Modelling to Explore Management Strategies to Optimise the Value of the Rock Lobster Fishery of Western Australia

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OBJECTIVES:
1. To develop a statistically sound biological model to represent the rock lobster assemblage within each region and its interaction with fishers within the constraints imposed by alternative management strategies;
2. to incorporate marketing data into the model to allow the prediction of changes in product value with different management scenarios; and
3. to determine the time-dependent set of management controls (size, catch, and effort) that would optimise the value of the landed product, and to identify alternative locally optimum sets of controls producing similar (but reduced) value.

NON-TECHNICAL SUMMARY:
The fishery for the western rock lobster (*Panulirus cygnus*) is Western Australia's most important single species fishery, and yields an average annual catch of 10,500 to 11,000 tonnes valued at between $200 and $300 million at the point of landing. With a high level of exploitation and a product with a high export value, the need was recognised for the development of appropriate models to evaluate alternative management strategies. This study describes the models that were developed.

A number of outcomes of the study may be identified. A size-structured model was developed for the *P. cygnus* fishery. The monthly growth transition matrices required for this model were estimated from tagging data. Data on beach prices received for lobster and costs of bait, fuel, gear and crew were collected for 1998/99. Examples of the use of the size-structured model to explore alternative management strategies, and the results of a calculation of the net relative value of the catch estimated by the size-structured model are presented. The relationship between vulnerability and carapace length of the lobsters was investigated, and the concentration of fishing effort on locations and depths where the smaller lobsters are located was found to be a major factor affecting the size composition of the catch. An age-structured model of the fishery was also developed. This model was used to investigate the effect of the management changes introduced to the fishery in 1993/94. An example of the use of this age-structured model to explore the consequences of an alternative management strategy and the uncertainty of the resulting estimates of egg production under the alternative strategies was presented.

The size-structured model that was developed for the fishery calculates the numbers of lobsters in the various length classes at each time step. The model uses 1 mm size classes and 1 month time steps. In other words, the model represents the number of lobsters in each 1 mm length class at the beginning of each month. Separate estimations of the parameters for this model were undertaken for each sex and each of five fishing regions around the Abrolhos Islands, Dongara, Jurien, Lancelin and Fremantle. Among the five regions tested, Fremantle

achieved the best fit of the model to the observed catch and effort data, while the region with the poorest fit was the Abrolhos Islands. The model fitted the data generally well in the Jurien and Lancelin regions, but less well in the Dongara region. To improve the model fit, an improved representation of the relationship between vulnerability and length will be necessary. Little information regarding this relationship is currently available from earlier studies, but an investigation (in this study) of the concentration of fishing effort on smaller lobsters reveals that it is an important factor in determining the size composition of the monthly catches.

To illustrate the capability of the size-structured model in the assessment of the impacts of alternative management strategies, the model was used to explore the effect on catches and on egg production resulting from the regulation introduced in 1993/94 requiring the release of setose female lobsters (those capable of carrying developing eggs).

The development of the size-structured model required the estimation of a set of growth transition matrices representing the monthly growth of lobsters in the fishery. This analysis proved valuable in improving understanding of moult increments and moulting times of western rock lobsters.

Details of beach prices received by fishers in the 1998/99 fishing season and of the costs incurred in fishing were collected and used in the model to calculate the net relative value of the estimated catches resulting from management strategies tested within the model. To illustrate the economic information produced by the model, details of the economic outputs of the model were generated for the 1998/99 fishing season.

An urgent request for management advice by the fishing industry and fishery managers arose before the length-structured model was completed. Consequently, an age-structured model was developed to provide the necessary advice. While addressing specific objectives that differed from those of the FRDC project, this model is pertinent to the FRDC project and is reported here. The structure of this model allowed calculation of the statistical uncertainty of the estimates produced by the model. Using this model, egg production in 1992-93 was estimated to have been 12% (95% confidence interval: 6 to 20%) of the original unfished egg production, but to have increased to 21% (95% confidence interval: 13 to 29%) by 1999-2000, when the target was 17%. The consequence of a change in management in 2001-2002 was examined. The risk of egg production in 2002-2003 falling below the target level increased from 10 to 33% with the proposed change.

Further development of the size-structured model is necessary before it is used for complex assessments. However, the age-structured model has provided a statistically sound model of the fishery that is being used to assess alternative management strategies. The economic data collected for this study can be used to calculate and compare the net relative value of the alternative strategies, allowing selection of the set of management controls that will produce the optimum net relative value for the fishery.

KEYWORDS: **lobster, model, stock assessment, economics**

1. Background

In the early 1990s, it was recognised that the spawning stock of the western rock lobster had been reduced to an unacceptable level thought to be less than 20% of the virgin level, and that management action was required to reduce the level of exploitation. Such management action was taken, and significant changes to the fishery regulations were introduced in 1992-93 and in 1993-94 that reduced exploitation and increased the survival of the lobsters, particularly enhancing the survival of mature female lobsters.

At that time, both industry and fishery managers accepted that no further increase in the average catch from the fishery could be achieved by increasing exploitation without also compromising the abundance of spawning female lobsters. An increase in the net economic return from the fishery could only be achieved by increasing the value of the catch or by reducing the costs required to take that catch.

Comparison of the monthly prices received by the processors from overseas markets with the supply of different product types, grades and quantities of product, over a number of years, had revealed that the magnitude of catches was poorly correlated with market demand (Anon., 1994). The catchability of the lobsters and the fishing seasons specified by fishery managers determined the quantities of catch supplied to the market, not the price received for those lobsters on the overseas markets. Thus, it appeared possible that by adjusting the flow of catch to respond to market demand, rather than expecting the market to respond to the quantity of product supplied, the price received for the catch might be increased.

While the costs of management controls have been considered implicitly by both fishers and by the Rock Lobster Industry Advisory Committee (RLIAC) when evaluating alternative management strategies, such costs have never been considered explicitly. For example, a recent proposal to extend the length of the fishing season was rejected by many fishers as they saw no demonstrated benefits in the proposal. Clearly the costs associated with alternative management strategies are of concern to fishers, and it is essential that appropriate consideration should be given to these, to ensure that proposed strategies are acceptable to fishers.

Since Walters *et al.* (1993) developed the spatial size-structured model that was used in the assessment of the fishery undertaken in the early 1990s, the advice required by managers has changed. Advice is required now to assess the fishery at a level of detail that can not be provided by the Walters *et al.* (1993) model, and to assess controls that were not considered within the model. Developments in technology have extended the capability of computers to handle the computing demands of more complex models. The Walters *et al.* (1993) model was constrained by both software and computing speed, and thus limited in its complexity and in the range of data that could be processed when fitting the model.

2. Need

Advice on the economic implications of alternative management strategies is required by the fishing industry and by the managers of the western rock lobster fishery. The range of alternative management strategies to be assessed was determined by the set of controls that had been promulgated by the RLIAC and by fishery managers for use in the fishery.

As the existing model (Walters *et al.*, 1993) was unable to examine the consequences of the proposed management strategies, or to provide advice at the required resolution, the need existed for the development of an appropriate new model. Thus there was a need for the development of a bio-economic model of the western rock lobster fishery, to explore the impacts of alternative management strategies on the economic return from the fishery and provide appropriate advice to fishery managers and to the fishing industry.

This model was required to have a structure that would permit evaluation of the alternative controls considered for use by the RLIAC. These controls included the use of specific levels of pot usage for different time periods within a season (including complete closure); adjustments to legal minimum and maximum carapace lengths for either sex to a resolution of 1 mm; and the requirement of fishers to release setose females for varying time periods within the year. A further control to be considered was the use of catch quota for different time periods within the year. It was recognised that implementation of such a catch quota in the input-controlled western rock lobster fishery might be achieved by estimating the pot quota required to achieve the catch, then allocating this effort to fishers in the form of an overall level of pot usage for each management zone of the rock lobster fishery.

The model was required to provide an assessment for each of the management zones, namely the north and south coastal zones and the Abrolhos Islands zone. It addition, it was required to estimate the value of the landed catch for the resulting size range, and to estimate the cost associated with achieving that catch. Further, an estimate of the egg production from each management zone, and the impact on this of the alternative management strategies, was to be provided.

Fundamental to satisfying these needs, the model to be developed for the fishery was required to provide an accurate description of the fishery, such that the relationships between catch, effort, growth, and the size composition of catches for each sex were accurately described. This would determine the accuracy of subsequent model predictions. There was also a need to investigate the uncertainty associated with model structure, and to determine the uncertainty associated with both parameter estimates and model predictions.

As little economic data had been collected previously by Fisheries WA, there was a need for the collection of price and fishing cost information, for use within the model when fitting and when estimating the economic impacts of the alternative management strategies.

Development of this bio-economic model was seen as an essential, strategic element of the research program for the western rock lobster fishery.

3. Objectives

The objectives of the project were:

(i) to develop a statistically sound biological model to represent the rock lobster assemblage within each region and its interaction with fishers within the constraints imposed by alternative management strategies;
(ii) to incorporate marketing data into the model to allow the prediction of changes in product value with different management scenarios;
(iii) to determine the time-dependent set of management controls (size, catch, and effort) that would optimise the value of the landed product, and to identify alternative locally optimum sets of controls producing similar (but reduced) value.

4. Methods

The project evolved into several sub-projects.

One set of tasks was focussed on the development of a size-structured model of the fishery (Sections 4.1, 4.2, and 4.3). This model required a set of monthly growth transition matrices to be estimated from an analysis of the available tagging data (Section 4.1). These matrices were essential inputs to the size-structured model for the western rock lobsters (Section 4.2). In order to illustrate the capability of the size-structured model in the exploration of alternative management strategies, the model was used to examine the impact of the regulation requiring release of setose female lobsters that was introduced in the 1993/94 management strategy (Section 4.3).

A second set of tasks centred on the collection of economic data for the fishery (Section 4.4), and the application of these data in the size-structured model to determine the relative economic impact of alternative management strategies.

A third element of the study was an investigation to determine whether vulnerability at length was related to the distribution of fishing effort (Section 4.5).

Finally, recognising that vulnerability at length was influenced strongly by the distribution of fishing, and that this factor, in combination with the weight given in model fitting to the catches derived from the smaller lobsters, were affecting the fit of the length-structured model to the fishery data, an alternative age-structured model was developed. This model was designed specifically to address the management measures introduced in the 1993/94 management strategy, and to provide estimates of the impact on egg production of alternative management strategies, together with an evaluation of the uncertainty associated with those predictions (Section 4.6). This provided a cross check on the length-structured model.

4.1 Growth transition matrices

The methods used to estimate the growth transition matrices, also called size or length transition matrices, are described in this section. To verify that the estimated transition matrices described the recorded growth of rock lobsters adequately, comparisons were made between the results estimated from the transition matrices and the observations. The verification included comparisons of length frequency and size-increment frequency data. The methods for estimating monthly and annual mean size increments and size-increment distributions from the transition matrices are presented at the end of this section.

4.1.1 Description of the growth transition matrix

It was assumed that the growth process of western rock lobsters is a stochastic process with stochasticity of monthly length increment associated with some known form of distribution function. Based on this assumption and an assumption on the form of the distribution function, the probability of a lobster growing from one size class to another within a specified time period can be estimated. The time period in this study is a month. It was assumed that the probability is dependent on the sex of the lobster and the area in which the lobster is located. Thus, the growth transition matrix was estimated independently for data from each region and for each sex.

For a given region and sex, denote $P_T(j,i)$ as the probability of a lobster growing from size-class *i* to size-class *j* within time period *T*. Here *T* is any month from January to December. Assuming the distribution function, denoted by *F*, is known, $P_T(j,i)$ was estimated using the following integration:

Eq. 4.1 $$P_T(j,i) \propto \int_{\ell^-(j)}^{\ell^+(j)} F(\phi(T,i), \ell(i), \ell)\mathrm{d}\ell,$$

where ℓ is length, $\ell^+(j)$ and $\ell^-(j)$ are the upper and the lower limits of the length of size-class *j*, respectively, $\ell(i)$ is the mid-length of size-class i, and $\phi(T,i)$ is a vector of parameters dependent on the time period *T* and the size-class i. The proportionality (*i.e.*, $\propto$) in Eq. 4.1 was chosen so that the constraint $\sum_{j=1}^{N} P_T(j,i) = 1$ was satisfied, where *N* is the number of size classes considered.

In the present study, *F* was chosen to be a gamma distribution, that is,

Eq. 4.2 $$F(\phi(T,i), \ell(i), \ell) = \frac{(\ell - \ell(i))^{(\alpha_i - 1)} e^{-(\ell - \ell(i))/\beta}}{\beta^{\alpha_i}\Gamma(\alpha_i)},$$

where α_i, β are the parameters of the distribution. $\Gamma(\cdot)$ is the gamma function.

The gamma distribution was also chosen in Sullivan *et al.* (1990) and Punt *et al.* (1997). Alternative distributions include the normal, log-normal, beta and Weibull distributions. However, when using a normal or beta distribution, attention must be given to the range of the independent variable. In Punt *et al.* (1997), where a normal distribution was chosen, $-\infty$ was used instead of $\ell^{-}(i)$ for the lower limit of the integration when estimating the $P_T(i,i)$ in Eq. 4.1.

In the case of the gamma distribution in this study, special care was taken to estimate the $P_T(i,i)$ (*i.e.*, probability of staying in the same size class) because the independent variable of the gamma distribution must not be negative. Consequently, the size class i was divided into n equal sub-classes, that is,

$$\ell^{-}(i) = \ell_0(i) < \ell_1(i) < \ell_2(i) < \cdots < \ell_{n-1}(i) < \ell_n(i) = \ell^{+}(i),$$

then

$$P_T(i,i) \propto \sum_{k=0}^{n-1} \int_{\ell_k(i)}^{\ell^{+}(i)} F(\phi_k(T,i), \ell_k(i), \ell)\, d\ell,$$

where $F(\phi_k(T,i), \ell_k(i), \ell)$ is defined in Eq. 4.2 by substituting $\ell(i)$ with $\ell_k(i)$. The same substitution was also adopted when estimating the shape parameter α_i in $F(\phi_k(T,i), \ell_k(i), \ell)$ later.

A normal distribution was tested as an alternative for the gamma distribution applied when estimating the size transition matrices, but the gamma distribution provided a better fit to the observed data. Bergh and Johnston (1992) used a beta distribution and scaled the size increments to be less than 1 by dividing them by a maximum possible length increment. A beta distribution was not chosen for the western rock lobster data because this would require specification of a maximum length increment. Other distributions, *i.e.*, log-normal and Weibull, have some difficulties when relating their parameters to the mean increment of length estimated from the von Bertalanffy growth curve in order to reduce the number of parameters in the estimation of size transition probabilities.

The mean of the gamma distribution in Eq. 4.2 is $\alpha_i \beta$. If $\Delta\ell(i)$ is denoted as the mean growth increment of individual lobsters initially in size-class i, then $\Delta\ell(i) = \alpha_i \beta$. Hence,

Eq. 4.3 $$\alpha_i = \Delta\ell(i) / \beta.$$

To describe the mean growth increment, we used the following equation which is derived from the von Bertalanffy model (von Bertalanffy, 1934):

Eq. 4.4 $$\Delta\ell(i) = (\ell_\infty - \ell(i))(1 - e^{-K\Delta t}),$$

where ℓ_∞ is the theoretical asymptotic carapace length (mm) of individual lobsters, and K is the growth rate within the time period T. Both ℓ_∞ and K are dependent on T. Δt is the elapsed time and was set as 1 month in this study.

Eq. 4.4 can be written as:

Eq. 4.5 $$\Delta\ell(i) = \ell_{\infty}(1-e^{-K\Delta t}) - (1-e^{-K\Delta t})\ell(i).$$

A new parameter δ is used as a substitute for $(1-e^{-K\Delta t})$ to simplify the above formula. Then Eq. 4.5 becomes

Eq. 4.6 $$\Delta\ell(i) = \ell_{\infty}\delta - \delta\ell(i), 1 > \delta \geq 0.$$

Recognising that the growth of mature females is likely to be different from the growth of immature females, different values of ℓ_{∞} and δ were assumed for mature and immature females, *i.e.*,

Eq. 4.7 $$\Delta\ell(i) = \begin{cases} \ell_{1\infty}\delta_1 - \delta_1\ell(i), & \ell(i) < \text{Lmat}; \\ \ell_{2\infty}\delta_2 - \delta_2\ell(i), & \ell(i) \geq \text{Lmat}, \end{cases}$$

where ‘Lmat’ represents the size at maturity for females, and its value in this study was set as the length at which 50% of females were mature within the region.

Using Eq. 4.1 to Eq. 4.3 and Eq. 4.6 or Eq. 4.7, $P_T(j,i)$, calculated from the parameters ℓ_{∞}, δ or $\ell_{1\infty}, \ell_{2\infty}, \delta_1, \delta_2$ and β, can be estimated for the time period *T*. From these probabilities $P_T(j,i)$, a matrix is formulated as follows:

$$\mathbf{P_T} = \begin{bmatrix} P_T(1,1) & 0 & \cdot & 0 & 0 \\ P_T(2,1) & P_T(2,2) & \cdot & 0 & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ P_T(N-1,1) & P_T(N-1,2) & \cdot & P_T(N-1,N-1) & 0 \\ P_T(N,1) & P_T(N,2) & \cdot & P_T(N,N-1) & P_T(N,N) \end{bmatrix}$$

which is the *growth transition matrix* or *size transition matrix,* where *T* is the time period and *N* is the number of size classes considered. Twelve transition matrices, $\mathbf{P_1}, \mathbf{P_2}, \cdots, \mathbf{P_{12}}$, represent the transition matrices from January to December, respectively.

4.1.2 Data specification

Since 1988, there have been annual tagging programs directed at gaining a better understanding of both the growth rates and movement of the western rock lobster. Tagging was conducted at locations throughout the fishery. Rock lobsters were tagged over the full depth range of the commercial fishery (*i.e.*, 0 to ~100m) using the research vessel “Flinders" and commercial fishing vessels.

Each rock lobster tagged had the following release information recorded: tag number and insertion position (ventral or dorsal), date of release, position (latitude and longitude) using Global Positioning System (GPS) technology, depth, sex, carapace length (mm), colour, breeding condition and any missing appendages. Tag recapture information supplied by both commercial and recreational fishers was the same as that mentioned above. Nearly 90,000 rock lobsters were tagged between 1988 and

1998. Recapture rates were variable for different years and locations, but in general recapture information was supplied to Fisheries W.A. for about 20 to 30% of the tagged lobsters that were released.

For a recaptured tagged lobster, the information recorded should contain at least the release date t_{rel}, the recapture date t_{rec}, the release length ℓ_{rel}, the recapture length ℓ_{rec}, the release location loc_{rel}, the recapture location loc_{rec}, and the sex s. In this study, if any one of the records t_{rel}, t_{rec}, ℓ_{rel}, ℓ_{rec}, loc_{rel}, loc_{rec}, and s for a recaptured lobster was missing, the lobster was excluded from the analysis. Negative growth increments were considered to be rare in *P. cygnus*, therefore only those lobsters with $\ell_{rec} \geq \ell_{rel}$ were considered in this analysis. We are aware that the inclusion of only positive size increments between release and recapture may have underestimated the probability of lobsters' not moulting, however we considered that the results would be less reliable if those negative size increments were included in our analysis because a significant level of noise or of measurement errors might have existed in the data.

In addition to the above constraints, only those lobsters at large for time periods greater than 2 months and less than 2 years (*i.e.*, $61 \leq t_{rec} - t_{rel} \leq 730$ days) were selected for analysis. This limitation was imposed because it was felt that periods at large between release and recapture that were too short might have led to an underestimate of growth of lobsters (because tagging might have affected the growth process), while periods that were too long would have created more calculations causing computer simulations to be extremely slow. In order to maximise the data available for the analysis, loss of legs or antennae was not considered when selecting the data; a filtered set of tagging data which excludes lobsters with missing appendages is to be re-analysed to ensure that the bias resulting from such data is eliminated.

In the present study, size transition matrices were estimated for five different regions of the western rock lobster commercial fishery based on the location of release of tagged lobsters (**Figure 1**). These regions were selected on the basis of differences in the biological and management characteristics and were defined as north of 28°S (Region 1), Abrolhos Islands (Region 2), the coastal region from 28°S to 30°S (Region 3), a region from 30°S to 30°48'S (Region 4), and a region from 30°48'S to 34°S (Region 5). The reason for using 30°48'S rather than 31°S to separate Region 4 and Region 5 was to group the tagging data appropriately, see **Figure 1**. The points are grouped satisfactorily using 30°48'S, but using 31°S would allocate part of the data around Lancelin to Region 4 and part to Region 5, which appears a less satisfactory grouping. However, in the size-structured model described later, the size transition matrices in Region 5 (as defined for the analysis of the tagging data) were applied to all regions south of 31° (*i.e.*, Lancelin and Fremantle regions), and the transition matrices in Region 4 (as defined here) were applied to the region between 30°S and 31°S (*i.e.*, Jurien region).

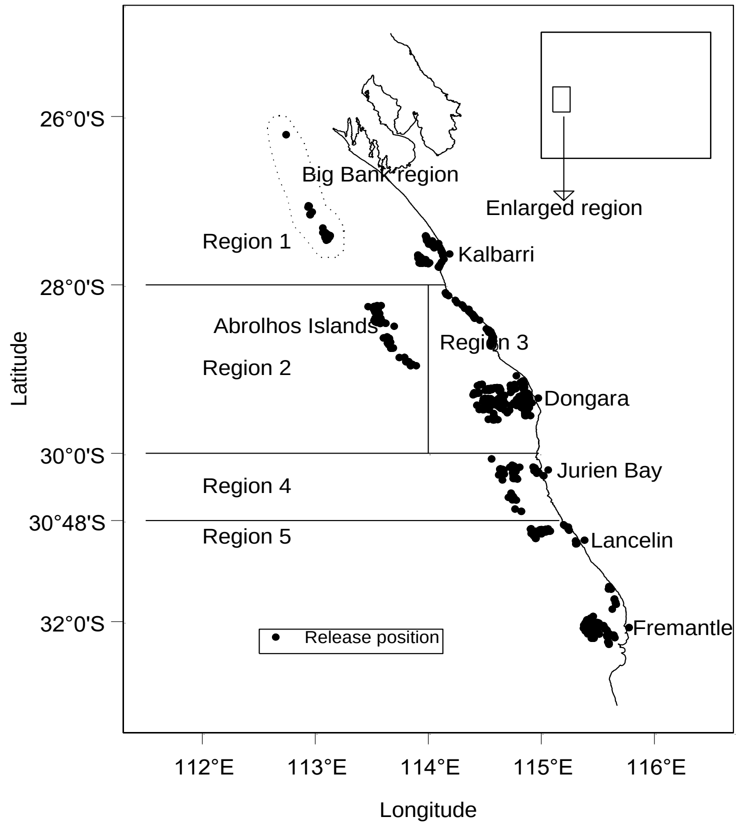


Figure 1. Location of regions and location of release of tagged western rock lobsters.

Most lobsters do not move far between release and recapture (Chubb, unpublished data). The regional identity of tagged lobsters was therefore taken as the location of release (*i.e.*, loc_{rel}).

Table 1 The number of recaptured lobsters used in this study for each region and each sex according to the above specification.

	Region 1 (Kalbarri)	Region 2 (Abrolhos)	Region 3 (Dongara)	Region 4 (Jurien)	Region 5 (Fremantle)
Male	676	847	1092	812	802
Female	1420	1635	3038	1599	1416

4.1.3 Log-likelihood

In this section the log-likelihood functions have been specified for two cases. For the first case, it was assumed that probability of recapture is independent of length, that is, selectivity is uniform. For the second case, the probability of recapture was assumed to be related to length, that is, selectivity is not uniform and is associated with the escape gaps fitted to the fishing pots.

(I) *Uniform selectivity*

The likelihood function for a given region and sex is defined below by assuming uniform selectivity. For convenience of description, denote $t_{rel} = day_{rel} / month_{rel} / year_{rel}$, similarly, $t_{rec} = day_{rec} / month_{rec} / year_{rec}$, where explicit date information (*i.e.*, day/month/year) is expressed in the release and recapture dates t_{rel} and t_{rec}.

For a specified tagged lobster with date at release t_{rel}, date at recapture t_{rec}, length at release ℓ_{rel}, and length at recapture ℓ_{rec}, the likelihood or the probability of this lobster growing from the size-class of ℓ_{rel} to the size-class of ℓ_{rec} within the time period from t_{rel} to t_{rec} is defined as follows:

Eq. 4.8 $$[\mathbf{P}_{T_M}\mathbf{P}_{T_{M-1}}\mathbf{P}_{T_{M-2}}\cdots\mathbf{P}_{T_1}]_{j,i},$$

which is the (j,i)-th element of the product matrix $\mathbf{P}_{T_M}\mathbf{P}_{T_{M-1}}\mathbf{P}_{T_{M-2}}\cdots\mathbf{P}_{T_1}$, where $i = \text{int}((\ell_{rel} - \ell_{\min})/d)+1$, $j = \text{int}((\ell_{rec} - \ell_{\min})/d)+1$, $\ell_{\min}$ is the minimum length considered, *d* is the size class step, and $\text{int}(\cdot)$ is a function that returns the integer part of a real number. In the present study, it was considered that $\ell_{\min}$ =60 mm and *d*=1 mm. The integer *M* and T_n, $n = 1,2,\cdots,M$ in Eq. 4.8 are defined as follows:

1) $$M^* = 12\left(year_{rec} - year_{rel}\right) + month_{rec} - month_{rel}$$

2) $$M = \begin{cases} M^* & \text{if } day_{rel} < 16 \text{ and } day_{rec} < 16 \\ M^*+1 & \text{if } day_{rel} < 16 \text{ and } day_{rec} \geq 16 \\ M^*-1 & \text{if } day_{rel} \geq 16 \text{ and } day_{rec} < 16 \\ M^* & \text{if } day_{rel} \geq 16 \text{ and } day_{rec} \geq 16 \end{cases}$$

3) $$T_1 = \begin{cases} month_{rel} \bmod 12 & \text{if } day_{rel} < 16 \\ \left(month_{rel}+1\right) \bmod 12 & \text{if } day_{rel} \geq 16 \end{cases}$$

4) $$T_n = \left(T_{n-1}+1\right) \bmod 12 \quad \text{for } n = 2,3,\ldots,M,$$

where the month is counted if the lobster is at liberty within the month for at least 16 days(*i.e.*, at least half of a month).

Eq. 4.8 is for one lobster only. The full likelihood is obtained as the product of the likelihoods for all selected (recaptured) lobsters of the given sex within the region, that is,

Eq. 4.9 $$\prod_n L_n ,$$

where *n* refers to the *n*-th lobster, and L_n is the likelihood of the *n*-th recaptured lobster defined by Eq. 4.8.

As usual, the log-likelihood

Eq. 4.10 $$L = \sum_n \log(L_n) ,$$

is used to be maximised instead of the likelihood, to estimate the unknown parameters of the process.

(II) *Non-uniform selectivity*

The above likelihood was derived by assuming uniform selectivity for recapturing a lobster within any size-class. In practice the fishing pots are required to be fitted with escape gaps to allow escape of lobsters with lengths below the minimum legal size (Bowen, 1963; Morgan, 1977). This results in a probability of capture that is dependent on length. In order that bias associated with the non-uniform selectivity is avoided, the formula for calculation of the log likelihood must allow for length selectivity.

In this study, the selectivity function was assumed to be a logistic curve of the following form:

Eq. 4.11 $$S_i = 1/(1+e^{-a\ell(i)+b}), \quad a>0, b>0 ,$$

where S_i represents the selectivity for the lobsters within the size class *i*, $\ell(i)$ is the mid-length of the size-class *i*, *a* and *b* are two positive parameters. It was assumed that the selectivity curve is known, and is derived by letting $S_{76} = 0.95$(approx.) and $S_{60} = 0.005$(approx.) (Brown and Caputi, 1986). Based on this, the values of *a* and *b* can be solved from Eq. 4.11 and the result is: *a*=0.379 mm^{-1} and *b*=25.7.

Denote $\mathbf{S} = [S_1, S_2, \cdots, S_N]^\tau$ (*N* is the number of size-classes considered) the vector of selectivity, where $^\tau$ means transpose of a vector. Then the likelihood in Eq. 4.10 can be modified by considering the above selectivity. Firstly, the likelihood for a single lobster in Eq. 4.8 can be modified as follows:

Eq. 4.12 $$[\mathbf{P}_{\mathbf{T_M}}\mathbf{P}_{\mathbf{T_{M-1}}}\mathbf{P}_{\mathbf{T_{M-2}}}\cdots\mathbf{P}_{\mathbf{T_1}}]_{j,i} S_j /([\mathbf{P}_{\mathbf{T_M}}\mathbf{P}_{\mathbf{T_{M-1}}}\mathbf{P}_{\mathbf{T_{M-2}}}\cdots\mathbf{P}_{\mathbf{T_1}}]_i \cdot \mathbf{S}^\tau) ,$$

where $[\mathbf{P}_{\mathbf{T_M}}\mathbf{P}_{\mathbf{T_{M-1}}}\mathbf{P}_{\mathbf{T_{M-2}}}\cdots\mathbf{P}_{\mathbf{T_1}}]_i$ represents the *i*-th column of the product matrix $\mathbf{P}_{\mathbf{T_M}}\mathbf{P}_{\mathbf{T_{M-1}}}\mathbf{P}_{\mathbf{T_{M-2}}}\cdots\mathbf{P}_{\mathbf{T_1}}$, which consists of all probabilities associated with growing from size-class *i* to the others during the time period from t_{rel} to t_{rec}. See Eq. 4.8 for the meaning of other items in Eq. 4.12.

Next the full log-likelihood L can be obtained by

Eq. 4.13 $$L = \sum_n \log(L_n),$$

where L_n is defined by Eq. 4.12 for a single lobster.

The log-likelihood defined by Eq. 4.13, *i.e.*, considering non-uniform selectivity, was used in the study below.

4.1.4 Estimation of growth transition matrices

Having defined the log-likelihood function (Eq. 4.13), then the size transition matrices for the months in which recapture data were available were estimated by maximising the log-likelihood. For the coastal regions, these months are from October to December and from January to June. For the Abrolhos Islands, where the fishery is closed from July to February, recaptures for the closed months are available only from research studies or from records of those lobsters that have migrated beyond the Abrolhos Islands management zone to the north coastal management zone. Although the data are limited, the analysis for the Abrolhos Islands region have been conducted using the same months as for the coastal fishery.

Estimation of the size transition matrix is equivalent to estimating the parameters $\ell_\infty(T), \delta(T), \beta(T)$, T=1, 2, 3, 4, 5, 6, 10, 11, 12, (total 27 parameters) for males, and $\ell_{1\infty}(T), \delta_1(T), \ell_{2\infty}(T), \delta_2(T), \beta(T)$, T=1, 2, 3, 4, 5, 6, 10, 11, 12, (total 45 parameters) for females, where $\ell_{1\infty}(T), \delta_1(T)$ are the growth parameters for immature females and $\ell_{2\infty}(T), \delta_2(T)$ for mature females, by maximising the log-likelihood in Eq. 4.13, and where T=1, 2, 3, 4, 5, 6, 10, 11, 12 represents the months from January to June and from October to December, respectively. It should be noted that recaptures in October were obtained during research studies, as the commercial fishery is closed during this month.

For those months without tagging data, that is, July, August and September in the coastal regions and July to February at the Abrolhos Islands, it was assumed that lobsters experience no growth during these months. Therefore the transition matrices for these months were assumed as identity matrices during the estimation of the log-likelihood. This is not an unreasonable assumption for the coastal regions as a major moult is not expected to occur over this period, however the assumption is unlikely to hold for the Abrolhos Islands region. Alternative assumptions will need to be considered for the lobsters in the Abrolhos Islands region in future studies.

For the females, a threshold value Lmat (see Eq. 4.7) is needed to identify when to use $\ell_{1\infty}(T), \delta_1(T)$ and when to use $\ell_{2\infty}(T), \delta_2(T)$ during the computations. In this study, Lmat was set as the length at which 50% of females are mature. Shown in **Table 2** are the values of Lmat for different regions according to Chubb (1991) and Chubb *et al*. (1994).

Table 2 Lmat in different regions

Region	1 (Kalbarri)	2 (Abrolhos)	3 (Dongara)	4 (Jurien)	5 (Fremantle)
Lmat (mm)	80	65	90	90	95

The problem of maximising the log-likelihood can be described as the following problem of optimisation subject to constraints:

For males: $\max\limits_{\ell_\infty,\delta,\beta} L = \min\limits_{\ell_\infty,\delta,\beta} (-L)$,

For females: $\max\limits_{\ell_{1\infty},\delta_1,\ell_{2\infty},\delta_2,\beta} L = \min\limits_{\ell_{1\infty},\delta_1,\ell_{2\infty},\delta_2,\beta} (-L)$,

subject to:

$\ell_\infty(T) > \ell_{\max}$ for each T, (for females, $\ell_{1\infty}(T) > \text{Lmat}$, $\ell_{2\infty}(T) > \ell_{\max}$);

$0 < \delta(T) < 1$ (for females, $0 < \delta_j(T) < 1$, j=1,2);

$\beta(T) > 0$,

where L is defined in Eq. 4.13, $\ell_{\max}$ is the maximum length considered, Lmat is given in **Table 2**. The reason for the above constraints is that the shape parameter of the gamma distribution determined by $\Delta\ell(i)/\beta$ must be positive.

Because the maximum sizes of lobsters seen differ considerably between fishing regions, a different value of $\ell_{\max}$ was used for each region and sex. The values of $\ell_{\max}$ (mm) used in this study are listed in **Table 3** (Fisheries Western Australia, unpublished data).

Table 3 $\ell_{\max}$ (mm) values for each region and sex

	Region 1 (Kalbarri)	Region 2 (Abrolhos)	Region 3 (Dongara)	Region 4 (Jurien)	Region 5 (Fremantle)
Male	130	110	130	150	140
Female	130	110	130	140	140

For the above optimisation problem, a routine in the IMSL FORTRAN Library called DBCONG was used, which minimises a general objective function subject to simple bounds with finite-difference gradient.

Depending on the number of lobsters used in the calculation and the precision required, the above computation generally required around 10 hours to converge using a computer with a Pentium I, 200 MHz CPU.

4.1.5 Estimation of length frequency

When the transition matrix for each month had been calculated, the length frequency of all lobsters at recapture could be predicted.

For a given tagged lobster, the product matrix $\mathbf{P}_{T_M}\mathbf{P}_{T_{M-1}}\mathbf{P}_{T_{M-2}}\cdots\mathbf{P}_{T_1}$ has been defined by Eq. 4.8. Let $\mathbf{V} = (V(1), V(2), \cdots, V(N))^{\tau}$ be the vector consisting of the *i*-th column of this product matrix, and *i* be the size class of the lobster at release (see the description below the Eq. 4.8, where *i* is defined). This $\mathbf{V}$ is actually a vector of the probabilities of the recapture length of the considered lobster lying within the various size classes at the time when it was recaptured.

Let $\mathbf{W} = (V(1)S_1, V(2)S_2, \cdots, V(N)S_N) / \sum_{i=1}^{N} V(i)S_i$, which incorporates the selectivity of capture, where S_i ($i=1,2,...,N$) defined in Eq. 4.11 is the selectivity for the lobsters in size-class *i*. Then the expected length frequency of recaptured lobsters can be estimated by summing $\mathbf{W}$ for all selected tagged lobsters, *i.e.*, $\sum_n \mathbf{W}_n$, where $\mathbf{W}_n$ is the vector defined above for the *n*-th lobster. If $\mathbf{U}$ is denoted as $\sum_n \mathbf{W}_n$, *i.e.*, $\mathbf{U} = \sum_n \mathbf{W}_n$, then for any size-class ℓ, the expected frequency can be predicted by $U(\ell)$, *i.e.*, the ℓ-th element of $\mathbf{U}$. It should be noted that this length frequency is the result of recaptures from lobsters of different sizes for different periods at liberty.

4.1.6 Estimation of size-increment frequency

The frequency of size-increments between release and recapture was also predicted from the estimated transition matrices in a similar way to that shown above. For a given tagged lobster, the vector $\mathbf{W}$ and the integer *i* were defined in the above section. A new vector can then be formulated as $\mathbf{X} = (W(i), W(i+1), \cdots, W(N), 0, \cdots, 0)$, where $W(i)$ is the *i*-th element of $\mathbf{W}$, and *N* is the number of length classes considered. The dimension of $\mathbf{X}$ is *N*. $\mathbf{X}$ is the vector consisting of the probabilities of the considered lobster in size class *i* at release with all size increments (*i.e.*, 0 mm, 1 mm,…, (*N*-*i*) mm) at recapture.

As with the calculation of expected length frequency, the size-increment frequency can be determined by summing $\mathbf{X}$ for all selected tagged lobsters. Let $\mathbf{Y} = \sum_n \mathbf{X}_n$, where $\mathbf{X}_n$ is the vector defined above for the *n*-th lobster. Then for any size increment ℓ, its frequency can be predicted by $Y(\ell)$, where $Y(\ell)$ is the ℓ-th element of $\mathbf{Y}$. Again, the resulting frequency distribution represents the length increments of lobsters of different release lengths over different periods at liberty.

4.1.7 Estimation of mean size increment

Based on the estimated values of parameters obtained by maximising the log-likelihood, the mean-size increment was estimated for the lobsters in each month and in each size-class using the formula in Eq. 4.6 for male lobsters or the formula in Eq. 4.7 for female lobsters.

4.1.8 Estimation of size-increment distribution

Having estimated mean-size increments, it was necessary to look at the distribution of size-increments for individuals. For a given initial size class and a given month, it was important to know how many or what proportion of lobsters within this initial size class had 0 mm, 1 mm, 2 mm, etc., size increments, respectively. Note that a 0 mm size increment means that the animals did not change size-class during the month, a 1 mm size increment means that the animals grew to a 1 mm larger size class than their initial size class, and similarly for 2 mm and larger size increments.

To estimate the distribution of size increments for individuals, it was necessary to examine the elements of the transition matrices. From the definition of the transition matrix, a (j,i)-th element of the matrix represents the probability of lobsters growing to size class j from size class i, which is equivalent to the probability of lobsters initially within size class i having a j-i mm size increment.

Based on information available, moult increments for the species are generally around 4mm but up to 7mm for males and immature females (Melville-Smith *et al.*, 1997). It should therefore be sufficient to look at size increments from 0mm to 7mm as increments larger than this size are rare. With this in mind, the relevant elements in each transition matrix are $P(i,i), P(i+1,i), P(i+2,i), \cdots, P(i+7,i)$, (see Section 4.1.1 for the definition of these elements). All these elements are dependent on month for a given region and sex.

Rather than examining $P(j,i)$, this study examined $100\,P(j,i)$, *i.e.*, the percentage of lobsters initially within size class i having j-i mm size increment during the month under investigation.

4.2 Size-structured modelling

Size-structured stock assessment models have been developed (e.g., Schnute, 1987; Sullivan *et al*., 1990) and applied to invertebrates (e.g., Bergh and Johnston, 1992; Johnston and Bergh, 1993; Zheng *et al*., 1995; Punt and Kennedy 1997). These models explicitly present the information about the variation of individuals' growth. The fundamental concept is a description of growth from one size-class to another instead of from one specific size to another. The state variable in these models is a vector which contains the numbers of animals in the various size classes. A set of probabilities of animals growing between size classes during the time step of the model, *i.e.*, a growth transition matrix, is a key input to these size structured models.

In this study a size-structured model was developed for the western rock lobster fishery. The state of the model was represented as the numbers of rock lobsters of each sex within each 1 mm length class, at each time step (month) and within each region. Five fishing regions were considered, which were four coastal regions (Dongara, Jurien, Lancelin, and Fremantle), and one offshore region (the Abrolhos Islands). This size-structured model extended the earlier model by Walters *et al*. (1993), which was a spatio-temporal model developed to examine the effectiveness of the regulatory system in preventing overfishing in the face of increasing exploitation. That model led to the introduction of significant changes to the management of the fishery in order to rebuild the breeding stock.

The growth information, represented as a growth transition matrix and input to the size-structured model developed in this study, was determined from tagging data separately, as discussed in the sections above.

4.2.1 Biological model

For a given fishing region and a given sex, the population dynamics model is described by:

Eq. 4.14 $$N_{t+1}(l) = \left[\sum_{k=1}^{l} X_t(l,k) N_t(k) + R_t(l) - \hat{C}_t(l) \right] e^{-M_t},$$

where the time step is one month;

- $N_t(l)$ represents the number of lobsters in size-class *l* at the beginning of time *t*;
- $X_t(l,k)$ is the fraction of lobsters in size-class *k* which grow into size-class *l* during the time *t* (*i.e.*, *growth transition matrix*);
- $R_t(l)$ is the recruitment into size class *l* at the beginning of time *t*. It was assumed that the recruitment is uniformly distributed over the smallest 4 size classes considered in the model, *i.e.*, 60 mm, 61 mm, 62 mm, and 63 mm, and $R_t(l)$=0 if *l* > 63 mm.
- $\hat{C}_t(l)$ represents the estimated number of lobsters in size-class *l* caught during the time *t*.;
- M_t represents the rate of natural mortality of lobsters during the time *t*.

Two levels of natural mortality were used. During the “whites” season from November to January, many of the lobsters are in a migratory phase and are exposed to a higher level of natural mortality than that experienced during the “reds” and the closed seasons. The natural mortality in the “whites” season was assumed higher than that in the “reds” and the closed seasons, from February to June. The natural mortality in the closed season (July-October) was assumed to be the same as that which is experienced in the “reds” season.

Two approaches were applied when estimating the model parameters. Firstly, the model was 'conditioned on catch' by assuming that the recorded total catch for the time step (*i.e.*, month in this study) was accurate and distributed over the length-classes appropriately given the number of lobsters in each length-class and the vulnerability of the lobsters in that length class. Alternatively, the model was 'conditioned on effort' by assuming that the recorded total fishing effort for the time step was accurate then calculating the catch for each length-class from the resulting fishing mortality associated with that effort.

4.2.2 Data specification

Length-monitoring data (*i.e.*, catch by size, month, sex, region, and category for females: non-setose, setose, spawner (ovigerous), and tar-spotted (bearing a spermatophore)) and monthly fishing effort data were used to estimate the model parameters.

(I) *Definition of regions and zones*

The western rock lobster fishery was divided into regions within which the biological characteristics were likely to be similar, and for which the same management regulations applied. Five fishing regions were considered in this study, which are the *Abrolhos Islands region*, *Dongara region* (north of 30°S), *Jurien region* (from 30°S to 31°S), *Lancelin region* (from 31°S to 32°S) and *Fremantle region* (south of 32°S) (**Figure 1**). Note that these regions are slightly different from those considered in the estimation of the growth transition matrices (Section 4.1.2), which were determined by the locations in which tagging was undertaken.

For management purposes, the western rock lobster fishery was also divided into three management zones, which are Zone A, Zone B and Zone C. The *Abrolhos Islands region* forms *Zone A*, the *Dongara region* (north of 30°S) forms *Zone B*, and the other three regions, *i.e.*, *Jurien region* (from 30°S to 31°S), *Lancelin region* (from 31°S to 32°S) and *Fremantle region* (south of 32°S) form *Zone C*. The results by management zone were also investigated when exploring the management strategies.

(II) *Monthly catch data by length, sex and region*

Length frequency data for the fishery were obtained from a research programme initiated in 1972. Monthly samples (of approximately 300 lobsters) of the catches made on the commercial fishing vessels within each of four depth categories (0-18, 18-37, 37-55, over 55 m) were measured at each of the locations, Dongara, Jurien Bay, Lancelin, and Fremantle (**Figure 1**). A single sample of the catch taken at the commencement of the Abrolhos Islands season has been measured since 1985. These data were weighted up and combined to form an estimate of the size composition of the total commercial catch taken from the fishery. The weighting given to each sample was calculated as the ratio of the monthly commercial catch in the depth zone (for the fishing region assumed to be represented by the sample) to the weight of rock lobsters in the sample that could be retained and marketed by fishers (*i.e*., excluding rock lobsters that could be released under regulations prohibiting landing of lobsters with carapace lengths falling outside the legal size range, egg-bearing females, or females with visible setae).

These data were available from the 1972/73 season to the 1998/99 season for the coastal regions (*i.e.*, locations (Dongara, Jurien Bay, Lancelin, and Fremantle), while for the Abrolhos Islands region, the data were available from 1985/86 to 1998/99.

(III) *Monthly effort data by region*

Fishers have a legal obligation to provide detailed estimates of monthly catches, applied fishing effort, and the location of these catches to Fisheries Western Australia, the government agency which is responsible for the management of the rock lobster fishery. Rock lobster processors also are required to provide monthly details of actual landings of rock lobsters which they receive. Together these two sets of data provided estimates of the total commercial catch of rock lobsters made within Western Australia. The catch and effort data contained within these datasets were analysed to produce a table of monthly catch, fishing effort, and catch per unit of fishing effort (CPUE) by 1^{o} fishing block, or by fishing region. Catches are measured in kilogram, and fishing effort is recorded as the number of pot lifts, that is, the number of occasions on which the pot used to catch lobsters has been set and lifted. The majority of pots are set for 1 to 2 days, and the effect of soak time on pot efficiency was ignored for this study.

The monthly data were available from the 1964/65 fishing season up to 1998/99 season, while annual data were recorded back to the 1944/45 fishing season. Details of the spatial or regional distribution of catch and effort for the fishing seasons prior to 1964/65 were not available; therefore, these earlier data were excluded from the analysis.

(IV) *Annual puerulus settlement indices by region*

Since 1968, the numbers of puerulus settling on artificial seaweed collectors (Phillips, 1972) during each month have been measured at each of a number of sites along the south western coast of Western Australia. The number of sites has increased since the study began, and now covers 9 locations. Predictions of future recruitment to the fishery based on the average number of puerulus per collector settling during each year, used as an index of the abundance of puerulus for that year, have proven to be very reliable (Caputi *et al*., 1995b). The puerulus settlement indices for collection sites located within each region used in this study were used as measures of puerulus settlement for the region. These data were used in a mathematical relationship within the model to estimate the subsequent recruitment to the smallest length classes considered in the model which are 60-63 mm (carapace length). This recruitment is expected 2 or 3 years following the settlement of the pueruli.

The latest season for which puerulus data were available for use within this study was 1998/99. While puerulus settlement data were available from 1968/69 to 1998/99, the data for some regions were only available for a subset of the period. For the regions and fishing seasons where puerulus data were not available, estimates of the missing puerulus data were determined from the observed catches using a local linear model fitted to the puerulus and catch data for the region.

(V) *Missing monthly catch data by length, sex and region in early years*

Because monthly catch and effort data by region only became available from 1964/65, it was decided in this study to run the model from 1964/65 rather than 1944/45, the fishing season when catch and effort data for the total fishery first became available.

As mentioned above, the length-frequency data were only available since 1972/73 for coastal regions and since 1985/86 for Abrolhos Islands region. As a result, the length-frequency data between 1964/65 and 1971/72 for coastal regions and between 1964/65 and 1984/85 for Abrolhos Islands region that were required to run the model in those years were missing. These missing data were interpolated using the monthly catch and effort data in these years as well as the average length frequency in earliest available 5 years of length frequency data (that is 1972/73-1976/77 for coastal regions and 1985/86-1989/90 for the Abrolhos Islands region). It was recognised that these five years would represent approximately four different years of puerulus settlement to the fishery, and thus, the resulting average would be less affected by years of good or bad puerulus settlement.

These interpolated data were only used to run the model and not to fit it. The data used for fitting the model were only the data in recent years (see Section 4.2.6). Consequently, the parameter estimates obtained when fitting the model should not have been affected greatly if the interpolated data were a slightly poor representation of the real length-frequency data for those missing years.

4.2.3 Model assumptions

The assumptions used when fitting the model to data are presented below. Basically these assumptions are related to the parameters in the model that are assumed known or the method by which other parameters are estimated.

(i) *Monthly growth transition matrices* X_t (*t* is the month from January to December) were assumed known in the model for each sex and for each region. These matrices were estimated independently based on tagging data as described in Section 4.1.

(ii) *Natural mortality* M_t, which represents the rate of natural mortality of lobsters during the time *t*, were assumed known. A time dependent natural mortality was used because of significantly different natural mortalities expected during the "whites" fishing season (November-January) while lobsters are migrating and vulnerable and the "reds" season (February-June). It was considered from biological observations that the natural mortality in the "whites" season would be higher than that in the "reds" season. In this modelling study, natural mortalities were assumed as M_t =0.025 month^{-1} when t =November, December and January (*i.e.*, the "whites" season) for each region, and M_t =0.0125 month^{-1} when t from February to October(*i.e.*, the "reds" and the closed seasons) for the southern regions of Lancelin and Fremantle, and M_t =0.0167 month^{-1} in the "reds" and closed seasons for the other regions, *i.e.*, the Abrolhos Islands, Dongara and Jurien. These values were estimated based on the estimated annual natural mortality of western rock lobster given by Morgan (1977), which is 0.226 year^{-1} or 0.0188 month^{-1} regardless of the "whites" and the "reds" seasons. We found that the goodness of model fitting to data was generally not sensitive to the above assumed values of natural mortality, but the estimated values of model parameters might be sensitive to those values.

(iii) *monthly recruitment* $R_t(l)$. Recruitment was assumed to enter the fishery only into the smallest four size-classes considered in the model, *i.e.*, from 60 mm to 63 mm, and $R_t(l)$ =0 if l>63 mm for any t. The reason that four size classes were considered was that the average moult increment is around 4mm (Melville-Smith *et al.*, 1997), that is, new recruits can be distributed over a 4 mm length range when they enter the fishery. A uniform distribution of recruits within the smallest 4 size classes was assumed in the model. To estimate the month-dependent recruitment, annual recruitment was estimated at first and then projected to each month based on an assumption regarding the relative monthly distribution of recruits. The estimation of annual recruitment is discussed in Section 4.2.4. An assumption on the monthly distribution of recruits was made based on the moulting periods identified from biological observations (Morgan, 1977), that is, 50% of the lobsters recruited in November and the remainder recruited in February. However, other monthly distributions of recruits were also tested, for example, 40% of the recruits in November, and 20% of the recruits in each of February, May and August, respectively (this distribution was used by Walters *et al*. (1993)). The modelling results were not sensitive to the assumptions on the monthly distribution of annual recruits that were tested.

(iv) *selectivity* S_l by pot, which is physically determined by the number of escape gaps included in the pot structure and the neck sizes of the entrances to those pots. It was assumed that the dependence of selectivity S_l on size l follows a logistic curve, that is, $S_l = 1/(1+e^{-al+b})$, where a and b are two parameters which were assumed known, as described in Section 4.1.3 (see Eq. 4.11). The selectivity curve was used in the estimation of the catch from the model.

4.2.4 Estimation of annual recruitment

In this study, two approaches for the estimation of annual recruitment were used and compared. One approach was to treat each year's recruitment as a parameter to be estimated (this approach was adopted in Punt and Kennedy (1997)), and the other was to estimate each year's recruitment based on earlier years' puerulus settlement indices. With the latter approach, several mathematical relationships between recruitment and puerulus indices were tested, including the relationship identified by Caputi *et al*. (1995b) in prediction of the catch from the puerulus indices at earlier years. It was found that the relationship which gave the best model fit to the data was a linear relationship (without a constant term) between recruitment and the puerulus indices from two, three and four years earlier. Note that no stock-recruitment relationship was used in the model.

(I) ***Approach one***: taking the recruitment in each year as a parameter.

It was assumed recruitment before the 1970/71 season was constant. Since 1970/71, a parameter representing the annual recruitment was estimated for each fishing season, that is, $R_{1970}, R_{1971}, \cdots, R_{1998}$, a total of 29 parameters.

Note that the model was fitted to the data from the 1980/81 season to the 1998/99 season, where 1998/99 data were the most recent available in this study. The constant recruitment before 1970 was estimated by using the average value of later years' recruitments, *i.e.*, $\sum_{i=1970}^{1998} R_i / 29$.

The reasons for assuming constant recruitment before 1970/71 were (1) to reduce the number of parameters, (2) there are no length-frequency data available before 1970/71, and (3) this assumption had little impact on the fit of the model to the data given that we only fitted the model to those data since the 1980/81 fishing season.

(II) ***Approach two***: using the relationship between puerulus settlement indices and subsequent recruitment.

Different relationships and different combinations of earlier years were tested during this study. Some of the mathematical relationships that were tested were:

(i) $R_t = a(P_{t-2} + P_{t-3})^b$,

(ii) $R_t = aP_{t-2}^b P_{t-3}^c$,

(iii) $R_t = aP_{t-2} + bP_{t-3}$,

(iv) $R_t = aP_{t-2} + bP_{t-3} + c$,

(v) $R_t = aP_{t-2} + bP_{t-3} + cP_{t-4} + d$,

(vi) $R_t = aP_{t-2} + bP_{t-3} + cP_{t-4}$,

where P_t is puerulus settlement index at the year/season *t*, R_t is the recruitment to the 60 mm CL size class at the year/season *t*, and *a,b,c* and *d* are the parameters. It should be noted that relationships (iii)-(vi) assume no density dependent mortality, although such mortality is believed to occur between settlement of pueruli and subsequent recruitment to the fishery.

Other combinations of earlier years' puerulus indices were also tested. It was found that the linear relationship with the puerulus indices of three earlier years, *i.e.*, relationship (vi) gave the best fit of the model to data. Therefore in this study relationship (vi) was used to estimate the recruitment, where *a,b* and *c* are parameters to be estimated.

The initial puerulus settlement index (*i.e.*, before fishing started) was estimated by using the mean of the available later years' puerulus settlement indices.

The first method, *approach one,* provided a better model fit than the second, *approach two*, but contains more parameters and has no ability to predict future recruitment levels. However, future recruitment levels could be predicted using *approach two* when puerulus settlement indices become available from the fishery and if the relationship identified between the puerulus indices and the recruitment provides a reasonable representation of the true relationship.

4.2.5 Estimation of initial population

An initial population by size class was required as the beginning population to input to the model to enable iteration over each time step. In this study, we estimated the initial population by assuming that (1) the population was in an unfished equilibrium and (2) there was no fishing before the first fishing season (*i.e.*, 1964/65) considered within the model. It was assumed that the model commences running at the start of the 1964/65 fishing season because the data required by the model are only available since then (Section 4.2.2).

Let the catch, *i.e.*, $\hat{C}_t(l)$ in the model, be equal to zero. The model was then iterated over 100 years starting with an arbitrary population. During each annual iteration of the model, the recruitment in each year was assumed constant. When using *approach one* to estimate the recruitment, the recruitment before fishing was estimated by the mean of the later years' recruitments. When using *approach two,* the puerulus settlement index before fishing was estimated by the mean of the later years' puerulus indices. The resulting population after the 100 years' iterations of the model was then considered as the initial population of the model.

4.2.6 Fitting the model to data

Tuning the model to the data usually involves two steps: (1) defining an objective function; (2) estimating the model parameters through optimising (either maximising or minimising) the objective function to achieve the best fit of the model to the observed data within the capacity of the optimisation technique employed. These two steps are described below.

4.2.6.1 Objective function

The objective function is a function associated with the errors between the model outputs and the actual observations. The output variable selected for use in this study was catch-per-unit-effort (CPUE), that is, CPUE was estimated from the model.

To estimate CPUE one could either assume the catch is known, *i.e.*, the model is conditioned on catch; or the effort is known, *i.e.*, model is conditioned on effort. Both cases were explored in this study.

The distribution of the errors is a key element to define the objective function. Different assumptions regarding the distributions of errors lead to different definitions of the likelihood functions, *i.e.*, the objective functions. The distribution of errors is usually assumed normal. In the case of the normal distribution, the likelihood function is equivalent to the objective function of the sum of squares. In this study, a function of sum of squared errors was used as the objective function. Detailed mathematical formulae will be given in the following two sections. The adequacy of the assumption of the normal distribution of errors was verified by constructing a Q-Q plot of the residuals between the model outputs and the observations.

4.2.6.1.1 Model conditioned on catch

In this approach, it was assumed that the total number of legal lobsters caught at each time step was known. The model then estimated the size distribution of the catch (*i.e.*, the number of legal lobsters caught at each length-class) and the fishing effort (number of pot lifts) at each time step. Below are the mathematical formulae used for the estimation.

First, the harvest rate H at each time step can be estimated as below:

Eq. 4.15
$$\hat{H}_t = \frac{\sum_l C_t(l)}{\sum_l \nu(t,l) N_t(l)} ,$$

where the numerator is the total number of legal lobsters caught at the time t, which was assumed known (note that, only the total number, *i.e.*, $\sum_l C_t(l)$ was assumed known and the catch in each size class, *i.e.*, $C_t(l)$ was assumed unknown); the denominator is the total number of vulnerable lobsters in the sea at the time t, which was estimated from the total population $N_t(l)$ (see Eq. 4.14) in each size class l calculated from the model multiplied by the vulnerability coefficient $\nu(t,l)$ for the size class.

The vulnerability coefficient is determined by the management regulations that are applied during the fishing season, the selectivity, and the vulnerability curve which is dependent on length. Based on the current management regulations for the western rock lobster fishery, vulnerability for under-size lobsters (*i.e.*, their sizes below the legal size) and protected females (*i.e.*, maximum size regulation and protection of setose, spawner and tar-spotted) must be released if they are caught. Therefore, the vulnerability coefficient for these lobsters was set to zero. For the other lobsters, it was assumed that the vulnerability coefficient equals the selectivity (determined by escape gap(s) and neck size of the pots) multiplied by the relative vulnerability curve, that is, Eq. 4.16 $$v(t,l) = S_l \upsilon(t,l) ,$$

where S_l is the selectivity which was defined in Eq. 4.11 in Section 4.1.3; $\upsilon(t,l)$ is the relative vulnerability for lobsters in size class *l* compared with that of lobsters at smaller size classes, that is, $\upsilon(t,l)$=1 for smaller *l* (details below).

Relative vulnerability $\upsilon(t,l)$ was assumed to be month and size dependent, but it was assumed that the vulnerability is dependent on size only in the peak fishing months, *i.e.*, November to January and March to April; and in other months, vulnerability was assumed to be same for all size classes, *i.e.*, $\upsilon(t,l)$=1 for any *l*. For those peak fishing months, the curve $\upsilon(t,l)$ was assumed as follows:

Eq. 4.17 $$\upsilon(t,l) = \begin{cases} 1 & \text{if } l \le 84\text{mm;} \\ k_1 l + k_2 & \text{if } 84\text{mm} < l < 91\text{mm;} \\ \vartheta(t) & \text{if } l \ge 91\text{mm,} \end{cases}$$

where $k_1 = (1 - \vartheta(t))/(84 - 91)$, $k_2 = 1 - 84k_1$, and $\vartheta(t)$ is a parameter dependent on *t*, *t* is the month from November to January and March to April. Basically here we assumed that the vulnerability linearly decreases with size. In future modelling, this assumption may need to be revisited, as it might be expected that, on average, larger lobsters might be less vulnerable in all months.

When the harvest rate was estimated in Eq. 4.15, fishing effort was then estimated by:

Eq. 4.18 $$\hat{E}_t = -\frac{1}{q_t}\ln(1 - \hat{H}_t) ,$$

where $\hat{E}_t$ is the estimated fishing effort (number of pot lifts) and q_t is the catchability at the time *t*, which is a parameter to be estimated. The above formula was derived from the relationship $\hat{H}_t = (1 - e^{-q_t \hat{E}_t})$.

Catch by size class was estimated by:

Eq. 4.19 $$\hat{C}_t(l) = \hat{H}_t v(t,l) N_t(l) ,$$

where $N_t(l)$ is the number of lobsters in size class *l* at the time *t* in the sea estimated from the model, see Eq. 4.14. Then, the *CPUE* could be estimated by dividing the estimated catch by the estimated effort, *i.e.,*

Eq. 4.20 $$CP\hat{U}E_t(l) = \hat{C}_t(l) / \hat{E}_t .$$

We now defined the objective function as follows:

Eq. 4.21 $$f_C(P) = \sum\nolimits_{t,l} (CP\hat{U}E_t(l) - CPUE_t(l))^2$$

where *P* represents a set of model parameters to be estimated; and the observed *CPUE* is just the observed catch divided by the observed effort. Note that this objective function of the sum of squared errors was based on the assumption:

Eq. 4.22 $$CPUE_t(l) = CP\hat{U}E_t(l) + \varepsilon ,$$

where $\varepsilon \sim N(0,\sigma^2)$ (*i.e.*, normal distribution).

Remarks

(1) We also tried the following objective function besides Eq. 4.21,

$$f_C(P) = \sum_{t,l} (\ln(C\hat{PUE}_t(l) + z) - \ln(CPUE_t(l) + z))^2$$

where the distribution of errors was assumed log-normal, a constant positive z added to $CPUE$ and $CP\hat{U}E$ was to make the logarithm operation work because the observed $CPUE$ and estimated $CP\hat{U}E$ may be zero. It was found that the results were quite sensitive to the selected values of z. However, the results were not found better than the result obtained by Eq. 4.21.

(2) In Eq. 4.21, the sum was actually not over all months (t) since the fishing started and all sizes (l) by 1mm considered in the model. The actual time t and size l for the summation were specified as follows: (I) only those t from November 1980 to June 1999 for the coastal regions and from November 1988 to June 1999 for the Abrolhos Islands region were considered in the sum; (II) the sizes l considered in the sum were: 1mm length classes used for the lobsters with C.L. between 76mm and 80mm, 5mm length classes used for the lobsters with C.L. between 81mm and 120mm, and a single size class for all lobsters with C.L. over 120mm. The reasons for choosing these t and l in the sum were: (i) the starting year of 1980 for the coastal regions and 1988 for the Abrolhos Islands region were chosen quite arbitrarily, but we considered that there were no observed length-frequency data before 1972 for the coastal regions and before 1985 for the Abrolhos Islands region, and there may be some difficulties in fitting the model to the data immediately after the year when the data first became available because the model may be in transient states when progressing from those years without length frequency data to the years with length frequency data; (ii) regarding the size classes considered in the sum, using 1mm between 76mm and 80mm had some considerations from management point of view because minimum legal size (currently 77 for whites season and 76 for reds season) may change up to 80mm; using 5mm between 81mm and 120mm was because it does not have much impact using 1mm or 5mm for these size classes from management point of view, while using 5mm did improve the model fitting to data significantly; similarly consideration was for putting all lobsters over 120mm in a single size class.

4.2.6.1.2 Model conditioned on effort

In this section it was assumed that the fishing effort (number of pot lifts) at each time step was known. The model then estimated the number of lobsters by size class caught at each time step. Below is a set of the mathematical formulae for the estimation.

First, harvest rate H at each time step was estimated by:

Eq. 4.23 $$\hat{H}_t = 1 - e^{-q_t E_t},$$

where the fishing effort E_t at the time *t* was assumed known. Catch by size class was estimated by:

Eq. 4.24 $$\hat{C}_t(l) = \hat{H}_t v(t,l) N_t(l),$$

where *v* is defined as in
Eq. 4.16 and *N* is the estimated population from the model (Eq. 4.14). Thus, the estimated *CPUE* is the estimated catch divided by the observed effort, *i.e.*,

Eq. 4.25 $$CP\hat{U}E_t(l) = \hat{C}_t(l) / E_t.$$

We then defined the objective function as follows:

Eq. 4.26 $$f_E(P) = \sum_{t,l} (CP\hat{U}E_t(l) - CPUE_t(l))^2,$$

where a normal distribution of errors was assumed as defined in Eq. 4.22.

Remarks

Here the same remarks apply as were made in Section 4.2.6.1.1.

4.2.7 Model parameters

In this section, a summary is provided of the model parameters, which were estimated by fitting the model to data.

(I) Monthly catchability

A number of monthly catchability parameters were used in the estimation of the model output variable, *i.e.*, CPUE, see Section 4.2.6.1. There are a total of eight monthly catchabilities, which are q_t, *t*=11, 12, 1, 2, 3, 4, 5, 6 (*i.e.*, from November to June) for the coastal regions and four catchabilities for *t*=3, 4, 5, 6 (*i.e.*, from March to June) for the Abrolhos Islands region. These catchabilities were the parameters estimated from the fitting procedure.

(II) Relative vulnerability

The relative vulnerability curve was assumed as in Eq. 4.17, where there was a parameter $\vartheta(t)$ associated with estimation of the curve for each month *t*. $\vartheta(t)$ is the relative vulnerability for large lobsters (*i.e.*, C.L. > 90mm). Based on the assumption we made (see the text above Eq. 4.17), only $\vartheta(t)$ with *t* =11, 12, 1, 3, 4 (*i.e.*, from November to January and March to April) needed to be estimated. Therefore, there were total of 5 parameters required for the coastal regions and two parameters (*i.e.*, *t*=3, 4) for the Abrolhos Islands region.

(III) Parameters for estimation of annual recruitment

As discussed in Section 4.2.4, there were 29 parameters using the method of *approach one*, and 3 parameters using the method of *approach two*. These parameters were estimated when fitting the model to data.

In conclusion, there were a total of 42 model parameters when estimating recruitment using *approach one* for the coastal regions (35 parameters for the Abrolhos Islands region) and 16 parameters when using *approach two* for coastal regions (9 parameters for the Abrolhos Islands region).

4.2.8 Estimation of parameters

Based on the descriptions in the previous sections, the model could now be computed by starting with selected initial values of the parameters which were required to be estimated, as listed in Section 4.2.7. These initial values were chosen, based on the available biological information. Then the objective functions defined in Section 4.2.6.1 could be evaluated.

The method of *simulated annealing* was used to search for the optimal values of the parameters by minimising the objective functions. The FORTRAN computer code of the method used in this study, ‘simann.f’, was developed by Goffe *et al*.(1994), and can be downloaded from Internet: http://wuecon.wustl.edu/~goffe/.

4.2.9 Analysis of parameter uncertainty

No analysis on parameter uncertainty is presented in this report. However, uncertainty of parameters could be assessed based on the variance-covariance matrix estimated from the inverse of the Hessian matrix of the objective function at the optimal values of the parameters. However, as the simulated annealing method that we used does not output information concerning the gradient of the objective function, the Hessian matrix was estimated by second-order differencing. Some preliminary analyses on estimation of the Hessian matrix were undertaken during this study, but it was found that the estimated Hessian matrix was not positive-definite, making it difficult to calculate the inverse of the Hessian matrix. Because of the limited time available, the analysis of parameter uncertainty has not been completed up to writing of this report. However, this work is planned in the near future as the model is developed further.

4.3 Exploration of an alternative management strategy

To illustrate the application of the size-structured model in assessing the effect of proposed changes to the management of the fishery, the impact of the setose regulation within the 1993/94 management package was examined. In principle, the model has the capacity to explore a wide variety of other management strategies besides those introduced in the 1993/94 package, for example, a strategy based on closure of portions of the fishing season.

The model used to estimate the impact on catch and breeding stock or egg production was conditioned on effort and used the estimated recruitment resulting from recorded puerulus settlement indices at earlier years. The puerulus settlement indices that will produce the subsequent recruitment over the next three to four years have already been recorded. By estimating this recruitment from the relationship between recruitment and puerulus settlement indices, the information available within these puerulus settlement indices is applied to provide good estimates of the levels of recruitment that might be expected in the near future.

The four elements of the 1993/94 management package were:

(1) a minimum size of 77mm during the whites season (from November to January) for both male and female lobsters;
(2) protection of large non-setose female lobsters, *i.e.*, maximum legal size applied for females;
(3) protection of setose females (those with ovigerous setae); and
(4) 82% pot usage.

To simplify future references to the alternative management strategies within this study, we introduce the following terminology:.

(1) The management strategy represented by the package of regulations introduced in 1993/94, as described above, is termed the *'1993/94 strategy'* ;
(2) The management strategy that would have applied if the regulations were those that applied in the 1991/92 fishing season is termed the *'original strategy'* ;
(3) The management strategy if only the setose element of the 1993/94 strategy had been applied is termed the *'setose strategy'*.

As indicated above, the regulation to protect of setose females was an element in the 1993/94 management strategy, *i.e*., setose females were not allowed to be retained by fishers and were required to be returned to the sea. We tested the impact of this element (*i.e*., retaining this element only and dropping the other three elements) on catch and egg production as above and compared the results with those obtained with the 1993/94 strategy and those obtained with the original strategy.

In order to examine the impact of these management elements, the method used for estimation of the annual egg production must be described.

4.3.1 Estimation of annual egg production

The annual egg production was estimated based on the relationship between fecundity and length, the relationship specifying the proportion of sexually mature females in each length class, and the relationship between the number of spawnings per mature female per year and length. These relationships were different for different fishing regions.

(I) **Relationship between fecundity and length** for all regions (Chubb *et al.*, 1989):

Eq. 4.27 $$fec(l) = 1.92 l^{2.69},$$

where *l* is the carapace length (mm), and *fec(l)* is the fecundity of lobsters with the size *l* (CL).

(II) **Relationship between proportion of spawners and length** (Chubb and Caputi, unpublished data):

Eq. 4.28

$$psp(l) = \begin{cases} 1/(1+e^{18.77-0.203l}), & \text{for Dongara, Jurien and Abrolhos regions;} \\ 1/(1+e^{57.09-0.987l+0.004l^2}), & \text{for Lancelin and Fremantle regions,} \end{cases}$$

where *l* is the carapace length (mm), and *psp(l)* is the proportion of female lobsters with the size *l* (CL) which are ovigerous or capable of breeding. As female lobsters at the Abrolhos Islands achieve maturity at a smaller size than those at Dongara and Jurien, an improved description of the relationship is required for the former region.

(III) **Relationship between the number of spawnings per mature female per year and length** (Chubb and Caputi, unpublished data):

Eq. 4.29

$$nsp(l) = \begin{cases} 1+1/(1+e^{4.075-0.0495l+0.484}), & \text{for Dongara, Jurien and Abrolhos regions;} \\ 1+1/(1+e^{4.075-0.0495l-0.484}), & \text{for Lancelin and Fremantle regions,} \end{cases}$$

where *l* is the carapace length (mm), and *nsp(l)* is the number of spawning times per year for lobsters with the size *l* (CL).

(IV) **Estimation of annual egg production:**

Eq. 4.30 $$\text{eggs} = \sum_{l=\text{MinL}}^{\text{MaxL}} N_1(l) \times nsp(l) \times psp(l) \times fec(l),$$

where *l* is the carapace length (mm), MaxL and MinL are the maximum and the minimum sizes considered in the model (*i.e.*, the size range in the model), respectively, $N_1(l)$ is the number of females in size class *l* at the end of January (it was assumed that most of female lobsters spawn in February although this is at the end of the spawning season and may result in a slight underestimate of egg production through mortality of spawning females), and $N_1(l)$ was estimated by the model (see Eq. 4.14).

Remark on pot usage:

An 82% pot usage was introduced in the 1993/94 package, and the recorded fishing effort reflects this reduction. It is possible that the efficiency of fishing effort may have increased with the reduction in pot usage, and that slightly reduced efficiency might result if full pot usage was again permitted. Rather than assuming a 21% increase in fishing effort if full pot usage was reintroduced, it was assumed that fishing effort would only increase by 18%. Therefore, when applying the option of full pot usage, we simply multiplied the actual fishing effort (*i.e.*, the observed fishing effort with 82% pot usage) by 118%, where 18% more fishing effort was assumed without the pot reduction than with the pot reduction. We were aware that this assumption may not be realistic as it assumes that the number of pot lifts will increase slightly with the increased pot quota, but it would not affect the test of the model's capability at this stage.

4.4 Economic analysis

The purpose of the economic component of the model was to enable the relative financial return associated with specific management strategies for the western rock lobster fishery to be assessed. Details of fishing costs and beach prices received by fishers were required for this assessment. The beach price is the price paid to fishers for rock lobsters delivered to the processing establishments. Thus a principle component of the study was the collection of the necessary economic data from processors involved in the fishery. The data for the fishers were obtained from the processors.

Processors were approached to provide beach price and fishing cost information for the study. Processors were identified as the group paying fishers for the product and providing them with primary goods required to undertake fishing activities (*i.e.*, fuel, bait and gear). As a consequence, these people were able to provide data more cost effectively than if a survey of fishers had been undertaken.

Economic data used in the model were based on beach price and fishing costs for the 1998/99 season. While additional economic data were collected for earlier seasons and for fishing costs not incorporated in the study, it was considered that information from the 1998/99 season provided the most accurate and current representation of the economic effects influencing the fishery. The study focussed on beach price and the variable costs of fishing, such as fuel, bait, gear, and crew, which may be affected by changes in the management strategy applied to the rock lobster fishery.

In order to ensure confidentiality of the beach price and fishing cost information provided by processors, all details identifying individuals have been excluded from this report and only averages have been used.

4.4.1 Methods

4.4.1.1 Collection of economic information

Processors in the fishery were invited to provide beach price and fishing cost information for the model. Of 13 processors, five provided beach price information and four provided fishing cost information. The five processors who provided information for the study were located throughout the area of jurisdiction of the fishery, with two from the north of the fishery (A and B zones) and three from the south (C zone).

Each processor who provided information for the study was interviewed using a standard survey form (**Appendix 3**) to obtain rock lobster price information and costs such as those associated with fuel, bait, gear and crew. Each processor either completed the information required in the survey form themselves or provided access to files containing the required information. The beach price and fishing cost information obtained from the survey (**Appendix 3**) was utilised in the study.

Beach price and fishing cost information obtained from the sample were placed into two separate data bases. The data were segregated to facilitate subsequent analyses for the purpose of deriving mean beach price and fishing cost information for the model.

4.4.1.2 Sample

The data provided by the five processors who provided information for the study represented information relevant to 338 of the 600 vessels in the fishery. The geographical distribution of processors ensured that a large sample of vessels from each of the management zones was represented in the study (**Table 4**).

Table 4 Number of vessels licensed for each management zone that were represented in the survey data

Zone	Number of vessels
A	160
B	80
C	98

Within each management zone, the number of pots each licensee was able to use varied considerably, with each licensee being restricted to a minimum of 52 pots and a maximum of 150 pots. The range of pot numbers used by licensees in each of the management zones was recorded and verified that licensees captured in the surveying method provided a cross section of licensees in the fishery (see **Table 5**).

Table 5 Range of pot numbers used by individual licensees represented by the survey data within each management zone

Zone	Range of pot numbers
A	61 - 131
B	80 - 131
C	55 - 135

4.4.1.3 Estimating beach price

The beach price data were extracted from the data base (see **Appendix 3**, part 1). For each month and each grade, the mean beach price ($/kg) was calculated. The resulting mean represented the average price paid to fishers for product of each grade.

4.4.1.4 Estimating fishing cost

Fishing cost information was collected from each of the three management zones. These data were used to calculate the seasonal and monthly cost of undertaking fishing activities within the individual management zones.

It was determined that only the actual variable costs of undertaking fishing activities would be incorporated in the model at this time. These costs included fuel, bait, gear and crew cost (deckhands).

The fishing cost data base contained records of the average monthly cost of fishing for vessels supplying the processor in each management zone from which the processor was receiving product. Separate records were included for fuel, bait, gear and crew.

(I) Costs dependent on pot usage

The fishing costs of fuel, bait and gear were treated as costs within the model that were affected by changes in pot usage, but which were not affected by changes in the catch in response to a change in management strategy. Under this definition, these costs remain constant for all management strategies applied to the model except those strategies that affect the fishing effort.

In the case of fuel and bait, the mean of these fishing costs was calculated on a monthly basis for individual management zones and applied in Eq. 4.33 to enable the monthly fishing cost for individual management zones to be determined.

In the case of gear, this fishing cost was calculated as a total for the 1998/99 season within each individual management zone. From the total gear cost figures recorded for the 1998/99 season by the processors within the survey, a mean for each individual management zone was derived from the sample. By dividing the mean calculated for each management zone by the number of months fishing is undertaken (*i.e.,* 7.5 in management zones B and C, and 4 in management zone A) a monthly gear cost in each management zone was calculated and applied in Eq. 4.33 to enable the monthly fishing cost for individual management zones to be estimated. For the purpose of the study the fishing cost of gear has been defined as all expenditure associated with ropes, floats and pots.

(II) Variable costs related to catch

The wages paid to deckhands were treated as a variable cost within the model. These were directly related to the value of the landed catch. For the purpose of the study only crew wages attributed to deckhands were included in the report. No 'wage' was assigned to those licensees who were acting as the skippers of their own vessels, as an explicit 'wage' was not being apportioned to the licensees, and such costs could not be readily identified.

From the survey information supplied by the processors, it was concluded that the majority of vessels were operating with two crew (deckhands) and the cost of these crew accounted for 20% of the landed value of the catch. Therefore the wage crew receive is considered proportional to catch. Monthly estimates of crew wages within each management zone were estimated by multiplying the value of the landed catch for the month by 20% (see Eq. 5.31). The monthly value of the landed catch for each management zone was calculated by multiplying the monthly catch within each grade by the beach price for that grade within the month, and adding the resulting values over all grades (see Eq. 5.32).

4.4.1.5 Application of economic data to the model

To calculate the landed value of the catch on a monthly basis within management zones the following equation was used:

Eq. 4.31 $$\mathrm{Vcatch}(m,\mathrm{Z}) = \sum_{\mathrm{g=A}}^{G} P_g(m,\mathrm{Z})C_g(m,\mathrm{Z}),$$

then the relative net value of landed catch can be estimated by:

Eq. 4.32 $$\mathrm{NVcatch}(m,\mathrm{Z}) = \mathrm{Vcatch}(m,\mathrm{Z}) - \mathrm{cost}(m,\mathrm{Z}),$$

where:
- Vcatch(m,Z) is the total landed value of catch in zone Z and month m;
- $P_g(m,\mathrm{Z})$ is the beach price of lobsters in grade g in zone Z and month m, where eight grade categories were considered, *i.e.*, from grade A to grade G;
- $C_g(m,\mathrm{Z})$ is the (either estimated or actual) catch in grade g;
- cost(m,Z) is the total cost estimated in Eq. 4.33;
- NVcatch(m,Z) is the relative net value of landed catch in zone Z and month m.

It should be noted that many of the fixed annual costs and variable costs other than bait, fuel, gear and crew costs have not been taken into account. Accordingly, the relative net value of the landed catch does not represent the true net value of the catch.

The following equation was used to estimate the total fishing cost for individual fishing months within management zones:

Eq. 4.33 $\mathrm{cost}(m, Z) = (\mathrm{fuel}(m,Z)+\mathrm{bait}(m,Z)+\mathrm{gear}(m,Z))\times \mathrm{Nvessels}(m,Z)+\mathrm{wage}(m,Z)$,

where
- cost(m,Z) is the total fishing cost for the zone Z in the month m with Z = A, B, or C, and m from November to June for the coastal regions and from March to June for the Abrolhos Islands region;
- Nvessels(m,Z) represents the number of vessels operating in the management zone Z in the month m;
- fuel(m,Z), bait(m,Z) and gear(m,Z) represent the average monthly cost per vessel for fuel, bait and gear, respectively;
- wage(m,Z) represents the crew wage, *i.e.,* the variable costs. This was estimated as 20% of total value of landed catch, *i.e.*, wage(m,Z) = 20% Vcatch(m,Z), where Vcatch(m,Z) is the total value of landed catch for the zone Z in the month m.

In order to estimate the landed value when applying different management strategies in the fishery, Eq. 4.31 and Eq. 4.32 were used with the catch $C_g(m, \mathrm{Z})$ being estimated from the model under the assumed management strategies. The following assumptions were made in relation to the application of Eq. 4.31 and Eq. 4.32:

- beach price received remains the same as those beach prices calculated in the study for the 1998/99 season regardless of the management strategy implemented;
- fixed fishing costs (*i.e.*, those costs associated with fuel, bait and gear) as defined by the study remain the same for all management strategies if fishing effort is not affected by the management strategy. In the case of testing a change in the number of potlifts (*i.e.,* fishing effort), a proportional change in fixed costs was assumed.

Monthly landed values generated in Eq. 4.31 and Eq. 4.32 when applying specific management strategies were then added over regions within each management zone to derive seasonal estimates of landed values in the individual management zones. Additionally, seasonal landed values in individual management zones were added to derive estimates of landed value for the entire fishery when implementing specific management strategies.

4.5 Vulnerability at length and concentration index

In earlier modelling studies of the dynamics of the western rock lobster fishery, it was assumed that relative vulnerability at length is a function of a logistic selectivity curve associated with the pot, its entrance, and the escape gaps fitted to the pot. A selection curve of this form assumes an almost constant selectivity of lobsters larger than the legal minimum size. However, examination of the length distribution of catches derived from research samples on vessels reveals that few large lobsters are caught. With the assumption of a logistic selection curve and with known growth curves, model estimates of the fishing mortality required to produce these observed length distributions of catches appeared unrealistically high. Walters *et al.* (1993), applied a length-based cohort analysis to catch at length data, and demonstrated that vulnerability of the western rock lobsters decreases with increasing carapace length.

Two hypotheses have been proposed to explain such reduction of vulnerability with length. The first hypothesis is that the behaviour of larger lobsters, in response to biological processes such as reduced frequency of moulting and reduced competition for food and shelter, is such that these lobsters are less likely to enter pots, and hence are less vulnerable to fishing effort. The second hypothesis is that fishing is concentrated inshore on the smaller lobsters. While both hypotheses are likely to be true, it is the latter hypothesis that has been considered in this study.

As noted by Gulland (1969), the catch rate calculated by dividing the recorded catch by the recorded fishing effort is unlikely to be directly proportional to the average density of fish if vessels concentrate fishing effort on local areas of higher concentrations of fish. The catch rate will be proportional to the density in the local areas that have been fished, weighted by the amount of fishing effort at each location. Gulland (1969) recognised that, provided "the ratio of the true density to the density weighted by the amount of fishing remains constant", the recorded catch rate will be proportional to the true density. Where the distribution of fish or the distribution of fishing effort with respect to those fish changes, it is possible that the catch rate may no longer be a valid index of the true density.

Gulland (1969) proposed that, by calculating the ratio of the observed catch to the weighted average of catch rates in the different regions, using the areas of the regions as weighting factors, a measure of effort would be determined which would "remain proportional to the fishing mortality regardless of changes in the distribution of fish and fishing". This was termed the effective effort, and represents the amount of effort which, if applied randomly with respect to the distribution of fish, would achieve the recorded catch. Gulland (1969) noted that this approach could also be used for subgroups of the population, such as age groups. The weighted average of the catch rates provided an index of the average density of fish in the population.

Morgan (1979a) applied the method described by Gulland (1969) to adjust fishing effort for the distribution of catch rates and fishing effort over the fishing blocks used by fishers when reporting monthly catches and fishing effort. This, in combination with a correction for seasonal changes in vulnerability, allowed Morgan (1979a) to calculate an estimate of effective effort and average catch rate over the entire fishery. While noting that the average size of lobsters caught varies with depth, and recognising that this should be considered when calculating effective fishing effort, Morgan (1979a) had only limited information on size composition of catches in the areas comprising the fishery, and therefore did not include this factor when calculating effective effort. However, Morgan (1979a) noted that, if the fishery was to expand into deeper water, the distribution of effort with respect to the distribution of the lobsters of different sizes would become an important factor in consideration of effective effort.

A measure of the degree to which fishing effort has been concentrated is provided by the concentration index (Rothschild and Robson, 1972; Morgan, 1979b), which is calculated as the ratio of effective effort to nominal effort.

The regions considered in this study were the Abrolhos Islands, the coastal fishery (excluding Abrolhos Islands zone) north of 30^{o}S, the region from 30 to 31 ^{o}S, the region from 31 to 32 ^{o}S, and the region from 32 to 33 ^{o}S. Areas of the various depth zones at each location were calculated from digitised depth contours and coastline.

Logbook data were assigned to the regions based on the recorded latitude and longitude, and the concession code. The data were summarised by region and depth zone for each month within the fishing season. Catch and effort data were obtained from the monthly returns provided by all fishers, and were classified into the regions using the 1^{o} block and concession code. The log book catch and effort were adjusted to total catch and effort by multiplying by the ratio of total catch to logbook catch for the month.

Length frequency data derived from the research monitoring programme for the Abrolhos Islands, Dongara, Jurien, Lancelin and Fremantle were allocated to one of the depth zones 0-10f, 10-20f, 20-30f, 30+f, based on the average depth from which the catches were made. Samples were combined if they were from the same location and depth zone and taken in the same year and month. The length samples at the Abrolhos Islands, Dongara, Jurien, Lancelin and Fremantle were assumed to represent the length composition of catches taken at the Abrolhos Islands, the coastal fishery (excluding Abrolhos Islands zone) north of 30^{o}S, the region from 30 to 31 ^{o}S, the region from 31 to 32 ^{o}S, and the region from 32 to 33 ^{o}S, respectively.

For each combined sample, an estimate of the commercial weight (kg) was calculated. For this, the total frequency for each sex of all lobsters of each carapace length that could be retained (in accordance with the fishery regulations in effect during the month) was multiplied by the estimated weight of a lobster at that size and sex. The resulting products were accumulated over the two sexes and over all carapace lengths. The result represents the weight of all lobsters in the sample that might be retained legally by a fisher. The frequency within each length category (whether retained or released) and class was then represented as the frequency per kg of commercial catch.

The weight-length relationships used in determining the live weight (gm) of a lobster from its carapace length (mm)were:

Males:

$$W = 0.0016068L^{2.8682}$$

Females:

$$W = 0.0025053L^{2.7780}$$

Weather conditions and distribution of fishing may result in missing samples. The assumption was made that, where a sample was missing for any month within the fishing season, for a region and depth zone, the last recorded sample would represent the size composition for the missing sample. For missing samples at the beginning of the fishing season, the size composition was assumed to be that of the first sample recorded for the depth zone and region for that fishing season.

The size composition of the catch (not landings) for each region and depth category for the period was estimated by multiplying the total catch by the estimated frequency per kg of commercial catch. Similarly, the catch rate of lobsters within each length class was estimated by multiplying catch rate within the depth and region for the period by the estimated frequency per kg of commercial catch. These calculations were carried out for each class and for each sex, including lobsters that were either retained or released. The data were analysed by month, but were also grouped into the whites (November to January) and reds (February to June) fishing seasons by combining the results for the various months.

Catch rates were combined by calculating the weighted average catch rate over regions, using the areas of the depth zones within the region as weighting factors. Total catch within each carapace length group was calculated by accumulating the numbers within the various depth zones.

An estimate of the effective effort for the carapace length class was calculated by dividing the total catch for the length class by the average catch rate over all depth zones. The concentration index for lobsters of each sex and length class was calculated by dividing the effective effort for those lobsters by the observed effort.

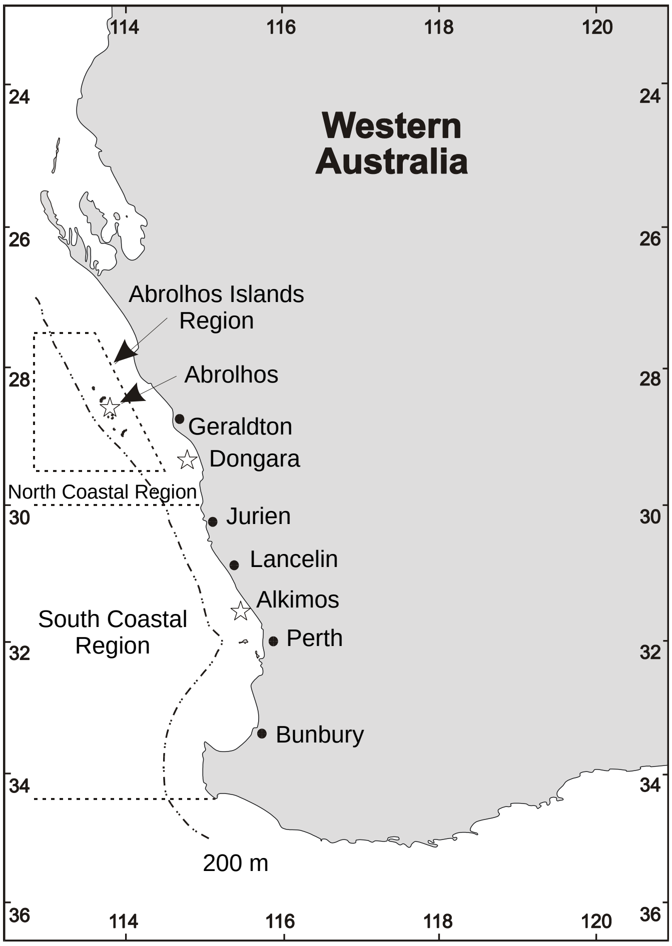


Figure 2. Map of the south western region of Western Australia, showing the three management zones, and the locations (☆) at which the levels of puerulus settlement were measured.

4.6 Age-structured model of impact of 1993/94 strategy

Prior to completion of the length-structured model, the RLIAC and fishery managers requested an evaluation of the impact of the individual regulations comprising the 1993/94 management package, and an urgent assessment of alternative management strategies to aid in determining future management directions for the western rock lobster fishery. As the length-structured model was incomplete and thus could not be used to provide the required information within the necessary time-frame , an age-structured model was developed to address the specific objectives identified for this new study. However, following the development and application of this alternative model, it was recognised that it also addressed many of the objectives of the FRDC project. As the model was pertinent to the objectives of the FRDC project and had been developed by staff who were members of the FRDC project team, during the period of the FRDC project, it was considered appropriate that details of this study should be presented within this FRDC report.

The fishery for western rock lobster, *Panulirus cygnus,* off the Western Australian coast extends from 21^{o} 44' S to 34^{o} 24' S, but practically, fishing extends from about 26^{o}S to 34^{o}S (**Figure 2**). The following summary of the details of the regulations used to manage the fishery is taken from Bowen and Hancock (1989), Brown (1991), and Brown *et al.* (1994). The fishery is divided into three management zones, namely two coastal regions bounded at 30^{o}S latitude, and a region around the Abrolhos Islands (**Figure 2**). Regulations requiring the release of rock lobsters with a carapace length less than the legal minimum length of 76 mm, and of egg-bearing ("berried") females were introduced early in the fishery's development. Limited entry was introduced into the fishery in 1963, constraining the number of vessels allowed to operate in the fishery (Bowen, 1980). Subsequent regulations were introduced to limit the number of pots (traps) that could be operated and to ensure that these pots were fitted with appropriate gaps to allow undersize lobsters to escape. The fishing season in the coastal sectors extends from November 15 to June 30 (0.625 years), while the fishery at the Abrolhos Islands opens on March 15 and closes on June 30 (0.292 years).

In the early 1990s, a size structured model was developed for the western rock lobster fishery (Walters *et al.*, 1993). Early results from this model suggested that the breeding stock in 1992-93 had been reduced to about 15-20% of the original unfished level. After considering this advice, the Rock Lobster Industry Advisory Committee (a Ministerial advisory body) noted, from international experience, that a breeding stock of about 25% of the original unfished level would ensure that recruitment would be maintained at appropriate levels (Anon., 1993). The Committee (RLIAC) advised the Minister for Fisheries that management action was necessary to rebuild the breeding stock. The RLIAC proposed that the breeding stock levels in each management zone that existed in the fishery in the late 1970s and early 1980s should be adopted as the target levels. Estimates of the biomass of breeding females in each zone for the 1992-93 season and for the late 1970s and early 1980s suggested that increases in the breeding stock levels, subsequently estimated at 49, 110 and 13%, were required in the south coastal, north coastal and Abrolhos Islands zones (**Figure 2**), respectively (Anon., 1993). The RLIAC accepted these figures as the basis for subsequent management advice for the fishery, and accordingly these percentage increases determined the targets against which the effectiveness of subsequent management action were judged.

Management measures introduced in 1992-93 were revised in 1993-94 to achieve the required recovery of the spawning stock. The status of the fishery was to be reviewed at the end of the 1997-98 fishing season to determine the extent to which the spawning stock had recovered.

The 1992-93 management plan for the fishery set a maximum carapace length of 115 mm for female lobsters in all management zones, and protected setose female lobsters (those with visible ovigerous setae) between November 15 and February 28 (0.292 years) in the coastal zones. Within the north coastal management zone, the plan also applied a 10% pot reduction between November 15 and January 9 (0.15 years), followed by a total closure from January 10 to February 9 (0.083 years). A requirement to declare the port of landing was introduced in the south coastal zone, but was dropped later in the 1992-93 fishing season.

Following a review of the 1992-93 fishing season, a revised management plan for the fishery was implemented for 1993-94 and continued in subsequent fishing seasons. This new strategy maintained aspects of the 1992-93 regulations that appeared valuable, and replaced other elements that appeared less useful.

The new regulations maintained minimum and maximum size regulations, reduction in pot quota, and increased the protection for mature female lobsters. The maximum legal carapace length in the Abrolhos and the north coastal zones was set at 105 mm. Recognising that the size composition of catches differed between the north and the south of the south coastal management zone, two maximum carapace lengths for female lobsters were specified initially for this region. The maximum length was set at 115 mm in the south of the zone and 105 mm in the north. Subsequently, from the 1997-98 season, the maximum legal carapace length for females was set at 115 mm throughout the south coastal zone (a value of 115 mm was used as the maximum legal carapace length for the south coastal zone in this study, which may lead to a slight underestimate of the resulting egg production). The 1993-94 plan required release of setose female lobsters throughout the fishing season. Pot usage was reduced by 18% of the pot holding that existed in 1992-93. The minimum legal carapace length was increased from 76 mm to 77 mm for the period from November 15 to January 31 (0.208 years).

In order to assess the effectiveness of the management measures in achieving an increased level of spawning stock, and to obtain information on the impact of the new regulations on the catches obtained by fishers, additional research data were required. A fishery-independent research survey of the breeding stock was initiated to obtain data on the relative annual egg production at selected sites throughout the fishery, and to avoid the potential bias inherent in fishery-dependent data resulting from the increasing effectiveness of fishing effort within the fishery. Voluntary daily logbooks (completed by 27.5 to 38.5% of the fishers from 1993-94 to 1997-98) were modified to collect data on releases of lobsters resulting from the new management regulations.

At the conclusion of the 1997-98 fishing season, fishery managers and the fishing industry sought an assessment of the fishery to determine whether the regulations had been effective in achieving the recovery of the spawning stock, to determine the effect of the individual management regulations (N. Hall and C. Chubb, unpublished data) and to provide guidance as to future management options for the fishery.

Based on the raw data collected from the fishery and the various research programs, and on fishers' observations of the increased number of setose lobsters that were released, the new regulations have been effective in producing a substantial increase in the spawning stock. However, some fishers are concerned that the regulations might have been overly conservative, resulting in loss of potential catch while achieving a spawning stock abundance that was in excess of what was necessary for sustainability. This, and the need to determine future directions for managing the rock lobster fishery, were additional industry concerns to be considered when reviewing the effectiveness of the management program and assessing the status of the fishery.

The specific aims for this new project were (1) to determine the level of estimated egg production for the assemblage of the western rock lobsters within each management zone, (2) to compare the current levels of estimated egg production with the target levels in order to determine whether the regulations had achieved the management objective, and (3) to develop a model that could be used to examine the impact on future egg production of alternative harvest strategies.

4.6.1 Data employed in the model

The data sets used in fitting the age-structured model differ slightly from those described earlier for the length-structured model. Details of the data that have been used in the age-structured model are therefore presented in the sections below.

4.6.1.1 Puerulus settlement

Information on the relative abundance of puerulus settling among the near-shore reefs was obtained from monthly counts of the puerulus that settled in artificial seaweed collectors (Phillips and Hall, 1978; Phillips, 1972) located at various sites throughout the fishery. An annual index of the settlement at each site, the mean number of puerulus caught per collector, was calculated. The time series of these settlement indices, P_t, from three sites, at the Abrolhos Islands, Dongara, and Alkimos (**Figure 2**) were used by Caputi *et al.* (1995a) to predict the catches within the three management zones of the western rock lobster fishery. Data for Dongara from 1968 to 1998, for Alkimos from 1982 to 1998 and for the Abrolhos Islands from 1971 to 1978 and from 1984 to 1998 were used in this study. When no annual index of puerulus settlement was available (e.g. for Alkimos prior to 1982), and when extrapolating beyond the range of recorded data, the average of the recorded indices of puerulus settlement for the site was used.

4.6.1.2 Annual catch and fishing effort for each region

Details of the annual landings of lobsters from the commercial fishery were obtained from monthly statistical returns provided by processors to Fisheries Western Australia (FWA). These data were supplemented by information on catches and fishing effort provided by licensed professional fishers in mandatory monthly statistical returns. These two data sets together provided the basis for determining both the total annual commercial catch and the nominal fishing effort (potlifts) applied to take that catch. The commercial catch and effort data from each management region, for the 1980-81 to 1998-99 fishing seasons, were used in this study.

As noted by Brown and Phillips (1994), the recreational catch in 1988-89 amounted to 460 t, *i.e.* approximately 3.8% of the commercial catch. The proportion of the annual catch taken by the recreational fishery has continued to grow. While a detailed assessment of the postal surveys of licensed recreational rock lobster fishers is yet to be completed (R. Melville-Smith, Fisheries WA, pers. comm.), preliminary catch estimates are available for the total recreational fishery for the period from 1986-87 to 1996-97. For the results presented in this report, the recreational catches for the three management regions were estimated by dividing the total annual recreational catch between regions in the same ratio as the recorded commercial catches. Subsequently, the model has been improved by dividing the catch between only the north and south coastal zones of the fishery, as little or no recreational fishing occurs at the Abrolhos Islands. The recreational catches for the fishing seasons from 1980-81 to 1985-86 were assumed to be identical to the catch in 1986-87, while that for 1997-98 was assumed to be identical to the catch in 1996-97.

The total annual catch for each region, C_t, was then estimated by adding the commercial and recreational catch estimates. An estimate of the equivalent commercial fishing effort, E_t, required to produce the combined total catch for each region was calculated by dividing the total catch by the catch rate recorded for the commercial fishery.

4.6.1.3 Independent breeding stock surveys

A research program to provide fishery-independent indices of the relative annual egg production was initiated in 1991. While other indices of egg production had been calculated previously from fishers' logbooks and fishery statistics, there was concern that these might be biased by the increasing efficiency of fishing effort within the fishery, coupled with possible changes to fishing practices in response to the introduction of new regulations. The research surveys were carried out throughout the Abrolhos Islands region using the Research Vessel "Flinders" and at sites in the north and south coastal management zones using chartered rock lobster fishing vessels. The sites for the annual surveys were selected from areas identified by fishers as locations where egg-bearing females were consistently caught.

The survey was conducted at each site over a ten-day period centred on the new moon immediately prior to the opening of the coastal fishing season, on November 15. At the coastal sites, fishing was undertaken using 80 standard pots, with a soak time of 2 days, and using a specified quantity of standard bait. At the Abrolhos Islands, 60 standard pots were fished with a soak time of 1 day. A new set of pots was used each year to ensure that the catch rates were not affected by the age of the pots. Pots were set within each site at locations recorded using the global positioning navigation system (GPS), and the same fishing locations were used during each annual survey.

For each lobster caught, the carapace length (mm) and sex were recorded. For female lobsters, the condition of the lobster (unmated juvenile, unmated setose female, mated adult female, egg-bearing female) was recorded. Using the relationship between egg production and carapace length (Chubb, 1991), the total egg production of the egg-bearing females present within the catches obtained from the survey was estimated. The estimate of total egg production per potlift obtained from the standard survey was assumed to be an index of the egg production of the assemblage of lobsters around the site. Data from each site within each of the management zones were combined using a general linear model (GLM). The research surveys between 1992 and 1998 provided the indices of egg production (million eggs per potlift), G_t, in each management zone that were used in this study.

4.6.1.4 Released lobsters

Estimates of the quantities (tonnes) of released setose females and of released non-setose, non-berried female lobsters larger than the maximum legal size were determined from logbook data. It should be noted that in most instances these numbers were estimated and not precise counts. No logbook records were kept of the quantities of 76 mm lobsters released between November 15 and January 31. The records of landed catch, released setose lobsters and female lobsters larger than the maximum size were collated. The resulting values were then weighted up based on the total landed catch for the fishing zone, where the latter was determined from mandatory monthly statistical returns from licensed fishers in combination with data from processors' monthly returns. Estimates of the released catches of setose lobsters, C_t^{Setose}, and of female lobsters larger than the maximum size, C_t^{MaxSize}, were available for the 1993-94 to 1997-98 fishing seasons.

4.6.2 Model

The model used to describe the fishery within each of the management zones was age and sex structured, and "conditioned on effort" (Punt, 1988). The assemblage of lobsters within each fishing region was assumed to be independent of the assemblages within the other two regions. The analyses were carried out separately for each of the management zones, and accordingly, the notation used in this section does not discriminate between regions.

While observed data from the fishery represented annual observations, time steps within the model were determined by the various periods into which each season was divided by the set of management regulations applying within that season and region. Each fishing season, *t*, was identified by the first calendar year of the pair of years. Hence $t = 1993$ refers to the 1993-94 fishing season. Fishing for the Abrolhos Islands region commences in March, during the second of the pair of calendar years for the fishing season. The duration (years) of period *j* within fishing season, *t*, was denoted by $T_{j,t}$.

Prior to 1992-93, the year was considered to comprise two periods. Fishing was carried out in the first period, $j = 1$, while $j = 2$ represented July 1 to November 14, when no fishing is permitted. For the coastal sectors from 1993-94, the year was divided into 3 periods, from November 15 to January 31 when the minimum legal carapace length is increased to 77 mm, from February 1 to June 30 when the minimum legal carapace length reverts to 76 mm, and the closed season from July 1 to November 14. Details of the periods are presented in **Table 6** to **Table 11**.

For this model, recruitment to the lobster assemblage within the management zone was considered to occur one year prior to the age at which the lobsters were first exploited. This decision was made in order that the contribution made by female lobsters to egg production in the Abrolhos region would be included in the calculated indices of egg production. The female lobsters in the Abrolhos Islands region reach 50% maturity at a carapace length of approximately 65 mm, approximately a year before they are exploited (Chubb, 1991).

The age of lobsters relative to the age at recruitment (one year prior to entry to the exploited stock) was denoted by *a*, and is referred to as 'age' in the remainder of this section. The maximum age considered in the analysis was *A*, where $A = 21$ years, thus allowing for 20 years of exploitation following entry of the lobsters into the exploited portion of the population.

It was assumed that recruitment to each region was proportional to some constant power of the lagged average puerulus settlement indices for that region. From Caputi *et al.* (1995a), the relationships assumed were:

Eq. 4.34
$$R_t = \begin{cases} k\left(\dfrac{P_{t-2}+P_{t-3}}{2}\right)^{0.121} & \text{for the Abrolhos Islands zone} \\ k\left(\dfrac{P_{t-2}+P_{t-3}}{2}\right)^{0.244} & \text{for the North Coastal zone} \\ k\left(\dfrac{P_{t-2}+P_{t-3}}{2}\right)^{0.314} & \text{for the South Coastal zone} \end{cases}.$$

R_t is the number of lobsters recruiting (at age *a*=0 years, one year prior to exploitation, hence the two and three year lag compared with the three and four year lag used by Caputi *et al.*, 1995a) to the stock in the management zone in year *t*. The recruitment indices that were considered by Caputi *et al.* (1995a) were the recorded catches in the management zones, rather than the number of lobsters recruiting to the assemblage. Thus, in the study by Caputi *et al*. (1995a), an effort term, $E^{0.916}$, was included in the equation for the north coastal management zone, but was not included in the current study.

The recruiting lobsters were assumed to comprise equal proportions of male and female lobsters. Hence, the number of lobsters of age *a*=0 years, of sex *s* in year *t* was given by

Eq. 4.35
$$N_{0,t}^{s} = 0.5R_t,$$

where $N_{a,t}^{s}$ is the number of lobsters of age *a* (for $0 \le a \le A$) and sex *s* in the stock at the beginning of fishing season *t*. The number of lobsters at the beginning of period *j* within the fishing season is denoted by $N_{a,j,t}^{s}$, where $N_{a,t}^{s} = N_{a,1,t}^{s}$.

The instantaneous rate of natural mortality, M, was assumed to be constant through time. The value estimated by Morgan (1977), M=0.226 year^{-1}, was used in this study. To test sensitivity of results, alternative values of 0.15 and 0.3 year^{-1} were also applied.

The number of lobsters of age a and sex s surviving to the end of period j within fishing season t was calculated as

Eq. 4.36 $$N_{a,j+1,t}^{s} = N_{a,j,t}^{s} \exp\left[-\left(M + F_{a,j,t}^{s}\right)T_{j,t}\right],$$

where the age and sex dependent fishing mortality in period j of fishing season t was denoted by $F_{a,j,t}^{s}$. The number of lobsters of age a surviving at the conclusion of the last period (the period from July 1 during which the fishery is closed to fishing and in which only natural mortality is applied) within a fishing season is the number of lobsters of age a+1 present at the beginning of the subsequent fishing season. Thus, the number of lobsters of age a and sex s surviving to the beginning of the following fishing season was calculated as

Eq. 4.37 $$N_{a+1,t+1}^{s} = N_{a,t}^{s} \exp\left\{-\left(M + \sum_{j} F_{a,j,t}^{s} T_{j,t}\right)\right\},$$

It was assumed that no lobsters survived beyond age A years.

The fishing mortality applied to the assemblage of lobsters of age a and sex s within the management region during period j of fishing season t was assumed to be calculated as

Eq. 4.38 $$F_{a,j,t}^{s} = q_{a,j,t}^{s} E_t,$$

where E_t was the annual nominal fishing effort (thousand potlifts) applied to the region, and $q_{a,j,t}^{s}$ was the catchability (thousand potlifts)$^{-1}$ of the lobsters of sex s and age a within period j of fishing season t. The term catchability is used to refer to the proportion of the lobsters within the assemblage (per unit of fishing effort) that were caught and retained by the fishers, thus determining the fishing mortality of lobsters within the assemblage associated with the fishing effort.

It was assumed that lobsters with ages, $a \geq a_{\mathrm{Large}}$, experienced a catchability that was less than that experienced by younger (smaller) lobsters. Another study (N. Hall and C. Chubb, unpublished data) had demonstrated that effective effort was strongly length dependent in the coastal zones of the fishery, partially due to the distribution of fishing effort. Lack of length samples throughout the fishing season at the Abrolhos Islands precluded such analysis in this region, but it was likely that the results obtained in the coastal zones were applicable for the Abrolhos zone. The biology of the lobsters, and in particular the size-dependent frequency of moulting and relationship of the phase of the moult cycle to feeding activity of the lobsters, also suggested that vulnerability would decrease with size of lobster. The value of a_{Large} was set at three years for this study. This value was selected as it represented two years of exploitation in the younger category, noting that female lobsters in the coastal sectors of the fishery experience approximately two years of exploitation before reaching maturity. To test sensitivity to this assumption, alternative values of two and four years were also examined.

Prior to 1992-93, the catchabilities were assumed to be constant through time and identical for male and female lobsters. These catchabilities were denoted q_S and q_L for small and large lobsters, respectively. While the regulation requiring release of egg bearing female lobsters, that was in effect prior to 1992-93, would have reduced the catchability of female lobsters, the assumption that male and female lobsters experienced identical catchabilities simplified the calculations for this assessment. Thus, for $t < 1992$, the catchability, $q^s_{a,j,t}$, of lobsters of age *a* and sex *s* during the period open to fishing, *j*=1, was

Eq. 4.39 $$q^s_{a,1,t} = \begin{cases} 0 & \text{for } a = 0 \\ q_S & \text{for } 0 < a < a_{\text{Large}}, \\ q_L & \text{for } a \geq a_{\text{Large}} \end{cases}$$

where $q_S \geq q_L$. Using these equations and estimates of these initial catchabilities, an estimate of the initial age-structure of the stock at the commencement of the 1980-81 fishing season was calculated from the time series of annual recruitment levels and the applied level of fishing effort in 1980-81 (assumed constant for earlier fishing seasons).

To model the impact of the regulation requiring release of setose female lobsters, it was recognised that the probability of capture of the female lobsters would be identical to that of the male lobsters, which experience the catchability, $q^m_{a,j,t}$. However, a proportion of the female lobsters caught would be setose. These would be discarded, while non-setose female lobsters would be retained. It was assumed that discarded lobsters of all types would experience no discard mortality given modern handling techniques and results from unpublished tagging studies. The discarded lobsters would continue to be exposed to fishing mortality during the remainder of the fishing season. On recapture, some of these lobsters might have moulted to a non-setose state and would be included in the landed catch, while others would be setose and thus would again be discarded. Hence, the resulting impact of the setose regulation was that the effective catchability of the female lobsters, $q^f_{a,j,t}$, would be less than the catchability of the males, $q^m_{a,j,t}$.

The relationship between the catchability of male and female lobsters, when regulations required that setose females be discarded, was assumed to be

Eq. 4.40 $$q^f_{a,j,t} = (1-\varphi_a)q^m_{a,j,t},$$

where φ_a represented the average proportion of the female lobsters at age *a* that were setose throughout the fishing season. It was recognised that this proportion was likely to be dependent on age. However to simplify the model, it was assumed that:

Eq. 4.41 $$\varphi_a = \begin{cases} \varphi_S & \text{for } 1 < a < a_{\text{Large}} \\ \varphi_L & \text{for } a \geq a_{\text{Large}} \end{cases}.$$

As the proportion of mature females increases and the frequency of moulting decreases with age, it was anticipated that $\varphi_L \geq \varphi_S$, however this relationship was not applied as a constraint when fitting the model. It was recognised that the proportion of female lobsters that were setose would vary through the fishing season, however it has been assumed constant in order to simplify the model.

Concern had been expressed by fishery managers that the efficiency of fishing effort had continued to increase in the period following the introduction of the 1993-94 regulations. To investigate the sensitivity of the assessment to this possibility, it was assumed that the annual catchability following the 1993-94 fishing season would increase by a fraction, *X*, each year. The scenarios examined included annual increases in efficiency of 0, 1 and 2%.

The impact of the maximum size regulation for female lobsters was modelled by setting the catchability to zero for all age classes for which the estimated length at the beginning of the fishing season was equal to or greater than the maximum carapace length.

Following the introduction of the 1993-94 management package, the number of male or female lobsters surviving to reach period $j = 2$ at age $a = 1$ year for the south and north coastal zones was calculated as

Eq. 4.42 $$N^s_{1,2,t} = N^s_{1,1,t}\left\{0.75\exp\left[-\left(M + F^s_{1,1,t}\right)T_{1,t}\right] + 0.25\exp\left[-MT_{1,t}\right]\right\}.$$

This reflected the requirement to release 76 mm lobsters from November 15, the opening date of the fishery in the coastal zones, to January 31 (0.2083 years). This regulation affected approximately 25% of the recruiting lobsters (assuming that these are uniformly distributed over the 4 mm carapace length range associated with a moult into the exploited portion of the stock from below the minimum legal carapace length of 76 mm).

Changes in pot usage resulting from the 1992-93 and 1993-94 regulations were evident in the time series of observed fishing effort recorded for each fishing region. However, in the north coastal region during 1992-93, the changes in pot usage occurred within the fishing season, while in subsequent fishing seasons the reduction in pot usage applied throughout the entire fishing season. The total effort that would have been applied in the north coastal zone in the absence of the 10% pot reduction and January closure was estimated as 18.6% higher than the recorded fishing effort. The adjusted effort was used when the model was calculated for 1992-93 in the north coastal zone. For the first period in this fishing season, the adjusted fishing effort was reduced by 10% to allow for the pot reduction imposed in this region.

From the management regulations specified for each management zone, a table of the effect of the various regulations on the catchability of lobsters was created for each region (**Table 6** to **Table 11**). Although the same notation was used, it is again noted that the parameters differed between management zones, and were estimated by running the model separately for each zone.

An estimate of the total annual egg production from each management zone, S_t, was obtained by summing the egg production over all age classes, where egg production within each age class was calculated by multiplying the number of females by the average egg production of each breeding female of that age, e_a. That is,

Eq. 4.43 $$S_t = \sum_{a=0}^{A} N_{a,t}^{f} e_a .$$

In his study on the reproductive biology of the western rock lobster, Chubb (1991) found that the carapace length at which 50% of the female lobsters were mature was 65 mm at the Abrolhos Islands, 90 mm at Dongara, and 95 mm at Two Rocks. These values were used as the values of length at maturity, L_{Mat}, in the Abrolhos zone, the north coastal and south coastal management zones, respectively.

The number of eggs produced by a mature female a years ($0 \le a \le a_{\max}$) after recruiting to the exploited stock of lobsters was calculated using the relationship determined by Chubb (1991):

Eq. 4.44 $$e_a = \begin{cases} 0 & \text{for } L_a < L_{Mat} \\ 2(1.92)L_a^{2.69} & \text{for } L_a \ge L_{Mat} \end{cases},$$

where L_a is the mean carapace length (mm) of females of age a at the beginning of the fishing season. It was assumed that each breeding female spawns twice (Chubb, unpublished data) at the beginning of each fishing season, hence the factor, 2, in the above equation.

Table 6 Effect of the management regulations on the catchabilities and on the size regulations for the south coastal zone (males).

Fishing Season	Period (years)	Catchability for $0 < a < a_{\text{Large}}$	Catchability for $a \geq a_{\text{Large}}$	Minimum carapace length (mm)
Prior to 1993-94	0.625	q_S	q_L	76
	0.375	0	0	
From 1993-94	0.208	$q_S(1+X)^{t-1993}$	$q_L(1+X)^{t-1993}$	77
	0.417	$q_S(1+X)^{t-1993}$	$q_L(1+X)^{t-1993}$	76
	0.375	0	0	

Table 7 Effect of the management regulations on the catchabilities and on the size regulations for the south coastal zone (females).

Fishing Season	Period (years)	Catchability for $0 < a < a_{\text{Large}}$	Catchability for $a \geq a_{\text{Large}}$	Maximum carapace length (mm)	Minimum carapace length (mm)
Prior to 1992-93	0.625	q_S	q_L		76
	0.375	0	0		
1992-93	0.292	$\varphi_S q_S$	$\varphi_L q_L$	115	76
	0.333	q_S	q_L	115	76
	0.375	0	0		
From 1993-94	0.208	$\varphi_S q_S(1+X)^{t-1993}$	$\varphi_L q_L(1+X)^{t-1993}$	115	77
	0.417	$\varphi_S q_S(1+X)^{t-1993}$	$\varphi_L q_L(1+X)^{t-1993}$	115	76
	0.375	0	0		

Table 8 Effect of the management regulations on the catchabilities and on the size regulations for the north coastal zone (males).

Fishing Season	Period (years)	Catchability for $0 < a < a_{\text{Large}}$	Catchability for $a \geq a_{\text{Large}}$	Minimum carapace length (mm)
Prior to 1992-93	0.625	q_S	q_L	76
	0.375	0	0	
1992-93	0.15	q_S	q_L	76
	0.083	0	0	
	0.392	q_S	q_L	76
	0.375	0	0	
From 1993-94	0.208	$q_S(1+X)^{t-1993}$	$q_L(1+X)^{t-1993}$	77
	0.417	$q_S(1+X)^{t-1993}$	$q_L(1+X)^{t-1993}$	76
	0.375	0	0	

Table 9 Effect of the management regulations on the catchabilities and on the size regulations for the north coastal zone (females).

Fishing Season	Period (years)	Catchability for $0 < a < a_{\text{Large}}$	Catchability for $a \geq a_{\text{Large}}$	Maximum carapace length (mm)	Minimum carapace length (mm)
Prior to 1992-93	0.625	q_S	q_L		76
	0.375	0	0		
1992-93	0.15	$\varphi_S q_S$	$\varphi_L q_L$	115	76
	0.083	0	0		
	0.059	$\varphi_S q_S$	$\varphi_L q_L$	115	76
	0.333	q_S	q_L	115	76
	0.375	0	0		
From 1993-94	0.208	$\varphi_S q_S(1+X)^{t-1993}$	$\varphi_L q_L(1+X)^{t-1993}$	105	77
	0.417	$\varphi_S q_S(1+X)^{t-1993}$	$\varphi_L q_L(1+X)^{t-1993}$	105	76
	0.375	0	0		

Table 10 Effect of the management regulations on the catchabilities and on the size regulations for the Abrolhos zone (males).

Fishing Season	Period (years)	Catchability for $0 < a < a_{\text{Large}}$	Catchability for $a \geq a_{\text{Large}}$	Minimum carapace length (mm)
Prior to 1993-94	0.292	q_S	q_L	76
	0.708	0	0	
From 1993-94	0.292	$q_S(1+X)^{t-1993}$	$q_L(1+X)^{t-1993}$	76
	0.708	0	0	

Table 11 Effect of the management regulations on the catchabilities and on the size regulations for the Abrolhos zone (females).

Fishing Season	Period (years)	Catchability for $0 < a < a_{\text{Large}}$	Catchability for $a \geq a_{\text{Large}}$	Maximum carapace length (mm)	Minimum carapace length (mm)
Prior to 1992-93	0.292	q_S	q_L		76
	0.708	0	0		
1992-93	0.292	q_S	q_L	115	76
	0.708	0	0		
From 1993-94	0.292	$\varphi_S q_S(1+X)^{t-1993}$	$\varphi_L q_L(1+X)^{t-1993}$	115	76
	0.708	0	0		

The carapace lengths (mm) of lobsters at the beginning of each fishing season were determined using relationships derived from the von Bertalanffy growth curves fitted to available tagging data for lobsters of each sex (filtered to include only recoveries from 330 to 390 days) using a robust regression method:

Eq. 4.45
$$L_{a+1} = \begin{cases} L_a + (141.4 - L_a)\{1 - \exp(-0.236)\} & \text{for males} \\ L_a + (122.5 - L_a)\{1 - \exp(-0.240)\} & \text{for females} \end{cases}.$$

Where sufficient tagging data existed, no significant difference was found between the parameters of the equations in different regions for the two sexes. Tagging data from the Abrolhos Islands region after filtering were insufficient (two males, six females), and the growth curves derived from other regions were applied to the Abrolhos region. However, it should be noted that this may overestimate growth at the Abrolhos Islands, resulting in the overestimation of fishing mortality for this region.

The length of lobsters at entry to the exploited assemblage within each region (at $a = 1$ year) was assumed to be 78 mm, assuming that an average moult increment of 4 mm would result in lobsters entering the exploited population with carapace lengths ranging from 76 to 80 mm. From this, and using the growth equation for each sex, an estimate was obtained of the length at age $a = 0$ years.

The annual catch, $\hat{C}_t$ (tonnes), for each region was estimated using the equation:

Eq. 4.46
$$\hat{C}_t = \sum_{s=m}^{f} \sum_{a=1}^{A} \sum_{j} \hat{C}_{a,j,t}^{s},$$

where

Eq. 4.47
$$\hat{C}_{a,j,t}^{s} = \frac{F_{a,j,t}^{s}}{M + F_{a,j,t}^{s}} \left(1 - \exp\left[-\left(M + F_{a,j,t}^{s}\right)T_{j,t}\right]\right) N_{a,j,t}^{s} W_{a}^{s}.$$

In this equation, the body weight (kg) of the lobsters, W_a^s, at age *a* was calculated from the carapace length (mm) at the beginning of the fishing season as

Eq. 4.48
$$W_a^s = \begin{cases} 0.0000016068\ L_a^{2.8682} & \text{for males} \\ 0.0000025053\ L_a^{2.778} & \text{for females} \end{cases}.$$

An estimate of the released catch of setose female lobsters within each fishing season (after 1993-94) was determined as

Eq. 4.49 $$\hat{C}_t^{\text{Setose}} = \sum_{a=1}^{A} \sum_j \left\{ \frac{1-\varphi_a}{\varphi_a} \hat{C}_{a,j,t}^f \right\},$$

where, for lobsters with carapace lengths greater than the maximum legal length, the catchabilities shown in **Table 7**, **Table 9** and **Table 11** were applied rather than the values of zero that were used when determining the landed catch and the number of lobsters surviving to the end of the fishing season.

An estimate of the released catch of non-setose female lobsters larger than the maximum legal length (after 1993-94) was calculated using

Eq. 4.50 $$\hat{C}_t^{\text{MaxSize}} = \sum_{a=1}^{A} \sum_j \hat{C}_{a,j,t}^f,$$

where, once again, for lobsters with carapace length greater than the maximum legal length, the catchabilities shown in **Table 7**, **Table 9** and **Table 11** were applied rather than the values of zero that were used when determining the landed catch and the number of lobsters surviving to the end of the fishing season.

It was assumed that the estimates of the egg production indices observed in the breeding stock surveys, G_t, were related to the egg production for the management zone, S_t, by

Eq. 4.51 $$G_t = \beta S_t + \varepsilon_t^{\text{Eggs}},$$

where $\varepsilon_t^{\text{Eggs}}$ represents observation error and is assumed to be a random variate drawn from a normal distribution with mean of zero. The log-likelihood associated with the egg production indices (ignoring constant terms) was calculated as

Eq. 4.52 $$\lambda_{\text{Eggs}} = -\frac{n_{\text{Eggs}}}{2} \log\left(\sum_{t=1992}^{1998} (G_t - \beta S_t)^2 \right),$$

where n_{Eggs} was the number of survey estimates, $n_{\text{Eggs}} = 7$ and it was assumed that the variance of these observations errors was equal to the mean squared error.

Similarly, it was assumed that

Eq. 4.53 $$C_t = \hat{C}_t + \varepsilon_t^{\text{Catch}},$$

Eq. 4.54 $$C_t^{\text{Setose}} = \hat{C}_t^{\text{Setose}} + \varepsilon_t^{\text{Setose}},$$

and

Eq. 4.55 $$C_t^{\text{MaxSize}} = \hat{C}_t^{\text{MaxSize}} + \varepsilon_t^{\text{MaxSize}},$$

where $\varepsilon_t^{\text{Catch}}$, $\varepsilon_t^{\text{Setose}}$, and $\varepsilon_t^{\text{MaxSize}}$ are random variates drawn from three normal distributions with means of zero. Log-likelihoods for these observations (ignoring constant terms) were calculated as

Eq. 4.56 $$\lambda_{\text{Catch}} = -\frac{n_{\text{Catch}}}{2}\log\left(\sum_{t=1991}^{1998}\left(C_t - \hat{C}_t\right)^2\right),$$

Eq. 4.57 $$\lambda_{\text{Setose}} = -\frac{n_{\text{Setose}}}{2}\log\left(\sum_{t=1993}^{1997}\left(C_t^{\text{Setose}} - \hat{C}_t^{\text{Setose}}\right)^2\right),$$

and

Eq. 4.58 $$\lambda_{\text{MaxSize}} = -\frac{n_{\text{MaxSize}}}{2}\log\left(\sum_{t=1993}^{1997}\left(C_t^{\text{MaxSize}} - \hat{C}_t^{\text{MaxSize}}\right)^2\right),$$

respectively, and the numbers of observations were $n_{\text{Catch}} = 8$, $n_{\text{Setose}} = 5$, and $n_{\text{MaxSize}} = 5$, respectively. The catches were converted to thousands of tonnes prior to use in Eq. 4.56, Eq. 4.57 and Eq. 4.58. Again, the variance of each observation error was assumed equal to the mean square error for the data set.

The objective function used when fitting the model was the combined log-likelihood

Eq. 4.59 $$\lambda = \lambda_{\text{Eggs}} + \lambda_{\text{Catch}} + \lambda_{\text{Setose}} + \lambda_{\text{MaxSize}}.$$

The model was fitted to the observed data using AD Model Builder (Fournier, 1994), which provided estimates of the variance-covariance matrix for the parameter sets. AD Model Builder also was used to estimate probability density functions for the profile likelihoods for the ratios of the level of egg production at the beginning of the 1992-93 and 1999-2000 fishing seasons relative to the egg production of the unfished stock in the same years. For the latter, the model was run with catchabilities set to zero, but using the annual recruitment determined from the observed puerulus settlements. The ratio will be termed the ‘egg ratio’, in future references.

The model was run till 2008-09, to investigate management options for the fishery. The annual fishing effort in 1999-2000, and each subsequent fishing season, was assumed to be maintained at the same level as the actual fishing effort recorded for

1998-99. Fishing efficiency was assumed to increase at the same rate as had been applied between 1994-95 and 1998-99. Two management scenarios were considered. In the first, the regulations introduced in 1993-94 were maintained for subsequent fishing seasons. For the second, the regulations requiring the release of all setose females and the release of non-setose females larger than the maximum legal size were removed for the 2001-02 fishing season, and then re-instated for subsequent fishing seasons. The egg ratio for 2002-03 was calculated for each scenario, and compared to illustrate the consequences of such a change to the current regulations.

5. Results/Discussion

In this section we present the results obtained through this study, including the results of the estimation of growth transition matrices; size-structured modelling; exploration of management strategies and economic analysis of product values, and investigation of effect of concentration of fishing effort on smaller lobsters determined within the FRDC project, and the results of the age-structured modelling determined in the concurrent Fisheries WA project.

5.1 Growth transition matrices

In Section 4.1, the method of estimation of growth transition matrices was described. Essentially the processes involved estimation of a set of growth parameters required by the von Bertalanffy growth curve and parameters for the gamma distributions which were assumed to describe the distribution of the growth/size increments of individuals at different sizes (carapace lengths) in a given month. In the following sub-sections, the resulting estimates of mean-size increment are presented, together with the estimates of length frequency and size-increment frequency of recaptured lobsters and estimates of size increment distribution.

5.1.1 Parameters

The set of parameters estimated for the growth transition matrices (Section 4.1.4) were:

for male: $\ell_{\infty}(T), \delta(T), \beta(T)$, T=1, 2, 3, 4, 5, 6, 10, 11, 12, (total 27 parameters);
for female: $\ell_{1\infty}(T), \delta_1(T), \ell_{2\infty}(T), \delta_2(T), \beta(T)$, T=1, 2, 3, 4, 5, 6, 10, 11, 12, (total 45 parameters): $\ell_{1\infty}(T), \delta_1(T)$ are the growth parameters for immature females and $\ell_{2\infty}(T), \delta_2(T)$ for mature females,

where T=1, 2, 3, 4, 5, 6, 10, 11 and 12 represent the months from January to June and from October to December.

Note that the parameter δ was used to substitute $(1-e^{-K\Delta t})$ to simplify the calculations without losing any growth information represented by the von

Bertalanffy growth curve, see Eq. 4.5 and Eq. 4.6. Therefore, the growth parameter K could be calculated as

$$K = -\ln(1-\delta)/\Delta t,$$

where Δt was set to 1 during the estimation, hence $K = -\ln(1-\delta)$.

5.1.2 Estimated mean size increment by month and size class

Based on the estimated parameter values, the mean-size increment was estimated for the lobsters in each month and in each size-class using the formula in Eq. 4.6 for males and the formula in Eq. 4.7 for females.

The results of the estimated monthly mean-size increment for each sex and each region are shown in **Figure 3**. Given a region and sex, lobsters at increasing size-classes have decreasing mean-size increments.

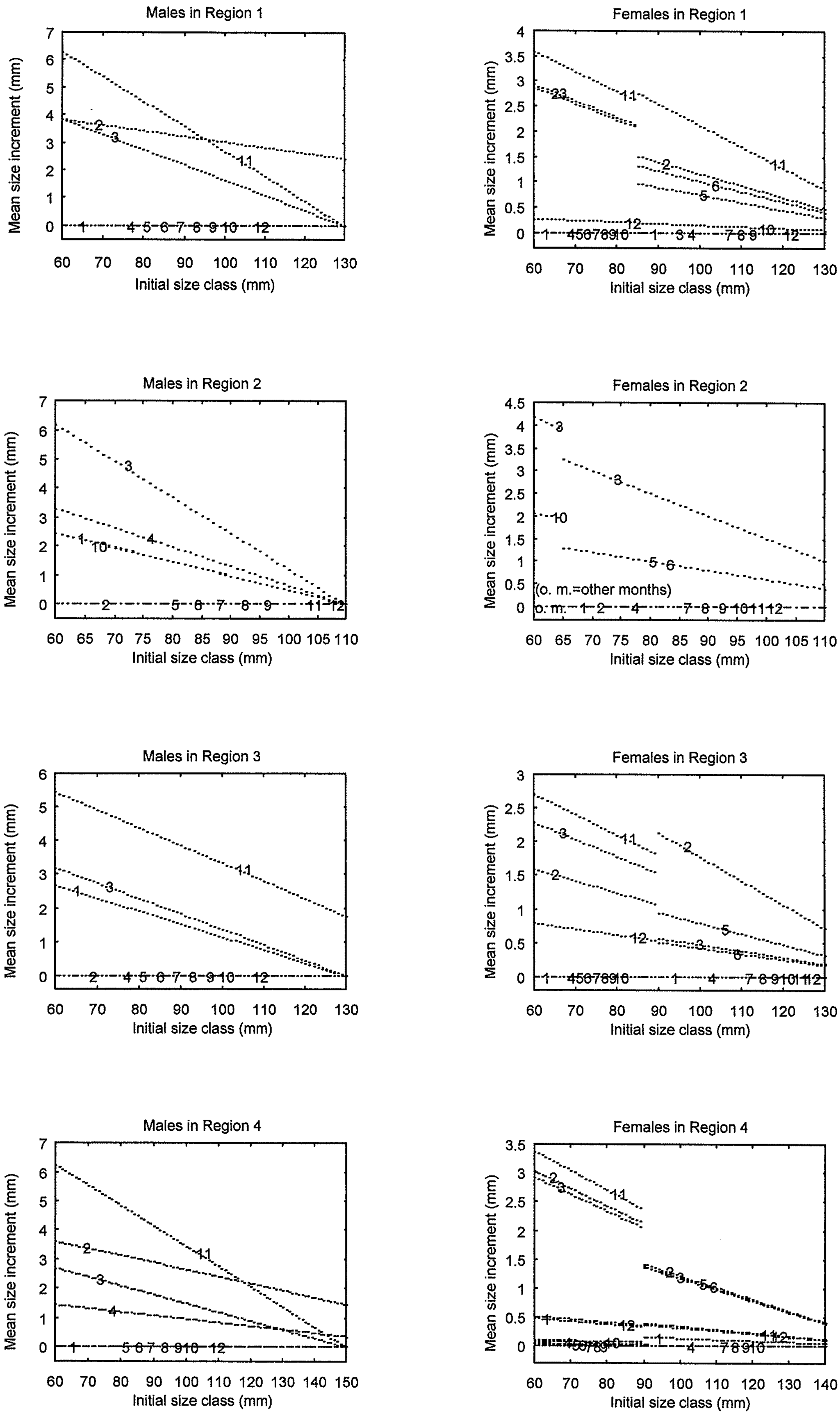
It should be noted that growth was treated as a continuous biological process. However, from the results shown in **Figure 3** there is a clear indication that peak growth occurs in February/March for all lobsters, in November for all males and immature females, and in May/June for all mature females. The results also showed that growth of some of the population may occur in other months such as January, April, October and December. Certainly these results are dependent on the availability of release and recapture data at different times of the year. But generally the results presented here are consistent with the available information regarding moulting periods for western rock lobsters (e.g., Chittleborough (1976); Morgan (1977); Phillips *et al.* (1977); Brown and Caputi (1983); Melville-Smith *et al.* (1997)).

5.1.3 Estimated annual mean size increment

The annual mean size increment was estimated by simply adding monthly mean size increments (**Figure 4**). In particular, the results in region 5 are consistent with the recent biological results obtained by Melville-Smith *et al.* (1997). The annual growth increment for smaller male lobsters ranges from 11-14 mm CL in the northern sector to 14-17 mm in the southern sector.

5.1.4 Estimated length frequency of recaptured lobsters

A measure of the accuracy of our estimation of the growth parameters or of the estimated transition matrices is to compare the estimated length frequency and size-increment frequency derived from the estimated transition matrices (see Sections 4.1.5 and 4.1.6 for the methods) with the observed length frequency and size-increment frequency of the recaptured lobsters.



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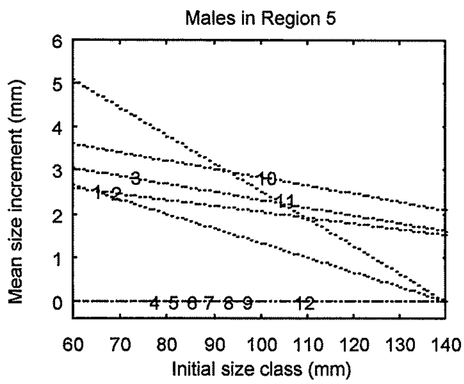


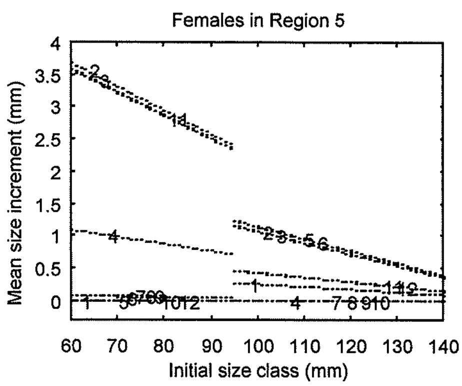
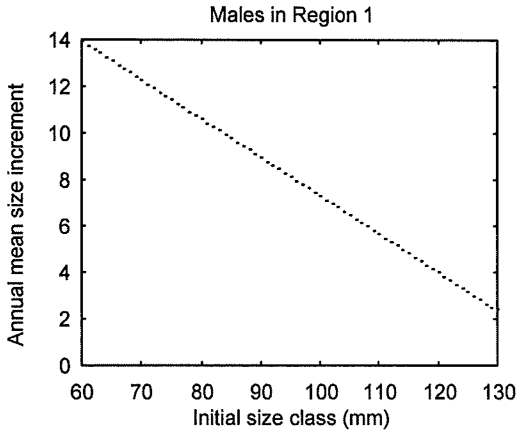
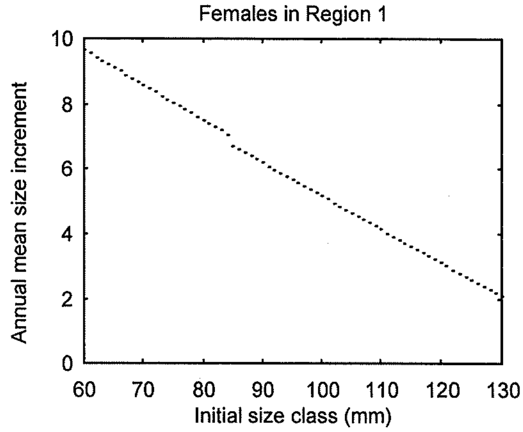
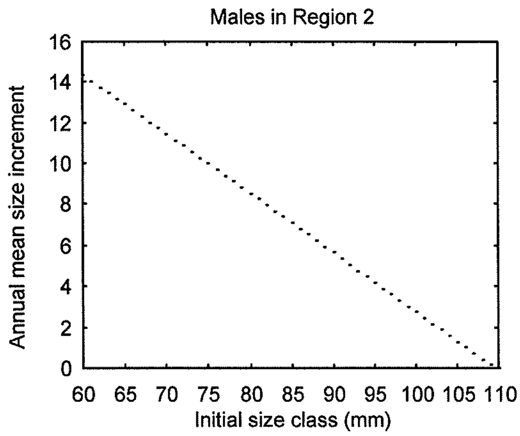
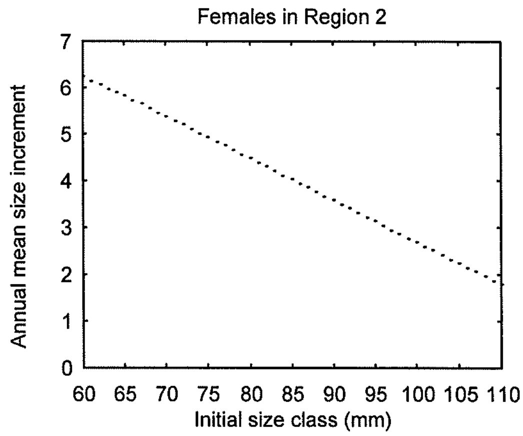


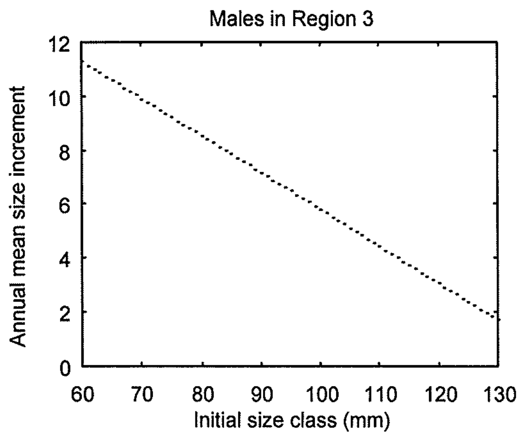
Figure 3. Monthly mean size increments of lobsters in different size classes for the five regions and two sexes. The plots in the left column are for males, and in the right column for females. The numbers 1,2,...,12 which label the lines in the plots represent the corresponding months.

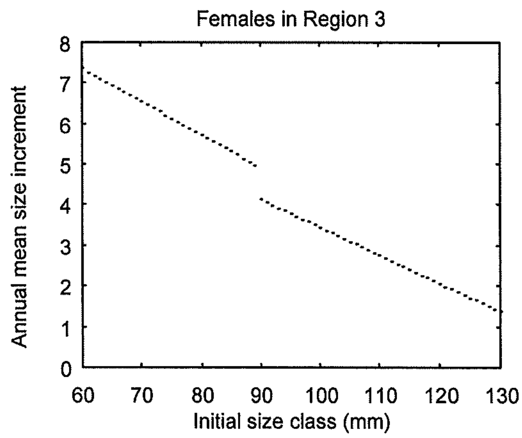

Males in Region 1
Annual mean size increment
Initial size class (mm)


Females in Region 1
Annual mean size increment
Initial size class (mm)


Males in Region 2
Annual mean size increment
Initial size class (mm)


Females in Region 2
Annual mean size increment
Initial size class (mm)


Males in Region 3
Annual mean size increment
Initial size class (mm)


Females in Region 3
Annual mean size increment
Initial size class (mm)

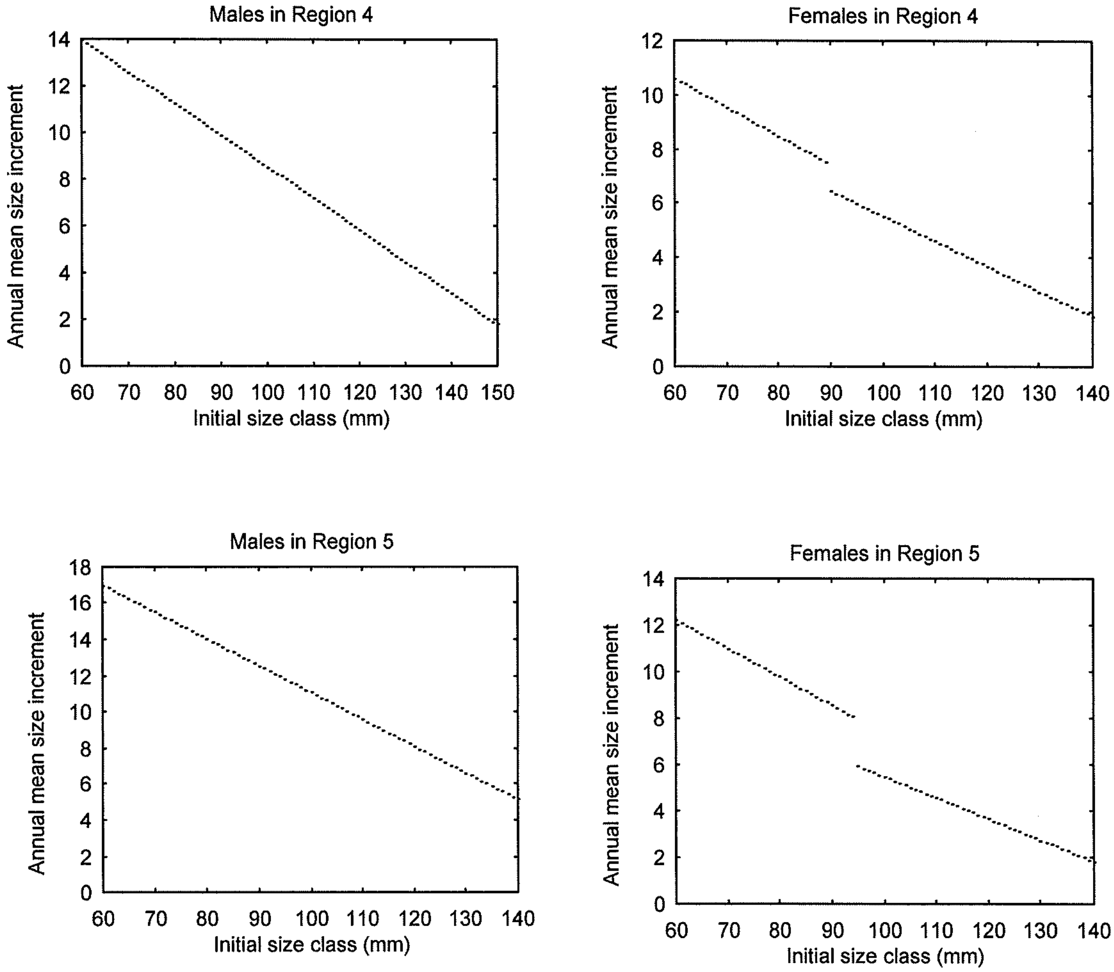


Figure 4. Annual mean size increments of lobsters in different size classes for the five regions and two sexes. The plots in the left column are for males, and in the right column for females. Separate curves were fitted for immature and mature female lobsters.

The predicted length frequency is compared with the observed length frequency for the five regions and two sexes in the plots shown in the left column of **Figure 5**. The observed length frequency distributions for recaptured lobsters are occasionally multi-modal, and have a very high peak around 75-80 mm carapace length. While the predicted length frequencies consistently do not match the high peak nor faithfully replicate the modal nature of the data, they are considered to be a reasonable fit to the observed data

5.1.5 Estimated size-increment frequency of recaptured lobsters

As above (Section 5.1.4), the size-increment frequency of recaptured lobsters was estimated from the estimated transition matrices using the method described in Section 4.1.6. The plots in the right column of **Figure 5** showed the results of the predicted size-increment frequency compared with the observed size-increment frequency for the five regions and two sexes. Here the estimated and the observed data matched reasonably accurately.

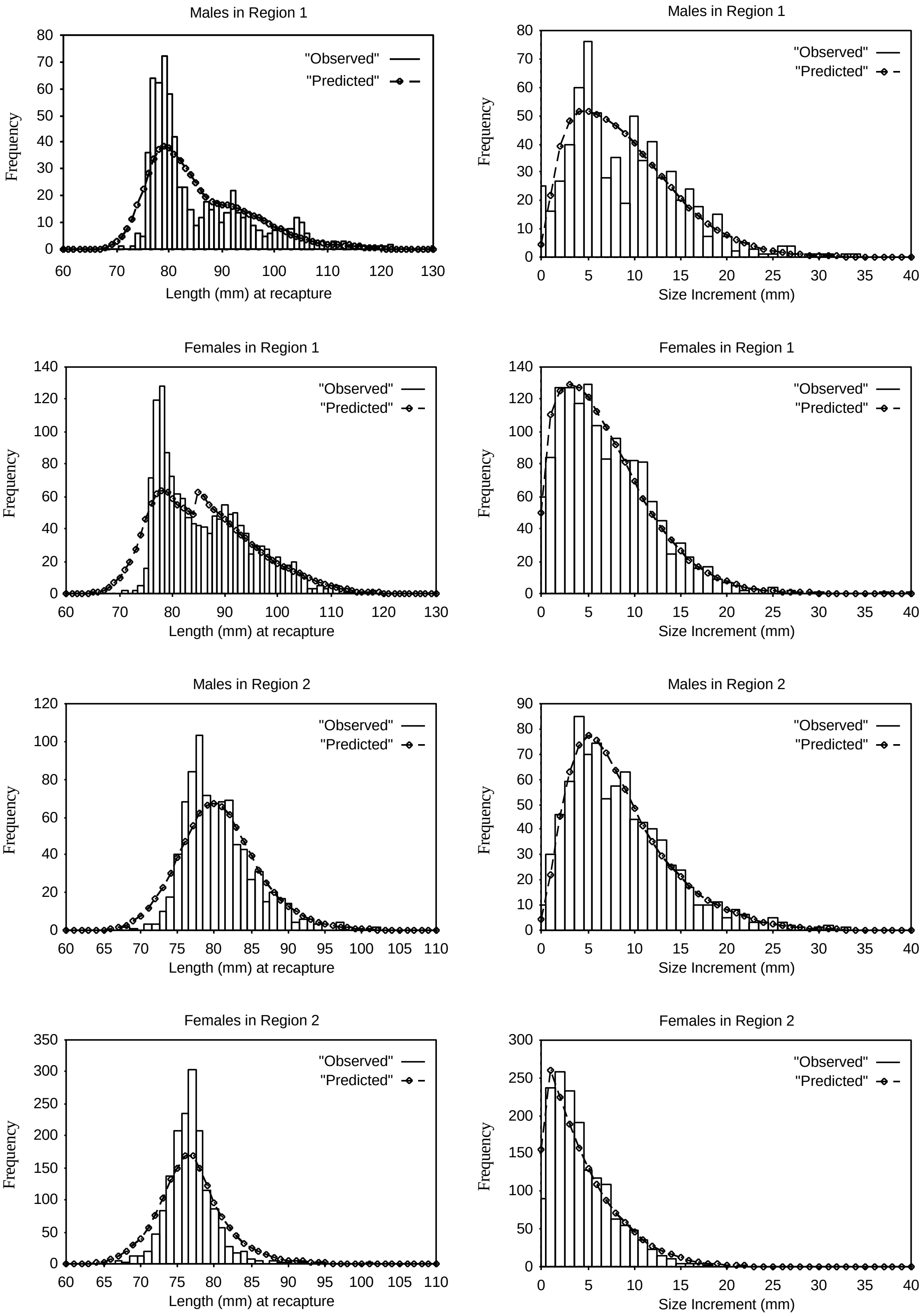
5.1.6 Estimated size-increment distribution

As described in Section 4.1.8, the percentages of lobsters initially within the size class *i* having a *j* mm size increment for any given month were calculated. These results estimate the probability of a lobster growing to any larger size class in a given month. These probabilities are exactly represented by the elements of the transition matrices (see Sections 4.1.1 and 4.1.8). **Figure 6** shows the results for each region and each sex.

Region 5 (*i.e.*, the Fremantle area) is examined below in more detail, to illustrate the interpretation of these results.

Results in region 5 for males were shown in **Figure 6** (5a), and for females in **Figure 6** (5b), where for a specified size increment the percentages were compared for different size classes and different months. The maximum length considered in region 5 was 140mm, therefore, all animals $\geq$ 140 mm (CL) were considered to lie within the same size class. In **Figure 6**, it should also be noted that the maximum initial size classes shown in the plots for different size increments are different: that is, for example, in **Figure 6** (5a) and **Figure 6** (5b), 140 mm for the plot of *P(k,k)**100, 139 mm for *P(k+1,k)**100,…, 134 mm for *P(k+6,k)**100, and 133 mm for *P(k+7,k)**100, where $P(k+i,k) = P_{(k+i),k}$, i =0,1,…,7.

From **Figure 6** (5a), if we look at an initial size class of 70mm, for example, then around 2% of male lobsters in this size class do not grow in November, 5% in February, 10% in March and October, 18% in January, and 100% in other months; similarly, around 15% of the male lobsters in this size class have a 4mm size increment in November, 11% in February, 10% in March and October, 8% in January, and 0% in other months.



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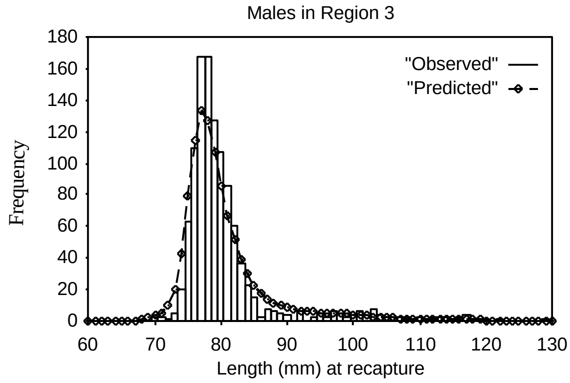

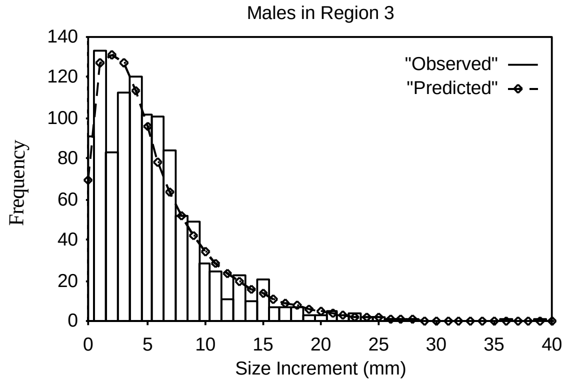

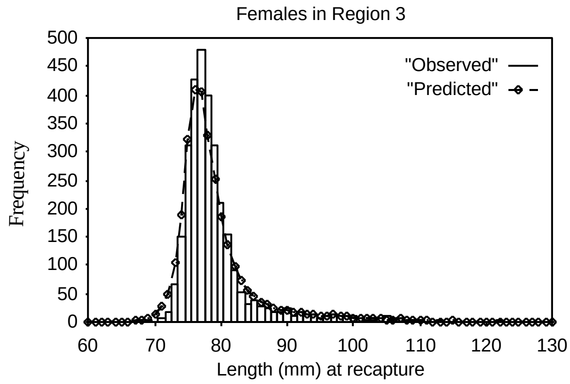

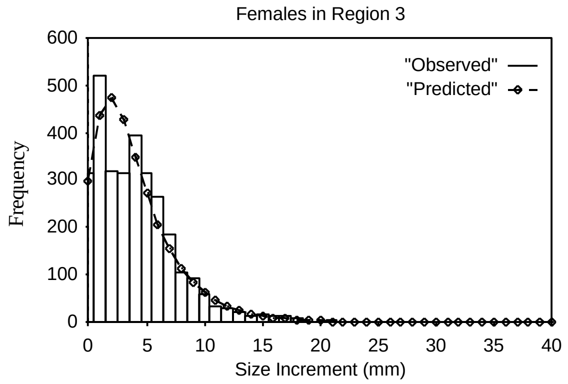

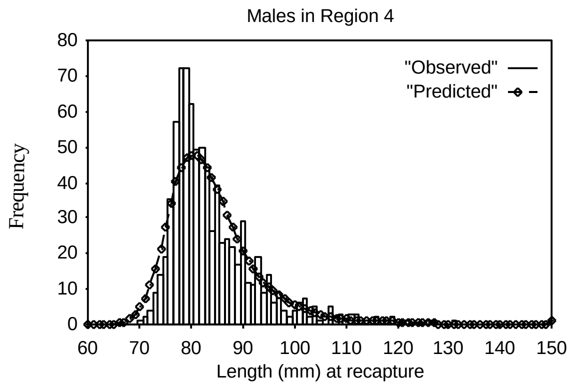

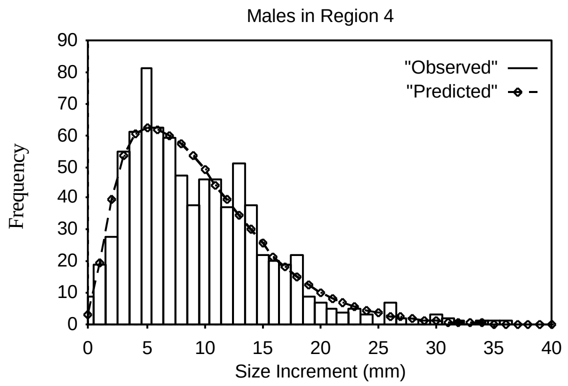

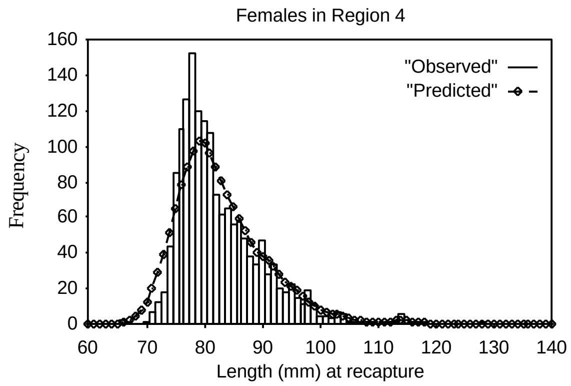

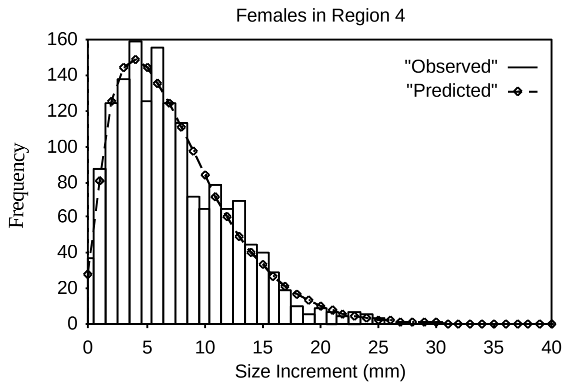

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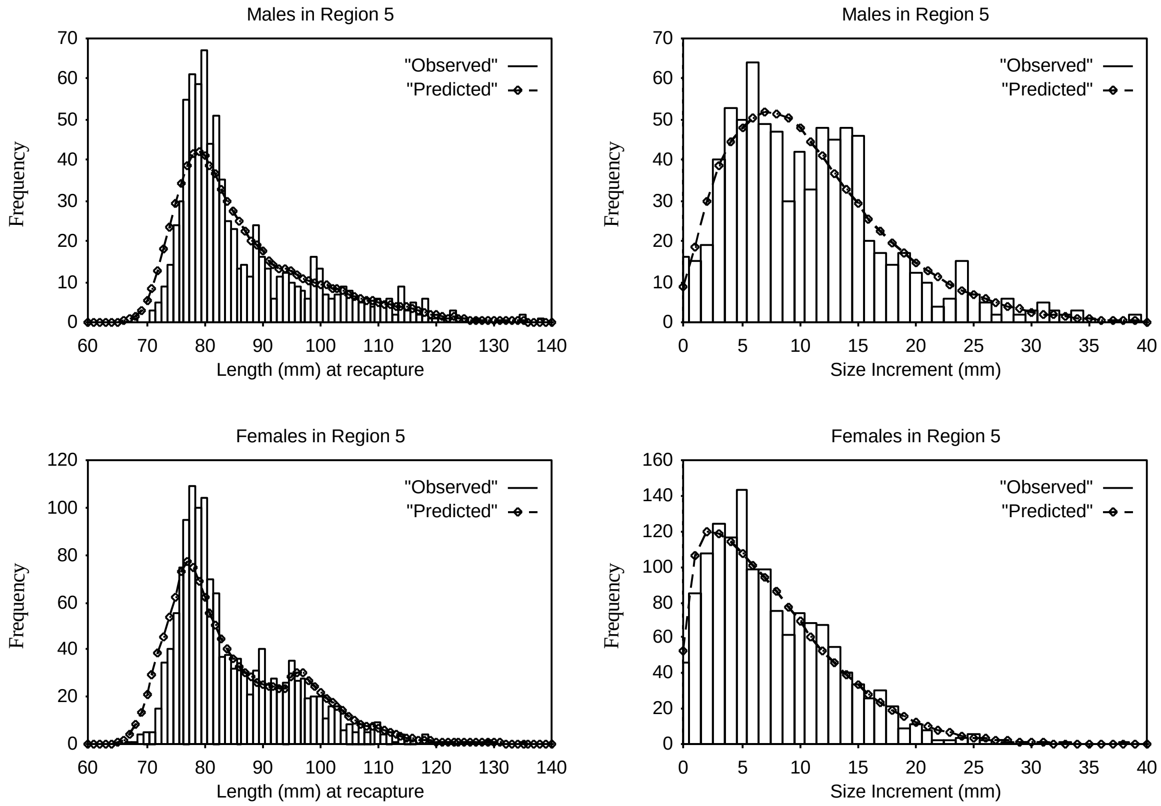


Figure 5. Comparison of the predicted and the observed length and size-increment frequencies for the five regions and two sexes. Plots in the left column are length-frequency, and in right column are size-increment frequency. These plots were obtained from all recaptured lobsters in the analysis for a given region and sex regardless of time at release and time at recapture (and length at release for the plots of size-increment frequency).

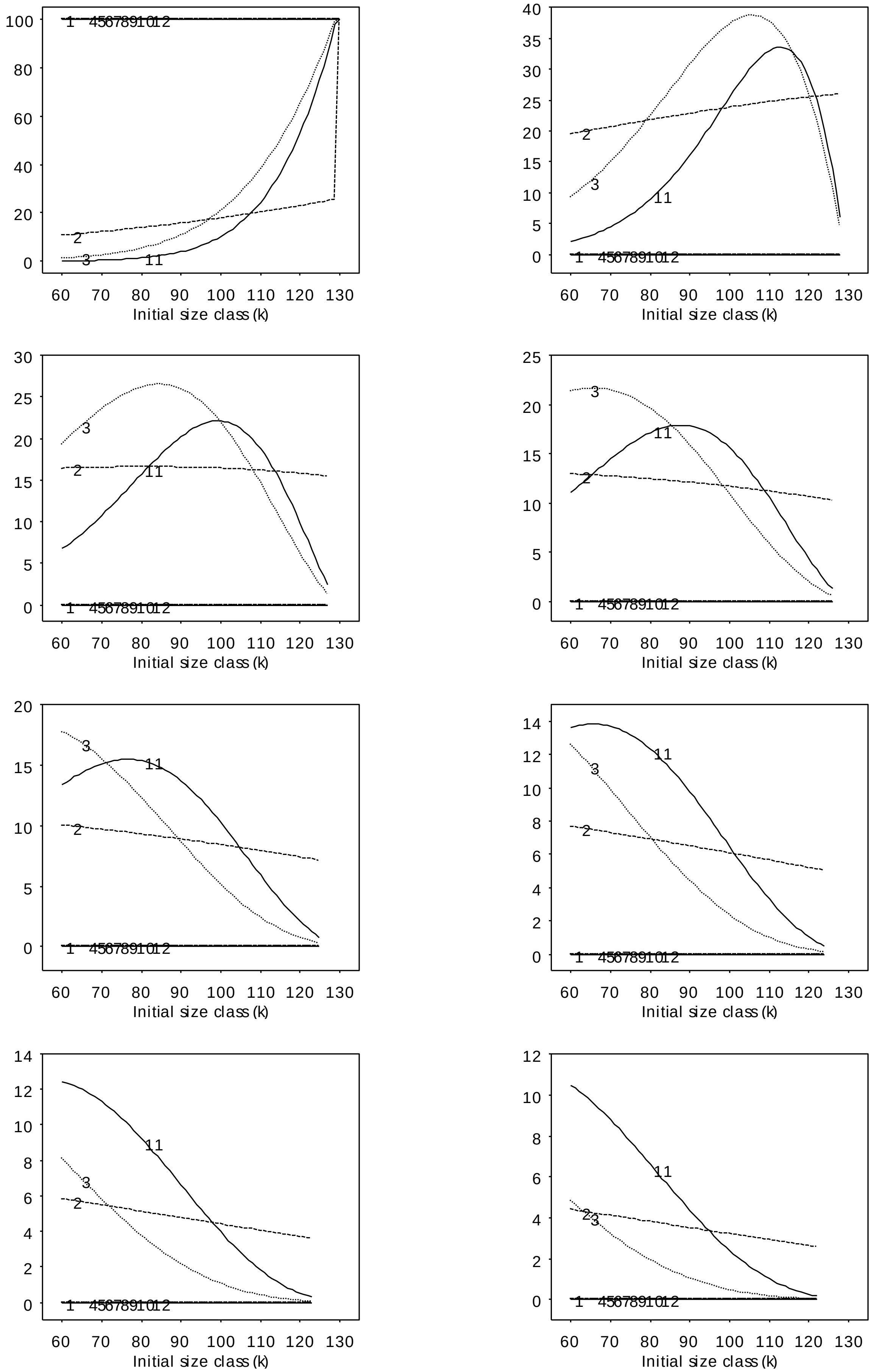


Figure 6 (1a) Males in Region 1

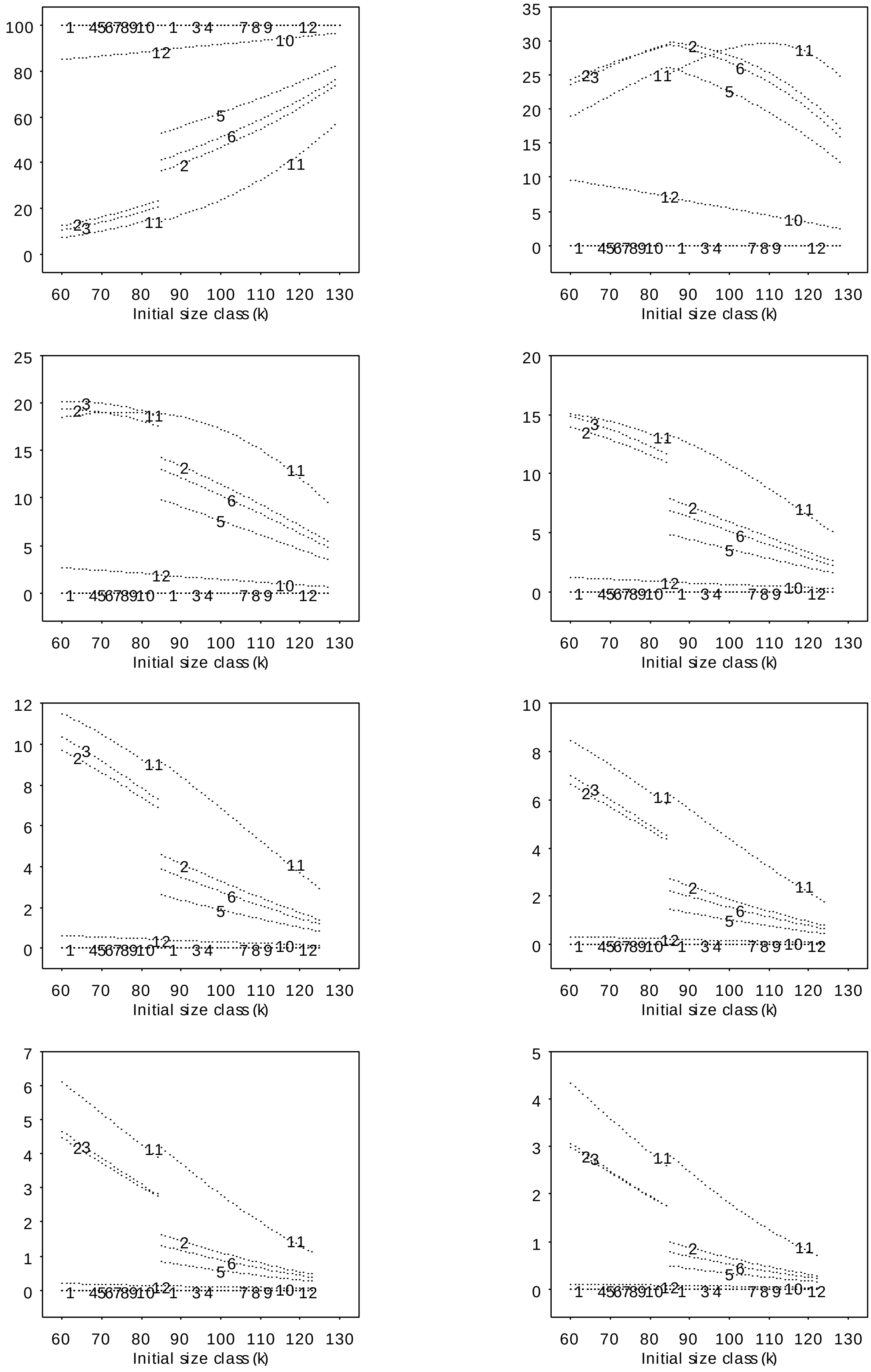


Figure 6 (1b)   Females in Region 1

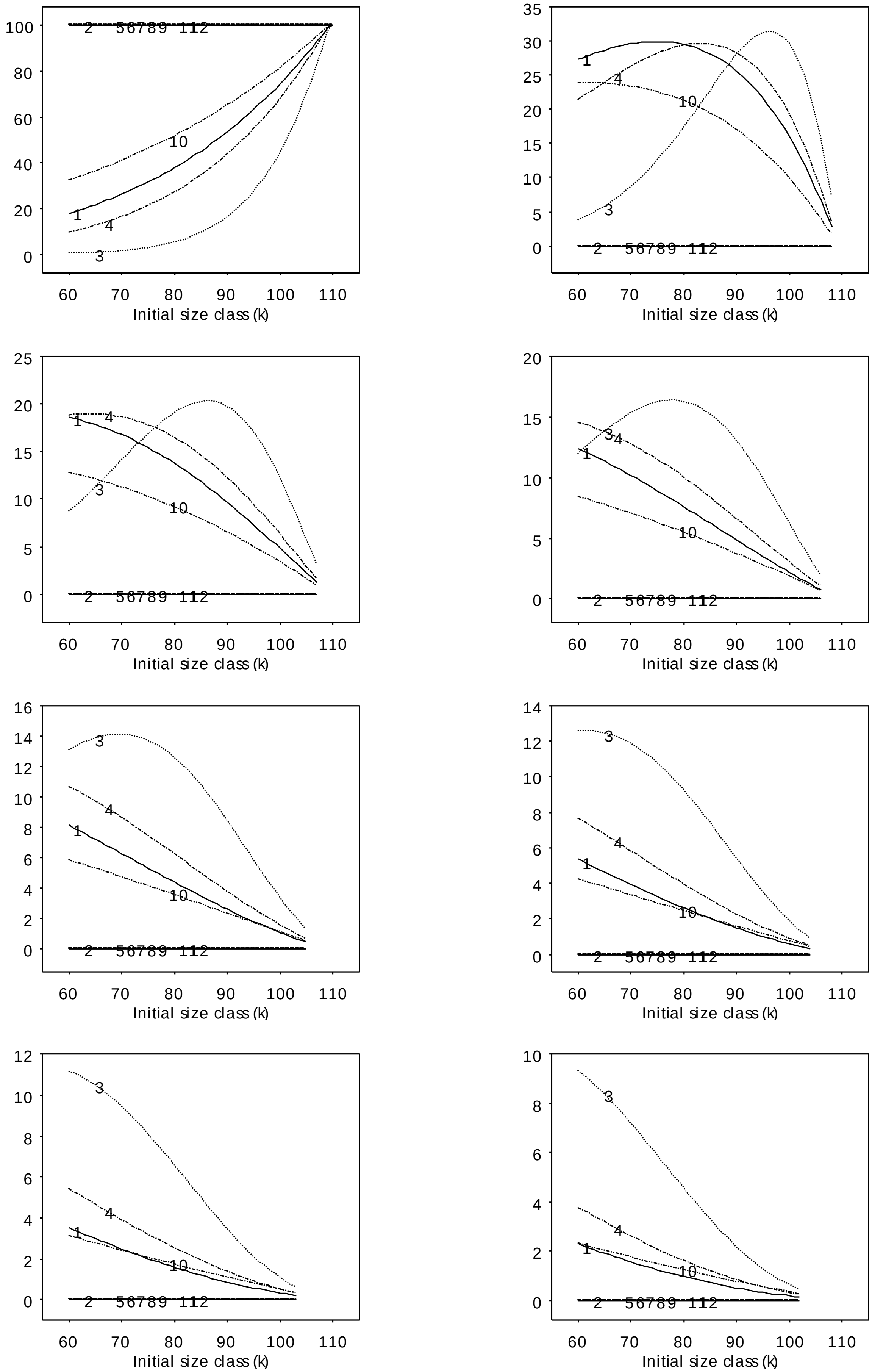


Figure 6 (2a) Males in Region 2

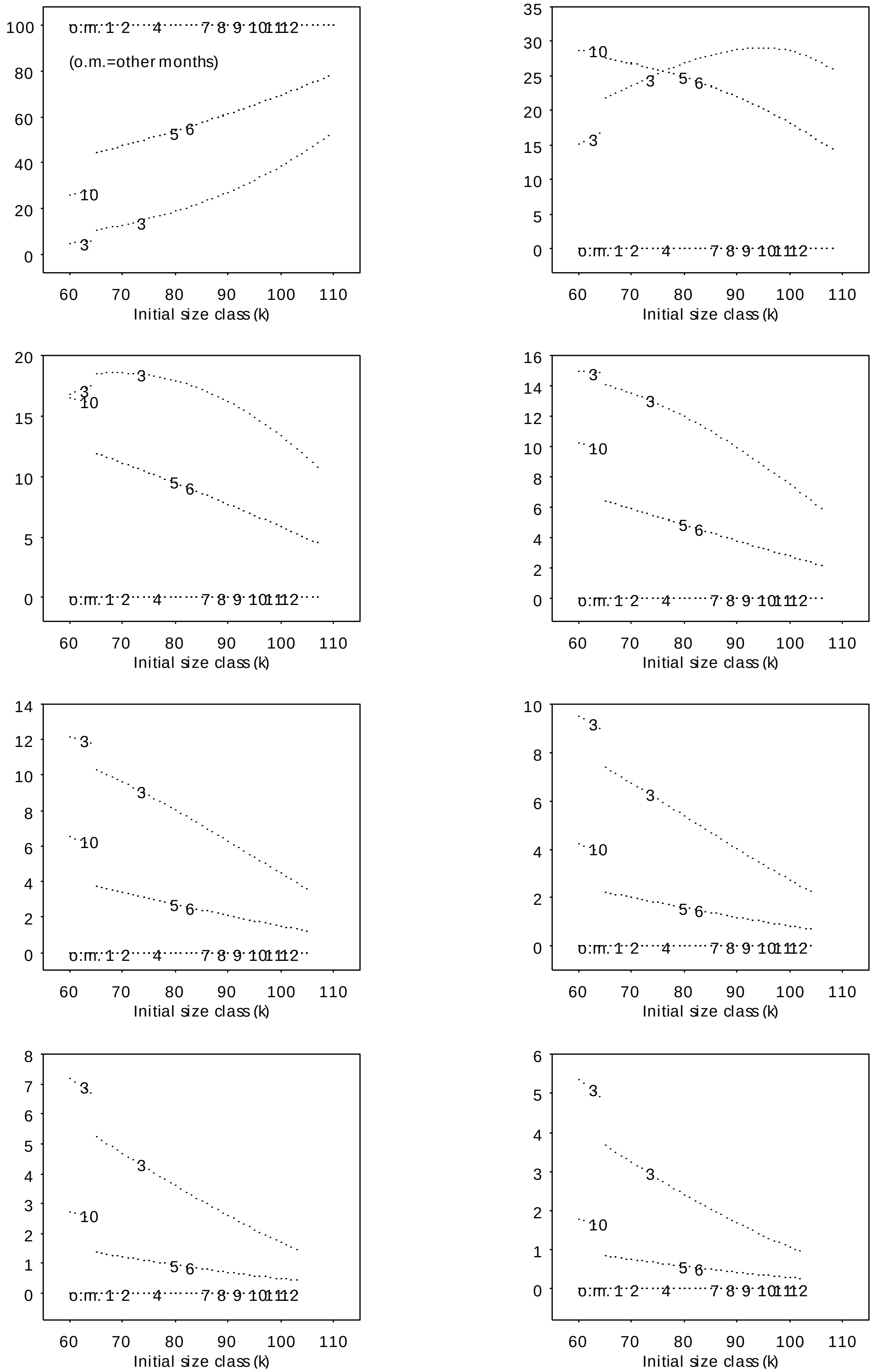


Figure 6 (2b) Females in Region 2

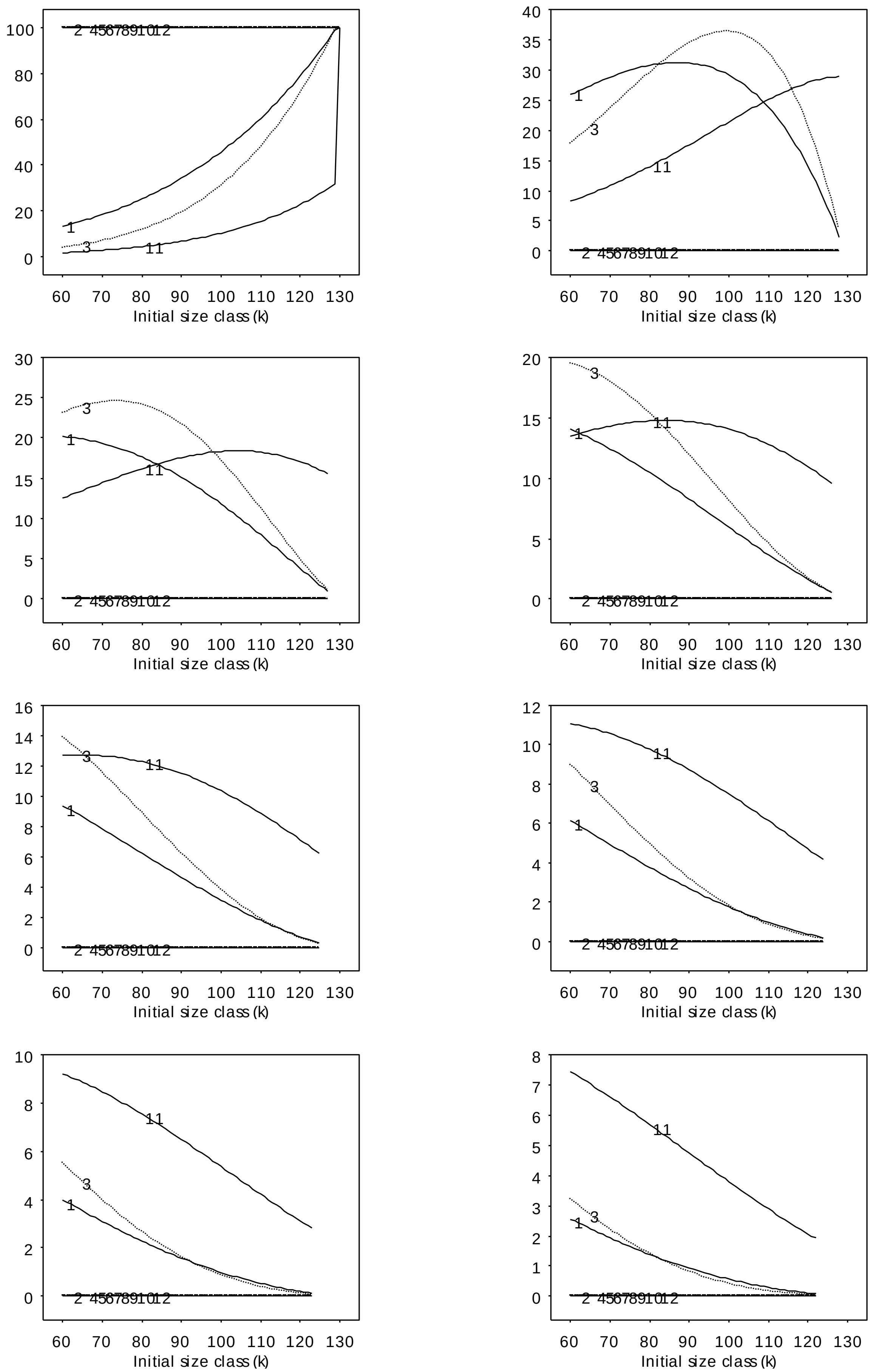


Figure 6 (3a)   Males in Region 3

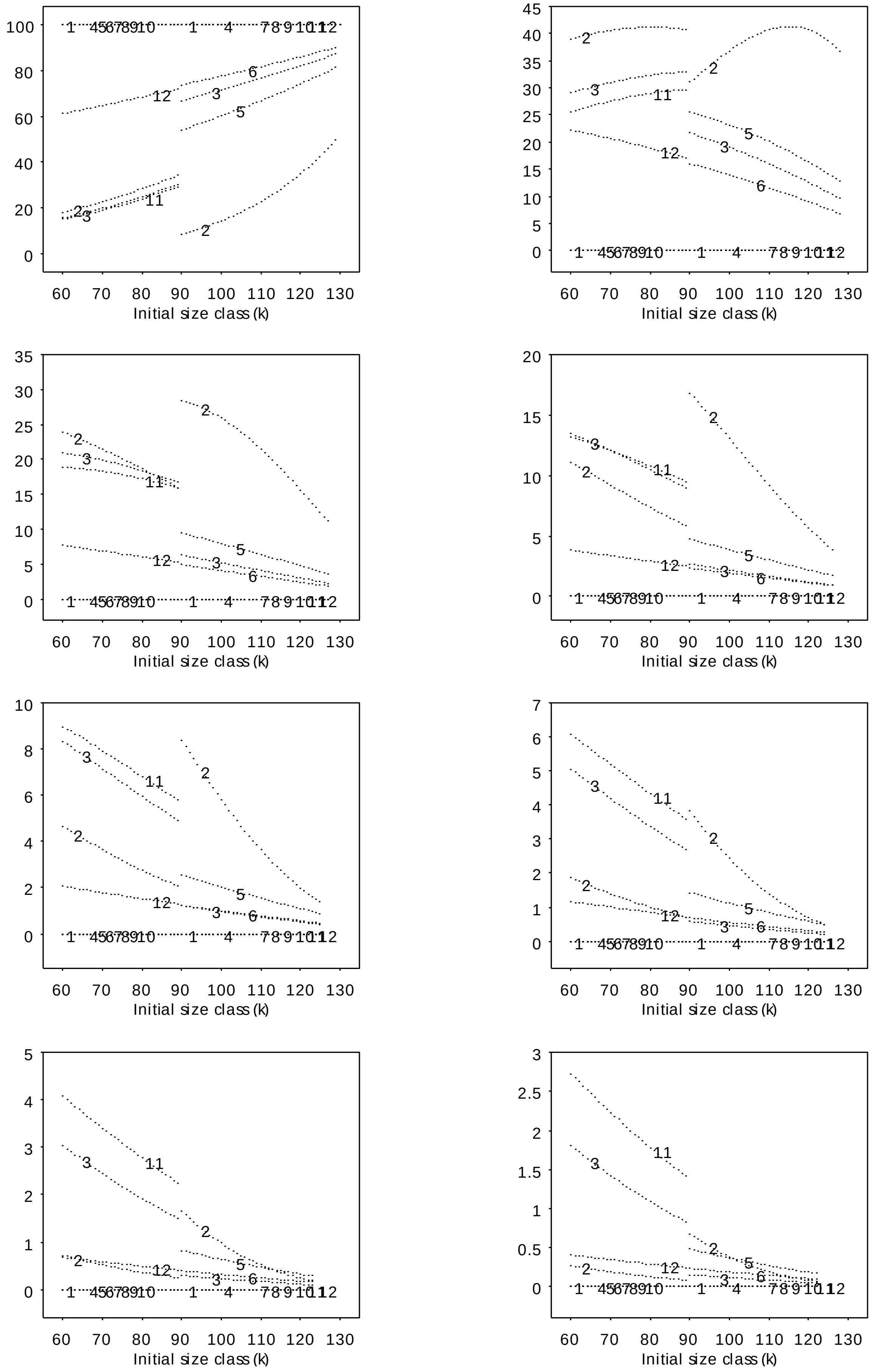


Figure 6 (3b) Females in Region 3

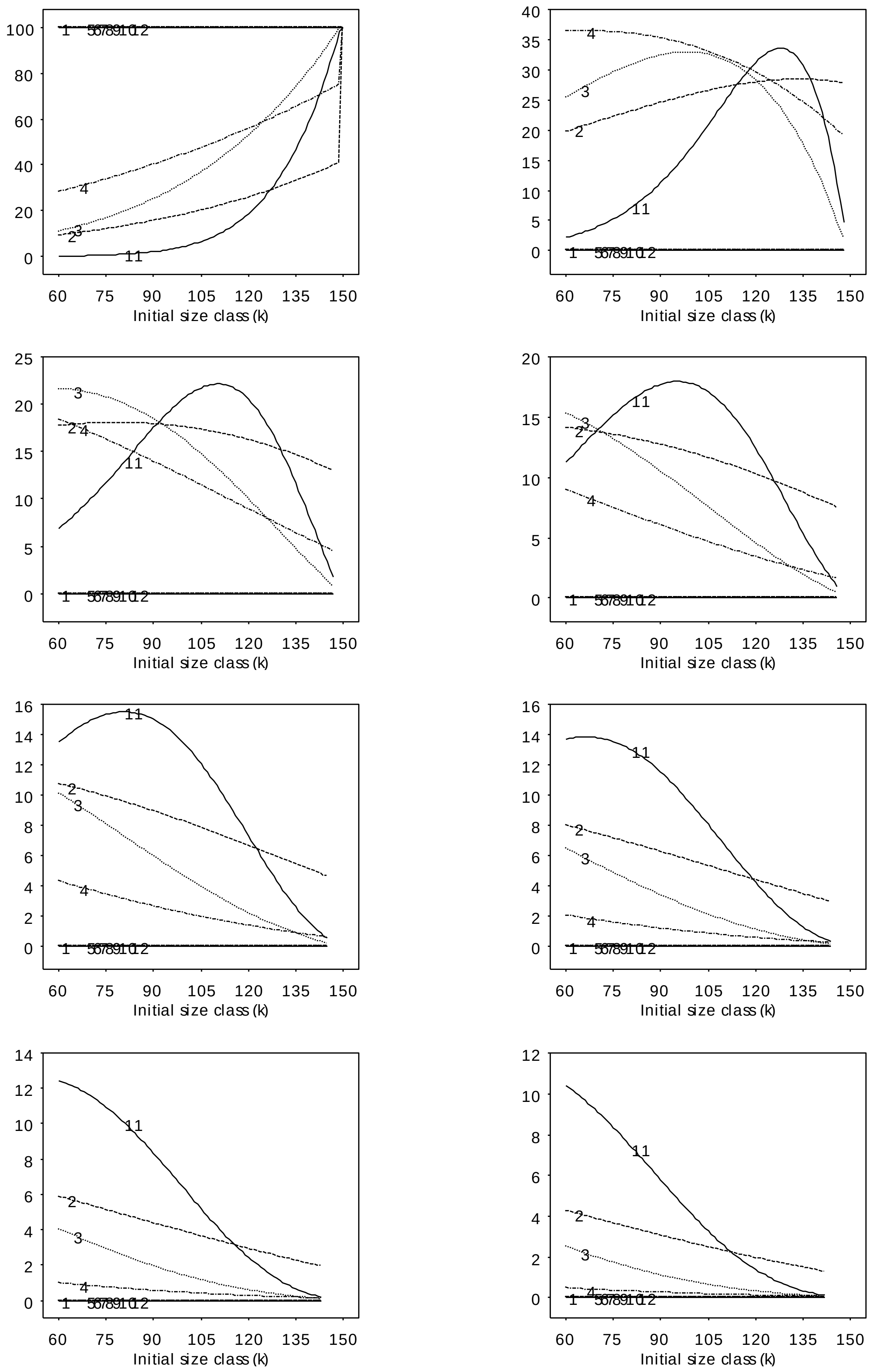


Figure 6 (4a) Males in Region 4

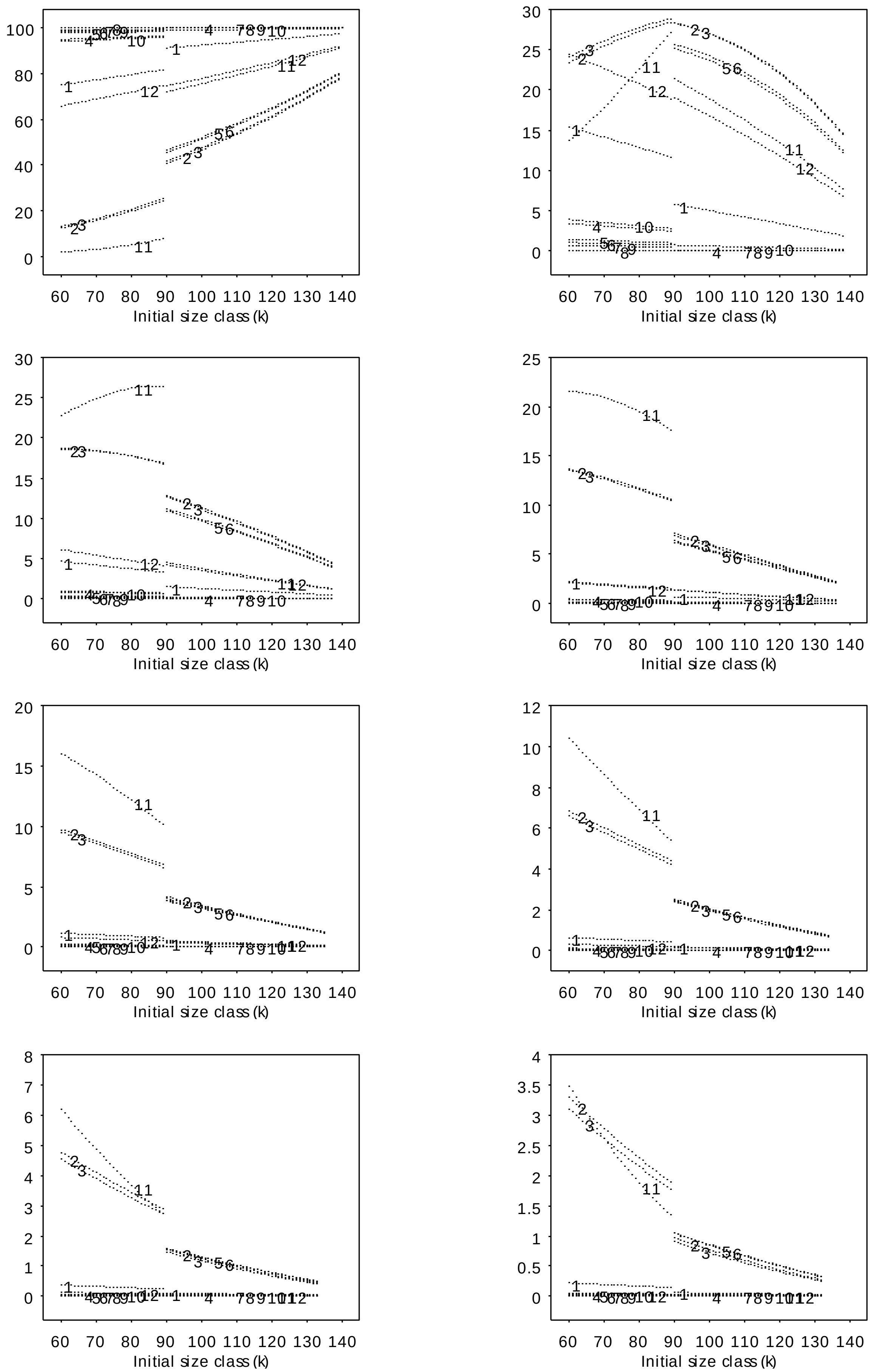


Figure 6 (4b) Females in Region 4

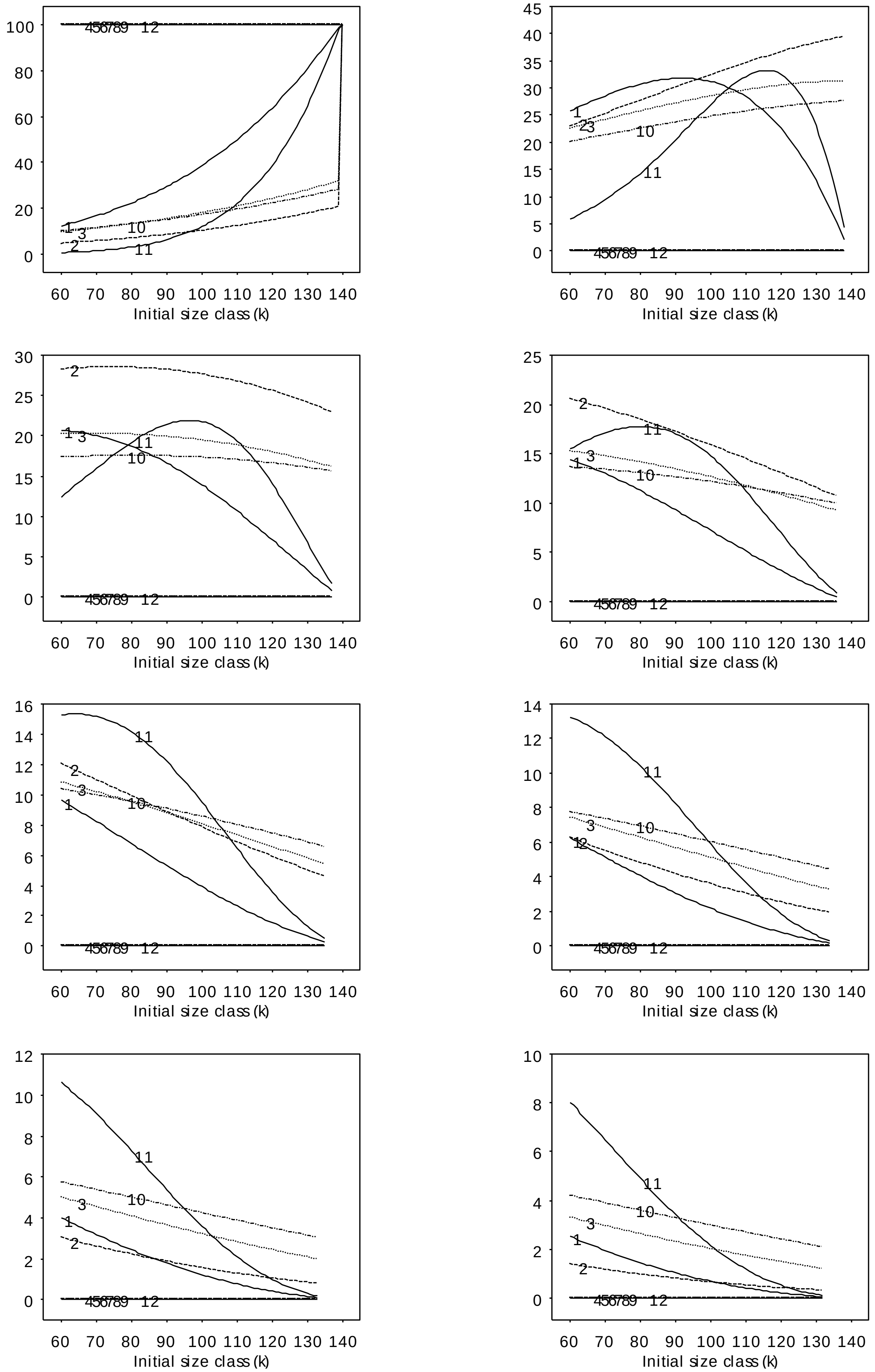


Figure 6 (5a) Males in Region 5

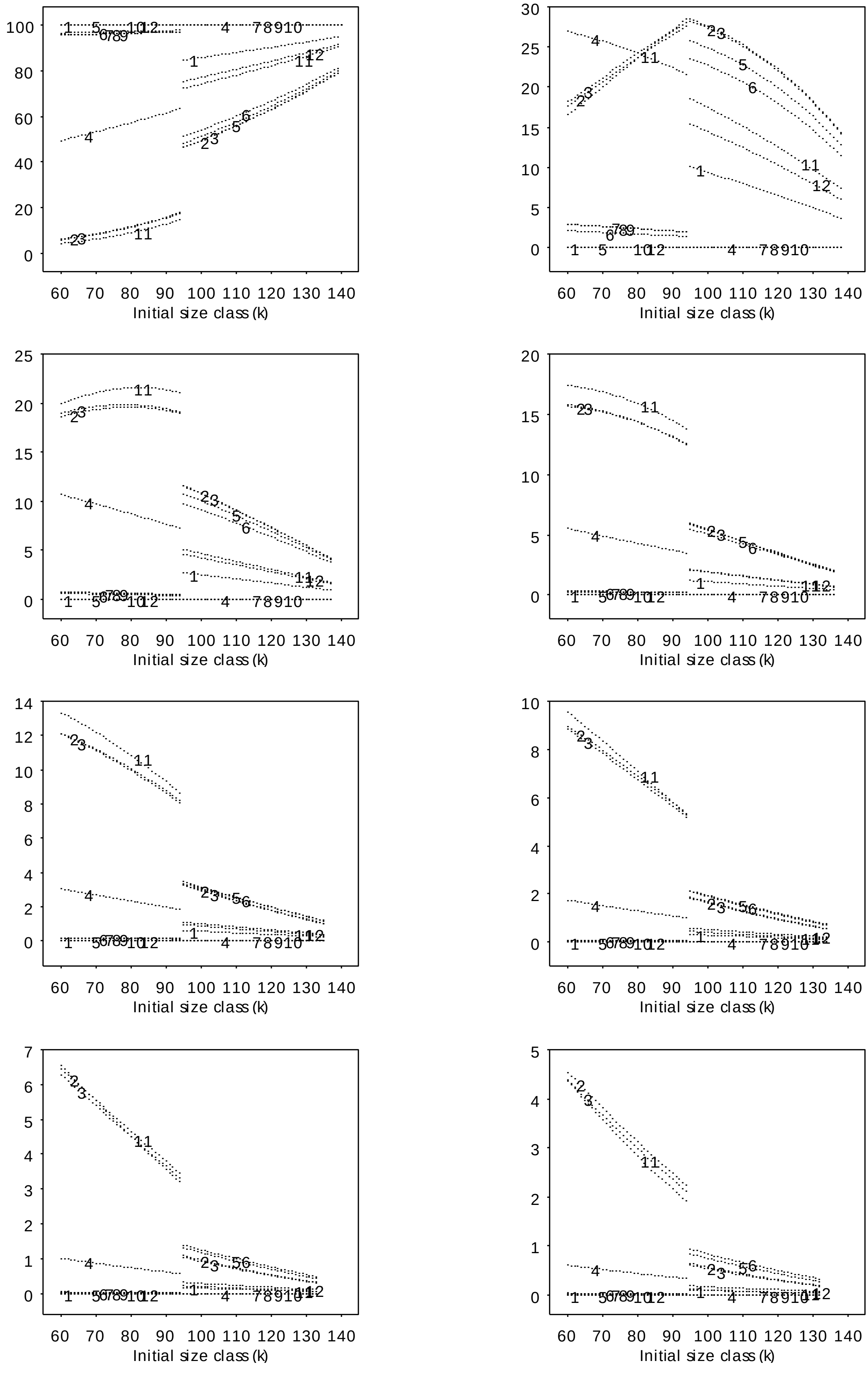


Figure 6 (5b) Females in Region 5

Figure 6. Percentages of lobsters within different initial size classes having different size increments at different months for the five regions and two sexes. *P(k+i,k)* is the *(k+i,k)*-th element in the transition matrix, *i*=0,1,…7. The numbers 1, 2, …, 12 labeled in each curve in the plots represent month from January to December, respectively. Given a size increment *i*, the plot *P(k+i,k)**100 against initial size class represents the percentages of animals within different initial size classes having the given size increment at different months. For female, different growth patterns are shown for mature and immature females, where the length at maturity (*i.e.,* Lmat) was listed in **Table 2.**

From **Figure 6** (5b), if we look at an initial size class of 70mm for immature females, for example, around 8% of lobsters in this size class do not grow in February, March and November, 50% in April, 95% in June, and 100% in other months; similarly we have around 12% of the immature female lobsters in this size class having a 4mm size increment in November, 11% in February and March, 3% in April, and 0% in other months. If we look at an initial size class of 120mm for mature females, for example, around 60% of lobsters in this size class do not grow in February, March, May and June, 80% in November and December, 90% in January, and 100% in other months; around 7% of the mature female lobsters in this size class have a 2mm size increment in February, March, May and June, 3% in November and December, 2% in January, and 0% in other months.

5.1.7 Discussion

The key assumption of the method (see Section 4.1.1) for estimation of growth transition matrices presented in this study was that the probabilities of transitions between different sizes were from a gamma distribution.

The indicator formed by comparing predicted length and size-increment frequencies with the observed frequencies showed that the estimated transition matrices in this study fitted the observed data reasonably well and the predicted results are therefore considered to be reliable.

However, it should be recognised that the transition matrices assumed that growth is continuous and thus the mean increment per month is not equivalent to the mean moult increment. This is due to the fact that the transition matrices reflect the probability of a particular size class of the whole population not growing or growing to a larger size class. This combination leads to the population mean size increment for that size class and the month. In order to validate the predictions of growth by the transition matrices with the information on growth from biological field studies, we need to estimate moult increment from the part of the population that is actually growing to a larger size or to assess growth on an annual basis. In this instance, the latter approach is more useful. The transition matrices predict that lobsters with an initial length of 60-85mm (CL) in region 5, for example, have a mean annual increment around 15mm (CL) and 10mm (CL) for males and females, respectively. Melville-Smith *et al*. (1997) reported that rock lobsters between 60 and 85mm (CL) in the Fremantle area (part of our region 5) had two moults per year and a mean moult increment of 6.67 (sd = 2.6) mm (CL) for males and 5.24 (sd=1.47) mm (CL) for females. Mean annual growth for these lobsters, therefore, was about 13mm (CL) and 10mm (CL) for males and females, respectively. Thus the predictions from the transition matrices are consistent with Melville-Smith *et al*'s (1997) result, suggesting that the transition matrices estimated in this study provide a realistic estimation of growth in region 5 and, by inference, across the whole fishery.

5.2 Size-structured modelling

The results presented in Section 5.1 showed that the estimated growth transition matrices provided a realistic description of growth across the whole fishery. This growth information was a key input to the size-structured model. In this section, the results from the study of the size-structured modelling are reported. The results basically reflect the capabilities of the size-structured model developed in this study. The capabilities include the ability of the model to predict catch and CPUE, to estimate recruitment and egg production, to explore various management strategies and to provide estimates of the economic impacts resulting from application of different management strategies. An illustration of the use of the model for exploring management strategies is presented in Section 5.3, and an example of the economic output available from the model is reported in Section 5.4. The model's ability to predict the catch and CPUE and the estimation of recruitment and egg production are presented below.

The results from the alternative model structures and approaches have been discussed in the report. However, in order to reduce the volume of the final document, it has been necessary to constrain the number of figures presented. Only those graphs resulting from the model when it was conditioned on effort, and for which recruitment was calculated from the preceding puerulus settlement indices, have been included. Graphical output from the analyses when the model was conditioned on catch have not been included as they were similar to those presented. Further, graphs have not been shown for the analyses when the levels of annual recruitment were estimated as model parameters (Section 4.2.4).

5.2.1 Model parameters

The set of parameters used within the fishery model is dependent on the model assumptions that were considered. Details of these model parameters were described in Section 4.2.7. Basically two cases were considered, where the model was either (1) conditioned on catch; or (2) conditioned on effort. In the first case, two further sub-cases were considered: (i) recruitment estimated from the puerulus settlement index; and (ii) annual recruitment estimated as a parameter in the model (see Section 4.2.4). When the model was conditioned on effort, the recruitment was estimated from the puerulus settlement indices, however, similar results to the case when the model was conditioned on catch and annual recruitment was estimated as a parameter would have been expected if the model had been conditioned on effort and the annual recruitment had been estimated as a model parameter.

5.2.2 Model predictions

For a given fishing region and sex (male or female), the model predicted the catch, *i.e.,* $\hat{C}_t(l)$ (number of lobsters caught) and CPUE, *i.e.,* $CP\hat{U}E_t(l)$ (number of lobsters caught per pot lift) by time t (month) and size class l (1mm) using the formulae in Eq. 4.19 and Eq. 4.20 when the model was conditioned on catch, and in Eq. 4.24 and Eq. 4.25 when the model was conditioned on effort. **Note:** all results presented below are catch in numbers (not in weight), unless mentioned otherwise.

For convenience, denote $\hat{C}_{y,m}(l,s,r)$ and $CP\hat{U}E_{y,m}(l,s,r)$ as the predicted catch and CPUE, respectively, with sex s and size class l at the month m of year y in region r, where five regions (r=1, 2, 3, 4 and 5) were considered, *i.e.,* Abrolhos Islands, Dongara, Jurien, Lancelin and Fremantle regions, and two sexes (s=1,2), *i.e.,* male and female. Note that the time t was replaced by the month m of year y because the time step in the model was a month.

Remarks

From the above notation, the predicted catches and CPUEs have five coordinate indices, *i.e.,* month, year, size, sex and region. The most detailed comparison between the model predictions and the actual data would be a comparison against these 5 coordinate indices, and the least detailed comparison would be a comparison against none of the five coordinate indices, *i.e.*, comparison between the predicted total catch/CPUE and the actual total catch/CPUE, where the total catch is estimated by $\sum_{y,m,l,s,r} \hat{C}_{y,m}(l,s,r)$, and total CPUE by $\sum_{y,m,l,s,r} CP\hat{U}E_{y,m}(l,s,r)$, and the sum is taken over all y, m, l, s, and r, thus the resultant sum (*i.e.*, total catch or CPUE) loses the resolution associated with any of the five coordinate indices.

In other words, the degree of detail of the comparison between the model predictions and the actual data is dependent on the selection of how many of the five coordinate indices are to be used in the comparison. For example, if we did not wish to show the model predictions against size class, we could sum the predicted catch/CPUE over all size classes; thus the summed predictions would have lost the associated size information. It is generally easier to match the model predictions containing less detailed information to the corresponding observed data, because more uncertainties and more variability exist in the data described at a greater level of resolution and which contain more information than the data reported at a lower resolution which contain less information.

The most detailed comparison of the model predictions with the actual data, *i.e.*, comparison made over the five coordinate indices, is presented below, while a less detailed comparison is presented later.

5.2.2.1 Prediction of CPUE by year, month, size, and sex

To show the model prediction in comparison with the actual data, we provided a comparison for the most recent season, *i.e*., 1998/99. The results of the comparison for other seasons were quite similar to those presented for the 1998/99 season. Only the results for CPUE were shown in this section. The accuracy of predictions for catch would have been similar to those presented for CPUE.

The catch rates estimated when the model was conditioned on effort, and recruitment strength was predicted from the puerulus settlement indices, are shown in **Figure 7**. The comparison between model prediction and the actual data is made against size, month, sex and region. The sizes shown in the figures are only those size classes used when fitting the model, *i.e.*, 1 mm classes from 76-80 mm and 5 mm classes from 81-120 mm and a single class for all lobsters with C.L. over 120 mm.

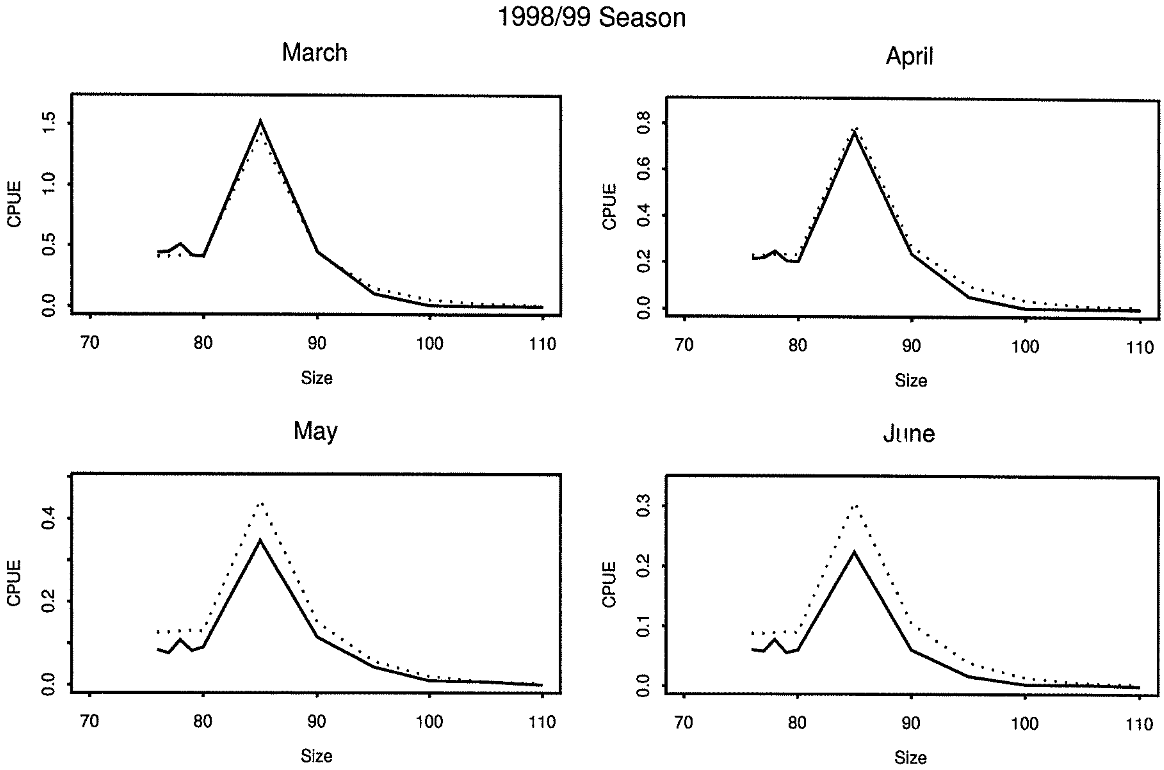
5.2.2.2 Prediction of Length-frequency

As discussed above, the model could predict catch and CPUE by time (year and month), size class (1mm), sex and region. This basically implies that the model has the capacity to provide a very detailed prediction of catch and CPUE. **Figure 7** showed such detailed predictions. In this section and the three subsequent sections, we provided some less detailed predictions. The length-frequency of the catch was considered to be a useful measurement or statistic for the fishery, and could be estimated by:

$$\mathrm{LF}^{\wedge}(l,s,r)=\sum_{y,m}\hat{C}_{y,m}(l,s,r),$$

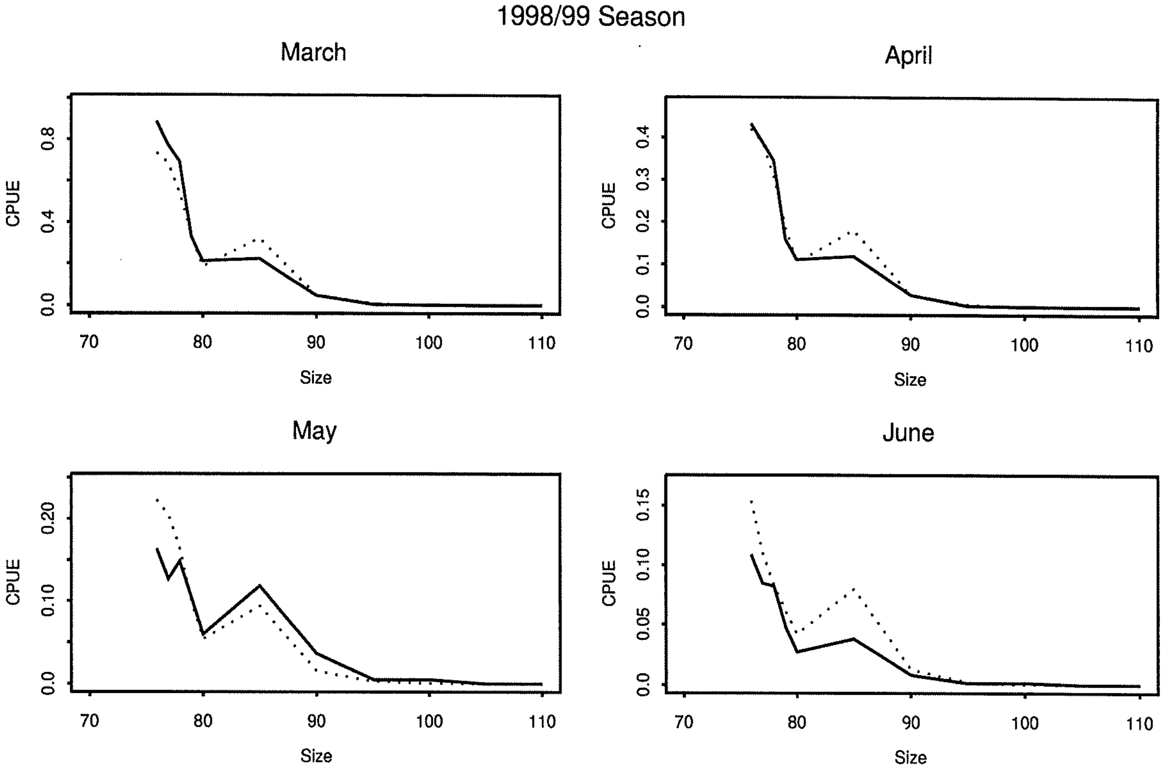
where the sum is taken over all historical years and months. The actual length-frequency could be estimated by substituting the estimated catch in the above formula by the actual catch.

The results for the model when conditioned on effort are shown in **Figure 8**. The results were presented by sex and region.



Abrolhos islands region - Males

Figure 7 (1a)



Abrolhos islands region - Females

Figure 7 (1b)

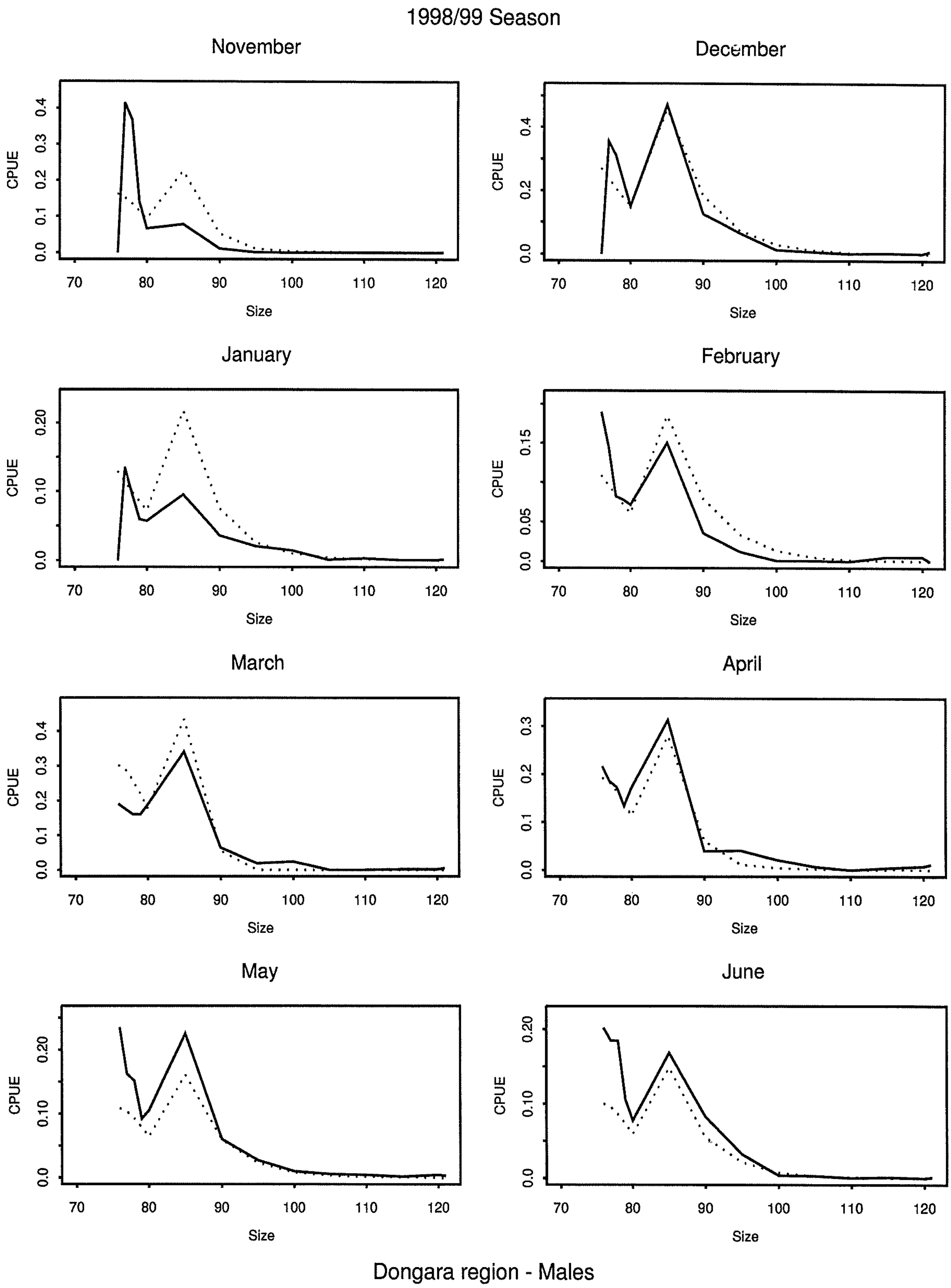
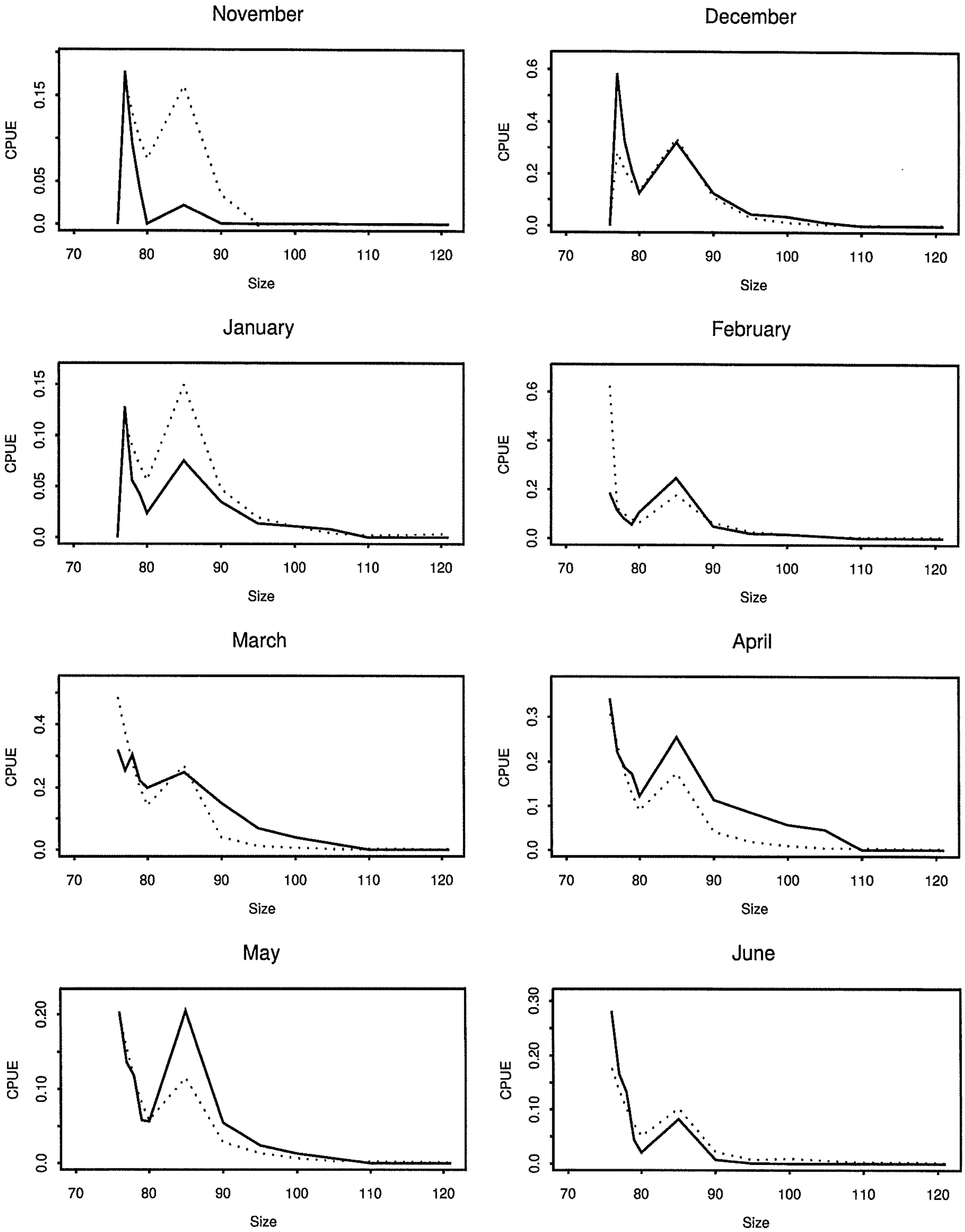

1998/99 Season
November
December
January
February
March
April
May
June
CPUE
Size
70
80
90
100
110
120
0.0
0.1
0.2
0.3
0.4
0.05
0.10
0.15
0.20
Dongara region - Males

Figure 7 (2a)

1998/99 Season



Dongara region - Females

Figure 7 (2b)

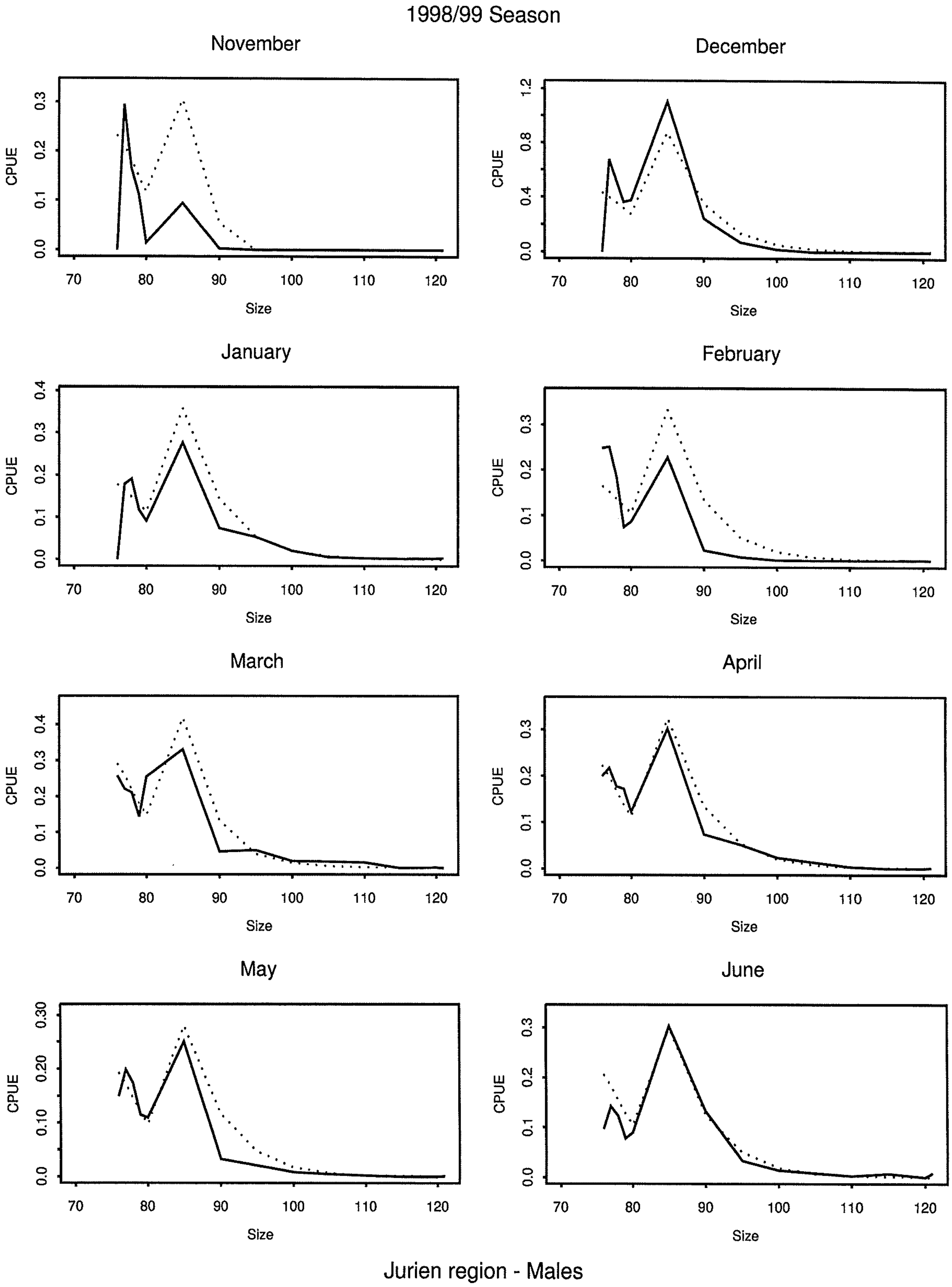
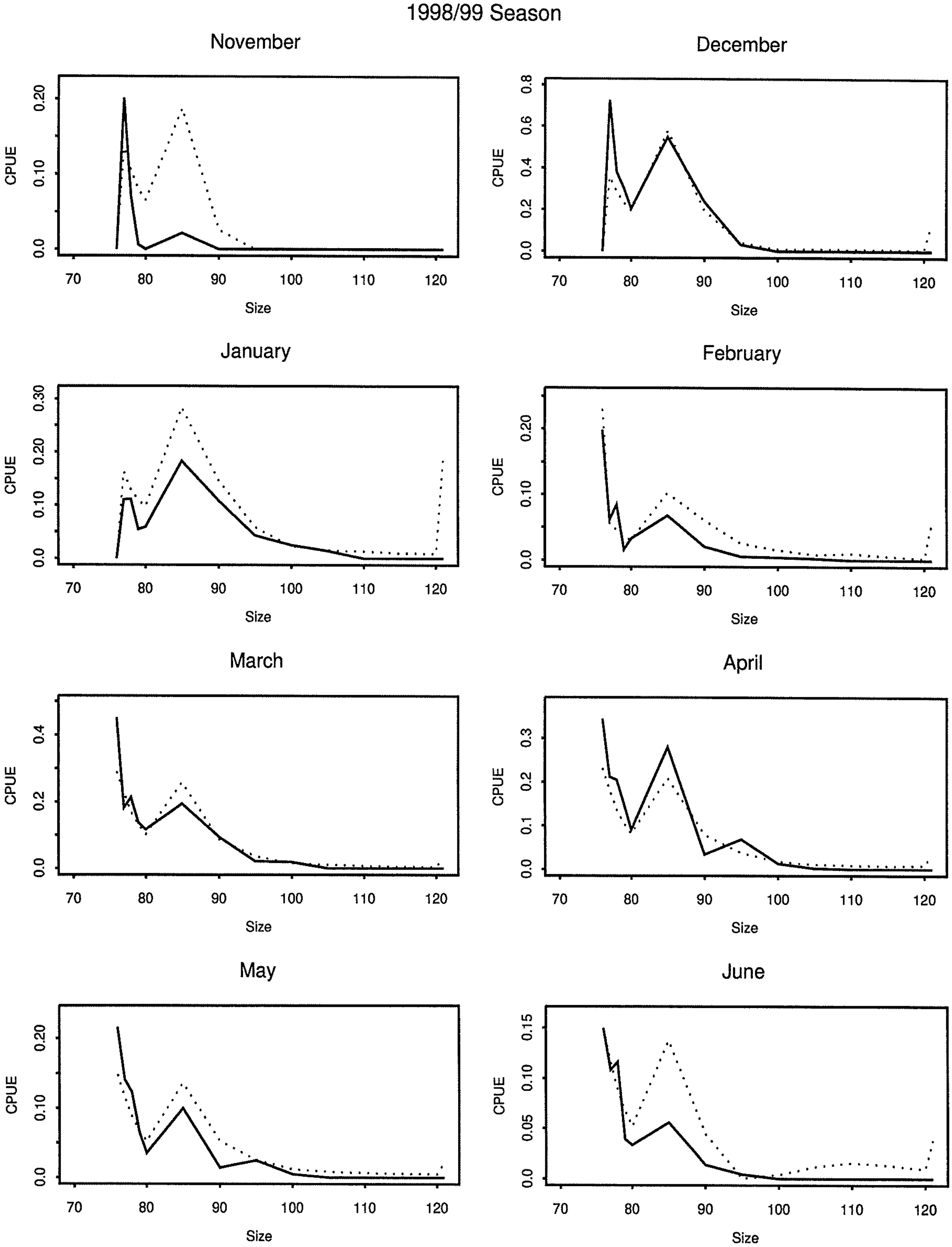

1998/99 Season
November
December
January
February
March
April
May
June
CPUE
Size
70
80
90
100
110
120
Jurien region - Males

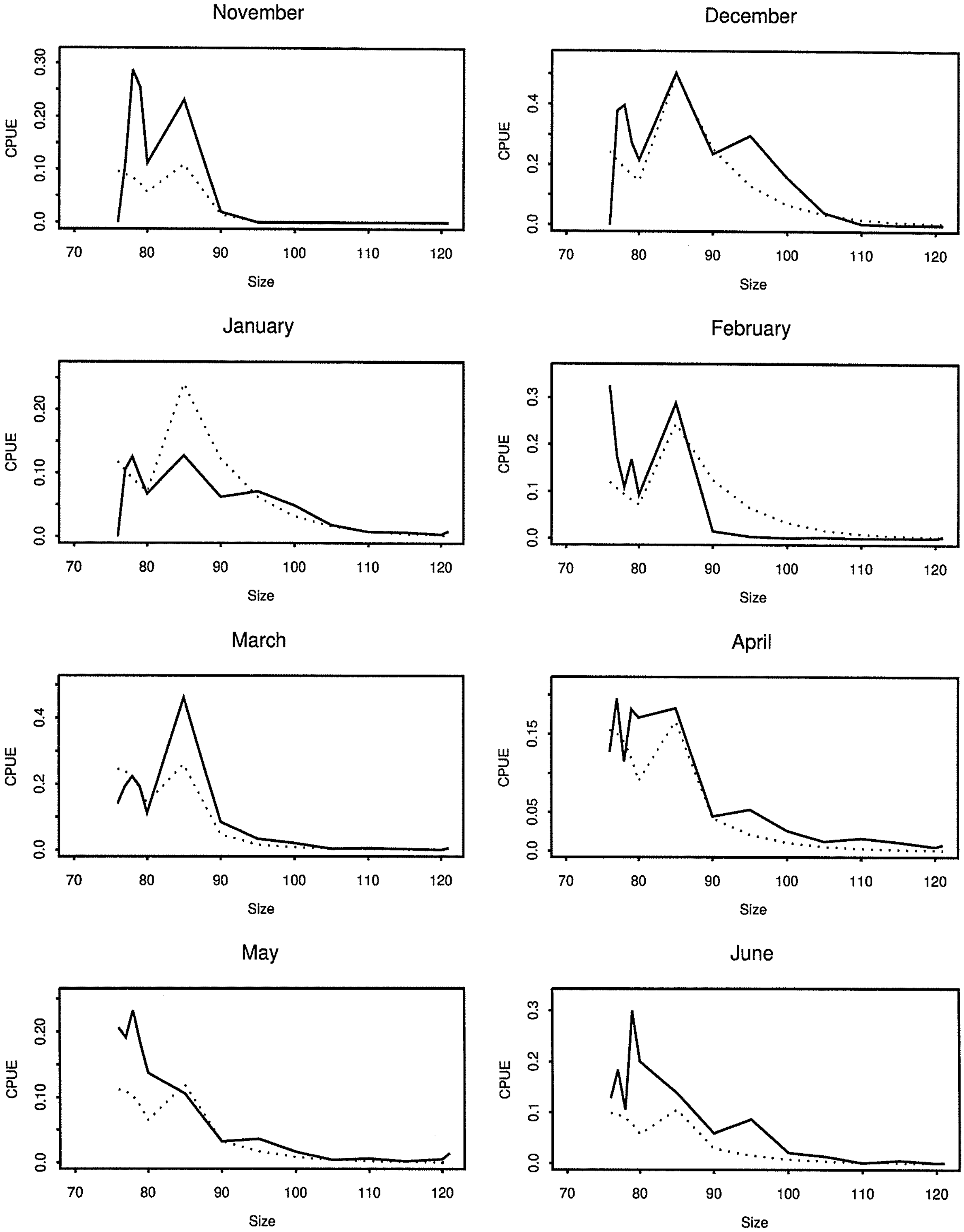
Figure 7 (3a)



Jurien region - Females

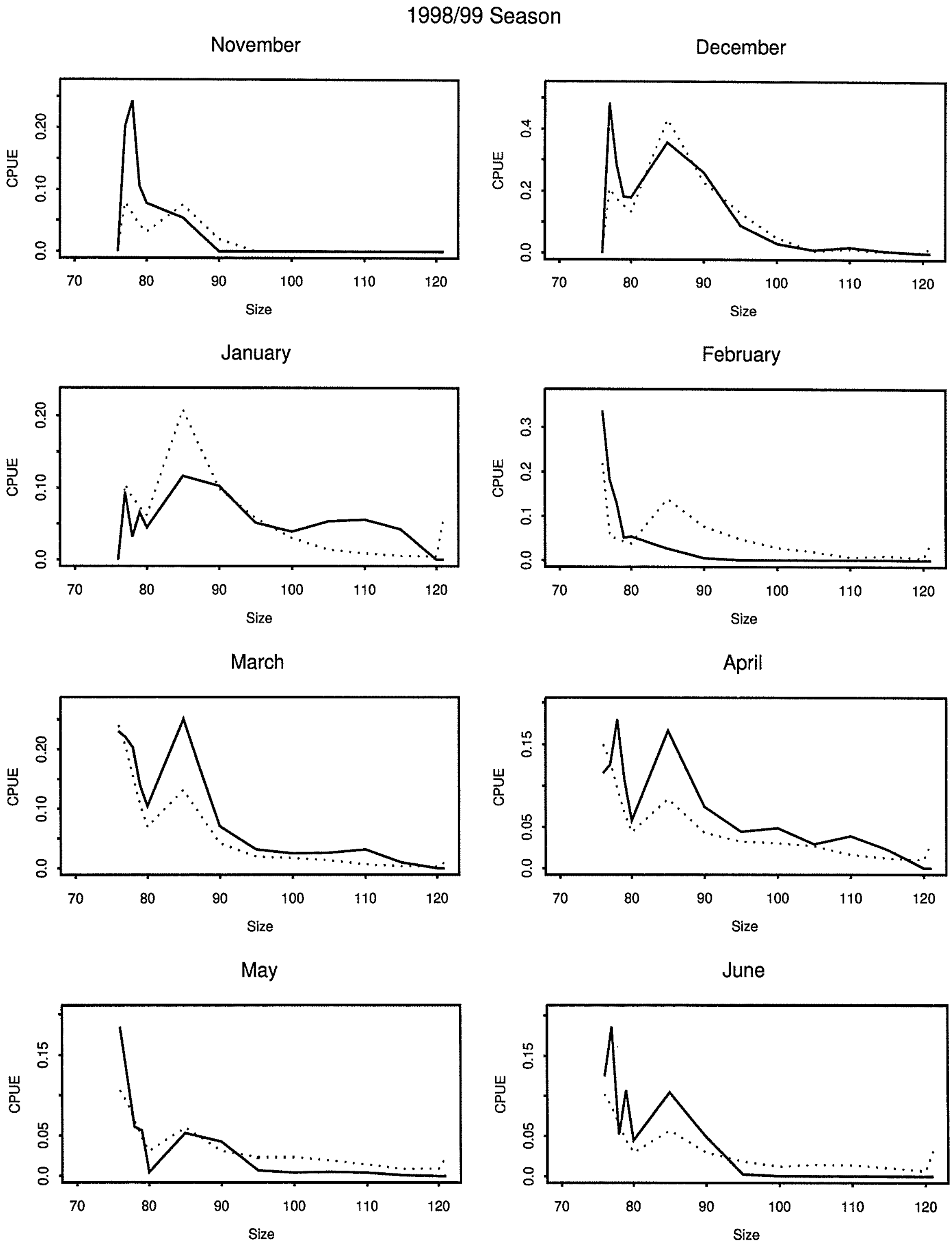
Figure 7 (3b)

1998/99 Season



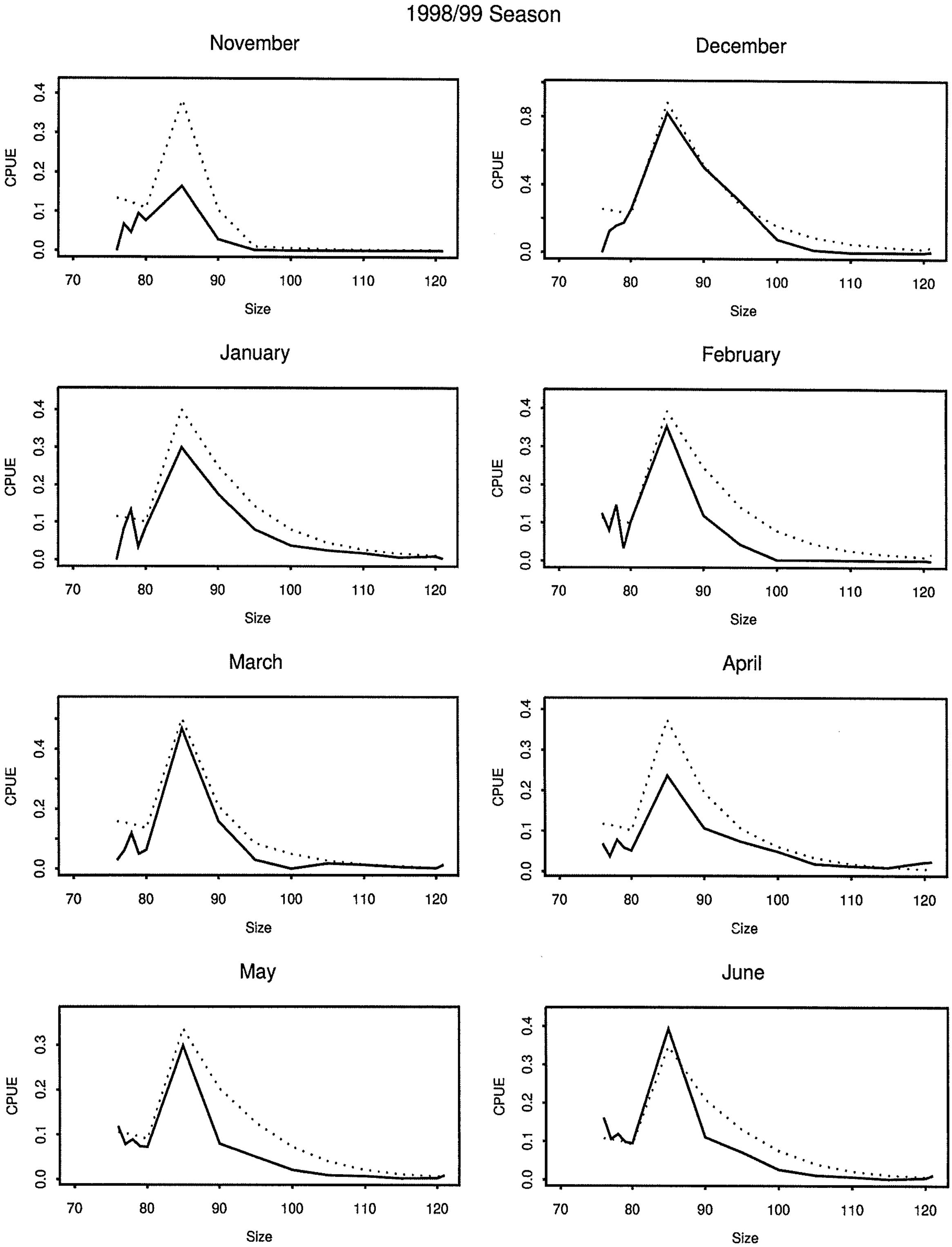
Lancelin region - Males

Figure 7 (4a)



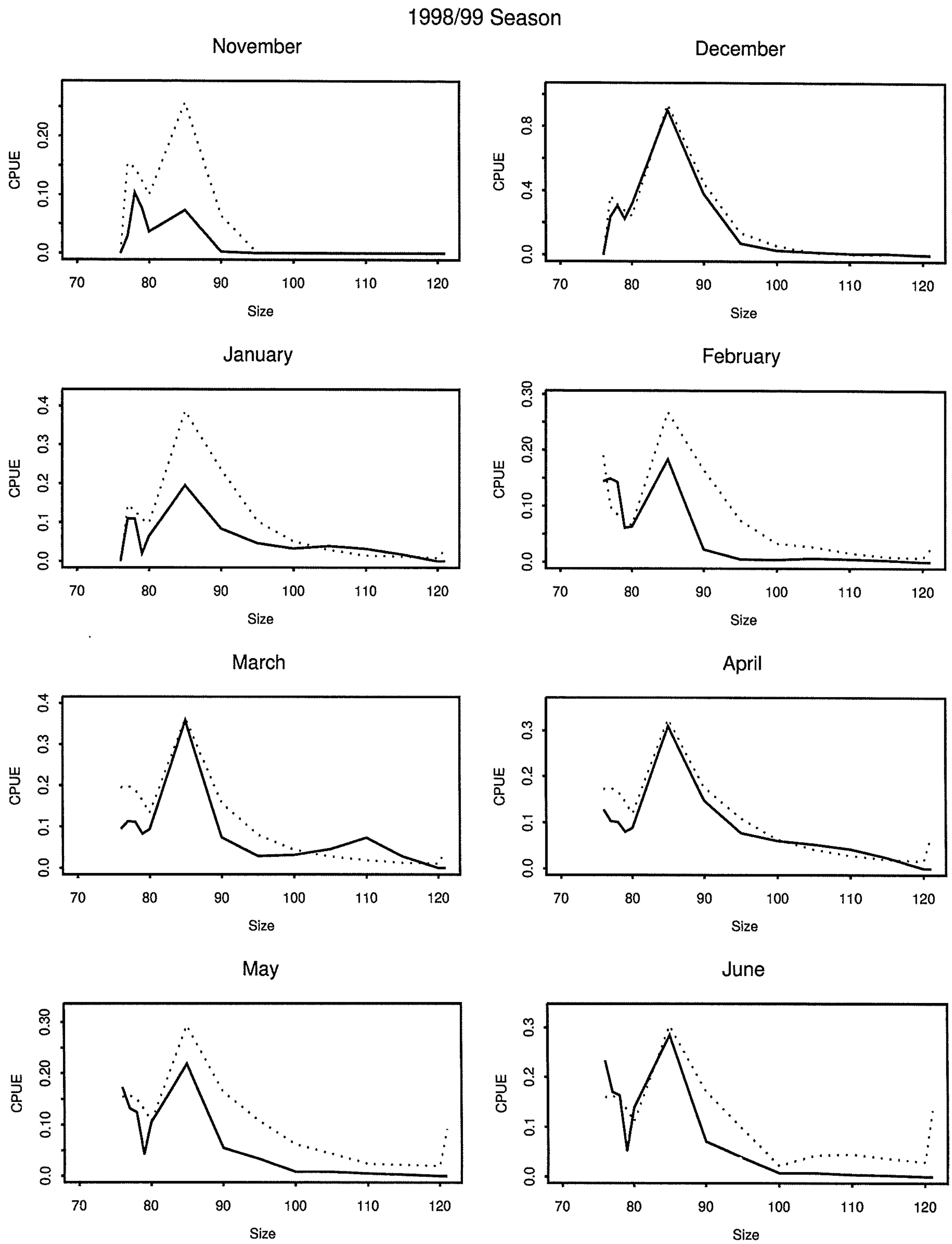
Lancelin region - Females

Figure 7 (4b)



Fremantle region - Males

Figure 7 (5a)



Fremantle region - Females

Figure 7 (5b)

Figure 7. Comparison of the model prediction (dotted line) on CPUE in 1998/99 fishing season by month, size class, sex and region with the observed data (solid line), where the model was conditioned on effort and the recruitment was estimated from earlier years' puerulus settlement indices. No adjustment has been made for different class intervals.

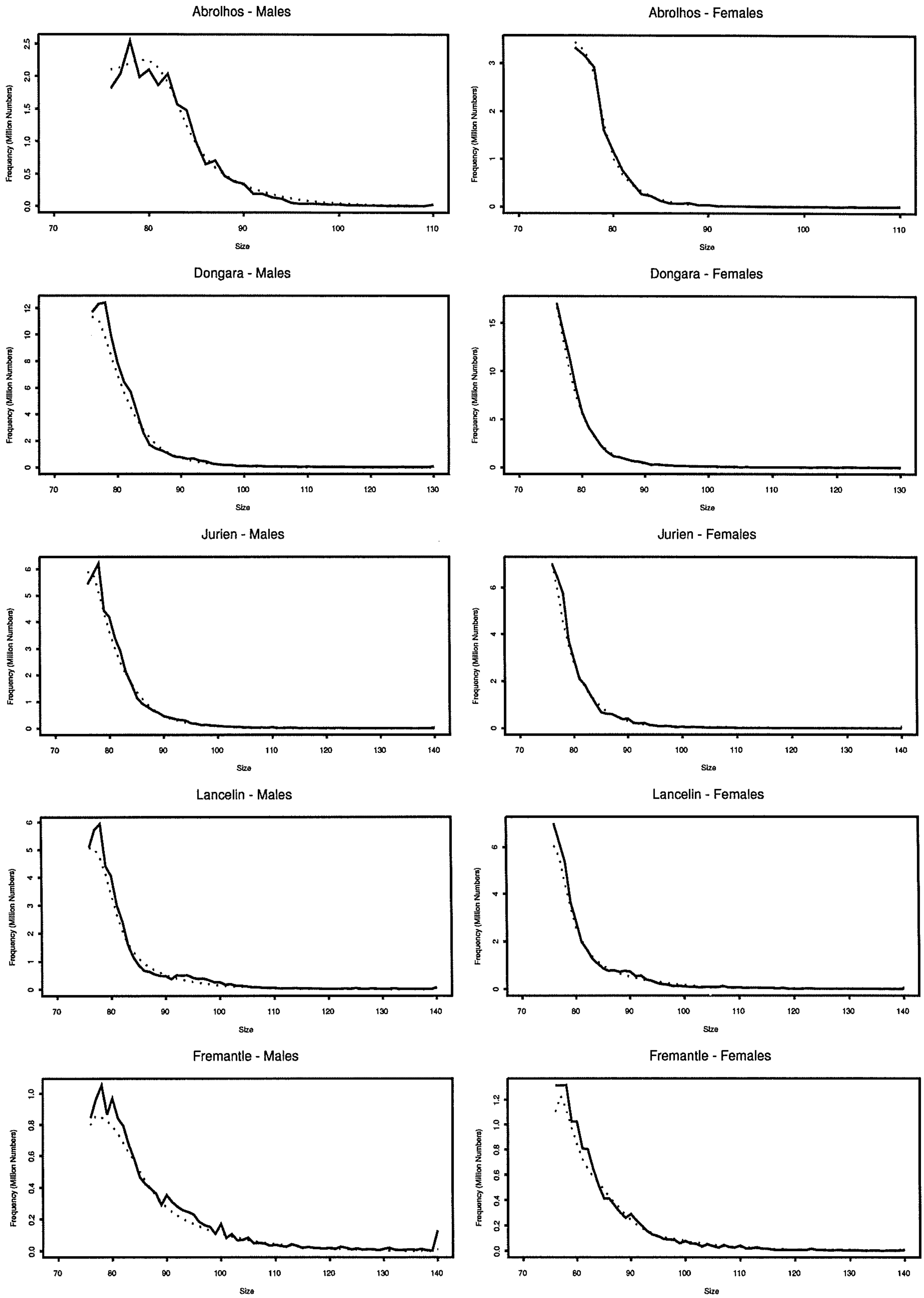


Figure 8. Comparison of the model prediction (dotted line) on length-frequency of catch by sex and region with the observed length-frequency (solid line), where the model was conditioned on effort and the recruitment was estimated from earlier years' puerulus settlement indices.

5.2.2.3 Prediction of annual catch by size class

In this section, we considered the model predictions of annual catch by size class, regardless of sex, which was estimated by:

Eq. 5.1 $$\mathrm{ACL}^{\wedge}(y,l,r) = \sum_{m,s} \hat{C}_{y,m}(l,s,r)\,,$$

where the sum was taken over two sexes and over all months in the year y. Note that the year y means a whole fishing season, that is, from November in the year y up to June in the year y+1, therefore, the months in the year y are November to December in the actual year y and January to June in the actual year y+1. The actual annual catch was estimated by substituting the estimated catch in the above formula by the actual catch.

The results with the model conditioned on effort are shown in **Figure 9**. The results were presented by region and showed eight typical size classes.

5.2.2.4 Prediction of annual catch

We considered other less detailed predictions by the model in this section. Annual catch was estimated by dropping *l* in the formula Eq. 5.1, that is,

$$\mathrm{AC}^{\wedge}(y,r) = \sum_{l,m,s} \hat{C}_{y,m}(l,s,r)\,,$$

where the sum was taken over two sexes, all size classes and all months in the year y. As mentioned in Section 5.2.2.3, the year y means a whole fishing season, that is, from November in the year y up to June in the year y+1. The actual annual catch was estimated by substituting the estimated catch in the above formula by the actual catch.

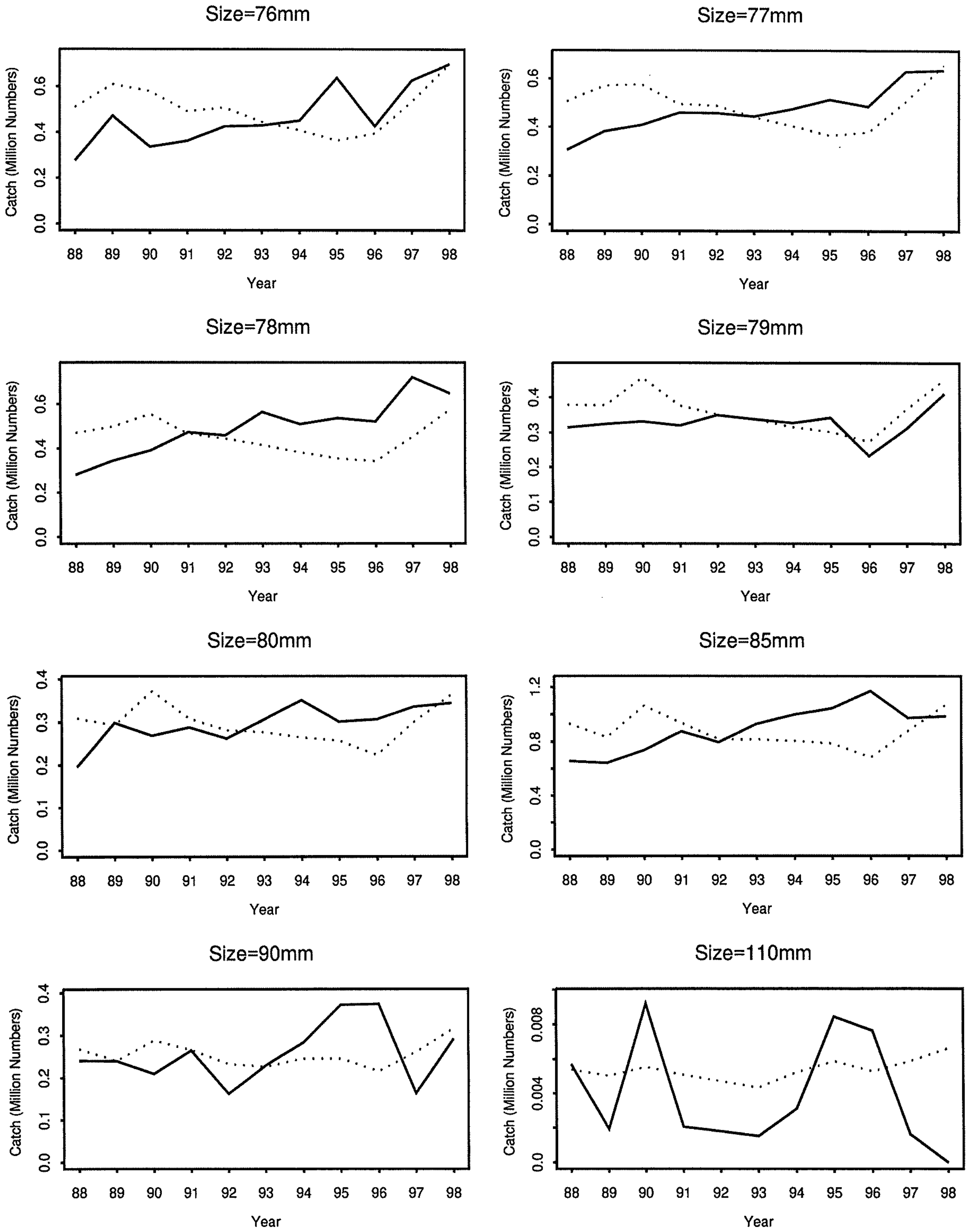
Because the model conditioned on catch assumed that total catch per month was known (then total catch per year was also known), it was not necessary to predict the annual catch in this case. As a result, the annual catch was predicted only when the model was conditioned on effort. The results by region are shown in **Figure 10**.

5.2.2.5 Prediction of monthly catch by year

The model prediction of catch by month and year regardless of size class was compared with the actual data. This catch by month and year was estimated by:

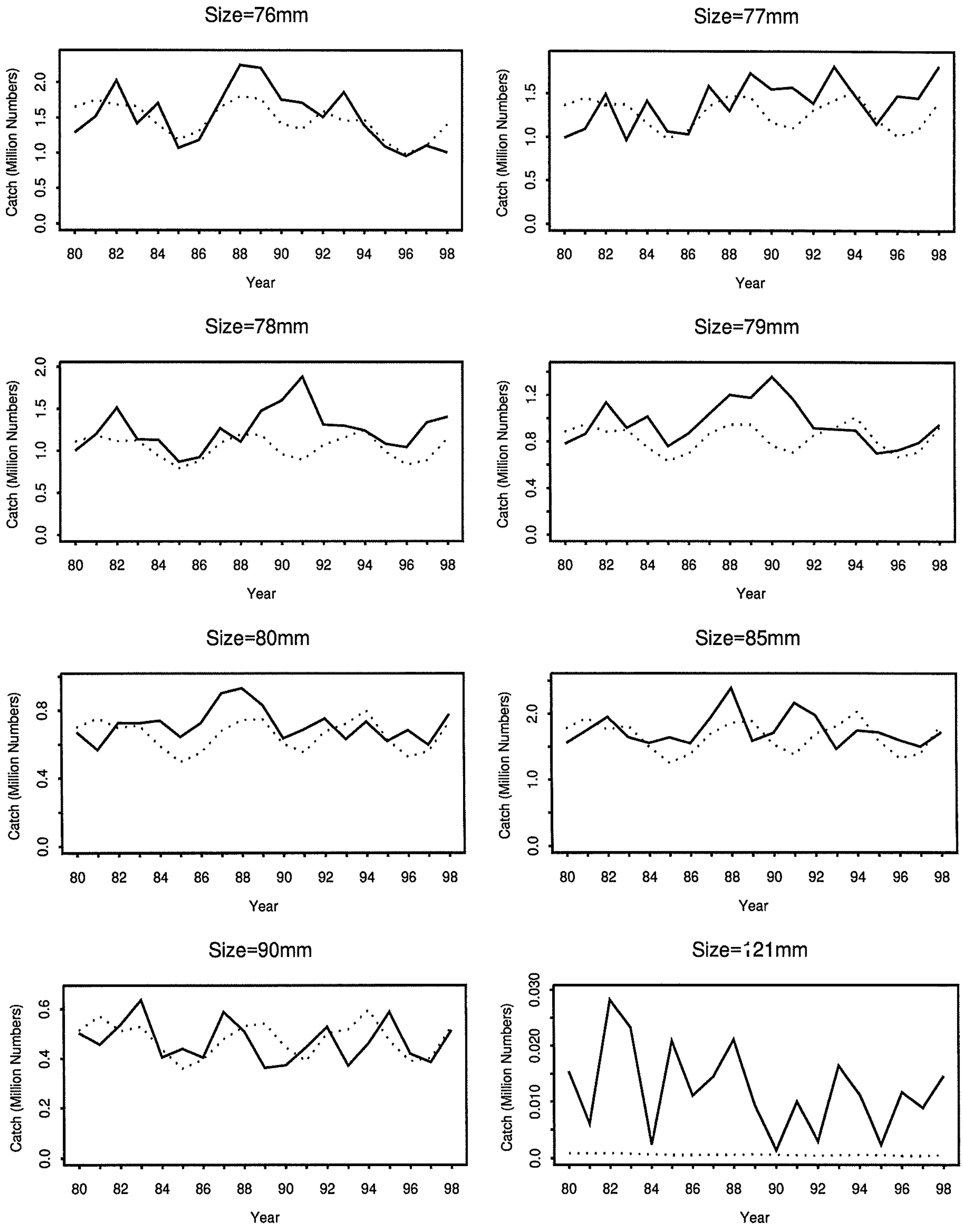
$$\mathrm{MCY}^{\wedge}(m,y,r) = \sum_{l,s} \hat{C}_{y,m}(l,s,r)\,,$$

where the sum was taken over two sexes and all size classes. The actual catch by month and year was calculated by substituting the estimated catch in the above formula by the actual catch.



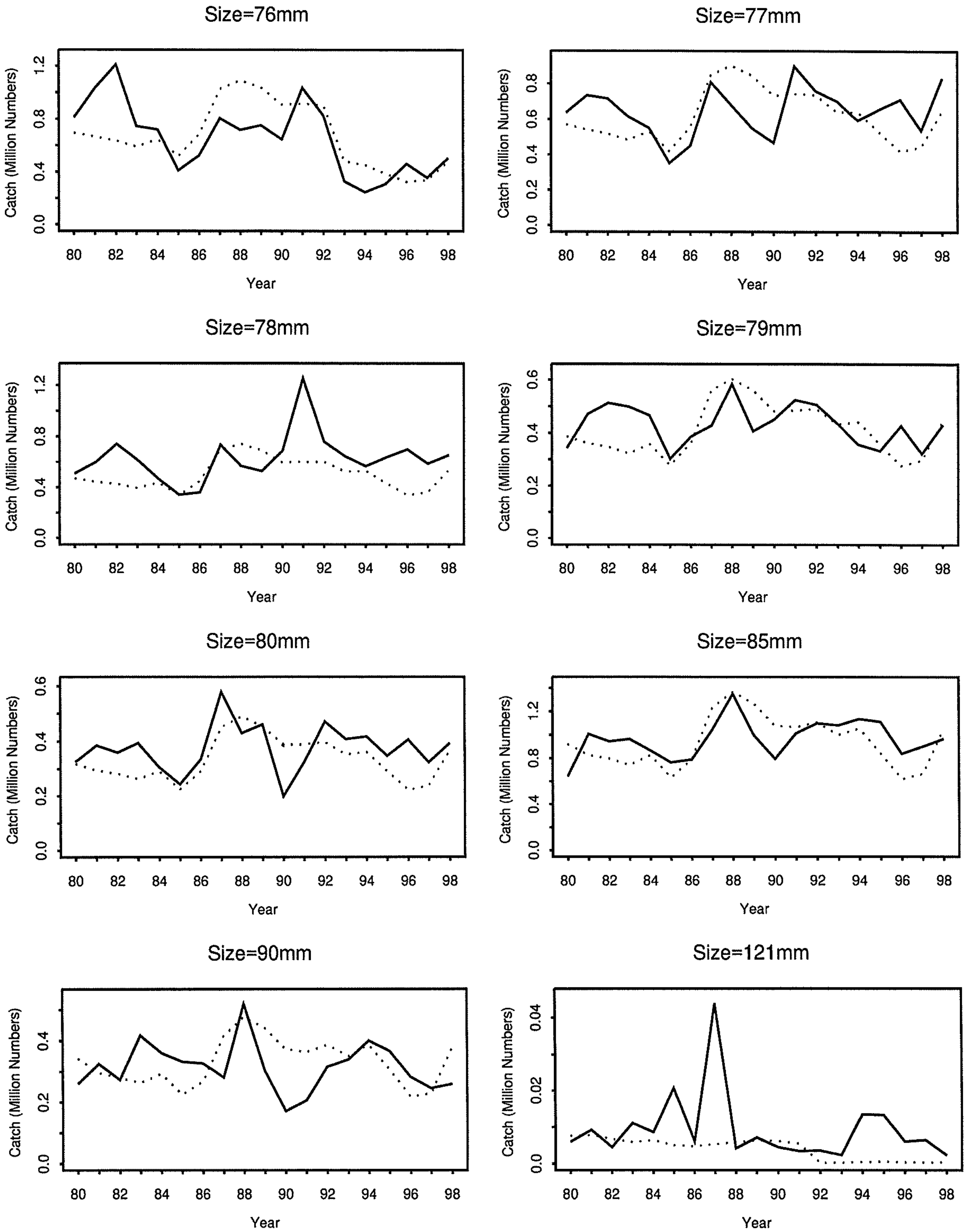
Abrolhos islands region

Figure 9 (a)



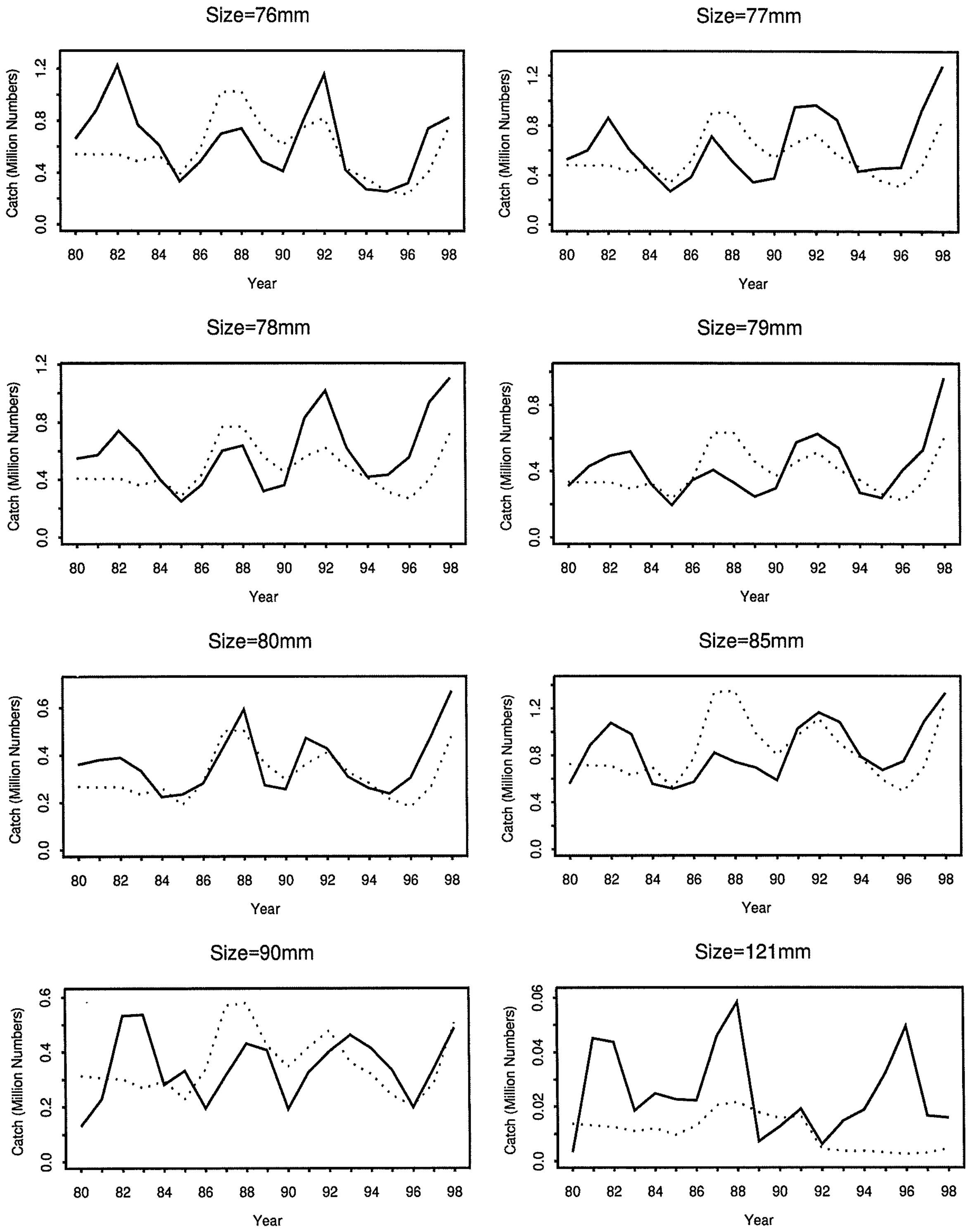
Dongara region

Figure 9 (b)



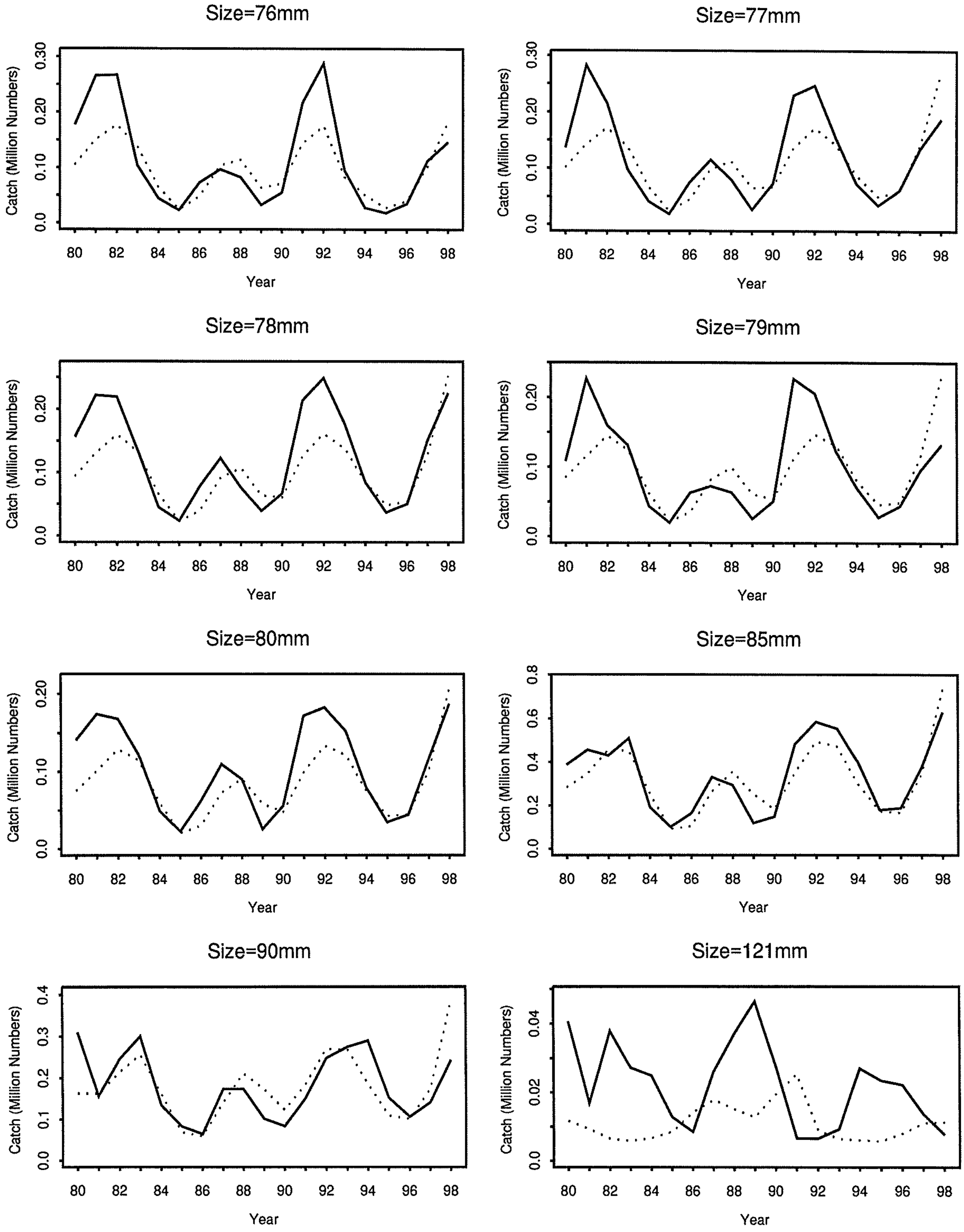
Jurien region

Figure 9 (c)



Lancelin region

Figure 9 (d)



Fremantle region

Figure 9 (e)

Figure 9. Comparison of the model prediction (dotted line) on annual catch by size class and region with the observed data (solid line), where only the results on eight representative size classes were shown. Here the model was conditioned on effort and the recruitment was estimated from earlier years' puerulus settlement indices.

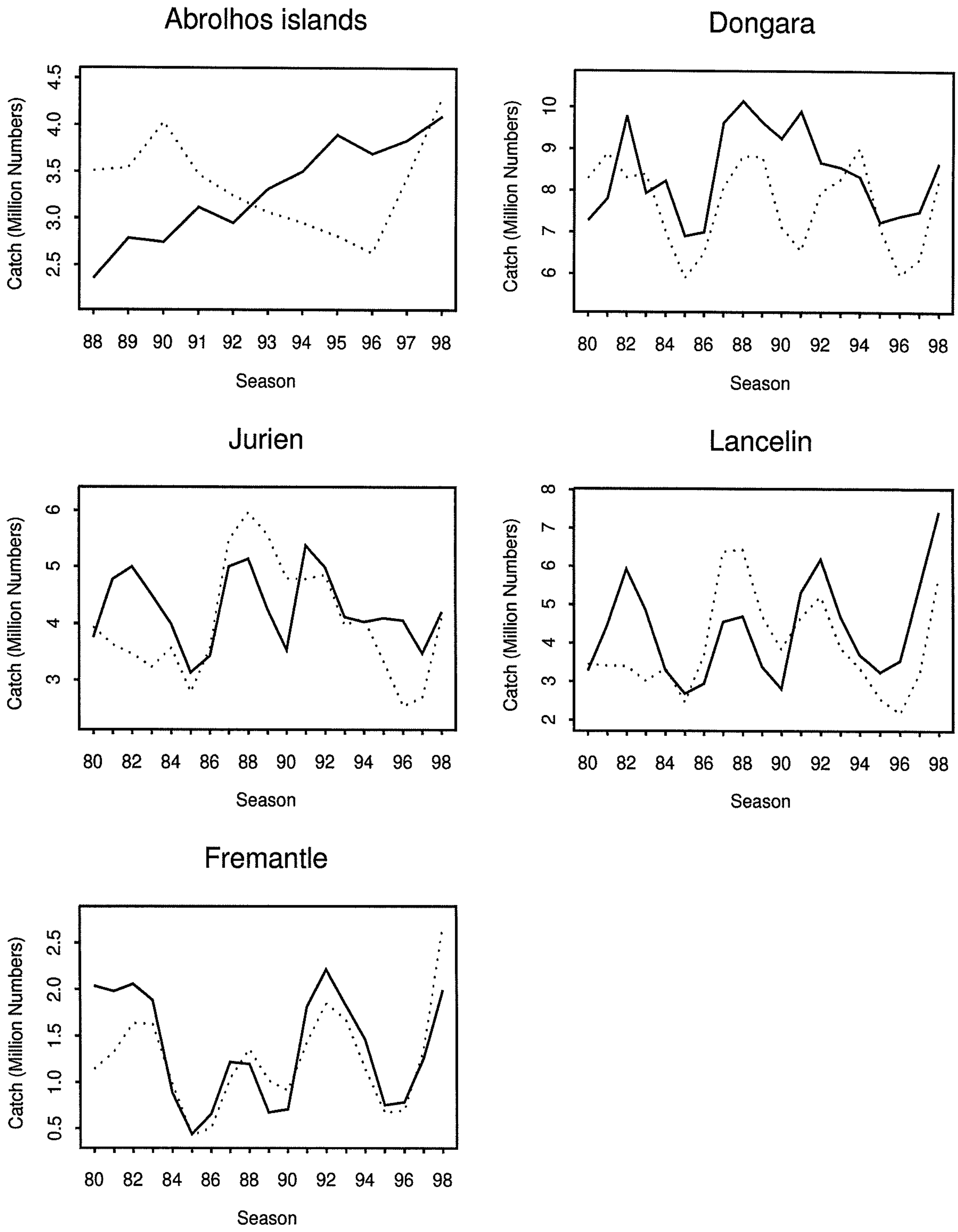


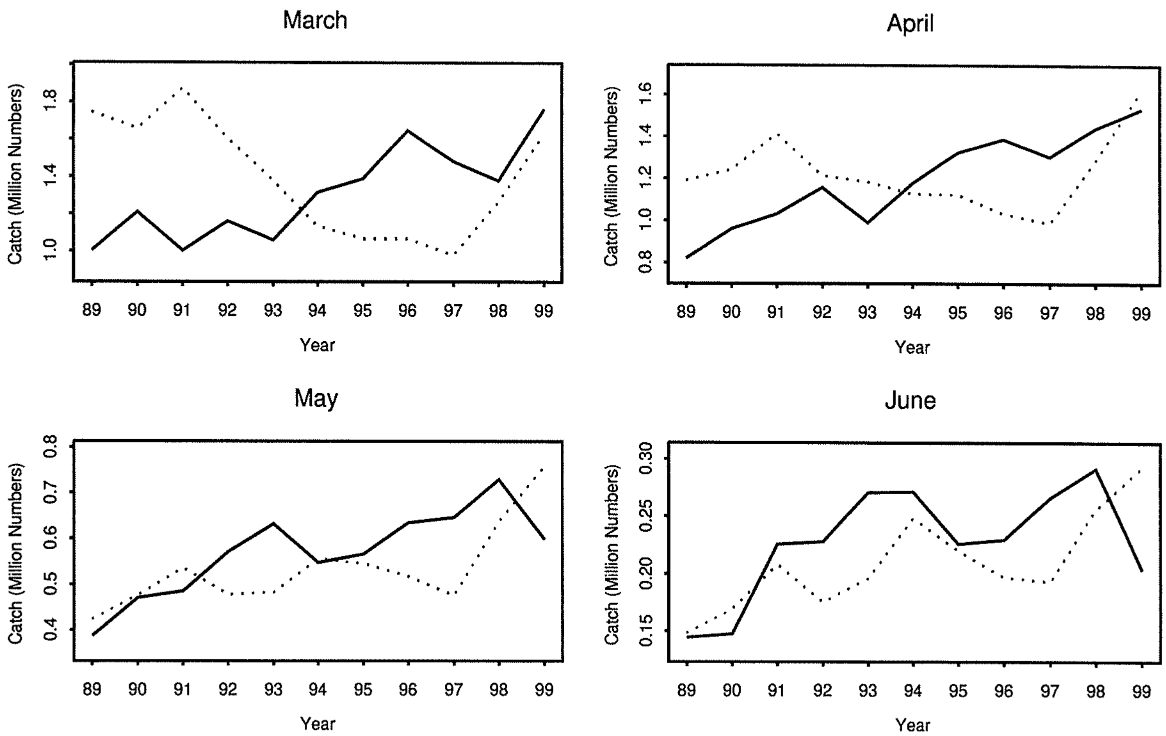
Figure 10. Comparison of the model prediction (dotted line) on annual catch by region with the observed data (solid line), where the model was conditioned on effort and the recruitment was estimated from earlier years' puerulus settlement indices.

Again it was not necessary to estimate monthly catch when the model itself was conditioned on catch (note that: ‘conditioned on catch’ in this study means the total number of lobsters caught per month was assumed known to the model). Therefore, only the results with the model conditioned on effort are needed, and these are shown in **Figure 11**.

5.2.3 Estimated annual recruitment

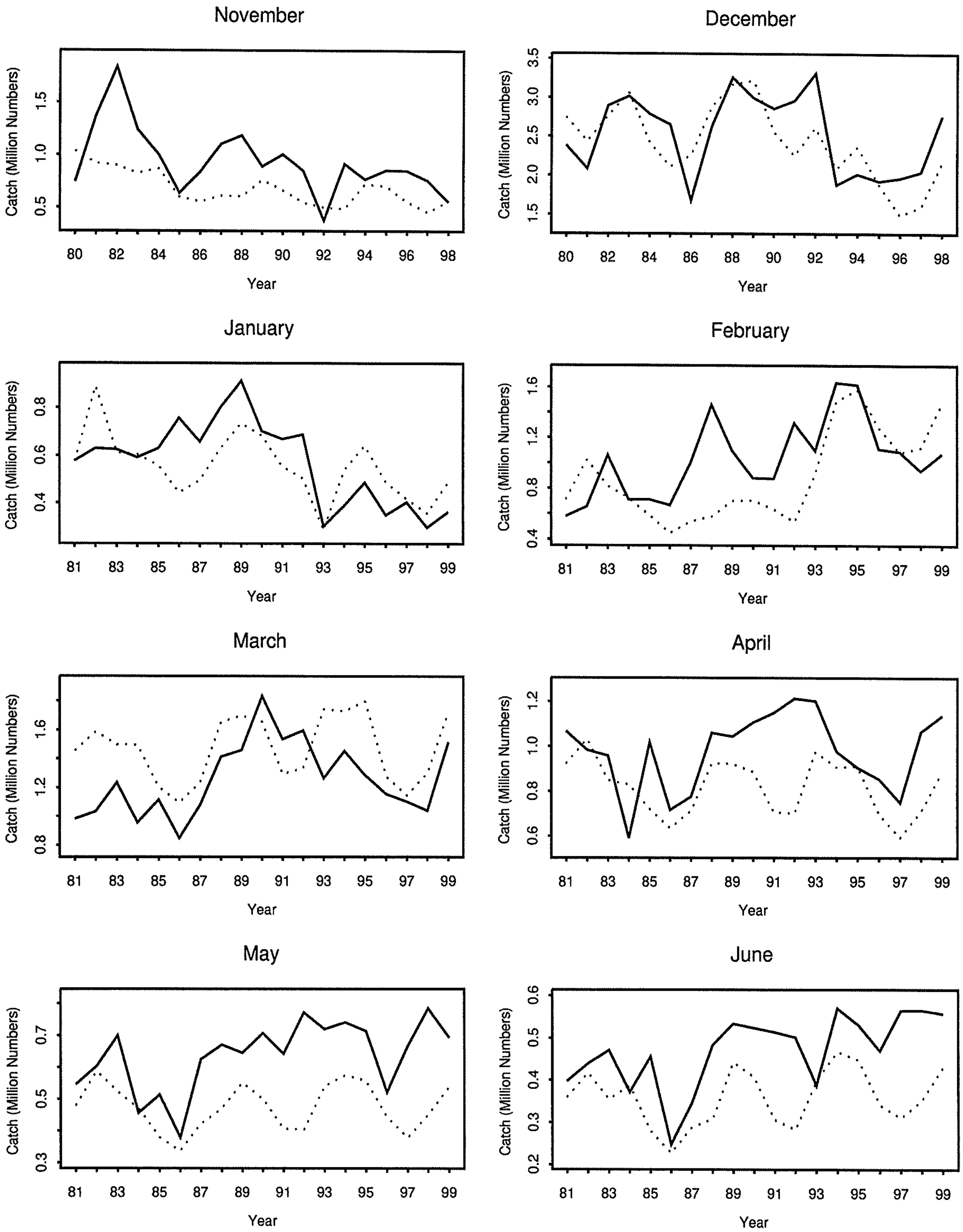
Details of the annual recruitment estimated by the model, see Section 4.2.4 for the method are discussed below. The results of conditioning on catch and conditioning on effort are presented separately. We show the results by region only, where the results were summed over two sexes.

When the model was conditioned on effort, we only considered the estimation of recruitment from the puerulus index. The annual recruitment was estimated from 1964/65, and the initial recruitment before 1964/65 was estimated as the averaged puerulus settlement indices in later years. The results by region are shown in **Figure 12**, where the recruitment marked by “O” in the plots represents the initial recruitment (*i.e*., before 1964/65) estimated in the model.



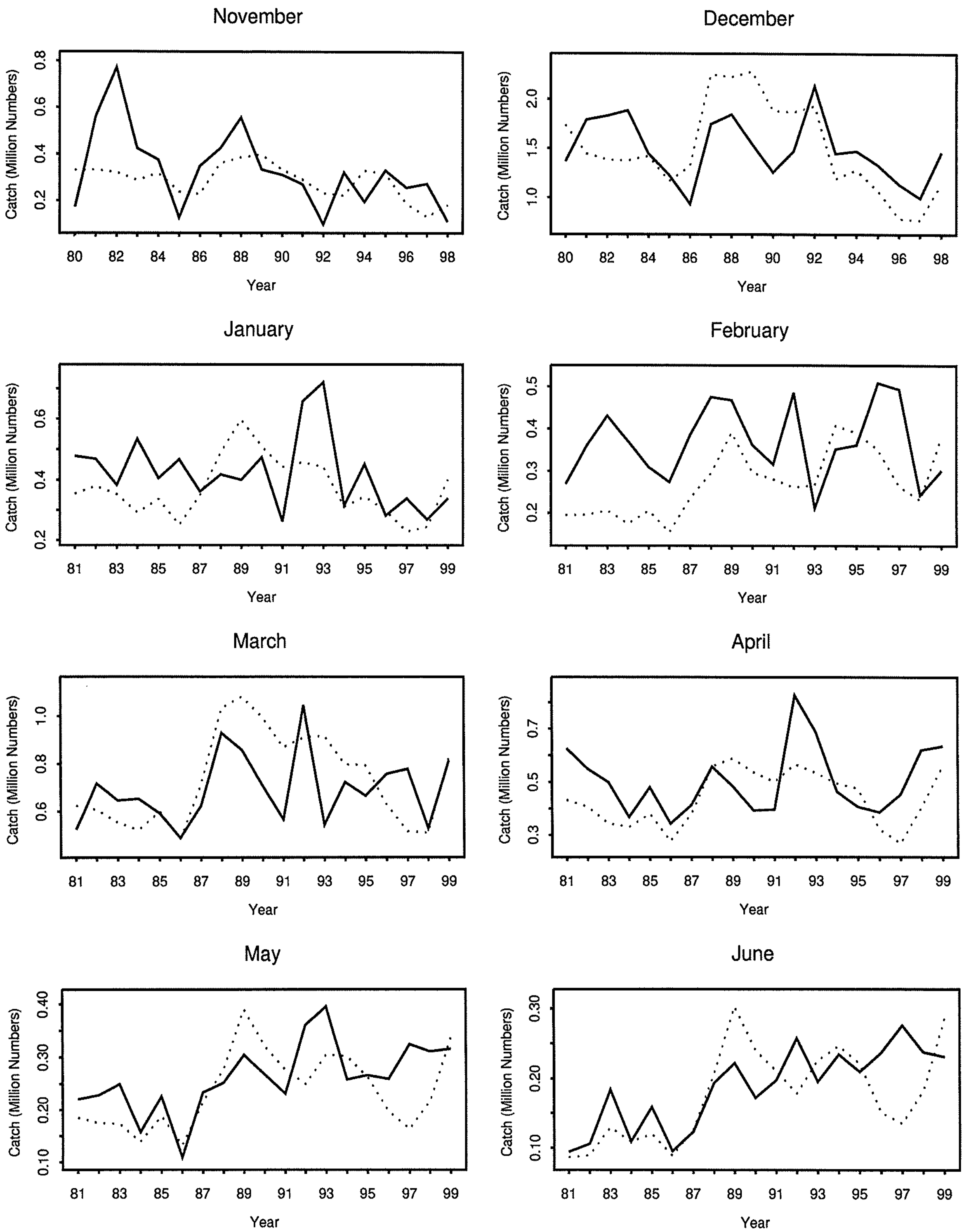
Abrolhos islands region

Figure 11 (a)



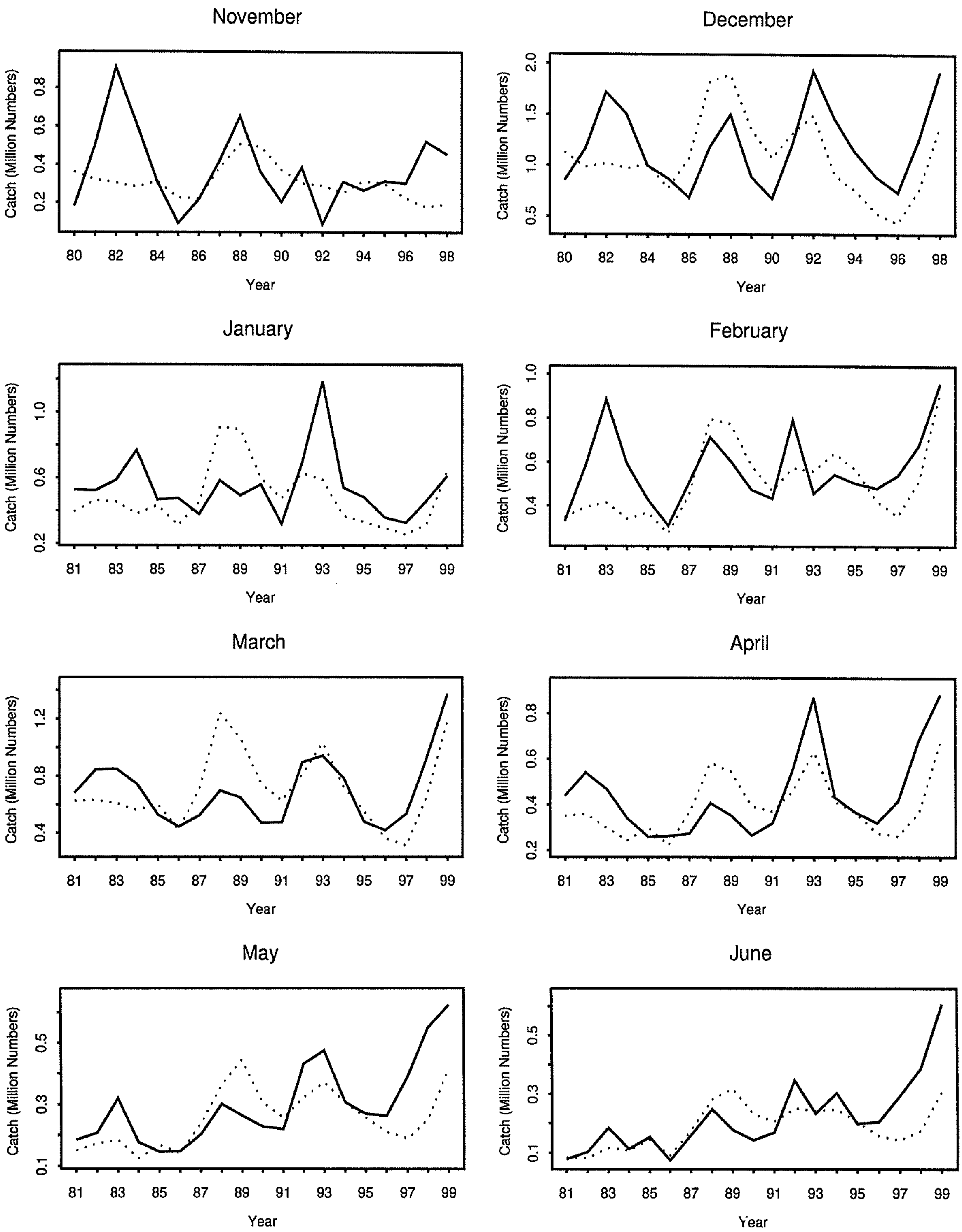
Dongara region

Figure 11 (b)



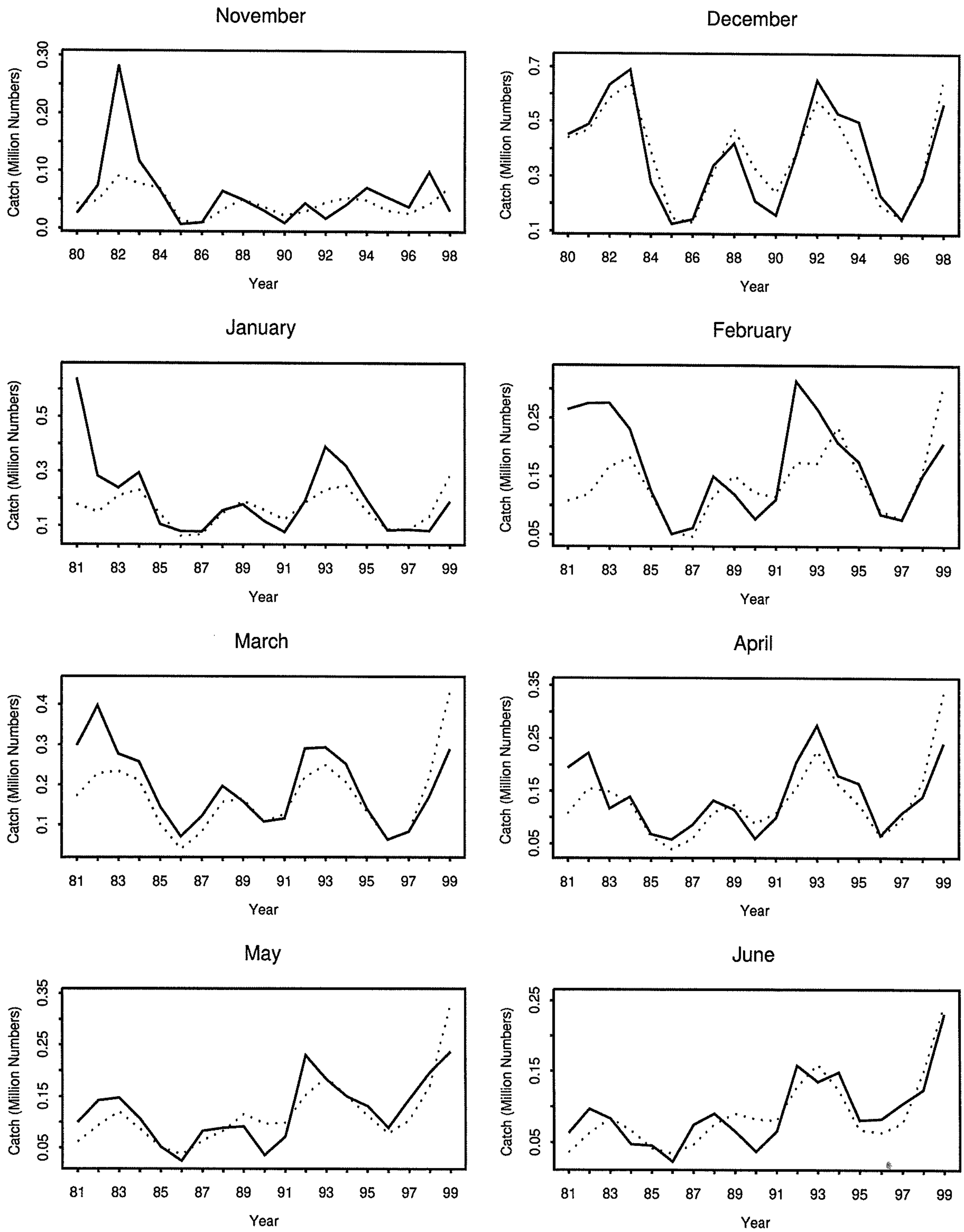
Jurien region

Figure 11 (c)



Lancelin region

Figure 11 (d)



Fremantle region

Figure 11 (e)

Figure 11. Comparison of the model prediction (dotted line) on monthly catch over all size classes by year and region with the observed data (solid line), where the model was conditioned on effort and the recruitment was estimated from earlier years' puerulus settlement indices.

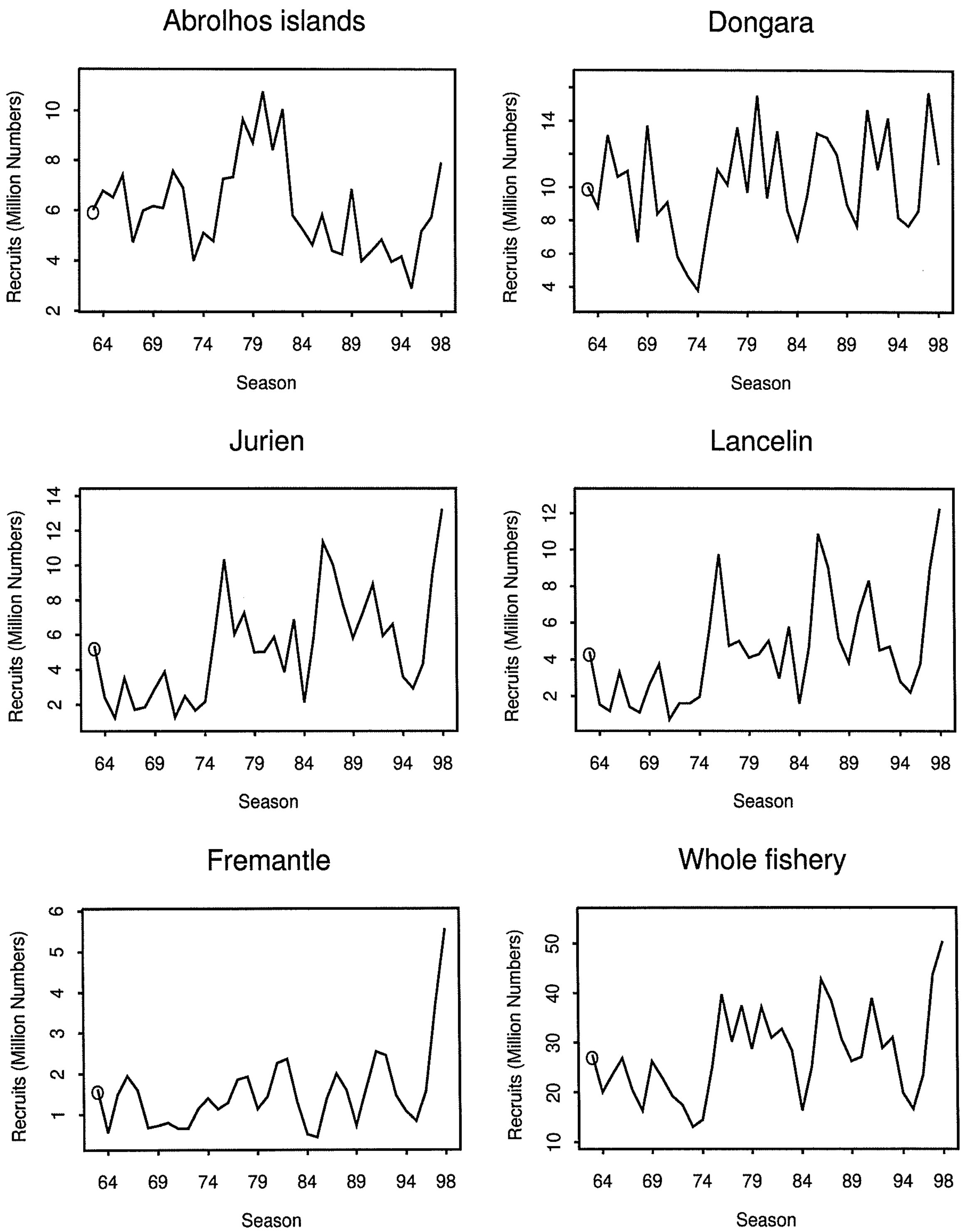


Figure 12

Figure 12. Estimated annual recruitment for each region as well as for the entire fishery catch, with the model conditioned on effort and with the recruitment estimated from puerulus settlement indices, where "O" marked at the beginning of each curve represents the estimated initial recruitment.

5.2.4 Estimated annual egg production

The model was also used to estimate the annual egg production by applying the method and formulae provided in Section 4.3.1. The results are presented by zone, where the result in zone A is equal to the result in the Abrolhos Islands region, the result in zone B is equal to the result in the Dongara region, and the result in zone C is equal to the sum over the results in the Jurien, Lancelin and Fremantle regions. The egg production levels after fishing were estimated since 1964/65 season, and the egg production levels before fishing were estimated based on the estimated populations in 1963/64. The absolute figures estimated for the egg production may not be of value as they are likely to change if different estimation formulae were to be used for the estimation. However, the relative figures of egg production are useful and relatively stable over alternative estimation formulae.

For convenience, denote Egg_0 as the egg productions before fishing started, which was estimated based on the populations in 1963/64, assuming no fishing having occurred; and Egg_t as the egg production level at the time *t*, where *t* is a fishing season from 1964/65 to 1998/99. The relative egg productions were estimated by dividing Egg_t by Egg_0, *i.e.,* Egg_t / Egg_0.

The results of relative egg productions by zone are shown in **Figure 13**, where the relative egg production marked by "O" in the plots, which is equal to 1, was obtained by Egg_0 / Egg_0.

5.2.5 Discussion

Three approaches were adopted in the estimation of the model parameters. The model was first conditioned on catch using two different methods for the estimation of annual recruitment (*i.e.*, estimated from the puerulus settlement indices and estimated as a model parameter) and the model was subsequently conditioned on effort with annual recruitment estimated from the puerulus indices.

The best results of the model fit to the observed data were obtained when recruitment was estimated as a model parameter. Using the same approach for the estimation of recruitment, a better fit of the model to the data was obtained when the model was conditioned on effort rather than conditioned on catch. This may be partly due to the lack of length-frequency data for catches in early years and the interpolated data may have poorly represented the fishery in those years, whereas the fishing effort data have been available since the first year (*i.e.,* 1964) considered in the model.

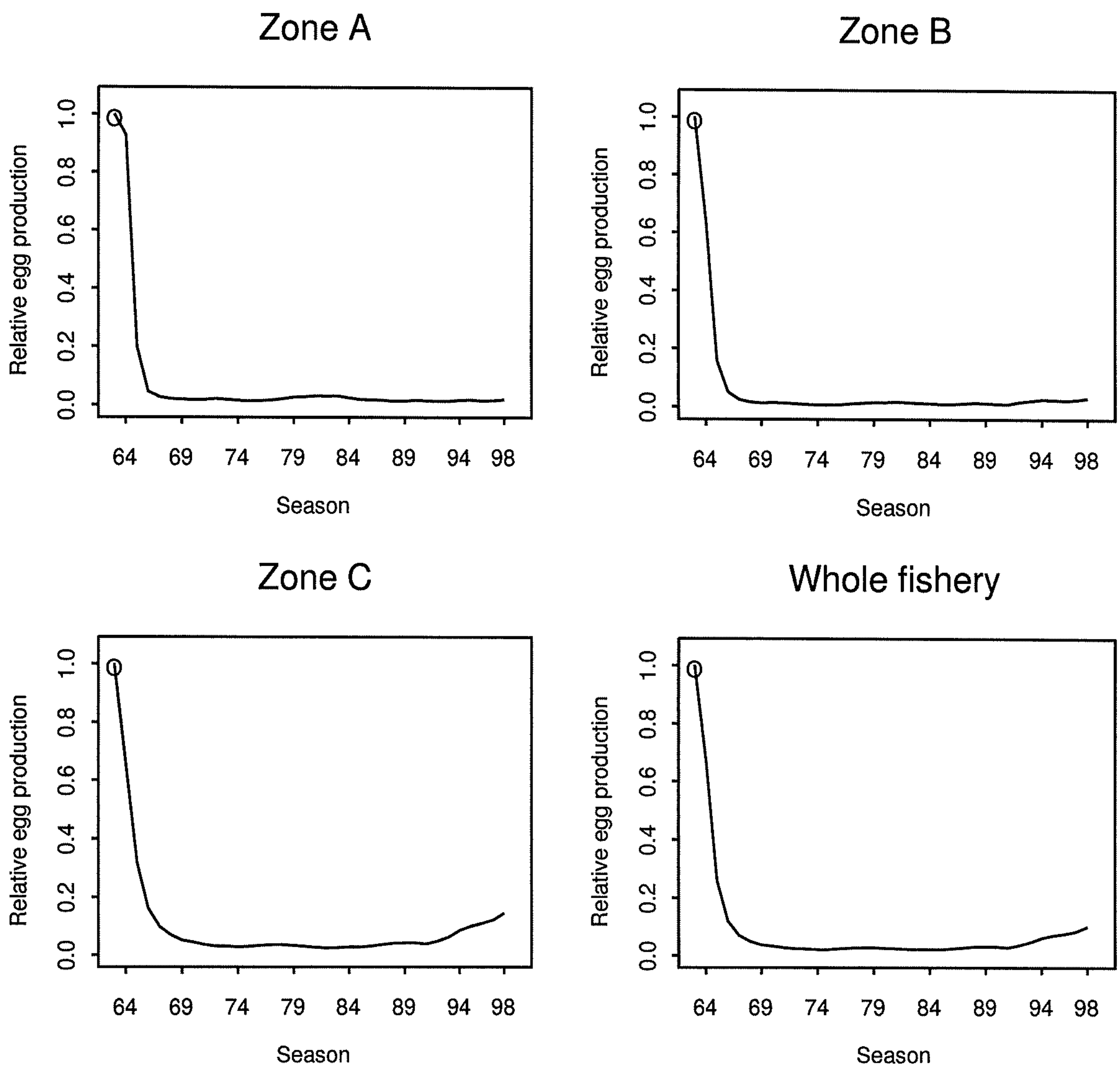


Figure 13

Figure 13. Estimated annual relative egg productions for each management zone as well as for the entire fishery, with the model conditioned on effort and with the recruitment estimated from puerulus settlement indices, where "O" marked at the beginning of each curve represents the point before fishing started and all relative values of egg productions in the plots in later years were relative to this point.

That the approach of recruitment estimated as a model parameter provided the best fit of the model to the data may be due to the model having many more parameters than the alternate approach. Therefore, in theory the more complex model should provide a better fit of the model to the data. The better result obtained with this approach also implies that better estimation of recruitment would play a very important role in improving the fit of the model to the data. Estimation of recruitment from puerulus settlement indices from earlier years has a biological explanation, however, the underlying mathematical relationship between puerulus indices and recruitment may be hard to identify. Although a few mathematical relationships were tested and a linear relationship provided the best model fit, the biological processes affecting survival of the lobsters between settlement as pueruli and subsequent recruitment to the fishery would suggest that survival should be density dependent.

Regarding the quality of the model's fit to the data, generally satisfactory results were found in the Fremantle region, while the results were poorer in other regions. Overall, at its current stage of development, the model has not fitted the observed data well enough to provide reliable outputs for complex management scenarios, and further work to improve the fit of the model is being undertaken. As the project progressed, it became clear that the system structure was considerably more complex than had previously been recognised. An important factor in determining the length composition of the catches was the relationship between vulnerability and the carapace length of the lobsters. Inconsistency in model output strongly suggested that vulnerability must reduce markedly with the length of the lobsters. Such a result was detected by Walters *et al.* (1993), who applied a length-based cohort analysis to catch at length data. The need within the model to better understand the effectiveness of fishing effort related to the distribution of the effort over the various depths relative to the size-dependent distribution of lobsters led to an independent study (Sections 4.5 and 5.5) that demonstrated a significant reduction in concentration of effort on the larger sized lobsters. Currently, within the model, a relatively simple representation of the reduced vulnerability of lobsters with carapace length has been described. However, the distribution of fishing with respect to depth varies throughout the fishing season, and the current model structure does not yet represent the complexity resulting from the changing concentration of fishing effort on the lobsters of the various lengths.

It is unclear why the result in Fremantle region is markedly better than that in other regions. It is suspected that the reason may be related to the quality of the data. The size composition data used within the model to estimate the size composition of the monthly catches is derived from research sampling at selected locations throughout the fishery. At the Abrolhos Islands, the length sample is taken at the beginning of the fishing season, and is assumed to represent the catches throughout the remainder of the fishing season. The representativeness of the samples is a concern, and the possibility of extending the sampling program throughout the entire fishery and through the entire fishing season by utilising length measurements provided from sampled catches by commercial fishers is being investigated.

As a result of an extensive research programme between 1977 and 1986 (Brown and Caputi, 1986), mortality of released undersized rock lobsters was significantly reduced by improved handling and by an increase in the number of escape gaps required in the pots used by fishers. The model currently assumes that discard mortality is zero, however this assumption will be modified as the model is further developed.

Other changes to modelling that may be recommended for consideration in the future include: (1) notwithstanding the necessity of management changes to minimum legal carapace length by 1 mm, rather than using 1 mm size class use a 2 mm or even larger size class for the state vector- this would significantly reduce the model complexity and avoid the impact of the measurement errors in carapace length which may possibly range up to 1 mm magnitude; (2) rather than estimating the growth transition matrices independently from tagging data, the growth transition matrices might be estimated simultaneously when fitting the model to the observed catch and effort data - this may improve the model fit to the data because it allows the model flexibility to estimate the growth of lobsters, rather than relying on totally independent tagging data.

An analysis of parameter uncertainty is not provided in this report. Difficulties were encountered in dealing with the non positive-definite Hessian matrix at the estimated 'optimal' parameter values. This may be due to the fact that the estimated parameter values were not optimal. Further investigation will be needed in the future. However, given the need to further improve the model fit to the data, analysis of the uncertainty of the current estimated parameters may not be useful until a better representation of the fishery data is provided.

5.3 Exploration of an alternative management strategy

In Section 5.2, results of the estimation of model parameters and model fitting to data were presented. As discussed in Section 5.2.5, further investigations are being undertaken to improve the model structure and the fit of the model to the data. The model has the capacity to explore various management strategies to examine the impact on the catch and on the breeding stock as well as on product values (see Section 5.4 for the economic analysis).

To illustrate this capacity of the model, in this section we have analysed the impact on catch and on egg production of the setose regulation within the management strategy which was introduced into the fishery in 1993/94 (see Section 4.3 for a detailed description of the 1993/94 management strategy). The objective of this exploration was to compare the impact of the alternative strategies against a strategy where the 1993/94 management package was not introduced and the regulations of earlier years (e.g., 1991/92) continued to be applied.

For convenience, denote C_t^p, C_t^{ap} and C_t^{np}, and Egg_t^p, Egg_t^{ap} and Egg_t^{np} as the estimated catch in the fishing season *t* and the egg production at the beginning of fishing season *t* obtained under the 1993/94 full package (*p*), under the alternative package (*ap*) which is the package to be tested, and under the original strategy (*np*) (*i.e*., dropping all elements of the 1993/94 package), respectively. For simplicity, only the impacts on the catch and egg production in a whole fishing season (*i.e.*, from November to June for coastal regions and from March to June for Abrolhos Islands region) were considered. The fishing seasons *t* considered were 1993/94 and onwards, that is, changes of regulations associated with the various management strategies were applied from the 1993/94 fishing season, while the management strategy applied before 1993/94 within the model was the strategy applying in the 1991/92 fishing season with the fishing effort as recorded in the fishery statistics.

We characterised the impacts of the management strategy on catch and egg production by looking at these ratios:

(1) ratios of catches and eggs under the alternative management strategy and the actual management strategy (*i.e.*, the 1993/94 strategy) that was applied to the fishery, which are:

$$C_t^{ap} / C_t^p,\ \ C_t^{np} / C_t^p;$$

$$\text{and}\ \ Egg_t^{ap} / Egg_t^p,\ \ Egg_t^{np} / Egg_t^p;$$

(2) ratios of catches and eggs under the alternative management strategy at the season *t* and at the first season (which is 1993/94 here) for which the management strategy was applied, which are:

$$C_t^{ap} / C_{93/94}^{ap},\ \ C_t^p / C_{93/94}^p,\ \ C_t^{np} / C_{93/94}^{np};$$

$$Egg_t^{ap} / Egg_{93/94}^{ap},\ \ Egg_t^p / Egg_{93/94}^p,\ \ Egg_t^{np} / Egg_{93/94}^{np}.$$

Note that all results presented were obtained using the parameters determined when the model was conditioned on effort and with recruitment estimated from the earlier years' puerulus settlement indices (see Section 4.3).

The resulting impact on catch of this alternative management strategy (the retention of only the protection of setose females element of the 1993/94 management strategy) are presented in **Figure 14**. The ratios of catches estimated by the model under the alternative management strategies relative to those obtained under the 1993/94 strategy are shown in the plots. The original strategy generally produces greater catches than the setose strategy for all regions from the 1993/94 to the 1998/99 seasons (**Figure 14**). Comparing the two curves in each of the plots, it is not difficult to observe that there was a higher impact at the introduction of the setose strategy followed by a lesser impact and then a higher impact again in all regions. The general trend of impact on catches of removing the other three elements (*i.e.*, minimum size, maximum size and pot reduction) compared with the 1993/94 strategy is: a higher impact at the start of the strategy and then a lower impact and then higher impact again.

The ratios of catches in 1993/94 onwards under different management strategies to those calculated for 1993/94 are displayed in **Figure 15**. There is little difference in the catch relative to the 1993/94 season (note that 1993/94 is the first season of testing the alternative strategies) between the original strategy and the setose strategy (**Figure 15**).

Figure 16 shows the resulting impact on egg production of this alternative management strategy. Shown in the plots are the ratios of the egg production estimated by the model under the alternative management strategies to those obtained under the 1993/94 strategy. The impact on egg production of the setose strategy is significantly different from that of the original strategy in all regions (**Figure 16**). This may be due to the direct relationship between the number of setose females and the resulting production of eggs.

Figure 17 shows the ratios of egg productions in 1993/94 onwards under different management strategies to those calculated for 1993/94. The egg production has a generally decreasing trend under the original strategy while an increasing trend under the 1993/94 strategy and a generally decreasing trend under the setose strategy in all regions except the Fremantle region where an increasing trend resulted from the setose strategy.

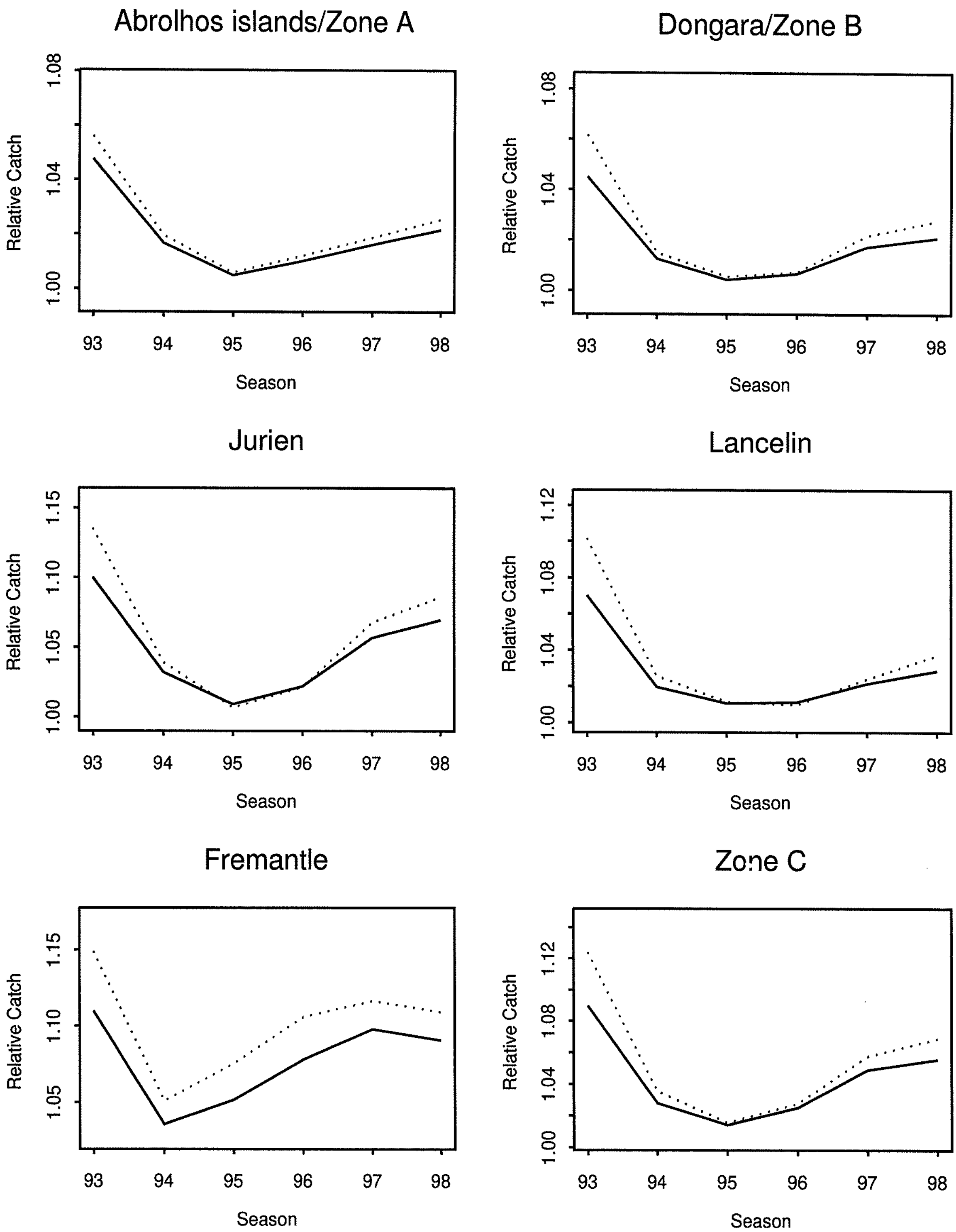


Figure 14. Impact on catch of retaining only the protection of setose element of the 1993/94 strategy. Shown in the plots are the ratios of catches estimated by the model under the alternative management strategies relative to those obtained under the 1993/94 strategy. The solid line represents the ratios of catches under the setose strategy relative to those under the 1993/94 strategy; the dotted line represents the ratios of catches under the original strategy relative to those under the 1993/94 strategy. The results are shown by region and by zone.

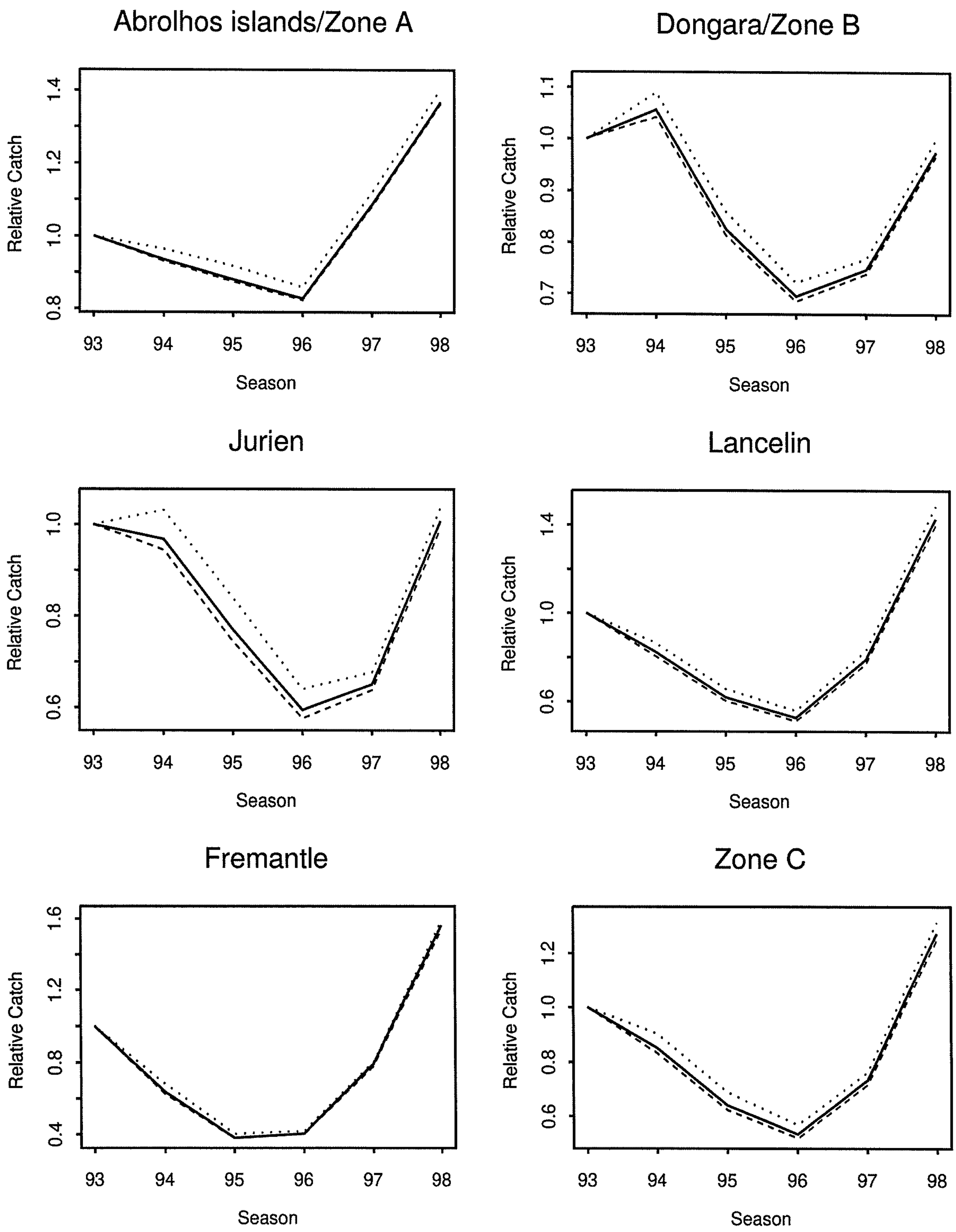


Figure 15. Same as **Figure 14**, but shown in the plots are the ratios of catches in 1993/94 onwards under different management strategies relative to those in 1993/94. The solid line represents the setose strategy; the dotted line represents the 1993/94 strategy; and the dashed line represents the original strategy.

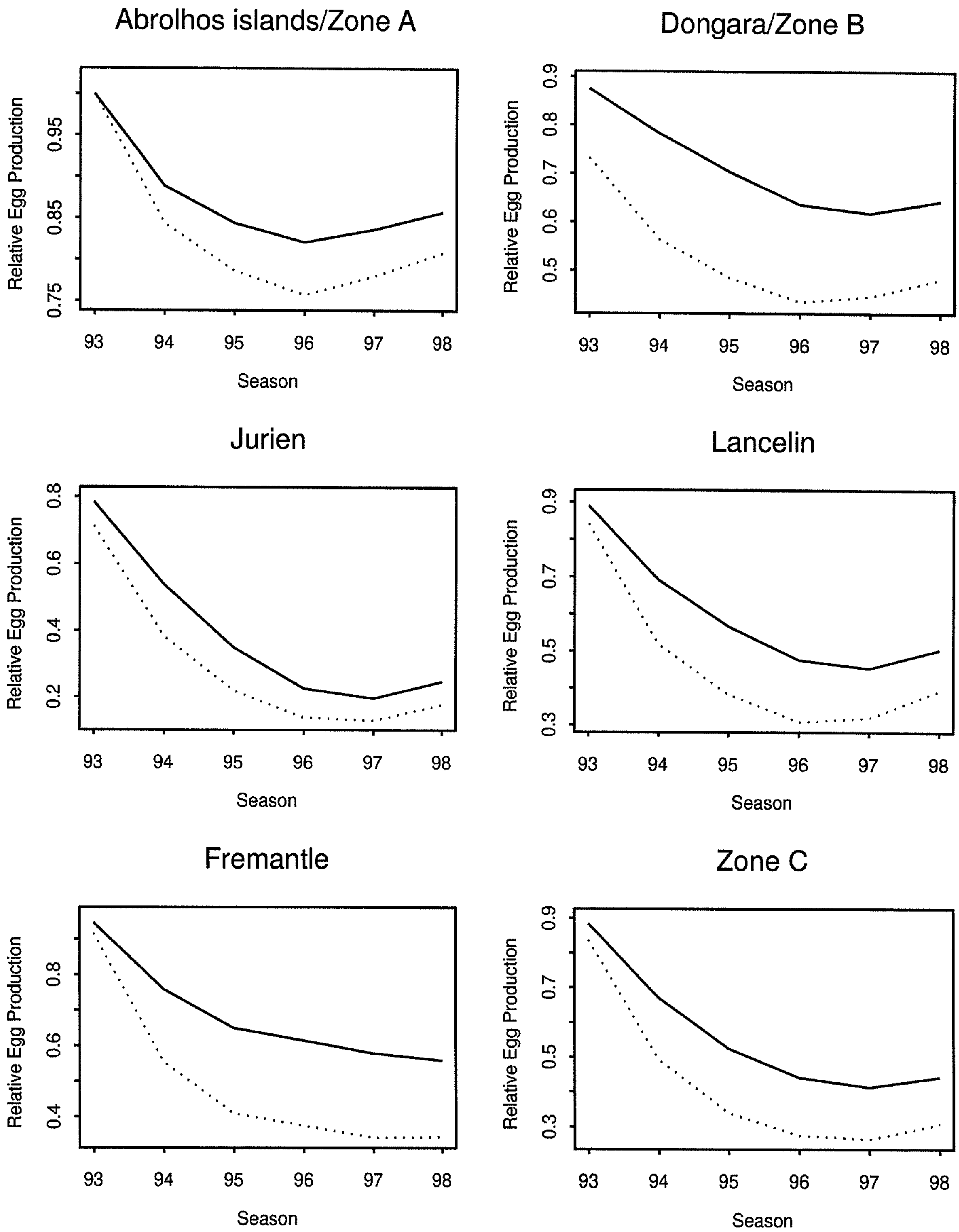


Figure 16. Impact on egg production of retaining only the protection of setose element of the 1993/94 strategy . Shown in the plots are the ratios of egg production estimated by the model under the alternative management strategies relative to those estimated under the 1993/94 strategy. The solid line represents the ratios of egg production under the setose strategy relative to those under the 1993/94 strategy; the dotted line represents the ratios of egg productions under the original strategy relative to those under the 1993/94 strategy. The results are shown by region and by zone.

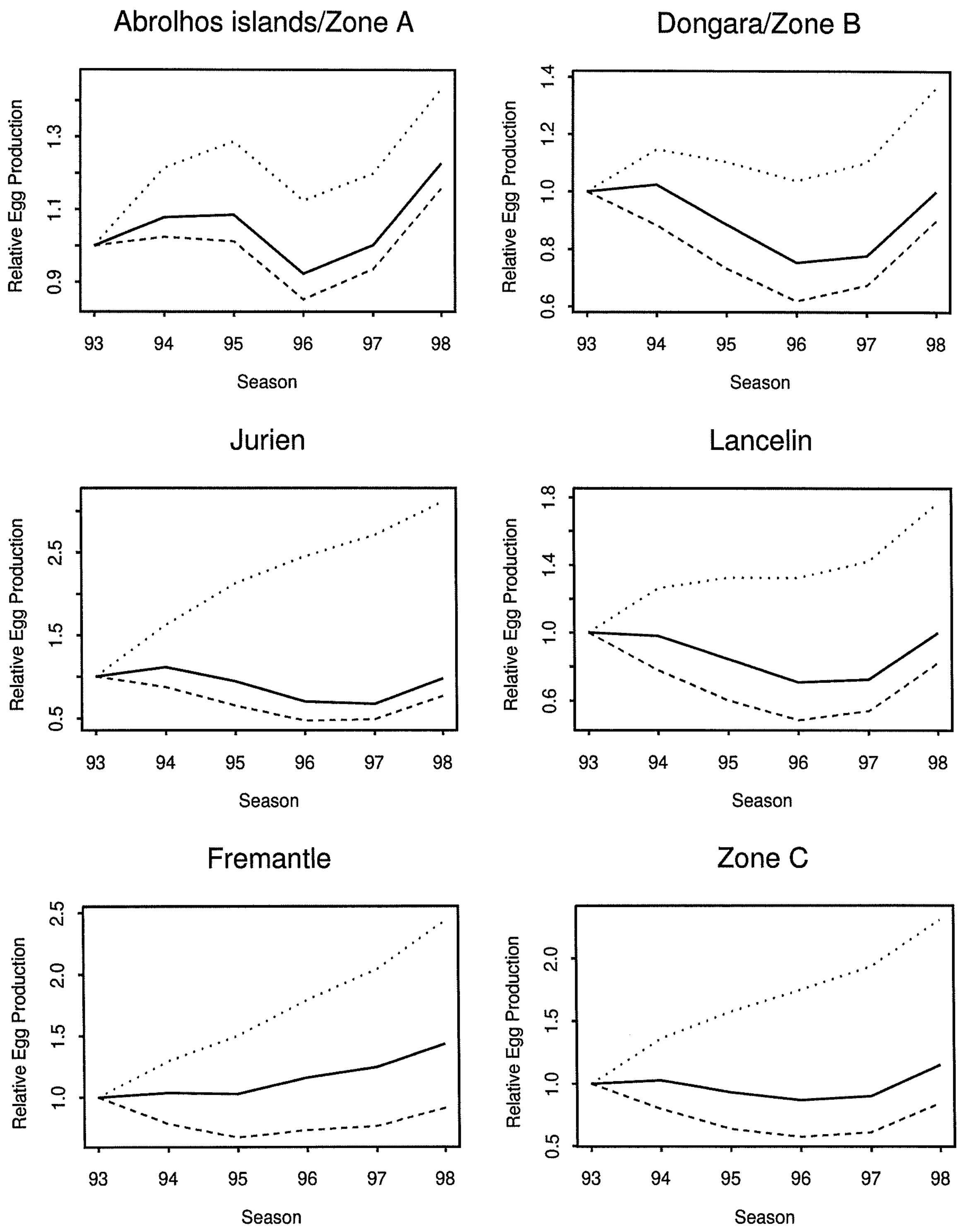


Figure 17. Same as **Figure 16**, but shown in the plots are the ratios of egg production in 1993/94 onwards under different management strategies relative to those obtained in 1993/94. The solid line represents the setose strategy; the dotted line represents the 1993/94 strategy; and the dashed line represents the original strategy.

5.3.1 Summary of results

The results presented above illustrate the capacity of the model in exploring an alternative management strategy. However, it should be recognised that the results obtained from any model are dependent on the assumptions used in developing the model and the accuracy and precision of results reflect the quality of the model fit to the data and the uncertainty associated with model predictions.

It should be noted that considerable logbook information on the catches (and releases) of setose female lobsters has now been collected from the fishery since the introduction of the 1993/94 management strategy. These data have not been included when fitting the length-structured model, but will be included as the model is developed further.

5.4 Economic Assessment

5.4.1 Economic data collected

5.4.1.1 Beach price

The mean and standard deviation of beach prices in dollars per kilogram ($/kg) from survey data for the 1998/99 season are shown in **Table 12**.

Table 12 Mean and standard deviation of beach price ($/kg) for product in each grade during the 1998/99 season

Grades	Months							
	Nov		Dec		Jan		Feb	
	Mean	sd	Mean	sd	Mean	sd	Mean	sd
A	16.48	1.62	16.66	1.43	17.52	1.15	17.52	1.17
B	16.48	1.62	16.66	1.43	17.52	1.15	17.52	1.17
C	16.48	1.62	16.66	1.43	17.52	1.15	17.52	1.17
D	17.28	1.18	17.26	1.16	17.92	1.27	17.92	1.28
E	18.08	0.17	17.66	0.94	17.92	1.27	17.92	1.28
F	18.08	0.17	17.66	0.94	17.92	1.27	17.92	1.28
G	18.08	0.17	17.66	0.94	17.92	1.27	17.92	1.28
Grades	Months							
	Mar		Apr		May		Jun	
	Mean	sd	Mean	sd	Mean	sd	Mean	sd
A	18.54	0.94	19.44	1.21	1.21	1.20	21.31	2.00
B	18.54	0.94	19.44	1.21	1.21	1.20	21.31	2.00
C	18.54	0.94	19.44	1.21	1.21	1.20	21.31	2.00
D	18.74	0.91	20.04	1.05	1.05	1.33	21.91	1.96
E	18.74	0.91	20.04	1.05	1.05	1.33	21.91	1.96
F	18.74	0.91	20.04	1.05	1.05	1.33	21.91	1.96
G	18.74	0.91	20.04	1.05	1.05	1.33	21.91	1.96

5.4.1.2 Fishing costs

5.4.1.2.1 Management Zone A

The mean fishing costs of bait, fuel and gear derived from the survey in dollars ($) on a monthly basis for individual vessels operating in management zone A during the 1998/99 season are shown in **Table 13**. The cost of transporting product on carrier boats was included within the fuel costs, in order to maintain consistency with those vessels that carted their own product to the processors.

Table 13 The average fishing cost per vessel ($/vessel) in the 1998/99 season for management zone A

Fishing Costs	Months			
	Mar	Apr	May	Jun
Bait	6592	6389	4333	3729
Fuel	3760	3037	2483	2345
Gear	769	769	769	769
Total	**11121**	**10195**	**7585**	**6843**

5.4.1.2.2 Management Zone B

The mean fishing costs of bait, fuel and gear derived from the survey in dollars ($) on a monthly basis for individual vessels operating in management zone B during the 1998/99 season are shown in **Table 14**.

Table 14 The average fishing cost per vessel ($/vessel) in the 1998/99 season for management zone B

Fishing Costs	Months							
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Bait	2658	5841	1913	3733	5709	5696	4417	3912
Fuel	1037	3080	1268	2223	3545	3452	3109	2565
Gear	695	695	695	695	695	695	695	695
Total	**4390**	**9616**	**3876**	**6651**	**9949**	**9843**	**8221**	**7172**

5.4.1.2.3 Management Zone C

The mean fishing costs of bait, fuel and gear derived from the survey in dollars ($) on a monthly basis for individual vessels operating in management zone C during the 1998/99 season are shown in **Table 15**.

Table 15 The average fishing cost per vessel ($/vessel) in the 1998/99 season for management zone C

Fishing Costs	Months							
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Bait	2673	5857	1923	3741	5725	5708	4445	3924
Fuel	1556	3405	1129	2177	3323	3322	3778	2283
Gear	466	466	466	466	466	466	466	466
Total	**4695**	**9728**	**3518**	**6384**	**9514**	**9496**	**8689**	**6673**

5.4.2 Determination of relative net value associated with management strategy

The economic information collected within the survey (Section 4.4) may be used within the model to compare the relative economic consequences of alternative management strategies under the assumption that the beach prices and the costs of fishing were the same as those observed for the 1998/99 fishing season. It is recognised that the actual economic outcome for future fishing seasons will be dependent on foreign exchange rates and prices on world markets, and on the costs of fishing during those fishing seasons. Comparisons between the alternative model outputs will provide a guide as to the relative merits of the alternative strategies, if 1998/99 economic conditions prevail. However, caution will need to be exercised in assessing the outputs of the model as economic circumstances for future years will differ from those presented for the 1998/99 fishing season. Nevertheless, it is the understanding of the relative magnitude and direction of the changes in value that is important when comparing alternative management strategies, and the results should prove valuable in focusing discussion on the merits of the alternative strategies.

The calculation uses outputs from the biological model as its inputs. These input data comprise estimates, for the selected management strategy, of the landed catch (kg) by grade within each month and details of the fishing effort (pot lifts) expended within each calendar month of the fishing season. A table of the landed value of catch within each grade and month is calculated from the beach price for each grade, and the total landed value within the month is calculated using Eq. 4.31. Effort-dependent costs for the month are calculated from the estimated fishing effort for the month using the average costs of fuel, bait and gear per vessel for the month. The catch-dependent cost is calculated from the expected catch for the month and the average cost of crew wages for the month. From this, a table of net values (after allowing for the effort and catch-dependent costs) of the monthly catches are calculated.

Such tables of the estimated net values of the monthly catches may be produced for each of the management strategies under consideration, and results compared to determine the impact of the alternative management strategies on the net values of the catches if the prices and costs present in 1998/99 had prevailed. Note that this is not the net value to the community of Western Australia, but reflects the profitability of the catching sector of the rock lobster fishery.

An example of such a table (**Table 16**) has been calculated for 1998/99 from the outputs produced by the biological model with the current set of management regulations (the full management strategy adopted in 1993/94) being applied to the fishery from the 1993/94 fishing season. This table illustrates the form of the economic output produced by the model. The economic information produced by the survey may be used within other biological models of the western rock lobster fishery, and its value is not limited to the length structured model developed within this project.

Table 16 Example of model calculation of the economic values (dollars) of landed catch by grade and month when applying the current strategy (*i.e.*, the full 1993/94 management package), where 'Value for the month' was calculated by adding value for each grade at that month (*i.e.*, Vcatch, see Eq. 4.31); 'Fixed cost' and 'Variable cost' (*i.e.*, crew wage) were described in Section 4.4.1.4; and 'Net value' was estimated by subtracting fixed and variable costs from the 'Value for the month' (*i.e.*, NVcatch, see Eq. 4.32). 'Total value for the season' was simply the sum of monthly landed value, monthly fixed cost, monthly variable cost and monthly net value, respectively.

(i) Values ($) by month and grade

ZONE A							
Month	Grade = A	B	C	D	E	F	G
3	5606311	7567589	842017	329679	70134	0	0
4	5804010	7846560	1001076	409124	87908	0	0
5	2777626	3768628	489901	201811	43068	0	0
6	1111739	1580780	216365	87804	18561	0	0
ZONE B							
Month	Grade = A	B	C	D	E	F	G
11	1544511	2558132	203266	28088	6864	774	95
12	5104571	10101665	1787986	822255	206093	16175	2151
1	1267471	2418213	297268	161295	53831	2866	383
2	6919898	4150828	685824	435308	149150	6177	823
3	7315545	6855327	305804	152965	36593	0	0
4	3845638	3538068	383124	263398	61867	999	123
5	2206781	2262854	389395	235434	51851	1971	242
6	1921116	1958140	269288	141353	47714	1711	206
ZONE C							
Month	Grade = A	B	C	D	E	F	G
11	1295562	2052956	131363	5369	3915	1907	1179
12	5904087	14819787	3892257	2513775	863428	270753	97376
1	2488018	6277465	1805988	1318806	583259	178974	47766
2	5504952	5498753	1679180	1212583	698368	233143	51196
3	9369724	9467234	1335242	970164	516786	125970	20106
4	5769131	6170463	1302445	1182795	766413	267895	23598
5	3988948	4474518	1044595	892142	511974	159730	29693
6	3389841	3820447	844276	524309	216079	58465	24264

(ii) Values ($) by month

Month	Value for the month	Fixed cost for the month	Variable cost for the month	Net value for the month
ZONE A				
3	14415730	2135808	2883146	9396776
4	15148678	1983848	3029735	10135094
5	7281034	1409545	1456206	4415282
6	3015249	710661	603049	1701538
Total value for the season =	39860688	6239862	7972136	25648690
ZONE B				
Month	Value for the month	Fixed cost for the month	Variable cost for the month	Net value for the month
11	4341730	1308620	868346	2164764
12	18040896	2859952	3608179	11572765
1	4201327	1129536	840265	2231525
2	12348008	1975615	2469601	7902791
3	14666234	2188905	2933246	9544082
4	8093217	1493239	1618643	4981334
5	5148528	1206982	1029705	2911840
6	4339528	931122	867905	2540500
Total value for the season =	71179464	13093971	14235890	43849600
ZONE C				
Month	Value for the month	Fixed cost for the month	Variable cost for the month	Net value for the month
11	3492251	1399408	698450	1394392
12	28361464	2889810	5672293	19799360
1	12700276	1044846	2540055	9115375
2	14878175	1889960	2975635	10012580
3	21805226	2825955	4361045	14618226
4	15482740	2792118	3096548	9594074
5	11101600	2478762	2220320	6402518
6	8877681	1788900	1775536	5313245
Total value for the season =	116699408	17109760	23339882	76249776

5.4.3 Discussion

5.4.3.1 Beach price

At the beginning of the 1998/99 season, considerable variation existed in the beach price received by the catching sector. Higher prices were sought for larger lobsters in November before the beach price, regardless of grade, became standardised in December for the remainder of the season.

Beach price is influenced primary by the export price received by the processing sector. This export price is based on exchange rate and selling price (Anon., 1994). The factors affecting export price can vary on a daily basis. Generally a modification in beach price is determined by the processing sector when a significant increase or decrease in export price over a prolonged period is substantive enough to justify its adjustment, although artificially high beach prices are often offered by processors wishing to maintain their supply of product.

When exploring the economic impact of alternative management strategies using the model, it is assumed that prices will remain the same as those prices derived in the study from the 1998/99 season. That is, the model examines the effect on the economics of the fishery assuming that costs and prices were those of the 1998/99 season. However, the adoption of different management strategies will vary the volume of product harvested and subsequently may influence the beach price received. The effect of volume supplied on beach price has not been incorporated into the study due to the complexity of the demand/ supply relationships that exist.

In the 1998/99 season, the largest catch ever recorded in the fishery was harvested, thus the monthly beach prices derived in the model, which are based on the 1998/99 season, cannot be considered typical. Supply and demand relationships of a scarce resource dictate that a reduced supply will result in a corresponding increase in price (Anderson, 1986). Therefore in years when catches are extremely high, economic theory suggests that the price per individual unit sold (*i.e.,* kilograms) will not be as high as in those years when harvests in the fishery are low. However, the situation is not that simple. The fluctuation in beach price received by the catching sector as a result of levels of catch is dependent on elasticity of demand of the product, exchange rate fluctuations, and the margins offered by processors seeking to maintain supply.

Lobster processors in the fishery consider that, even though the 13,000 tonne catch in the 1998/99 season was substantially greater than catches in previous years, the export price received was not significantly affected as existing markets were expanded, new markets were developed to accommodate the larger catch, and there was a favourable exchange rate.

Currency exchange rates have played an extremely significant role in determining the past profitability of the rock lobster industry. With a relatively minor domestic market for western rock lobster, the beach prices received by fishers are strongly influenced by fluctuations in exchange rates. Global economic forces also affect the economies of the countries to which the rock lobsters are exported, influencing the demand for lobsters and the prices received for the product from overseas markets.

The assumption that beach price in individual months remains constant when applying different management strategies to the model must be considered in the context of using beach price information based on the 1998/99 season. Without a more detailed study to investigate the relationship between supply and demand, estimates of the likely economic impact of alternative management strategies must be accepted with caution, recognising the implicit assumption that the prices and costs are those recorded for 1998/99.

5.4.3.2 Fishing costs

The average fuel, bait and gear costs for individual licensees in each of the management zones for the 1998/99 season were calculated from the survey data (see **Table 13**-**Table 15**). The size of vessels and number of pots allocated to individual vessels varies considerably in each of the management zones (see **Table 5**). This diversity in vessel length and pot allocation has the ability to significantly influence fishing costs described in the study. By including a sample of vessels in each management zone that represents the full range of vessel length and pot allocation, the data used in this study are considered to be representative of the diversity in fishing costs on a management zone basis. However it should be noted that variation in fishing costs between vessels will occur in the fishery. The diversification in areas fished and vessel dynamics (*i.e*., vessel length, engine size and number, fuel consumption etc.) within management zones means that fishing costs cannot be standardised. Therefore the average costs used in the analysis may not be representative of the individual fishers, but are the average costs expected within the zone.

Within each of the individual management zones there is a significant variation in the fishing costs defined in the study. It can be observed from the results, however, that in all three management zones the fishing costs, as defined by the study, are significant in those months when catches are traditionally high. This suggests that fishing cost is a function of catch, particularly in the case of crew wages where 20% of the landed value of the catch is attributed to wages. However, it should be noted that fishing costs that are dependent on fishing effort rather than catch will be related to the level of catch as the latter is also dependent on fishing effort.

A variety of different bait types are used in the fishery, with the selection of bait type and the quantity used being a personal preference. The cost of the specific bait type and the quantity used are the factors which determine the cost of bait. The survey data are distributed over all management zones, and are considered representative of the range of bait types and quantities used.

Additionally fuel prices vary from location to location, with fuel in more remote locations fetching higher prices. To ensure that a representative sample of fuel costs in individual management zones was obtained, data were collected from vessels operating from ports throughout the management zones. The sample is also representative of the variation in fuel consumption between fishers that exists in the fishery. Within each management zone the distances that fishers travel varies, therefore variation in fuel expenditure between licensees occurs.

A distinct differentiation in costs between fishers occurs in management zone A as a result of the considerable distance from the mainland to the fishing grounds. Hence, fishers either remain at the Abrolhos Islands for the duration of the season (March to June), returning infrequently to the mainland or return once the holding capacity of the vessel is full. In the latter case, this is usually every second or third day. For those vessels that do not return to the mainland frequently, the cost of paying a cartage company to transport product from the Abrolhos Islands to the mainland is incurred. The effort-dependent fishing costs (*i.e*., fuel, bait and gear) collected by the survey within this management zone are representative of both vessels returning to the mainland frequently and those remaining at the Abrolhos Islands for the duration of the season, as the cost of cartage is included in the fuel cost for those vessels using carrier boats (it should be noted that the cost of such cartage is related to catch, rather than effort, and a more detailed analysis of these cartage costs should be considered in future studies).

The continued collection of beach price and fishing cost information in subsequent years will enable the variation in data over time to be observed. The collection of this information will also provide the means to analyse the effect of supply and demand relationships on beach price in both the short and long term.

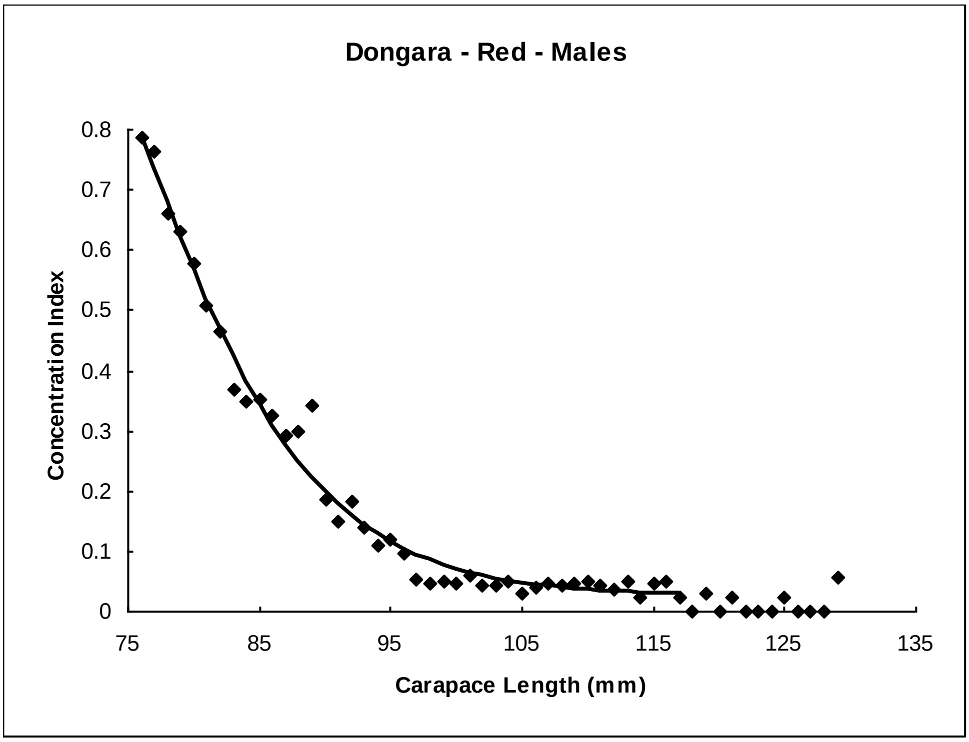


Figure 18. Concentration indices at length for male lobsters at Dongara in the period from February to June, 1995. A curve has been subjectively fitted to the data.

5.5 Vulnerability at length and concentration index

In general, the concentration index declined rapidly with length (**Figure 18**). The decline was usually more marked in the reds period than the whites, possibly as a consequence of the fishery following the migration of the lobsters out to deeper water where the larger lobsters are located during the whites season. The relationship varied considerably from month to month, and estimates of the concentration index were found (from bootstrapping) to be less precise for the larger lobsters, as relatively fewer of these are contained in the length samples obtained in the research monitoring program.

Clearly, the estimated length composition of the catch is strongly influenced by the concentration of effective fishing effort on smaller lobsters. Similarly fishing mortality of lobsters will be reduced as the lobsters become larger.

In future modelling of the western rock lobster fishery, the concentration of effort on smaller lobsters should be represented within the model structure. It is likely that this factor was responsible for the poor fit obtained by the length-structured model, especially as the relationship between concentration index and length varies markedly from month to month. The index is likely to have been affected by the 1993/94 management strategy, particularly the setose regulation.

5.6 Age-structured model of impact of 1993/94 strategy

5.6.1 The south coast management zone

The results of fitting the data for the south coastal management zone are presented in **Table 17** to **Table 22**. A plot of the fitted data is shown in **Figure 19** for the baseline case, in which $a_{\mathrm{Large}} = 3$ years, $M = 0.226$ year^{-1}, and the annual increase in fishing efficiency was $X = 0.01$. The results for this case are presented in each table, in order to assist comparison with the results arising from alternative assumptions.

Subjectively, based on the distribution of residuals in **Figure 19**, the model produced a good fit to the annual catches and an adequate fit to the indices of egg production and released catches of setose females, but a poor fit to the releases on non-setose females larger than the maximum legal size. However, the observed indices of egg production suggest a positive trend, while the model estimates suggest that egg production has now stabilised.

Using the estimated parameters for the baseline case, it was determined from the data for the south coastal zone that the annual harvest of the younger male lobsters was 41% in 1991-92, but had been reduced to 37% in 1998-99. The recruitment to the exploited assemblage (> 76 mm carapace length) in 1998-99 was estimated to be 21.4 million lobsters.

Catchability of the older lobsters for the baseline case was only 36% of that for younger lobsters in the south coastal management zone (**Table 17**).

Table 17 Parameter estimates (and standard deviations) for the rock lobster assemblage in the south coastal management region when $a_{\text{Large}} = 3$ years and $M = 0.226$ year^{-1}.

	Annual increase in efficiency, X		
Parameter	0.00	0.01	0.02
λ	36.8	37.8	38.3
k (1000 lobsters per puerulus)	7200 (470)	7200 (530)	7300 (630)
β (per 1000 potlifts)	0.00004 (0.000013)	0.00004 (0.000013)	0.00004 (0.000014)
q_S (per 1000 potlifts)	0.00013 (0.000022)	0.00013 (0.000021)	0.00013 (0.000022)
q_L (per 1000 potlifts)	0.00005 (0.000015)	0.00005 (0.000015)	0.00004 (0.000015)
φ_S	0.0000 (0.00095)	0.0000 (0.00087)	0.0000 (0.00080)
φ_L	0.53 (0.074)	0.55 (0.070)	0.56 (0.069)

Table 18 Estimates of the egg ratio (and standard deviations) for the rock lobster assemblage in the south coastal management region when $a_{\text{Large}} = 3$ years and $M = 0.226$ year^{-1}.

Season and management scenario	Annual increase in efficiency, X		
	0.00	0.01	0.02
1992-1993	0.15 (0.049)	0.16 (0.055)	0.18 (0.065)
1999-2000	0.26 (0.058)	0.27 (0.063)	0.29 (0.072)
2002-2003 with no management changes	0.29 (0.058)	0.29 (0.063)	0.29 (0.071)
2002-2003 without setose and max size in 2001-2002	0.26 (0.060)	0.26 (0.064)	0.26 (0.073)

Table 19 Parameter estimates (and standard deviations) for the rock lobster assemblage in the south coastal management region when $X = 0.01$ years and $M = 0.226$ year^{-1}.

Parameter	Age (years) at which decreased vulnerability of lobsters is assumed		
	$a_{\text{Large}} = 2$	$a_{\text{Large}} = 3$	$a_{\text{Large}} = 4$
λ	33.8	37.8	35.9
k (1000 lobsters per puerulus)	6900 (320)	7200 (530)	7200 (560)
β (per 1000 potlifts)	0.00005 (0.000012)	0.00004 (0.000013)	0.00004 (0.000015)
q_S (per 1000 potlifts)	0.00019 (0.000030)	0.00013 (0.000021)	0.00010 (0.000021)
q_L (per 1000 potlifts)	0.00007 (0.000015)	0.00005 (0.000015)	0.00005 (0.000018)
φ_S	0.000 (0.0019)	0.0000 (0.00087)	0.000 (0.0043)
φ_L	0.35 (0.046)	0.55 (0.070)	0.65 (0.126)

Table 20 Estimates of the egg ratio (and standard deviations) for the rock lobster assemblage in the south coastal management region when $X = 0.01$ years and $M = 0.226$ year^{-1}.

Season and management scenario	Age (years) at which decreased vulnerability of lobsters is assumed		
	$a_{\text{Large}} = 2$	$a_{\text{Large}} = 3$	$a_{\text{Large}} = 4$
1992-1993	0.13 (0.033)	0.16 (0.055)	0.16 (0.061)
1999-2000	0.23 (0.044)	0.27 (0.063)	0.27 (0.069)
2002-2003 with no management changes	0.25 (0.045)	0.29 (0.063)	0.28 (0.070)
2002-2003 without setose and max size in 2001-2002	0.22 (0.044)	0.26 (0.064)	0.25 (0.071)

Table 21 Parameter estimates (and standard deviations) for the rock lobster assemblage in the south coastal management region when $a_{\text{Large}} = 3$ years and the annual increase in efficiency is $X = 0.01$.

Parameter	Natural mortality, M (year^{-1})		
	$M = 0.15$	$M = 0.226$	$M = 0.3$
λ	39.6	37.8	35.2
k (1000 lobsters per puerulus)	5600 (220)	7200 (530)	9500 (1460)
β (per 1000 potlifts)	0.00004 (0.000012)	0.00004 (0.000013)	0.00004 (0.000020)
q_S (per 1000 potlifts)	0.00017 (0.000016)	0.00013 (0.000021)	0.00010 (0.000032)
q_L (per 1000 potlifts)	0.00005 (0.000015)	0.00005 (0.000015)	0.00004 (0.000018)
φ_S	0.0000 (0.00079)	0.0000 (0.00087)	0.000 (0.0011)
φ_L	0.57 (0.069)	0.55 (0.070)	0.54 (0.090)

Table 22 Estimates of the egg ratio (and standard deviations) for the rock lobster assemblage in the south coastal management region when $a_{\text{Large}} = 3$ years and the annual increase in efficiency is $X = 0.01$.

Season and management scenario	Natural mortality, M (year^{-1})		
	$M = 0.15$	$M = 0.226$	$M = 0.3$
1992-1993	0.09 (0.028)	0.16 (0.055)	0.23 (0.107)
1999-2000	0.18 (0.037)	0.27 (0.063)	0.36 (0.109)
2002-2003 with no management changes	0.20 (0.037)	0.29 (0.063)	0.37 (0.110)
2002-2003 without setose and max size in 2001-2002	0.17 (0.038)	0.26 (0.064)	0.34 (0.114)

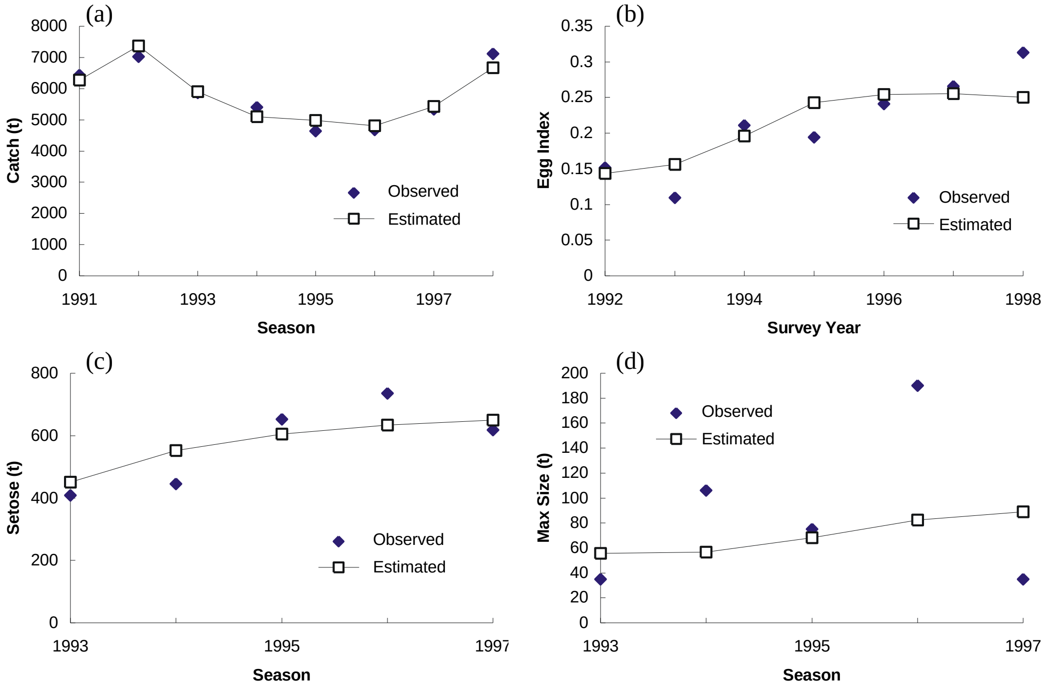


Figure 19. Model estimates for the south coastal management region: (a) combined catch (t) from commercial and recreational fishers; (b) indices of egg production (million eggs per potlift) from research surveys; (c) biomass (t) of released setose female lobsters; and (d) biomass (t) of released non-setose female lobsters larger than the maximum legal size.

Although no setose lobsters were present in the younger age-classes, 55% of the older female lobsters were estimated to be setose, and thus released following capture (**Table 17**). Egg production at the beginning of the 1992-93 fishing season for the baseline case had been reduced to approximately 16% of the egg production for the unfished stock, but recovered and was predicted to be approximately 27% at the beginning of the 1999-2000 fishing season (**Table 18**).

The sensitivity of model estimates of the level of egg production relative to the egg production of the unfished stock for annual increases in fishing efficiency between 0 and 2% per annum was examined, and results for the south coastal zone are presented in **Table 18**. Egg production at the beginning of the 1992-93 fishing season was estimated to be 15% of that of the unfished stock if no increase in fishing efficiency had occurred following 1993-94, 16% if fishing efficiency had increased by 1% per year, and 18% if the increase had been 2% per year. With these annual increases in fishing efficiency, egg production for 1999-2000 was predicted to have improved to 26, 27 and 29% of the egg production for the unfished stock, respectively. With continued application of the current regulations, egg production at the beginning of the 2002-2003 fishing season was predicted to be 29% of the egg production for the unfished stock, regardless of the annual increase in fishing efficiency. However, egg production in 2002-2003 was predicted to be reduced to 26% if fishers were permitted to land setose females and females larger than the maximum legal size during 2001-2002.

The age, a_{Large}, determining the age classes to be grouped as younger and older lobsters was varied between two and four years, and results for the south coastal management region are presented in **Table 19** and **Table 20**. Increasing this age resulted in a decrease in the catchability of the younger lobsters and reduced the difference between the catchabilities of the younger and older lobsters (**Table 19**). The proportion of older lobsters that were considered to be setose increased as a_{Large} was increased from two to four years. The ratio of the egg production in 1992-93 relative to the egg production of the unfished stock was estimated to be 13% when $a_{\text{Large}} = 2$ years, 16% when $a_{\text{Large}} = 3$ years, and 16% when $a_{\text{Large}} = 4$ years (**Table 20**). In response to the regulations introduced in 1992-93 and 1993-94, this ratio had increased to 23, 27 or 27% when a_{Large} was two, three or four years, respectively. By the 2002-2003 fishing season, the egg production ratio was predicted to further increase to 25, 29 or 28%, respectively, if the current regulations continued, but would be 22, 26 or 25%, respectively, if the setose and maximum size regulations for female lobsters were dropped for the 2001-2002 fishing season.

The effect of uncertainty in the estimate of natural mortality was examined for the south coastal management zone (**Table 21** and **Table 22**). Higher estimates of the catchability of the younger lobsters resulted when the estimate of natural mortality was decreased (**Table 21**). The estimated ratio of egg production in 1992-93 relative to that for the unfished stock decreased from 16% when $M = 0.226$ year^{-1} to 9% when $M = 0.15$ year^{-1}, and increased to 23% when $M = 0.3$ year^{-1} (**Table 22**). Under the management regulations introduced in 1992-93 and 1993-94, the ratio increased to 18, 27 or 36% for values of M of 0.15, 0.226 and 0.3 year^{-1}, respectively. Continued use of the present regulations resulted in egg ratio predictions of 20, 29 and 37%, respectively, while removing the requirement for the release of setose lobsters and lobsters larger than the maximum legal length for 2001-2002 produced predictions of 17, 26 and 34%, respectively.

5.6.2 The north coastal management zone

Parameter estimates for the north coastal zone are presented in **Table 23** to **Table 28**.

Table 23 Parameter estimates (and standard deviations) for the rock lobster assemblage in the north coastal management region when $a_{\mathrm{Large}} = 3$ years and $M = 0.226$ year^{-1}.

Parameter	Annual increase in efficiency, X		
	0.00	0.01	0.02
λ	44.2	44.1	43.9
k (1000 lobsters per puerulus)	4200 (170)	4200 (160)	4100 (160)
β (per 1000 potlifts)	0.00020 (0.000065)	0.00021 (0.000070)	0.00022 (0.000077)
q_S (per 1000 potlifts)	0.00042 (0.000059)	0.00043 (0.000060)	0.00044 (0.000061)
q_L (per 1000 potlifts)	0.00008 (0.000025)	0.00008 (0.000025)	0.00008 (0.000026)
φ_S	0.14 (0.029)	0.14 (0.028)	0.14 (0.028)
φ_L	0.69 (0.094)	0.68 (0.099)	0.67 (0.103)

Table 24 Estimates of the egg ratio (and standard deviations) for the rock lobster assemblage in the north coastal management region when $a_{\mathrm{Large}} = 3$ years and $M = 0.226$ year^{-1}.

Season and management scenario	Annual increase in efficiency, X		
	0.00	0.01	0.02
1992-1993	0.04 (0.018)	0.04 (0.018)	0.04 (0.017)
1999-2000	0.12 (0.033)	0.11 (0.032)	0.10 (0.031)
2002-2003 with no management changes	0.14 (0.036)	0.12 (0.034)	0.11 (0.032)
2002-2003 without setose and max size in 2001-2002	0.12 (0.034)	0.10 (0.032)	0.09 (0.030)

Table 25 Parameter estimates (and standard deviations) for the rock lobster assemblage in the north coastal management region when $X = 0.01$ years and $M = 0.226$ year^{-1}.

Parameter	Age (years) at which decreased vulnerability of lobsters is assumed		
	$a_{\text{Large}} = 2$	$a_{\text{Large}} = 3$	$a_{\text{Large}} = 4$
λ	49.5	44.1	42.0
k (1000 lobsters per puerulus)	4500 (160)	4200 (160)	4000 (170)
β (per 1000 potlifts)	0.00013 (0.000035)	0.00021 (0.000070)	0.00026 (0.000101)
q_S (per 1000 potlifts)	0.00071 (0.000091)	0.00043 (0.000060)	0.00035 (0.000059)
q_L (per 1000 potlifts)	0.00005 (0.000014)	0.00008 (0.000025)	0.00013 (0.000060)
φ_S	0.12 (0.038)	0.14 (0.028)	0.15 (0.023)
φ_L	0.70 (0.086)	0.68 (0.099)	0.68 (0.100)

Table 26 Estimates of the egg ratio (and standard deviations) for the rock lobster assemblage in the north coastal management region when $X = 0.01$ years and $M = 0.226$ year^{-1}.

Season and management scenario	Age (years) at which decreased vulnerability of lobsters is assumed		
	$a_{\text{Large}} = 2$	$a_{\text{Large}} = 3$	$a_{\text{Large}} = 4$
1992-1993	0.07 (0.023)	0.04 (0.018)	0.03 (0.017)
1999-2000	0.17 (0.033)	0.11 (0.032)	0.09 (0.034)
2002-2003 with no management changes	0.18 (0.035)	0.12 (0.034)	0.10 (0.037)
2002-2003 without setose and max size in 2001-2002	0.16 (0.034)	0.10 (0.032)	0.08 (0.034)

Table 27 Parameter estimates (and standard deviations) for the rock lobster assemblage in the north coastal management region when $a_{\mathrm{Large}} = 3$ years and the annual increase in efficiency is $X = 0.01$.

Parameter	Natural mortality, M (year^{-1})		
	$M = 0.15$	$M = 0.226$	$M = 0.3$
λ	44.1	44.1	43.8
k (1000 lobsters per puerulus)	3600 (130)	4200 (160)	4800 (220)
β (per 1000 potlifts)	0.00018 (0.000058)	0.00021 (0.000070)	0.00024 (0.000088)
q_S (per 1000 potlifts)	0.00048 (0.000059)	0.00043 (0.000060)	0.00040 (0.000062)
q_L (per 1000 potlifts)	0.00006 (0.000018)	0.00008 (0.000025)	0.00009 (0.000035)
φ_S	0.14 (0.027)	0.14 (0.028)	0.14 (0.030)
φ_L	0.72 (0.086)	0.68 (0.099)	0.64 (0.113)

Table 28 Estimates of the egg ratio (and standard deviations) for the rock lobster assemblage in the north coastal management region when $a_{\mathrm{Large}} = 3$ years and the annual increase in efficiency is $X = 0.01$.

Season and management scenario	Natural mortality, M (year^{-1})		
	$M = 0.15$	$M = 0.226$	$M = 0.3$
1992-1993	0.03 (0.012)	0.04 (0.018)	0.05 (0.023)
1999-2000	0.08 (0.023)	0.11 (0.032)	0.14 (0.041)
2002-2003 with no management changes	0.10 (0.025)	0.12 (0.034)	0.14 (0.043)
2002-2003 without setose and max size in 2001-2002	0.08 (0.023)	0.10 (0.032)	0.12 (0.040)

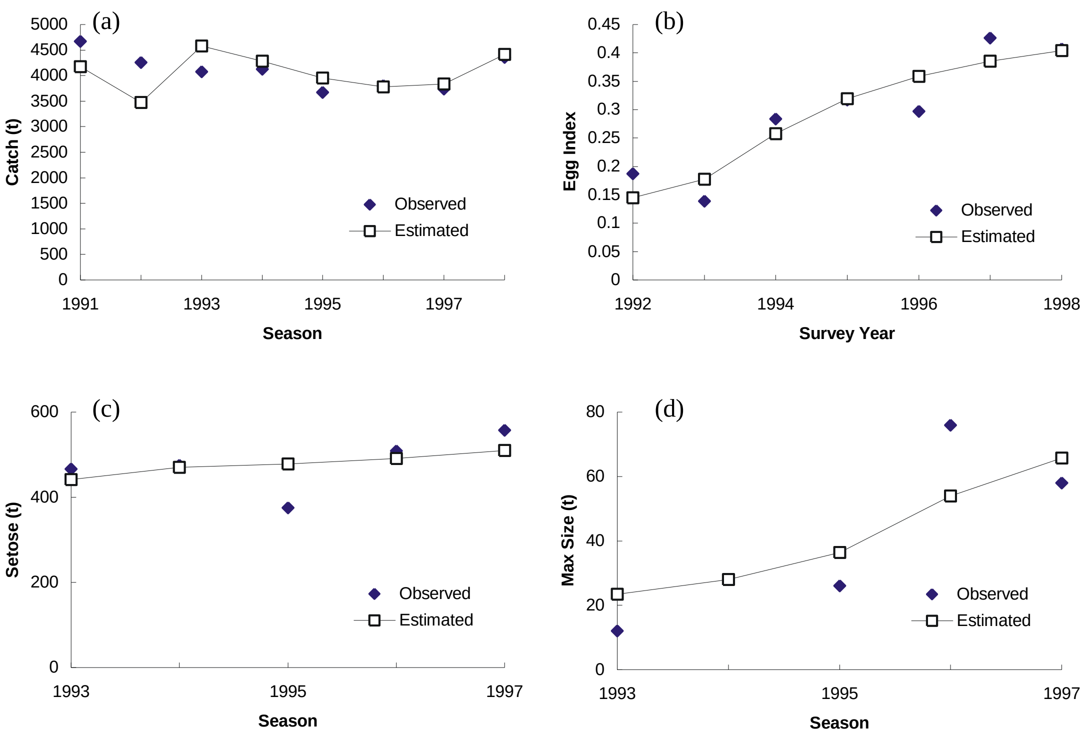


Figure 20. Model estimates for the north coastal management region: (a) combined catch (t) from commercial and recreational fishers; (b) indices of egg production (million eggs per potlift) from research surveys; (c) biomass (t) of released setose female lobsters; and (d) biomass (t) of released non-setose female lobsters larger than the maximum legal size.

The estimated catches for the north coastal management zone for the baseline case (in which $a_{\text{Large}} = 3$ years, $M = 0.226$ year^{-1}, and the annual increase in fishing efficiency was $X = 0.01$) were not as close to the observed catches (**Figure 20**) as had been observed for the south coastal management zone (**Figure 19**). The model estimated a much greater reduction in catch in 1992-93 than was observed; the model assumes constant catchability within the year, but the January closure occurred during a period of the year when catches (and catchability) were usually low. Again, as with the south coastal management zone, estimates of the egg production indices and of the released catches of setose females were adequate, but observations of the released catches of non-setose lobsters larger than the maximum legal length were poorly estimated although the trend appeared to be represented, and the estimates were better than those for the south coastal zone.

Using the estimated parameters for the baseline case, it was determined from the data for the north coastal zone that the annual harvest of the younger male lobsters was 70% in 1991-92, but had been reduced to 65% in 1998-99. The recruitment to the exploited assemblage (> 76 mm carapace length) in 1998-99 was estimated to be 11.5 million lobsters.

The estimated catchability of the older lobsters for the baseline case was only 18% of that for younger lobsters for the north coastal management zone (**Table 23**). A small proportion (14%) of the female lobsters in the younger age-classes were estimated to be setose, while approximately 68% of the older female lobsters were setose, and were released following capture (**Table 23**). Egg production at the beginning of the 1992-93 fishing season for the baseline case had been reduced to approximately 4% of the egg production for the unfished stock, but this was predicted to increase to approximately 11% by the beginning of the 1999-2000 fishing season (**Table 24**).

Alternative estimates of the annual increase in fishing efficiency of 0, 1 and 2% per annum were applied and the model fitted to the data for the north coastal zone in order to determine the sensitivity of model estimates of the level of egg production relative to the egg production of the unfished stock. Results are presented in **Table 24**. Egg production at the beginning of the 1992-93 fishing season was estimated to be 4% of that of the unfished stock for all three levels of annual efficiency increase. By 1999-2000, egg production was predicted to have improved to 12, 11 and 10% of the egg production for the unfished stock for annual increases in efficiency from 1993-94 of 0, 1 and 2%, respectively. With no change to the present regulations, egg production at the beginning of the 2002-2003 fishing season was predicted to be 14% of the egg production for the unfished stock if there was no increase in fishing efficiency, 12% if a 1% annual increase in efficiency applied, and 11% if the annual efficiency increase was 2%. If fishers were permitted to land setose females and females larger than the maximum legal size during 2001-2002, egg production in 2002-2003 was predicted to be reduced to 12% if no increase in efficiency occurred, 10% if the efficiency increase was 1% per year, and 9% if a 2% annual increase in efficiency occurred.

The age, a_{Large}, determining the age-classes to be grouped as younger and older lobsters was varied between two and four years, and results for the north coastal management region are presented in **Table 25**. As with the south coastal management zone, increasing the age resulted in a decrease in the catchability of the younger lobsters and reduced the difference between the catchabilities of the younger and older lobsters. When a_{Large} was increased to four years, an increasing proportion of the younger female lobsters were found to be setose. However, the proportion of the older female lobsters that were setose remained relatively constant. The ratio of the egg production in 1992-93 relative to the egg production of the unfished stock was estimated to be 7% when $a_{\text{Large}} = 2$ years, 4% when $a_{\text{Large}} = 3$ years, and 3% when $a_{\text{Large}} = 4$ years (**Table 26**). In response to the regulations introduced in 1992-93 and 1993-94, this ratio had increased to 17, 11 or 9% when a_{Large} was two, three or four years, respectively. By the 2002-2003 fishing season, the egg production ratio was predicted to further increase to 18, 12 or 10%, respectively, if the current regulations continued, but would be 16, 10, or 8%, respectively, if the setose and maximum size regulations for female lobsters were dropped for the 2001-2002 fishing season.

The effect of uncertainty in the estimate of natural mortality was examined, and results for the north coastal management zone are presented in **Table 27**. Higher estimates of the catchability of the younger lobsters resulted when the estimate of natural mortality was decreased, while the catchability of the older lobsters decreased.

Fewer older female lobsters were considered to be setose as the estimate of natural mortality was increased. The estimated ratio of egg production in 1992-93 relative to that for the unfished stock decreased from 4% when $M = 0.226$ year^{-1} to 3% when $M = 0.15$ year^{-1}, and increased to 5% when $M = 0.3$ year^{-1} (**Table 18**). Under the management regulations introduced in 1992-93 and 1993-94, the ratio increased to 8, 11 or 14% for values of *M* of 0.15, 0.226 and 0.3 year^{-1}, respectively. Continued use of the present regulations resulted in egg ratio predictions of 10, 12 and 14%, respectively, while removing the requirement for the release of setose lobsters and lobsters larger than the maximum legal length for 2001-2002 produced predictions of 8, 10 and 12%, respectively.

5.6.3 The Abrolhos Islands management zone

Estimates of the parameters for the Abrolhos Island region are presented in **Table 29** to **Table 34**.

Table 29 Parameter estimates (and standard deviations) for the rock lobster assemblage in the Abrolhos Islands management region when $a_{\text{Large}} = 3$ years and $M = 0.226$ year^{-1}.

	Annual increase in efficiency, X		
Parameter	0.00	0.01	0.02
λ	33.6	33.6	33.6
k (1000 lobsters per puerulus)	3320 (66)	3310 (64)	3300 (62)
β (per 1000 potlifts)	0.00068 (0.000074)	0.00068 (0.000075)	0.00069 (0.000076)
q_S (per 1000 potlifts)	0.0046 (0.00047)	0.0046 (0.00047)	0.0046 (0.00047)
q_L (per 1000 potlifts)	0.0046 (0.00047)	0.0046 (0.00047)	0.0046 (0.00048)
φ_S	0.10 (0.028)	0.10 (0.028)	0.10 (0.029)
φ_L	1.000 (0.0015)	1.000 (0.0016)	1.000 (0.0018)

Table 30 Estimates of the egg ratio (and standard deviations) for the rock lobster assemblage in the Abrolhos Islands management region when $a_{\text{Large}} = 3$ years and $M = 0.226$ year^{-1}.

Season and management scenario	Annual increase in efficiency, X		
	0.00	0.01	0.02
1992-1993	0.191 (0.0036)	0.191 (0.0036)	0.191 (0.0037)
1999-2000	0.228 (0.0080)	0.225 (0.0078)	0.222 (0.0075)
2002-2003 with no management changes	0.216 (0.0092)	0.210 (0.0086)	0.204 (0.0079)
2002-2003 without setose and max size in 2001-2002	0.192 (0.0063)	0.187 (0.0056)	0.183 (0.0050)

Table 31 Parameter estimates (and standard deviations) for the rock lobster assemblage in the Abrolhos Islands management region when $X = 0.01$ years and $M = 0.226$ year^{-1}.

Parameter	Age (years) at which decreased vulnerability of lobsters is assumed		
	$a_{\text{Large}} = 2$	$a_{\text{Large}} = 3$	$a_{\text{Large}} = 4$
λ	31.3	33.6	32.2
k (1000 lobsters per puerulus)	3380 (117)	3310 (64)	3290 (80)
β (per 1000 potlifts)	0.00060 (0.000116)	0.00068 (0.000075)	0.00055 (0.000069)
q_S (per 1000 potlifts)	0.0038 (0.00154)	0.0046 (0.00047)	0.0023 (0.00042)
q_L (per 1000 potlifts)	0.0021 (0.00112)	0.0046 (0.00047)	0.0023 (0.00042)
φ_S	0.000 (0.0024)	0.10 (0.028)	0.10 (0.043)
φ_L	0.64 (0.20)	1.000 (0.0016)	1.000 (0.0036)

Table 32 Estimates of the egg ratio (and standard deviations) for the rock lobster assemblage in the Abrolhos Islands management region when $X = 0.01$ years and $M = 0.226$ year^{-1}.

Season and management scenario	Age (years) at which decreased vulnerability of lobsters is assumed		
	$a_{\text{Large}} = 2$	$a_{\text{Large}} = 3$	$a_{\text{Large}} = 4$
1992-1993	0.20 (0.026)	0.191 (0.0036)	0.23 (0.017)
1999-2000	0.27 (0.051)	0.225 (0.0078)	0.29 (0.025)
2002-2003 with no management changes	0.26 (0.056)	0.210 (0.0086)	0.28 (0.027)
2002-2003 without setose and max size in 2001-2002	0.22 (0.048)	0.187 (0.0056)	0.25 (0.024)

Table 33 Parameter estimates (and standard deviations) for the rock lobster assemblage in the Abrolhos Islands management region when $a_{\mathrm{Large}} = 3$ years and the annual increase in efficiency is $X = 0.01$.

Parameter	Natural mortality, M (year^{-1})		
	$M = 0.15$	$M = 0.226$	$M = 0.3$
λ	35.0	33.6	32.2
k (1000 lobsters per puerulus)	3000 (55)	3310 (64)	3660 (78)
β (per 1000 potlifts)	0.00073 (0.000079)	0.00068 (0.000075)	0.00064 (0.000073)
q_S (per 1000 potlifts)	0.0051 (0.00037)	0.0046 (0.00047)	0.0041 (0.00060)
q_L (per 1000 potlifts)	0.0051 (0.00038)	0.0046 (0.00047)	0.0041 (0.00060)
φ_S	0.10 (0.021)	0.10 (0.028)	0.10 (0.037)
φ_L	1.000 (0.0015)	1.000 (0.0016)	1.000 (0.0015)

Table 34 Estimates of the egg ratio (and standard deviations) for the rock lobster assemblage in the Abrolhos Islands management region when $a_{\mathrm{Large}} = 3$ years and the annual increase in efficiency is $X = 0.01$.

Season and management scenario	Natural mortality, M (year^{-1})		
	$M = 0.15$	$M = 0.226$	$M = 0.3$
1992-1993	0.120 (0.0015)	0.191 (0.0036)	0.268 (0.0074)
1999-2000	0.143 (0.0037)	0.225 (0.0078)	0.31 (0.014)
2002-2003 with no management changes	0.134 (0.0044)	0.210 (0.0086)	0.29 (0.015)
2002-2003 without setose and max size in 2001-2002	0.117 (0.0025)	0.187 (0.0056)	0.264 (0.0110)

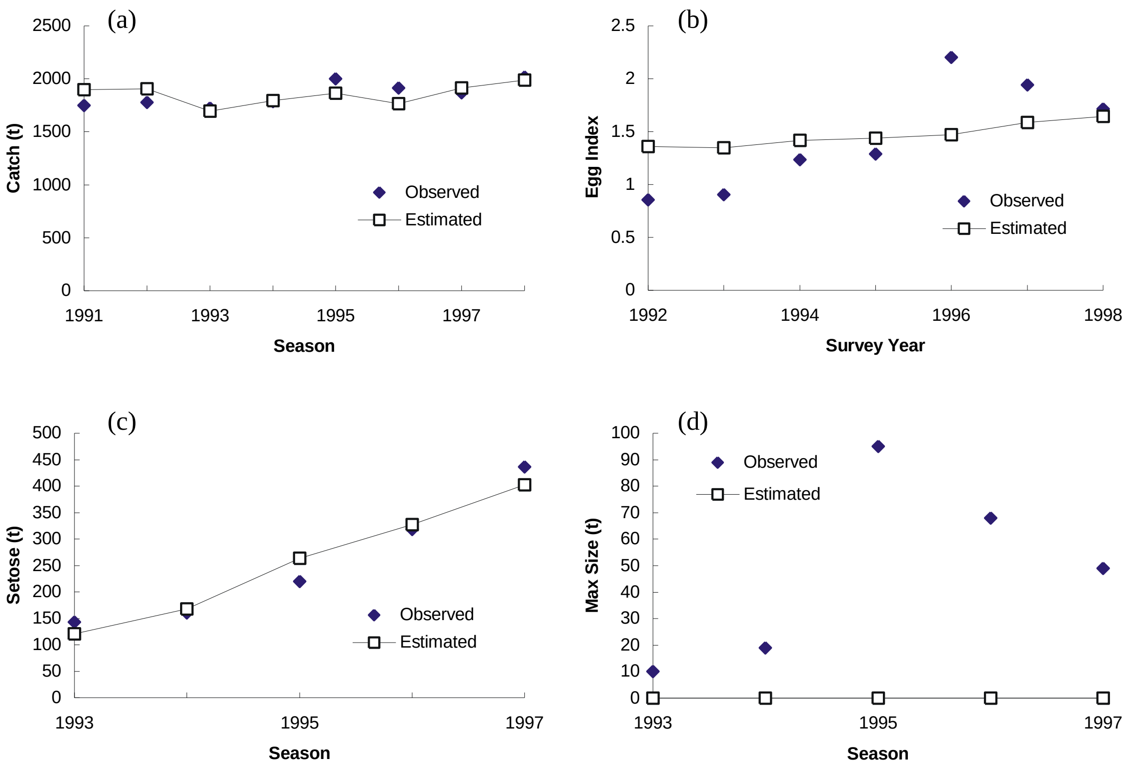


Figure 21. Model estimates for the Abrolhos Islands management region: (a) combined catch (t) from commercial and recreational fishers; (b) indices of egg production (million eggs per potlift) from research surveys; (c) biomass (t) of released setose female lobsters; and (d) biomass (t) of released non-setose female lobsters larger than the maximum legal size.

While estimates of annual catches and of the released catches of setose female lobsters agreed reasonably well with the data observed for the Abrolhos Islands management zone from the baseline scenario ($a_{\text{Large}} = 3$ years, $M = 0.226$ year^{-1}, and $X = 0.01$), the model produced relatively poor estimates of observed egg production indices, and estimated the released catches of non-setose female lobsters larger than the maximum legal size to be almost zero (**Figure 21** and **Table 29**). The increase in egg production is relatively small at the Abrolhos Islands as many sub-legal sized female lobsters are mature and already were protected by the minimum size regulation. The released catch of setose females increases more markedly, as these catches relate to those lobsters that are legal-sized, and are not affected by the sub-legal sized group of mature female lobsters. Although fishing mortality was estimated to be relatively high, the low estimates of non-setose females larger than the maximum legal size resulted from the high proportion of the older age group that was estimated to be setose in this zone (100%); the model predicted that few non-setose females from these older age-classes would have been caught.

Using the estimated parameters for the baseline case, it was determined from the data for the Abrolhos Islands zone that the annual harvest of the younger male lobsters was 86% in 1991-92, but had been reduced to 80% in 1998-99. The recruitment to the exploited assemblage (> 76 mm carapace length) in 1998-99 was estimated to be 4.7 million lobsters.

Catchability of the older lobsters for the baseline case was approximately the same as that for younger lobsters in the Abrolhos management zone (**Table 29**). Approximately 10% of female lobsters in the younger age-classes and 100% of the older females were estimated to be setose. This result is unexpected, as the female lobsters at the Abrolhos Island attain maturity at a smaller size. Egg production at the beginning of the 1992-93 fishing season for the baseline case had been reduced to approximately 19% of the egg production for the unfished stock, but had increased to approximately 22% at the beginning of the 1999-2000 fishing season (**Table 30**).

The sensitivity of model estimates of the level of egg production relative to the egg production of the unfished stock for annual increases in fishing efficiency between 0 and 2% per annum was examined, and results for the Abrolhos Islands zone are presented in **Table 30**. Egg production at the beginning of the 1992-93 fishing season was estimated to be 19% of that of the unfished stock regardless of the annual increase in efficiency. By 1999-2000, egg production was predicted to have improved to 22.8, 22.5 and 22.2% of the egg production for the unfished stock for efficiency increases of 0, 1 and 2% per year, respectively. With continued application of the current regulations, egg production at the beginning of the 2002-2003 fishing season was predicted to be 21.6, 21.0 and 20.4% of the egg production for the unfished stock, respectively. However, egg production in 2002-2003 was predicted to be reduced to 19.2, 18.7, or 18.3%, respectively, if fishers were permitted to land setose females and non-setose females larger than the maximum legal size during 2001-2002.

The age, a_{Large}, determining the age-classes to be grouped as younger and older lobsters was varied between two and four years, and results for the Abrolhos Islands management region are presented in **Table 31**. When a_{Large} was set to two years, few of the younger female lobsters and only 64% of the older female lobsters were found to be setose, but when set to three or four years, approximately 10% of the younger females were estimated to be setose, while 100% of the older female lobsters were predicted to be setose. The ratio of the egg production in 1992-93 relative to the egg production of the unfished stock was estimated to be 20% when $a_{\mathrm{Large}} = 2$ years, 19.1% when $a_{\mathrm{Large}} = 3$ years, and 23% when $a_{\mathrm{Large}} = 4$ years (**Table 32**). In response to the regulations introduced in 1992-93 and 1993-94, this ratio had increased to 27, 22.5 or 29% when a_{Large} was two, three or four years, respectively. By the 2002-2003 fishing season, the egg production ratio was predicted to further increase to 26, 21 or 28%, respectively, if the current regulations continued, but would be 22, 18.7, or 25%, respectively, if the setose and maximum size regulations for female lobsters were dropped for the 2001-2002 fishing season.

The effect of uncertainty in the estimate of natural mortality was examined, and results for the Abrolhos Islands management zone are presented in **Table 33**. Higher estimates of the catchability resulted when the estimate of natural mortality was decreased. The estimated ratio of egg production in 1992-93 relative to that for the unfished stock decreased from 19.1% when $M = 0.226$ year^{-1} to 12.0% when $M = 0.15$ year^{-1}, and increased to 26.8% when $M = 0.3$ year^{-1} (**Table 34**). Under the management regulations introduced in 1992-93 and 1993-94, the ratio increased to 14.3, 22.5 or 31% for values of M of 0.15, 0.226 and 0.3 year^{-1}, respectively. Continued use of the present regulations resulted in egg ratio predictions of 13, 21 and 29%, respectively, while removing the requirement for the release of setose lobsters and lobsters larger than the maximum legal length for 2001-2002 produced predictions of 12, 19 and 26%, respectively.

5.6.4 Management targets

Using the estimated values of the egg ratio for 1992-93 from the model baseline case, and the target relative increases in the biomass of breeding female lobsters upon which the Rock Lobster Industry Advisory Committee had agreed (Anon., 1993), estimates of the target egg ratio to be achieved by the 1993-94 regulations were calculated as 24, 8 and 22% for the south coastal, north coastal and Abrolhos Islands management zones, respectively, and 17% for the entire fishery. These are termed the ‘target egg ratios’ in subsequent references within this section. To confirm that these reflected egg ratio levels approximately equivalent to those of the late 1970s and early 1980s, an estimate of the egg ratio for 1980-81 was calculated using the baseline case. This resulted in egg ratio estimates of 17, 7, 21 and 15% for the south coastal zone, the north coastal zone, the Abrolhos Islands zone, and the entire fishery, respectively. It should be noted that the 1980-81 fishing effort had been applied within the model for fishing seasons prior to 1980-81, and that no allowance had been made in the model for increasing efficiency from 1980-81 to 1992-93. However, the model estimates of the egg ratio for 1980-81 were similar in magnitude to the target egg ratios for the north coastal and Abrolhos Islands management zones, but lower than the RLIAC target egg ratios for the south coastal zone and for the entire stock.

The estimated egg ratios for 1999-2000, from the baseline case, were 27, 11, and 22% for the south coastal, north coastal and Abrolhos regions, respectively, and 21% for the entire fishery. The target egg ratios were exceeded in the south and north coastal zones, and achieved at the Abrolhos Islands zone. For the entire rock lobster stock, the egg ratio (21%) estimated for 1999-2000 exceeded the target egg ratio (17%).

The profile likelihood distribution for the estimated egg ratio for the south coastal management zone at the beginning of the 1992-93 season was compared with the distribution at the beginning of 1999-2000 (**Figure 22**). The probability of the ratio lying below the target egg ratio (24%) in 1992-93 was 87%, but this had been reduced to 34% by 1999-2000. For the north coastal management zone (**Figure 22**), the probability of the egg ratio lying below the target egg ratio of 8% was 96% in 1992-93, but had been reduced to 24% by 1999-2000. The profile likelihood distribution for the Abrolhos Islands (**Figure 22**) reflected the presence of mature female lobsters below the minimum legal carapace length, which contribute to egg production. This reservoir of egg production resulted in an egg ratio that exceeded 18% of the unfished egg production in both 1992-93 and 1999-2000. The distribution in 1999-2000 for the

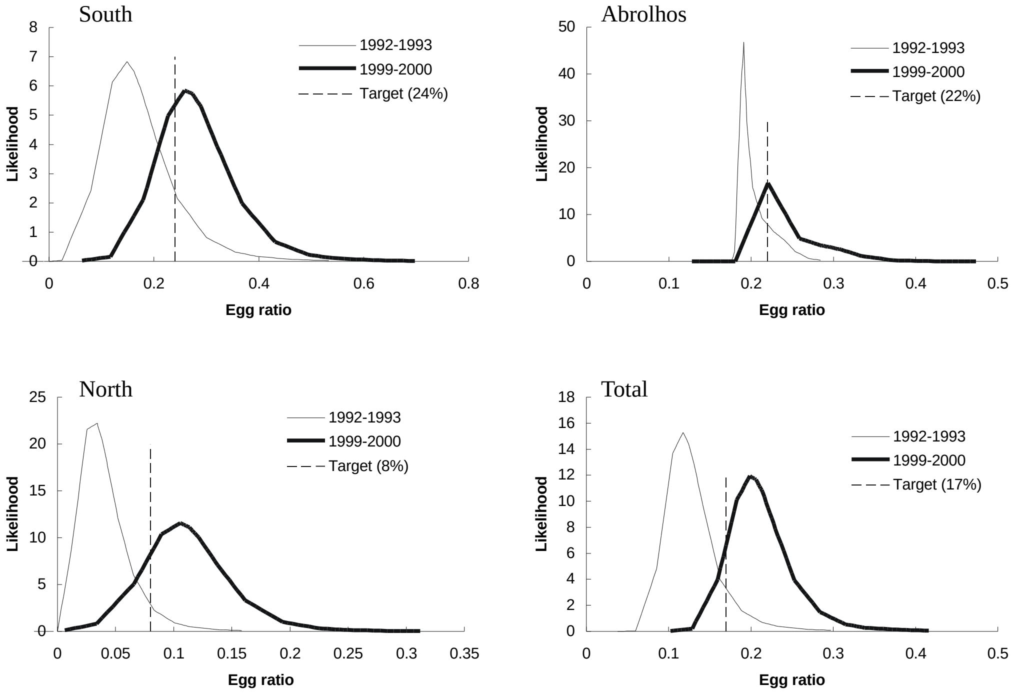


Figure 22. The profile likelihood distributions of egg production in the 1992-93 and 1999-2000 fishing seasons for each management region and for the total fishery expressed as proportions of the unfished egg production for the region and for the stock, respectively.

Abrolhos Islands zone was again shifted towards higher levels of the egg ratio. The probability of the ratio lying below the target egg ratio of 22% was 84% in 1992-93 but had been reduced to 41% in 1999-2000.

Profile likelihood distributions were calculated for the combined egg distribution from the three management zones, in order to determine the current status of egg production for the western rock lobster stock. The 95% confidence region for the egg ratio of the stock in 1999-2000 was estimated to be from 13 to 29%. The likelihood distribution of the ratio of the estimated egg production in 1992-93 relative to the egg production of the unfished stock was compared with the likelihood distribution for the ratio in 1999-2000 (**Figure 22**). The probability that the egg ratio in 1992-93 was below the target egg ratio of 17% was 92%. By the 1999-2000 fishing season, this probability had been reduced to 14%.

5.6.5 Comparison of alternative management arrangements

The profile likelihood distribution of the predicted egg ratio in 2002-2003 resulting from continued application of the current management arrangements was compared with the likelihood distribution resulting from relaxation of the setose and maximum size regulations for the 2001-2002 fishing season. The results for the south coastal management zone show that the egg ratio was reduced by 0.03 through allowing the additional catch (**Figure 23**). The probability of the egg ratio falling below the target egg ratio of 24% was increased from 26 to 44%. In the north coastal management zone (**Figure 23**), the egg ratio was reduced by 0.02, while the probability of the egg ratio lying below the target egg ratio of 8% increased from 18 to 35%. For the Abrolhos Islands zone (**Figure 23**), the egg ratio fell by 0.02, and the probability that the egg ratio might lie below the target egg ratio of 22% increased from 54 to 76%.

Relaxation of the setose and maximum size regulations for the 2001-2002 fishing season resulted in the profile likelihood distribution of the egg ratio for 2002-2003 presented in **Figure 23**. The egg ratio was reduced by 0.02, compared with the egg ratio resulting from continued application of the current regulations. The probability of the egg ratio falling below the target egg ratio of 17% increased from 10 to 33%.

5.6.6 Discussion

Examination of the data shown in **Figure 22** clearly demonstrates that the management measures introduced for the western rock lobster fishery in 1992-93 and 1993-94 were successful in rebuilding the stock. The egg ratio of 21% for the rock lobster stock in 1999-2000 represented a 66% increase from the level of 12% in 1992-93. While the egg ratio for the Abrolhos Islands had achieved the target set by the Rock Lobster Industry Advisory Committee, the egg ratios in the south and north coastal management regions had recovered to levels in excess of the target levels. From this, it was concluded that the management measures introduced in 1992-93 and 1993-94 had been successful in achieving the objectives set by RLIAC. The results from analyses applying different assumptions regarding the annual increase in fishing efficiency, the age boundary distinguishing younger and older lobsters, and natural mortality were examined, and the above conclusion that the target had been achieved was found to be robust with respect to the alternative assumptions.

The introduction in 1992-93 and in 1993-94 of strong management measures intended to reduce the level of exploitation, particularly for female lobsters, provided a valuable opportunity for fishery scientists. The contrast in the data introduced by such management action was evident in the observed data subsequently obtained from the fishery. Using the very evident response resulting from the management changes, information on the level of fishing mortality and the state of the stock could be obtained through modelling. The results of that modelling exercise have been reported in this section. However, without the opportunity afforded by the management change, this model would not have been successful as it uses the response to the changed level of exploitation to derive its estimates of the parameters.

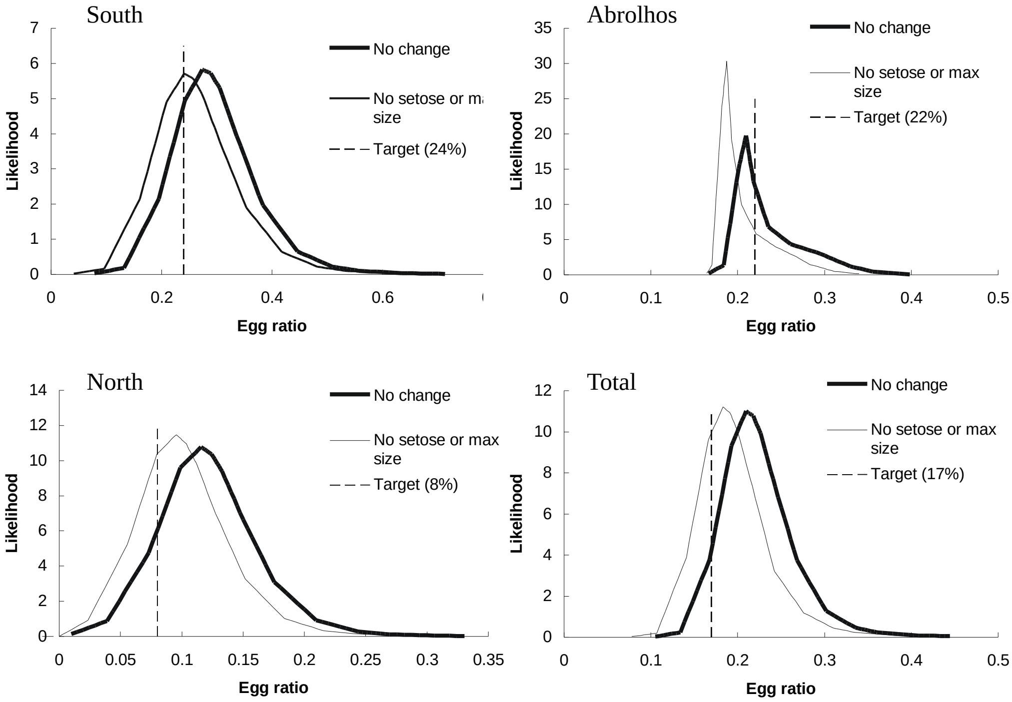


Figure 23 Comparison of the profile likelihood distributions of the expected egg production in the 2002-2003 season for each management region, and for the entire fishery, expressed as a proportion of the unfished egg production for the region, and for the stock, between (a) continued application of the 1993-94 management strategy in 2001-2002 and (b) application of only the 18% pot reduction and minimum size regulations in 2001-2002 (dropping the maximum size and setose regulations).

The model was restricted to the use of data that was obtained principally from the period immediately prior to and following the management changes. While some effort data for earlier years and the full time series of puerulus indices were used, no attempt was made to fit the model to catch rate data or other observations for the earlier period. To this extent, the model is therefore independent of the earlier assessment of the fishery described by Walters *et al*. (1993). While providing a useful opportunity to compare the results from the current study with earlier results, it should be noted that the stock assessment resulting from the new model has not utilised information available from earlier years, and a future model incorporating such information might produce a more accurate assessment of the state of the fishery.

Early application of the size-structured model developed by Walters *et al.* (1993) had suggested that egg production had been reduced to 15 to 20% of the original unfished level (Anon., 1993). Further analyses resulted in the values reported in Walters *et al.* (1993), suggesting that egg production had fallen to 25 to 35% of the original unfished level. The difference between these values reflects the uncertainty of the parameter estimates, slight changes in assumptions, and the weighting given to different data when fitting the size-structured model. The constraints of the computing hardware and software available at the time of development of the size-structured model precluded a full assessment of the imprecision and uncertainty associated with parameter estimates of this relatively complex model. Improvements in technology and software since that time, in combination with the much simpler model structure considered in this section, made it possible to undertake a more thorough investigation of the uncertainties associated with the new model.

Results from this study suggest that the egg ratio in 1992-93 was 12%, a lower figure than reported to the RLIAC (Anon., 1993) or by Walters *et al.* (1993). From the analysis of the profile likelihood distribution, the 95% confidence interval for the egg ratio in 1992-93 was 6 to 20%. A consequence of the lower level of egg production estimated for 1992-93 was that the target egg ratio, as determined by the relative increase in the biomass of breeding stock that was adopted by the RLIAC (Anon., 1993), was 17%, rather than the 25% level that the Advisory Committee had possibly intended. This reflects the fact that both the level of original unfished egg production and the level of egg production at a specific time are model-dependent estimates. While the absolute level may depend on the model used, it should be noted that 1999-2000 egg ratio was slightly greater than the egg ratio estimated to be present in the late 1970s and early 1980s.

Although the 1993/94 management strategy has resulted in reduced exploitation of female lobsters, further increases in fishing efficiency can, over time, result in a decline in egg production to the levels that existed in the early 1990s. The protection afforded to females larger than the maximum legal carapace length is ineffective if few female lobsters survive to reach that size. Thus, although egg production has increased to the target level, there is the potential for it to decline below the target level if fishing mortality continues to increase. The level of egg production will require continued monitoring, and the fishery will possibly require further management intervention at some future time, to ensure that egg production remains at an appropriate level.

As with all models, the model that was developed for the western rock lobster fishery was considerably simpler than the system that it was intended to represent. Thus, the ability of the model to adequately represent all aspects of the fishery was constrained by the level of abstraction that was applied. For example, the inability of the model to describe the catches in 1992-93 in the north coastal zone reflects the assumption made within the model that fishing mortality within a fishing season is constant, and yet it is known that both catchability and the distribution of actual fishing effort are not constant in the fishery. Indeed, the January closure that was introduced in the north coastal management zone closed the fishery when catch rates were low, thus having less impact on actual catches than would be predicted by the model. Thus, the model appears to have over-estimated the impact of the 1992-93 management package in the north coastal zone.

The use of common growth curves for male and female lobsters within all management zones is identified as a possible source of bias. Morgan (1977) noted differences in the asymptotic length of lobsters between sexes and localities, with those in the Abrolhos Islands zone growing to a smaller size than those in the coastal regions. If the growth curve that was applied within this study overestimates the growth of these lobsters, it is likely that the estimates of fishing mortality will be overestimated, and the estimates of proportion setose are likely to be biased. It should be noted that the egg production indices at the Abrolhos Islands were poorly estimated by the model, and estimates of the releases of non-setose females larger than the maximum legal size were zero. It is possible that the egg ratio estimates for this area are underestimated. This aspect of the model will be re-examined as the model is extended.

The failure of the model to represent the released catches of non-setose female lobsters larger than the maximum legal size possibly may be attributed to the use within the model of a deterministic growth curve. Variability in the growth of individual lobsters is a characteristic of the growth of western rock lobsters. A further explanation for the poor estimates possibly is associated with the assumption that the assemblage is treated as a single unit and spatial structure is ignored. The fishery operates over a range of depths, and the average size of the lobsters increases with depth. The spatial distribution of fishing may affect the catches of the larger female lobsters, such that model estimates of the released catches are poor.

Concentration of fishing effort on the smaller lobsters has been shown to reduce the relative vulnerability of the larger lobsters (Section 5.5). Biological processes may also be factors that further reduce relative vulnerability as the size of the lobsters increases. Within the age-structured model, reduced vulnerability of the larger lobsters has been represented in a very simple form, by classifying the lobsters into two categories where the older lobsters have a reduced vulnerability compared with the younger lobsters. This simplification may have failed to describe adequately the true relationship between vulnerability and length and thus introduced bias into the assessment, possibly explaining the poor representation of the catches of non-setose female lobsters that were larger than the maximum legal carapace length.

Other assumptions made within the model reflect the availability of data of the form required within the model. Some assumptions, such as the assumption that male and female lobsters within each age-class experienced the same level of fishing mortality prior to the introduction of the new management regulations in 1992-93 and 1993-94, were necessary if the model was to be applied to the data that were available at the time of the study. However, the protection of egg-bearing ("berried") females would reduce the fishing mortality of female lobsters during the spawning season. Thus, this assumption is clearly inappropriate, and an enhancement to the existing model that is more realistic will need to be considered when the available data for the fishery have been reanalysed, and when the monthly proportions of berried females within each size class have been determined. Other information, such as the proportion of setose females, has been estimated by fitting the model to the available data. This indirect approach to determining the proportion of setose females should be replaced in a future model by estimates of the proportion of setose females within each size-class or age-class determined from direct observations of the catch brought on board each vessel prior to sorting and discard of lobsters that may not be legally retained and landed.

Simplification of the current model appears possible and appropriate. For example, estimates of the catchabilities of both the younger and older lobsters at the Abrolhos Islands were found to be virtually identical. Clearly, the assumption of a common level of catchability would reduce the complexity of the model and yet still provide an adequate representation of the western rock lobster fishery within this region. Another opportunity to reduce the complexity of the model is provided by the negligible proportion of setose females for the younger age-classes in the south coastal management zone.

The study has identified several issues that need to be addressed by fisheries managers. For example, the limit reference point for the fishery has still to be clearly defined. The current specification as a target egg ratio includes no specification of the acceptable level of risk associated with an estimate of the egg ratio falling below the target. Rather than being expressed as an average egg ratio level against which the estimated egg ratio is compared, it might be preferable to define the limit reference point as an egg ratio level and an acceptable level of risk that the estimated egg ratio might fall below that level. For example, let us assume that the profile likelihood distribution retains the same shape as estimated for 1999-2000 but was shifted such that the mean egg ratio was equal to the target egg ratio. From the resulting profile likelihood distribution, there would then be a 20% risk that the egg ratio fell below 14%. From this, the target egg ratio of 17% might be re-expressed in the form of a limit reference point and acceptable level of risk. Thus, in this example, 20% is the acceptable level of risk that the estimated egg ratio for the fishery might be less than the reference point of 14%. If the probability that the estimated egg ratio falls below 14% exceeds 20%, then appropriate management action would be required.

In the western rock lobster fishery, levels of egg production that were lower than those experienced in the late 1970s and early 1980s proved successful in maintaining subsequent recruitment to the fishery over the subsequent two decades. Using this experience, a valid argument may be mounted that the egg production of the late 1970s and early 1980s may be used as a limit reference point for the fishery, with experience from the western rock lobster fishery in the 1980s and 1990s demonstrating that this level of egg production has provided adequate recruitment to the fishery. However, it might be also argued that the set of puerulus settlements that occurred within this period was unique, and that the egg ratio of the late 1970s and early 1980s might not be sufficient if a series of adverse years of puerulus settlement were encountered. A review of the reference points used in other lobster fisheries, the basis for these, and an assessment of the performance of the reference points in assuring subsequent recruitment would be useful, and would assist managers of the western rock lobster fishery in setting an appropriate limit reference point.

The model has been demonstrated to be a valuable tool for assessment of the impact of alternative management strategies. The study presented an evaluation of the impact on egg production of a proposed management change. A similar evaluation could have been presented of the impact on the resulting catch. The Rock Lobster Industry Advisory Committee has requested an examination of the response of the fishery to a set of alternative management strategies for the 2001-2002 fishing season. The model developed for this study will be used to assess the impact of each proposal on the egg production in 2002-2003 and on the catches in 2001-2002 and 2002-2003.

It should be noted that extension of the age-structured model to calculate the relative economic impact of the alternative management strategies is relatively straightforward, requiring calculation of relative net value of the annual catch using the average annual price of lobsters within each grade and the average annual costs for bait, gear, fuel, and crew. The computer routine to select the optimum management strategy from a set of alternative strategies also would be a relatively simple programming task.

The age-structured model that has been described has made use of data that were not available in the earlier study by Walters *et al.* (1993). The conclusions regarding the status of the egg production within the fishery at 1992-93 from the new assessment are similar to those reached by that earlier study. Egg production in the fishery had fallen to between approximately 6 to 20% of the egg production of the unfished stock by 1992-93. The new model has provided an assessment for the individual management zones, and provided estimates of the uncertainty associated with estimates of key indicator variables, that were not available from the earlier study. The results from this study demonstrate the value to fisheries managers and to the fishing industry of such an analysis by clearly identifying the response of the fishery to an alternative management strategy and the associated risk that egg production might fall to an unacceptable level. A range of management strategies proposed for the western rock lobster fishery are currently being evaluated using this model, and will be considered by the fishing industry and fishery managers in 2000.

5.7 General discussion

As the project progressed, feedback was received from a number of industry sources advising of concern that the third objective of the project might provide sensitive information that should be reviewed in consultation with informed industry representatives before broad dissemination. Such a review mechanism already exists within RLIAC, and results of modelling should appropriately be discussed in this forum to ensure acceptance that the outputs are accurate and accepted by fishery scientists, managers and industry representatives prior to wider release.

While the size-structured model requires further development before the model is used to assess complex management strategies, the age-structured model provides reasonable estimates of the expected response of the western rock lobster fishery to alternative management controls, and the statistical uncertainty associated with that response. The reported likelihood distributions from the latter model represent the uncertainty of parameter estimates (reflecting both the information content of the data and bias arising from inadequate model structure). It would be a simple task to extend the calculations of this latter model to use the available economic data in order to produce estimates of the relative net value associated with the alternative controls. A range of computer routines are readily available to locate the set of parameters that will optimise an objective function, and these could easily be adapted to determine the set of management controls that would optimise the net relative value of the lobster fishery. Thus, extension of the project to fulfil the third objective is seen as a relatively simple task.

However, the economic data currently available represent only the prices and costs associated with a single fishing season, and while the model outputs derived from these data may provide insight to the consequences of alternative management strategies, appropriate caution should be observed in using the model outputs. Further, since only a subset of the costs of fishing have been considered, there is a need for the fishing industry to have input when considering model outputs.

The major beneficiaries of the model exploration will be the fishing industry, yet they are also the group that bears the economic risk if management strategies are introduced that fail to perform as predicted by model outputs. Thus, it is appropriate that the results of modelling are discussed with the fishing industry, and that their acceptance is gained for the biological components of the model prior to applying the model to optimise the net relative economic value of the fishery. Accordingly, the third objective of the FRDC project, to determine the optimum set of management controls, has not yet been undertaken. It will be undertaken when appropriate, following consultation with RLIAC.

Further development of the size-structured model is required to improve its fit to the fishery data for the western rock lobster. In particular, there is a need to improve the representation within the model of the relationship between the relative vulnerability of the lobsters and their carapace length. At present, little information concerning this relationship is available. This study has suggested that the concentration of fishing effort on the smaller lobsters may be a major factor in determining the relative vulnerability at length. However, the concentration of effort varies throughout the fishing season with monthly changes in the distribution of fishing effort and the distribution of lobsters, and differs between fishing regions. While the current structure of the size-structured model is a slight enhancement of similar size-structured models applied to lobster and crab fisheries in Tasmania, South Africa and Alaska, it appears that further complexity may need to be introduced to the model for the western rock lobster in order to improve the representation of the vulnerability-length relationship.

6. Benefits

The western rock lobster fishing industry will receive the benefits that flow from this study, through improved ability to assess the biological impacts and the broad economic consequences resulting from alternative management strategies. The age-structured model is already providing valuable advice and is being used in current assessments of alternative management strategies. However, further development of the length-structured model is required, possibly extending the model structure to include the concentration of fishing effort on the lobsters within the various depth ranges (see Section 7). Recreational fishers will also benefit as a consequence of the improved understanding of the fishery. The results of the investigation of the concentration of fishing effort on smaller lobsters, and the impact that this has on the relative vulnerability at length, are likely to be of relevance in the assessment of other lobster fisheries.

7. Further Development

7.1 Growth transition matrix during the closed seasons

Currently opportunities for collecting tagging data during closed seasons are limited to occasions when research fishing is undertaken, such as the pre-season independent breeding stock study. Some limited data are also available from research studies undertaken in earlier years. Therefore, growth information for these closed seasons is very limited and was considered inadequate for estimation of growth parameters for these months. In the present model, no growth was assumed during the period of closure in order to reduce the number of parameters. However, clearly this assumption is inappropriate for the rock lobsters within the Abrolhos Islands zone, and is a possible source of error for estimates of growth in the other regions. In further model development, alternative assumptions shall be considered. However, without additional tag release and recapture data within the closed seasons, growth within these months will remain a source of model uncertainty. Although limited recapture data are likely to become available, recaptures within the fishing season of lobsters tagged in a series of releases during different months of the closed season may provide the necessary information content. Alternatively, moult stages may be examined within research samples taken during the closed season allowing estimation of moult frequency at length, and supplementing information on moult increment obtained from aquarium studies. In the future, if such data could be collected during the closed seasons, the growth transition matrices could be re-estimated. This would allow better representation of the fishery by the model.

7.2 Vulnerability and large lobsters

Based on the results presented, the present length-structured model does not provide a good representation of the number of large lobsters (particularly with carapace length > 110 mm) in the population. The reason for this is that less information on the catch of large lobsters is available, and the objective function is relatively insensitive to the numbers of larger lobsters estimated within the model but is strongly influenced by the numbers of smaller lobsters. A simple assumption was made in the model concerning the dependence of vulnerability on the length of the lobsters. However, currently the data used by the model do not permit estimation of the vulnerability-length relationship. An improved estimation of the vulnerability, in particular, of large lobsters, would allow better estimation of population size for those large lobsters. The improved estimation of the populations for large females would lead to significantly improved estimation of the breeding stock or egg production, as the large females produce greater numbers of eggs per individual.

Another point that may need to addressed in the future is that vulnerability at size should be considered when estimating the growth transition matrices. Currently, only selectivity of lobsters (associated with escape gaps and neck size of pots) was considered in fitting the growth transition matrices to data.

7.3 Migration

Both models ignore the issue of migration, particularly from inshore to breeding areas offshore, but also between regions (particularly between the north coastal management zone and the Abrolhos Islands zone). Ultimately the models should be restructured to allow for effort dynamics between the shallower and deeper fishing grounds. It should be noted that the distribution of fishing effort, in combination with the non-homogeneous distribution of lobsters of different lengths, results in the concentration of fishing effort on smaller lobsters. In the current version of the length-structured model, the effect is to increase the apparent relationship between vulnerability of lobsters and length. This relationship reflects a combination of the biological and behavioural factors affecting the relative catchability of lobsters of different lengths, and the concentration by fishers on grounds where the smaller lobsters are more prevalent. By introducing a depth structure to the model, the changing distribution of fishing effort through the fishing season should provide a more accurate description of the impact of this effort distribution on the effective effort applied to lobsters of different lengths

7.4 Temporal resolution

Another direction for model development would be to replace the monthly time step by a weekly time step. Although daily logbook data are available from a subset of the fishery, total catch and effort data from mandatory statistical returns and length monitoring samples are available only at monthly resolution. The availability of detailed data at the appropriate resolution will constrain the introduction of greater temporal resolution to the model structure.

7.5 Setose and maximum size data

The length-structured model was fitted to the data for fishing seasons prior to 1993/94 when little information was available on catches of setose females, and information on catches of the larger females was only available from processors records of production and from the research monitoring programme. The data that have subsequently become available provide much more information, and reflect the contrast in the fishery arising from the introduction of the 1993/94 management strategy.

7.6 Improved representation

When fitting the length-structured model, it was assumed that the management strategy in 1992/93 was unchanged from that applying in previous fishing seasons. While significant changes to management occurred in 1992/93, it is considered that the effect of these changes were generally insignificant. However, to ensure that the effect of these management changes is considered, the structure of the model will need to be modified in order to account for the regulations that applied within this fishing season.

7.7 Collection of economic data

The data collected for the 1998/99 fishing season have proved valuable in assessing the relative economic consequences of alternative management strategies. However, it is recognised that these data represent the prices and costs within a single fishing season, and that considerable variation may exist between fishing seasons. In order that assessments are not biased through use of a single set of economic data and to provide an estimate of the uncertainty associated with such data, it would be valuable if economic data might be collected on a regular basis, thereby ensuring that the economic assessments might reflect the inter-annual variability in prices and costs.

8. Conclusion

The three objectives of this project (see Section 3) were:

(i) to develop a statistically sound biological model to represent the fish stock and its interaction with fishers within the constraints of management strategies;
(ii) to incorporate marketing data into the model to allow the prediction of changes in product value with different management scenarios;
(iii) to determine the time-dependent set of management controls (size, catch, and effort) that would optimise the value of the landed product, and to identify alternative locally optimum sets of controls producing similar (but reduced) value.

A size structured model of the fishery was developed, representing the fish stock by 1 mm size classes and 1 month time steps. In order to produce this model, a detailed analysis of tagging data was undertaken resulting in estimates of the growth transition matrices describing growth within each calendar month for males and for immature and mature females. The size-structured model incorporated those management controls required by the fishery managers, and an example of its use to explore an alternative management strategy was presented (Sections 4.3 and 5.3). Examination of the modelling results revealed the need to improve the representation of the fishery by the model. Further work is to be undertaken, in particular analyses to address the relationship between relative vulnerability and length and the concentration of fishing effort on smaller lobsters (Section 5.5).

Recognising that the representation of the fishery data by the size-structured model was not yet of the quality required for assessment of complex management strategies, an alternative age-structured model was developed, focussing particularly on the response of the fishery to recent management changes. By generating profile likelihood distributions of the model outcomes (such as catch rate and egg production), the uncertainty associated with parameter estimates (reflecting possible inadequacy in model structure) was specifically addressed, allowing an assessment of the impact of alternative management strategies. This model satisfied objective (i) of this project, to produce a statistically sound biological model to represent the fishery dynamics and to allow exploration of alternative management strategies.

The second objective of the project (ii) was to incorporate marketing data into the model to allow the prediction of changes in product value with different management scenarios. Economic data for 1998/99 were collected from processors and analysed to determine average beach price for each grade of product and the costs of fuel, bait, gear and crew costs within each management zone. These data were then used within the size-structured model to estimate the relative net value of the estimated catch resulting from a specified management strategy (see **Table 16**). Although similar calculations have not yet been carried out using the age-structured model, the data are available for such analysis and the calculations are relatively simple to perform. Extension of the age-structured model to undertake such calculations is regarded as relatively trivial.

The third objective of the project (iii) was to determine the time-dependent set of management controls (size, catch, and effort) that would optimise the value of the landed product, and to identify alternative locally optimum sets of controls producing similar (but reduced) value. As noted in Section 5.7, concern has been expressed by some sectors of the fishing industry that results of such assessment should be reviewed by experienced members of the fishing industry, fishery managers, and fishery scientists before dissemination to the wider industry. Further, there was a need to ensure that the model of the fishery dynamics was satisfactory before applying the model to determine the optimum set of management controls, and that the uncertainty of the economic outcomes associated with different sets of annual costs and prices needed to be incorporated within the assessment. A number of computer routines are available to determine the optimum set of controls (parameters) provided that the objective function may be evaluated for each specified set of controls; the models presented in this study carry out the necessary calculation of the objective function. Nevertheless, because of the sensitive nature of the economic assessment and the economic consequences to the fishing industry of such assessment, it was decided that the objective of identifying the optimum set of controls should be deferred until the industry has assessed and accepted the model of the fishery dynamics.

In summary, the study has extended the range of models available to assess the impact of alternative management strategies for the western rock lobster fishery. Considerable benefits have resulted from the analysis, including an improved understanding of the growth of the lobsters, and an improved understanding of the factors affecting the relationship between vulnerability and length. While the size-structured model requires further development, the study has identified the information that is needed in order that the representation of the fishery may be improved. The economic data collected within the study have allowed the models to be extended such that economic impacts of alternative management strategies might be investigated. Development of the age-structured model has provided fishery managers with the ability to assess alternative management strategies, an understanding of the uncertainties associated with these strategies, and an evaluation of the risk involved with each strategy that the egg production might fall below the accepted level.

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10. Appendix 1: Intellectual Property

Two models of the western rock lobster fishery have been produced. The first of these is a length-structured model, while the second is an age-structured model developed for use with the specific data arising from the introduction of the 1993/94 management strategy for the western rock lobster fishery. The intellectual property resulting from the project takes the form of the mathematical description of each model, as reported within this report, and the computer code representing the implementation of each mathematical model. Within the computer code, various routines have been drawn from public domain sources, or represent commercial software packages, as in the case of AD Model Builder.

The intellectual property produced by the FRDC project comprises the mathematical model and computer code associated with the length-structured model, while the mathematical model and computer code developed for the age-structured model represent the intellectual property produced by the concurrent Fisheries WA project.

11. Appendix 2: Staff

Mr. Norm Hall	*(Principal investigator)*
Dr. Liangyue Cao	*(Modeller and Co-investigator)*
Dr. Nick Caputi	*(Co-investigator)*
Dr. Chris Chubb	*(Co-investigator)*
Dr. Roy Melville-Smith	*(Biologist)*
Dr. Henry Cheng	*(Statistician)*
Mr. Steven Shanks	*(Economist)*

12. Appendix 3: Survey form for economic information

Standard survey form for collecting economic information

Processor information - Data Forms

The following form has been designed to enable economic information you provide to be applied to the “Value Optimisation Model”. The information you provide in this form will be aggregated to ensure any future representation of this information will be unable to distinguish you personally.

Date: ____________________________
Processor/ Supplier:____________________________
Contact person: ____________________________
Address: ____
Phone: ____________________________

(1) Beach Price - 1998/99 season

Number of vessels supplying:____________
Management zones supplying from:________________
Number in each management zone: A:_______B:_______C:________

Average beach price by month.

Month

	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Price($)								

If you were supplying price by grade to fishers within months what were these prices for the 1998/99 season.

Month

	Grade	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Price by grade in $	A								
	B								
	C								
	D								
	E								
	F								
	G								

(2) Export Price 1998/99 - by grade if available

If you are able to supply product type by grade for the 1998/99 season this information would be extremely useful for our research. Additionally if you have supplied product in months outside the 1998/99 season this information would be extremely useful.

		Month							
	Grade	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Price by grade in AUS $	A								
	B								
	C								
	D								
	E								
	F								
	G								

(3) Bait 1998/99

If you are supplying bait to the operators servicing your premises are you able to break down by zone the amount fishers paid for bait on a monthly basis.

		Month							
	Zone	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Amount paid by zone $	A								
	B								
	C								

(4) Fuel 1998/99

If you are supplying fuel to the operators servicing your premises are you able to break down by region the amount fishers paid for fuel as a total for individual months within management zones. Additionally if not all vessels supplying your premises are receiving fuel from you could you please indicate the number on a monthly basis if possible.

		Months							
	Region	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Amount paid by region $	A								
	B								
	C								

(5) Gear (ropes, floats and pots) 1998/99

If you are supplying gear to the operators servicing your premises are you able to break down by management zone the total amount fishers spent on gear in individual months of the 1998/99 season. Additionally if not all fishers are purchasing gear from your premises, please indicate the number that would regularly purchase gear.

		Months							
	Region	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Amount paid by zone $	A								
	B								
	C								

(6) Crew Payments - 1998/99

If you have an indication of the percentage of catch that fishers are paying crew within different management zones, could you provide us with this information.

Region	Percentage of catch paid to crew
A	
B	
C	

Any general comments you have in relation to the above mentioned information or additional comments you wish to make to aid our research would be extremely useful.

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