against the same parameters used in the constant recruitment model (Table 6.6). These simulations did not attain complete stability, the population showing either a consistent increasing or decreasing trend with time. Natural mortality has the largest effect, ranging from a reduction in numbers to almost zero to numbers 9 orders of magnitude higher than tuned.

TESTING DIFFERENT HARVESTING STRATEGIES

The lobster populations in the following simulations did not level off, even after 100-year simulations, therefore increasing or decreasing tendencies after 100 years are indicated by arrows in all figures.

Change in fishing pressure :

Fig. 6.11 shows the results of simulations in which fishing pressure was altered at the two fishing grounds. The results at different fishing pressures are the same as in the constant recruitment model for the Cape Peninsula. At Dassen Island, heavy fishing pressure on females results in reduced population numbers and a smaller increase in harvest. The mean size of individuals in the catch (not illustrated) is slightly reduced with increased fishing pressure.

FIGURE 6.11 : The results of changing fishing pressure on *J. lalandii* at the two fishing grounds as simulated by the lobster stock-recruitment model. Arrows indicate the increase/decrease in population numbers after a simulation period of 100 years. If there is a changeover in the increasing/decreasing trends, this is indicated by a dotted vertical line.

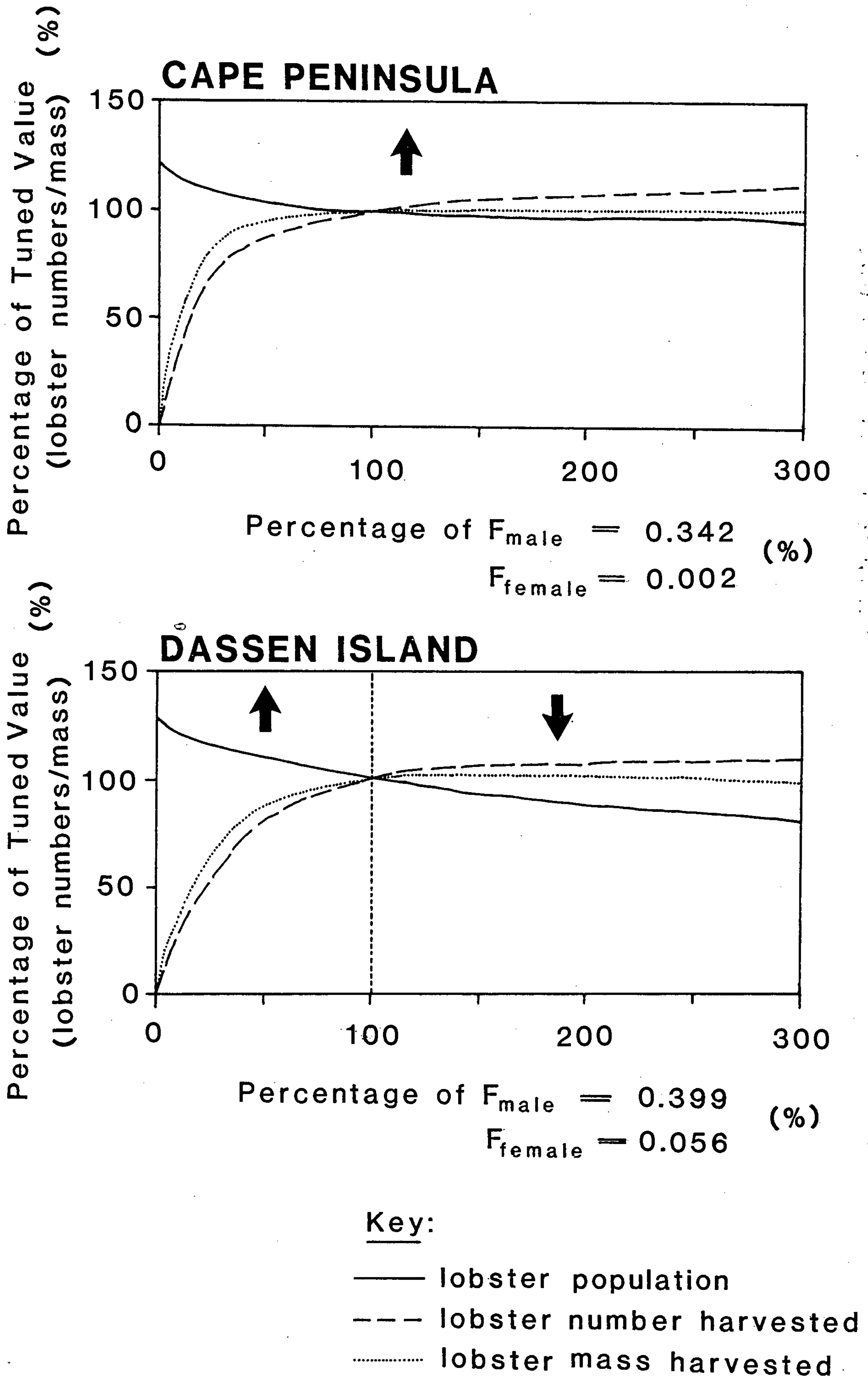


FIGURE 6.12 : The results of changing the minimum catchable size of *J. lalandii* at the two fishing grounds as simulated by the lobster stock-recruitment model. The vertical broken line shows the present minimum catchable size (89 mm carapace length). Arrows indicate the increase/decrease in population numbers after a simulation period of 100 years. If there is a changeover in the increasing/decreasing trends, this is indicated by a dotted vertical line.

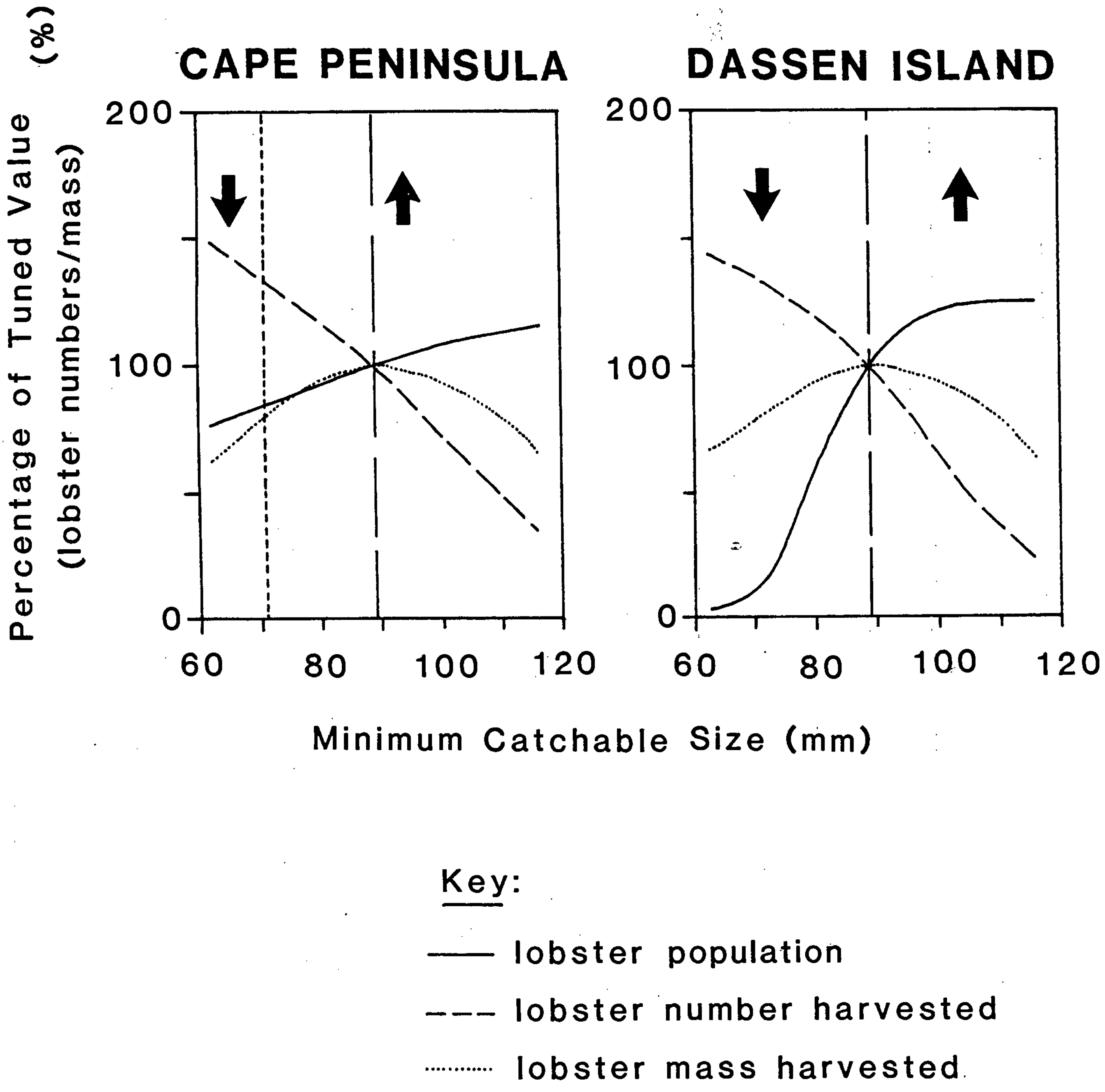
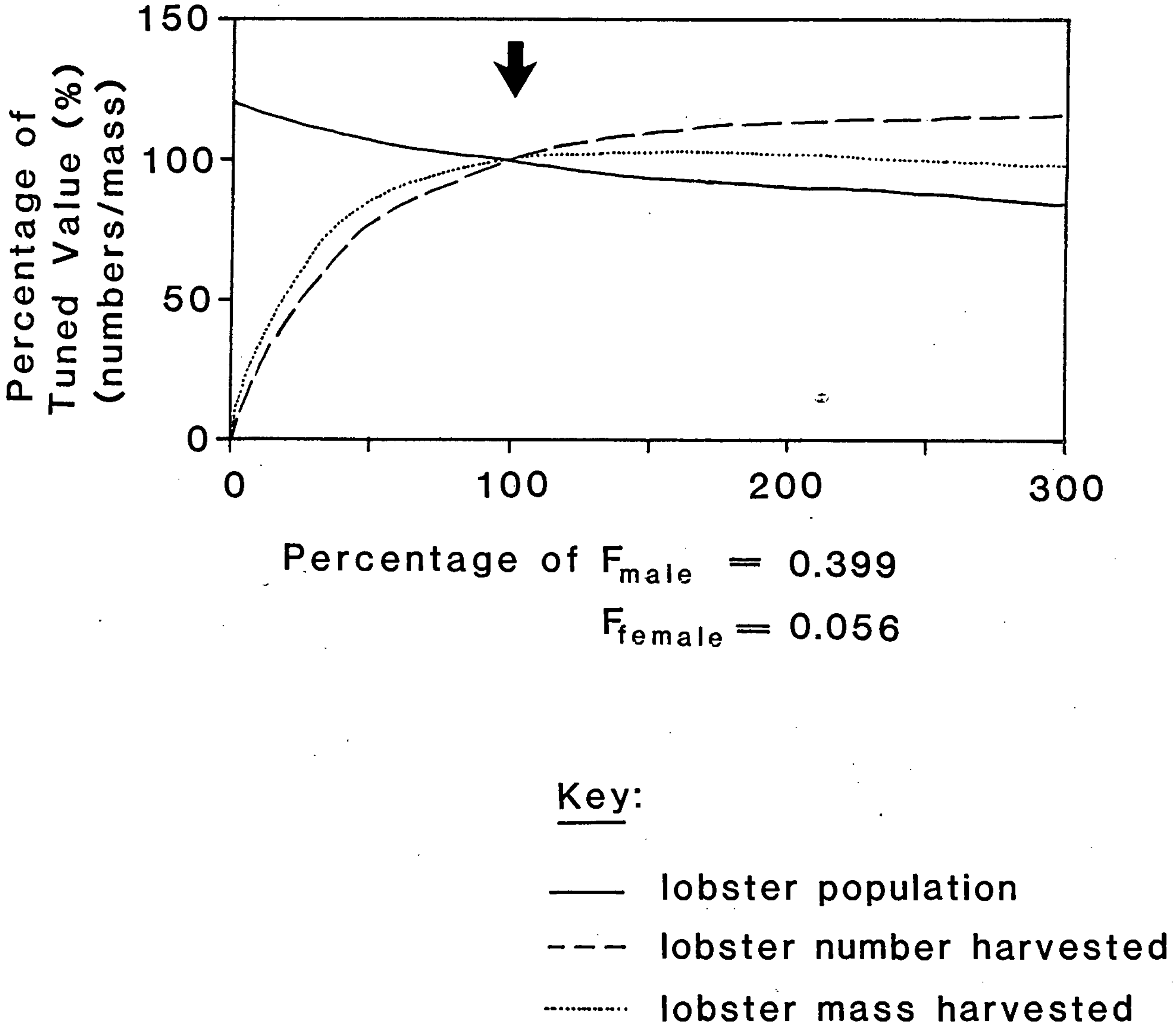


FIGURE 6.13 : The results of changing fishing pressure on *J. lalandii* from a "heavy" harvesting rate (F) at the sanctuary, Robben Island as simulated by the lobster stock-recruitment model. Arrows indicate the increase/decrease in population numbers after a simulation period of 100 years.



Harvesting of males only :

Since the standing stock of lobsters in the stock-recruitment model depends on the number of females in the population, a simulation was carried out to test the effect of outlawing the harvesting of females at the two fishing grounds (not illustrated). In the Cape Peninsula ground this made no difference to population numbers or the mass harvested because female fishing mortality is low. At Dassen Island, however, the total population of lobsters increased by 20 % while the harvested mass was larger by 15 %. These results are based on the assumption that the legislation affects all parent stocks from which recruitment is derived.

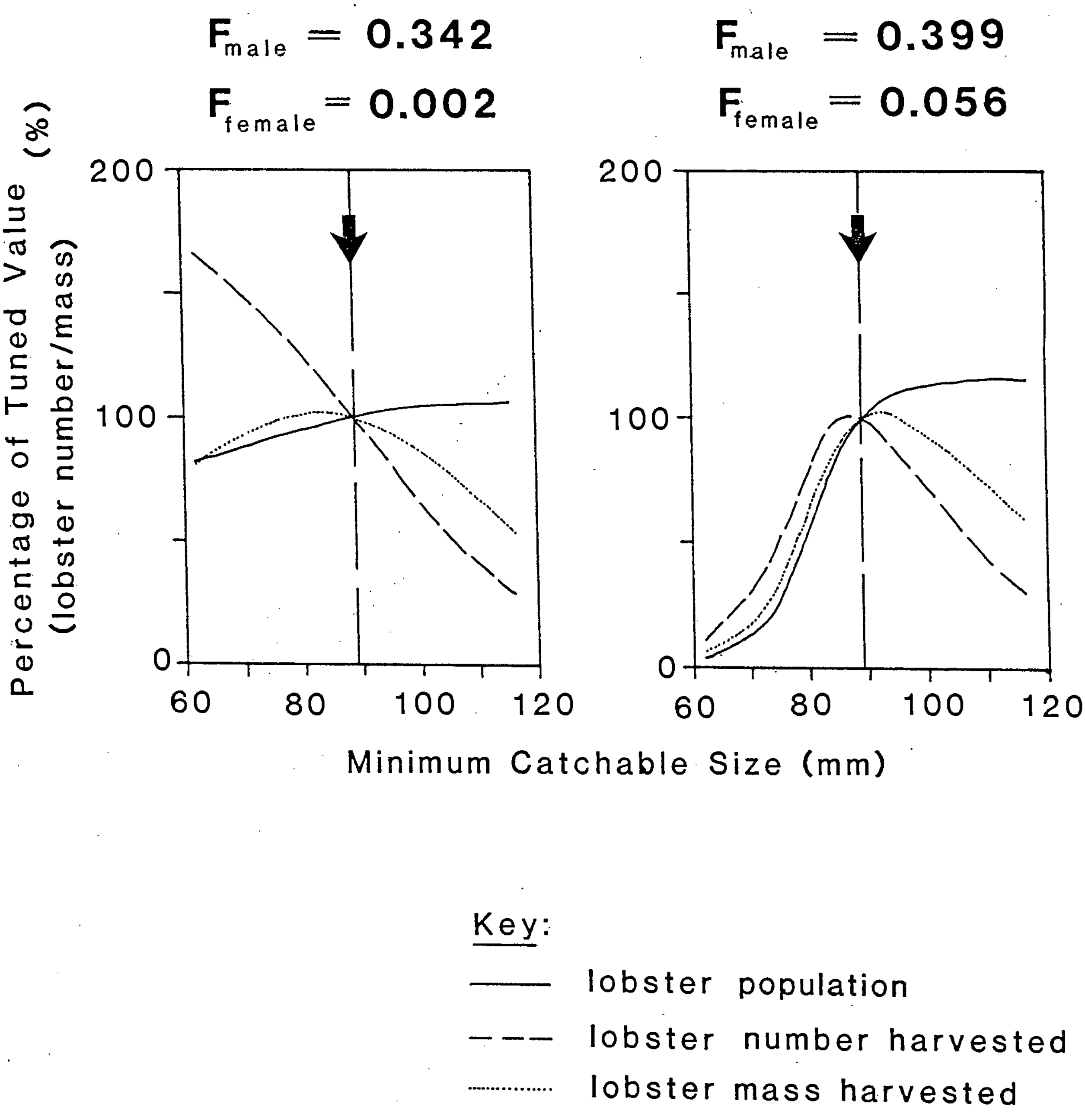
Change in minimum catchable size :

The same trends in number and mass harvested are shown at both fishing grounds for different minimum catchable sizes (Fig. 6.12). Both show an optimal harvested mass at the current minimum catchable size of 89 mm carapace length. The change in population numbers is different in each area at small minimum catchable sizes, having a more marked effect at Dassen Island where fishing pressure on females is greater. The results of both models are similar for the Cape Peninsula, whereas the patterns at Dassen Island are different using the model incorporating the stock-recruiment relationship. The changes in mean size of individuals in the catch (not illustrated) are similar to those of the constant recruitment model.

Cessation of harvesting at fishing grounds :

Stopping fishing at the Cape Peninsula had the same effect using this model and the constant recruitment model. However, at Dassen Island the increase in population numbers with no fishing is marginally greater than in the constant recruitment model because a larger number of females are available to produce more eggs (not illustrated).

FIGURE 6.14 : The results of changing the minimum catchable size at "moderate" and "heavy" harvesting rates of *J. lalandii* at the sanctuary, Robben Island as simulated by the lobster stock-recruitment model. The vertical broken line shows the present minimum catchable size (89 mm carapace length). Arrows indicate the increase/decrease in population numbers after a simulation period of 100 years.



Fishing in a sanctuary :

The change in population numbers with introduction of fishing to the Robben Island sanctuary at moderate and heavy fishing intensities (not illustrated) is similar to that of the constant recruitment model. A yield of 318 - 333 tons per annum is predicted, slightly lower than that estimated by the constant recruitment model. In this model the smaller harvest was produced at the heavier fishing rate (and higher female fishing mortality). Changing fishing pressure from the heavier harvesting rate leads to an increase in number and mass harvested with increased fishing pressure which is less using this model because the total population is reduced (Fig. 6.13) . As with the constant recruitment model, the mean size of individuals in the catch is slightly reduced with increased fishing pressure (not illustrated).

If the minimum catchable size is changed (Fig. 6.14) the results of the two models are similar at the moderate fishing mortality rate (F_{male} = 0.342, F_{female} = 0.002) although the optimal minimum catchable size is slightly larger (83 mm) using the stock-recruitment model. Reduction of the minimum catchable size below the present level leads to a sharp decrease in population number, number harvested and the mass harvested at heavy fishing pressures. This is the opposite trend to that shown by the constant recruitment model which predicts an optimal minimum catchable size of 70 mm. Both this and the constant recruitment model predict similar decreases in the mean size of individuals in the catch when the minimum catchable size is reduced (not illustrated).

DISCUSSION

In the constant recruitment model, Dassen Island, which has the densest lobster population has the lowest egg/larval mortality. Robben Island, having the sparsest population has proportionately heavier egg/larval mortality and the Cape Peninsula is intermediate. The mortality rates may differ because there are differing periods of larval drift to each area and differences in the larval settling potential of each area. Natural mortality of the adult size classes increases from the Cape Peninsula to Dassen Island to Robben Island. This is to be expected from the model since this sequence shows an increase in growth rate. There is heavier natural mortality in all size classes in areas of faster growth, compensating for the more rapid growth through the size classes. Female fishing mortality (F) was much less than first estimated. This is not unexpected because the number of females harvested is 2 to 3 orders of magnitude lower than that of males (see Table 4.14).

The most interesting effects of different parameters on lobster population size structure are those of growth and fishing. Mortality rate and the mortality-size distribution have little effect. The second peak of the size-frequency distributions for both sexes, representing newly-matured adults, is formed by the reduction in growth rate once individuals reach maturity (> 60 mm carapace length). The second peak may be emphasized because there are two sets of growth data (for juveniles and adults) from different sources, and there is a sharp drop in annual increment at the onset of maturity (see Fig 2.2). The height of the second (adult) peak is inversely related to the rate of growth, and is more marked in females because their growth rate is slower than that of males. This explains the sequence in peak height, following the progression from slowest (Cape Peninsula) to fastest (Robben Island) adult growth rates in the tuned size-frequency distributions (Fig. 6.1). Harvesting individuals larger than the minimum catchable size has a very marked influence on population size composition. The number of harvestable-sized individuals is greatly increased if there is no exploitation of the legal size classes and the entire distribution is flattened (Fig. 6.4). This explains the tuned male size-frequency distribution at the sanctuary (Robben Island) not declining as markedly as the other male distributions. A change in fishing pressure at the fishing grounds should also alter the balance between harvestable and non-harvestable individuals and therefore change the size structure of the population.

The model incorporating a linear stock-recruitment relationship does not reach steady state because there is no density limitation of females, thus control of population fecundity is unconstrained. An approximately stable state was attained in the tuned simulations because the mortality of females balanced recruitment. However, any change which alters the equality results in the model population being unable to reach steady state. The stock-recruitment model is thus far more sensitive to parameter change than the constant recruitment model because it is density-independent. The inability of the stock-recruitment model to reach steady state makes it less useful for management. Nevertheless, it is interesting to compare the results of different harvesting strategies using this model with those of the constant recruitment model. If more females are removed by fishing in the stock-recruitment model this results in reduced recruitment and consequently a smaller harvest than predicted by the constant recruitment model. At the Cape Peninsula the annual fishing mortality of females is negligible (0.002) and the results of the two models are very similar. At Dassen Island the annual fishing mortality of females is higher (0.056) although still small compared to that of males.

The similarity between the two models with change in fishing pressure is caused by the small number of mature females that are harvestable. From simulations, only 5.7 % (Cape Peninsula) and 6.7 % (Dassen Island) of all mature females are shown to be of legal harvestable size. Table 6.3 shows that only 0.06 % (the Cape Peninsula) and 3.4 % (Dassen Island) of catches are comprised of females. This prevents drastic collapse or explosion in the lobster population with increased or decreased fishing mortality, as would otherwise be expected with such simulations. All Dassen Island simulations in which more females are harvested (increased fishing pressure and a lower minimum catchable size) lead to reduced harvest being predicted by the stock-recruiment model. Conversely, cessation of, or decrease in fishing, harvesting of males only, or increase in minimum catchable size results in greater recruitment leading to a greater increase in population numbers being predicted by the stock-recruitment model at Dassen Island than the constant recruitment model. The introduction of fishing to Robben Island and changing the fishing intensity and minimum catchable size results in little difference between models if female fishing mortality is small. Increasing fishing pressure or decreasing the minimum catchable size at Robben Island with heavy fishing mortality rate results in smaller increases in harvest as compared to the predictions of the constant recruitment model, in response to the reduced total fecundity of fewer females.

The lobster model based on constant recruitment provides useful information about the harvesting strategies of lobsters. The yield estimates are all sustainable because they are based on stable simulation output. Differences in growth and fishing mortality rates at two fishing grounds and a sanctuary give wide scope for exploring management strategies by modelling. Increased fishing pressure does not appear to improve harvest for the increased effort in either area, especially at the Cape Peninsula where growth is slower. Doubling the current effort at Dassen Island (where lobsters grow at the estimated "overall" growth rate) may increase the mass harvested by approximately 13 % with a large reduction in catch per unit effort. Cessation of fishing at either area causes a large (250+ %) increase in numbers of larger individuals and the overall population increases by a maximum of 25 %.

Off the Cape Peninsula the current minimum catchable size gives the best yield in terms of mass harvested, but at Dassen Island the optimal minimum catchable size is somewhat smaller (70- mm carapace length). This leads to an increase of approximately 35 % in harvested mass whereas the number harvested is increased to more than 300 % of the present Dassen Island catch. The mean size of individuals in the catch is reduced from 96 mm to less than 80 mm. If the fast-growing lobster population at Robben Island were to be exploited, a harvest of at least 340 tons per annum would seem sustainable with little change in the overall population number. A large amount of fishing effort would be required to increase the mass yield by an additional 12 % or the number harvested by 30 %. The optimal minimum catchable size off Robben Island appears to be smaller than the present minimum size although this changes with different fishing pressures. Using a reduced fishing effort (F_{male} = 0.342, F_{female} = 0.002) the model predicts a catchable size closer to 80 mm than the current 89 mm although the increase in mass harvested is marginal (3 %). The number harvested increases by approximately 30 % and the mean size of individuals caught is reduced from 95 mm to 91 mm. At higher fishing mortality (F_{male} = 0.399, F_{female} = 0.056) a minimum catchable size even smaller (70 mm) would appear to be optimal. The mass harvested might increase by 10 % while the number caught would increase by almost 90 % with the mean size of individuals caught being reduced from 98 mm to 79 mm.

CHAPTER 7

Lobster-mussel models

CHAPTER 7 : LOBSTER-MUSSEL MODELS

The simulations have been divided into two sections : those in which lobster and mussel recruitment is assumed to be constant and those in which a linear stock-recruitment relationship is used for lobsters.

A. WITH CONSTANT RECRUITMENT

TUNING

The interaction between lobsters and mussels is such that the growth rate of lobster adults (> 60 mm carapace length) is dependent on mussel availability, whereas juvenile lobster growth is constant throughout. The "fast" adult growth rate was used as input in this model for all areas and mussel availability was used to slow this growth rate to that appropriate to the Cape Peninsula and Dassen Island lobster grounds where growth is slower than at Robben Island. In the case of Robben Island, where lobsters grow optimally, it was tuned with the minimum number of mussels adequate to maintain this natural growth rate. Most of the tuned parameter values from the two single-species constant recruitment models of lobster and mussel populations were used in the lobster-mussel model for each area. Predation by lobsters is one form of mussel natural mortality and removes a large portion of the model mussel population. Therefore, zero mussel natural mortality was used except in the last size class which is not subject to predation. The number of mussels was altered by adjusting mussel egg mortality (to three significant figures) so that the growth rates approximated those of each area (Table 7.1). Mussel egg mortality values do not show the same trend from area to area as in the mussel model, and all values are somewhat larger than the corresponding figures in the mussel model.

TABLE 7.1 : Tuned values for parameters of the lobster-mussel constant recruitment model which retains the tuned values of the single-species models except for mussel egg mortality which is its tuning parameter. Values in parentheses below each area name give the total population of lobsters in each area. Mussel egg mortality values in parentheses are values from the mussel single-species model.

PARAMETER	ORIGINAL VALUE	TUNED VALUE		
		CAPE PENINSULA (66 450 240)	DASSEN ISLAND (146 245 106)	ROBBEN ISLAND (6 550 123)
<u>Mussel model</u>				
Eggs per spawning (EGG)	9.735×10^{15}	2.762×10^{15}	2.762×10^{15}	2.762×10^{15}
<u>Lobster model</u>				
Eggs per spawning (EGG)	1.488×10^{12}	0.688×10^{12}	0.688×10^{12}	0.688×10^{12}
Monthly egg/ larval mortality	1.000	1.076	0.978	1.109
Monthly natural mortality (male/female)				
7	0.008/0.008	0.006/0.006	0.011/0.010	0.006/0.008
8	0.008/0.010	0.005/0.008	0.014/0.012	0.008/0.011
9	0.008/0.015	0.005/0.010	0.015/0.013	0.011/0.016
10	0.008/0.019	0.006/0.011	0.016/0.014	0.015/0.021
11	0.010/0.023	0.006/0.012	0.017/0.015	0.018/0.024
12	0.015	0.007	0.018	0.020
13	0.019	0.007	0.019	0.022
14	0.023	0.008	0.020	0.024
Female monthly fishing mortality (FIS)	0.038	0.0002	0.007	-
<u>Lobster-mussel model</u>				
Mussel egg mortality at spawning (EGGMOR)	11.550	10.965 (13.084)	10.305 (11.199)	11.388 (11.982)

TABLE 7.2 : Ratio of total lobster population to mussel population at each area as calculated from the original population estimates and as simulated by the lobster-mussel constant recruitment model.

AREA	GROWTH RATE	LOBSTER/MUSSEL RATIO	
		CALCULATED ($\times 10^{-3}$)	TUNED ($\times 10^{-4}$)
Cape Peninsula	"SLOW"	2.4	4.2
Dassen Island	"OVERALL"	0.8	3.7
Robben Island	"FAST"	0.5	2.5

FIGURE 7.1 : Size-frequency distributions of A. ater populations from the Cape Peninsula, Dassen Island and Robben Island as simulated by the lobster-mussel constant recruitment model and compared to the observed distribution from Robben Island (D.E. Pollock, unpublished data).

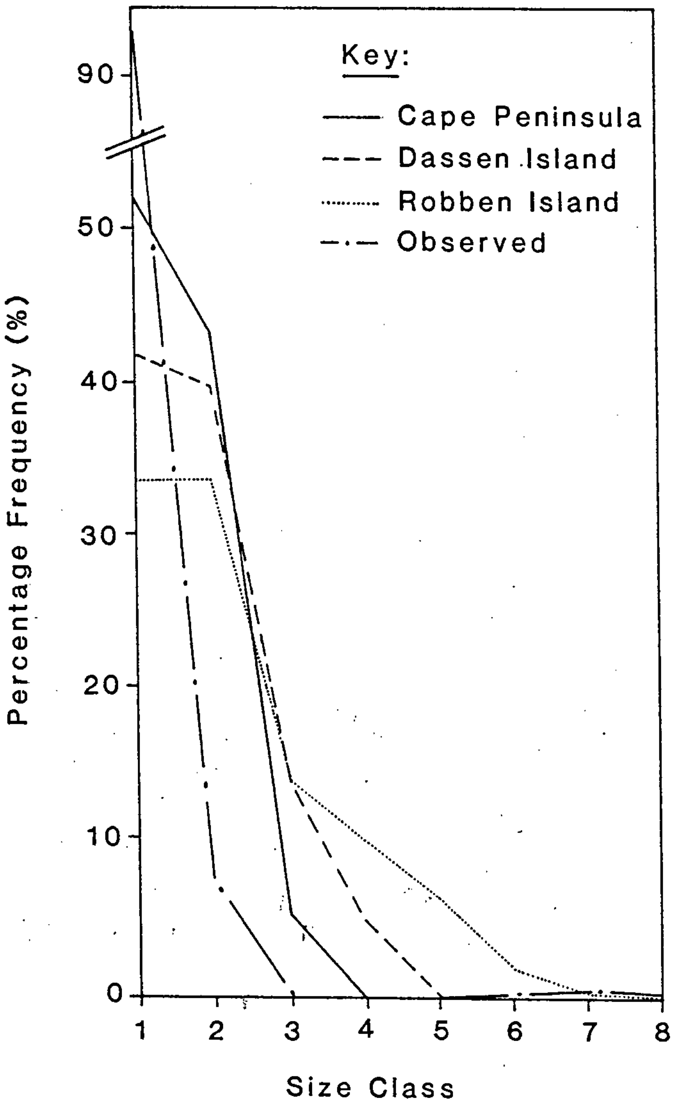


TABLE 7.3 : Percentage of optimal ("fast") growth rate calculated from the appropriate growth rates and simulated for the Cape Peninsula ("slow" growth) and Dassen Island ("overall" growth) using the lobster-mussel constant recruitment model.

AREA	PERCENTAGE OF OPTIMAL GROWTH IN DIFFERENT SIZE CLASSES							
	7	8	9	10	11	12	13	14
MALES :								
Cape Peninsula								
- tuned	78.2	59.1	53.7	46.7	22.5	10.1	100.0	100.0
- calculated	71.4	61.5	50.0	45.5	40.0	33.3	25.0	20.0
Dassen Island								
- tuned	100.0	98.0	98.0	89.8	67.0	51.5	45.3	33.1
- calculated	85.7	80.8	75.0	72.7	70.0	66.7	62.5	60.0
FEMALES :								
Cape Peninsula								
- tuned	78.2	59.1	53.7	46.7	22.5			
- calculated	60.0	66.7	50.0	57.1	60.0			
Dassen Island								
- tuned	100.0	98.0	98.0	89.8	67.0			
- calculated	80.0	83.3	100.0	100.0	100.0			

TABLE 7.4 : Maximum ages and corresponding maximum sizes for male and female lobsters at the Cape Peninsula and Dassen Island as estimated by the appropriate growth rates at each and when modelled using the lobster-mussel constant recruitment model.

AREA	MALES		FEMALES	
	AGE (years)	MAXIMUM CARAPACE LENGTH (mm)	AGE (years)	MAXIMUM CARAPACE LENGTH (mm)
CAPE PENINSULA				
- calculated	58	140	100	110
- tuned	54	140	100	105
DASSEN ISLAND				
- calculated	30	139	63	110
- tuned	34	139	70	110

The Dassen Island and Robben Island simulations were stable after 100 years but the Cape Peninsula took 150 years for the output, including the growth rate, to stabilize. Tuned values for the lobsters differed by less than 20 % and in most cases only a 2 % difference was found. Since altering the number of mussels was the only way of tuning the model without changing the population size structure of the lobsters, the mussel population numbers vary considerably from the values calculated originally (Appendix G). However, the ratio of lobster numbers to mussel numbers, an indication of mussel availability to predators, keeps the same tendency to decrease with increasing growth rate as that calculated (Table 7.2).

The mussel size-frequency distribution differs between areas with the greatest impact of lobster predation occurring around the Cape Peninsula and least at Robben Island (Fig. 7.1). The number of mussels in size classes 5, 6 and 7 (Cape Peninsula) and 6 and 7 (Dasssen Island) are reduced to zero because predation exceeds availability in these classes. The distributions are similar to that observed at Robben Island (D.E. Pollock, unpublished data). Table 7.3 shows the growth rate of each sex as a percentage of the "fast" rate, and computed from the ratio of mussels required to mussel availability in the model populations of the Cape Peninsula and Dassen Island grounds. This shows that the growth increments calculated by the model in these two areas are not exactly equivalent to those of the given "slow" and "overall" estimates of growth. In the Cape Peninsula area male size classes 13 and 14 grow optimally because there are so few individuals competing for food in these classes. The Robben Island population grows "fast" and therefore has 100 % growth in each size class. The model sets a maximum age for each sex equivalent to that attained at the "slow" growth rate. If growth is reduced below the "slow" rate then it is assumed that the lobsters will never attain maximum size. Table 7.4 shows that at the slower growth rates estimated by the model, the maximum ages and sizes are similar to those calculated from the age-length

TABLE 7.5 : Results of the sensitivity analysis on the lobster-mussel constant recruitment model. The range of figures show male (M) and female (F) values. The rate of growth is indicated as "fast" (F), "overall" (O) or "slow" (S). If the growth rate is slowed to less than the determined "slow" growth, it is assumed the maximum size cannot be reached so the sizes reached by the maximum ages (58 and 100 years for males and females, respectively) are shown.

SENSITIVITY PARAMETER		OUTPUT (% OF TUNED VALUE)										
		LOBSTERS							MUSSEL NUMBERS	LOBSTER GROWTH RATE	LOBSTER MAXIMUM CARAPACE LENGTH (mm)	
		TOTAL NUMBER		NUMBER OF CATCHABLE SIZE		NUMBER HARVESTED		MASS HARVESTED				
		M	F	M	F	M	F				M	F
CAPE PENINSULA												
Lobster parameters :												
Natural	+20%	9	8	10	22	20	21	12	2267	F	-	-
mortality	-20%	1764	1387	0	0	0	0	0	30	S	69	66
Fishing	+20%	88	97	106	351	119	421	130	121	S	-	-
mortality	-20%	102	100	114	100	96	80	98	98	S	123	103
Eggs	+20%	164	130	45	0	45	0	39	66	S	103	87
	-20%	71	77	95	338	94	337	116	563	F	-	-
"Overall" growth		107	102	89	73	89	73	86	91	S	118	103
"Slow" growth		150	112	14	0	14	0	11	69	S	93	82
Optimal	+20%	137	109	37	0	37	0	33	66	S	103	87
Eating	-20%	88	97	118	421	118	421	145	562	F	-	-
Mussel parameters :												
Eggs	+20%	88	97	118	422	118	421	145	580	F	-	-
	-20%	137	109	37	0	37	0	33	51	S	103	87
Egg	+20%	148	115	0	0	0	0	0	3	S	72	69
mortality	-20%	88	97	118	422	118	421	145	19677	F	-	-
Remaining	+20%	100	100	100	100	100	100	100	100	S	-	-
mussels	-20%	100	100	100	100	100	100	100	100	S	-	-
"Slow" growth		100	100	100	100	100	100	100	100	S	-	-
"Fast" growth		90	97	117	352	116	351	130	76	S	-	-
DASSEN ISLAND												
Lobster parameters :												
Natural	+20%	12	11	10	6	9	5	9	1741	F	-	-
mortality	-20%	1280	1056	0	0	0	0	0	23	S	72	71
Fishing	+20%	99	100	94	99	107	112	108	122	F	-	-
mortality	-20%	102	100	105	81	88	70	88	91	S	-	-
Eggs	+20%	148	127	8	0	8	0	6	58	S	108	103
	-20%	80	80	81	81	81	81	84	4675	F	-	-
"Overall" growth		112	103	47	9	14	9	40	78	S	118	106
"Slow" growth		116	104	27	0	27	0	22	73	S	122	95
Optimal	+20%	124	106	7	0	7	0	5	58	S	108	101
Eating	-20%	100	100	102	101	101	101	105	467	F	-	-
Mussel parameters :												
Eggs	+20%	100	100	102	101	102	101	105	488	F	-	-
	-20%	124	106	6	0	6	0	4	45	S	104	95
Egg	+20%	134	108	0	0	0	0	0	3	S	76	72
mortality	-20%	100	100	101	102	101	102	105	13242	F	-	-
Remaining	+20%	100	100	99	97	98	97	98	100	O	-	-
mussels	-20%	100	100	101	101	101	101	101	100	O	-	-
"Slow" growth		100	100	101	102	101	102	101	372	O	-	-
"Fast" growth		100	100	101	102	101	102	105	71	F	-	-
ROBBEN ISLAND												
Lobster parameters :												
Natural	+20%	9	8	7	4	-	-	-	1408	F	-	-
mortality	-20%	1941	1440	0	0	-	-	-	19	S	69	69
Eggs	+20%	152	135	21	0	-	-	-	44	S	107	99
	-20%	80	80	80	80	-	-	-	384	F	-	-
"Overall" growth		112	106	68	7	-	-	-	61	S	118	104
"Slow" growth		117	108	48	0	-	-	-	56	S	111	96
Optimal	+20%	127	112	17	0	-	-	-	44	S	104	95
Eating	-20%	100	100	100	100	-	-	-	390	F	-	-
Mussel parameters :												
Eggs	+20%	100	100	100	100	-	-	-	406	F	-	-
	-20%	128	112	17	0	-	-	-	34	S	103	98
Egg	+20%	152	117	0	0	-	-	-	2	S	72	69
mortality	-20%	100	100	100	100	-	-	-	13354	F	-	-
Remaining	+20%	100	100	100	100	-	-	-	100	F	-	-
Mussels	-20%	100	100	100	100	-	-	-	100	F	-	-
"Slow" growth		106	103	93	28	-	-	-	278	S	130	105
"Fast" growth		100	100	100	100	-	-	-	79	F	-	-

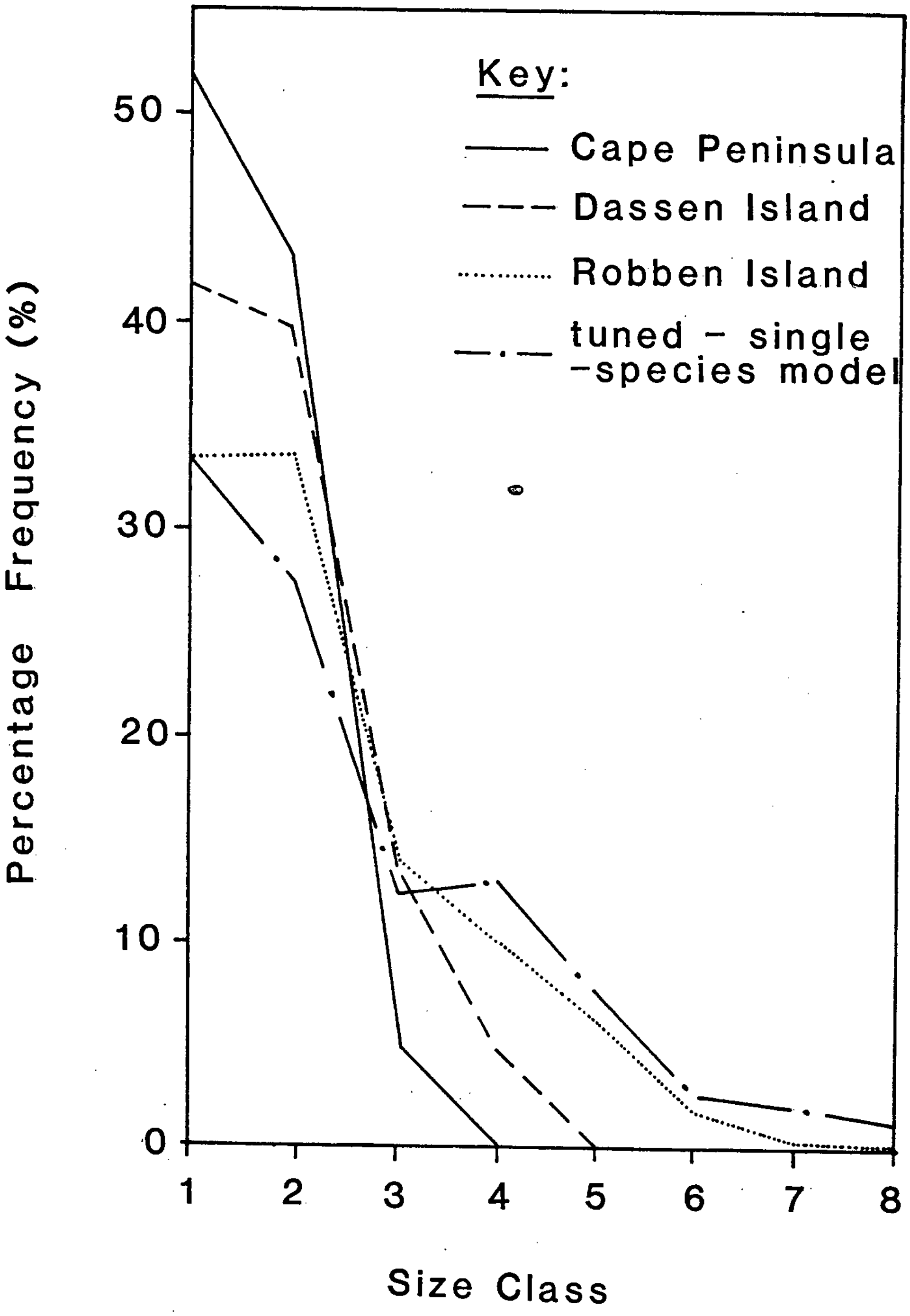
distributions.

The lobster size-frequency distributions at the Cape Peninsula and Dassen Island changed slightly from those simulated by the lobster single-species model because their appropriate growth rates are not exactly as calculated. Consequently, the lobster sex ratios in different size classes, the percentage of males in the population, of harvestable size and in the catch, are also marginally different from those of the lobster model. In the lobster-mussel model, the stable tuned values cannot be used as input for further simulations because all runs must commence with a "fast" growth rate which is reduced according to food availability. The 100-year runtime for Dassen Island and Robben Island and the 150-year runtime for the Cape Peninsula, used in tuning were used in further simulations and the stable endpoint values in further simulations compared with the those of the tuned output.

SENSITIVITY ANALYSIS

Sensitivity analyses on the lobster-mussel model involved testing all the parameters tested in the lobster and mussel models, the optimal number and kilojoule requirement of mussels by lobsters and the number of unobtainable mussels to ± 20 % of their values. Of the lobster-mussel model parameters only the sensitivity to kilojoule value of mussel flesh was not tested. Comparison of this sensitivity analysis to those of the single-species models gives an indication of the sensitivity of this model to its structure, which includes the change in lobster growth rate. The output used is the same as in the two single-species models but the maximum age and the corresponding size of lobsters were also noted (Table 7.5). A 20 % change in parameter values tended to change growth rates to the extremes, caused by either an excess or a shortage of mussels. This results in different numbers of individuals in various size classes being subjected to

FIGURE 7.2 : The effect of different intensities of predation from *J. lalandii* populations at the Cape Peninsula, Dassen Island and Robben Island on *A. ater* population size structure as simulated by the lobster-mussel constant recruitment model. This is compared to the size distribution resulting from linearly decreasing mortality with *A. ater* size (tuned distribution from mussel single-species model for all areas, see Fig. 5.1).



the size-based parameters for different periods of time with consequent changes in population numbers. Of the lobster parameters, a 20 % reduction in natural mortality caused the most substantial changes to the growth rate, slowing it so that no individuals attained harvestable size. Of the mussel parameters, reducing the number of eggs spawned or increasing the egg mortality had an equally large effect. In all three areas the number of unobtainable mussels made no difference to growth rate or other output.

EFFECTS OF PREDATION ON POPULATION SIZE STRUCTURE

Predation may have a marked effect on the size composition of the prey population (Fig. 7.2). Depending on the predation intensity, some size classes may have substantially reduced numbers whereas a linearly decreasing natural mortality with size does not result in such marked declines in larger mussel size classes.

TESTING DIFFERENT LOBSTER HARVESTING STRATEGIES

Simulations were carried out to investigate changes in lobster harvesting strategies at both fishing grounds, the Cape Peninsula and Dassen Island and the sanctuary, Robben Island. The three areas have different lobster growth rates and the fishing pressure at the two fishing grounds differs. The annual fishing mortality of the Cape Peninsula is smaller (F_{male} = 0.342, F_{female} = 0.002) than that of the Dassen Island fishing ground (F_{male} = 0.399, F_{female} = 0.056).

Change in fishing pressure :

Simulations were carried out in which fishing pressure was increased and decreased at the two fishing grounds (Fig. 7.3a). At different fishing pressures, especially at fishing mortalites close to the tuned F values the trends are not smooth. A large increase in fishing pressure leads to

FIGURE 7.3 : The results of changing fishing pressure at two fishing grounds in terms of _J. lalandii_ and _A. ater_ populations and _J. lalandii_ harvest (a) and _J. lalandii_ growth rate (b) as simulated by the lobster-mussel constant recruitment model.

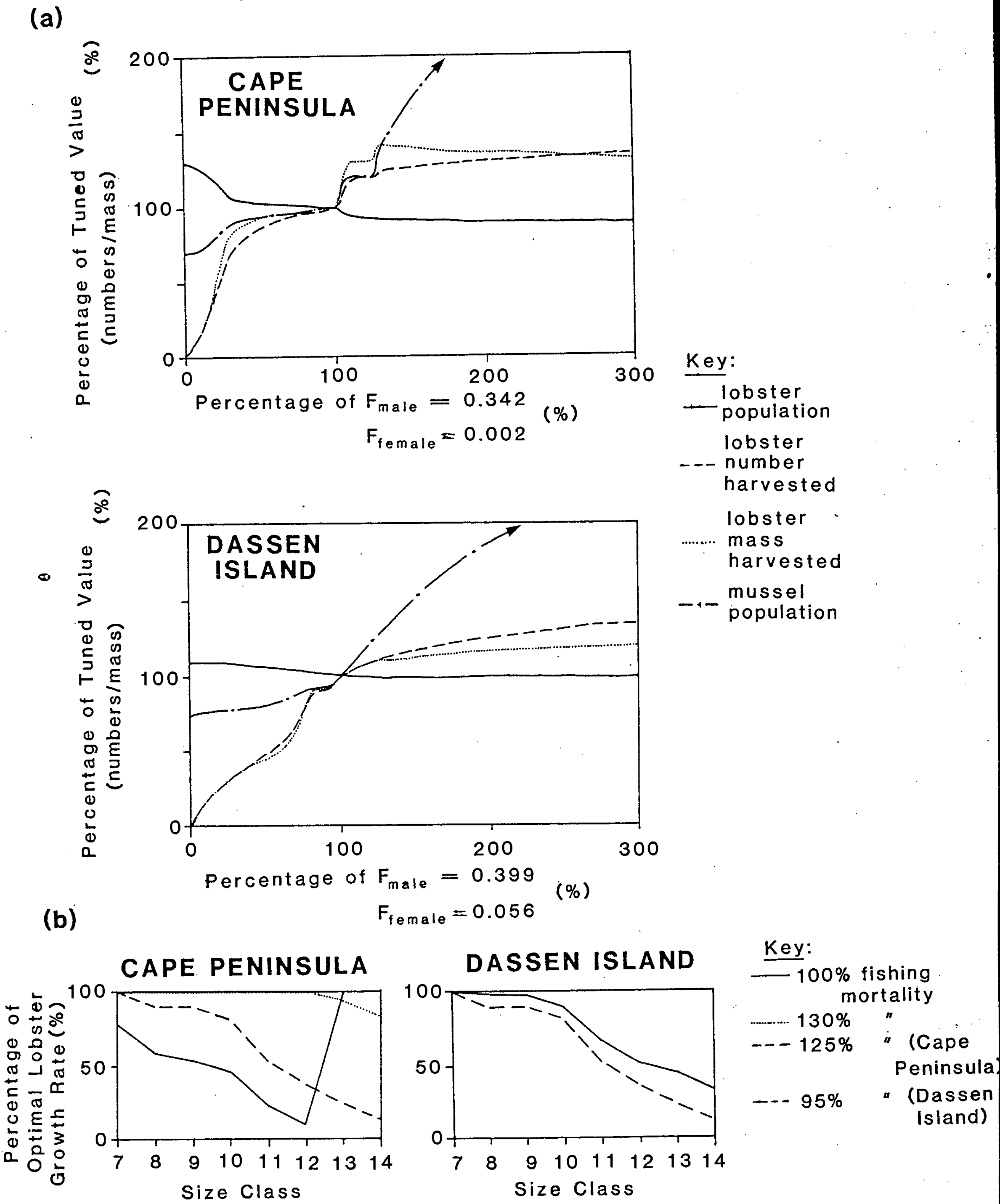
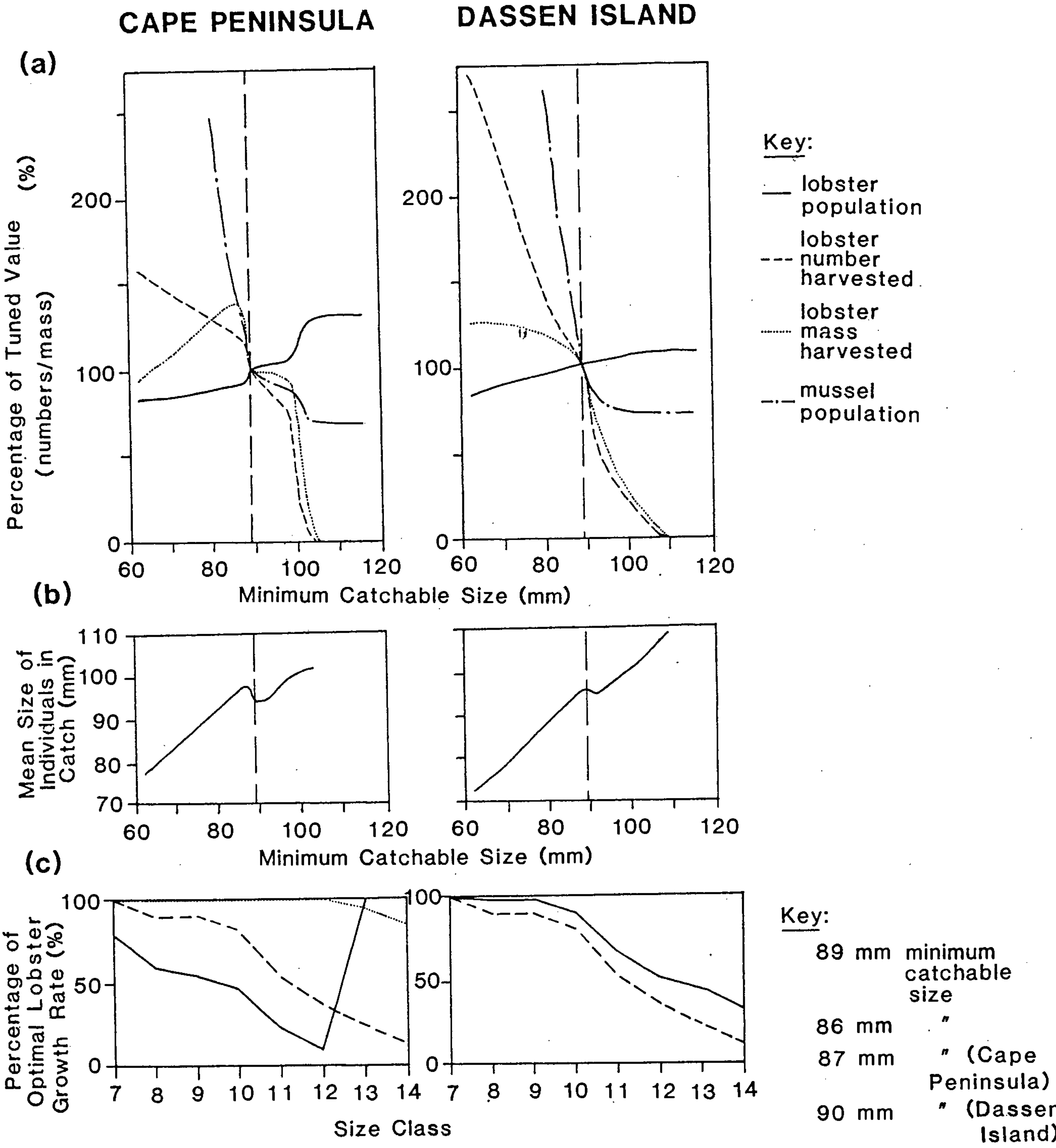


TABLE 7.6 : Fishing pressures (as percentages of tuned fishing mortalities) which show a change from one growth rate to another at the two fishing grounds using the lobster-mussel constant recruitment model.

FISHING MORTALITY	GROWTH RATE	YEARS TO REACH MAXIMUM SIZE (MALE/FEMALE)
CAPE PENINSULA		
100 % (tuned)	"SLOW"	54/100
+ 25 %	"SLOW"	58/81
+ 30 %	"FAST"	23/60
DASSEN ISLAND		
- 5 %	"SLOW"	58/80
100 % (tuned)	"OVERALL"	34/70
+ 5 %	"FAST"	22/60

FIGURE 7.4 : The results of changing the minimum catchable size at the two fishing grounds in terms of *J. lalandii* and *A. ater* populations, *J. lalandii* harvest (a and b) and *J. lalandii* growth rate (c) as simulated by the lobster-mussel constant recruitment model. The vertical broken line indicates the present minimum catchable size (89 mm carapace length).



stabilization with a slightly reduced mean size of individuals in the catch (not illustrated). At intense fishing pressures the predation of mussels by the reduced lobster numbers is less and large mussel populations develop. At both fishing grounds there is a very sharp changeover point from one growth rate to another (Table 7.6). At the Cape Peninsula, a 5 % change in fishing mortality results in the growth rate changing from "slow" to "fast". At Dassen Island, a 5 % decrease reduces the growth rate from the "overall" estimate to "slow" and an equivalent increase results in a "fast" growth rate. Fig. 7.3b shows how the growth rate of each size class of lobsters (same for males and females) is affected by a change in fishing pressure.

<u>Change in minimum catchable size</u> :

Simulations in which the minimum catchable size of lobsters was increased and decreased from the present size (89 mm carapace length) were carried out at the two fishing grounds and showed population trends which were not smooth (Fig. 7.4a). As the minimum catchable size is reduced, more lobster are fished and predation by lobsters on mussels is decreased, allowing larger mussel populations. There is a difference between the Cape Peninsula and Dassen Island in terms of mass harvested. As minimum catchable size is reduced, the mass harvested at the Cape Peninsula increases to a peak (86 mm minimum catchable size) and then decreases when the minimum catchable size is reduced further. At Dassen Island, the mass harvested shows an inverse s-shaped curve with minimum catchable size, the maximum harvest occurring below 70 mm minimum catchable size. The mean size of the individuals in the catch is increased/decreased with increase/lowering of the minimum catchable size, respectively (Fig. 7.4b). Mean sizes of individuals in the catch fluctuate around the present minimum catchable size when the lobster growth rate is changing. The effect of changing the minimum catchable size has major consequences for the growth rate (Table 7.7). In the Cape Peninsula area, a 1 mm change in the minimum catchable

TABLE 7.7 : Change from one growth rate to another at different minimum catchable sizes at the two fishing grounds using the lobster-mussel constant recruitment model.

MINIMUM CATCHABLE SIZE	GROWTH RATE	YEARS TO REACH MAXIMUM SIZE (MALE/FEMALE)
CAPE PENINSULA		
89 mm (tuned)	"SLOW"	54/100
87 mm	"SLOW"	58/82
86 mm	"FAST"	23/60
DASSEN ISLAND		
90 mm	"SLOW"	58/81
89 mm (tuned)	"OVERALL"	34/70
88 mm	"FAST"	22/60

size causes the lobster growth rate to change from "slow" to "fast". At Dassen Island, a 1 mm change on either side of the present minimum catchable size results in either a slower or faster growth rate than the tuned growth rate. Fig. 7.5c shows how the growth rate of each size class (same for both sexes) is affected by a change in the minimum catchable size.

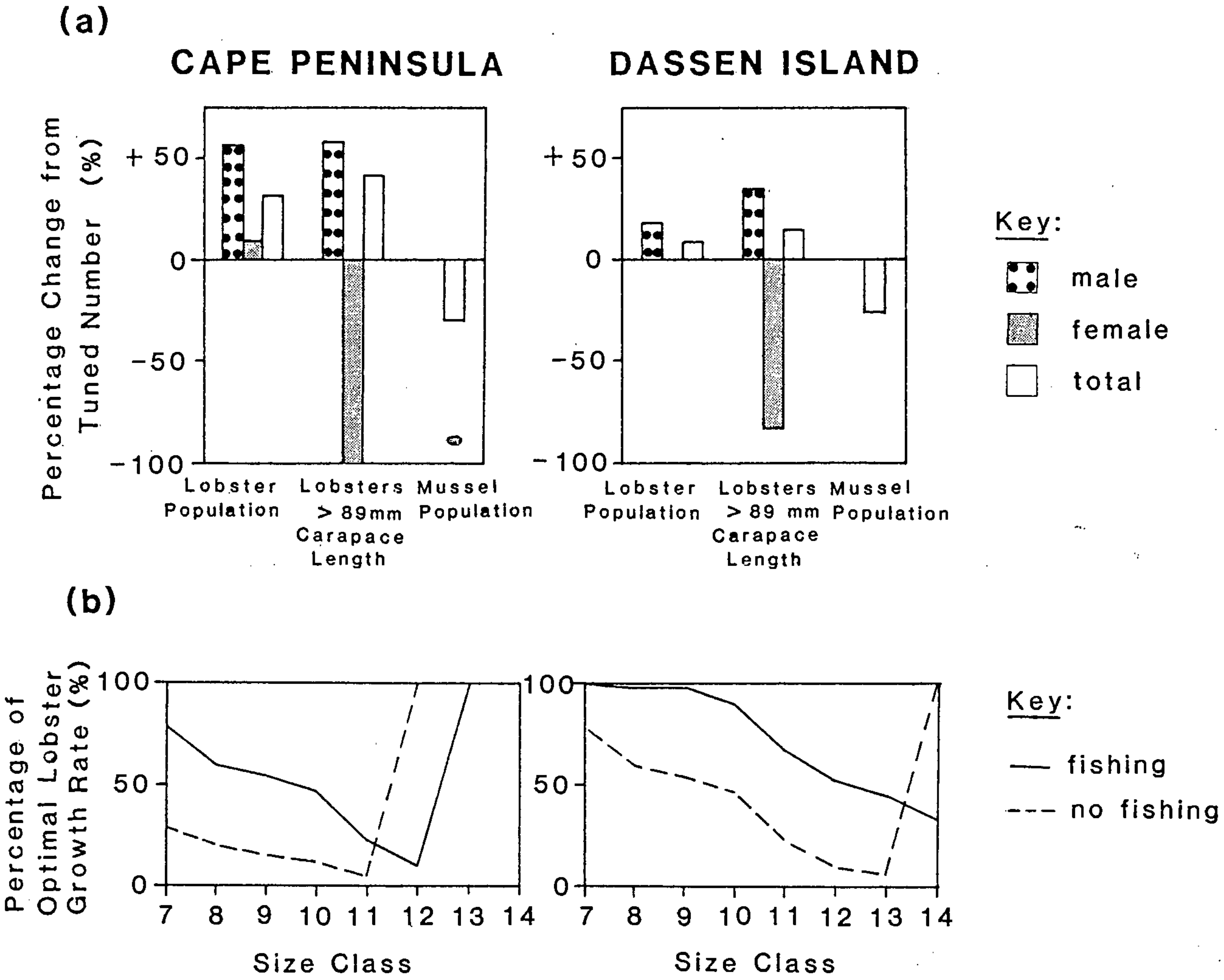
Cessation of harvesting at fishing grounds :

The effect of ceasing harvesting at both fishing grounds is an increase in total lobster numbers with more males over the minimum catchable size, and a reduced mussel population (Fig. 7.5a). The growth rate slows down at both fishing grounds so that the maximum carapace lengths of 140 mm (males) and 110 mm (females) are not reached. In the Cape Peninsula area, maximum sizes of 103 mm and 87 mm were attained for males and females, respectively. The growth rate was not as slow at Dassen Island, males and females reaching maximum sizes of 123 mm amd 103 mm, respectively. The number of females over the minimum catchable size was reduced to zero (Cape Peninsula) and 17 % (Dassen Island) because their growth rate is so slowed down that many do not reach harvestable size (89 mm). Fig. 7.5b shows how the growth increments in each size class (same for both sexes) are reduced when fishing is stopped.

Fishing in a sanctuary :

Fishing in the present sanctuary, Robben Island, shows the same effects for lobsters as using the single-species lobster model because the growth rate remains optimal (see Fig. 6.8) even though the number of mussels is increased approximately three-fold. Likewise, the effects of changing fishing pressure or changing the minimum catchable size are the same as simulated by the single-species lobster model because optimal growth is maintained (see Figs 6.9, 6.10). Changes in predation pressure on mussels with changes in lobster population size result in the mussel population

FIGURE 7.5 : The results of ceasing harvesting at the two fishing grounds in terms of *J. lalandii* and *A. ater* populations (a) and *J. lalandii* growth rate (b) as simulated by the lobster-mussel constant recruitment model.



increasing or decreasing. Reducing fishing pressure and increasing the minimum catchable size causes the mussel population to decrease to its present size. The number of mussels increases by a maximum of 25 % with increased fishing pressure on lobsters; a reduced minimum catchable size of 62 mm indirectly results in the mussel population increasing two-fold from the population levels at the current minimum catchable size.

B. WITH A LOBSTER STOCK-RECRUITMENT RELATIONSHIP

TUNING

The tuned parameters of the lobster-mussel constant recruitment model were used as input values and only lobster egg/larval mortality used to tune this model to give growth rates appropriate for each area. Stability was not reached at Robben Island but the model for this area was tuned with a simulation time of 100 years until no slowing of the growth rate occurred. The appropriate "slow" growth rate was tuned for the Cape Peninsula model using a 250-year simulation time. Even after a simulation of 500 years, it was not possible to attain a stable growth rate approximating the observed growth rate of Dassen Island because growth rate fluctuates in response to both mussel availability and changing lobster recruitment. The populations of Dassen Island were therefore not simulated using this stock-recruitment model. The tuned egg/larval mortality value for Robben Island is the same as in the constant recruitment model while that for the Cape Peninsula is slightly larger than the value for the other two models (Table 7.8).

Tuned lobster output differed by no more than 11 % from the calculated values but for the mussels there is a large difference (Appendix G). Table 7.9 shows that the ratio of lobsters to mussels remains high for the slower growing lobster populations in both models. The size-frequency

TABLE 7.8 : Tuned values of monthly egg/larval mortality from the constant recruitment and stock-recruitment models.

PARAMETER	CAPE PENINSULA	DASSEN ISLAND	ROBBEN ISLAND
Constant recruitment lobster and lobster-mussel models	1.076	0.978	1.109
Stock-recruitment lobster model	1.135	1.089	1.110
Stock-recruitment lobster-mussel model	1.146	-	1.110

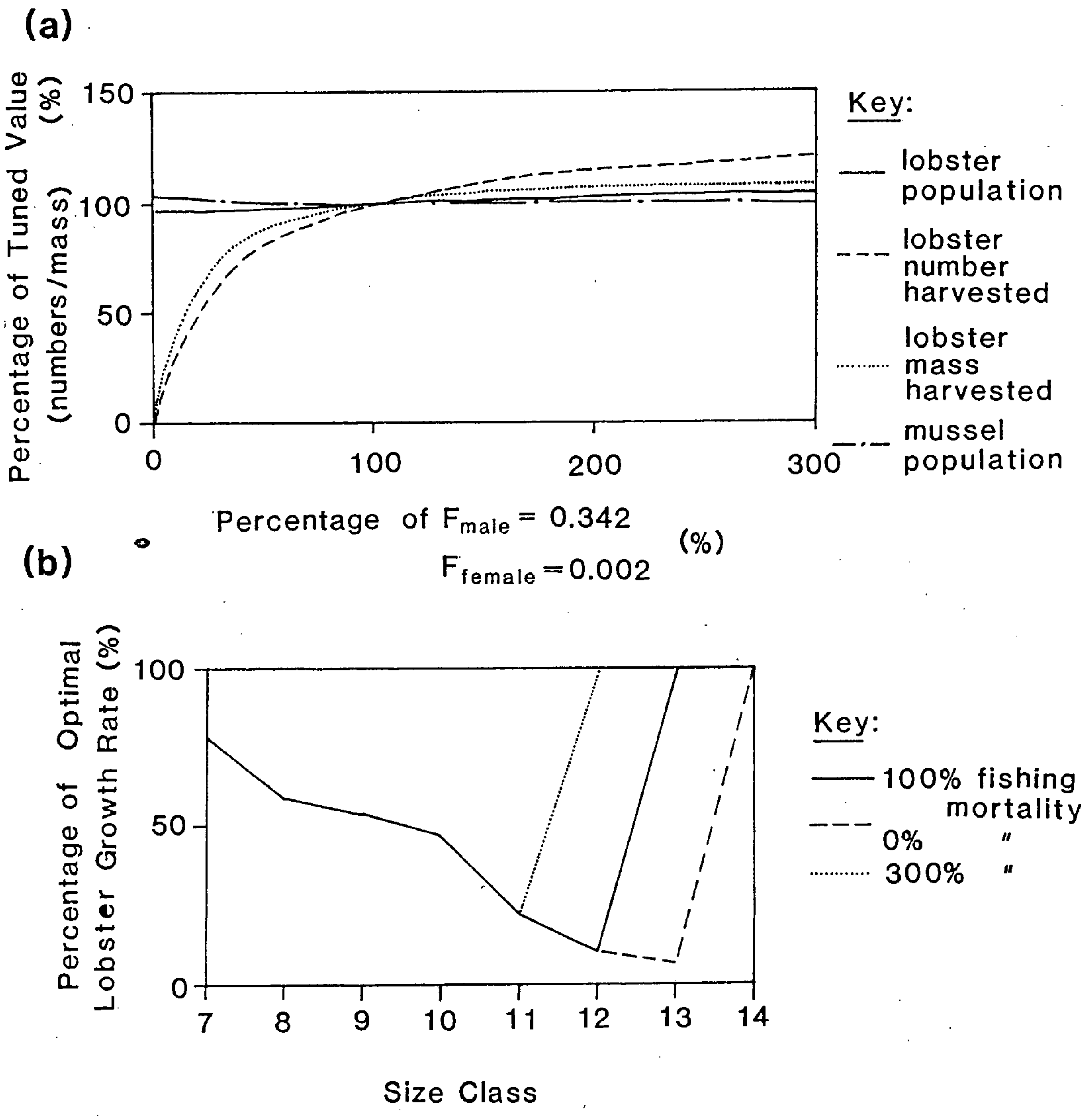
TABLE 7.9 : Ratio of total lobster population to mussel population at each of the areas modelled using the stock-recruitment model (S-R) compared to the constant recruitment model (C).

AREA	GROWTH RATE	LOBSTER/MUSSEL RATIO		
		CALCULATED ($\times 10^{-3}$)	TUNED (C) ($\times 10^{-4}$)	TUNED (S-R) ($\times 10^{-4}$)
Cape Peninsula	"SLOW"	2.4	4.2	4.4
Robben Island	"FAST"	0.5	2.5	2.0

TABLE 7.10 : Results of the sensitivity analysis on the lobster-mussel stock-recruitment model. The range of figures show male (M) and female (F) values. The rate of growth is indicated as "fast" (F), "overall" (O) or "slow" (S). If the growth rate is slowed to less than the determined "slow" growth, it is assumed the maximum size cannot be reached and the sizes reached by the maximum ages (58 and 100 years for males and females, respectively) are shown.

SENSITIVITY PARAMETER		OUTPUT (% OF TUNED VALUE)										
		LOBSTERS							MUSSEL NUMBERS	LOBSTER GROWTH RATE	LOBSTER MAXIMUM CARAPACE LENGTH (mm)	
		TOTAL NUMBER		NUMBER OF CATCHABLE SIZE		NUMBER HARVESTED		MASS HARVESTED				
		M	F	M	F	M	F				M	F
CAPE PENINSULA												
Lobster parameters :												
Natural	+20%	0	0	0	0	0	0	0	2515	F	-	-
mortality	-20%	1078	822	0	0	0	0	0	31	S	84	73
Fishing	+20%	100	101	91	101	105	121	102	100	S	-	-
mortality	-20%	101	98	112	98	94	79	97	100	S	123	103
Eggs	+20%	109	108	96	56	94	51	97	104	S	136	101
	-20%	26	28	35	129	35	130	43	1764	F	-	-
"Overall" growth		92	95	99	285	96	285	102	135	O	-	-
"Slow" growth		17	17	17	17	17	17	17	1992	S	-	-
Optimal	+20%	83	83	83	83	83	83	83	101	S	-	-
Eating	-20%	126	126	126	126	126	126	126	99	S	-	-
Mussel parameters :												
Eggs	+20%	121	121	121	121	121	121	121	119	S	-	-
	-20%	79	79	79	79	79	79	79	81	S	-	-
Egg	+20%	11	12	12	37	12	38	14	19	F	-	-
mortality	-20%	455	482	580	1723	570	1692	695	12028	F	-	-
Remaining	+20%	100	100	100	100	100	100	100	100	S	-	-
mussels	-20%	100	100	100	100	100	100	100	100	S	-	-
"Slow" growth		104	108	111	349	108	352	126	553	F	-	-
"Fast" growth		101	106	120	350	116	350	137	164	F	-	-
ROBBEN ISLAND												
Lobster parameters :												
Natural	+20%	0	0	0	0	-	-	-	1203	F	-	-
mortality	-20%	237	147	0	0	-	-	-	16	S	88	77
Eggs	+20%	133	126	88	11	-	-	-	42	S	122	108
	-20%	25	25	27	33	-	-	-	841	F	-	-
"Overall" growth		55	54	51	46	-	-	-	51	O	-	-
"Slow" growth		24	23	19	3	-	-	-	539	S	-	-
Optimal	+20%	80	80	80	80	-	-	-	136	F	-	-
Eating	-20%	99	99	99	99	-	-	-	332	F	-	-
Mussel parameters :												
Eggs	+20%	100	100	100	100	-	-	-	343	F	-	-
	-20%	77	77	77	77	-	-	-	109	F	-	-
Egg	+20%	9	9	9	9	-	-	-	18	F	-	-
mortality	-20%	100	100	100	100	-	-	-	106	F	-	-
Remaining	+20%	100	100	100	100	-	-	-	100	F	-	-
Mussels	-20%	100	100	100	100	-	-	-	100	F	-	-
"Slow" growth		79	79	79	79	-	-	-	538	F	-	-
"Fast" growth		101	101	101	101	-	-	-	76	F	-	-

FIGURE 7.6 : The results of changing fishing pressure in the Cape Peninsula fishing ground as simulated by the lobster-mussel stock-recruitment modelin terms of *J. lalandii* and *A. ater* populations and *J. lalandii* harvest and (a and b) and *J. lalandii* growth rate (c) .



distributions and therefore the sex ratio in different size classes for the Cape Peninsula and Robben Island are approximately the same as in the constant recruitment model as are the percentages of males in the population, of catchable size and in the catch. Fractional differences in each size class have caused slight changes from the constant recruitment model in the increments for "slow" lobster growth at the Cape Peninsula using this model.

SENSITIVITY ANALYSIS

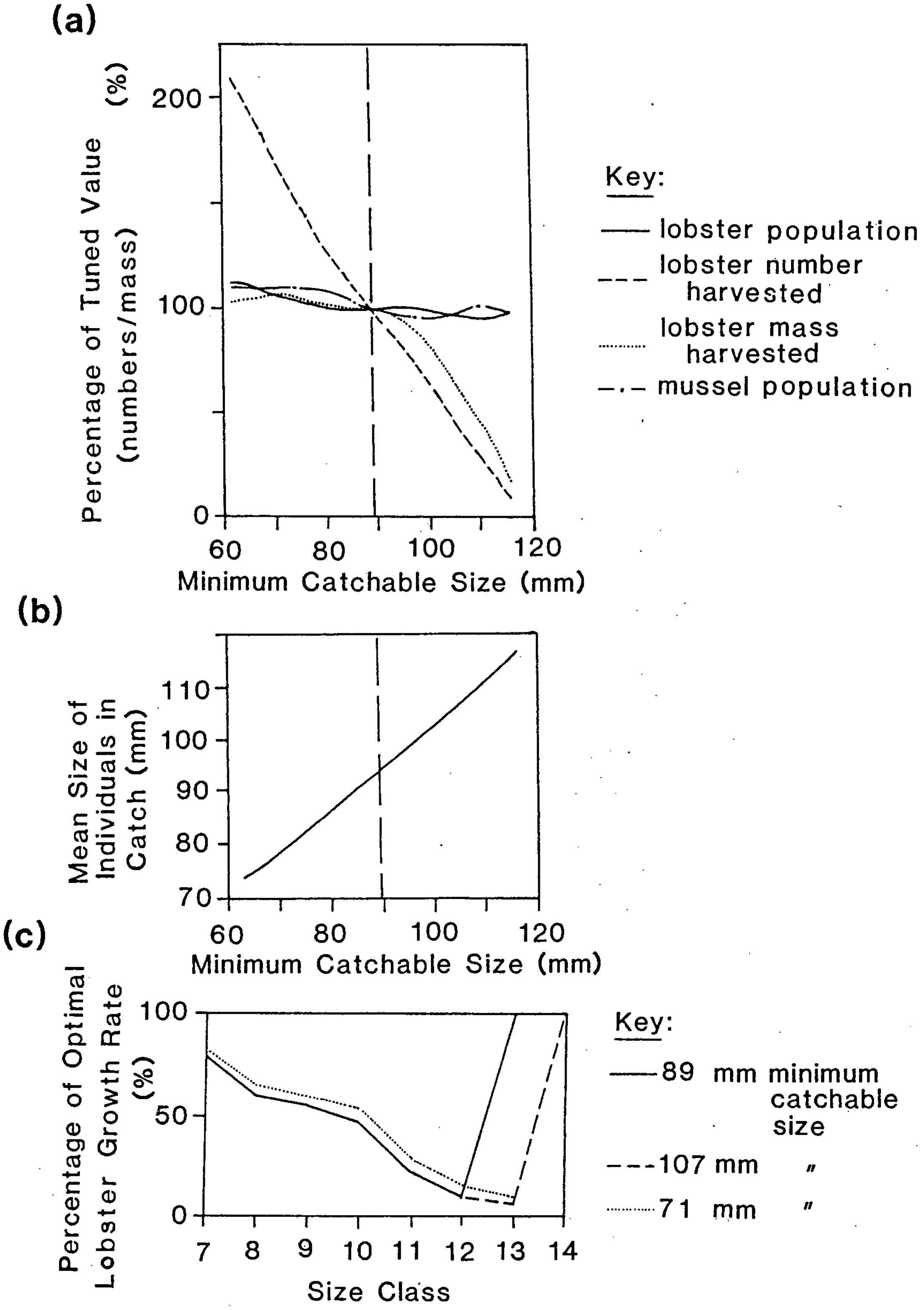
The sensitivity analyses of the same parameters as in the constant recruitment model (Table 7.10) show that any parameter that causes the growth rate to be increased to a "fast" rate at the Cape Peninsula or to remain at this optimal rate (Robben Island) has the greatest effect on numbers. These simulations do not reach steady state and all show decreasing lobster numbers and increasing numbers of mussels. Of the remaining parameters which result in stable output, a decrease in lobster natural mortality has the greatest slowing effect on growth so that neither sex reaches harvestable size (89 mm carapace length). When slower growth rates are input there is a large drop in lobster numbers and an increase in mussel numbers.

TESTING DIFFERENT LOBSTER HARVESTING STRATEGIES

Change in fishing pressure :

A change in fishing pressure results in no sudden changes in growth rate at the Cape Peninsula and the output is thus more stable than in the constant recruitment model (Fig. 7.6a). The mussel and lobster populations remain fairly consistent at any fishing intensity. Only a marginal increase in harvest is shown at a large fishing mortality. There is a slight reduction of the mean size of the individuals in the catch (not illustrated) at heavy fishing mortalities. Fig. 7.6b shows how the growth rate of different-sized

FIGURE 7.7 : The results of changing the minimum catchable size at the Cape Peninsula fishing ground in terms of *J. lalandii* and *A. ater* populations and *J. lalandii* harvest (a and b) and *J. lalandii* growth rate (c) as simulated by the lobster-mussel stock-recruitment model. The vertical broken line indicates the present minimum catchable size (89 mm carapace length).



lobsters of both sexes is marginally affected by the change in fishing pressure. The growth rate is "slow" at all levels although at zero fishing it slows slightly more so that males reach a maximum size of only 123 mm as opposed to the normal 140 mm. At 300 % of the present fishing mortality the male growth rate is equivalent to the "overall" estimate of growth.

Harvesting of males only :

A harvest which excluded the capture of females was simulated, but it made negligible difference (± 1 %) to the population numbers and harvested mass and there was no change in the growth rate (not illustrated).

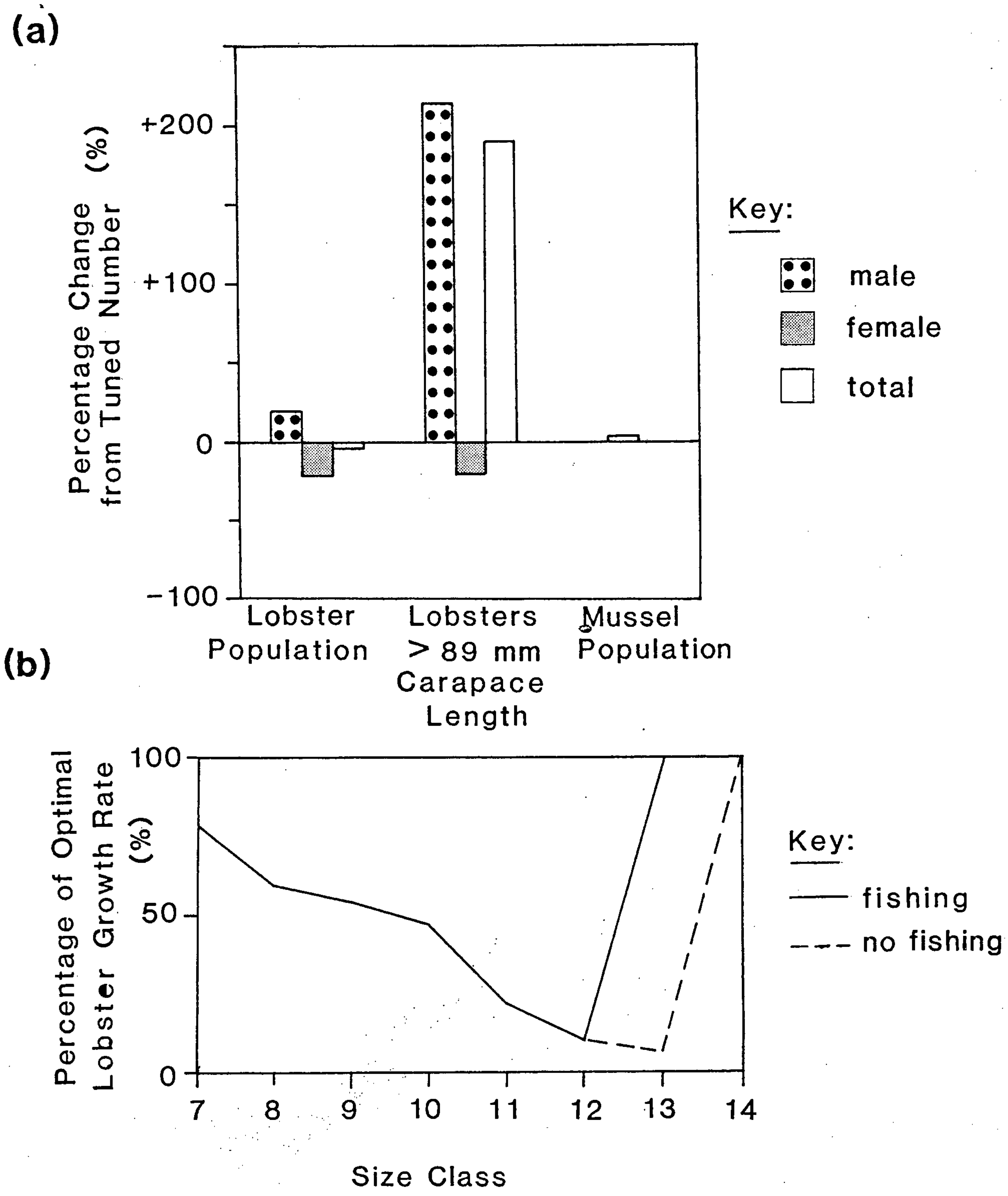
Change in minimum catchable size :

The total populations of lobsters and mussels remain fairly constant when the minimum catchable size is altered at the Cape Peninsula (Fig. 7.7a). The number of lobsters harvested is highest at the smallest minimum catchable size (62 mm carapace length) while the mass harvested is largest (although only by a small percentage) at a minimum catchable size just above 70 mm. The mean size of individuals in the catch is reduced at this 70 mm minimum catchable size (Fig. 7.7b). For males there is further reduction of the "slow" growth rate so that maximum size is not reached at legal sizes well below and above the present minimum catchable size of 89 mm. At minimum catchable sizes of less than 70 mm and above 107 mm, males reach maximum sizes of 128 mm and 123 mm, respectively. The effect on growth rate is greater on males than females because it is the sizes greater than the females maximum size that are most affected. Fig. 7.7c shows how the growth increment differs in each size class (same for both sexes) with different minimum catchable size regulations.

Cessation of harvesting at fishing grounds :

The cessation of harvesting at the Cape Peninsula had very little effect on the total lobster and mussel populations, although the percentage of

FIGURE 7.8 : The effect of ceasing harvesting in the Cape Peninsula fishing ground in terms of *J. lalandii* and *A. ater* populations (a) and *J. lalandii* growth rate (b) as simulated by the lobster-mussel stock-recruitment model.



harvestable males is increased (Fig. 7.8a). The growth rate is reduced slightly so that males reach a maximum size of 123 mm compared to 140 mm. Female growth is affected little because the growth rate is only reduced in the larger size classes above female maximum size (Fig. 7.8b).

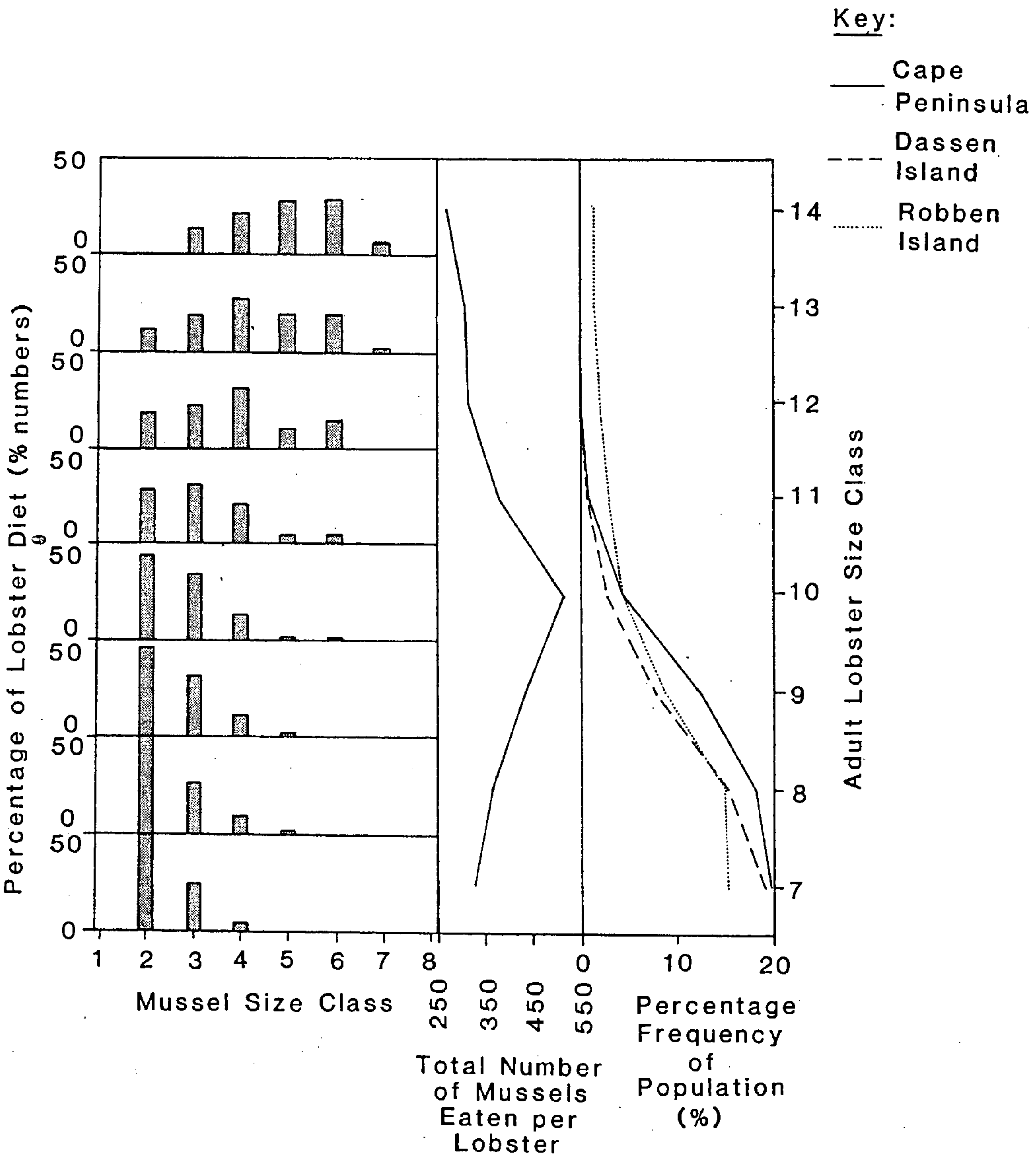
Fishing in a sanctuary :

In all simulations in which fishing took place at Robben Island (not illustrated) the results are the same as using the lobster model based on a stock-recruitment relationship because the optimal growth rate is maintained (see Figs 6.13, 6.14). In all simulations there is a general increasing trend in lobsters and a decrease in mussels after 100 years of simulation. The number of mussels is increased by 150 to 200 % when lobsters are harvested at Robben Island because of the reduced lobster population and consequent decrease in predation. With increased fishing pressure the mussels may increase by an additional 30 %. When the minimum catchable size is reduced below the current size of 89 mm carapace length, the lobster population becomes very small and mussels may increase four-fold in standing stock. Reducing fishing pressure and increasing the minimum catchable size causes the mussel population to decrease to the present level with no lobster exploitation.

DISCUSSION

The main purpose of this model is to investigate the harvesting strategies of lobster at areas in which the rates of growth of this species vary in response to the abundance of their prey, mussels. It is based on the assumption that the growth rate of different-sized lobsters is directly affected by the availability of mussels of correct size. The relative proportions of mussels of different sizes consumed by different-sized lobsters need to be correct for the model to be realistic. However, the

FIGURE 7.9 : Size composition and total number of *A. ater* from each size class in the diet of different-sized *J. lalandii* calculated from the data of Griffiths and Seiderer (1980) and size-frequency distributions of model lobster populations from the Cape Peninsula, Dassen Island and Robben Island.



exact numbers consumed are not important since the model is tuned by adjusting the overall number of mussels. Using the availability of mussels to tune the growth rate of lobsters at each area results in mussel abundance at these areas differing from those calculated, but does not detract from the main objective of the model. Most important is that the ratio of lobsters to mussels is highest in areas of slowest growth as a result of there being less food for more predators and vice versa. The difference between the calculated range of growth rates for each lobster size class and that computed by the model is a result of two features. It is assumed in the model that the growth of males and females of the same size are equally affected and the rate of growth is only dependent on mussel availability. The two factors are not entirely realistic but are simplifications of the natural situation.

The Cape Peninsula lobster population has the greatest impact on mussels reducing numbers in some size classes to zero. The Dassen Island lobster population does so but to a lesser extent (Fig. 7.1). The individuals which reach the largest size class may be considered to have reached a "refuge in size" from predation (Paine, 1965). At Robben Island the drop in mussel numbers in the larger size classes is less marked because there is less predation pressure. The observed mussel distribution from Robben Island (D.E. Pollock, unpublished data) shows a strong decline in numbers with increase in size, and over 90 % of individuals are less than 10 mm. However, as suggested in Chapter 2, variability in growth and natural mortality rates have profound effects on population size structure.

Fig. 7.9 shows both the size composition and the total number of mussels from each size class consumed by a single lobster (estimated from the data of Griffiths and Seiderer, 1980) and the tuned size-frequency distributions of lobster populations from each area. Lobster size classes 7, 8 and 9 have the largest number of individuals and would consume most mussels from size classes 2 and 3. Lobster size class 10 has fewer individuals but this class consumes the most mussels, also mainly from size classes 2 and 3. If the mussel size-frequency distribution is treated as the dependent variable, comparison of the lobster size-frequency distributions shows that the Cape Peninsula population would consume most of these smaller sizes of mussels followed by the Dassen Island and Robben Island populations. Therefore it is not unexpected that heavy exploitation of these small mussel size classes leads to the great reduction in numbers in the larger classes shown by the model distributions. Penney and Griffiths (1984) found that prey size preferences by various predators may profoundly affect prey population size structure particularly by depleting prey within the preferred size range. Pollock (1978) and Griffiths (1981) also observed that _J. lalandii_ can obliterate _A. ater_ beds rapidly through predation. The model confirms that differing natural mortality in the form of predation or other losses can greatly alter the size structure of the mussel population.

The lobster-mussel models with different lobster recruitment patterns both produce some unstable or irregular results, but for different reasons. When a constant recruitment pattern is used, fine tuning is required to reach growth rates appropriate for each area. If the ratio of lobsters to mussels results in a change in lobster growth rate, this occurs over a very narrow range of parameter values as shown by the sensitivity analysis (Table 7.5). In the model in which a linear stock-recruitment relationship is assumed, density-dependence resulting from the influence of mussel availability on the lobster growth rate creates a stability which was absent in the single-species stock-recruitment model. In the density-dependent situations, changes in growth rate are "smoothed" so that there are no sharp cutoff points between very different rates. However, use of the stock-recruitment model is limited since any change leading to optimal lobster growth being achieved (such as in all the Robben Island simulations) causes densityindependence in recruitment and a model unable to reach steady state. The output from both models is discussed, bearing these features in mind, but only the "realistic" situations used as beneficial model results in terms of management policy.

Using the constant recruitment model the trends of the Cape Peninsula and Dassen Island populations of lobsters and mussels are very sensitive close to the present fishing mortality value (when fishing mortality is changed) and near to present minimum catchable size (when this is altered from 89 mm carapace length). A 5 % change in fishing mortality or a 1 mm change in the minimum catchable size retards or accelerates the growth rate to either extreme. The constant recruitment model suggests that with increased fishing one could attain a harvested mass some 20 % higher at Dassen Island or approximately 30 % higher at the Cape Peninsula. In both areas the number harvested increases by approximately 30 % with a slight reduction in mean size of individuals in the catch. At this heavy fishing intensity the mussel population would increase very rapidly. Optimal minimum catchable size predicted by the constant recruitment model is 86 mm or < 70 mm for areas of "slow" growth (Cape Peninsula) and the "overall" growth estimate (Dassen Island) respectively, with the mussels reaching very large population sizes at both of these limits. However the sensitivity of the model in terms of growth rate places some doubt on the usefulness of the results. Both models indicate that cessation of fishing at fishing grounds results in increased lobster numbers and heavier predation with fewer remaining mussels. This retards the lobster growth rate (of males in particular) so that maximum size is not reached.

Neither model gives more information about introducing fishing to Robben Island and thereafter changing the fishing policy than the density-independent single-species lobster models, because growth rate remains optimal. However, the fluctuations in the mussel population in response to the intensity of predation can be monitored. Any harvesting strategy that reduces lobsters causes an increase in the mussel population, and vice versa. The sustainable catch of at least 340 tons per annum at Robben Island is probably an underestimate for two reasons. Firstly, if fishing were introduced, the number of individuals dying from natural mortality would probably be reduced. Secondly, the growth rate estimated here is based on the optimal recorded growth but this may not be the fastest possible rate. An excess of mussels may lead to even faster growth rates which may result in a larger catch.

The inconsistency of the trends of the constant recruitment model reduces its value as a potential management tool. The simulations which are most informative are those simulating the harvesting strategies of the slow-growing Cape Peninsula lobster population with the stock-recruitment model, because optimal growth is not achieved. The yields estimated with different harvesting strategies are sustainable because they are based on stable output. The lobsters, in particular the females, show no sudden changes in the growth rate when fishing intensity or the minimum catchable size was altered. Both predator and prey populations maintain stability in these two sets of simulations. A marked reduction or increase in fishing pressure or a smaller or larger minimum catchable size may cause slight retardation or acceleration of male growth, respectively. Increase in fishing pressure to above double the present harvesting rate would make little difference (< 10 %) to the mass harvested although a 20 % increase in the number caught (with a slightly lower mean size of catch individuals) could be expected. If the minimum catchable size were changed to 70 mm only a 7 % better yield in terms of mass is predicted. A corresponding 70 % increase in the number harvested would be expected but the mean size of the catch would drop from 95 mm to 80 mm. in terms of mass is predicted. A corresponding 70 % increase in the number harvested would be expected but the mean size of the catch would drop from 95 mm to 80 mm.

CHAPTER 8

Conclusions

CHAPTER 8 : CONCLUSIONS

Economically, the ideal state for a fishery is to have a maximal sustainable harvest, while ecologically, it should have the least disruptive effect on the ecosystem. There is evidence that predators may determine the structure and productivity of a system (Mann, 1981). If increased exploitation of a predator species is under consideration, it is essential to consider components of other trophic levels that may be affected. Mann (1981) suggests that exploitation should be controlled so that stocks are not severely stressed, thereby guarding against ecosystem changes that may be irreversible. There may be chain reactions such as that believed to have occurred in a Nova Scotia kelp bed ecosystem (Breen and Mann, 1976; Mann, 1981; Wharton and Mann, 1981). Overexploitation of lobster (<u>Hommarus americanus</u>) in this area reduced the population so that their prey, urchins (<u>Strongylocentrotus droebachiensis</u>) increased. Overgrazing by urchins led to destruction of the kelp (<u>Lammanaria longicruris</u>, <u>L. digitata</u> and <u>Argarum cribrosum</u>). Lobster were then subjected to a reduced food supply and increased predation as a result of lack of shelter from the kelp, and their population decreased further.

The relationship between growth of lobsters and availability of their prey is well documented both locally for <u>Jasus lalandii</u> and <u>Aulacomya ater</u> (Newman and Pollock, 1974b, 1977; Pollock, 1979; Pollock and Beyers, 1981; Pollock <u>et al.</u>, 1982) and for other species (Kurata, 1962; Witham <u>et al.</u>, 1964; Chittleborough, 1975, 1976). These interacting predator and prey species are the most abundant benthic carnivore found in kelp beds (Field <u>et al.</u>, 1977; Velimirov <u>et al.</u>, 1977) and the largest sessile component of benthos (Pollock, 1979), respectively, on the west coast of South Africa. The importance of maintaining stability of these two species should therefore not be underestimated as they may have profound influences on other trophic levels, effects which have not been modelled. The models have shown the effects that different parameters have on population size composition. Growth and fishing, in particular, can alter the size structure of a lobster population to a degree. The effects of growth and predation on the mussel prey population may cause great changes to the size composition of the population. The size structure of the prey population is highly variable and the intensity of predation may have large effects on mussels and therefore on other ecosystem components. The use of such a variable population size composition in estimation of exploitation by mussels on another species must be regarded carefully.

Population parameters and recruitment

The collection of data for population parameters provides a comprehensive compilation of information about a species, synthesises a large portion of research carried out on the given species and highlights areas in which data is lacking. Growth is an important parameter in fisheries biology, having a profound effect on the harvesting strategy of a species. Therefore an attempt was made to combine a number of existing data sets on growth in order to obtain overall growth estimates and ranges for both J. lalandii and A. ater. Growth of both J. lalandii and A. ater was found to be very slow and highly variable. There are inadequacies in the data sets for the two species (such as recruitment rates and natural mortality rate of mussels). These are difficult to quantify and are highly specific to particular areas. The quality of the data is sufficient for the level of resolution of the model and this has been satisfactorily confirmed by the sensitivity analyses. Using these analyses, unexpected results highlight any irregularites in the model structure, providing information on the extent to which one can interpret the simulations and can also help determine the controlling processes in a population or system.

A central problem in population dynamics models is that of recruitment. Hancock (1980) questions the validity of restrictions which preserve spawning stock. Such restrictions assume that there is a relationship between parent stock and recruitment, but no good correlations between lobster stock and number of recruits have been shown. Morgan (1980) suggests that populations may be limited by habitat, and not by recruitment. However, both of these authors acknowledge that for most populations, limiting factors are unknown and conservative treatment should force management to assume that egg production is an important factor. Only sub-populations of the entire South African west coast stocks of *J. lalandii* and *A. ater* were modelled (in the areas of the Cape Peninsula, Dassen Island and Robben Island). The assumption of constant recruitment to each of these sub-populations is possibly not completely unrealistic. Recruitment depends on the whole populations of these two species as there is wide larval dispersal and the area of substrate suitable for settlement of larval recruits at each area sets an upper limit for each sub-population. However, if recruitment at all fishing grounds is reduced by a new harvesting policy, recruitment to each sub-population may also be limited. As a protection against this, sanctuaries protect some sub-populations that produce a number of recruits and the present fishing season does to some extent protect females as they moult during the season and there is restriction on harvesting soft-shelled and berried females.

The models and their limitations

In building models, one has to balance complexity in making the model more realistic against simplicity which facilitates interpretation. Simple models do not account for all factors but more complicated multi-species models either tend to produce what is intuitively obvious or follow directly from the assumptions and they may demand too much from the data (Gulland, 1979). In such models it is therefore difficult to distinguish between the model effects and "real" ones. Nevertheless Gulland (1979) suggests that the careful use of multi-species models can provide useful guidance in fishery management and may result in better decisions than those based on a single-species approach. Measures to control exploitation range from regulations based on empirical reasoning to comprehensive management policies involving detailed studies of the population dynamics of the species for use in quantitative models to describe the fishery (Hancock, 1980).

Four models of lobster populations, each differing in complexity, were formulated to investigate optimal exploitation of J. lalandii. The models are all age-based models using a simple conversion factor for using length-based parameters as functions of age. This is neccessary for Crustacea as ageing is difficult in such slow growing species. First there is a single-species model in which constant recruitment and growth are assumed. This was then expanded to include a stock-recruitment relationship. The next step was enlargement of the single-species constant recruitment model to include a mussel-dependent growth function for lobsters. The final stage was incorporation of a stock-recruitment relationship for lobsters into this two-species model. Of these four models the most simple and the most complex models provided the most practical management information without complications that cause instability and necessary fine-tuning. The single-species model incorporating a stock-recruitment relationship was unstable due to a lack of any density-dependence to regulate reproductive output. The lobster-mussel constant recruitment model required fine-tuning and marginal changes in parameter values caused rapid retardation or acceleration of the lobster growth rate. Use of the lobster-mussel model incorporating a stock-recruitment relationship was also limited as only simulations in which maximal lobster growth was not attained yielded stable results with density-dependence being maintained by means of the mussel dependent growth rate. Thus results for the fast-growing Robben Island lobster population produced no more information than the single-species models because mussel availability does not retard lobster growth at Robben Island. The effect of lobster exploitation of the mussel population was explored in the stock-recruitment model of the Cape Peninsula sub-populations. However the prey population was very stable under conditions of varying harvesting strategies so no further interpretation is attempted, except to bear in mind the large effect predation has on population size structure. The simplest model, that of a single lobster population in which constant recruitment and growth are assumed, produced the most conclusive information for the whole spectrum of areas, growth rates and harvesting rates modelled.

The recommendations and discussion of management of lobsters are based on the results of the simulation models and depend on the validity of the concepts and assumptions which surround the models. A limitation of the models is that each model is tuned once for each area and subsequent simulations only involve changes in one parameter. Therefore biological factors including intrinsic changes in populations such as the changing natural mortality with increase/decrease in fishing mortality are not accounted for. A population which is subjected to exploitation may compensate for increased mortality by means of accelerated recruitment rates and faster growth (Graham, 1943; Rounsefell and Everhard, 1953) although this may be more difficult to achieve in slow-growing species (Heydorn <u>et al</u>., 1968). The results presented do not indicate the period it would take for stocks to stabilize if harvesting policy were altered. It is difficult to distinguish between initial fluctuations as the model adjusts to parameters and the natural response of the populations. Changes in parameters such as growth rate would take many years to be realized in future stocks. However, the results all indicate yields that would be sustainable in the long-term.

Optimal harvesting strategies

An important feature shown by all of the lobster models is that the results of the sensitivity analyses in which a range of lobster growth rates were applied to each area, confirm that a faster growth rate does yield a better harvest. Therefore any policy which results in the growth of lobsters being accelerated, all other factors being equal, should yield a larger harvest. A broader view for management is obtained by using different areas of varying species abundance with differing growth and harvesting rates and different recruitment patterns. Only the simulations of the single-species constant recruitment model and the lobster-mussel model for the Cape Peninsula populations incorporating a lobster stock-recruitment relationship produced valid results useful for management.

The changes in present harvesting strategy which were tested include changing fishing pressure and altering the minimum catchable size at two fishing grounds, the Cape Peninula and Dassen Island. For interest the effect of prohibiting fishing was explored in existing fishing grounds but this did not make a substantial difference to the populations. Optimal harvest can be measured in terms of either number caught or harvested mass. The mean size of individuals in the catch is associated with this, and may have economic implications because there may be an optimal marketable size. Any increase in fishing effort or decrease in minimum catchable size at any area causes an increase in the number of lobster harvested, however small. Optimal harvest in terms of these models is therefore taken as the largest harvested mass and thereafter the number caught and mean size of individuals in the catch can be considered. Changes in fishing pressure were investigated using the models and these produced curves equivalent to Beverton and Holt (1957) yield per recruit curves because recruitment is constant or with very little fluctuation because of the small female harvest. All simulations showed that no increase in the fishing effort currently being employed at either of the two fishing grounds appears to be warranted for the small increase in harvest.

A lobster-mussel model formulated by Seiderer et al. (1982) was based on the length distributions of the populations and constant recruitment was assumed. The effect of reducing the minimum catchable size from the current 89 mm to 70 mm was tested. They concluded that this would increase lobster yield by 24 % as a result of an accelerated lobster growth rate. Their model may be compared to the constant recruitment lobster-mussel model presented here although this is based on the age distribution of the population. This present model predicts the same results in a population growing at the "overall" estimate of growth, showing that the yield would increase by 25 % at a minimum catchable size of 70 mm. However, the results predicted by this model should be viewed with caution because there were sharp changes in growth rate, a feature also found in the Seiderer et al. (1982) model.

The growth rate and intensity of fishing effort affect the choice of optimal minimum catchable size. For the smaller harvesting rate of the slow-growing Cape Peninsula lobster population, the single-species constant recruitment model predicts that the present minimum catchable size (89 mm carapace length) is optimal. However, using the lobster-mussel model with variable recruitment, a minimum catchable size of approximately 70 mm would yield a slightly better (+ 7 %) harvested mass. A large (+ 70 %) increase in the number caught could be expected. The mean individual size of the catch may drop from 95 mm to 80 mm, possibly making some of this harvest less marketable. At the larger harvesting rate and faster growth rate of the Dassen Island population, an optimal minimum catchable size of 70 mm or slightly less produces a better harvested mass by approximately 35 %. The number caught increases by more than three times that currently harvested. The mean size of individuals in the catch decreases from 96 mm to less than

80 mm but the large increase in number and mass harvested may be worthwhile in spite of the drop in mean size of individuals in the catch.

If fishing were introduced to the sanctuary, Robben Island, a sustainable harvest of at least 340 tons per annum is predicted by the lobster constant recruitment model at the current minimum catchable size and would appear to have little effect on the population. In this area in which lobsters grow fast, a minimum catchable size in the range 70 to 80 mm is predicted as optimal depending on whether exploitation is heavy or moderate. Under moderate exploitation, the 80 mm minimum catchable size causes an increase in harvested mass that is marginal (3 %) while the number caught may be increased to 30 %. The consequent reduction in the mean size of individuals in the catch is small (95 mm to 91 mm). The optimal 70 mm catchable size predicted under heavy exploitation rate results in an increase of approximately 10 % in harvested mass with a corresponding increase of 90 % in numbers caught. The mean size of individuals in the catch is reduced from 97 to 79 mm.

The difference in optimal harvesting policy for sub-populations which have different growth rates and are exploited at different fishing pressures complicates decisions when a single harvesting strategy has to be applied to the entire lobster population spanning a number of fishing grounds. An extension of the models to include economic factors would be useful in producing results of optimal harvesting strategy based on a balance between the equally important socio-economic implications and biological considerations. Three conclusions about harvesting strategy can be drawn from the model simulations. Firstly, no increase in fishing effort would provide an increase in yield in accordance with the increased effort. This finding reflects that of Newman and Pollock (1977) who used yield per recruit curves for male J. lalandii based on the population dynamics of Dassen Island. Secondly, exploitation of lobster at the present sanctuary, Robben Island would yield a substantial harvest with no obvious adverse effect on the population. The last and most complicated management decision is that of choice of a minimum catchable size. Ideally a two-dimensional set of combinations of all possible harvesting rates and minimum catchable sizes at each of the growth rates would give the optimal harvesting strategy for each area. Newman and Pollock (1977) suggested that lowering of the minimum catchable size from 89 mm to 80 mm would maintain or increase the equilibrium yield per recruit of males, depending on the relative magnitudes of growth and natural mortality. For females, with a much reduced growth rate, an increase in yield per recruit could also be expected at the reduced minimum size. Based on the assumptions of the models presented here, an initial observation is that the present 89 mm minimum catchable size appears to be appropriate for slow-growing lobster such as occur in the Cape Peninsula ground. With greater fishing effort, a smaller minimum catchable size is optimal. A minimum catchable size of 70 mm, somewhat smaller than the current one of 89 mm, and an annual harvesting mortality of approximately F = 0.4 would be optimal in terms of harvested mass. Choice of a minimum catchable size closer to 80 mm at an annual harvesting rate of aproximately F = 0.34 would probably yield a harvest that is optimal in terms of both mass and number harvested if a large mean size of individuals in the catch provides better marketability. This conservative minimum catchable size would cause the least change to other components of the ecosystem, effects which have not been modelled. In addition it would allow females to spawn before they are of catchable size as sexual maturity is reached at approximately 70 mm (Heydorn, 1965) and would therefore guard against a possible reduced recruitment caused by "recruitment overfishing".

AKNOWLEDGEMENTS

ACKNOWLEDGEMENTS

I would like to thank Professor J.G. Field (MBRI), the supervisor of the project for useful discussions and advice; Dr D.S. Butterworth (UCT) for his valuable assistance with the modelling; Dr D.E. Pollock (SFRI) and Dr C.L. Griffiths (MBRI) for use of their data and their advice; Mr A. Barkai (MBRI), Dr J.H.M. David (SFRI), Mr A.H. Fricke (NRIO) and Mr P. Zoutendyk (NRIO) for use of their unpublished data. Financial support from the South African National Committee for Oceanographic Research through the Benguela Ecology Program is gratefully acknowledged. I would also like to thank the Computing Service of UCT for their cooperation and help during the course of this project.

REFERENCES

REFERENCES

BACKUS, J. (1960). Observations on the growth rate of the spiny lobster. Calif. Fish and Game 46: 177-181

BAIRD, R.H. (1966). Factors affecting the growth and condition of mussels (Mytilus edulis L.). Fish. Invest., Lond, Ser II 25: 1-33

BERRY, P.F. (1971). The biology of the spiny lobster Panulirus homarus (Linnaeus) off the east coast of southern Africa. S. Afr. Assoc. mar. biol. Res., Invest. Rep. 28: 1-76

BERRY, P.F. (1978). Reproduction, growth and production in the mussel Perna perna (L.) on the east coast of South Africa. S. Afr. Assoc. mar. biol. Res., Invest. Rep. 48: 1-28

BEVERTON, R.J.H., HOLT, S.J. (1957) On the dynamics of exploited fish populations. Fish. Invest. Ser II Salmon Freshwater Fish G B Minist Agric. Fish. Food. 533 pp.

BEYERS, C.J. DE B. (1979). Stock assessment and some morphometric and biological characteristics of the rock lobster Jasus lalandii on Marshall rocks, its main commercila fishing area off South West Africa, 1971-1974. Investl. Rep. Sea. Fish. Br. S. Afr. 117: 1-26

BOWEN, B.K., CHITTLEBOROUGH, R.G. (1966). Preliminary assessments of stocks of the Western Australian crayfish, Panulirus cygnus George. Aust. J. Mar. Freshwater Res. 17: 93-121

BRANCH, G.M., BRANCH, M.L. (1981). The Living Shores of southern Africa. Struik, Cape Town. 272 pp.

BRADBURY, J.H. (1977). Growth rates of Tasmanian rock lobster Aust. CSIRO Div. Fish. Oceanogr. Circ. 7: 32 pp

BRADSTOCK, C.A. (1950). A study of the marine spiny crayfish, Jasus lalandii (Milne-Edwards) including accounts of autospasy. Zool. Publ. Victoria Univ. Wellington 7: 1-38

BREEN, P.A., MANN, K.H. (1976) Changing lobster abundance and the destruction of kelp beds by sea urchins. Mar. Biol. 34: 137-142

BURKENROAD, M.D. (1951). Measurement of the natural growth rates of decapod crustaceans. Proc. Gulf. and Caribb. Fish. Inst. 25-26

CHITTLEBOROUGH, R.G. (1975). Environmental factors affecting growth and survival of juvenile western rock lobsters Panulirus longipes (Milne-Edwards). Aust. J. Mar. Freshwater Res. 26: 177-196

CHITTLEBOROUGH, R.G. (1976). Growth of juvenile Panulirus longipes cygnus George on coastal reefs compared with those reared under optimal environmental conditions. Aust. J. Mar. Freshwater Res. 27: 279-295

CHITTLEBOROUGH, R.G., PHILLIPS, B.F. (1975). Fluctuations of year-class stength and recruitment in the western rock lobster Panulirus longipes (Milne- Edwards) Aust. J. Mar. Freshwater Res. 26: 317-328

COOK, P.A. (1978). A prediction of some possible effects of thermal pollution on marine organisms on the west coast of South Africa, with particular reference to the rock lobster, Jasus lalandii. Trans. R. Soc. S. Afr. 43: 107-118

DU PLESSIS, A.J. (1977). Larval development, settlement and growth of the black mussel Choromytilus meridionalis in the Saldahna Bay region. Trans. R. Soc. S. Afr. 42: 303-316

FIELD, J.G., JARMAN, N.G., DIECKMANN, G.S., GRIFFITHS, C.L., VELIMIROV, B., ZOUTENDYK, P. (1977) Sun, waves, seaweed and lobsters : the dynamics of a west coast kelp bed. S. Afr. J. Sci. 73: 7-10

FIELDER, D.R. (1964). The spiny lobster, Jasus lalandei (H. Milne-Edwards), in South Australia. 1. Growth of captive animals. Aust. J. Mar. Freshwater Res. 15: 77-92

FORD, R.F (1977). Growth patterns of lobsters. Circ. Div. Fish. Oceanogr. CSIRO. 7: 83-102

GEORGE, R.W. (1958). The status of the "white" crayfish in Western Australia. Aust. J. Mar. Freshwater Res 9: 537-545

GRAHAM, M. (1943). The Fish Gate. Faber and Faber, London. 196 pp.

GRIFFITHS, C.L., KING, J.A. (1979a). Some relationships between size, food availablility and energy balance in the ribbed mussel Aulacomya ater. Mar. Biol. 51: 141-149

GRIFFITHS, C.L., KING, J.A. (1979b). Energy expended on growth and gonad output in the ribbed mussel, Aulacomya ater. Mar Biol. 53: 217-222

GRIFFITHS, C.L., SEIDERER, J.L. (1980). Rock-lobsters and mussels - limitations and preferences in a predator-prey interaction. J. exp. mar. Biol. Ecol. 44: 95-109

GRIFFITHS, R.J. (1977). Reproductive cycles in littoral populations of Choromytilus meridionalis (Kr.) and Aulacomya ater (Molina) with a quantitative assessment of gamete production in the former. J. exp. mar. biol. Ecol. 30: 53-71

GRIFFITHS, R.J. (1981). Population dynamics and growth of the bivalve Choromytilus meridionalis (Kr.) at different tidal levels. Estuarine Coastal Shelf Sci. 12: 101-118

GULLAND, J.A. (1979) An overview of applications of operations research in fishery management. In: NATO symposium on applied operations research in fishing 1: 155-172

HANCOCK, D.A. (1980) Introduction, Part II Management In: Cobb, J.S., Phillips, B.F. (eds) The Biology and Management of Lobsters, Acedemic Press, New York p. 181-188

HANCOCK, D.A., EDWARDS, E. (1967). Estimation of annual growth in the edible crab (Cancer pagurus L.) J. Cons. perm. int. Explor. Mer. 31: 246-264

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. Investl. Rep. Sea Fish. Br., S. Afr. 53: 32 pp.

HEYDORN, A.E.F. (1969a). Notes on the biology of Panulirus homarus and on the length/weight relationships of Jasus lalandii. Investl. Rep. Sea Fish. Br., S. Afr. 69: 27 pp.

HEYDORN, A.E.F. (1969b). The rock lobster of the South African west coast Jasus lalandii (H. Milne-Edwards). 2. Population studies, behaviour, reproduction, moulting and migration. Investl. Rep. Sea Fish. Br., S. Afr. 71: 52pp.

HEYDORN, A.E.F., NEWMAN, G.G., ROSSOUW, G.S. (1968). Trends in the abundance of West coast rock-lobster, Jasus lalandii (Milne-Edwards). Fish. Bull., S. Afr. 5: 1-10

HIATT, R.W. (1948). The biology of the lined shore crab, Pachygrapsus crassipes Randall. Pac. Sci. 2: 135-213

HICKMAN, V.V. (1945). Notes on the Tasmanian marine crayfish, Jasus lalandii (Milne Edwards). Pap. Proc. R. Soc. Tasmania. 27-38

HUGHES, J.T., MATTHIESSEN, G.C. (1962). Observations on the biology of the American lobster Homarus americanus. Limnol. Oceanogr. 7: 414-421

JONES, R. (1974). Assessing the long-term effects of changes in fishing effort and mesh size from length composition data. Cons. Int. explor. Mer, Document CM1974/F:33, 13 pp. (mimeo)

KANCIRUK, P. (1980). Ecology of juvenile and adult Panuliridae (spiny lobsters) In: Cobb, J.S., Phillips, B.F. (eds). The Biology and Management of Lobsters Vol. II, Acedemic Press, New York p. 59-96

KENSLER, C.B. (1967). Fecundity in the marine spiny lobster, <u>Jasus verreuaxi</u> (H. Milne-Edwards) (Crustacea : Decapoda : Panuliridae) N. Z. J. Mar. Freshwater Res. 1: 143-155

KURATA, H. (1962). Studies on the age and growth of Crustacea. Bull. Hokkaido Reg. Fish. Res. Lab. 24: 1-115

KUTHALINGHAM, M.D.K., LUTHER, G. and LAZARUS, S. (1980). Rearing of early juveniles of spiny lobster <u>Panulirus versicolor</u> (Latreille) with notes on lobster fishery in Vizhinjam area. Indian J. fish. 27: 17-23

LAZARUS, B.I. (1967). The occurence of phyllosomata off the Cape with particular reference to <u>Jasus lalandii</u>. Investl. Rep. Sea Fish. Br., S. Afr. 63: 38 pp.

LEWIS, R.K. (1977). Studies on juvenile and adult stages of western populations of southern rock lobster (<u>Jasus novaehollandiae</u>) in the southeast region of South Australia Aust. CSIRO Div. Fish. Oceanogr. Circ. 7: 36pp

MANN, K.H. (1981) Management of resources in the coastal zone : Laminaria and lobsters in Nova Scotia. Lindberg lecture series, Mar. Biol. Lab. 16pp.

MARCHESSEAULT, G.D., SAILA, S.B. and PALM, W.J. (1976). Delayed recruitment models and their application to the American lobster (<u>Homarus americanus</u>) fishery. J. Fis. Res. Board. Can. 33: 1779-1787

MAUCHLINE, J. (1976). The Hiatt growth diagram for crustacea. Mar. Biol. 35 : 79-84

MAUCHLINE, J. (1977). Growth of shrimps, crabs and lobsters - an assessment. J. cons. int. explor. mer. 37: 162-169

MILLER, R.J., MANN, K.H., SCARRATT, D.J. (1971). Production potential of a seaweed-lobster community in eastern Canada. J. Fish. Res. Board. Canada. 28: 1733-1738

MORGAN, G.R. (1972). Fecundity in the western rock lobster, Panulirus longipes cygnus (George) (Crustacea : Decapoda : Panuliridae). Aust. J. Mar. Freshwater Res. 23: 133-141

MORGAN, G.R. (1977). Aspects of the population dynamics of the western rock lobster and their role in management. PhD Thesis, University of Western Australia.

MORGAN, G.R. (1980). Population dynamics of spiny lobsters. In: Cobb, J.S., PHILLIPS, B.F. (eds) The Biology and Management of Lobsters, Vol. II. Ecology and Management. Acedemic Press, New York, p. 189-217

MORGAN, G.R., PHILLIPS, B.F., JOLL, L.M. (1982). Stock and recruitment relationships in Panulirus cygnus, the commercial rock (spiny) lobster of Western Australia. Fish. Bull. U.S. 80: 475-486

MOSSOP, B.K.E. (1922). The rate of growth of the sea mussel (Mytilus edulis L.) at St. Andrews, New Brunswick; Digby, Nova Scotia; and in Hudson Bay. Trans R. Can. Inst. 14: 3-22

MUNRO, J.L. (1974). The biology, ecology, exploitation and management of Caribbean reef fishes. Univ. West Indies Zool. Dep., Res. Rep. 3: 1-57

MUUS, K. (1973). Settling, growth and mortality of young bivalves in the Oresund. Ophelia 12: 79-116

NEWCOMBE, C.L. (1935). A study of the community relationships of the sea mussel Mytilus edulis L. Ecology 16: 234-243

NEWMAN, G.G. (1973). Assessment and management of some marine stocks in Southern Africa. PhD Thesis, University of Stellenbosch. 268pp.

NEWMAN, G.G., POLLOCK, D.E. (1971). Biology and migration of rock lobster Jasus lalandii and their effect on availability at Elands Bay, South Africa. Investl. Rep. Sea Fish. Br. S. Afr. 94: 24 pp.

NEWMAN, G.G., POLLOCK, D.E. (1974a). Biological cycles, maturity and availability of rock lobster Jasus lalandii on two South African fishing grounds. Investl. Rep. Sea Fish. Br., S. Afr. 107: 16pp.

NEWMAN, G.G., POLLOCK, D.E. (1974b). Growth of the rock lobster Jasus lalandii and its relationship to benthos. Mar. Biol. 24: 339-346

NEWMAN, G.G., POLLOCK, D.E. (1977). The population dynamics of the rock lobster Jasus lalandii on two South African fishing grounds. ICSEAF. Coll. Sc. Pap., Madrid 4: 175-187

PAINE, R.T. (1965) Natural history, limiting factors and energetics of the opisthobranch Navanax inermis. Ecology 46: 603-619

PATERSON, N.F. (1969). The behaviour of captive Cape rock lobsters, Jasus lalandii (H. Milne Edwards). Ann. S. Afr. Mus. 52: 225-264

PEACOCK, N.A. (1974). A study of the spiny lobster fishery of Antigua and Barbuda. Gulf. Caribb. Fish. Inst. Univ. Miami, Proc. 26: 117-130

PENNEY, A.L., GRIFFITHS, C.L. (1984) Prey selection and the impact of the starfish Marthasterias glacialis (L.) and other pedators on the mussel Choromytilus meridionalis (Krauss). J. exp. mar. Biol. Ecol. 74: 19-36

PHILLIPS, B.F.; JOLL, L.M.; SANDLAND, R.L. and WRIGHT, D. (1983). Longevity, reproductive condition and growth of the western rock lobster, Panulirus cygnus George, reared in aquaria. Aust. J. mar. freshwater Res. 34: 419-429

POLLOCK, D.E. (1973). Growth of juvenile rock lobster Jasus lalandii. Investl. Rep. Sea Fish. Br., S. Afr. 106: 16pp.

POLLOCK, D.E. (1978). Growth and production rates of the rock lobster Jasus lalandii (H. Milne-Edwards). PhD Thesis, University of the Witwatersrand, 226pp.

POLLOCK, D.E. (1979). Predator-prey relationships between the rock lobster Jasus lalandii and the mussel Aulacomya ater at Robben Island on the Cape West Coast of Africa. Mar. Biol. 52: 347-356

POLLOCK, D.E. (1981). Population dynamics of rock lobster, Jasus tristani at the Tristan da Cunha group islands. Fish. Bull. S. Afr. 15: 49-66

POLLOCK, D.E. (1982). The fishery for and the population dynamics of the west coast rock lobster related to the environment in the Lambert's Bay and Port Nolloth areas. Investl. Rep. Sea Fish. Br., S. Afr. 124: 57 pp.

POLLOCK, D.E. and AUGUSTYN, C.J. (1982). Biology of the rock lobster Panulirus gilchristi with notes on the South African fishery. Fish. Bull. S. Afr. 16: 57-73

POLLOCK, D.E., AUGUSTYN, C.J. and GOOSEN, P.C. (1982). The rock lobster Jasus lalandii and its environmental biology on the Saldanha-Columbine fishing ground off the Cape West Coast, 1978 - 1981. Investl. Rep. Sea Fish. Br., S. Afr. 125: 30 pp.

POLLOCK, D.E. and BEYERS, C.J. de B. (1981). Environment, distribution and growth rates of the West Coast rock-lobster Jasus lalandii (H. Milne-Edwards). Trans. R. Soc. S. Afr. 44: 379-400

POLLOCK, D.E. and ROSCOE, M.J. (1977). The growth at moulting of crawfish Jasus tristani at Tristan da Cunha, South Atlantic. J. cons int. mer. 37: 144-146

RICKER, W.E. (1958). Handbook of computatons for biological statistics of fish populations. Bull. Fish. Res. Board Can. 119: 1-300

ROUNSEFELL, G.A., EVERHART, W.A. (1953). Fishery Science, its Methods and Applications. Wiley and Sons, New York, 444pp.

SEED, R. (1969). The ecology of Mytilus edulis L. (Lamellibranchiata) on exposed rocky shores II. Growth and mortality, Oecologia (Berl) 3: 317-350

SEIDERER, L.J.; HAHN, B.D. and LAWRENCE, L. (1982). Rock-Lobsters, mussels and man : a mathematical model. Ecol. Model. 17: 225-241

SHEARD, K. (1962). The Western Australian Crayfishery 1944-1961. Paterson Brokensha, Perth 107pp.

SILBERBAUER, B.I. (1971). The biology of the South African rock lobster Jasus lalandii (H. Milne Edwards). 1. Development. Investl. Rep. Sea Fish. Br., S. Afr. 92: 70pp.

SMALE, M.J. (1978). Migration, growth and feeding in the Natal rock lobster Panulirus homarus (Linnaeus). S. Afr. Assoc. mar. biol. Res. Investl. Rep. 47: 1-56

SMITH, F.G.W. (1950). Caribbean spiny lobster investigations. Proc. Gulf and Caribb. Fish. Inst. 128-134

STREET, R.J. (1969). The New Zealand crayfish Jasus edwardsii (Hutton 1875). An account of growth, moulting and movements in southern waters, with notes on reproduction and predators. Fish. Tech. Rep. N.Z. Fish. Res. Div. 30: 53 pp.

SUCHANEK, T.H. (1978). The ecology of Mytilus edulis L. in exposed rocky intertidal communities. J. exp. mar. Biol. Ecol. 31: 105-120

THEISEN, B.F. (1973). The growth of Mytilus edulis L. (Bivalvia) from Disko and Thule District, Greenland. Ophelia 12: 59-77

THOMPSON, R.J. (1979). Fecundity and reproductive effort in the blue mussel (Mytilus edulis), the sea urchin (Strongylocentrotus droebachiensis) and the snow crab (Chinocetes opilio) from populations in Nova Scotia and Newfoundland. J. Fish. Res. Board. Can. 36: 955-964

VELIMIROV, B., FIELD J.G., GRIFFITHS, C.L., ZOUTENDYK, P. (1977) The ecology of kelp bed communities in the Benguela upwelling system. Analysis of biomass and spatial distribution. Helgol. wiss. Meeresunters 30: 495-518

VRANCKX, R. (1973). Evolution du stock de langoustes sur les fonds de peche des iles Saint Paul et Nouvelle - Amsterdam de 1962 a 1970. Bull. Mus. Natl. Hist., Nat. Ecol. Gen. 155: 193-203

WHARTON, W.G., MANN, K.H. (1981) Relationship between destructive grazing by the sea urchin, Strongylocentrotus droebachiensis, and the abundance of American lobster, Homarus americanus, on the Atlantic coast of Nova Scotia. Can J. Fish. Aquat. Sci. 38: 1339-1349

WICKENS, P.A. and GRIFFITHS, C.L. (1985). Predation by Nucella cingulata (Linnaeus, 1771) on mussels, particularly Aulacomya ater (Molina, 1782). Veliger. 27: 366-374

WITHAM, R., INGLE, R.M., SIMS, H.W. (1964). Notes on postlarvae of Panulirus argus. Q. J. Fla. Acad. Sci. Quart. J. 27: 289-297

YOUNG, J.Z. (1950). The Life of Invertebrates. Clarendon Press, London

APPENDICES

APPENDIX A : DOCUMENTATION FOR PROGRAM "GROWTH"

A. PROGRAM SPECIFICATION

Growth simulation : This program (stored in "SIMUL*MODEL.GROWTH" on a Sperry 1100/81) generates a age-length distribution from a set of monthly or daily growth increments for different size classes.

B. INSTRUCTIONS FOR USE

1. Input Specifications :

The following is a runstream for program execution.

```
 1. @RUN,Z/N RUNID,ACCOUNT-NO,SIMUL,TIME,PAGES
 2. @ASG,A MODEL.
 3. @ASG,CP FLOBMEAN.,F50
 4. @ASG,T TEMP*GROFILE.
 5. @ASG,A BMDP*83.
 6. @USE 12.,TEMP*GROFILE.
 7. @USE 13.,FLOBMEAN.
 8. @XQT MODEL.GROWTH
 9.  FEMALE LOBSTER - MEAN GROWTH
10. 10 D 10 10
11. 0.02261
12. 0.02817
13. 0.03838
14. 0.03442
15. 0.01070
16. 0.00548
17. 0.00343
18. 0.00274
19. 0.00192
20. 0.00137
21. @BMDP*83.BMDP BMDP6D
22. /PROBLEM TITLE IS "FEMALE LOBSTER - MEAN GROWTH".
23. /INPUT VARIABLES ARE 2.
24.          FORMAT IS "(1X,I3,7X,F6.2)".
25. /PLOT  YVAR IS LENGTH.
26.        XVAR IS YEARS.
27. /END
28. @ADD TEMP*GROFILE.
29. @FIN
```

The data (lines 9 to 20 in this runstream) should be entered as follows :

```
CARD 1   : HEADING (STARTING IN COL 2, UP TO 60 CHARACTERS)
CARD 2   : THE FOLLOWING FOUR DATA ITEMS SHOULD BE SEPARATED BY ONE
           BLANK.
           1) THE NUMBER OF SIZE CLASSES FOR WHICH THERE IS DATA
           2) "D" FOR DAILY GROWTH RATES OR "M" FOR MONTHLY RATES
           3) RANGE OF A SIZE CLASS
           4) STARTING LENGTH
CARD 3 + : GROWTH RATES FOR EACH SIZE CLASS STARTING WITH THE
           SMALLEST CLASS, ONE PER CARD
```

The files "SIMUL*FLOBMEAN" and "TEMP*GROFILE" are output files.

2. Output format :

There are three forms of output : a table (Example 1) giving lengths at age (years), a BMDP plot of the distribution and a file (in this case "SIMUL*FLOBMEAN") containing only the lengths of different age classes.

Example 1 :

```
       FEMALE LOBSTER - MEAN GROWTH

            YEARS           LENGTH
            -----           ------

              0              10.00
              1              18.24
              2              28.06
              3              41.20
              .                .
              .                .
             63             109.69
```

3. Restrictions on Generality :

Only daily or monthly growth rate data can be input.

Only yearly age classes are output.

4. Run Time :

The program may take up to 20 seconds to run for a simulation such as this where an age of 63 years is reached.

C. CONCEPTUAL OVERVIEW

The algorithm is described in Chapter 2. Since data are not always available for the whole size range of an individual, a starting length for growth can be specified. However the subsequent age-length distribution is therefore not true and time for the individual to reach this starting length must be accounted for in order to yield representative ages. Two files are created by the program. One is a temporary file for use by BMDP for plotting and the second, containing only the lengths of different ages is for further use in for example, the program "FREQ" (see Appendix E and F), and as storage for incorporation into a data file.

D. PROGRAM DESIGN

The program comprises one FORTRAN routine with two main sections of calculation. The first calculates the time taken to grow through each size class. The second determines the length of each age class. The output is written to two files, one for BMDP and one for further use, and a printout of a table and a BMDP plot of the results is made.

E. PROGRAM CODE

The FORTRAN IV code for the program written for a SPERRY 1100/81 is given in Appendix B.

APPENDIX B : FORTRAN CODE FOR PROGRAM GROWTH"

```
*                                  ************************
*                                  **                    **
*                                  **  PROGRAM "GROWTH"  **
*                                  **                    **
*                                  **  GROWTH SIMULATION **
*                                  **                    **
*                                  ************************

*-------------------------------------------------------------------------
*                            VARIABLE AND PARAMETER DECLARATION
*-------------------------------------------------------------------------

      INTEGER RANGE
*                                    RANGE OF A SIZE CLASS
      INTEGER ITIME
*                                    INTEGER TIME TAKEN TO GROW THROUGH A SIZE
*                                    CLASS
      INTEGER TOTTIM(0:50)
*                                    CUMULATIVE TIME TAKEN TO GROW THROUGH ALL
*                                    SIZE CLASSES
      INTEGER YEARS
*                                    COUNTER OF NUMBER OF YEARS TAKEN TO GROW
*                                    THROUGH SIZE CLASSES
      REAL TIME
*                                    REAL TIME TAKEN TO GROW THROUGH A SIZE CLASS
      INTEGER SIZES
*                                    NUMBER OF SIZE CLASSES FOR WHICH THERE
*                                    IS DATA
      REAL STALEN
*                                    STARTING LENGTH
      REAL LEN(0:50)
*                                    ARRAY CONTAINING CALCULATED LENGTHS OF
*                                    EACH SIZE CLASS
      REAL GROWTH(50)
*                                    ARRAY CONTAINING GROWTH RATES OF EACH
*                                    SIZE CLASS
      REAL SLOPE
*                                    SLOPE OF LINE DRAWN BETWEEN AGE-LENGTH
*                                    POINTS AT UPPER AND LOWER LIMITS OF A SIZE
*                                    CLASS
      REAL YINT
*                                    Y-INTERCEPT OF LINE DRAWN BETWEEN AGE-LENGTH
*                                    POINTS AT UPPER AND LOWER LIMITS OF SIZE
*                                    CLASS
      REAL LENAGE
*                                    LENGTH AT YEARLY INTERVALS
      REAL YTIME
*                                    NUMBER OF MONTHS OR DAYS IN A NUMBER OF YEARS
      CHARACTER*   60 HEAD
*                                    HEADING
      CHARACTER*   1 TIMINT
*                                    INDICATOR AS TO MONTHLY OR DAILY GROWTH DATA

*-------------------------------------------------------------------------
*                                 FORMAT STATEMENTS
*-------------------------------------------------------------------------

5     FORMAT ( )
15    FORMAT (A60)
25    FORMAT (1H1,A60)
35    FORMAT (/,/,' YEARS     LENGTH ',/,' -----      -------',/)
45    FORMAT (I2,1X,A1,1X,I2,1X,F2.0)
55    FORMAT ('   0',7X,F6.2)
65    FORMAT (1X,I3,7X,F6.2)
75    FORMAT (F6.2)

*-------------------------------------------------------------------------
*                              OPEN OUTPUT FILES
*-------------------------------------------------------------------------

      OPEN (12)
      OPEN (13)

*-------------------------------------------------------------------------
*                              READ IN DATA
*-------------------------------------------------------------------------

      READ (*,15) HEAD
      READ (*,45) SIZES, TIMINT, RANGE, STALEN
      READ (*,5) (GROWTH(I), I = 1,SIZES)
```

```
*-----------------------------------------------------------------------------
*             PRINT HEADINGS AND INITIALIZE VARIABLES
*-----------------------------------------------------------------------------


      DO 40 I = 0,50
40       TOTTIM(I) = 0
      ITIME = 0
      YEARS = 0


      WRITE (*,25) HEAD
      WRITE (*,35)
      WRITE (*,55) STALEN
      LEN(0) = STALEN
      LEN(1) = STALEN
      YEARS = 1

*-----------------------------------------------------------------------------
*               CALCULATE CUMULATIVE TIME TO GROW THROUGH EACH
*               SIZE CLASS
*-----------------------------------------------------------------------------


      DO 20 I = 1,SIZES
         TIME = ((INT(STALEN/RANGE) + 1)*RANGE - LEN(I - 1))/GROWTH(I)
         ITIME = TIME
         IF (TIME .GT. ITIME) ITIME = ITIME + 1
        LEN(I)= GROWTH(I)*ITIME + LEN(I - 1)
         TOTTIM(I) = TOTTIM(I - 1) + ITIME
20    CONTINUE

*-----------------------------------------------------------------------------
*                 CALCULATE UPPER LENGTH LIMIT OF EACH AGE CLASS
*                 AND PRINT OUT RESULTS
*-----------------------------------------------------------------------------


      DO 30 I = 1,SIZES
        SLOPE = (LEN(I) - LEN(I - 1))/(TOTTIM(I) - TOTTIM(I - 1))
        YINT = LEN(I) - SLOPE*TOTTIM(I)
100     IF (TIMINT .EQ. 'D') YTIME = YEARS*364.25
        IF (TIMINT .EQ. 'M') YTIME = YEARS*12
        IF (YTIME .LT. TOTTIM(I)) THEN
          LENAGE = SLOPE*YTIME + YINT
          WRITE (12,65) YEARS, LENAGE
          WRITE (*,65) YEARS, LENAGE
          WRITE (13,75) LENAGE
          YEARS = YEARS + 1
          GOTO 100
        ENDIF
30    CONTINUE

*-----------------------------------------------------------------------------
*                           CLOSE OUTPUT FILES AND END
*-----------------------------------------------------------------------------


      CLOSE (12)
      CLOSE (13)

      END
```

APPENDIX C : DOCUMENTATION FOR PROGRAM "LOBMUS" - Lobster-Mussel Models

A. PROGRAM SPECIFICATION

Lobster - mussel models : This program (stored in SIMUL*MODEL.LOBMUS on a SPERRY 1100/81) is designed to run simulation models of a lobster and mussel population, separately and together with species interaction.

B. INSTRUCTIONS FOR USE

1. Input Specifications :

The following is a runstream for program execution.

```
1. @RUN,Z/N RUNID,ACCOUNT-NO,SIMUL,TIME,PAGES
2. @ASG,A MODEL.
3. @ASG,A CAPELOB.
4. @XQT MODEL.LOBMUS
5. L
6. 50
7  1
8. @ADD CAPELOB.
9. @FIN
```

The data (lines 5 to 7) are defined as follows :

CARD 1 : The letter "L", "M" or "B" depending on whether the lobster, mussel or lobster-mussel model is required.

CARD 2 : The number of years for which the program is to be run.

CARD 3 : A "1, "2", "3" or "4" depending on whether no stock-recruit relationship, a linear, Beverton and Holt or Ricker stock-recruit relationship is required.

The file "SIMUL*CAPELOB" is the name of the data file (Example 1). Data must be entered into this file in the following order :

CARD 1 : TITLE (UP TO 50 CHARACTERS)
CARD 2 + : DATA FOR EACH PARAMETER/VARIABLE MUST BE PRECEDED BY A LINE WHICH CONTAINS THE FOLLOWING INFORMATION :
1. PARAMETER/VARIABLE NAME (UP TO 9 CHARACTERS)
2. FIRST DIMENSION STARTING IN COL 11
3. SECOND DIMENSION AFTER ONE BLANK
FOR ONE DIMENSIONAL PARAMETERS/VARIABLES, THE VALUES MUST BE ENTERED ONE TO A LINE. FOR TWO DIMENSIONAL PARAMETERS/VARIABLES VALUES IN ALL OF THE COLUMNS (SECOND DIMENSION) OF EACH ROW (FIRST DIMENSION) MUST BE ENTERD ON ONE LINE.

Example 1 :

```
ROBBEN ISLAND - 80 MM CATCH SIZE LIMIT
MLOBNUM   22 1
3440000000
3293300
2519800
    .
    .
NUMOPTEAT 14 8
65 166 79 14 0 0 0 0
48 182 96 31 5 0 0 0
    .
    .
```

All of the parameters/variables must be entered regardless of the model being used. Chapter 4 indicates the acronym for each parameter/variable. They must be entered in the following order : MLOBNUM, FLOBNUM, MLOBLEN, FLOBLEN, MLOBMOR, FLOBMOR, MLOBFIS, FLOBFIS, MLOBGRO, FLOBGRO, LOBMASS, LOBEGG, LOBDENDEP, LOBCATLIM, NUMOPTEAT, KJOPTEAT, MUSKJ, MUSNUM, MUSLEN, MUSMOR, MUSGRO, MUSDENDEP, MUSLEFT, MUSEGG, MUSEGGMOR.

Data for a lobster sanctuary must be entered with zero fishing mortality (MLOBFIS and FLOBFIS). The minimum catchable size must be entered with the correct size in order for the program to calculate the number of individuals over the catchable size. For lobsters, the number of age classes must be equal to or less than the number that will be created by the input growth rate. If this is not done, the individuals in older extra classes will accumulate in the last class and the numbers will not balance in the end. If mussel growth rate is changed the mussel age-frequency and age-length distribution must also be changed so that there are the correct number of age classes for the growth rate.

2. Output Format :

There are three types of output depending on the model which is being run. These are given in the form of tables and graphs, the latter only for simulation times of 100 years or less.

Mussel model :

Tables -

annually : population number

at end of simulation period : size-frequency distribution (number and % number)
age-frequency distribution

Graphs -

annual population number
size-frequency distribution (number and log number)
age-frequency distribution

Lobster model :

Tables -

annually : population number (males, females and total)
number over minimum catchable size "
number harvested "
mass harvested

at end of simulation : male and female size-frequency distribution (number and % number)
male and female age-frequency distribution
percentage males in each size class

Graphs -

annual population number (male, female and total)
" number over minimum catchable size "
" number harvested "
" mass harvested
male and female size-frequency distributions (number and log number)
male and female age-frequency distributions "
percentage males in each size class

Lobster-mussel model :

In addition to the output of the lobster and mussel models, annual tabulation of the percentage of optimal growth rate in each size class for males and female is printed.

3. <u>Guide to error messages</u> :

In the case of the upper length limit of one age class exceeding the proceding age class limit, the following error message is output :

```
"FOR  FEMALE LOBSTERS THE GROWTH RATE OF AGE CLASS 9 IS SLOWER THAN THAT  OF
AGE CLASS 8.
CONSEQUENTLY  THE  UPPER LENGTH LIMIT OF THE 8 YEARS  OLDS  (85.9)  EXCEEDS
THAT OF THE 9 YEARS OLDS (85.5)

***************************** EXECUTION HALTED ****************************"
```

3. Restrictions on Generality :

The following parameters are set as constants in the program but can easily be changed and the program recompiled -

Maximum ages of 58 and 100 and 39 years for male and female lobster respectively and mussels.

Maximum sizes of 140, 110 and 80 mm for male and female lobster and mussels respectively.

Age of lobster maturity is 70 + mm.

Month of moulting is 10 (October).

Lobster open fishing season is months 11 to 12 and 1 to 6 ie : November to June.

The maximum number of years for which the model can handle graphics is 100 years but longer runs are possible although no graphical output will be produced.

4. Run Time :

The following run times are minimums for 100-year runs on maximum growth rate :

Lobster-mussel model : > 8 minutes

Lobster model : > 7 minutes

Mussel model : > 1 minute

C. CONCEPTUAL OVERVIEW

The program is designed so that either of the three models can be run by simply changing one line of input. The concept of the model is explained in Chapter 3.

D. PROGRAM DESIGN

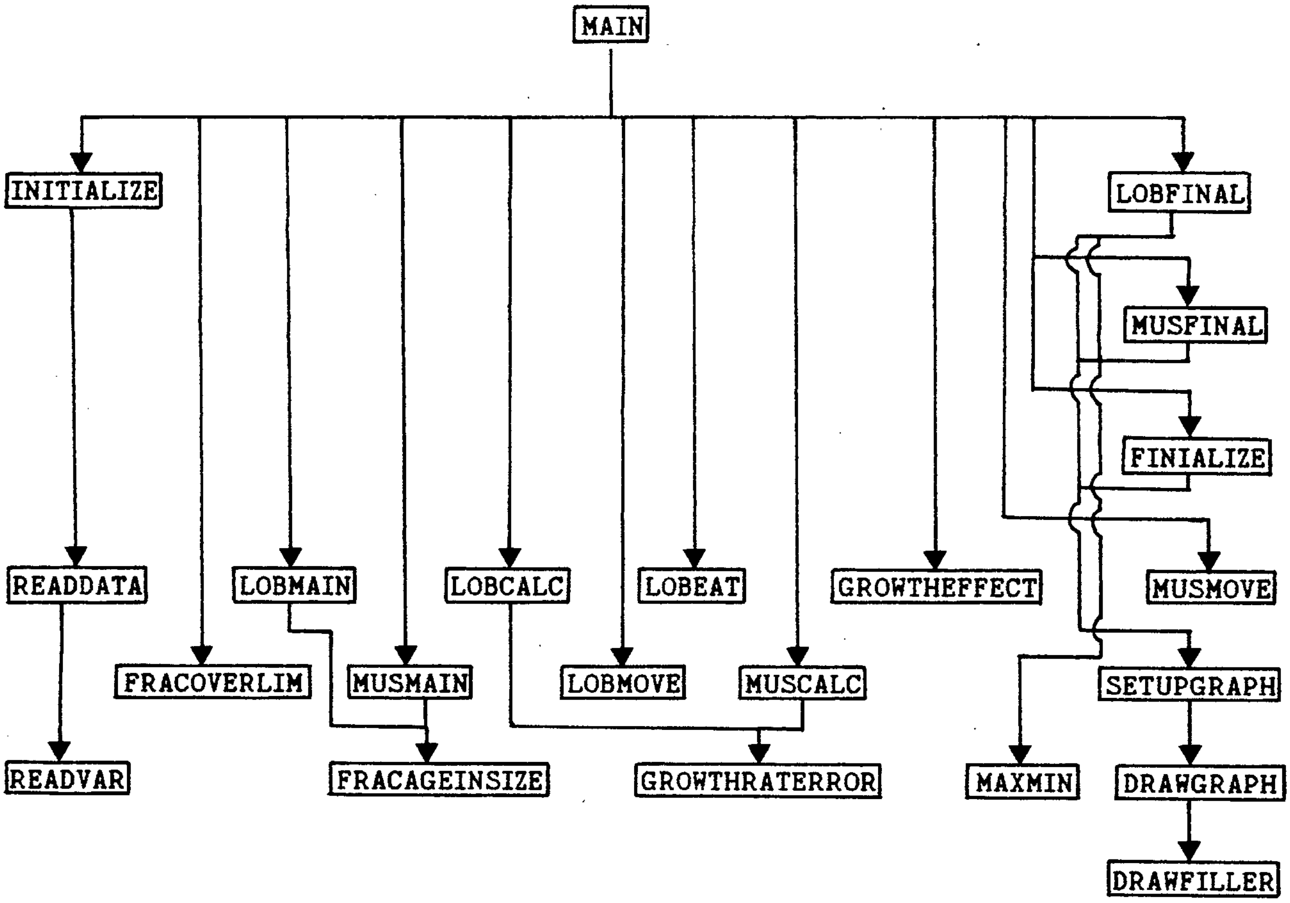
1. Overall description :

The program, of 2500 lines, is written in Pascal and is selfcontained in that it handles data input and the output in both tabulated and graphical form is produced by the program. Regardless of the model required, data for both lobsters and mussels is entered but only the relevant data is used.

2. Data structures :

The data structures are all explained in the declaration section of the program.

3. Inter-relationship among procedures :



4. Function of each procedure :

Input procedures -

At the beginning of a run, READDATA reads in a variable name and dimensions from the input file for each input parameter/variable, and calls READVAR which reads in the actual data values for the parameter/variable. Six array sizes are specified and the data read into the applicable one. READDATA also sets the maximum age of the lobsters and mussels according to the input.

General procedures -

FRACAGEINSIZE, called monthly for each model, determines the relative proportions with which an age class falls into size classes for lobsters and/or mussels.

FRACOVERLIM, called monthly for the lobster and lobster-mussel models, determines the fraction of each age class that falls over the minimum catchable size.

GROWTHRATERROR is called if an error occurs in the lobster-mussel model when one age class has a slower growth rate than its preceding class so that its length limit is lower than this preceding class. Execution is halted once an error message has been printed out.

Graph procedures -

MAXMIN determines the upper and lower limits of a set of values in order to give a range for a graph axis.

DRAWFILLER writes out a given character a specified number of times.

SETUPGRAPH, called at the end of a run, sets up an array with values to be inserted onto a graph and then calls DRAWGRAPH to implement this. DRAWGRAPH plots a graph with specified titles, axis values etc.

Lobster - mussel procedures -

LOBEAT, called monthly in the lobster-mussel model only, determines the number of mussels that can be consumed by lobsters.

GROWTHEFFECT, called annually in the month before moulting in the lobster-mussel model, determines the number of kilojoules, in terms of mussel flesh, available for lobster consumption and changes the lobster growth rates accordingly.

Lobster procedures (called only in the lobster and lobster-mussel models) -
LOBMAIN, called monthly, calls FRACAGEINSIZE for both males and females and determines the number of individuals of both sexes in each size class.

LOBCALC, called monthly, does all the calculations that determine the change in numbers of lobster individuals of both sexes and implements the annual increase in size of each age class at the moult and calls GROWTHRATERROR if necessary. It also determines the maximum age which may change with change in growth rate.

LOBMOVE, called each year, determines the number of eggs spawned according to either constant recruitment or a linear, Beverton and Holt, or Ricker stock-recruit curve. The number of individuals and the upper length limit of each age class are moved to the next age class. The total number, the number over the catch size limit and the mean catch size of each sex and as a total are calculated.

Mussel procedures (called by mussel model only) -
MUSMAIN, called monthly, calls FRACAGEINSIZE and determines the number of individuals in each size class.

MUSCALC does all the monthly calculations that determine the change in number and size of mussels in each age class. GROWTHERROR may be called.In particular months, constant recruitment occurs.

MUSMOVE is called each year to move the number and length limit of each age class into the proceding one and to determine the total number of mussels.

Main procedures -
The main procedure calls INITIALIZE to write out headings and do the intial calculations. It loops monthly for the specified number of years calling all the relevant procedures depending on the model, to do the necessary calculations. It then sets up some arrays for initial graphs and calls

MUSFINAL, LOBFINAL and FINIALIZE which call the procedures for printing out graphs and print out headings and output information.

E. PROGRAM VALIDATION

Each computation was checked with test data.

One error procedure was included for the case when one age class may overtake another.

F. PROGRAM CODE

The PASCAL code for the program written for a SPERRY 1100/81 is given in Appendix D.

APPENDIX D : PASCAL CODE FOR PROGRAM "LOBMUS"

```
                                   (********************************)
                                   (********************************)
                                   (**                            **)
                                   (**      PROGRAM "LOBMUS"      **)
                                   (**                            **)
                                   (** ROCK-LOBSTER - MUSSEL MODEL **)
                                   (**                            **)
                                   (********************************)
                                   (********************************)

(****************************************************************************************************)

                                   (****************)
                                   (* DECLARATIONS *)
                                   (****************)

PROGRAM MAIN (INPUT,OUTPUT);

                                 (* ================ *)
                                 (* LABEL DECLARATION *)
                                 (* ================ *)

LABEL 99;

                                 (* =================== *)
                                 (* CONSTANT DECLARATION *)
                                 (* =================== *)

CONST
  MMAXAGE      =  58;                           (* MAXIMUM NUMBER OF MALE LOBSTER AGE CLASSES *)

  FMAXAGE      = 100;                           (* MAXIMUM NUMBER OF FEMALE LOBSTER AGE CLASSES *)

  MLOBSIZ      =  14;                           (* NUMBER OF MALE LOBSTER SIZE CLASSES *)

  FLOBSIZ      =  11;                           (* NUMBER OF FEMALE LOBSTER SIZE CLASSES *)

  MAXMUSAGE    =  39;                           (* NUMBER OF MUSSEL AGE CLASSES *)

  MUSSIZ       =   8;                           (* NUMBER OF MUSSEL SIZE CLASSES *)

  LOBJUVLEN    =  10;                           (* SET UPPER LENGTH LIMIT OF *)
                                                (* FIRST LOBSTER AGE CLASS *)

  MOULT        =  10;                           (* MONTH OF THE MOULT *)

  LOBFSEA1     =   1;
  LOBFSEA2     =   6;                           (* FIRST AND LAST MONTHS OF FIRST *)
                                                (* LOBSTER FISHING SEASON *)

  LOBFSEA3     =  11;
  LOBFSEA4     =  12;                           (* FIRST AND LAST MONTHS OF SECOND *)
                                                (* LOBSTER FISHING SEASON *)

  SIZSTEP      =  10;                           (* RANGE OF A LOBSTER OR MUSSEL SIZE CLASS *)

  LOBMATSIZ    =   8;                           (* LOBSTER SIZE AT MATURITY *)

  PAGESIZE     =  62;                           (* NUMBER OF LINES PER OUTPUT PAGE *)

  GRAHEIGHT    =  50;                           (* HEIGHT OF OUTPUT GRAPH *)

  GRAWIDTH     = 100;                           (* WIDTH OF OUTPUT GRAPH *)

  VARNAMESIZE  =   9;                           (* NUMBER OF CHARACTERS IN A VARIABLE NAME *)

  MFSIZMIN2    =  23;                           (* SUM OF NUMBER OF MALE AND FEMALE *)
                                                (* SIZE CLASSES - 2 FOR AN ARRAY *)
                                                (* INDICATING THE CHANGE IN GROWTH RATE *)


  LOBSTERS_ONLY           = 'L';
  MUSSELS_ONLY            = 'M';
  BOTH_LOBSTERS_MUSSELS   = 'B';
                                                (* THE ABOVE ARE INDICATORS AS TO THE *)
                                                (* TYPE OF MODEL REQUIRED *)

  MALE_LOBSTER    = 'M';
  FEMALE_LOBSTER  = 'F';
  TOTAL_LOBSTERS  = 'T';
  LOBSTER         = 'L';
  MUSSEL          = 'M';
                                                (* THE ABOVE ARE SYMBOLS FOR THE OUTPUT *)
                                                (* GRAPHS *)
```

```
  LOBAGETITLE       = 'LOBSTER AGE (YRS)  ';
  LOBHARMASTITLE    = 'HARVESTED (TONS)   ';
  LOBHARTITLE       = '    HARVESTED      ';
  LOBLIMTITLE       = ' OVER CATCH LIMIT  ';
  LOBMASTITLE       = 'MASS OF LOBSTERS   ';
  LOBNUMTITLE       = 'NUMBER OF LOBSTERS';
  LOBSIZETITLE      = 'LOBSTER SIZE (MM)  ';
  LOGTITLE          = '   (NATURAL LOG)   ';
  MUSAGETITLE       = 'MUSSEL AGE (YRS)   ';
  MUSNUMTITLE       = 'NUMBER OF MUSSELS  ';
  MUSSIZETITLE      = 'MUSSEL SIZE (MM)   ';
  SEXPATTITLE       = 'PERCENTAGE MALES   ';
  TIMETITLE         = '        TIME(YEARS) ';

                                        (* THE ABOVE ARE TITLES FOR THE OUTPUT *)
                                        (* GRAPHS *)


                        (* ================ *)
                        (* TYPE DECLARATION *)
                        (* ================ *)


TYPE

  LOBAGE_ARRAY           = ARRAY [1..FMAXAGE] OF REAL;
  LOBSIZ_ARRAY           = ARRAY [1..MLOBSIZ] OF REAL;
  MUSAGE_ARRAY           = ARRAY [1..MAXMUSAGE] OF REAL;
  MUSSIZ_ARRAY           = ARRAY [1..MUSSIZ] OF REAL;
  LOBAGE_MUSSIZ_ARRAY    = ARRAY [1..FMAXAGE,1..MUSSIZ] OF REAL;
  LOBSIZ_MUSSIZ_ARRAY    = ARRAY [1..MLOBSIZ,1..MUSSIZ] OF REAL;
  LOBAGE_LOBSIZ_ARRAY    = ARRAY [1..FMAXAGE,1..MLOBSIZ] OF REAL;
  MUSAGE_MUSSIZ_ARRAY    = ARRAY [1..MAXMUSAGE,1..MUSSIZ] OF REAL;
  MAXAGE_ARRAY           = ARRAY [0..FMAXAGE] OF REAL;
  MAXLOBSIZ_ARRAY        = ARRAY [0..MLOBSIZ] OF REAL;
  MAXMUSSIZ_ARRAY        = ARRAY [0..MUSSIZ] OF REAL;
  MAXAGE_MAXSIZ_ARRAY    = ARRAY [1..FMAXAGE,1..MLOBSIZ] OF REAL;
  VARNAME_ARRAY          = ARRAY [1..VARNAMESIZE] OF CHAR;
  GRAHEIGHT_ARRAY        = ARRAY [0..GRAHEIGHT] OF REAL;
  GRADATA_ARRAY          = ARRAY [1..GRAWIDTH,1..11] OF REAL;
  GRAPH_ARRAY            = ARRAY [1..GRAHEIGHT,1..GRAWIDTH] OF CHAR;
  GROWTH_ARRAY           = ARRAY [1..MFSIZMIN2] OF REAL;

                                       (* THE ABOVE ARE DECLARATIONS *)
                                       (* FOR ALL SIZES OF ARRAYS *)


                     (* ==================== *)
                     (* VARIABLE DECLARATION *)
                     (* ==================== *)


VAR

                          (* GENERAL *)


   AGE : INTEGER;                      (* DUMMY NUMBER OF AGE CLASSES *)

   CHARAC : CHAR;                      (* ONE OUTPUT CHARACTER *)

   COUNT : INTEGER;                    (* INTEGER COUNTER FOR GRAPH OUTPUT *)

   D1, D2 : INTEGER;                   (* FIRST AND SECOND DIMENSIONS OF *)
                                       (* INPUT VARIABLES *)

   DATAARR : MUSSIZ_ARRAY;             (* DUMMY ARRAY INTO WHICH INPUT IS READ *)

   DATAMAT : GRADATA_ARRAY;            (* MATRIX STORING DATA FOR OUTPUT *)

   DATAVAR : REAL;                     (* DUMMY VARIABLE INTO WHICH INPUT IS READ *)

   DCOL : INTEGER;                     (* INDICATOR AS TO WHICH COLUMN OF *)
                                       (* THE DATA MATRIX HOLDS THE VALUES *)
                                       (* FOR THE PARTICULAR GRAPH REQUIRED *)

   DUM : CHAR;                         (* DUMMY VARIABLE INTO WHICH A BLANK *)
                                       (* IS READ *)

   DUMLEN1, DUMLEN2 : REAL;            (* DUMMY LOBSTER OF MUSSEL LENGTHS *)

   DUMLOBFRAC : LOBAGE_LOBSIZ_ARRAY;   (* DUMMY FRACTION OF AGE CLASS IN A *)
                                       (* PARTICULAR LOBSTER SIZE CLASS *)

   DUMMUSFRAC : MUSAGE_MUSSIZ_ARRAY;   (* DUMMY FRACTION OF AGE CLASS IN A *)
                                       (* PARTICULAR MUSSEL SIZE CLASS *)

   FIRSTNO : INTEGER;                  (* NUMBER USED IN GRAPH AXES OUTPUT *)

   FRAC : MAXAGE_MAXSIZ_ARRAY;         (* DUMMY FRACTION OF AGE CLASS IN A *)
                                       (* PARTICULAR SIZE CLASS *)

   FRACLEN : LOBAGE_ARRAY;             (* DUMMY LENGTH OF A LOBSTER *)
                                       (* OR MUSSEL AGE CLASS *)

   FRACLOB : LOBAGE_LOBSIZ_ARRAY;      (* DUMMY FRACTION OF AGE CLASS IN A *)
                                       (* PARTICULAR LOBSTER SIZE CLASS *)

   FRACMUS : MUSAGE_MUSSIZ_ARRAY;      (* DUMMY FRACTION OF AGE CLASS IN A *).
                                       (* PARTICULAR MUSSEL SIZE CLASS *)

   GRA : CHAR;                         (* TYPE OF GRAPH REQUIRED *)

   GRAMAT : GRAPH_ARRAY;               (* MATRIX STORING POINTS ON A GRAPH *)

   GROWTHCHANGE : GROWTH_ARRAY;        (* INDICATOR AS TO WHETHER THE GROWTH *)
                                       (* RATE OF A PARTICULAR MALE OR FEMALE *)
                                       (* LOBSTER SIZE CLASS WAS CHANGED *)

   MAXVALUE, MINVALUE : REAL;          (* MAXIMUM AND MINIMUM VALUES *)
                                       (* OF A PARTICULAR VARIABLE *)
                                       (* FOR GRAPH LIMITS *)
```

```
INT : REAL;                                   (* INTERVAL BETWEEN Y-AXIS POINTS *)

LA, LS : INTEGER;                             (* COUNTER FOR NUMBER OF LOBSTER AGE *)
                                              (* AND SIZE CLASSES RESPECTIVELY *)

LA1 : LOBAGE_ARRAY;                           (* DUMMY FLOBAGE ARRAY *)

LAMS5 : LOBSIZ_MUSSIZ_ARRAY;                  (* DUMMY MLOBSIZ MUSSIZ ARRAY *)

LEN : MAXLOBSIZ_ARRAY;                        (* UPPER LENGTH LIMIT OF SIZE CLASSES *)
                                              (* FOR LOBSTERS OR MUSSELS *)

LIM : GRAHEIGHT_ARRAY;                        (* VALUES OF POINTS ON Y-AXIS *)

LINE : INTEGER;                               (* COUNTER FOR NUMBER OF LINES OUTPUT *)

LS2 : LOBSIZ_ARRAY;                           (* DUMMY MLOBSIZ ARRAY *)

MA, MS : INTEGER;                             (* COUNTER FOR NUMBER OF MUSSEL AGE AND *)
                                              (* SIZE CLASSES RESPECTIVELY *)

MA3 : MUSAGE_ARRAY;                           (* DUMMY MUSAGE ARRAY *)

MAX, MIN : REAL;                              (* UPPER AND LOWER SIZE LIMITS OF *)
                                              (* EACH AGE CLASS FOR LOBSTERS OR MUSSELS *)

MODEL : CHAR;                                 (* INDICATOR AS TO WHICH OF THE THREE *)
                                              (* MODELS IS REQUIRED *)

MONTH : INTEGER;                              (* MONTHLY COUNTER *)

MS4 : MUSSIZ_ARRAY;                           (* DUMMY MUSSIZ ARRAY *)

NUM1, NUM2, NUM3, NUM4 : INTEGER;             (* INTEGER COUNTERS *)

NUM5, NUM6 : REAL;                            (* REAL COUNTERS *)

S : INTEGER;                                  (* DUMMY COUNTER FOR EITHER NUMBER OF *)
                                              (* LOBSTER OR MUSSEL SIZE CLASSES *)

SIZ : INTEGER;                                (* DUMMY NUMBER OF SIZE CLASSES *)

SPACE : REAL;                                 (* NUMBER OF SPACES BETWEEN EACH *)
                                              (* POINT ON X-AXIS *)

SPEC : CHAR;                                  (* INDICATOR AS TO WHETHER *)
                                              (* THERE IS AN ERROR IN THE *)
                                              (* GROWTH RATE OF A MALE OR *)
                                              (* FEMALE LOBSTER OR A MUSSEL *)

SPECIES : CHAR;                               (* INDICATOR AS TO LOBSTER  *
                                              (* OR MUSSEL *)

TIME : INTEGER;                               (* COUNTER FOR THE RUN TIME *)

TIMES : REAL;                                 (* NUMBER OF TIMES A CHARACTER *)
                                              (* IS TO BE PRINTED *)

TITLE : ARRAY [1..50] OF CHAR;                (* TITLE OF DATA *)

TYPEARR : CHAR;                               (* INDICATOR AS TO THE SIZE OF THE ARRAY *)

UPPERX, LOWERX : REAL;                        (* UPPER AND LOWER LIMITS OF X-AXIS *)

UPPERY, LOWERY : REAL;                        (* UPPER AND LOWER LIMITS OF Y-AXIS *)

VALUE : REAL;                                 (* DUMMY VALUE OF A VARIABLE *)

VAR6 : REAL;                                  (* DUMMY VARIABLE *)

VARNAME : VARNAME_ARRAY;                      (* INPUT VARIABLE NAME *)

X,Y : INTEGER;                                (* COUNTERS FOR X- AND Y- AXES *)

XAXIS : REAL;                                 (* RANGE BETWEEN UPPER AND LOWER *)
                                              (* LIMITS OF X-AXIS *)

XWIDTH : INTEGER;                             (* NUMBER OF POINTS ON THE *)
                                              (* X-AXIS *)

XTITLE, YTITLE : CHAR;                        (* X- AND Y-AXIS TITLES *)

YEARS : INTEGER;                              (* NUMBER OF YEARS FOR WHICH THE MODEL *)
                                              (* IS TO RUN *)

                          (* ROCK-LOBSTERS *)

GRO : LOBSIZ_ARRAY;                           (* DUMMY MUSSEL-DEPENDENT ANNUAL *)
                                              (* GROWTH INCREMENT *)

LOBMATUR : REAL;                              (* LOBSTER SPAWNING STOCK *)

LOBCATLIM : REAL;                             (* LOBSTER CATCH SIZE LIMIT *)

LOBDENDEP : REAL;                             (* LOBSTER DENSITY DEPENDENT *)
                                              (* FACTOR AFFECTING MORTALITY *)

LOBEGG : LOBSIZ_ARRAY;                        (* DEPENDING ON STOCK-RECRUIT *)
                                              (* RELATIONSHIP : *)
                                              (* 1 -     CONSTANT NUMBER OF *)
                                              (*         EGGS SPAWNED ANNUALLY *)
                                              (*         IN FIRST COMPARTMENT *)
                                              (* 2 -     FECUNDITY OF DIFFERENT - *)
                                              (*         SIZED FEMALES *)
                                              (* 3,4 -   IN FIRST TWO COMPARTMENTS *)
                                              (*         THE COEFFICIENTS OF *)
                                              (*         DENSITY INDEPENDENT AND *)
                                              (*         DEPENDENT  MORTALITY *)
                                              (*         FOR BEVERTON AND HOLT (3) *)
                                              (*         AND RICKER (4) *)
```

```
LOBEGGMOR : REAL;                           (* LOBSTER  MONTHLY EGG MORTALITY *)

LOBFREQ : LOBSIZ_ARRAY;                     (* DUMMY NUMBER OF LOBSTERS *)
                                            (* IN EACH SIZE CLASS *)

LOBGRO : LOBSIZ_ARRAY;                      (* DUMMY ANNUAL GROWTH INCREMENT *)

LOBLEN : MAXLOBSIZ_ARRAY;                   (* UPPER LENGTH LIMIT OF EACH LOBSTER *)
                                            (* SIZE CLASS *)

LOBLIMFRAC : LOBAGE_ARRAY;                  (* FRACTION OF EACH LOBSTER SIZE CLASS *)
                                            (* THAT IS OVER THE CATCH SIZE LIMIT *)

LOBMASS : LOBSIZ_ARRAY;                     (* WHOLE WET MASS OF LOBSTERS *)
                                            (* IN EACH SIZE CLASS *)

LOBMEANCAT : REAL;                          (* MEAN SIZE OF TOTAL CATCH IN A YEAR *)

LOBNUM : LOBAGE_ARRAY;                      (* DUMMY NUMBER OF MALE OR *)
                                            (* FEMALE LOBSTERS *)

LOBNUMEAT : LOBSIZ_MUSSIZ_ARRAY;            (* DUMMY NUMBER OF MUSSELS *)
                                            (* EATEN FROM  A MUSSEL SIZE *)
                                            (* CLASS BY A LOBSTER SIZE CLASS *)

LOBSEXRAT :REAL;                            (* PERCENTAGE MALES IN A LOBSTER SIZE CLASS *)

LOBTOT : REAL;                              (* TOTAL NUMBER OF LOBSTERS OVER 10 MM *)
                                            (* IE : POST-LARVAL STAGES *)

LOBTOTLIM : REAL;                           (* NUMBER OF LOBSTERS OVER THE CATCH LIMIT *)

LOBTOTMASHAR : REAL;                        (* TOTAL MASS OF LOBSTERS HARVESTED *)

LOBTOTNUMHAR : REAL;                        (* TOTAL NUMBER OF LOBSTERS HARVESTED *)

MAXLOBFREQ, MINLOBFREQ : REAL;              (* MAXIMUM AND MINIMUM NUMBER OF *)
                                            (* LOBSTERS FROM ANY SIZE CLASS *)
                                            (* OVER THE WHOLE TIME PERIOD *)

MAXLOBLIM, MINLOBLIM : REAL;                (* MAXIMUM AND MINIMUM NUMBER OF *)
                                            (* LOBSTERS OVER THE CATCH LIMIT *)
                                            (* OVER THE WHOLE TIME PERIOD *)

MAXLOBMASHAR, MINLOBMASHAR : REAL;          (* MAXIMUM AND MINIMUM MASS OF LOBSTERS *)
                                            (* HARVESTED OVER THE WHOLE TIME PERIOD *)

MAXLOBNUM, MINLOBNUM : REAL;                (* MAXIMUM AND MINIMUM NUMBER OF LOBSTERS *)
                                            (* OVER THE WHOLE TIME PERIOD *)

MAXLOBNUMHAR, MINLOBNUMHAR : REAL;          (* MAXIMUM AND MINIMUM NUMBER OF LOBSTERS *)
                                            (* HARVESTED OVER THE WHOLE TIME PERIOD *)

MAXLOGLOBFREQ, MINLOGLOBFREQ : REAL;        (* MAXIMUM AND MINIMUM LOG NUMBER OF *)
                                            (* LOBSTERS IN ANY SIZE CLASS *)

MAXLOGLOBNUM, MINLOGLOBNUM : REAL;          (* MAXIMUM AND MINIMUM LOG NUMBER OF *)
                                            (* LOBSTERS IN ANY AGE CLASS *)

MLGRO, FLGRO : LOBSIZ_ARRAY;                (* MUSSEL-DEPENDENT MALE AND FEMALE *)
                                            (* LOBSTER GROWTH INCREMENT *)

MLLEN, FLLEN : REAL;                        (* SUM OF GROWTH INCREMENTS OF *)
                                            (* DIFFERENT SIZE CLASSES FOR AN AGE *)
                                            (* CLASS *)

MLNUM, FLNUM : REAL;                        (* NUMBER OF MALE AND FEMALE LOBSTERS*)
                                            (* REMOVED FROM AN AGE CLASS *)

MLNUMHAR, FLNUMHAR : REAL;                  (* NUMBER OF MALE AND FEMALE *)
                                            (* LOBSTER HARVESTED FROM *)
                                            (* AN AGE CLASS *)

MLOBAGE, FLOBAGE : INTEGER;                 (* NUMBER OF MALE AND FEMALE *)
                                            (* AGE CLASSES *)

MLOBFRAC, FLOBFRAC : LOBAGE_LOBSIZ_ARRAY;   (*   MALE AND FEMALE FRACTION OF AGE CLASS *)
                                            (* IN A PARTICULAR LOBSTER SIZE CLASS *)

MLOBFREQ, FLOBFREQ : LOBSIZ_ARRAY;          (* NUMBER OF LOBSTERS OF DIFFERENT AGES *)
                                            (* IN EACH SIZE CLASS FOR MALES AND FEMALES *)

MLOBFIS, FLOBFIS : LOBSIZ_ARRAY;            (* MALE AND FEMALE MONTHLY FISHING *)
                                            (* MORTALITY OF EACH LOBSTER SIZE CLASS *)

MLOBGRO, FLOBGRO : LOBSIZ_ARRAY;            (* MALE AND FEMALE LOBSTER MONTHLY GROWTH *)
                                            (* INCREMENT FOR EACH SIZE CLASS *)

MLOBLEN, FLOBLEN : LOBAGE_ARRAY;            (* UPPER SIZE LIMIT OF EACH MALE AND *)
                                            (* FEMALE LOBSTER AGE CLASS *)

MLOBLIM, FLOBLIM : REAL;                    (* NUMBER OF MALE AND FEMALE LOBSTERS *)
                                            (* OVER THE CATCH LIMIT *)

MLOBLIMFRAC, FLOBLIMFRAC : LOBAGE_ARRAY;    (* FRACTION OF EACH LOBSTER *)
                                            (* AGE CLASS OVER THE CATCH *)
                                            (* SIZE LIMIT *)

MLOBMOR, FLOBMOR : LOBSIZ_ARRAY;            (* MALE AND FEMALE MONTHLY NATURAL *)
                                            (* MORTALITY OF EACH LOBSTER SIZE CLASS *)

MLOBMEANCAT, FLOBMEANCAT : REAL;            (* MEAN SIZE OF CATCH IN *)
                                            (* ANY MONTH *)

MLOBNUM, FLOBNUM : LOBAGE_ARRAY;            (* MALE AND FEMALE LOBSTER NUMBERS *)

MLOBNUMHAR, FLOBNUMHAR : REAL;              (* NUMBER OF MALE AND FEMALE *)
                                            (* LOBSTERS HARVESTED ANNUALLY *)

MLOBPERCENT, FLOBPERCENT : REAL;            (* TOTAL OF PERCENT SIZE *)
                                            (* FREQUENCY DISTRIBUTION *)
                                            (* FOR MALES AND FEMALES *)
```

```
MLOBTOT, FLOBTOT : REAL;                    (* MALE AND FEMALE LOBSTER TOTAL NUMBERS *)
                                            (* OVER 10 MM IE : POST-LARVAL STAGES *)

MLOBTOTNUMHAR, FLOBTOTNUMHAR : REAL;        (* TOTAL NUMBER OF MALE *)
                                            (* AND FEMALE LOBSTERS HARVESTED *)
                                            (* ANNUALLY *)

RECRUIT : INTEGER;                          (* INDICATOR AS TO TYPE OF *)
                                            (* STOCK-RECRUIT RELATIONSHIP, *)
                                            (* IF ANY, IS REQUIRED *)

TOTEGG : REAL;                              (* TOTAL NUMBER OF LOBSTER *)
                                            (* EGGS SPAWNED PER YEAR *)

                         (* MUSSELS *)

MAXLOGMUSFREQ, MINLOGMUSFREQ : REAL;        (* MAXIMUM AND MINIMUM LOG NUMBER *)
                                            (* OF MUSSELS IN EACH SIZE CLASS *)

MAXLOGMUSNUM, MINLOGMUSNUM : REAL;          (* MAXIMUM AND MINIMUM LOG NUMBER *)
                                            (* OF MUSSELS IN EACH AGE CLASS *)

MAXMUSFREQ, MINMUSFREQ : REAL;              (* MAXIMUM AND MINIMUM NUMBER *)
                                            (* OF MUSSELS IN EACH SIZE CLASS *)
                                            (* OVER THE WHOLE TIME PERIOD *)

MAXMUSNUM, MINMUSNUM : REAL;                (* MAXIMUM AND MINIMUM TOTAL NUMBER *)
                                            (* OF MUSSELS OVER THE WHOLE TIME PERIOD *)

MLEN : REAL;                                (* SUM OF GROWTH INCREMENTS OF DIFFERENT *)
                                            (* MUSSEL SIZES FOR AN AGE CLASS *)

MNUM : REAL;                                (* NUMBER OF MUSSELS REMOVED *)
                                            (* FROM AN AGE CLASS *)

MSLEN : MAXLOBSIZ_ARRAY;                    (* UPPER LENGTH LIMIT OF EACH *)
                                            (* MUSSEL SIZE CLASS *)

MUSAGE : INTEGER;                           (* NUMBER OF MUSSEL AGE CLASSES *)

MUSDENDEP : REAL;                           (* MUSSEL DENSITY DEPENDENT *)
                                            (* FACTOR AFFECTING MORTALITY *)

MUSEGG : REAL;                              (* TOTAL NUMBER OF MUSSEL EGGS *)
                                            (* SPAWNED IN ONE YEAR *)
                                            (* OF DIFFERENT AGES *)

MUSEGGMOR : REAL;                           (* MUSSEL EGG MORTALITY *)

MUSFRAC : MUSAGE_MUSSIZ_ARRAY;              (* FRACTION OF AGE CLASS IN A PARTICULAR *)
                                            (* MUSSEL SIZE CLASS *)

MUSFREQ : MAXMUSSIZ_ARRAY;                  (* NUMBER OF MUSSELS IN EACH SIZE CLASS *)

MUSGRO : MUSSIZ_ARRAY;                      (* MUSSEL MONTHLY GROWTH INCREMENT *)
                                            (* FOR EACH SIZE CLASS *)

MUSLEFT : REAL;                             (* PERCENTAGE OF MUSSELS THAT CANNOT *)
                                            (* BE CONSUMED FROM EACH MUSSEL SIZE CLASS *)

MUSLEN : MUSAGE_ARRAY;                      (* UPPER LENGTH LIMIT OF EACH MUSSEL *)
                                            (* AGE CLASS *)

MUSMOR : MUSSIZ_ARRAY;                      (* MONTHLY NATURAL MORTALITY OF EACH *)
                                            (* MUSSEL SIZE CLASS *)

MUSNUM : MUSAGE_ARRAY;                      (* NUMBER OF MUSSELS PER AGE CLASS *)

MUSPERCENT : REAL;                          (* TOTAL OF PERCENT SIZE *)
                                            (* FREQUENCY DISTRIBUTION *)

MUSTOT : REAL;                              (* TOTAL NUMBER OF MUSSELS *)

               (* LOBSTER - MUSSEL INTERACTION *)

KJOPTEAT : LOBSIZ_ARRAY;                    (* OPTIMAL NUMBER OF KJ EATEN PER LOBSTER *)
                                            (* PER SIZE CLASS PER MONTH *)

LOBTOTEAT : MUSSIZ_ARRAY;                   (* NUMBER OF MUSSELS EATEN FROM EACH *)
                                            (* MUSSEL SIZE CLASS *)

LOBKJEAT : LOBSIZ_ARRAY;                    (* NUMBER OF KJ EATEN PER LOBSTER AGE *)
                                            (* CLASS FOR MALES OR FEMALES *)

MLOBNUMEAT, FLOBNUMEAT : LOBSIZ_MUSSIZ_ARRAY;
                                            (* NUMBER OF MUSSELS EATEN FROM EACH *)
                                            (* MUSSEL SIZE CLASS PER MALE OR FEMALE *)
                                            (* LOBSTER AGE CLASS *)

MUSKJ : MUSSIZ_ARRAY;                       (* NUMBER OF KJ PER MUSSEL PER MUSSEL *)
                                            (* SIZE CLASS *)

NUMOPTEAT : LOBSIZ_MUSSIZ_ARRAY;            (* NUMBER OF MUSSELS FROM EACH MUSSEL SIZE *)
                                            (* CLASS EATEN MONTHLY PER LOBSTER PER *)
                                            (* LOBSTER SIZE CLASS *)


(**********************************************************************)
(**********************************************************************)
```

```
                                      (********************)
                                      (*                  *)
                                      (* INPUT PROCEDURES *)
                                      (*                  *)
                                      (********************)


                                   (* ================= *)
                                   (* PROCEDURE READVAR *)
                                   (* ================= *)


PROCEDURE READVAR (NUM4             : INTEGER;
                   TYPEARR          : CHAR;
                   VAR LA1          : LOBAGE_ARRAY;
                   VAR LS2          : LOBSIZ_ARRAY;
                   VAR MA3          : MUSAGE_ARRAY;
                   VAR MS4          : MUSSIZ_ARRAY;
                   VAR LAMS5        : LOBSIZ_MUSSIZ_ARRAY;
                   VAR VAR6         : REAL;
                   D1               : INTEGER;
                   D2               : INTEGER);


BEGIN
  NUM1 := 1;

  REPEAT
    IF (TYPEARR <> '5')
      THEN
        BEGIN
          READLN (DATAVAR);
          WRITE (DATAVAR);
        END
      ELSE
        BEGIN
          FOR NUM2 := 1 TO D2 DO
            BEGIN
              READ (DATAARR[NUM2]);
              WRITE (DATAARR[NUM2]);
            END;
          READLN;
          WRITELN;
        END;

    IF (((MODEL = 'L') AND (NUM4 > 14)) OR
       ((MODEL = 'M') AND (NUM4 < 18)))
      THEN
        CASE TYPEARR OF
          '1' : LA1[NUM1] := 0;
          '2' : LS2[NUM1] := 0;
          '3' : MA3[NUM1] := 0;
          '4' : MS4[NUM1] := 0;
          '5' : FOR NUM2 := 1 TO D2 DO
                  LAMS5[NUM1, NUM2] := 0;
          '6' : VAR6 := 0;
        END
      ELSE
        CASE TYPEARR OF
          '1' : LA1[NUM1] := DATAVAR;
          '2' : LS2[NUM1] := DATAVAR;
          '3' : MA3[NUM1] := DATAVAR;
          '4' : MS4[NUM1] := DATAVAR;
          '5' : FOR NUM2 := 1 TO D2 DO
                  LAMS5[NUM1, NUM2] := DATAARR[NUM2];
          '6' : VAR6 := DATAVAR;
        END;
    NUM1 := NUM1 + 1;
  UNTIL (NUM1 = (D1 + 1));
  IF (TYPEARR <> '5')
    THEN
      WRITELN;
  WRITELN;
END;

(**************************************************************************************************)

                                        (* ================== *)
                                        (* PROCEDURE READDATA *)
                                        (* ================== *)


PROCEDURE READDATA;


BEGIN
  NUM4 := 0;
  WHILE NOT EOF DO
    BEGIN
      NUM4 := NUM4 + 1;
      FOR NUM3 := 1 TO VARNAMESIZE DO
        BEGIN
          READ (VARNAME[NUM3]);
          WRITE (VARNAME[NUM3]);
        END;
      READ (DUM);
      READLN (D1, DUM, D2);
      WRITELN (D1,D2);
      IF (NUM4 = 1)
        THEN
          MLOBAGE := D1;
      IF (NUM4 = 2)
        THEN
          FLOBAGE := D1;
      IF (NUM4 = 18)
        THEN
          MUSAGE := D1;
```

```
    CASE NUM4 OF
         1 : READVAR (NUM4, '1', MLOBNUM, LS2,       MA3,     MS4,     LAMS5,     VAR6,      D1, D2);
         2 : READVAR (NUM4, '1', FLOBNUM, LS2,       MA3,     MS4,     LAMS5,     VAR6,      D1, D2);
         3 : READVAR (NUM4, '1', MLOBLEN, LS2,       MA3,     MS4,     LAMS5,     VAR6,      D1, D2);
         4 : READVAR (NUM4, '1', FLOBLEN, LS2,       MA3,     MS4,     LAMS5,     VAR6,      D1, D2);
         5 : READVAR (NUM4, '2', LA1,     MLOBMOR,   MA3,     MS4,     LAMS5,     VAR6,      D1, D2);
         6 : READVAR (NUM4, '2', LA1,     FLOBMOR,   MA3,     MS4,     LAMS5,     VAR6,      D1, D2);
         7 : READVAR (NUM4, '2', LA1,     MLOBFIS,   MA3,     MS4,     LAMS5,     VAR6,      D1, D2);
         8 : READVAR (NUM4, '2', LA1,     FLOBFIS,   MA3,     MS4,     LAMS5,     VAR6,      D1, D2);
         9 : READVAR (NUM4, '2', LA1,     MLOBGRO,   MA3,     MS4,     LAMS5,     VAR6,      D1, D2);
        10 : READVAR (NUM4, '2', LA1,     FLOBGRO,   MA3,     MS4,     LAMS5,     VAR6,      D1, D2);
        11 : READVAR (NUM4, '2', LA1,     LOBMASS,   MA3,     MS4,     LAMS5,     VAR6,      D1, D2);
        12 : READVAR (NUM4, '2', LA1,     LOBEGG,    MA3,     MS4,     LAMS5,     VAR6,      D1, D2);
        13 : READVAR (NUM4, '6', LA1,     LS2,       MA3,     MS4,     LAMS5,     LOBDENDEP, D1, D2);
        14 : READVAR (NUM4, '6', LA1,     LS2,       MA3,     MS4,     LAMS5,     LOBCATLIM, D1, D2);
        15 : READVAR (NUM4, '5', LA1,     LS2,       MA3,     MS4,     NUMOFTEAT, VAR6,      D1, D2);
        16 : READVAR (NUM4, '2', LA1,     KJOPTEAT,  MA3,     MS4,     LAMS5,     VAR6,      D1, D2);
        17 : READVAR (NUM4, '4', LA1,     LS2,       MA3,     MUSKJ,   LAMS5,     VAR6,      D1, D2);
        18 : READVAR (NUM4, '3', LA1,     LS2,       MUSNUM,  MS4,     LAMS5,     VAR6,      D1, D2);
        19 : READVAR (NUM4, '3', LA1,     LS2,       MUSLEN,  MS4,     LAMS5,     VAR6,      D1, D2);
        20 : READVAR (NUM4, '4', LA1,     LS2,       MA3,     MUSMOR,  LAMS5,     VAR6,      D1, D2);
        21 : READVAR (NUM4, '4', LA1,     LS2,       MA3,     MUSGRO,  LAMS5,     VAR6,      D1, D2);
        22 : READVAR (NUM4, '6', LA1,     LS2,       MA3,     MS4,     LAMS5,     MUSDENDEP, D1, D2);
        23 : READVAR (NUM4, '6', LA1,     LS2,       MA3,     MS4,     LAMS5,     MUSLEFT  , D1, D2);
        24 : READVAR (NUM4, '6', LA1,     LS2,       MA3,     MS4,     LAMS5,     MUSEGG,    D1, D2);
        25 : READVAR (NUM4, '6', LA1,     LS2,       MA3,     MS4,     LAMS5,     MUSEGGMOR, D1, D2);
      END;
    END;
  END;

                    *****************************************************************************}
{**************************************************************************************

                                        {**********************}
                                        {*                    *}
                                        {* GENERAL PROCEDURES *}
                                        {*                    *}
                                        {**********************}


                                      {* ======================= *}
                                      {* PROCEDURE FRACAGEINSIZE *}
                                      {* ======================= *}


PROCEDURE FRACAGEINSIZE (SPECIES      : CHAR;
                         AGE          : INTEGER;
                         MIN          : REAL;
                         MAX          : REAL;
                         VAR FRACLOB  : LOBAGE_LOBSIZ_ARRAY;
                         VAR FRACMUS  : MUSAGE_MUSSIZ_ARRAY;
                         SIZ          : INTEGER;
                         LEN          : MAXLOBSIZ_ARRAY);

BEGIN

  IF (MIN <> MAX)
    THEN
      BEGIN
        FOR S := 1 TO SIZ DO
          BEGIN
            FRAC[AGE,S] := 0;

            IF ((MIN >= LEN[S - 1]) AND (MAX <= LEN[S]))
              THEN
                FRAC[AGE,S] := 1;

            IF ((MIN <= LEN[S]) AND (MIN >= LEN[S - 1]) AND (MAX >= LEN[S]))
              THEN
                FRAC[AGE,S] := (LEN[S] - MIN)/(MAX - MIN);

            IF ((MIN <= LEN[S - 1]) AND (MAX <= LEN[S]) AND (MAX >= LEN[S - 1]))
              THEN
                FRAC[AGE,S] := (MAX - LEN[S - 1])/(MAX - MIN);

            IF ((MIN <= LEN[S]) AND (MIN <= LEN[S - 1]) AND (MAX >= LEN[S]))
              THEN
                FRAC[AGE,S] := (LEN[S] - LEN[S - 1])/(MAX - MIN);

          END;

        FOR S := 1 TO SIZ DO
          IF (SPECIES = 'L')
            THEN
              BEGIN
                FRACLOB[AGE,S] := FRAC[AGE,S];
                IF ((SIZ = FLOBSIZ) AND (S > FLOBSIZ))
                  THEN
                    FRACLOB[AGE,S] := 0;
              END
            ELSE
              FRACMUS[AGE,S] := FRAC[AGE,S];
      END
    ELSE
      BEGIN
        IF (SPECIES = 'L')
          THEN
            FRACLOB[AGE,SIZ] := 1
          ELSE
            FRACMUS[AGE,SIZ] := 1;
      END;

END;
                                                                                        *}
{****************************************************************************************
```

```
                              (* ====================== *)
                              (* PROCEDURE FRACOVERLIM  *)
                              (* ====================== *)


PROCEDURE FRACOVERLIM (FRACLEN           : LOBAGE_ARRAY;
                       VAR LOBLIMFRAC : LOBAGE_ARRAY);

BEGIN
  FOR LA := 2 TO FLOBAGE DO
    BEGIN
      IF (FRACLEN[LA] <= LOBCATLIM)
        THEN
          LOBLIMFRAC[LA] := 0;
      IF (FRACLEN[LA - 1] >= LOBCATLIM)
        THEN
          LOBLIMFRAC[LA] := 1;
      IF ((FRACLEN[LA - 1] < LOBCATLIM) AND (FRACLEN[LA] > LOBCATLIM))
        THEN
          LOBLIMFRAC[LA] := (FRACLEN[LA] - LOBCATLIM)/(FRACLEN[LA] - FRACLEN[LA - 1]);
    END;
END;

(******************************************************************)

                         (* ========================= *)
                         (* PROCEDURE GROWTHRATERROR  *)
                         (* ========================= *)


PROCEDURE GROWTHRATERROR (DUMLEN1 : REAL;
                          DUMLEN2 : REAL;
                          AGE     : INTEGER;
                          SPEC    : CHAR);


BEGIN
  WRITELN;
  IF (SPEC = '1')
    THEN
      WRITE ('FOR MALE LOBSTERS ');
  IF (SPEC = '2')
    THEN
      WRITE ('FOR FEMALE LOBSTERS ');
  IF (SPEC = '3')
    THEN
      WRITE ('FOR MUSSELS ');
  WRITELN ('THE GROWTH RATE OF AGE CLASS ',AGE:2,' IS SLOWER THAN THAT OF',
           ' AGE CLASS ',(AGE - 1):2,'.');
  WRITELN ('CONSEQUENTLY THE UPPER LENGTH LIMIT OF THE ',(AGE - 1):2,
           ' YEAR OLDS (', DUMLEN1:5:2,') EXCEEDS THAT OF THE ',
           AGE:2,' YEAR OLDS (', DUMLEN2:5:2,')');
  WRITELN;
  WRITE ('*************************************************');
  WRITE (' EXECUTION HALTED ');
  WRITELN ('*************************************************');
  GOTO 99;

END;

(******************************************************************)


                              (********************)
                              (*                  *)
                              (* GRAPH PROCEDURES *)
                              (*                  *)
                              (********************)

                              (* ================ *)
                              (* PROCEDURE MAXMIN *)
                              (* ================ *)


    PROCEDURE MAXMIN (VALUE              : REAL;
                      VAR MAXVALUE : REAL;
                      VAR MINVALUE : REAL);

    BEGIN
      IF (VALUE > MAXVALUE)
        THEN
          MAXVALUE := VALUE;
      IF ((TIME = 1) OR (TIME = (YEARS + 1)))
        THEN
          MINVALUE := VALUE;
      IF (VALUE < MINVALUE)
        THEN
          MINVALUE := VALUE;
    END;

    (******************************************************************)
```

```
                               (* ==================== *)
                               (* PROCEDURE DRAWFILLER *)
                               (* ==================== *)


PROCEDURE DRAWFILLER (CHARAC : CHAR;
                      TIMES  : REAL);


BEGIN
  NUMS := 0;
  WHILE (NUMS <> TIMES) DO
    BEGIN
      WRITE (CHARAC);
      NUMS := NUMS + 1;
    END;
END;

(*********************************************************************************************)

                          (* =================== *)
                          (* PROCEDURE DRAWGRAPH *)
                          (* =================== *)


PROCEDURE DRAWGRAPH (YTITLE   : CHAR;
                      XTITLE  : CHAR;
                      XWIDTH  : INTEGER);


BEGIN
  SPACE := TRUNC((GRAWIDTH - XAXIS)/XAXIS);

  WRITE (' ':30);
  DRAWFILLER ('*',((XAXIS - 1)*SPACE + XAXIS + 2));
  WRITELN;
  FOR Y := GRAHEIGHT DOWNTO 1 DO
    BEGIN
      IF (Y = (GRAHEIGHT/2))
        THEN
          CASE YTITLE OF
            'A','B','C','J' : WRITE (LOBNUMTITLE,LIM[Y],'*');
            'D'             : WRITE (LOBMASTITLE,LIM[Y],'*');
            'E'             : WRITE (SEXRATTITLE,LIM[Y],'*');
            'F'             : WRITE (LOBSIZETITLE,LIM[Y],'*');
            'G','K'         : WRITE (MUSNUMTITLE,LIM[Y],'*');
          END;
       IF (Y = (GRAHEIGHT/2 - 1))
         THEN
           CASE YTITLE OF
             'B'                   : WRITE (LOBLIMTITLE,LIM[Y],'*');
             'C'                   : WRITE (LOBHARTITLE,LIM[Y],'*');
             'D'                   : WRITE (LOBHARMASTITLE,LIM[Y],'*');
             'J','K'               : WRITE (LOGTITLE,LIM[Y],'*');
             'A','L','F','G','H'   : WRITE (' ':18,LIM[Y], '*');
           END;
       IF ((Y <> GRAHEIGHT/2) AND (Y <> (GRAHEIGHT/2 - 1)))
         THEN
           WRITE (' ':18,LIM[Y],'*');
       WRITE (GRAMAT[Y,1]);
       X := 2;
       WHILE (X <> (XAXIS + 1)) DO
         BEGIN
           DRAWFILLER (' ',SPACE);
           WRITE (GRAMAT[Y,X]);
           X := X + 1;
         END;
       WRITELN ('*');
     END;
     WRITE (' ':30,'*I');
     NUM6 := 0;
     WHILE (NUM6 <> (XAXIS - 1)) DO
       BEGIN
         DRAWFILLER ('*',SPACE);
         WRITE ('I');
         NUM6 := NUM6 + 1;
       END;
     WRITELN ('*');
     LINE := 52;
     CASE XTITLE OF
       'I','L','M' :               BEGIN
                                     WRITE (' ':31);
                                       IF (XWIDTH <= 50)
                                         THEN
                                           BEGIN
                                             FIRSTNO := 2;
                                             COUNT := XWIDTH DIV 10;
                                             IF (COUNT*10 <= XWIDTH)
                                               THEN
                                                 COUNT := COUNT + 1;
                                             WRITE ('I');
                                             FOR NUM3 := 1 TO 2 DO
                                               BEGIN
                                                 FOR NUM1 := 1 TO COUNT DO
                                                   IF (((NUM1*10 - XWIDTH) <= 10) AND
                                                      (((XWIDTH - NUM1*10) < 0) OR (NUM3 = 2)))
                                                     THEN
                                                       BEGIN
                                                         IF (((NUM1*10 - XWIDTH) <> 10)
                                                            AND ((XWIDTH - NUM1*10) <> 0))
                                                           THEN
                                                             BEGIN
                                                               IF (NUM3 = 1)
                                                                 THEN
                                                                   BEGIN
                                                                     IF (NUM1 = 1)
                                                                       THEN
                                                                         FOR NUM2 := FIRSTNO TO XWIDTH DO
                                                                           BEGIN
                                                                             DRAWFILLER (' ',SPACE);
                                                                             WRITE (NUM2:1);
                                                                           END
```

```
                             ELSE
                               FOR NUM2 := 1 TO
                                   (XWIDTH-(NUM1-1)*10+1) DO
                                 BEGIN
                                   DRAWFILLER (' ',SPACE);
                                   WRITE ((NUM1 - 1):1);
                                 END;
                         END;
                     IF (NUM3 = 2)
                       THEN
                         BEGIN
                            IF ((XWIDTH - NUM1*10) >= 10)
                              THEN
                            FOR NUM2 := FIRSTNO TO 9 DO
                           BEGIN
                             DRAWFILLER (' ',SPACE);
                             WRITE (NUM2:1);
                           END
                      ELSE
                        FOR NUM2 := FIRSTNO TO
                          (XWIDTH - NUM1*10) DO
                           BEGIN
                             DRAWFILLER (' ',SPACE);
                             WRITE (NUM2:1);
                           END;
                         END;
                   END
                 ELSE
                   BEGIN
                     IF (NUM3 = 1)
                       THEN
                         BEGIN
                           DRAWFILLER (' ',SPACE);
                           WRITE ((NUM1 - 1):1);
                         END
                       ELSE
                         BEGIN
                           DRAWFILLER (' ',SPACE);
                           WRITE ('0');
                         END;
                   END;
              END
           ELSE
             BEGIN
               IF ((NUM1 = 1) OR (FIRSTNO = 0))
                 THEN
                   FOR NUM2 := FIRSTNO TO 9 DO
                     BEGIN
                       DRAWFILLER (' ',SPACE);
                       WRITE (NUM2:1);
                     END
                 ELSE
                   FOR NUM2 :=  1 TO 10 DO
                     BEGIN
                       DRAWFILLER (' ',SPACE);
                       WRITE ((NUM1 - 1):1);
                     END;
              END;
        WRITELN;
        LINE := LINE + 1;
        COUNT := COUNT - 1;
        DRAWFILLER (' ',(31 + 9*(SPACE + 1) - SPACE));
        FIRSTNO := 0;
      END;
  END
ELSE
  BEGIN
    FOR NUM3 := 1 TO 2 DO
      BEGIN
        WRITE (' ':4);
        IF (NUM3 = 1)
          THEN
            WRITE ('5');
        FOR NUM1 := 1 TO XWIDTH DIV 10 DO
          BEGIN
            IF ((XWIDTH - (NUM1*10 DIV 5)*5) >= 5)
              THEN
                BEGIN
                  IF (NUM3 = 1)
                    THEN
                      BEGIN
                        WRITE (' ':4);
                        WRITE (NUM1:1);
                        WRITE (' ':4);
                        WRITE (NUM1:1);
                      END
                    ELSE
                      BEGIN
                        WRITE (' ':4);
                        WRITE ('0');
                        WRITE (' ':4);
                        WRITE ('5');
                      END;
                END
              ELSE
                BEGIN
                  IF (NUM3 = 1)
                    THEN
                      BEGIN
                        IF (NUM1 = 10)
                          THEN
                            BEGIN
                              WRITE (' ':4);
                              WRITE ('1');
                            END
                          ELSE
                            BEGIN
                              WRITE (' ':4);
                              WRITE (NUM1:1);
                            END;
                      END
                    ELSE
                      BEGIN
                        WRITE (' ':4);
                        WRITE ('0');
                      END;
                END;
```

```
                                    END;
                                      LINE := LINE + 1;
                                      WRITELN;
                                      WRITE (' ':32);
                                    END;
                                END;
                            IF (XWIDTH = 160)
                              THEN
                                BEGIN
                                  WRITELN (' ':98,'0');
                                  LINE := LINE + 1;
                                END;
                            WRITELN; WRITELN;
                            IF (XTITLE = 'I')
                              THEN
                                WRITELN (' ':60,TIMETITLE)
                              ELSE
                                IF (XTITLE = 'L')
                                  THEN
                                    WRITELN (' ':60,LOBAGETITLE)
                                  ELSE
                                    WRITELN (' ':60,MUSAGETITLE);
                            LINE := LINE + 3;
                          END;

     'F','H'      :    BEGIN
                            WRITE (' ':28);
                            NUM6 := 1;
                            WHILE (NUM6 <> (XAXIS + 1)) DO
                              BEGIN
                                WRITE (NUM6*10:3:0);
                                IF (NUM6 < 10)
                                  THEN
                                    DRAWFILLER (' ',(SPACE - 4))
                                  ELSE
                                    DRAWFILLER (' ',(SPACE - 5));
                                NUM6 := NUM6 + 1;
                              END;
                            WRITELN; WRITELN; WRITELN;
                            IF (XTITLE = 'F')
                              THEN
                                WRITELN (' ':60,LOBSIZETITLE)
                              ELSE
                                WRITELN (' ':60,MUSSIZETITLE);
                            LINE := LINE + 4;
                          END;
              END;

 FOR NUM4 := 1 TO (PAGESIZE - LINE) DO
   WRITELN;

END;

(**********************************************************************************************)

                            (* ==================== *)
                            (* PROCEDURE SETUPGRAPH *)
                            (* ==================== *)


PROCEDURE SETUPGRAPH (GRA    : CHAR;
                      UPPERY : REAL;
                      LOWERY : REAL;
                      UPPERX : REAL;
                      LOWERX : REAL;
                      DCOL   : INTEGER;
                      YTITLE : CHAR;
                      XTITLE : CHAR;
                      XWIDTH : INTEGER);


BEGIN

  CASE XTITLE OF
   'I','L','M'  : XAXIS := TRUNC(UPPERX - LOWERX);
   'F','H'      : XAXIS := TRUNC ((UPPERX - LOWERX)/10);
  END;
  FOR Y := 1 TO GRAWIDTH DO
    FOR X := 1 TO GRAHEIGHT DO
      GRAMAT[X,Y] := ' ';
  LIM[0] := -1;
  LIM[1] := LOWERY;
  INT := (UPPERY - LOWERY)/(GRAHEIGHT - 1);
  FOR NUM1 := 2 TO GRAHEIGHT DO
    LIM[NUM1] := LIM[NUM1 - 1] + INT;
  X := 1;
  WHILE (X <> (XAXIS + 1)) DO
    BEGIN
      FOR Y := 1 TO GRAHEIGHT DO
        CASE GRA OF
          '1' : BEGIN
                  IF (((DATAMAT[X,DCOL] > LIM[Y - 1]) AND
                      (DATAMAT[X,DCOL] <= LIM[Y]))
                      OR ((DATAMAT[X,DCOL] > LIM[GRAHEIGHT])
                      AND (Y = GRAHEIGHT)))
                        THEN
                          GRAMAT[Y,X] := MALL_LOBSTERS;
                  IF (((DATAMAT[X,DCOL + 1] > LIM[Y - 1]) AND
                      (DATAMAT[X,DCOL + 1] <= LIM[Y]))
                      OR ((DATAMAT[X,DCOL + 1] > LIM[GRAHEIGHT])
                      AND (Y = GRAHEIGHT)))
                        THEN
                          GRAMAT[Y,X] := FEMALE_LOBSTERS;
                  IF (((DATAMAT[X,DCOL + 2] > LIM[Y - 1]) AND
                      (DATAMAT[X,DCOL + 2] <= LIM[Y]))
                      OR ((DATAMAT[X,DCOL + 2] > LIM[GRAHEIGHT])
                      AND (Y = GRAHEIGHT)))
                        THEN
                          GRAMAT[Y,X] := TOTAL_LOBSTERS;
                END;
```

```
        '2' : BEGIN
                 IF (((DATAMAT[X,DCOL] > LIM[Y - 1]) AND
                    (DATAMAT[X,DCOL] <= LIM[Y]))
                    OR ((DATAMAT[X,DCOL] > LIM[GRAHEIGHT])
                    AND (Y = GRAHEIGHT)))
                      THEN
                        GRAMAT[Y,X] := MALE_LOBSTERS;
                 IF (((DATAMAT[X,(DCOL + 1)] > LIM[Y - 1]) AND
                    (DATAMAT[X,(DCOL + 1)] <= LIM[Y]))
                    OR ((DATAMAT[X,DCOL + 1] > LIM[GRAHEIGHT])
                    AND (Y = GRAHEIGHT)))
                      THEN
                        GRAMAT[Y,X] := FEMALE_LOBSTERS;
              END;
        '3' : BEGIN
                 IF (((DATAMAT[X,DCOL] > LIM[Y - 1]) AND
                    (DATAMAT[X,DCOL] <= LIM[Y]))
                    OR ((DATAMAT[X,DCOL] > LIM[GRAHEIGHT])
                    AND (Y = GRAHEIGHT)))
                      THEN
                        GRAMAT[Y,X] := MALE_LOBSTERS;
              END;
        '4' : BEGIN
                 IF (((DATAMAT[X,DCOL] > LIM[Y - 1]) AND
                    (DATAMAT[X,DCOL] <= LIM[Y]))
                    OR ((DATAMAT[X,DCOL] > LIM[GRAHEIGHT])
                    AND (Y = GRAHEIGHT)))
                      THEN
                        GRAMAT[Y,X] := MUSSEL;
              END;
      END;
      X := X + 1;
    END;

    DRAWGRAPH (YTITLE,XTITLE,XWIDTH);

END;


(*******************************************************************************************************)
(*******************************************************************************************************)


                         (**********************************)
                         (*                                *)
                         (* ROCK-LOBSTER - MUSSEL PROCEDURES *)
                         (*                                *)
                         (**********************************).


                         (* =============== *)
                         (* PROCEDURE LOBEAT *)
                         (* =============== *)


PROCEDURE LOBEAT;

BEGIN
   FOR MS := 1 TO MUSSIZ DO
     LOBTOTEAT[MS] := 0;

   FOR LS:= 2 TO MLOBSIZ DO
     FOR MS:= 1 TO MUSSIZ DO
       BEGIN
         MLOBNUMEAT[LS,MS] := NUMOFTEAT[LS,MS]*MLOBFREQ[LS];
         FLOBNUMEAT[LS,MS] := NUMOFTEAT[LS,MS]*FLOBFREQ[LS];
         LOBTOTEAT[MS] := LOBTOTEAT[MS] + MLOBNUMEAT[LS,MS] + FLOBNUMEAT[LS,MS];
       END;

   FOR MS:= 1 TO MUSSIZ DO
     BEGIN
       IF (LOBTOTEAT[MS] > MUSFREQ[MS]*(1 - MUSLEFT)) THEN
         BEGIN
           FOR LS := 2 TO MLOBSIZ DO
             IF (LOBTOTEAT[MS] <> 0) THEN
               BEGIN
                 MLOBNUMEAT[LS,MS] := MLOBNUMEAT[LS,MS]*MUSFREQ[MS]*(1-MUSLEFT)/LOBTOTEAT[MS];
                 FLOBNUMEAT[LS,MS] := FLOBNUMEAT[LS,MS]*MUSFREQ[MS]*(1-MUSLEFT)/LOBTOTEAT[MS];
               END;
           LOBTOTEAT[MS] := MUSFREQ[MS]*(1 - MUSLEFT);
         END;
     END;
END;

(*******************************************************************************************************)

                               (* ===================== *)
                               (* PROCEDURE GROWTHEFFECT *)
                               (* ===================== *)


PROCEDURE GROWTHEFFECT (SPEC       : CHAR;
                        LOBNUM     : LOBAGE_ARRAY;
                        LOBNUMEAT  : LOBSIZ_MUSSIZ_ARRAY;
                        SIZ        : INTEGER;
                        LOBFREQ    : LOBSIZ_ARRAY;
                        LOBGRO     : LOBSIZ_ARRAY;
                        VAR GRO    : LOBSIZ_ARRAY);

BEGIN
   FOR LS := 2 TO MLOBSIZ DO
     LOBKJEAT[LS] := 0;

   FOR LS:= 2 TO SIZ DO
     FOR MS:= 1 TO MUSSIZ DO
       LOBKJEAT[LS] := LOBKJEAT[LS] + MUSKJ[MS]*LOBNUMEAT[LS,MS];
```

```
  FOR LS:= 2 TO SIZ DO
    BEGIN
      IF ((LOBFREQ[LS] <> 0) AND (LOBKJEAT[LS] < KJOPTEAT[LS]*LOBFREQ[LS]))
        THEN
          BEGIN
            GRO[LS] := LOBGRO[LS]*(LOBKJEAT[LS]/(KJOPTEAT[LS]*LOBFREQ[LS]));
            IF (SPEC = '2')
              THEN
                GROWTHCHANGE[LS - 1] := LOBKJEAT[LS]/(KJOPTEAT[LS]*LOBFREQ[LS])
              ELSE
                GROWTHCHANGE[LS + (MLOBSIZ - 2)] := LOBKJEAT[LS]/(KJOPTEAT[LS]*LOBFREQ[LS]);
          END
        ELSE
          GRO[LS] := LOBGRO[LS];
  END;

END;

(**********************************************************************************************)
(**********************************************************************************************)

                       (**************************)
                       (*                        *)
                       (* ROCK-LOBSTER PROCEDURES *)
                       (*                        *)
                       (**************************)

                   (* ================= *)
                   (* PROCEDURE LOBMAIN *)
                   (* ================= *)


PROCEDURE LOBMAIN;


BEGIN

  FOR LS := 0 TO MLOBSIZ DO
    LOBLEN[LS] := LS*SIZSTEP;

  FOR  LA:= 1 TO MLOBAGE DO
    BEGIN
      IF (LA = 1)
        THEN
          BEGIN
            IF (MONTH = MOULT)
              THEN
                MIN := LOBJUVLEN
              ELSE
                MIN := 0
          END
        ELSE
          MIN := MLOBLEN[LA - 1];
      MAX := MLOBLEN[LA];
      FRACAGEINSIZE (LOBSTER, LA, MIN, MAX, MLOBFRAC, DUMMUSFRAC, MLOBSIZ, LOBLEN);
    END;

  FOR LA := 1 TO FLOBAGE DO
    BEGIN
      IF (LA = 1)
        THEN
          BEGIN
            IF (MONTH = MOULT)
              THEN
                MIN := LOBJUVLEN
              ELSE
                MIN := 0
          END
        ELSE
          MIN := FLOBLEN[LA - 1];
      MAX := FLOBLEN[LA];
      FRACAGEINSIZE (LOBSTER, LA, MIN, MAX, FLOBFRAC, DUMMUSFRAC, FLOLSIZ, LOBLEN);
    END;

  FOR LS := 1 TO MLOBSIZ DO
    BEGIN
      MLOBFREQ[LS] := 0;
      FLOBFREQ[LS] := 0;
    END;

  FOR LS := 1 TO MLOBSIZ DO
    BEGIN
      FOR LA := 1 TO FLOBAGE DO
        BEGIN
          MLOBFREQ[LS] := MLOBFREQ[LS] + MLOBFRAC[LA,LS]*MLOBNUM[LA];
          IF (MLOBFREQ[LS] < 1)
            THEN
              MLOBFREQ[LS] := 0;
          FLOBFREQ[LS] := FLOBFREQ[LS] + FLOBFRAC[LA,LS]*FLOBNUM[LA];
          IF (FLOBFREQ[LS] < 1)
            THEN
              FLOBFREQ[LS] := 0;
        END;
    END;

END;

(*******************************************************************************************)
```

```
                (* ================= *)
                (* PROCEDURE LOBCALC *)
                (* ================= *)


PROCEDURE LOBCALC;


BEGIN

  LOBTOTLIM := 0;
  MLOBLIM := 0;
  FLOBLIM := 0;
  IF (MONTH = MOULT)
    THEN
      BEGIN
        MLOBAGE := MMAXAGE;
        FLOBAGE := FMAXAGE;
      END;
  LA := 1;

  WHILE (LA <= FMAXAGE) DO
    BEGIN
      MLOBNUMHAR := 0;
      FLOBNUMHAR := 0;
      MLNUM := 0;
      FLNUM := 0;
      MLLEN := 0;
      FLLEN := 0;
      FOR LS:= 1 TO MLOBSIZ DO
        BEGIN
          MLNUMHAR := 0;
          FLNUMHAR := 0;
          IF (((MONTH >= LOBFSEA1) AND (MONTH <= LOBFSEA2)) OR
              ((MONTH >= LOBFSEA3) AND (MONTH <= LOBFSEA4))) THEN
               BEGIN
                 MLNUM := MLNUM + MLOBFRAC[LA,LS]*MLOBNUM[LA]*EXP(-(LOBDENDEP*MLOBMOR[LS]))
                           *((1 - MLOBLIMFRAC[LA]) + MLOBLIMFRAC[LA] * EXP(-MLOBFIS[LS]));
                 FLNUM := FLNUM + FLOBFRAC[LA,LS]*FLOBNUM[LA]*EXP(-(LOBDENDEP*FLOBMOR[LS]))
                           *((1 - FLOBLIMFRAC[LA]) + FLOBLIMFRAC[LA] * EXP(-FLOBFIS[LS]));
                 IF (((MLOBLIMFRAC[LA]*MLOBFIS[LS] + MLOBMOR[LS]) <> 0)
                   AND (LOBCATLIM < MLOBLEN[LA])) THEN
                     MLNUMHAR := MLOBLIMFRAC[LA]*MLOBFIS[LS]/(MLOBMOR[LS] +
                                 MLOBLIMFRAC[LA]*MLOBFIS[LS])*MLOBFRAC[LA,LS]*MLOBNUM[LA]
                                *(1- EXP(-(LOBDENDEP*MLOBMOR[LS])))*((1 - MLOBLIMFRAC[LA])
                                + MLOBLIMFRAC[LA] * EXP(-MLOBFIS[LS])));
                 IF (((FLOBLIMFRAC[LA]*FLOBFIS[LS] + FLOBMOR[LS]) <> 0)
                   AND (LOBCATLIM < FLOBLEN[LA])) THEN
                     FLNUMHAR := FLOBLIMFRAC[LA]*FLOBFIS[LS]/(FLOBMOR[LS] +
                                FLOBLIMFRAC[LA]*FLOBFIS[LS])*FLOBFRAC[LA,LS]*FLOBNUM[LA]
                                *(1-EXP(-(LOBDENDEP*FLOBMOR[LS])))*((1 - FLOBLIMFRAC[LA])
                                + FLOBLIMFRAC[LA] * EXP(-FLOBFIS[LS])));

                 MLOBNUMHAR := MLOBNUMHAR + MLNUMHAR;
                 FLOBNUMHAR := FLOBNUMHAR + FLNUMHAR;
                 LOBTOTMASHAR := LOBTOTMASHAR + (MLNUMHAR + FLNUMHAR)*LOBMASS[LS];
               END
             ELSE
               BEGIN
                 MLNUM := MLNUM + MLOBFRAC[LA,LS]*MLOBNUM[LA]*EXP(-(LOBDENDEP*MLOBMOR[LS]));
                 FLNUM := FLNUM + FLOBFRAC[LA,LS]*FLOBNUM[LA]*EXP(-(LOBDENDEP*FLOBMOR[LS]));
               END;

           IF (MONTH = MOULT)
             THEN
               BEGIN
                 IF ((MLOBLEN[LA] = 0) AND (MLOBLEN[LA-1] > LOBLEN[LS-1])
                 AND (MLOBLEN[LA-1] < LOBLEN[LS]))
                   THEN
                     BEGIN
                       MLOBLEN[LA] := MLOBLEN[LA-1];
                       MLOBFRAC[LA,LS] := 1;
                     END;
                 IF ((MLGRO[LS] <> 0) AND (MLOBFRAC[LA,LS] <> 0))
                   THEN
                     IF ((LOBLEN[LS] - MLOBLEN[LA])/MLGRO[LS] < 1)
                       THEN
                         BEGIN
                           IF (LS <= (MLOBSIZ - 1))
                             THEN
                               MLLEN := (LOBLEN[LS] - MLOBLEN[LA]) + MLGRO[LS + 1]*
                                       (1 - (LOBLEN[LS] - MLOBLEN[LA])/MLGRO[LS])

                             ELSE
                               MLLEN := LOBLEN[LS] - MLOBLEN[LA];
                         END
                       ELSE
                         MLLEN := MLGRO[LS];

                 IF (LS <= FLOBSIZ)
                   THEN
                     BEGIN
                       IF ((FLOBLEN[LA] = 0) AND (FLOBLEN[LA-1] > LOBLEN[LS-1])
                       AND (FLOBLEN[LA-1] < LOBLEN[LS]))
                         THEN
                           BEGIN
                             FLOBLEN[LA] := FLOBLEN[LA-1];
                             FLOBFRAC[LA,LS] := 1;
                           END;
                       IF ((FLGRO[LS] <> 0) AND (FLOBFRAC[LA,LS] <> 0))
                         THEN
                           BEGIN
                             IF ((LOBLEN[LS] - FLOBLEN[LA])/FLGRO[LS] < 1)
                               THEN
                                 BEGIN
                                   IF (LS <= (FLOBSIZ - 1))
                                     THEN
                                       FLLEN := (LOBLEN[LS] - FLOBLEN[LA]) + FLGRO[LS + 1]*
                                               (1 - (LOBLEN[LS] - FLOBLEN[LA])/FLGRO[LS])

                                     ELSE
                                       FLLEN := LOBLEN[LS] - FLOBLEN[LA];
                                 END
                             ELSE
                               FLLEN := FLGRO[LS];
                       END;
                   END;
        END;
      END;
```

```
      IF (LA <= MLOBAGE)
        THEN
          MLOBNUM[LA] := MLNUM;
      IF (MLOBNUM[LA] < 1)
          THEN
            MLOBNUM[LA] := 0;
      IF (LA <= FLOBAGE)
        THEN
          FLOBNUM[LA] := FLNUM;
      IF (FLOBNUM[LA] < 1)
        THEN
          FLOBNUM[LA] := 0;

      IF ((LA <> 1) AND (LOBCATLIM < MLOBLEN[LA])) THEN
          IF (LOBCATLIM > MLOBLEN[LA - 1])
            THEN
              MLOBMEANCAT := MLOBMEANCAT + MLOBNUMHAR * (LOBCATLIM +
                              (MLOBLEN[LA] - LOBCATLIM)/2)
            ELSE
              MLOBMEANCAT := MLOBMEANCAT + MLOBNUMHAR * (MLOBLEN[LA - 1] +
                              (MLOBLEN[LA] - MLOBLEN[LA - 1])/2);
      IF ((LA <> 1) AND (LOBCATLIM < FLOBLEN[LA])) THEN
          IF (LOBCATLIM > FLOBLEN[LA - 1])
            THEN
              FLOBMEANCAT := FLOBMEANCAT + FLOBNUMHAR * (LOBCATLIM +
                              (FLOBLEN[LA] - LOBCATLIM)/2)
            ELSE
              FLOBMEANCAT := FLOBMEANCAT + FLOBNUMHAR * (FLOBLEN[LA - 1] +
                              (FLOBLEN[LA] - FLOBLEN[LA - 1])/2);

      MLOBTOTNUMHAR := MLOBTOTNUMHAR + MLOBNUMHAR;
      FLOBTOTNUMHAR := FLOBTOTNUMHAR + FLOBNUMHAR;
      IF (MONTH = MOULT)
        THEN
          BEGIN
            IF (LA <= MLOBAGE)
              THEN
                BEGIN
                  MLOBLEN[LA] := MLOBLEN[LA] + MLLEN;
                  IF (MLOBLEN[LA] >= LOBLEN[MLOBSIZ])
                    THEN
                      BEGIN
                        MLOBAGE := LA;
                        MLOBLEN[LA] := LOBLEN[MLOBSIZ];
                      END;
                  IF  ((LA = MMAXAGE) AND (MLOBAGE = MMAXAGE))
                    THEN
                      MLOBAGE := LA;
                END;
            IF (LA <= FLOBAGE)
              THEN
                BEGIN
                  FLOBLEN[LA] := FLOBLEN[LA] + FLLEN;
                  IF (FLOBLEN[LA] >= LOBLEN[FLOBSIZ])
                    THEN
                      BEGIN
                        FLOBAGE := LA;
                        FLOBLEN[LA] := LOBLEN[FLOBSIZ];
                      END;
                  IF ((LA = FMAXAGE) AND (FLOBAGE = FMAXAGE))
                    THEN
                      FLOBAGE := LA;
                END;
          END;

      IF ((LA = FLOBAGE) AND (LA <> FMAXAGE))
        THEN
          LA := FMAXAGE - 1;
      LA := LA + 1;
    END;

    FOR LA := 2 TO FLOBAGE DO
      BEGIN
        IF ((MLOBLEN[LA - 1] > MLOBLEN[LA]) AND (LA <= MLOBAGE))
          THEN
            GROWTHRATEERROR (MLOBLEN[LA - 1], MLOBLEN[LA], LA, '1');
        IF ((FLOBLEN[LA - 1] > FLOBLEN[LA]) AND (LA <= FLOBAGE))
          THEN
            GROWTHRATEERROR (FLOBLEN[LA - 1], FLOBLEN[LA], LA, '2');
      END;

    LOBTOTNUMHAR := MLOBTOTNUMHAR + FLOBTOTNUMHAR;

END;
(***************************************************************************************************)

                             (* ================= *)
                             (* PROCEDURE LOBMOVE *)
                             (* ================= *)


PROCEDURE LOBMOVE;


BEGIN

  LOBMATUR := 0;
  TOTEGG := 0;
  FOR LS := LOBMATSIZ TO MLOBSIZ DO
    LOBMATUR := LOBMATUR + FLOBFREQ[LS] + MLOBFREQ[LS];;

  CASE RECRUIT OF
    1 : TOTEGG := LOBEGG[1];
    2 : FOR LS := LOBMATSIZ TO FLOBSIZ DO
          TOTEGG := TOTEGG + FLOBFREQ[LS] * LOBEGG[LS];
    3 : IF (LOBMATUR <> 0)
          THEN
            TOTEGG := 1/(LOBEGG[1] + LOBEGG[2]/LOBMATUR)
          ELSE
            TOTEGG := 0;
    4 : TOTEGG := LOBEGG[1] * LOBMATUR * EXP(-LOBEGG[2] * LOBMATUR);
  END;
```

```
MLOBTOT := 0;
FOR LA := MLOBAGE DOWNTO 1 DO
  BEGIN
    IF (LA = 1)
      THEN
        MLOBNUM[1] := TOTEGG/2;

    IF (LA = MLOBAGE)
      THEN
        MLOBNUM[MLOBAGE] := MLOBNUM[MLOBAGE] + MLOBNUM[MLOBAGE - 1];

    IF ((LA <> 1) AND (LA <> MLOBAGE))
      THEN
        MLOBNUM[LA] := MLOBNUM[LA - 1];


    IF (LA = 1)
      THEN
        MLOBLEN[LA] := LOBJUVLEN;

    IF (LA <> 1)
      THEN
        MLOBLEN[LA] := MLOBLEN[LA - 1];

    IF (LA <> 1)
      THEN
        MLOBTOT := MLOBTOT + MLOBNUM[LA];

   FOR LS := 2 TO MLOBSIZ DO
                MLOBLIM := MLOBLIM + MLOBLIMFRAC[LA]*MLOBNUM[LA]*MLOBFRAC[LA,LS];

  END;

FLOBTOT := 0;
FOR LA := FLOBAGE DOWNTO 1 DO
  BEGIN
    IF (LA = 1)
      THEN
        FLOBNUM[1] := TOTEGG/2;

    IF (LA = FLOBAGE)
      THEN
        FLOBNUM[FLOBAGE] := FLOBNUM[FLOBAGE] + FLOBNUM[FLOBAGE - 1];

    IF ((LA <> 1) AND (LA <> FLOBAGE))
      THEN
        FLOBNUM[LA] := FLOBNUM[LA - 1];

    IF (LA = 1)
      THEN
        FLOBLEN[LA] := LOBJUVLEN;

    IF (LA <> 1)
      THEN
        FLOBLEN[LA] := FLOBLEN[LA - 1];

    IF (LA <> 1)
      THEN
           FLOBTOT := FLOBTOT + FLOBNUM[LA];
            FOR LS := 2 TO FLOBSIZ DO
               FLOBLIM := FLOBLIM + FLOBLIMFRAC[LA]*FLOBNUM[LA]*FLOBFRAC[LA,LS];
   END;

   LOBTOT := MLOBTOT + FLOBTOT;

   LOBTOTLIM := MLOBLIM + FLOBLIM;

   IF (MLOBTOTNUMHAR <> 0)
     THEN
       MLOBMEANCAT := MLOBMEANCAT/MLOBTOTNUMHAR
     ELSE
       MLOBMEANCAT := 0.0;
   IF (FLOBTOTNUMHAR <> 0)
     THEN
       FLOBMEANCAT := FLOBMEANCAT/FLOBTOTNUMHAR
     ELSE
       FLOBMEANCAT := 0.0;
   IF ((MLOBTOTNUMHAR + FLOBTOTNUMHAR) <> 0)
     THEN
       LOBMEANCAT := (MLOBMEANCAT*MLOBTOTNUMHAR + FLOBMEANCAT*FLOBTOTNUMHAR)/
                     (MLOBTOTNUMHAR + FLOBTOTNUMHAR)

     ELSE
       LOBMEANCAT := 0.0;

END;

 ************************************************************************)
(************************************************************************)
(************************************************************************)
```

```
                           (*********************)
                           (*                   *)
                           (* MUSSEL PROCEDURES *)
                           (*                   *)
                           (*********************)

                           (* ================ *)
                           (* PROCEDURE MUSMAIN *)
                           (* ================ *)


PROCEDURE MUSMAIN;

BEGIN

  FOR MS:= 0 TO MUSSIZ DO
    MSLEN[MS] := MS*SIZSTEP;

  FOR MA:= 1 TO MUSAGE DO
    BEGIN
      IF (MA = 1)
        THEN
          BEGIN
           IF (MONTH = 0)
             THEN
               MIN := 0
             ELSE
               MIN := MONTH*MUSGRO[1];
          END
        ELSE
          MIN := MUSLEN[MA - 1];
      MAX := MUSLEN[MA];
      FRACAGEINSIZE (MUSSEL, MA, MIN, MAX, CUMLOBFRAC, MUSFRAC, MUSSIZ, MSLEN);
    END;

  FOR MS := 1 TO MUSSIZ DO
    MUSFREQ[MS] := 0;

  FOR MA := 1 TO MUSAGE DO
    FOR MS:= 1 TO MUSSIZ DO
      BEGIN
        MUSFREQ[MS] := MUSFREQ[MS] + MUSFRAC[MA,MS]*MUSNUM[MA];
        IF (MUSFREQ[MS] < 1)
          THEN
            MUSFREQ[MS] := 0;
      END;

END;

(**************************************************************************************************)

                         (* ================ *)
                         (* PROCEDURE MUSCALC *)
                         (* ================ *)


PROCEDURE MUSCALC;

BEGIN

  FOR MA:= 1 TO MUSAGE DO
    BEGIN
      MNUM := 0;
      MLEN := 0;
      FOR MS:= 1 TO MUSSIZ DO
        BEGIN
          IF (MODEL = 'M')
            THEN
              MNUM := MNUM + MUSFRAC[MA,MS]*MUSNUM[MA]*EXP(-MUSDENDEP*MUSMOR[MS])
            ELSE
              IF (MUSFREQ[MS] <> 0)
                THEN
                  MNUM := MNUM + MUSFRAC[MA,MS]*MUSNUM[MA]*(1 - LOBTOTEAT[MS]
                     /MUSFREQ[MS])*EXP(-MUSDENDEP*MUSMOR[MS]);

          IF (MUSFRAC[MA,MS] <> 0)
            THEN
              IF ((MSLEN[MS] - MUSLEN[MA])/MUSGRO[MS] < 1)
                THEN
                  BEGIN
                    IF (MS <= (MUSSIZ - 1))
                      THEN
                        MLEN := (MSLEN[MS] - MUSLEN[MA]) + MUSGRO[MS + 1]*
                                 (1 - (MSLEN[MS] - MUSLEN[MA])/MUSGRO[MS])
                      ELSE
                        MLEN := MSLEN[MS] - MUSLEN[MA]
                  END
                ELSE
                  MLEN := MUSGRO[MS];

        END;

      MUSNUM[MA] := MNUM;
      IF (MUSNUM[MA] < 1)
        THEN
          MUSNUM[MA] := 0;

      MUSLEN[MA] := MUSLEN[MA] + MLEN;

      IF (MA <> 1)
        THEN
          BEGIN
            IF ((MUSLEN[MA - 1] > MUSLEN[MA]) AND (MA <= MUSAGE))
              THEN
                GROWTHRATERROR (MUSLEN[MA - 1], MUSLEN[MA], MA, '3');
          END;
```

```
    END;

  IF ((MONTH = 4) OR (MONTH = 8))
    THEN
      MUSNUM[1] := MUSNUM[1] + MUSEGG*EXP(-MUSEGGMOR);

END;

(*******************************************************************************************)

                       (* ================= *)
                       (* PROCEDURE MUSMOVE *)
                       (* ================= *)


PROCEDURE MUSMOVE;


BEGIN
  MUSTOT := 0;

  FOR MA:= MUSAGE DOWNTO 1 DO
    BEGIN
      IF (MA = 1)
        THEN
          MUSNUM[1] := MUSEGG*EXP(-MUSEGGMOR);

      IF (MA = MUSAGE)
        THEN
          MUSNUM[MUSAGE] := MUSNUM[MUSAGE] + MUSNUM[MUSAGE - 1];

      IF ((MA <> 1) AND (MA <> MUSAGE))
        THEN
          MUSNUM[MA] := MUSNUM[MA - 1];

      IF (MA = 1)
        THEN
          MUSLEN[1] := MUSGRO[1]*12;

      IF (MA <> 1)
        THEN
          MUSLEN[MA] := MUSLEN[MA - 1];

      MUSTOT := MUSTOT + MUSNUM[MA];

    END;

END;

(******************************************************************************************)
(******************************************************************************************)


                           (*******************)
                           (*                 *)
                           (* MAIN PROCEDURES *)
                           (*                 *)
                           (*******************)

                       (* ==================== *)
                       (* PROCEDURE INITIALIZE *)
                       (* ==================== *)

PROCEDURE INITIALIZE;

BEGIN

  READLN;
  READLN (MODEL);
  READLN (YEARS);
  READLN (RECRUIT);
  FOR NUM1 := 1 TO 49 DO
    WRITELN;

  CASE MODEL OF
     'L' : WRITE ('ROCK LOBSTER MODEL : RUN TIME IS ',YEARS:3,' YEARS',' ':3);
     'M' : WRITE ('MUSSEL MODEL : RUN TIME IS ',YEARS:3,' YEARS',' ':3);
     'B' : WRITE ('ROCK LOBSTER-MUSSEL MODEL : RUN TIME IS ',YEARS:3,' YEARS',' ':3);
  END;

  NUM1 := 0;
  WHILE NOT EOLN DO
    BEGIN
      NUM1 := NUM1 + 1;
      READ (TITLE[NUM1]);
      WRITE (TITLE[NUM1]);
    END;
  READLN;

  CASE RECRUIT OF
    1 : WRITE (' ':3,'NO STOCK-RECRUIT');
    2 : WRITE (' ':3,'LINEAR STOCK-RECRUIT');
    3 : WRITE (' ':3,'BEVERTON+HOLT STOCK-RECRUIT');
    4 : WRITE (' ':3,'RICKER STOCK-RECRUIT');
  END;
  WRITELN; WRITELN;

  READDATA;
  FOR NUM1 := 1 TO 11 DO
    WRITELN;
```

```
   CASE MODEL OF
     'L' : BEGIN
             WRITELN ('  TIME                   NUMBER OF LOBSTERS',
                 '                NUMBER OVER CATCH LIMIT                 ',
                   '            NUMBER HARVESTED             MASS HARVESTED');
             WRITELN (' (YEARS)     MALES          FEMALES         TOTAL',
                 '         MALES          FEMALES         TOTAL       ',
                 '     MALES         FEMALES        TOTAL            (TONS)');
             WRITELN ('---------------------------------------------------',
                   '-----------------------------------------------------',
                 '-----------------------------------------');

             LOBMAIN;
             LINE := 4;
           END;

     'M' : BEGIN
             WRITELN ('TIME (YEARS)  TOTAL NO OF MUSSELS');
             WRITELN ('------------  --------------------');
             MUSMAIN;
             LINE := 3;
           END;

     'B' : BEGIN
             WRITELN (' TIME (YEARS)',' ':30,'MAXIMUM AGE OF MALES, FEMALES (YEARS)');
             WRITELN ('---------------------------------------------------',
                   '-----------------------------------------------------',
                 '-----------------------------------------');

             WRITELN;
             WRITELN (' ':25,'PERCENTAGE OF OPTIMAL GROWTH RATE IN EACH SIZE CLASS',
                 ' (% / SIZE CLASS)');
             WRITELN ('---------------------------------------------------',
                   '-----------------------------------------------------',
                 '-----------------------------------------');

             WRITELN;
             WRITELN ('                 NUMBER OF LOBSTERS',
                 '                  NUMBER OVER CATCH LIMIT                    ',
                 ' NUMBER HARVESTED                MASS HARVESTED  NUMBER OF');
             WRITELN ('     MALES          FEMALES         TOTAL',
                 '            MALES          FEMALES         TOTAL        ',
                 'MALES          FEMALES        TOTAL           (TONS)        MUSSELS');
             WRITELN ('---------------------------------------------------',
                   '-----------------------------------------------------',
                 '-----------------------------------------');
             WRITELN ('---------------------------------------------------',
                   '-----------------------------------------------------',
                 '-----------------------------------------');

             LOBMAIN;
             MUSMAIN;
             LINE := 11;
           END;
   END;

   WRITELN; WRITELN;
   LINE := LINE + 2;
   FOR NUM1 := 1 TO 10 DO
     FOR NUM2 := 1 TO GRAWIDTH DO
       DATAMAT[NUM2,NUM1] := 0;

END;

(******************************************************************************************)

                                (* ================= *)
                                (* PROCEDURE FINALIZE *)
                                (* ================= *)


PROCEDURE FINALIZE;

BEGIN
   IF (MODEL <> 'M')
     THEN
       BEGIN
         SETUPGRAPH ('1',MAXLOBNUM,MINLOBNUM,YEARS,0,1,'A','1',YEARS);
         SETUPGRAPH ('1',MAXLOBLIM,MINLOBLIM,YEARS,0,4,'B','1',YEARS);
         SETUPGRAPH ('1',MAXLOBNUMHAR,MINLOBNUMHAR,YEARS,0,7,'C','1',YEARS);
         SETUPGRAPH ('3',MAXLOBMASHAR,MINLOBMASHAR,YEARS,0,10,'D','1',YEARS);

   IF (MODEL = 'B')
     THEN
       SETUPGRAPH ('4',MAXMUSNUM,MINMUSNUM,YEARS,0,11,'G','1',YEARS);
   END;

   IF (MODEL = 'M')
     THEN
       SETUPGRAPH ('4',MAXMUSNUM,MINMUSNUM,YEARS,0,1,'G','1',YEARS);

   FOR NUM1 := 1 TO 13 DO
     FOR NUM2 := 1 TO GRAWIDTH DO
       DATAMAT[NUM2,NUM1] := 0;

 END;

(******************************************************************************************)
```

```
                                   (* ================= *)
                                   (* PROCEDURE LOBFINAL *)
                                   (* ================= *).


PROCEDURE LOBFINAL;

BEGIN
  WRITELN ('MALE SIZE FREQUENCY DISTRIBUTION                          ',
          'FEMALE  SIZE FREQUENCY DISTRIBUTION');
  WRITELN ('--------------------------------                          ',
  '---------------------------------');
  WRITELN;
  WRITELN ('     LENGTH          NUMBER        %                      ',
          ' LENGTH             NUMBER        %');
  WRITELN ('     ------          ------        -              ',
  '      ------              ------           -');
  WRITELN;
  MLOBPERCENT := 0;
  FLOBPERCENT := 0;
  IF (MLOBTOT = 0) THEN
    MLOBTOT := 1;
  IF (FLOBTOT = 0) THEN
    FLOBTOT := 1;
  WRITELN ('     ',LOBLEN[1]:2:0,'          ',MLOBFREQ[1],
          '                ',LOBLEN[1]:2:0,'              ',FLOBFREQ[1]);

  FOR LS := 2 TO MLOBSIZ DO
    BEGIN
      IF (LOBLEN[LS] <= 110) THEN
        IF (LOBLEN[LS] < 100) THEN
          BEGIN
            IF ((MLOBFREQ[LS]/MLOBTOT*100 > 10) AND (FLOBFREQ[LS]/FLOBTOT*100 < 10)) THEN
              WRITELN ('     ',LOBLEN[LS]:2:0,' ':6,MLOBFREQ[LS],'    ',MLOBFREQ[LS]/MLOBTOT*100:4:2,
              ' ':15,LOBLEN[LS]:2:0,' ':9,FLOBFREQ[LS],'     ',FLOBFREQ[LS]/FLOBTOT*100:4:2);
            IF ((MLOBFREQ[LS]/MLOBTOT*100 > 10) AND (FLOBFREQ[LS]/FLOBTOT*100 > 10)) THEN
              WRITELN ('     ',LOBLEN[LS]:2:0,' ':6,MLOBFREQ[LS],'    ',MLOBFREQ[LS]/MLOBTOT*100:4:2,
              ' ':15,LOBLEN[LS]:2:0,' ':9,FLOBFREQ[LS],'    ', FLOBFREQ[LS]/FLOBTOT*100:4:2);
            IF ((MLOBFREQ[LS]/MLOBTOT*100 < 10) AND (FLOBFREQ[LS]/FLOBTOT*100 < 10)) THEN
              WRITELN ('     ',LOBLEN[LS]:2:0,' ':6,MLOBFREQ[LS],'     ',MLOBFREQ[LS]/MLOBTOT*100:4:2,
              ' ':15,LOBLEN[LS]:2:0,' ':9,FLOBFREQ[LS],'     ',FLOBFREQ[LS]/FLOBTOT*100:4:2);
            IF ((MLOBFREQ[LS]/MLOBTOT*100 < 10) AND (FLOBFREQ[LS]/FLOBTOT*100 > 10)) THEN
              WRITELN ('     ',LOBLEN[LS]:2:0,' ':6,MLOBFREQ[LS],'     ',MLOBFREQ[LS]/MLOBTOT*100:4:2,
                ' ':14,LOBLEN[LS]:3:0,' ':9,FLOBFREQ[LS],'    ',FLOBFREQ[LS]/FLOBTOT*100:4:2);
          END
            ELSE
              WRITELN ('  ',LOBLEN[LS]:3:0,' ':6,MLOBFREQ[LS],'     ',MLOBFREQ[LS]/MLOBTOT*100:4:2,
              ' ':14,LOBLEN[LS]:3:0,' ':9,FLOBFREQ[LS],'    ',FLOBFREQ[LS]/FLOBTOT*100:4:2)
      ELSE
        WRITELN ('  ',LOBLEN[LS]:3:0,'          ',MLOBFREQ[LS],'    ', MLOBFREQ[LS]/MLOBTOT*100:4:2);
        MLOBPERCENT := MLOBPERCENT + MLOBFREQ[LS]/MLOBTOT*100;
        FLOBPERCENT := FLOBPERCENT + FLOBFREQ[LS]/FLOBTOT*100;
        DATAMAT[LS,1] := MLOBFREQ[LS];
        DATAMAT[LS,2] := FLOBFREQ[LS];
        MAXMIN (MLOBFREQ[LS], MAXLOBFREQ, MINLOBFREQ);
        IF (MLOBFREQ[LS] <> 0)
          THEN
            DATAMAT[LS,3] := LN(MLOBFREQ[LS]);
        MAXMIN (DATAMAT[LS,3], MAXLOGLOBFREQ, MINLOGLOBFREQ);
        IF (LOBLEN[LS] <= 110)
          THEN
            BEGIN
              MAXMIN (FLOBFREQ[LS], MAXLOBFREQ, MINLOBFREQ);
              IF (FLOBFREQ[LS] <> 0)
                THEN
                  DATAMAT[LS,4] := LN(FLOBFREQ[LS]);
              MAXMIN (DATAMAT[LS,4], MAXLOGLOBFREQ, MINLOGLOBFREQ);
            END;
    END;

        WRITELN;
        WRITELN (' ':28,'(',MLOBPERCENT:5:2,')',' ':39,'(',FLOBPERCENT:5:2,')');

  FOR NUM1 := 1 TO 40 DO
    WRITELN;

IF (YEARS <= 100)
  THEN
    BEGIN
      SETUPGRAPH ('2',MAXLOBFREQ,MINLOBFREQ,LOBLEN[MLOBSIZ],0,1,'A','F',0);
      SETUPGRAPH ('2',MAXLOGLOBFREQ,MINLOGLOBFREQ,LOBLEN[MLOBSIZ],0,3,'J','F',0);
        END;

      WRITELN ('  MALE AGE FREQUENCY DISTRIBUTION            ',
      '          FEMALE  AGE FREQUENCY DISTRIBUTION');
      WRITELN ('  -------------------------------            ',
      '          ---------------------------------');
      WRITELN;
      WRITELN ('    AGE      LENGTH              NUMBER                   ',
              ' AGE      LENGTH              NUMBER');
      WRITELN ('    ---      ------              ------                ',
      '      ---      ------                ------');
      WRITELN;
      LINE := 6;
      MAXLOBNUM := 0;
      MINLOBNUM := 0;
      FOR LA := 1 TO FLOBAGE DO
        BEGIN
          IF (LA <= MLOBAGE)
            THEN
              BEGIN
                WRITELN ('     ',LA:2,'        ',MLOBLEN[LA]:4:1,'           ',MLOBNUM[LA],
                '                   ',LA:2,'        ',FLOBLEN[LA]:4:1,'             ',FLOBNUM[LA]);
                DATAMAT[LA,5] := MLOBNUM[LA];
                MAXMIN (MLOBNUM[LA], MAXLOBNUM, MINLOBNUM);
                IF (MLOBNUM[LA] <> 0)
                  THEN
                    DATAMAT[LA,7] := LN(MLOBNUM[LA]);
                MAXMIN (DATAMAT[LA,7], MAXLOGLOBNUM, MINLOGLOBNUM);
              END
            ELSE
              WRITELN (' ':52,LA:2,'        ',FLOBLEN[LA]:4:1,'              ',FLOBNUM[LA]);
```

```
          DATAMAT[LA,6] := FLOBNUM[LA];
          MAXMIN (FLOBNUM[LA], MAXLOBNUM, MINLOBNUM);
          IF (FLOBNUM[LA] <> 0)
            THEN
              DATAMAT[LA,8] := LN(FLOBNUM[LA]);
          MAXMIN (DATAMAT[LA,8], MAXLOGLOBNUM, MINLOGLOBNUM);
          LINE := LINE + 1;
          IF (LINE > PAGESIZE)
            THEN
              LINE := LINE - PAGESIZE;
    END;

  FOR NUM1 := 1 TO (PAGESIZE - LINE + 2) DO
    WRITELN;

  IF (YEARS <= 100)
    THEN
      BEGIN
  SETUPGRAPH ('2',MAXLOBNUM,MINLOBNUM,FLOBAGE,0,5,'A','L',FLOBAGE);
  SETUPGRAPH ('2',MAXLOGLOBNUM,MINLOGLOBNUM,FLOBAGE,0,7,'J','L',FLOBAGE);
      END;

  WRITELN ('     LOBSTER SEX RATIOS');
  WRITELN ('     ------------------');
  WRITELN;
  WRITELN ('  LENGTH         PERCENTAGE MALES');
  WRITELN ('  ------         ----------------');
  WRITELN;
  FOR LS := 1 TO MLOBSIZ DO
    BEGIN
      IF ((MLOBFREQ[LS] + FLOBFREQ[LS]) <> 0)
        THEN
          LOBSEXRAT := MLOBFREQ[LS]/(MLOBFREQ[LS] + FLOBFREQ[LS])*100
        ELSE
          LOBSEXRAT := 100;
      DATAMAT[LS,1] := LOBSEXRAT;
      IF (LOBLEN[LS] >= 100)
        THEN
          WRITELN ( LOBLEN[LS]:3:0,'               ',LOBSEXRAT:5:1)
        ELSE
          WRITELN (' ', LOBLEN[LS]:2:0,'                ',LOBSEXRAT:5:1);
    END;

  FOR NUM1 := 1 TO 42 DO
  WRITELN;

IF (YEARS <= 100) THEN
  SETUPGRAPH ('3',100,0,LOBLEN[MLOBSIZ],0,1,'E','F',0);

END;

(*******************************************************************************************)

                                   (* ================== *)
                                   (* PROCEDURE MUSFINAL *)
                                   (* ================== *)


PROCEDURE MUSFINAL;

BEGIN

  FOR NUM1 := 1 TO 10 DO
    FOR NUM2 := 1 TO GRAWIDTH DO
      DATAMAT[NUM2,NUM1] := 0;

  WRITELN ('MUSSEL SIZE FREQUENCY DISTRIBUTION');
  WRITELN ('----------------------------------');
  WRITELN;
  WRITELN ('   LENGTH     NUMBER        %');
  WRITELN ('   ------     ------        -');
  WRITELN;
  MUSPERCENT := 0;
  IF (MUSTOT = 0) THEN
    MUSTOT := 1;
  FOR MS := 1 TO MUSSIZ DO
    BEGIN
      IF (MUSFREQ[MS]/MUSTOT*100 < 10)
        THEN
          WRITELN ('  ',MSLEN[MS]:2:0,'    ',MUSFREQ[MS],'    ',MUSFREQ[MS]/MUSTOT*100:4:2)
        ELSE
          WRITELN ('  ',MSLEN[MS]:2:0,'    ',MUSFREQ[MS],'   ',MUSFREQ[MS]/MUSTOT*100:4:2);
      MUSPERCENT := MUSPERCENT+ MUSFREQ[MS]/MUSTOT*100;
      DATAMAT[MS,1] := MUSFREQ[MS];
      IF (MUSFREQ[MS] <> 0)
        THEN
          DATAMAT[MS,2] := LN(MUSFREQ[MS]);
      MAXMIN (MUSFREQ[MS], MAXMUSFREQ, MINMUSFREQ);
      MAXMIN (DATAMAT[MS,2], MAXLOGMUSFREQ, MINLOGMUSFREQ);
    END;

  WRITELN;
  WRITELN (' ':26,'(',MUSPERCENT:5:2,')');
  FOR NUM1 := 1 TO 45 DO
    WRITELN;

  IF (YEARS <= 100)
    THEN
      BEGIN
        SETUPGRAPH ('4',MAXMUSFREQ,MINMUSFREQ,MSLEN[MUSSIZ],0,1,'G','H',0);
        SETUPGRAPH ('4',MAXLOGMUSFREQ, MINLOGMUSFREQ,MSLEN[MUSSIZ],0,2,'K','H',0);
      END;

  WRITELN ('MUSSEL AGE FREQUENCY DISTRIBUTION');
  WRITELN ('---------------------------------');
  WRITELN;
  WRITELN ('     AGE     LENGTH     NUMBER');
  WRITELN ('     ---     ------     ------');
  WRITELN;
  LINE := 6;
  MAXMUSNUM := 0;
  MINMUSNUM := 0;
```

```
  FOR MA := 1 TO MUSAGE DO
    BEGIN
      WRITELN ('     ',MA:2,'       ',MUSLEN[MA]:3:1,'    ',MUSNUM[MA]);
      DATAMAT[MA,3] := MUSNUM[MA];
      IF (MUSNUM[MA] <> 0)
        THEN
          DATAMAT[MA,4] := LN(MUSNUM[MA]);
      MAXMIN (MUSNUM[MA], MAXMUSNUM, MINMUSNUM);
      MAXMIN (DATAMAT[MA,4], MAXLOGMUSNUM, MINLOGMUSNUM);
        LINE := LINE + 1;
      IF (LINE > PAGESIZE)
        THEN
          LINE := LINE - PAGESIZE;
    END;

  FOR NUM1 := 1 TO (PAGESIZE - LINE + 2) DO
    WRITELN;

  IF (YEARS <= 100)
    THEN
      BEGIN
        SETUPGRAPH ('4',MAXMUSNUM,MINMUSNUM,MUSAGE,0,3,'G','M',MUSAGE);
        SETUPGRAPH ('4',MAXLOGMUSNUM, MINLOGMUSNUM,MUSAGE,0,4,'K','M',MUSAGE);
      END;
END;

{*******************************************************************************}

                    (* EXECUTABLE STATEMENTS OF MAIN PROGRAM *)


BEGIN

  INITIALIZE;

  FOR TIME:= 1 TO YEARS DO
    BEGIN
      FOR LS := 1 TO MLOBSIZ DO
        MLGRO[LS] := MLOBGRO[LS];
      FOR LS := 1 TO FLOBSIZ DO
        FLGRO[LS] := FLOBGRO[LS];
        FOR NUM1 := 1 TO MFSIZMIN2 DO
          GROWTHCHANCE[NUM1] := 1.0;
      MLOBTOTNUMHAR := 0;
      FLOBTOTNUMHAR := 0;
      LOBTOTMASHAR := 0;
      MLOBMEANCAT := 0;
      FLOBMEANCAT := 0;

      FOR MONTH:= 1 TO 12 DO
        CASE MODEL OF
          'L' : BEGIN
                  FRACOVERLIM (MLOBLEN, MLOBLIMFRAC);
                  FRACOVERLIM (FLOBLEN, FLOBLIMFRAC);
                  LOBCALC;
                  LOBMAIN;
                END;

          'M' : BEGIN
                  MUSCALC;
                  MUSMAIN;
                END;

          'B' : BEGIN
                  FRACOVERLIM (MLOBLEN, MLOBLIMFRAC);
                  FRACOVERLIM (FLOBLEN, FLOBLIMFRAC);
                  LOBEAT;
                  IF (MONTH = (MOULT - 1))
                    THEN
                      BEGIN
                        GROWTHEFFECT ('2',MLOBNUM,MLOBNUMEAT,MLOBSIZ,MLOBFREQ,MLOBGRO,MLGRO);
                        GROWTHEFFECT ('3',FLOBNUM,FLOBNUMEAT,FLOBSIZ,FLOBFREQ,FLOBGRO,FLGRO);
                      END;
                  LOBCALC;
                  LOBMAIN;
                  MUSCALC;
                  MUSMAIN;
                END;
        END;

      MONTH := 0;

      CASE MODEL OF
        'L' : BEGIN
                LOBMOVE;
                LOBMAIN;
                WRITELN (TIME:4,'     ',MLOBTOT,FLOBTOT,
                LOBTOT,MLOBLIM,FLOBLIM,LOBTOTLIM,
                MLOBTOTNUMHAR,FLOBTOTNUMHAR,LOBTOTNUMHAR,LOBTOTMASHAR);
                IF (YEARS <= 100)
                  THEN
                    BEGIN
                DATAMAT[TIME,1] := MLOBTOT;
                DATAMAT[TIME,2] := FLOBTOT;
                DATAMAT[TIME,3] := LOBTOT;
                DATAMAT[TIME,4] := MLOBLIM;
                DATAMAT[TIME,5] := FLOBLIM;
                DATAMAT[TIME,6] := LOBTOTLIM;
                DATAMAT[TIME,7] := MLOBTOTNUMHAR;
                DATAMAT[TIME,8] := FLOBTOTNUMHAR;
                DATAMAT[TIME,9] := LOBTOTNUMHAR;
                DATAMAT[TIME,10] := LOBTOTMASHAR;
                END;
                LINE := LINE + 1;
              END;

        'M' : BEGIN
                MUSMOVE;
                MUSMAIN;
                WRITELN (TIME : 6,'              ', MUSTOT);
                IF (YEARS <= 100)
                  THEN
                    BEGIN
                DATAMAT[TIME,1] := MUSTOT;
                END;
                LINE := LINE + 1;
              END;
```

```
'B' : BEGIN
          LOBMOVE;
          LOBMAIN;
          MUSMOVE;
          MUSMAIN;
          WRITELN (' ':5,TIME: 3,' ':10,'(',MLOBAGE:3,' ,',FLOBAGE:3,')');
          WRITELN;
          WRITE (' MALES :   ');
          FOR NUM1 := 2 TO MLOBSIZ DO
             IF (NUM1 < 10)
                THEN
                   WRITE ((GROWTHCHANGE[NUM1 - 1]*100):5:1,'/',NUM1:1)
                ELSE
                   WRITE ((GROWTHCHANGE[NUM1 - 1]*100):5:1,'/',NUM1:2);
          WRITELN;
          WRITE (' FEMALES :');
          NUM2 := MLOBSIZ - 2;
          FOR NUM1 := 2 TO FLOBSIZ DO
             IF (NUM1 < 10)
                THEN
                   WRITE ((GROWTHCHANGE[NUM1 + NUM2]*100):5:1,'/',NUM1:1)
                ELSE
                   WRITE ((GROWTHCHANGE[NUM1 + NUM2]*100):5:1,'/',NUM1:2);
          WRITELN; WRITELN;
          WRITELN (MLOBTOT,FLOBTOT,LOBTOT,MLOBLIM,FLOBLIM,LOBTOTLIM,
                   MLOBTOTNUMHAR,FLOBTOTNUMHAR,LOBTOTNUMHAR,LOBTOTMASHAR,MUSTOT);
          WRITELN; WRITELN;
          IF (YEARS <= 100)
            THEN
               BEGIN
          DATAMAT[TIME,1] := MLOBTOT;
          DATAMAT[TIME,2] := FLOBTOT;
          DATAMAT[TIME,3] := LOBTOT;
          DATAMAT[TIME,4] := MLOBLIM;
          DATAMAT[TIME,5] := FLOBLIM;
          DATAMAT[TIME,6] := LOBTOTLIM;
          DATAMAT[TIME,7] := MLOBTOTNUMHAR;
          DATAMAT[TIME,8] := FLOBTOTNUMHAR;
          DATAMAT[TIME,9] := LOBTOTNUMHAR;
          DATAMAT[TIME,10] := LOBTOTMASHAR;
          DATAMAT[TIME,11] := MUSTOT;
        END;
          LINE := LINE + 8;

        END;
     END;
     MAXMIN (MLOBTOT, MAXLOBNUM, MINLOBNUM);
     MAXMIN (FLOBTOT, MAXLOBNUM, MINLOBNUM);
     MAXMIN (LOBTOT, MAXLOBNUM, MINLOBNUM);
     MAXMIN (MLOBTOTNUMHAR, MAXLOBNUMHAR, MINLOBNUMHAR);
     MAXMIN (FLOBTOTNUMHAR, MAXLOBNUMHAR, MINLOBNUMHAR);
     MAXMIN (LOBTOTNUMHAR, MAXLOBNUMHAR, MINLOBNUMHAR);
     MAXMIN (LOBTOTMASHAR, MAXLOBMASHAR, MINLOBMASHAR);
     MAXMIN (MLOBLIM, MAXLOBLIM, MINLOBLIM);
     MAXMIN (FLOBLIM, MAXLOBLIM, MINLOBLIM);
     MAXMIN (LOBTOTLIM, MAXLOBLIM, MINLOBLIM);
     MAXMIN (MUSTOT, MAXMUSNUM, MINMUSNUM);

     IF (LINE > PAGESIZE)
       THEN
         LINE := LINE - PAGESIZE;

   END;

 IF ((MODEL = 'B') OR (MODEL = 'L'))
   THEN
     BEGIN
       WRITELN; WRITELN;
       WRITELN ('THE MEAN SIZE OF THE CATCH IS ',MLOBMEANCAT:4:1,
               ' FOR MALES ',FLOBMEANCAT:4:1,' FOR FEMALES ',
               LOBMEANCAT:4:1,' FOR BOTH SEXES COMBINED');
       LINE := LINE + 3;
     END;

 IF (LINE > PAGESIZE)
   THEN
     LINE := LINE - PAGESIZE;

 IF (LINE < PAGESIZE) THEN
   FOR NUM1 := 1 TO (PAGESIZE - LINE) DO
     WRITELN;
   WRITELN; WRITELN;

   IF (YEARS <= 100) THEN
     FINALIZE;
   IF (MODEL <> 'M') THEN
     LOBFINAL;
   IF (MODEL <> 'L') THEN
     MUSFINAL;

99 : END.

(**************************************************************************)
(**************************************************************************)
```

APPENDIX E : DOCUMENTATION FOR PROGRAM "FREQ"

A. PROGRAM SPECIFICATION

Calculation of age frequency distribution : This program (stored in "SIMUL*MODEL.FREQ" on a SPERRY 1100/81) generates an age-frequency distribution from a percentage size frequency distribution, a total population number and an age-length distribution (computed by the program "GROWTH").

B. INSTRUCTIONS FOR USE

1. Input Specifications :

The following is a runstream for program execution.

```
 1. @RUN,Z/N RUNID,ACCOUNT-NO,SIMUL,TIME,PAGES
 2. @ASG,A MODEL.
 3. @ASG,CP DASMUSMEAN.,F50
 4. @ASG,T TEMP*AGEFILE.
 5. @ASG,A BMDP*83.
 6. @USE 12.,TEMP*AGEFILE.
 7. @USE 13.,DASMUSMEAN.
 8. @XQT MODEL.FREQ
 9.  MUSSEL - MEAN GROWTH - DASSEN ISLAND AGE FREQUENCY
10. 27395000000 8 33 10 0 0 0
11. 91.7
12. 7.07
13. 0.054
14. 0.014
15. 0.038
16. 0.178
17. 0.506
18. 0.440
19. 6.55
20. 16.17
21. 29.46
      .

      .
49. 79.25
50. 79.99
51. @BMDP*83.BMDP BMDP6D
52.  /PROBLEM  TITLE  IS  'MUSSEL  - MEAN  GROWTH  - DASSEN  ISLAND  AGE
    FREQUENCY'
53. /INPUT     VARIABLES ARE 2.
54.            FORMAT IS '(I3,F20.0)'.
55. /VARIABLE  NAMES ARE YEARS, NUMBER.
56. /PLOT      YVAR IS NUMBER.
57.            XVAR IS YEARS.
58. /END
59. @ADD TEMP*AGEFILE.
60. @FIN
```

The data (lines 9 to 50 in this runstream) should be entered as follows :

CARD 1 : HEADING (STARTING IN COL 2, UP TO 60 CHARACTERS)

CARD 2 : THE FOLLOWING DATA ITEMS SHOULD BE SEPARATED BY ONE BLANK

1) TOTAL NUMBER IN POPULATION
2) NUMBER OF SIZE CLASSES
3) NUMBER OF AGE CLASSES
4) RANGE OF EACH SIZE CLASS
5) LOWER LENGTH LIMIT OF FIRST SIZE CLASS
6) LOWER LENGTH LIMIT OF FIRST AGE CLASS
7) STARTING AGE

CARD 3 + : PERCENTAGE FREQUENCY IN EACH SIZE CLASS, ONE PER CARD

CARD (4 + NO. OF SIZE CLASSES) : UPPER LENGTH LIMIT OF EACH AGE CLASS, ONE PER CARD

In this runstream, the last set of data points (upper length limits) start on line 19. The files, "SIMUL*DASMUSMEAN" and "TEMP*AGEFILE" are output files.

2. Output Format :

There are three forms of output : a table (Example 1) giving the age-frequency distributions, a BMDP plot of the distribution and a file (in this case, "SIMUL*DASMUSMEAN") containing only the number of individuals in each age class.

Example 1 :

```
   MUSSEL - MEAN GROWTH - DASSEN ISLAND AGE FREQUENCY

 THE GIVEN DATA PRODUCES THE FOLLOWING AGE LENGTH DISTRIBUTION :

           AGE          CALCULATED NUMBER
           ---          -----------------

            1              25421422848
            2               1638349056
            3                 14772992
            .                    .
            .                    .
           32                 18799232
           33                 12919808
```

3. Restrictions on Generality :

Only yearly age classes are output.

4. Run Time :

The program may take up to 20 seconds to run if 100 age classes are involved.

C. CONCEPTUAL OVERVIEW

The algorithm is described in Chapter 4. Since frequency data are not always available for the whole size/age range of an individual, a starting length for the size frequency distribution and for the first age class can be specified. Two files are created by the program. One is a temporary file for use by BMDP plotting and the second, containing only the number of individuals in different age classes is a storage file for incorporation into a data file.

D. PROGRAM DESIGN

The program comprises one FORTRAN routine encompassing three main sections of calculation. The first calculates the cumulative size frequency distribution. The second determines the cumulative number of individuals in each age class and the third calculates the absolute number in each age class. The output is written to two files, one for use by BMDP and one for further use, and a printout of a table and a BMDP plot of the results is made.

E. PROGRAM CODE

The FORTRAN IV code for the program written for a SPERRY 1100/81 is given in Appendix F.

APPENDIX F: FORTRAN CODE FOR PROGRAM "FREQ"

```
*                *******************************************
*                **                                       **
*                **            PROGRAM "FREQ"             **
*                **                                       **
*                ** AGE FREQUENCY DISTRIBUTION CALCULATION **
*                **                                       **
*                *******************************************
*
*----------------------------------------------------------------------
*            VARIABLE AND PARAMETER DECLARATION
*----------------------------------------------------------------------

      INTEGER SIZCLS
*                                NUMBER OF SIZE CLASSES
      INTEGER AGE
*                                NUMBER OF AGE CLASSES
      INTEGER FIRAGE
*                                FIRST AGE CLASS
      INTEGER RANGE
*                                RANGE OF EACH SIZE CLASS
      INTEGER SIZ(0:20)
*                                UPPER LENGTH LIMIT OF EACH SIZE CLASS
      INTEGER A,S
*                                COUNTERS FOR NUMBER OF AGE AND SIZE CLASSES
      REAL TOTNUM
*                                TOTAL NUMBER OF INDIVIDUALS IN POPULATION
      REAL FREQ(20)
*                                PERCENTAGE FREQUENCY IN EACH SIZE CLASS
      REAL LEN(0:200)
*                                UPPER LENGTH LIMIT OF EACH AGE CLASS
      REAL NUM(0:200)
*                                NUMBER OF INDIVIDUALS IN EACH AGE CLASS
      REAL CUMFRQ(0:20)
*                                CUMULATIVE NUMBER OF INDIVIDUALS IN EACH
*                                SIZE CLASS
      REAL SLOPE
*                                SLOPE OF LINE DRAWN BETWEEN LENGTH-NUMBER
*                                POINTS AT MIDPOINTS OF TWO NEIGHBOURING
*                                SIZE CLASSES
      REAL STAAGE
*                                LOWER LENGTH LIMIT OF FIRST AGE CLASS
      REAL STASIZ
*                                LOWER LENGTH LIMIT OF FIRST SIZE CLASS
      REAL YINT
*                                Y-INTERCEPT OF A LINE DRAWN BETWEEN LENGTH-
*                                NUMBER POINTS AT MIDPOINTS OF TWO
*                                NEIGHBOURING SIZE CLASSES
      CHARACTER*60 HEAD
*                                HEADING

*----------------------------------------------------------------------
*              FORMAT STATEMENTS
*----------------------------------------------------------------------

5     FORMAT ( )
65    FORMAT (A60)
15    FORMAT (/,/,' AGE    CALCULATED NUMBER',/,
     &' ---    -----------------')
25    FORMAT (/,/,' AGE    SMOOTHED NUMBER',/,
     &' ---    ---------------')
35    FORMAT (I3,F20.0)
45    FORMAT (1H1,A60)
55    FORMAT (F20.0)

*----------------------------------------------------------------------
*                OPEN OUTPUT FILES
*----------------------------------------------------------------------

      OPEN (12)
      OPEN (13)

*----------------------------------------------------------------------
*                  READ IN DATA
*----------------------------------------------------------------------

      READ (*,65) HEAD
      READ (*,5) TOTNUM, SIZCLS, AGE, RANGE, STASIZ, STAAGE, FIRAGE
      READ (*,5) (FREQ(S), S = 1,SIZCLS)
      READ (*,5) (LEN(A), A = FIRAGE,AGE)
```

```
*-----------------------------------------------------------------------
*        PRINT HEADING AND INITIALIZE VARIABLES
*-----------------------------------------------------------------------

      WRITE (*,45) HEAD
      WRITE (*,5)
      WRITE (*,5) 'THE GIVEN DATA PRODUCES THE FOLLOWING AGE',
     &            ' LENGTH DISTRIBUTION :'
      WRITE (*,15)
      SIZ(0) = STASIZ
      LEN(0) = STAAGE
      CUMFRQ(0) = 0
      NUM(0) = 0

*-----------------------------------------------------------------------
*            CALCULATE CUMULATIVE FREQUENCY OF EACH SIZ CLASS
*-----------------------------------------------------------------------

      DO 10 S = 1,SIZCLS
10       CUMFRQ(S) = FREQ(S)*0.01*TOTNUM + CUMFRQ(S - 1)

*-----------------------------------------------------------------------
*          CALCULATE CUMULATIVE NUMBER IN EACH AGE CLASS
*-----------------------------------------------------------------------

      A = FIRAGE
      DO 20 S = 1,SIZCLS
        SIZ(S) = S*RANGE + STASIZ
        SLOPE = (CUMFRQ(S) - CUMFRQ(S - 1))/(SIZ(S) - SIZ(S - 1))
        YINT = CUMFRQ(S) - SLOPE*SIZ(S)
 100    IF ((LEN(A) .LT. SIZ(S)) .OR. (S .EQ. SIZCLS)) THEN
          NUM(A) = SLOPE*LEN(A) + YINT
          A = A + 1
          IF (A .LE. AGE) GOTO 100
        ENDIF
20    CONTINUE

*-----------------------------------------------------------------------
*          CALCULATE NUMBER IN EACH AGE CLASS
*-----------------------------------------------------------------------

      DO 30 A = AGE,FIRAGE,-1
30    NUM(A) = NUM(A) - NUM(A-1)

*-----------------------------------------------------------------------
*                         PRINT RESULTS
*-----------------------------------------------------------------------

      DO 80 A = FIRAGE,AGE
        WRITE (*,35) A,NUM(A)
        WRITE (12,35) A,NUM(A)
80    WRITE (13,55) NUM(A)

      WRITE (*,5)

*-----------------------------------------------------------------------
*                     CLOSE OUTPUT FILES
*-----------------------------------------------------------------------

      CLOSE (12)
      CLOSE (13)

      END
```

APPENDIX G : TUNED OUTPUT FROM ALL MODELS

CAPE PENINSULA

	CALCULATED	MODEL				
		MUSSEL	LOBSTER CONSTANT RECRUIT-MENT	LOBSTER STOCK-RECRUIT-MENT	INTERACTION CONSTANT RECRUIT-MENT	INTERACTION STOCK-RECRUIT-MENT
Number of lobsters (excl. larval stages) (x 10^{6}) :						
Males	31.079		30.853	31.491	30.579	31.036
Females	35.372		36.995	37.653	36.515	37.036
Total	66.451		67.848	69.145	67.094	68.073
Number of lobsters of catchable size (x 10^{6}) :						
Males	4.724		5.065	5.156	5.154	5.240
Females	1.094		0.490	0.492	0.562	0.574
Total	5.818		5.555	5.647	5.716	5.814
Number of lobsters harvested (x 10^{3}) :						
Males	1226.600		1151.800	1171.700	1173.400	1193.600
Females	0.982		0.674	0.676	0.772	0.790
Total	1227.600		1152.500	1172.300	1174.200	1194.400
Mass harvested (tons) :	530		527	536	530	539
Mean size of catch individuals (mm)	94.0		95.0	95.0	94.8	94.8
Number of mussels (X 10^{10}) :	2.740	2.740			15.940	15.590

DASSEN ISLAND

	CALCULATED	MODEL			
		MUSSEL	LOBSTER CONSTANT RECRUIT MENT	LOBSTER STOCK-RECRUIT MENT	INTERACTION CONSTANT RECRUIT MENT
Number of lobsters (excl. larval stages) (x 10^6) :					
Males	65.581		67.085	65.144	64.775
Females	80.664		81.422	78.834	80.545
Total	146.250		148.510	143.980	145.320
Number of lobsters of catchable size (x 10^6) :					
Males	7.684		7.691	7.465	9.075
Females	1.470		1.395	1.348	1.870
Total	9.154		9.086	8.813	10.945
Number of lobsters harvested (x 10^3) :					
Males	1762.900		1735.000	1683.800	2048.100
Females	46.130		60.760	58.720	81.620
Total	1808.700		1795.700	1742.500	2129.800
Mass harvested (tons) :	830		834	809	1011
Mean size of catch individuals (mm)	96.0		95.6	95.6	96.6
Number of mussels (X 10^{10}) :	18.048	18.040			39.586

ROBBEN ISLAND

	CALCULATED	MODEL				
		MUSSEL	LOBSTER CONSTANT RECRUITMENT	LOBSTER STOCK-RECRUITMENT	INTERACTION CONSTANT RECRUITMENT	INTERACTION STOCK-RECRUITMENT
Number of lobsters (excl. larval stages) (x 10^{6}) :						
Males	20.810		20.881	20.585	20.881	20.467
Females	20.751		21.578	21.275	21.578	21.152
Total	41.560		42.459	41.860	42.459	41.620
Number of lobsters of catchable size (x 10^{6}) :						
Males	6.136		6.070	5.989	6.070	5.954
Females	0.414		0.408	0.403	0.408	0.401
Total	6.550		6.478	6.392	6.478	6.355
Number of mussels (X 10^{10}) :	8.248	8.245			16.977	21.343

24 OCT 1985