MINISTRY OF FISHERIES
Te Tautiaki i nga tini a Tangaroa

ISSN 1175-1584

Assessment of the NSS stock of red rock lobster (*Jasus edwardsii*) for 1999

Paul J. Starr
Nokome Bentley

New Zealand Fisheries Assessment Report 2002/28
June 2002

Assessment of the NSS stock of red rock lobster (*Jasus edwardsii*) for 1999

Paul J. Starr
Nokome Bentley

New Zealand Seafood Industry Council
Private Bag 24 901
Wellington

New Zealand Fisheries Assessment Report 2002/28
June 2002

Published by Ministry of Fisheries
Wellington
2002

ISSN 1175-1584

Citation:
Starr, P.J.; Bentley, N. (2002).
Assessment of the NSS stock of red rock lobster (*Jasus edwardsii*) for 1999.
New Zealand Fisheries Assessment Report 2002/28. 50 p.

This series continues the informal
New Zealand Fisheries Assessment Research Document series
which ceased at the end of 1999.

EXECUTIVE SUMMARY

Starr, P.J.; Bentley, N. (2002). Assessment of the NSS stock of red rock lobster (*Jasus edwardsii*) for 1999.

New Zealand Fisheries Assessment Report 2002/28. **50 p.**

A revised size-based model for assessing New Zealand rock lobster stocks is described, and applied to the Otago/Stewart Island/Fiordland substock (NSS). Considerable improvements to the 1998 size-based model were introduced for this assessment. These include separating the model into two seasonal time steps per year and the incorporation of the tagging data into the model to allow the simultaneous estimation of the growth parameters while fitting the model.

This assessment was initially characterised by difficulty in obtaining plausible fits to the current data which led to the inclusion of a considerable amount of historical information which had not yet been included in a full NSS stock assessment. The inclusion of these data led to a more plausible assessment but it was not possible to use Bayesian methods to complete the assessment. The posterior mode results for the stock assessment indicate that this stock is below the B_{MSY} reference point and that *MSY* is larger than the current removals. The failure of the stock to respond to substantial cuts in total removals since 1990 is explained by the model to be due to lower than average recruitment in recent years.

1. INTRODUCTION

The rock lobster fishery is the most valuable inshore fishery in New Zealand. The red rock lobster (*Jasus edwardsii*) makes up most of the catch, although small amounts of packhorse lobster (*Jasus verreauxi*) are taken in the north of the North Island. Most of the catch is taken by commercial potting, although recreational diving activities are significant in some areas.

Before 1990, the fishery was primarily managed by "input control" methods. These included setting minimum legal size limits, recreational bag limits, prohibitions on the taking of ovigerous females and soft-shelled lobsters, and some local area closures. In 1990, the fishery was brought into the Quota Management System which uses maximum allowable catch levels as "output controls". However, the "input control" regulations were kept as well. Ten Quota Management Areas (QMAs), each with a separate Total Allowable Commercial Catch (TACC), were put in place in 1990. The revision to the Fisheries Act in 1996 also requires the Minister to set a Total Allowable Catch (TAC) which includes all known sources of fishing mortality, including commercial catch, recreational catch, customary Māori catch, illegal catch, and fishing related mortalities.

The Fisheries Act 1996 requires that fish stocks be maintained at or above B_{MSY}, the biomass that will maintain the maximum sustainable yield (*MSY*). To achieve this target, TACs and TACCs are adjusted where necessary by the Minister of Fisheries based on advice from the Ministry of Fisheries. The Ministry bases its advice on the results of stock assessments. This report describes the assessment of the NSS substock carried out in 1999 by the Science Unit of the New Zealand Seafood Industry Council.

2. DESCRIPTION OF THE ASSESSMENT MODEL

A sex and size structured model of the New Zealand rock lobster fishery was developed in 1998 (Starr et al. 1999). Much of the model structure and dynamics was based on a similar model for the rock lobster fishery in Tasmania (Punt & Kennedy 1998). For each sex, the number of individuals in each tail width size class was updated each year according to natural and fishing mortality, growth, and recruitment. Size-specific vulnerabilities and weights were used to calculate exploitation rates from catch data and to apply these to individual size classes.

As a result of applying the model to stock assessments to four stocks in 1998 (Starr et al. 1999, Breen & Kendrick 1998) several deficiencies in the model structure and dynamics were identified. In 1999, these deficiencies were addressed by making a number of changes to the model. These changes are highlighted below in a brief overview of the model's structure and dynamics. A more detailed description of the model is provided in Appendix 1.

2.1 Structure

The 1998 model had an annual time step which meant that it was unable to model the impact of changes in the seasonal distribution of catch. This has consequences for the dynamics of the population, because during the winter mature females are ovigerous and thus are prohibited from being retained in the catch. The recent shift towards a winter fishery implies a reduction in the exploitation rate on females which should be incorporated in the assessment. A half-yearly time step was introduced into the model to address these issues: the periods chosen relate to the egg bearing status of females and the moulting periods of both sexes. The two seasons are defined as the 'autumn-winter' (1 April to 30 September) season and the 'spring-summer' (1 October to 31 March) season.

In the 1998 model, the lobster population was structured by size (2 mm tail width classes) and by sex (male and female). The number of berried, and thus invulnerable, females in each year was modelled as a proportion of the females in each size class according to a logistic function with an estimated maximum proportion. This assumes that a mature female has the same probability of becoming immature as an immature female does of becoming mature. This misspecification was addressed by structuring the female part of population according to maturity. That is, in the 1999 model, the population was divided into three components: males, immature females, and mature females.

2.2 Dynamics

2.2.1 Initial conditions

At the beginning of the first period the population is assumed to be in an unexploited equilibrium with average recruitment and no fishing mortality (Eq 1).

2.2.2 Recruitment

At the beginning of each period, equal numbers of males and females recruit into the smaller size classes. Total annual recruitment is determined by an average recruitment parameter and by annual recruitment deviations (Eq 2). The proportion of recruits entering each size class is modelled as a normal distribution with a specified mean and standard deviation and truncated at the smallest size class (Eq 3).

2.2.3 Growth

In the 1998 model, lobster growth was represented using the Schnute growth model (Schnute 1981, Francis 1995). With the change to a seasonal time step, it was necessary to either assume constant growth throughout the year or specify seasonality in growth. Rather than modifying the existing continuous growth model it was more appropriate to incorporate seasonality by explicitly modelling the discrete moult-based growth of lobster. The new moult-based growth model defines a primary and secondary moulting season for each sex (males and females). The probability of moulting in the secondary season is dependent upon a single parameter representing the maximum size of lobsters that moult twice a year (Eq 6). The moult increment at each moult is a linear function of pre-moult size (Eq 4). The product of the moult probability, moult increment, and variance of the moult increment (Eq 5) are used to generate a size transition matrix (Eq 8). Along with recruitment, the transition matrix is used to update the number of individuals in each size class for each sex before fishing and natural mortality in the following year (Eq 9).

2.2.4 Vulnerability

Fishing mortality is applied through size and sex specific vulnerability. These vulnerabilities are used to calculate the biomass of lobsters available to the legal and illegal fisheries. The vulnerability curve is modelled as a compound normal distribution with separate variance parameters for each side of the distribution mode. This results in a distribution which has increasing vulnerability from the initial length class to an estimated maximum, followed by decreasing vulnerability. In addition, the relative maximum vulnerabilities of males, immature females, and mature females in each season are estimated (Eq 10).

The ascending limb variance is assumed to change when there were changes in escape gap regulations which caused a change in the proportion of smaller fish retained in commercial pots. The use of a single variance parameter for the descending limb of the curve over the entire period assumes that there have been no changes in the relative vulnerability of large lobster with changes in escape gaps.

2.2.5 Maturity

During each period immature females have a probability of maturing that is dependent upon their size (Eq 11).

2.2.6 Mortality

The model includes four sources of mortality; natural mortality, legal removals (including commercial and recreational), handling mortality associated with the legal fishery, and illegal removals. Natural mortality is assumed to be constant and independent of sex and age.

The annual exploitation rate of legal fishing is calculated as the ratio of legal catch to legal biomass (Eq 12). Legal biomass is defined as the mass of males and females in the size classes above their respective minimum legal size limits, adjusted for their relative vulnerability (Eq 13). In the autumn-winter season, all mature females are assumed to be ovigerous and thus make no contribution to the legal biomass.

The annual rate of illegal fishing mortality is calculated similarly (Eq 14). The illegal fishery is assumed to have the same vulnerability as the legal fishery but disregards regulations on size limits and the condition of females. Illegal biomass is therefore defined as the mass of males and females in each size classes adjusted for their relative vulnerability (Eq 15).

All sources of mortality are applied simultaneously at the beginning of each period (Eq 17). The handling mortality rate is a fixed proportion of all lobsters that are released and is thus proportional to legal fishing mortality.

2.3 Parameter estimation

Parameters are estimated by maximising a likelihood function which is the product of six likelihood components: (i) fits to observed catch at size; (ii) fits to observed size increments of tagged lobster; (iii) fits to observed biomass indices; (iv) fits to puerulus settlement indices; (v) parameter priors; and (vi) a recruitment residuals.

Model predictions of the proportion of males, immature females, and mature females of each size class in the legal fishery catch (Eq 18) are fitted to observed proportions using a robust normal likelihood function (Eq 19). The robust likelihood eliminates the influence of observed outliers that have either high or low predicted probability (Fournier et al. 1990).

The predicted size of each tagged lobster at the time of recapture is calculated by simulating each moult during the time at liberty. A normal likelihood function is used to compare predicted and observed sizes at recapture (Eq 20).

For each period, the predicted biomass index is calculated from the predicted legal biomass and an analytically estimated catchability constant (Eqs 21,22). This is fitted to the observed CPUE index using a log-normal likelihood function (Eq 23). Predicted settlement indices are calculated and fitted to in the same manner (Eqs 24, 25, 26).

Annual recruitment residuals are penalised using a log-normal likelihood function assuming a mean of zero and a fixed standard deviation (Eq 27).

2.4 Model outputs

2.4.1 Bayesian estimation procedure

The model has been implemented to allow priors to be placed on parameters that are estimated so that Bayesian posterior distributions can be generated for the performance indicators. The parameter estimates from the mode of the joint posterior distributions (PME – Posterior Mode Estimate) were found by minimising the total negative log likelihood using quasi-Newton minimisation (AD Model Builder™, Otter Research Ltd.). These estimates include information from data, such as catch size frequencies, tag increments and biomass indices, <u>and</u> information from parameter priors (e.g., the log-normal prior on annual recruitment variation). The PME is used in the same manner as a maximum likelihood estimate (MLE).

Bayesian estimation procedures were employed to estimate uncertainty in model estimates of biomass, yield and future projections for this model. This procedure was conducted in the following steps:

a. PME estimates were made.

b. The joint posterior distribution of parameters was estimated using a Markov Chain Monte Carlo procedure (MCMC).

c. A large number of samples of the joint posterior distribution were taken and the mean, median, and 90% confidence intervals of the distribution of the parameters and variables of interest were estimated.

d. For each sample of the posterior, 5-year projections (encompassing the 1998–99 to 2003–04 assessment years) were done using assumed catches. Annual recruitment was randomly sampled from a lognormal distribution with a mean equal to the estimated average recruitment and the same variance used to penalise recruitment residuals in the parameter estimation. This step, in conjunction with c), was used to calculate the fishery performance indicators.

2.4.2 Performance indicators

The Rock Lobster Fishery Assessment Working Group (RLFAWG) agreed to use the following performance indicators as measures of the status and risk for each substock assessed. These performance indicators were calculated for each management scenario investigated.

Table 1: Performance indicators used to assess the status of the fishery being modelled.

1.	$\mathrm{E}\left(\frac{B_{CUR}}{B_{MSY}}\right)$	Expected value of $B_{CURRENT}$ as a proportion of B_{MSY}
2.	$\mathrm{E}\left(\frac{B_{PROJ}}{B_{MSY}}\right)$	Expected value of $B_{PROJECT}$ as a proportion of B_{MSY}
3.	$\mathrm{E}\left(\frac{B_{PROJ}}{B_{CUR}}\right)$	Expected value of $B_{PROJECT}$ as a proportion of $B_{CURRENT}$
4.	$\mathrm{E}\left(\frac{B_{CUR}}{B_0}\right)$	Expected value of $B_{CURRENT}$ as a proportion of B_0

5. $E\left(\frac{Catch_{98-99}}{B_{98-99}}\right)$ Expected value of catch to biomass ratio in 1998–99 (U_{98})

6. $E\left(\frac{Catch_{04-05}}{B_{04-05}}\right)$ Expected value of catch to biomass ratio in 2004–05 (U_{04})

7. $P(B_{CUR} > B_{MSY})$ Probability that $B_{CURRENT}$ is greater than B_{MSY}

8. $P(B_{PROJ} > B_{CUR})$ Probability that $B_{PROJECT}$ is greater than $B_{CURRENT}$

Note that $B_{CURRENT}$ is defined as the beginning season biomass on 1 April 1999 which is the beginning of the autumn-winter season for the 1999–2000 fishing season. Similarly, $B_{PROJECT}$ is defined as the beginning season biomass on 1 April 2004 which is the beginning of the autumn-winter season for the 2004–2005 fishing season. B_0, B_{MSY}, $B_{CURRENT}$ and $B_{PROJECT}$ are defined as the total recruited biomass at the beginning of autumn-winter season. B_0 is defined as the equilibrium biomass in 1945. B_{MSY} is calculated by finding U_{MAX}, the exploitation rate that maximises yield, from a deterministic equilibrium population using the model parameter vector. U_{MAX} is applied to the season in whichever season has the highest $U_{1998,SEASON}$. The optimal exploitation rate for the other season will be $U_{MAX}\frac{U_{98-99,other\_season}}{U_{98-99,higher\_season}}$.

Estimates of vulnerable biomass are made for the beginning of the autumn-winter for each fishing year (1 April to 31 March). Vulnerable biomass includes all fish selected based on the estimated relative vulnerabilities, the fishery selectivity functions and the MLS regulations. As these values have changed over the period being assessed, derived quantities of management interest (such as B_{MSY} and B_0) have been calculated as all lobster above the MLS based on the 1999 regulations, assuming that vulnerabilities and selectivities of these lobster equals one.

3. DEFINITION OF NEW ZEALAND LOBSTER SUBSTOCKS

The fishery for *Jasus edwardsii* occurs around the whole of New Zealand. Evidence for separate stocks based on genetics, morphology, movement, population parameters, catch per unit effort trends, larval distribution, and parasites has been reviewed (Booth & Breen 1992). Based on this work, in 1994 the RLFAWG agreed to define four stocks for assessment purposes from eight of the nine quota management areas:

Quota Management Area	Fishstock	Assessment stock
Northland	CRA 1	NSN
Bay of Plenty	CRA 2	
Gisborne	CRA 3	NSC
Wellington/Hawkes Bay	CRA 4	
Canterbury/Marlborough	CRA 5	
Chatham Islands	CRA 6	CHI
Otago	CRA 7	NSS
Southern	CRA 8	
Westland/Taranaki	CRA 9	Not defined
Kermadec	CRA 10	

As yet, the CRA 9 Quota Management Area has not been assigned to a stock and no rock lobster catch has been recorded from CRA 10 (Kermadec Islands).

This document describes the 1999 assessment for the NSS stock.

4. ASSESSMENT MODEL INPUTS

This section describes the data and parameter inputs used for the NSS assessment. These inputs include the period over which the model was run, catch data, catch rate indices, annual size frequencies, and the priors and point values used for estimated and fixed parameters respectively.

There is considerable variation within the NSS stock in the size frequencies observed in the catch. There are substantial differences between CRA 7 and CRA 8, and within CRA 8, there are differences between Stewart Island (Area 924) fishery and Fiordland (Areas 926 to 928). In the past, the NSS assessment has been conducted by fitting the model to Fiordland data but is scaled up to the NSS as a whole by using catch data for the entire stock. One of the goals of the 1999 assessment of the NSS substock was to include data from Stewart Island in the stock assessment. It was hoped that an examination of the data would provide information on how best to incorporate the Stewart Island information into future stock assessments.

A summary of all the data and the data sources used in the 1999 NSS stock assessment is provided in Table 2. A discussion of these data and their sources is provided later in this document.

Table 2: Data types and sources for the 1999 assessments in the NSS assessment. Year codes apply to the first 9 months of each fishing year. NA, not applicable or not used; RLIC, Rock Lobster Industry Council; NIWA, National Institute of Water and Atmospheric Research.

Data type	Data source	Begin year	End year
Historical catch rate	Annala & King (1983)	1963	1972
Modern CPUE	FSU & CELR	1979	1998
Historical size frequencies	Street (1970)	1964	1969
Research size frequencies	NIWA	1984	1996
Logbook size frequencies	RLIC	1993	1998
Settlement indices[1]	NIWA (Booth et al. 2000)	1986	1998
Historical tag recovery data	NIWA (Annala & Bycroft 1988)	1978	1988
Current tag recovery data	RLIC & NIWA	1997	1998
Historical MLS regulations	Annala (1983)	1945	1998
Escape gap regulation changes	Annala (1983)	1945	1998

[1] Chalky Inlet (CHI001) (Booth et al. 2000)

4.1 Period included in the model and definition of fishing year and season

The model simulation begins in 1945, the first year for which catch data are available. Until 1979, catch data are collated by calendar year. After that date, catch, catch rate, and size frequency data are summarised by fishing year, spanning the period 1 April to 31 March. Fishing years are labelled in Appendix 2 using the first calendar year in each pair (for example, the 1996–97 assessment year which covers the period 1 April 1996 to 31 March 1997 is labelled as '1996').

Two seasons are defined in this model: a) "autumn-winter" which spans the period 1 April to 30 September; and b) "spring-summer" which includes the period 1 October to 31 March.

4.2 Structure of size frequency data

Tail width size frequency data from research sampling and from voluntary logbook programmes were binned into 2 mm size classes from 30 to 90 mm. These limits spanned the size range of most lobsters caught in the catch. Two-millimetre size classes were considered small enough to provide enough resolution in the model without being too small to be affected by measurement error. Note that the voluntary logbook programme measured lobster to an accuracy of 1.0 mm while the research sampling accuracy was 0.1 mm. As the convention has been to round down all measured lengths, 0.5 mm was added to each voluntary logbook measurement before binning to avoid introducing bias into the calculated size frequencies.

4.3 Control variables

The catch data, the CPUE abundance indices and other annual and seasonal information used in the NSS stock assessment are provided in Appendix 2.

4.3.1 Catches

The assessment model requires annual values of legal and illegal catch. Legal catch is defined as the total weight of lobsters taken in accordance with existing regulations on the minimum legal size limit and the maturity state of females (i.e., berried or non-berried). Illegal catch is taken without regard to these regulations and includes lobsters both above and below the size limit and females both in berry and unberried. Three types of catches are considered when collating annual legal and illegal catch totals.

4.3.1.1 Commercial reported

From 1945 to 1978, total reported annual commercial catches were obtained from Breen & Kendrick (1998). Beginning on 1 January 1979, catches were taken from data compiled by the Fisheries Statistics Unit (FSU) and held by the Ministry of Fisheries. Three months of catch pertaining to 1 January 1979 to 31 March 1979 are added to the annual catch for 1978. From 1 April 1979 to 31 March 1986, catch totals from the FSU were used to calculate catch by fishing year. Beginning 1 April 1986, catch totals by fishing year were obtained from Quota Management Returns (QMRs) maintained by the Ministry of Fisheries. QMR catches were not available by QMA for the 1986–87 and 1987–88 fishing years. Therefore, the proportional splits by QMA from the FSU catch data for those fishing years were used to apportion the total New Zealand QMR catches into QMA totals. Catches for CRA 7 and CRA 8 from the QMR were summed to provide the NSS catch by fishing year after 1 April 1988.

4.3.1.2 Commercial unreported

Estimates of unrecorded commercial catch have been made for the calendar years 1974 to 1980 by comparing recorded catches with export weights of lobster and assigning the discrepancy to stocks in proportion to the recorded commercial catch (Breen 1991).

4.3.1.3 *Recreational*

The RLFAWG agreed to assume that in 1945 recreational catches were 20% of current levels and that they increased at a constant rate until 1980. After that year, it was assumed that catches have remained constant at current levels. Levels of recreational catch were estimated using the best estimate of mean weight available at the time of the survey (Table 3).

The method used to calculate the recreational catch was changed slightly compared to previous lobster stock assessments. This was done to address a problem which arises because the stock assessment model assumes that the distribution of lobster by size is the same in the recreational fishery as in the commercial fishery. This can lead to problems if the average weight used to estimate the recreational catch was higher than the average weight in the equivalent commercial catch. If the recreational catch used in the model were estimated using a higher average weight than in the model, then the model assigns a larger number of lobster to that catch than actually were taken. It was decided that it was better to preserve the number of lobster caught as this is the more accurate information coming from recreational survey. This goal was accomplished by using mean weights from logbook data corresponding to each recreational fishery to calculate the catch by weight based on the number (i.e. the mean of the available recreational catch estimates) of lobster caught by the recreational fishery. The revised recreational catch by weight was then applied to all model years from 1980 onwards (including future years). Estimates by weight of the recreational catch used are provided in Table 4.

Table 3: Estimates of the recreational rock lobster harvest (t) from telephone and diary surveys in 1992 and in 1996 (–, not available). Mean weights are based either on weights reported in the diaries or from boat ramp surveys (Teirney et al. 1997).

	1992 survey		1996 survey	
QMA	Estimated number of lobsters	Estimate (t)	Estimated number of lobsters	Estimate (t)
CRA 7	6 000	1–6	3 000	–
CRA 8	32 000	15–60	22 000	16

Table 4: Estimates of NSS annual recreational catch by weight for the period 1980 to 1998 used in 1998 and 1999 assessments.

Recreational catch estimate used in 1998 assessment	34 t
Recreational catch estimate used in 1999 assessment	20.1 t

4.3.1.4 Legal catch

Legal catch in the model is defined as the sum of the commercial reported, the commercial unreported, and the recreational catch.

4.3.1.5 Illegal catch

There are two categories of illegal catch: one is the catch which is taken without regard to the existing regulations but may eventually be included in the legal catch totals. For instance, this category includes holding berried females in pots until they release their eggs. The other category of illegal catch includes lobster which never enter into the catch reporting system. It is necessary to separate these categories as the former category needs to be subtracted from the reported legal catch to avoid double counting of catch. In the model, it is assumed that both categories of illegal catch have the same size and female maturity distributions as the legal catch, but that all lobster are retained. Estimates of illegal catches have been obtained from the Ministry of Fisheries Compliance Section for the 1990–91 to 1996–97 fishing years (Table 5).

Table 5: Estimates of illegal rock lobster catches (t) for the NSS stock. These estimates have been made by the Ministry of Fisheries Compliance Section (P. Breen, NIWA Ltd, *in litt.* 4/8/98). Note that estimates are not available for all years.

Calendar/ Fishing year	NSS
1979	11
1987	55
1990–91	74
1992–93	104
1994–95	90
1995–96	60
1996–97	68

However, estimates were partitioned between "reported" and "unreported" illegal catch only for the 1996–97 fishing year. These proportions were applied to all previous years with illegal catch. It was assumed that no illegal catch was taken before 1978–79 and interpolation was used to fill the years without illegal catch estimates. Illegal catches were assumed to be the same in the final two assessment years (1997–98 and 1998–99) as in the 1996–97 fishing year.

4.3.1.6 Seasonal split of catches

Catch data were split into seasonal periods from 1 April 1979 to the present by applying calculated proportional splits from the FSU and Catch Effort Landing Returns (CELR: held by the Ministry of Fisheries) data to the reported catches by fishing year (Table 6). Seasonal catch information was not available for the period 1973 to 1978 and the mean seasonal split for the period 1 April 1979 to 31 March 1982 was applied to this period (Table 6). Monthly catch data spanning the period 1 January 1963 to 31 December 1973 were available for statistical areas specific to Fiordland. These data have been summarised by year in Annala & King (1983) and monthly data were used to calculate seasonal splits for Fiordland (Figure 1) for the period 1 April 1963 to 31 March 1973.

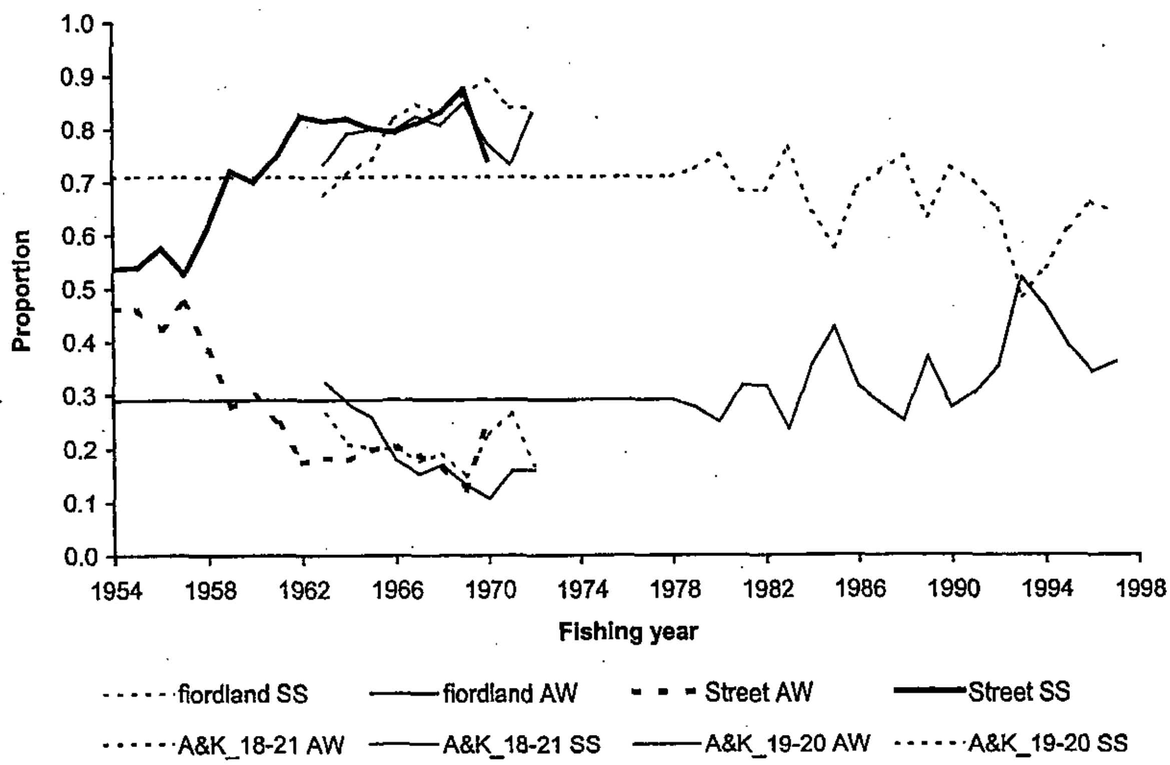

Figure 1: **Seasonal proportions of catch used in the NSS assessment model (AW, autumn-winter; SS, spring-summer). Proportions shown for Fiordland seasons were calculated from the FSU and CELR catch data which begin in 1979. The fixed extensions backward from 1978 are the average SS and AW proportions calculated for each area from 1979 to 1982. The thick heavy lines are the seasonal proportions calculated from the Street (1970 and 1973) data for "Bluff–Stewart Island, Riverton and Milford". The thin lines from 1963 to 1972 are the seasonal proportions calculated from the Annala & King (1983) monthly data for Fiordland (Areas 19 & 20) and for Southland (Areas 18-21).**

Street (1970, 1973) provided tables of historical catches by month for an area labelled as "Bluff–Stewart Island, Riverton and Milford". Catches from these tables were summed over the appropriate months to provide estimates for the seasonal split by year for the period 1 April 1954 to 31 March

1971. These data include Stewart Island catches as well as Fiordland catches, but are the only data available to estimate the catches splits from 1 April 1954 to 31 March 1963 (Table 6). The seasonal split estimates using the Street data are comparable to the seasonal split estimates from the Annala & King data for the period of overlap and show a trend from an evenly divided fishery in the mid-1950s to a predominantly spring-summer fishery in the late 1960s (Figure 1). An average seasonal split for the period 1 April 1954 to 31 March 1957 was used to split the catch before 1954 (Table 6).

Table 6: Data sets used to calculate seasonal proportions in the NSS assessment model.

Period	Data set
Pre-1954	Average (1954–1957) from Street data
1954–1962	Street data
1963–1972	Annala & King (1983) data
1973–1978	Average (1979–1982) from FSU data
1979–present	FSU–CELR data

The recreational fishery was split between the two seasons by assuming that 90% of the recreational catch was taken during the spring-summer season. Illegal catches were split between seasons by using the appropriate annual split from the legal commercial fishery.

4.3.2 Regulation history

4.3.2.1 Conversion of total length and tail width regulations

Conversion formulae were used to convert MLS regulations and historical data to tail width measurements. Sorenson (1970) provides conversion factors for total length to tail length in inches (Table 7). Breen et al. (1988) provided conversion factors for tail length to tail width in millimetres (Table 7).

Table 7: Parameter estimates for the conversion of total length to tail length and from tail length to tail width. Conversion factors for total length to tail length (in inches) are taken from Sorensen (1970). Conversion factors for tail length to tail width (in millimetres) are taken from Breen et al. (1988).

	Total length (in.) to tail length (in.)		Tail length (in.) to tail width (mm)	
	Male	Female	Male	Female
Slope	0.571	0.604	0.369	0.475
Intercept	0.196	-0.032	-2.75	-16.24

4.3.2.2 MLS regulation history

Annala (1983) provided an overall summary of regulations in the New Zealand rock lobster fishery up to 1982, including the timing of the introduction of minimum size limit regulation changes in the 'Southern' conservancies (Table 8). Booth et al. (1994) provided a summary of the regulation changes which occurred in the 'Southern' QMA during the period of changeover from a tail length to a tail width regulation (Table 8). The sequence of minimum legal sizes by sex and year expressed as tail width (in millimetres) is presented in Figure 2 and the size limits used in each year are given in Appendix 2.

Table 8: **Summary of historical minimum size limit regulations. The regulation changes up to 1959 taken from Annala (1983). The regulation changes from 1988 to 1990 are summarised from Table 1 in Booth et al. (1994). Regulations are expressed in inches (designated as ") or in millimetres. Model interpretations in millimetres tail width have been made using the *conversion factors provided* in Table 7. The lower size limit of 5.75 inches tail length was used from 1952 to 1958. Abbreviations: TL, total length; tl, tail length; TW, tail width.**

	Regulation		Model interpretation in tail width (mm)	
Year	Males	Females	Males	Females
1945	No limit	No limit	No limit	No limit
1950	9" TL	9" TL	47	49
1952	10" TL or 5.75" tl	10" TL or 5.75" tl	51	53
1959	6" tl	6" tl	53	56
1988	54 mm TW	58 mm TW	54	58
1989	54 mm TW	152 mm tl	54	56
1990	54 mm TW	57 mm TW	54	57

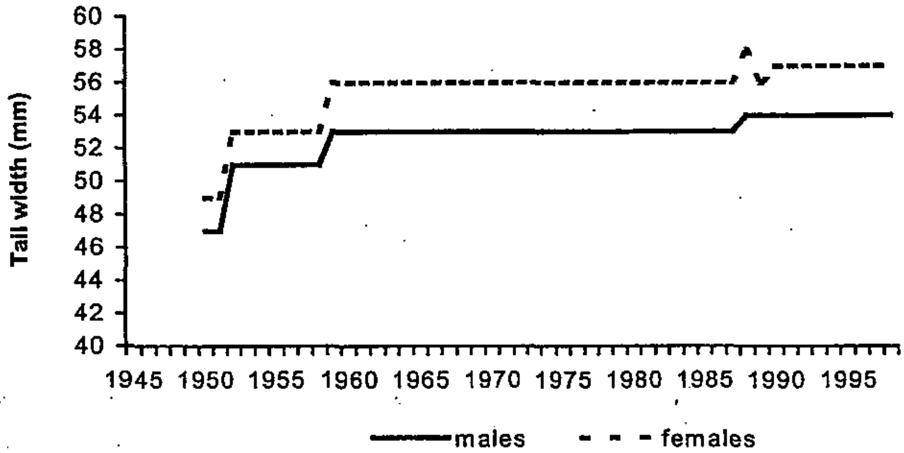

Figure 2.: Sequence of minimum legal sizes by calendar year for each sex as presented in Table 8 converted to tail width in millimetres.

4.3.2.3 Escape gaps

Annala (1983) noted that, before June 1970, escape gaps were not used as a management measure in New Zealand. Street (1973) also discussed the introduction of escape gaps, but concluded, on the basis of limited sampling, that the escape gaps were not effective. Annala (1983) noted that the escape gap size was set at 54 x 305 mm in all New Zealand with the exception of Otago. Escape gap regulations were changed again in July 1993 and the assessment model incorporates these changes by fitting separate selectivity functions for three periods: a) 1945 to 1969; b) 1970 to 1992; and c) 1993 to the present.

4.3.2.4 Prohibition on the taking of berried females

Historical information provided by Annala (1983) indicated that, in the period from 1945 to the present, there is only a two-year period (1950 & 1951) during which the taking of berried females was allowed by regulation. Given that this is a very short period relative to the total model period, these two years were not included in the model reconstruction of the fishery.

4.4 State variables

4.4.1 Biomass indices

CPUE of legal lobsters is used as an index of legal biomass. Two sources of catch and effort data are available for the NSS stock: 1) catch and number potlifts associated with the catch from the FSU and CELR data bases held by the Ministry of Fisheries; and 2) catch and the number of days associated with the catch from historical monthly data held by NIWA.

4.4.1.1 FSU and CELR data

For the NSS, the standardised abundance indices were estimated from catch per potlift data from the FSU and CELR data bases using catch from Fiordland (statistical areas 926 to 928). Seasonal relative indices of catch rates are generated by standardising for month and statistical area (Maunder & Starr 1995, Breen & Kendrick 1998). These indices are made relative to a base season which is defined as the season with the absolute index which has the lowest standard deviation. The raw mean catch per potlift is then used to adjust all the indices into absolute terms. These indices are reported in Appendix 2.

4.4.1.2 Historical data

Monthly catch and effort (days fishing) data spanning the period 1963 to 1973 are available for statistical areas specific to Fiordland and have been summarised by Annala & King (1983). Monthly catch and effort data from this data set were used to calculate unstandardised catch per day for each season from 1 April 1963 to 31 March 1973 using the Fiordland data (Areas 19 and 20) and are reported in Appendix 2.

4.4.2 Size frequencies

4.4.2.1 Recent data

Data on the size of lobsters entering pots in the CRA 8 legal catch were available from research sampling on commercial vessels and from voluntary logbook programmes. Estimates of the annual length frequency were obtained by using length frequency data that had been summarised by area/month strata and weighted by the relative proportion of the commercial catch taken in that stratum and the number of days sampled (see below). When there was more than one source of size frequency data available within a single stratum, the length data from each source were fitted separately. It was assumed that the length frequency data used were representative of the commercial catch. Size frequencies were generated from data derived from Fiordland only (statistical areas 926 to 928).

An estimate of the effective sample size is required to calculate the variance in the catch-at-size likelihood equation. Using the absolute number of lobsters measured is likely to under-estimate the variance because there is sampling variation in addition to multinomial sampling error. A sample which has fewer lobsters measured over more vessels and time periods within a fishery is likely to be more representative of the fishery than one that has measured many lobsters but is concentrated over a few vessels and time periods. The index of effective sample size was calculated for each year which took into account the relative catch in the statistical area/month stratum sampled, the number of lobster sampled and the number of days fishing sampled:

$$W_{m,y} = S \frac{C_{j,y}}{\sum_{j=1}^{n_j} C_{j,y}} \sqrt[3]{N_{m,y}} \sqrt[3]{D_{m,y}}$$

where, $C_{j,y}$ is the catch in stratum j in period y and n_j is the total number of strata sampled. $N_{m,y}$ is the number of lobster sampled by method m (research sampling or logbook data) in period y and $D_{m,y}$ is the number of sampling days by method m in period y. The cube root was chosen so as to not overly weight the effective sample size by the number of lobster sampled. The scalar (S) is 63, based on a hypothetical "perfect sample" of 5000 measurements from all cells in which catches were reported in a year.

4.4.2.2 Historical data

Street (1970) provided a figure containing size frequency data from Fiordland for 1964 and 1966 to 1969 (Figure 3). The proportional frequencies in these figures were calculated by digitising from the published graphs and the lengths were converted from total length in inches to tail width in millimetres using the conversion factors provided in Table 7.

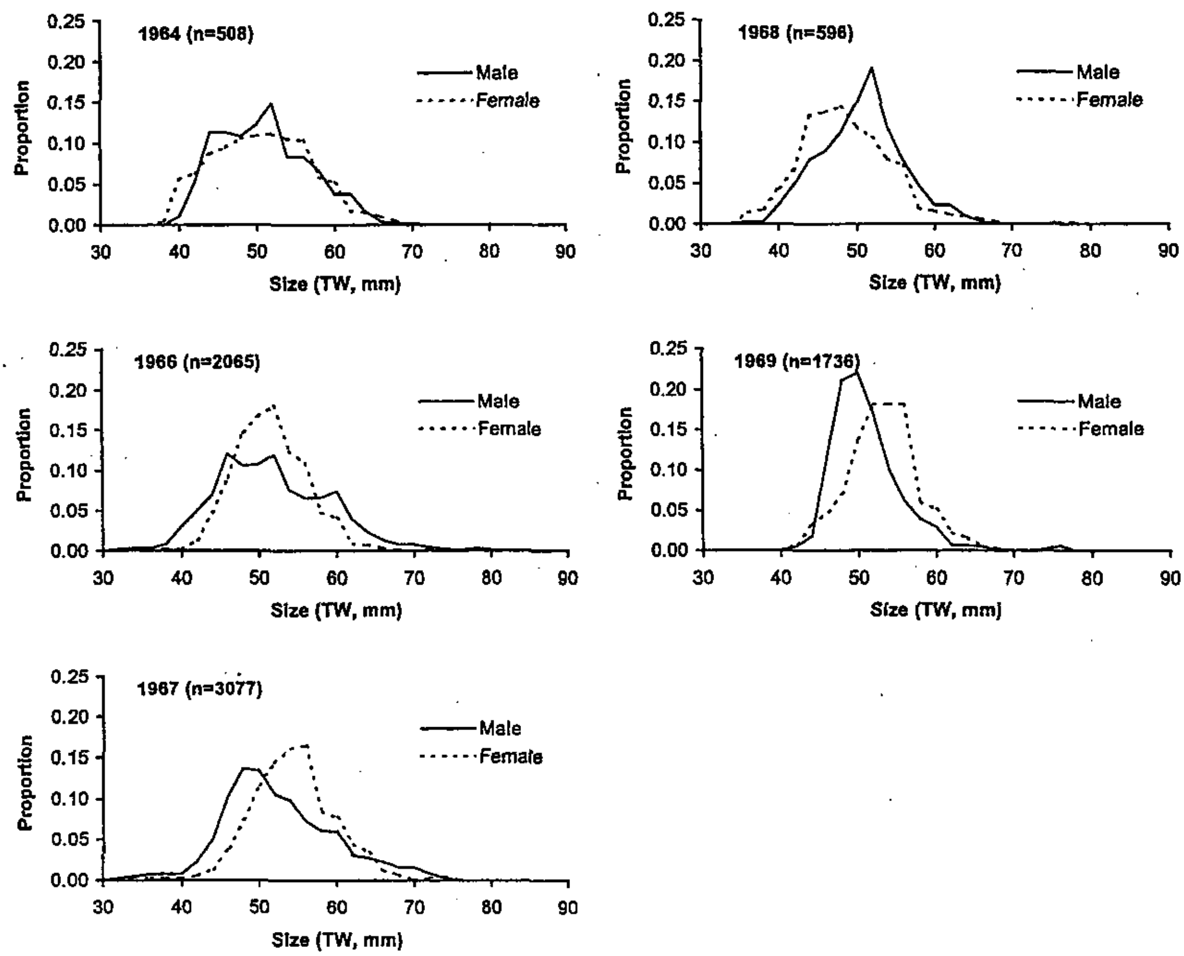

Figure 3: **Five years of historical size frequencies from Fiordland (from Street 1970). The proportional frequencies have been calculated by digitising from the published graph and the lengths have been converted from total length in inches to tail width in millimetres using the conversion factors provided in Table 7. Frequencies have been converted from bins of 0.5 inches to bins of 2 mm tail width for inclusion in the model.**

These size frequency data were used in the model as if they were taken in the spring-summer season only. Mature and immature females were summed before fitting to the female data. The effective sample size was based only on the square root of the number of lobster sampled. This was the same as assuming that all the lobster were sampled on a single day (see equation in Section 4.4.2.1).

4.4.3 Settlement indices

The model was fitted to indices of recruitment based on the observed settlement of puerulus into collectors as a sensitivity to the base case assessment. Settlement data from Chalky Inlet in Fiordland were used (Booth et al. 2000) as indices and are provided in Appendix 2. These indices are the mean of the monthly observations from March to October from 1985 to 1998 (Booth et al. 2000).

4.4.4 Tagging data

Two sources of tag recovery data are available (Table 9). The first comes from tagging experiments reported by Annala & Bycroft (1988) performed in Fiordland in the early 1980s. The second come from tag recovery experiments conducted since 1996 by the Rock Lobster Industry Council (RLIC) under funding from the Ministry of Fisheries "required services" (D. Banks, NIWA, pers. comm.). These data are the primary source of information for estimating growth in the model and have been prepared in the following manner.

1. Only recoveries which spanned at least one season were used. This meant that all recoveries that took place within the season of release were excluded.
2. No distinction was made for re-releases and subsequent recaptures of the same tag. Thus all multiple recaptures were treated as independent data records.
3. Only the most extreme growth increment errors were dropped and negative growth increments were allowed. About 10% of the growth increments are less than 0.0 in both data sets (Table 9). None of the Annala & Bycroft data were dropped and less than 1% of the RLIC data were excluded.

Each recovery event was introduced into the model with a release and recovery tail width (so that the increment can be calculated and the release tail width put in the correct size bin) and a release and recovery seasonal period. This latter information allowed the number of seasons at large to be calculated as well as the number of expected moults.

Table 9: Summary of tag release and recovery data used in the 1999 NSS assessment by data source. (RLIC, Rock Lobster Industry Council tagging)

	Total Tags			Tags recoveries with increments <0		
	Male	Female	Total	Male	Female	Total
RLIC	143	402	545	8	42	50
Annala & Bycroft (1988)	643	925	1568	80	77	157
Total	786	1327	2113	88	119	207

4.5 Parameter priors

For all parameters estimated, priors were set after discussions in the RLFAWG (Table 10). The basis for these priors are outlined below. Some parameters were fixed and the values chosen are presented in Table 11.

Table 10: Parameters estimated in the model and their prior distributions. Prior types: U, uniform; N, normal; L, lognormal; TW, tail width.

	Prior Type	Bounds	Mean	c.v.
Log R_0 (mean of the log of the recruitment)	U	1–50	–	–
M (natural mortality)	L	0.01–0.35	0.12	0.5
Recruitment deviations	N [1]	-2.3–2.3	0	0.4
TW (mm) at growth=0 (male & female)	N	60–130	90	0.1
Max TW (mm) for moult in off-season (male & female)[2]	U	30–130	–	–
Slope: TW vs. growth increment (male & female)	U	-10–0	–	–
TW (mm) at 50% probability female maturity	U	30–90	–	–
(TW [mm] at 95% probability female maturity) – (TW [mm] at 50% probability female maturity)	U	0–30	–	–
Relative vulnerability: males autumn-winter	U	0–1	–	–
Relative vulnerability: immature females autumn-winter	U	0–1	–	–
Relative vulnerability: immature and mature females spring-summer	U	0–1	–	–
Relative vulnerability: mature females autumn-winter	U	0–1	–	–
Variance of ascending limb of vulnerability ogive –before 1970 (males & females)	U	1–500		
Variance of ascending limb of vulnerability ogive 1970 to 1992 (males & females)	U	1–500		
Variance of ascending limb of vulnerability ogive –from 1993 (males & females)	U	1–500	–	–
Variance of descending limb of vulnerability ogive (males & females)[3]	L	100–10 000	1 000	1

[1] Normal in logspace = lognormal (bounds equivalent to 0 to 10)
[2] Fixed at 30 mm in the NSS base case assessment
[3] Fixed at 9 999 in base case assessment. Agreed to use 1998 priors for these parameters as a sensitivity

Table 11: Fixed parameter values used in base case assessments. (TW, tail width [mm])

Parameter	Value
Growth standard deviation [mm]	2
Relative vulnerability of males in the spring-summer season	1
TW [mm] at maximum fishery selectivity (male)	54
TW [mm] at maximum fishery selectivity (female)	57
CPUE c.v.	0.3
Historical catch per day c.v.	0.4
Settlement c.v. [1]	0.3
Recruitment residual c.v.	0.4
Maximum exploitation rate	80%
Handling mortality	10%

[1] Sensitivity assessments only

4.5.1 Natural mortality and recruitment

An informative prior was placed on M, based on the presumption that the mean of this distribution was reasonably well established but a large c.v. was required to allow the model to choose from a wide distribution of possible values (Table 10). Wide uniform bounds were placed on the prior for average recruitment. Annual recruitment multipliers were specified by a log-normal prior with bounds set from 0 to 10. In the model, recruitment multipliers are specified in log space as deviations from 0.0.

4.5.2 Female maturity

Uniform priors with wide bounds were used for the two size at maturity parameters, m_{50} and $m_{95} - m_{50}$.

4.5.3 Vulnerability

All relative maximum vulnerabilities by sex category (males, immature females and mature females) were calculated relative to males in the spring-summer season. This category was assumed to have the highest relative vulnerability (relative vulnerability = 1.0) of the six possible categories of season and sex category. Thus each of the five remaining categories can be scaled to be equal to or less than 1.0. Only four of these parameters were estimated as it was assumed that immature and mature females in the spring-summer season would have the same vulnerability. Priors for these four parameters were uniform between 0.0 and 1.0.

Uniform priors with very wide bounds were used for the parameter describing the ascending side of each of the three vulnerability ogives estimated in the NSS model (see Section 4.3.2).

4.5.4 Growth rates

The parameter which specifies the size at which the expected growth ceases is poorly determined in this model given the available data. This parameter is analogous to the L_∞ parameter of the von-Bertalanffy growth equation. Model estimates of this parameter tended to be very large and unrealistic when a non-informative prior was used. Therefore, a informative prior with a relatively small c.v. was used to constrain the model estimates of this parameter into a realistic range. Uniform priors with wide bounds were used for the growth parameters specifying the slope of the growth equation and the probability of moulting in the secondary growth season.

4.6 Weighting of likelihoods

Relative weights were assigned to each of likelihoods associated with each of the data input types (Table 12). These relative weights were assigned empirically to help solve some of the inherent problems found in this assessment. Low relative weights were assigned to the size frequency and tagging data as these data sets were quite large and tended to overwhelm other data sources. A very high weight was given to the penalty for exceeding the maximum exploitation rate as there was a tendency for the model to prefer low initial biomasses and to allow extremely high levels of depletion. Weights on the CPUE , historical catch rates and on the priors were set at intermediate levels to allow these sources of information to contribute to the overall likelihood.

Table 12: Relative weights for the different data types used in the base case assessments for the NSS assessment.

Likelihood type	Weight
Modern CPUE	10
Historical catch rates	10
Size frequencies	1
Tags	1
Priors	10
Recruitment deviations	1
Penalty for exceeding maximum exploitation rate	1 000

4.7 Fixed parameters

4.7.1 Size of recruits

The parameters governing the size distribution of recruits were fixed at $\phi_g = 30$ mm and $\gamma_g = 2$ mm for this assessment.

4.7.2 Recruitment variation

The RLFAWG agreed to set the coefficient of variation for recruitment at 0.4. Recruitment residuals were estimated only for those years where information existed in the size frequency data. Recruitment residuals were estimated from 1954 to 1995. The earliest year is set by the amount of historical information available and the last year is set by the number of observations available for the youngest cohort.

4.7.3 Recruitment age

The age of recruitment to the fishery was set to two, the approximate age of 30 mm tail width lobsters for the "base case" and most of the sensitivity analyses. This parameter was varied from one to four when fitting to the settlements indices.

4.7.4 Vulnerability

The RLFAWG agreed to fix the size at maximum vulnerability for each sex to the 1999 size limit regulation. This was done to reduce the number of parameters estimated by the model. The RLFAWG also agreed to fix the right hand limb of the vulnerability ogive to a large value to ensure that there was no reduction in the vulnerability of large lobster. This parameter was estimated with the same priors as used in 1998 as a sensitivity to the base case.

4.7.5 Growth

The standard deviation of growth was fixed at 2 mm as this value was consistent with the equivalent standard deviation estimated for Fiordland in 1998 (Starr et al. 1999) and with the tagging data used in the model. Growth in the secondary moulting season for either sex was not estimated (that is, the parameter was fixed at 30 mm) as there appeared to be insufficient information in the tagging data to estimate these parameters. The resulting model interpretation is that lobsters of each sex only moult in the corresponding primary season. Estimates of the secondary moulting parameters in early model runs were usually on one or the other bound of the prior.

4.7.6 Coefficients of variation used for fitting to observed data

Fixed c.v.s of 0.3 and 0.4 were used for the modern and historical catch/effort abundance indices respectively. A c.v. of 0.3 was used when fitting to settlement data.

4.7.7 Mortality rates

Handling mortality was assumed to be 10% of all lobsters that were discarded. The maximum rate of fishing mortality was set at 80% of the total population of vulnerable lobster.

4.7.8 Size-weight relationship

The parameters of the size to weight relationship were fixed at values estimated from catch sampling data (Table 13) and these parameters were applied as indicated in Eq 16 (Appendix 1).

Table 13: Parameters of the size (TW, tail width) to weight relationship [a TW^b (weight in kilograms, TW in millimetres)] (Breen & Kendrick NIWA, unpublished data).

		Females		Males	
Stock	Statistical areas	a	b	a	b
NSS	927 & 928	1.04 E-05	2.63	3.39 E-06	2.97

5. ASSESSMENT RESULTS

5.1 Catches used for projections

The catch trajectory used for projections to estimate the performance indicators are provided in Table 14 (see Section 2.4 for description of how the projections were done).

Table 14: Catches used in the five year projections for the NSS substock. Projected catches are based on the current TACC and the current estimates of recreational and illegal catches.

Population modelled	Commercial catch (t)	Recreational catch (t)	Reported illegal catch (t)	Unreported illegal catch (t)
NSS	783 [1]	20	38 [2]	33

[1] Consists of 72 t for CRA 7 (=average catch from 1994–95 to 1998–99) and the CRA 8 TACC (711 t)
[2] Estimated at 5% of the combined CRA 7 and CRA 8 catch

5.2 Results before incorporation of historical data

For the initial fits to the NSS data, none of the historical data series described in Sections 4.3 and 4.4 were used and the approach adopted was similar to that described for the 1998 assessment (Starr et al. 1999). The primary difference in the parameter estimation between these early fits and the priors provided in Table 10 was that a non-informative prior was for the parameter which specifies the size at which the expected growth ceases. The data sources used began in 1979 (except for the catch history) and the seasonal split applied to the historical catch data is specified by the horizontal line shown in Figure 1. The relative weighting between these data sources were left at their natural level (Weight=1, see Table 12 for final weights used). However a relative weight of 1000 was placed on the penalty assigned to exceeding the maximum exploitation rate.

The fits from these initial runs to the CPUE data and to the tagging data are not satisfactory (Figure 4 and Table 15). The fit to the CPUE data between 1989 and 1995 (a period which should contain some of the better available data) is particularly poor. The fit to the size frequency data is difficult to judge but seems acceptable. Model estimates of current biomass are extremely low (lower than in the 1998 assessment) and model estimates of exploitation rate are very high since the early 1980s (Table 15).

The model estimates substantial recruitment anomalies in the late 1970s or early 1980s which may alias misspecification in the way catch is removed from the stock before the 1970s (Figure 4). The estimated recruitment deviations also vary between the fits presented (Figure 4). The estimated growth parameters for the size at which growth ceases are near or at the bounds of the priors. This leads to estimates of the slope growth parameters which are very shallow as the two parameters are highly correlated (Table 15). The estimate for female vulnerability in the spring-summer season is low, leading to a large cryptic population (Table 15).

Table 15: Model likelihoods, stock indicator estimates, and PME parameter estimates for initial NSS assessment runs. These results do not include historical data described in Sections 4.3 and 4.4. Fixed parameters are indicated by bold type. (SD, standard deviation)

	Settlement not fitted	Settlement not fitted & growth SD = 2	Settlement Fitted (lag=2)
Parameter estimates			
R_0 (number of recruits)	1 309 988	1 659 738	1 031 354
M	0.041	0.050	0.033
TW at growth=0 (male, mm)	123.8	130.0	119.3
TW at growth=0 (female, mm)	130.0	130.0	129.1
Max TW for moult in off-season (male, mm)	79.2	76.8	80.1
Max TW for moult in off-season (female, mm)	61.3	61.8	63.3
Slope: TW vs. growth increment (male)	-0.031	-0.028	-0.032
Slope: TW vs. growth increment (female)	-0.018	-0.017	-0.018
Growth Std (mm)	3	2	3
TW at 50% probability female maturity (mm)	60.21	61.00	60.09
(TW at 95% probability female maturity) – (TW at 50% probability female maturity) (mm)	6.17	7.50	6.09
Relative vulnerability: males autumn-winter	1.000	1.000	1.000
Relative vulnerability: immature females autumn-winter	0.653	0.590	0.652
Relative vulnerability: immature and mature females spring-summer	0.632	0.546	0.664
Relative vulnerability: mature females autumn-winter	0.573	0.447	0.560
Variance of ascending limb of vulnerability ogive (male, before 1993)	51.57	53.09	52.53
Variance of ascending limb of vulnerability ogive (female, before 1993)	57.70	64.40	56.61
Variance of ascending limb of vulnerability ogive (male, from 1993)	13.11	13.17	13.64
Variance of ascending limb of vulnerability ogive (female, from 1993)	18.18	19.48	17.72
Indicators			
B_{curr}/B_{msy}	9.3%	11.5%	6.5%
B_{curr}/B_0	1.9%	2.4%	1.3%
U_{curr}	72.4%	58.7%	100.7%
Likelihoods			
LikeCPUE	3.58	-2.15	3.54
LikeLF	-4 385.48	-4 319.70	-4 350.07
LikeTags	4 747.50	4 490.34	4 744.72
LikePriors	2.56	1.77	3.57
LikeRdevs	45.91	17.81	51.50
PenaltyU	0.44	0.00	0.71
Likesettle	0	0	25.21
LikeTotal	414.50	188.08	479.18

The model could not be properly fitted to data from Stewart Island because there are few mature females in the size-frequency data from both the research catch sampling and logbook programmes. Previous tagging studies have suggested that lobster just below the size of maturity make migrations towards Fiordland. However, because of the way the 1999 assessment model is structured, the model would interpret the lack of mature females as the result of extremely low vulnerability for these females in the autumn-winter fishery and that there is large size at maturity for females.

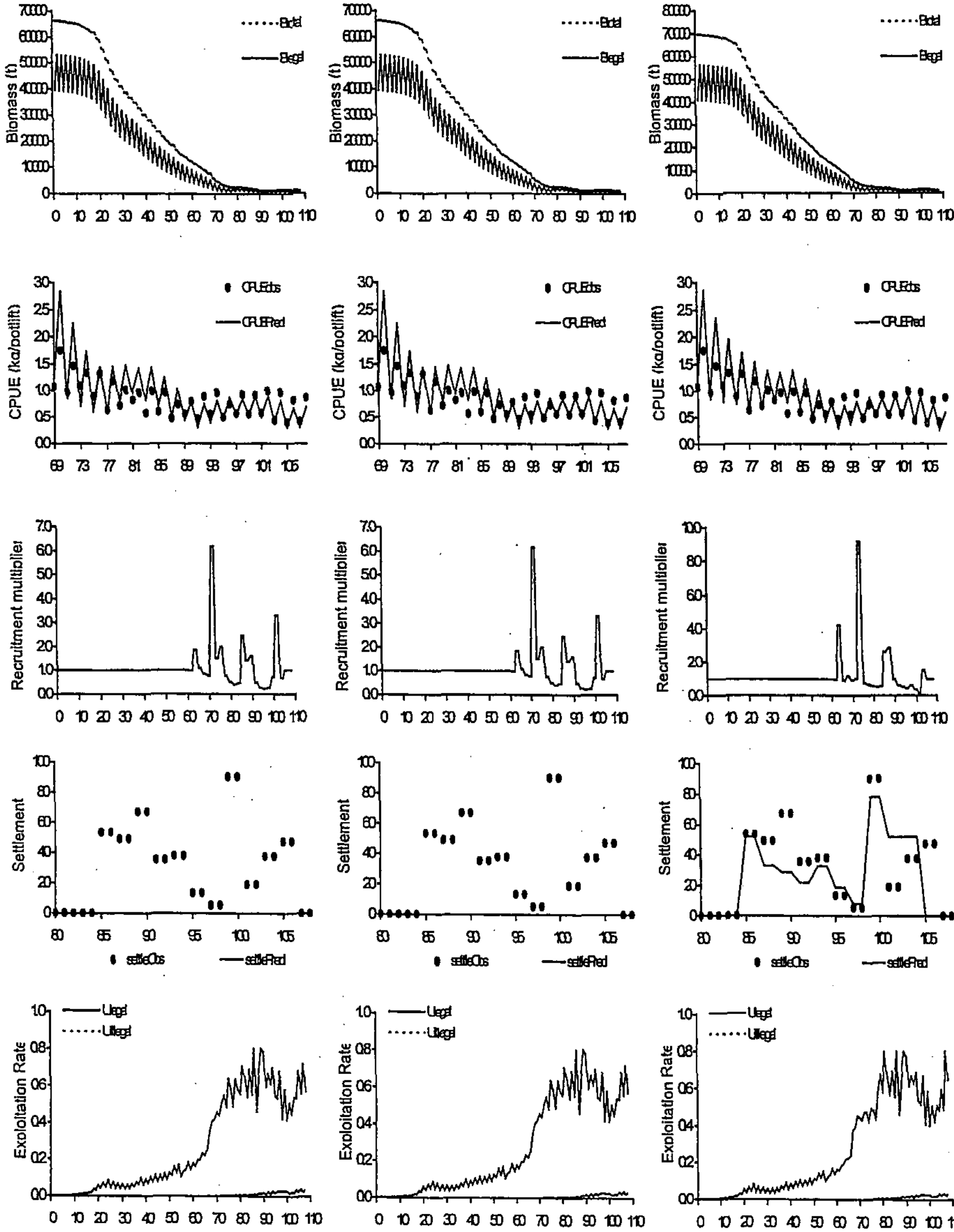

Figure 4: **Plots of initial NSS assessment runs without using historical information (parameter estimates provided Table 15). Left column: settlement not fitted; centre column: settlement not fitted & growth standa deviation=2; right column: settlement fitted.**

The sensitivity to the standard deviation growth parameter (which is fixed) is not satisfactory. The RLFAWG agreed to use a fixed value of 2.0 for this parameter as this is the value estimated from the tagging data when the growth parameters were estimated outside of the model. This is also the value used in 1998 based on a different model of growth

In general, the RLFAWG agreed that the results from these initial fits to the data were not completely satisfactory or credible. It was also agreed that the assessment would likely be improved if historical information on length frequencies, catch and effort, seasonal splits and regulation changes could be incorporated into the model.

5.3 Results and sensitivity analyses using all data

As the fits to the data reported in Section 5.2 were not believed to be entirely credible, the RLFAWG felt that there was a possibility that the model was misspecified as it used estimates of modern selectivity and the current MLS regulations to project backward in time. Ordinarily this is not a problem if most of the catch history is fairly recent, but it could result in misspecification if a substantial amount of the historical catch is not correctly removed from the population.

In the NSS, a major part of the exploitation history of this fishery occurred before 1970 with very large catches (up to 4000 t per year) being removed in the 1950s. Different MLS regulations existed at this time and pots were not required to have escape gaps. Therefore, historical information on this fishery has been incorporated into this assessment. This included: 1) a vector of MLS regulations by sex (Section 4.3.2); 2) the estimation of an additional set of parameters to describe the selectivity before the introduction of escape gap regulations (Section 4.3.2); 3) the addition of historical catch per day estimates for the 1960s (Section 4.4.1); and 4) the inclusion of size frequency data from the 1960s (Section 4.4.2). These data and their sources are presented in Section 4 and Appendix 2. As a result of including these historical data sources, it was possible to estimate recruitment deviations beginning in 1955. Base case PME results for this assessment are presented in Table 16 and the "base case" PME biomass trajectory is shown in Figure 5.

A series of sensitivity runs is presented in Table 16 and plotted in Figure 7 to Figure 10. The sensitivity analyses performed on the NSS substock included removing the historical CPUE and size frequency data. Each of the main data sources were also removed: CPUE, size frequency, and tag recovery data. The model structure which included the vector of the MLS regulations and the changing selectivity functions was not changed for any of sensitivity runs.

Model estimates of performance indicators did not change much when the historical CPUE data or when all the CPUE data were removed (Table 16, Figure 7). The model performed reasonably well when the size frequency data were excluded and gave estimates for the performance indicators which were in a similar range to the base case (Table 16, Figure 8). Dropping the tagging data gave rise to a biomass trajectory which nearly rebounded to B_0 in the late 1970s (Table 16, Figure 9, left column). The estimates for the performance indicators were also not credible. Estimating the right hand limb of the selectivity function gave rise to a large cryptic virgin biomass and performance indicator estimates that were not believable (Table 16, Figure 9, right column). Most of the sensitivities investigated indicated that the stock is currently below B_{MSY}, except when the tagging data were excluded and when the right hand limb of the selectivity function was estimated.

Fitting to the Chalky Inlet settlement indices improved the fits to the recent (post 1978) CPUE data when the recruitment lags to the fishery were set at two or three (Table 16, Figure 10). These lags also resulted in the best fits overall. Performance indicator estimates for all four lags investigated (one to four years) were similar to the base case (Table 16), with each lag estimating that the stock is below B_{MSY}. In general, fitting the settlement indices degraded the fit to the size frequencies but improved the fits to the tagging data and to the recruitment deviations when compared to the base case. It appears that the inclusion of the settlement indices slightly improves the overall fit of the model.

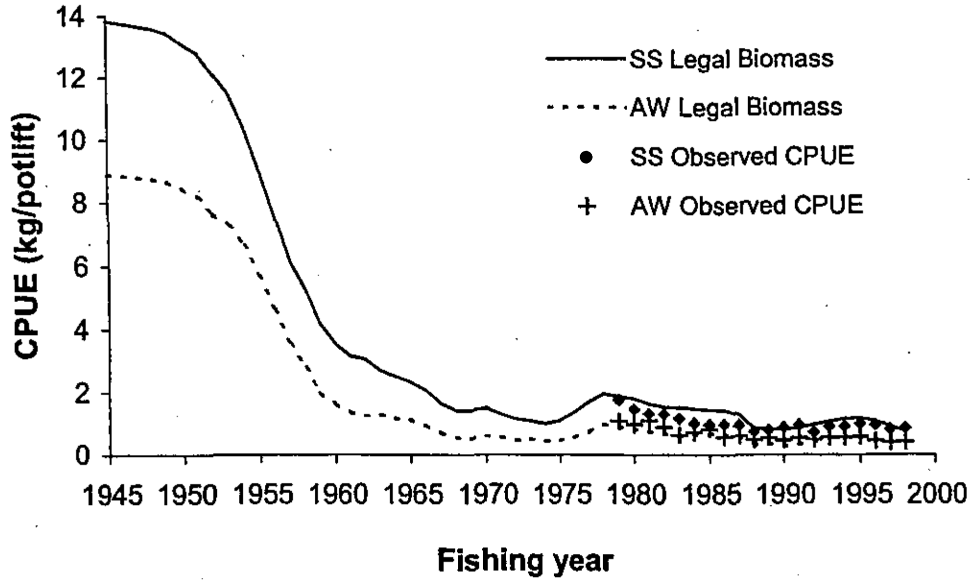

Figure 5: Biomass trajectories for the NSS substock from the base case assessment PME (posterior mode estimate). Fitted CPUE data points are indicated, beginning with the 1979–80 fishing year, expressed as kg/potlift. AW, autumn/winter season; SS, spring/summer season.

5.4 Problems with the Bayesian analysis

Difficulty was encountered when attempting to fit this model and the associated data, both initially with the PME "best fit" and later attempting to obtain Bayesian posteriors using the methods outlined in Section 2.4.1. It appears that the likelihood surface which defines the available solutions to these model data is highly irregular, with many local minima which may trap the fitting process. It is not certain that a true minimum was attained in this model fitting process, but this is probably the case, given the extensive searching that was undertaken within the constraints made on the key parameters.

When the Bayesian MCMC procedure was applied to the chosen base case, the searching algorithm would not stay near the fitted minimum. Instead, it wandered off into a set of parameter estimates which gave much poorer fits than the best fit. This behaviour precludes any credibility for the estimated derived parameters using Bayesian procedures. Careful investigation into the causes of this behaviour showed that it was the estimation of the long time series of correlated recruitment residuals which was responsible for the loss of fit, with deviations from the best fit causing substantially poorer fits to the size frequency data. However, once the MCMC procedure had moved away from the best fit region, it appeared that it could not return to it. Estimating fewer recruitment residuals (i.e. starting from a more recent year than 1955) did not solve the problem and resulted in changed estimates for the derived parameters, indicating that there is a fairly large sensitivity to the number of years of recruitment residuals estimated which can affect the model conclusions.

Table 16: **Summary table of results for NSS base case and sensitivity assessments. All reported results are for the PME "best fit" to the data.**

		Sensitivity analyses									
		CPUE indices excluded		LF data excluded			Fit to settlement indices				
	Base case	Annala & King catch *rate indices*	All CPUE biomass *indices*	Historical LF data	All LF data	Tag data excluded	Lag=1	Lag=2	Lag=3	Lag=4	Estimate VarR
Parameter estimates											
R_0 (number of recruits)	3 172 000	3 048 000	2 842 000	2 676 000	4 073 000	1 673 000	2 676 000	3 613 000	2 786 000	2 758 000	3 048 000
M	0.102	0.099	0.097	0.076	0.115	0.128	0.095	0.110	0.093	0.094	0.067
TW at growth=0 *(male, mm)*	102.1	102.5	103.8	102.7	96.3	92.7	100.0	102.8	100.8	102.7	100.8
TW at growth=0 (female, mm)	96.1	96.1	97.9	99.9	92.8	59.9	96.5	98.3	99.8	95.2	91.8
Slope: TW vs. growth increment (male)	-0.062	-0.062	-0.064	-0.067	-0.083	-2.719	-0.067	-0.064	-0.067	-0.061	-0.068
Slope: TW vs. growth increment (female)	-0.067	-0.067	-0.065	-0.056	-0.066	-0.322	-0.068	-0.059	-0.058	-0.068	-0.070
TW at 50% probability female maturity (mm)	60.81	60.80	60.79	60.94	61.13	62.90	60.79	61.14	60.83	60.82	61.01
(TW at 95% probability female maturity) – (TW at 50% probability female maturity) (mm)	7.21	7.21	7.19	6.80	0.39	8.64	7.26	7.36	6.70	7.20	6.88
Relative vulnerability: males autumn-winter	1.000	1.000	0.830	1.000	1.000	0.779	1.000	1.000	1.000	1.000	1.000
Relative vulnerability: immature females autumn-winter	0.730	0.710	0.513	0.588	1.000	0.796	0.739	0.636	0.708	0.729	0.589
Relative vulnerability: immature and mature females spring-summer	0.945	0.940	0.942	0.843	1.000	0.700	0.985	0.796	0.958	0.945	0.828
Relative vulnerability: mature females autumn-winter	0.612	0.601	0.430	0.629	0.998	0.381	0.663	0.611	0.716	0.618	0.577
Variance of ascending limb of vulnerability ogive (male < 1970)	*54.92*	53.85	51.15	1.00	1.00	74.97	55.47	52.95	55.03	54.95	57.51
Variance of ascending limb of vulnerability ogive (female <1970)	*59.57*	*59.36*	*59.00*	*500.00*	*60.30*	88.10	*60.10*	57.89	60.04	59.55	*65.75*
Variance of ascending limb of vulnerability ogive (male, 1971–92)	45.86	46.07	43.15	51.22	500.00	85.75	47.80	48.92	51.28	46.03	51.28

		Sensitivity analyses									
		CPUE indices excluded		LF data excluded			Fit to settlement indices				
	Base case	Annala & King catch rate indices	All CPUE biomass indices	Historical LF data	All LF data	Tag data excluded	Lag=1	Lag=2	Lag=3	Lag=4	Estimate VarR
Variance of ascending limb of vulnerability ogive (female, 1971–92)	62.66	62.14	58.96	62.63	1.00	88.57	59.28	62.06	59.41	62.76	62.82
Variance of ascending limb of vulnerability ogive (male,1993–98)	14.11	14.07	15.13	13.06	500.00	52.49	13.73	11.93	13.46	14.29	12.61
Variance of ascending limb of vulnerability ogive (female,1993–98)	21.13	21.11	21.21	18.44	500.00	27.97	19.75	18.62	18.37	20.93	18.21
Variance of descending limb of vulnerability ogive (male) [VarR]	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000	225.33
Variance of descending limb of vulnerability ogive (female) [VarR]	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000
Indicators											
B_{proj}/B_{curr}	140%	138%	157%	278%	213%	118%	81%	143%	124%	33%	193%
B_{curr}/B_{msy}	37.2%	36.5%	28.6%	20.2%	39.8%	553.1%	45.9%	40.8%	32.5%	40.4%	185.3%
B_{proj}/B_{msy}	51.9%	50.3%	45.0%	56.2%	85.0%	655.0%	37.1%	58.4%	40.5%	13.2%	356.9%
B_{curr}/B_0	4.7%	4.6%	3.7%	2.7%	8.0%	52.3%	5.8%	5.3%	4.3%	5.0%	5.7%
U_{curr}	58.6%	58.0%	70.2%	68.2%	31.6%	5.7%	47.2%	52.4%	60.7%	53.5%	23.6%
U_{proj}	38.3%	38.4%	40.6%	22.4%	13.5%	4.4%	53.2%	33.3%	44.4%	148.6%	11.2%
Likelihoods											
LikeCPUE	9.76	14.68	0.00	32.55	-89.77	-68.41	21.19	-9.05	-4.61	12.48	0.45
LikeCR	61.52	0.00	0.00	37.29	13.93	20.95	62.68	62.03	61.63	62.32	64.20
LikeLF	-4 653.49	-4 656.76	-4 685.39	-4 315.30	0.00	-3 661.69	-4 651.53	-4 596.01	-4 576.55	-4 647.82	-4 714.44
LikeTags	4 911.88	4 908.22	4 892.77	4 859.65	4 853.83	0.00	4 910.37	4 875.74	4 871.35	4 913.46	4 870.04
LikePriors	76.43	77.28	81.13	84.71	67.57	120.94	74.51	79.06	79.05	77.31	116.23
LikeRdevs	86.13	83.31	88.78	31.19	21.34	41.38	112.86	70.52	86.59	98.17	48.67
PenaltyU	0.000	0.000	0.000	0.000	0.000	0.000	0.011	0.001	0.030	0.018	0.000
Likesettle	0.00	0.00	0.00	0.00	0.00	0.00	42.17	27.29	34.26	40.30	0.00
LikeTotal	492.24	426.72	377.30	730.10	4 866.91	-3 546.83	572.26	509.58	551.75	556.23	385.16

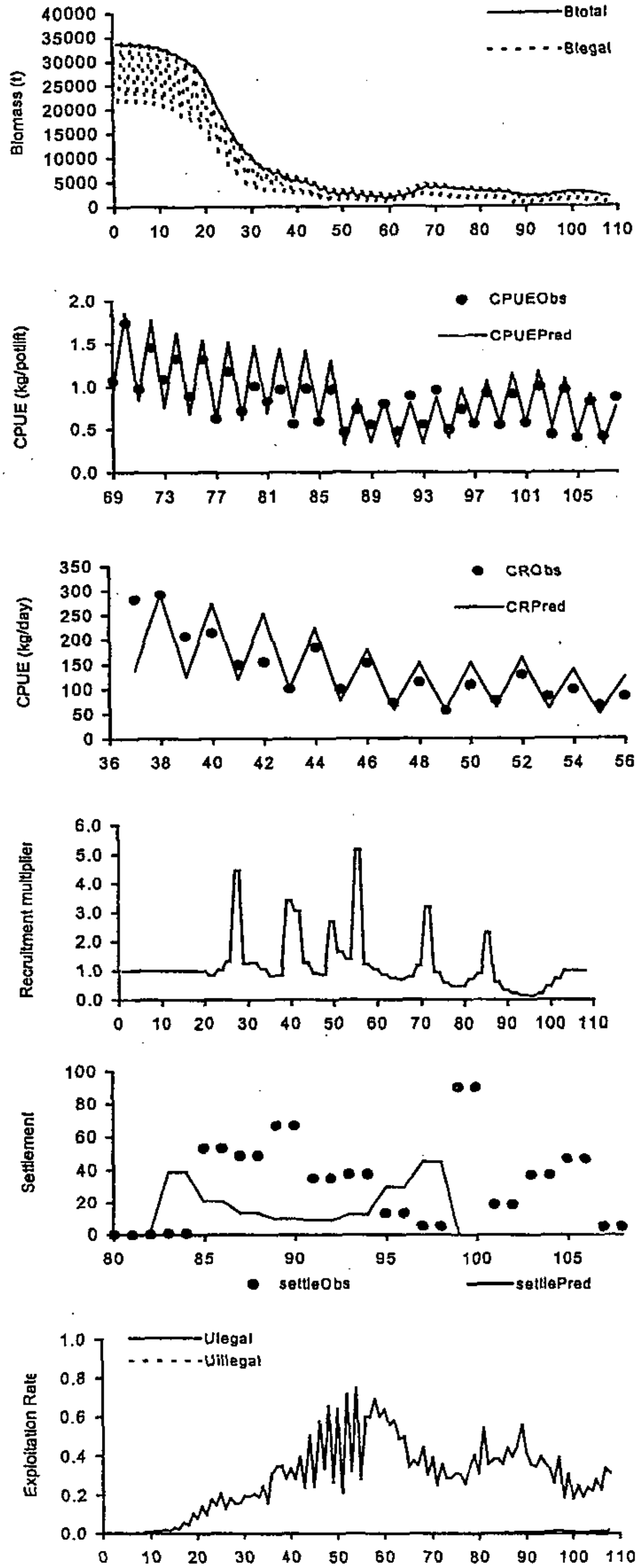

Figure 6: **NSS base case assessment: biomass trajectory, fit to CPUE data, recruitment multipliers, relationship with settlement indices and seasonal exploitation rates.**

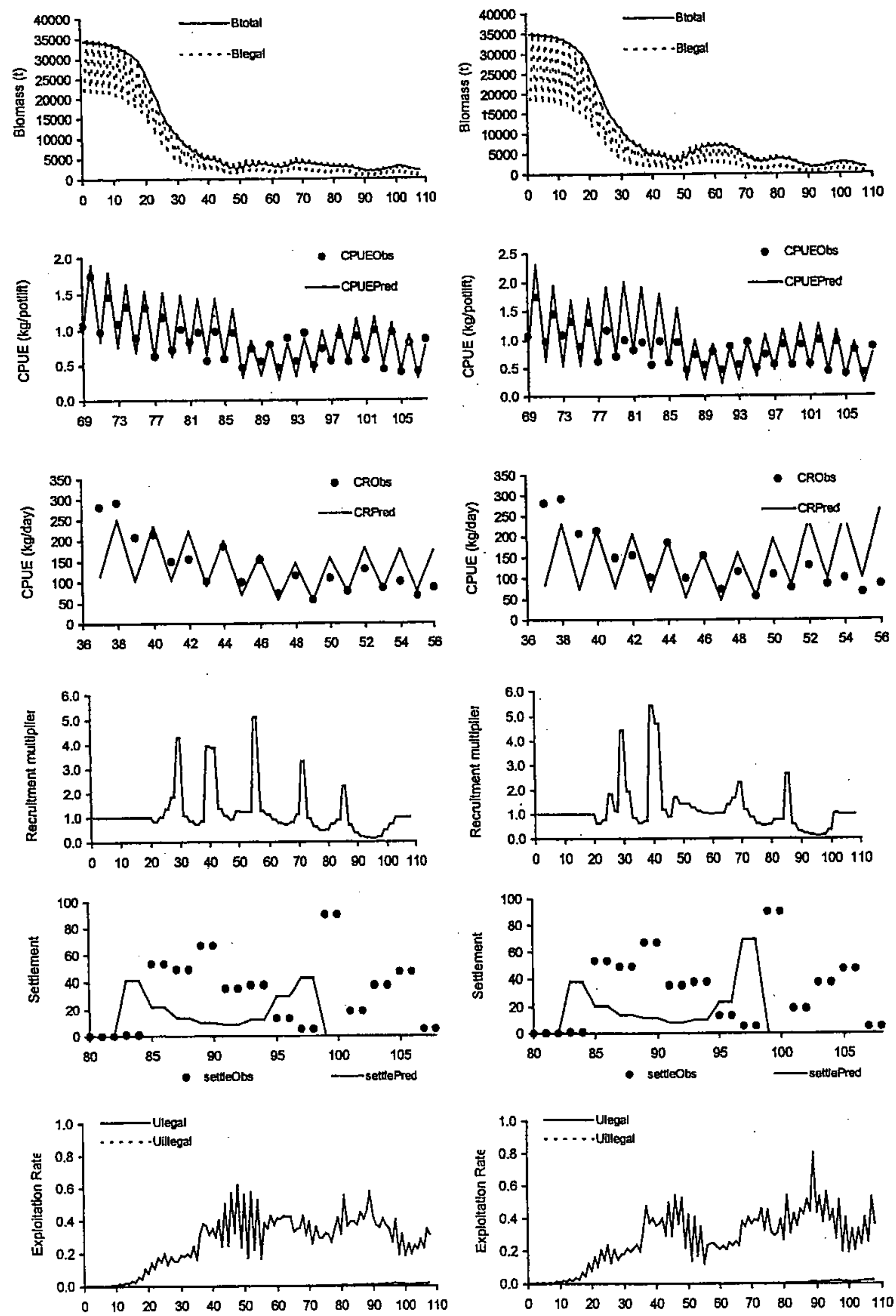

Figure 7: **NSS sensitivity assessment runs. left column: drop Annala & King catch rate indices; right column: drop all catch and effort biomass indices. Panels in each column as defined in Figure 6.**

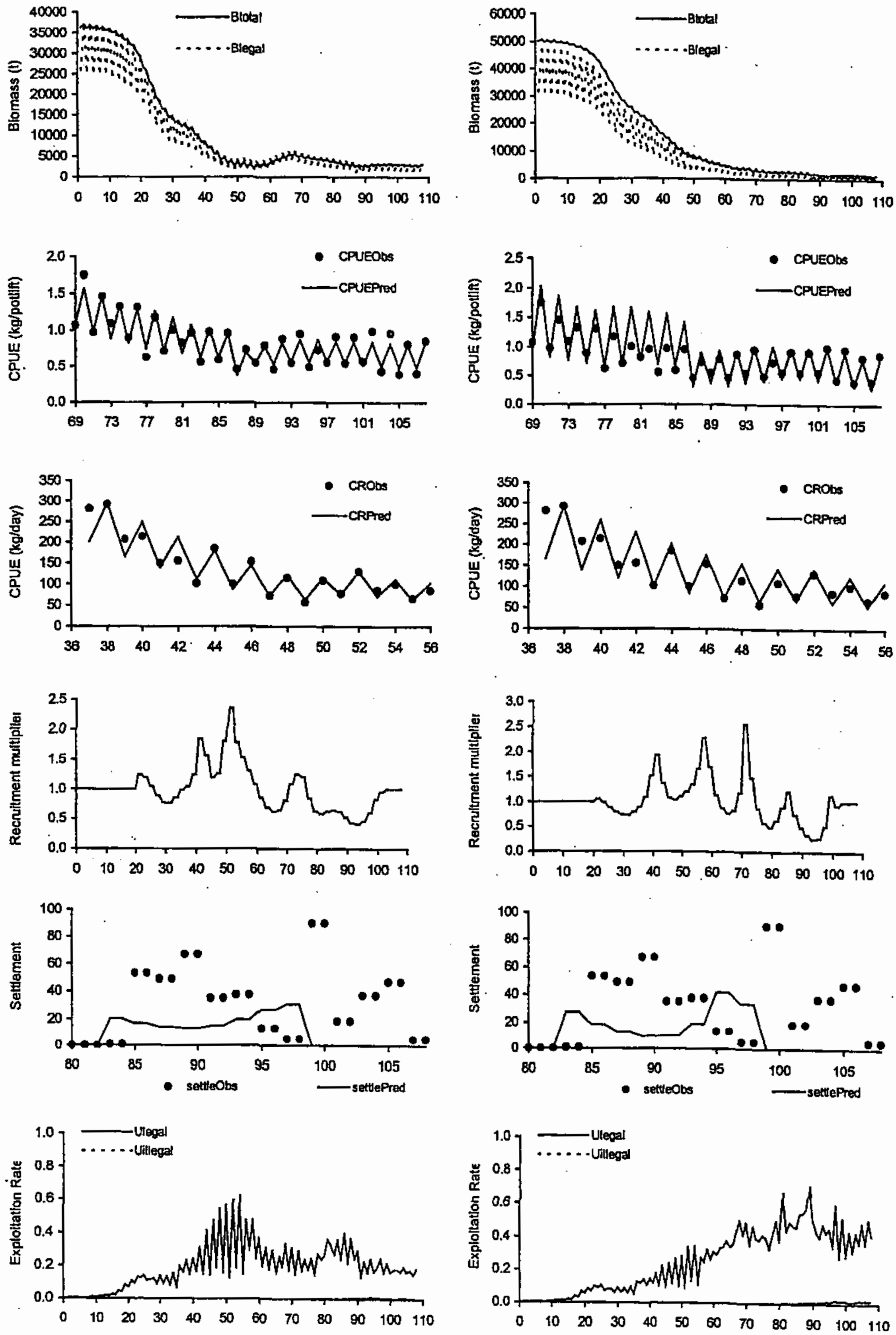

Figure 8: NSS sensitivity assessment runs. left column: drop historical Street size frequency data; right column: drop all size frequency data. Panels in each column as defined in Figure 6.

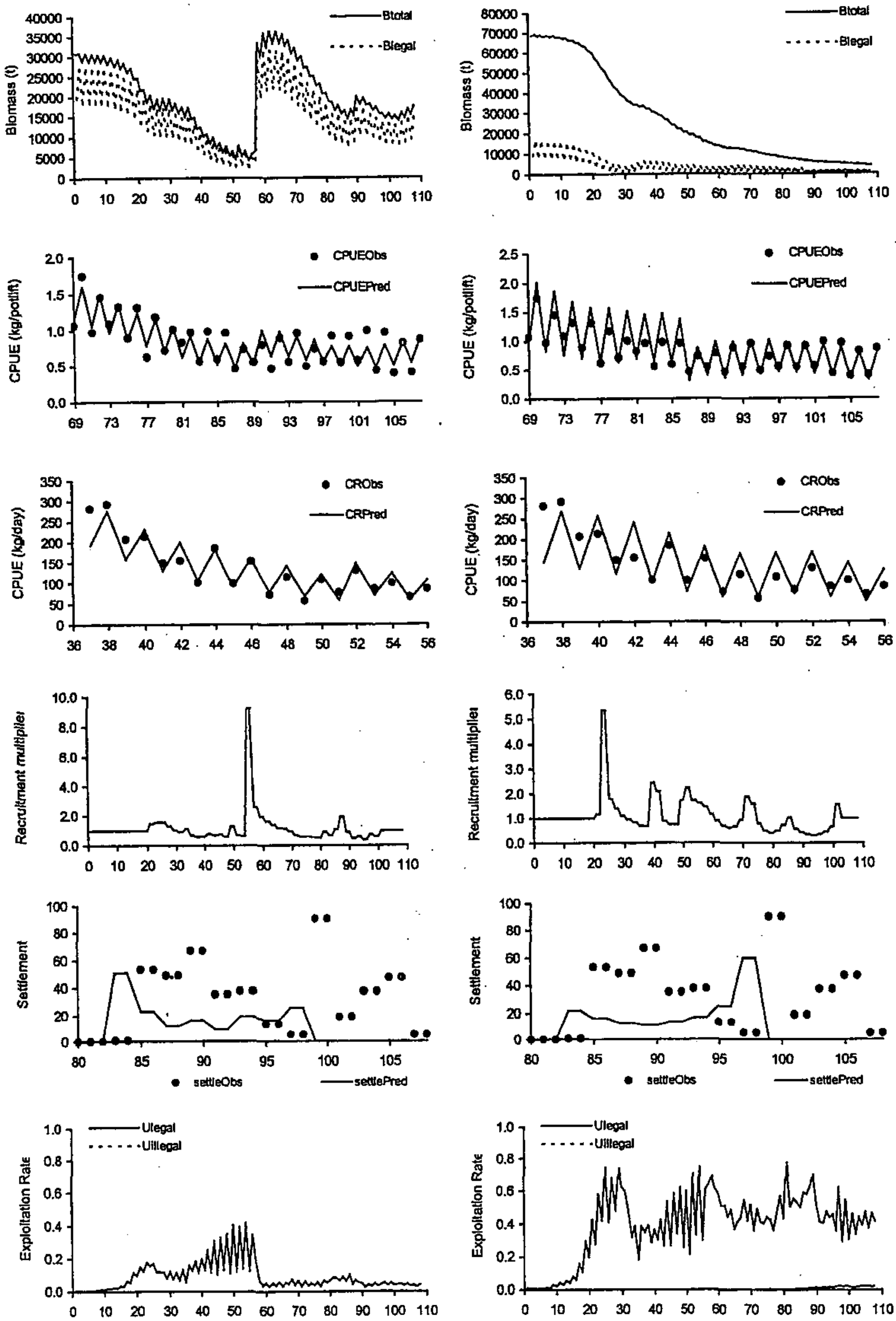

Figure 9: NSS sensitivity assessment runs. left column: drop all tagging data; right column: estimate *descending limb of selectivity curve. Panels in each column as defined in Figure 6.*

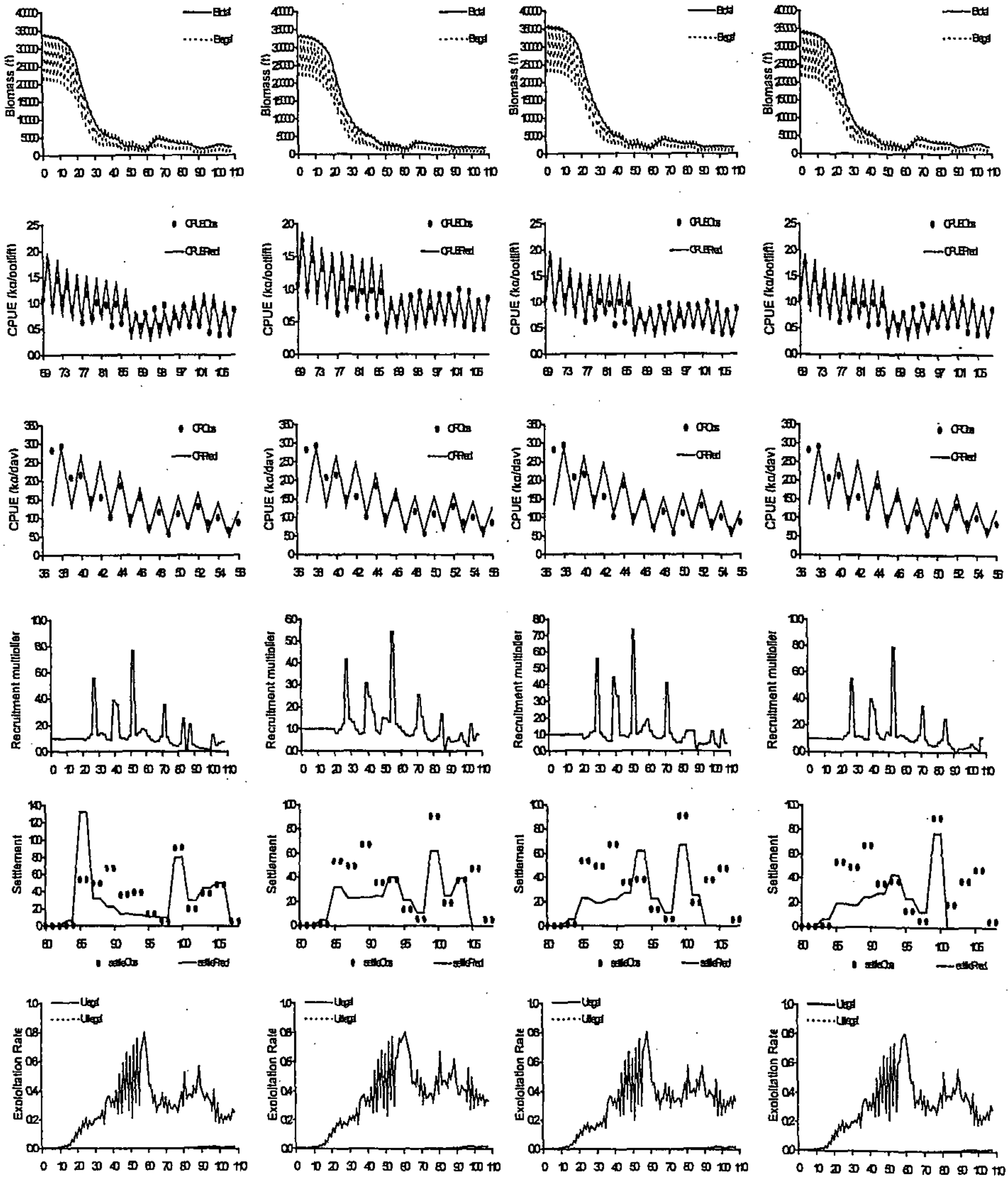

Figure 10: NSS sensitivity assessment runs with settlement fitted. Columns 1 to 4 (left to right): lags=1 to 4. Panels in each column as defined in Figure 6.

6. DISCUSSION

The 1999 stock assessment modelling for the NSS stock was improved in a number of aspects. These included better model specification and the inclusion of historical data sets. This work points the way forward to alternative methods of dealing with known differences in the dynamics of the lobster in different subareas of the NSS.

6.1 Model specification

A number of improvements were made in the stock assessment model in 1999 (see Section 2). Overall these changes have led to a more realistic model with a parameterisation which appears to be more in keeping with the processes that are thought to be active in lobster population dynamics. The major improvement in realism was the division of the year into two seasons. This allowed for a better representation of the composition of the catch in terms of the segments of the lobster population being harvested and in the specification of growth.

The removal of some parameters which existed in the 1998 stock assessment model, such as the maximum proportion of berried and spent females (Starr et al. 1999) and the variance for the descending limb of the selectivity curve, appears to have resulted in a model that has a lower capacity to hide model misspecifications. Such parameters are often able to hide model misspecifications and with their removal, misspecifications become apparent as poor fits to the data.

Another major improvement in the model structure was the estimation of the growth model using the tagging data along within the context of the population dynamics model. This ensured that model growth estimates would be consistent with the observed size frequency data as well as the remainder of the processes which are thought to be active in lobster population dynamics. This is particularly important within a size-based model because the growth dynamics are the primary time-based process which set the rest of the model processes.

Problems encountered with the generation of Bayesian posteriors were likely associated with this low tolerance in the model, but were not directly a cause of it. It appears that the maximum likelihood fit to the data and the priors was highly localised in parameter space due to the low tolerance in the model. The failure of the MCMC algorithm that was used to produce a Bayesian posterior was symptomatic of this, but should be regarded as a technical fault rather than a fault of the model.

6.2 Use of historic data

An obvious source of misspecification in earlier fits to the model were errors in historical catches and their seasonal split. Particularly in NSS, this an important issue because of the large catches which were taken during the early history of this fishery. In addition to inaccurate catch histories, early model runs had little data to help the parameter estimation process before 1979. Sensitivity analyses suggested that the historical catch rate and size frequency data were inconsistent with more recent data. Furthermore, the inclusion of these data allowed the estimation of a longer time series of recruitment residuals. This improved the fit of the model significantly and has major implications for yield estimates, particularly when compared to the alternative of assuming that recruitment is constant during the entire early history of the fishery. For instance, note that the initial biomass levels estimated in Figure 4 (which did not use the historical data and which assumed constant recruitment before 1975) are nearly double those in Figure 6 which used the historical data and which estimated recruitment residuals right back to the early 1950s. We recommend that the availability of historic data be further investigated and that such data be incorporated into the assessments for other New Zealand rock lobster stocks.

6.3 Spatial differentiation

It is clear that the 1999 stock assessment model is not appropriate for fitting to Stewart Island data on its own. The substantial differences in the composition of the catch between Stewart Island and Fiordland also suggest that combining data from both areas may be inappropriate. This suggests that an NSS assessment that is based on data from both areas will need make use of a model specific to Stewart Island or will require explicit spatial modelling which includes movement between these areas within the NSS.

7. ACKNOWLEDGMENTS

This work was carried out under Ministry of Fisheries contract CRA9801 awarded to the New Zealand Rock Lobster Industry Council. Previous versions of this document benefited from review by members of the Rock Lobster Fishery Assessment Working Group.

8. REFERENCES

Annala, J.H. (1983). New Zealand rock lobsters: Biology and fishery. *Fisheries Research Division Occasional Publication 42.* 36 p.

Annala, J.H.; Bycroft, B.L. (1988). Growth of rock lobsters (*Jasus edwardsii*) in Fiordland, New Zealand. *New Zealand Journal of Marine and Freshwater Research 22*: 29–41.

Annala, J.H.; King, M.R. (1983). The 1963–73 New Zealand rock lobster landings by statistical area. *Fisheries Research Division Occasional Publication: Data Series No. 11.* 20 p.

Annala, J.H.; Sullivan, K.J. (Comps.) (1998). Report from the Mid-Year Fishery Assessment Plenary, November 1998: stock assessments and yield estimates. 44 p. (Unpublished report held in NIWA Greta Point library, Wellington.)

Booth, J.D.; Breen, P.A. (1992). Stock structure in the New Zealand red rock lobster, *Jasus edwardsii.* New Zealand Fisheries Assessment Research Document 92/20. 34 p. (Draft report held in NIWA library, Wellington.)

Booth, J.D.; Forman, J.S.; Stotter, D.R.; Bradford, E. (2000). Settlement indices for 1998 and 1998-99 juvenile abundance of the red rock lobster, *Jasus edwardsii. New Zealand Fisheries Assessment Report 2000/17.* 35 p.

Booth, J.D.; Robinson, M.; Starr, P.J. (1994). Recent research into New Zealand rock lobsters, and a review of rock lobster catch and effort data. New Zealand Fisheries Assessment Research Document 94/7. 56 p. (Draft report held in NIWA Greta Point library, Wellington.)

Bradford, E. (1997). Estimated recreational catches from Ministry of Fisheries North region marine recreational fishing surveys, 1993–94. New Zealand Fisheries Assessment Research Document 97/7. 16 p. (Draft report held in NIWA library, Wellington.)

Breen, P.A. (1991). Assessment of the red rock lobster (*Jasus edwardsii*) North and South Island stock, November 1991. New Zealand Fisheries Assessment Research Document 91/16. 24 p. (Draft report held in NIWA library, Wellington.)

Breen, P.A.; Anderson, O.F. (1993). Fishing intensity on the red rock lobster (*Jasus edwardsii*) North and South Island stock. New Zealand Fisheries Assessment Research Document 93/3. 43 p. (Draft report held in NIWA library, Wellington.)

Breen, P.A., Booth, J.D.; Tyson, P.J. (1988). Feasibility of a minimum size limit based on tail width for the New Zealand red rock lobster, *Jasus edwardsii. New Zealand Fisheries Technical Report No. 6.* 16 p.

Breen, P.A.; Kendrick, T.H. (1998). The 1996 assessment for the New Zealand red rock lobster (*Jasus edwardsii*) fishery. New Zealand Fisheries Assessment Research Document 98/13. 42 p. (Draft report held in NIWA library, Wellington.)

Fournier, D.A.; Sibert, J.R.; Majkowski, J.; Hampton, J. (1990). MULTIFAN a likelihood-based method for estimating growth parameters and age-composition from multiple length frequency data sets illustrated using data for southern bluefin tuna (*Thunnus maccoyii*). *Canadian Journal of Fisheries and Aquatic Sciences 47*: 301–317.

Francis, R.I.C.C. (1995). An alternative mark-recapture analogue of Schnute's growth model. *Fisheries Research 23*: 95–111.

Maunder, M.N.; Starr, P.J. (1995). Rock lobster standardised CPUE analysis. New Zealand Fisheries Assessment Research Document 95/11. 28 p. (Draft report held in NIWA library, Wellington.)

Punt, A.E.; Kennedy, R.B. (1998). Population modelling of Tasmanian rock lobster resources. *Marine and Freshwater Research 48*: 967–980.

Schnute, J. (1981). A versatile growth model with statistically stable parameters. *Canadian Journal of Fisheries and Aquatic Sciences 38*: 1128–1140.

Sorenson, J.H. (1970). New Zealand rock lobster *Jasus edwardsii* carapace and tail measurements. *New Zealand Marine Department Fisheries Technical Report No. 53*. 32 p.

Starr, P.J.; Bentley, N.; Maunder, M.N. (1999). Assessment of the NSN and NSS stocks of red rock lobster (*Jasus edwardsii*) for 1998. New Zealand Fisheries Assessment Research Document 99/34. 45 p. (Draft report held in NIWA library, Wellington.)

Teirney, L.D.; Kilner, A.R.; Millar, R.B.; Bradford, E.; Bell, J.D. (1997). Estimation of recreational harvests from 1991–92 to 1993–94. New Zealand Fisheries Assessment Research Document 97/15. 43 p. (Draft report held in NIWA library, Wellington.)

APPENDIX 1. Assessment model

The parameters and variables in the model can be divided into:

- **Structural parameters** that are fixed and influence the structure of the model.
- **Control variables** that are known and influence the history of the fishery in the model.
- **Dynamic parameters** that influence the dynamics of the stock and the fishery and can be estimated or fixed at assumed values.
- **State variables** that describe the modelled state of the stock and can be used to derive model predictions.
- **Likelihood variables** that are used in calculating the model likelihood from model predictions.

The major parameters of the model, and variables derived from them, are described in Table 17. The model uses a half-year time step: autumn-winter (*AW*) from 1 April to 30 September and spring-summer (*SS*) from 1 October to 31 March. Season is subscripted as p in Table 17 and can be calculated from the time step t by $(t-1)\ \mathrm{Mod}\ 2+1$. Three sex categories, denoted by the subscript g, are kept distinct in the model: males (*male*), immature females (*female*), and mature females (*femmat*).

Table 17. Major variables and parameters of the assessment model.

Structural parameters	
$\bar{S}_{s_{\min}}$	Smallest size modelled
$s_{\max}$	Number of size classes modelled
$\bar{S}_s$	Size of an individual in size class s (mid point of the size class bounds)
$\mathbf{I}$	Identity matrix for model size classes
Control variables	
C_t^{legal}	Legal catch weight in time step t
$C_t^{illegal}$	Illegal catch weight in time step t
l_g	Minimum legal size limit for sex g
$L_{s,g}$	Legal status flag (zero or one) for individuals of sex g and size s. Note that all mature females are assumed to be berried in *AW* and are therefore not legal
Dynamic parameters	
R_0	Average annual recruitment for each sex in an unexploited population
M	Instantaneous rate of natural mortality
δ	Survival rate in one half-year time step
d	Proportion of discarded animals that die
ϕ	Mean of the size distribution of recruits (males and immature females only)
γ	Standard deviation of the size distribution of recruits (males and immature females only)
r_g^p	Relative vulnerability for sex g and season p.
η_g	Size of maximum vulnerability of sex g
ν_g^l	Variance of the left hand limb of the vulnerability curve for sex g
ν_g^r	Variance of the right hand limb of the vulnerability curve for sex g
b_g	Decline in growth increment by size (slope of growth increment function)

S_g^∞	Size at which growth ceases for sex g (x-intercept of growth increment function)
S_g^m	Maximum size at which moulting occurs during secondary moulting season for sex g
φ	Variability in moult increments
m_{50}	Size at which there is a 50% probability of a female maturing in one time step
m_{95}	Size at which there is a 95% probability of a female maturing in one time step
a_g	Scalar of the size-weight relationship for sex g
b_g	Exponent of the size- weight for sex g
Derived variables	
$\mathbf{R}_0$	Vector of average recruitment at size in an unexploited population at equilibrium
$\mathbf{N}_{0,g}$	Vector of numbers at size for sex g in an unexploited population at equilibrium
$\mathbf{X}_g^p$	Growth transition matrix for sex g during season p
$X_{s,s',g}^p$	Proportion of individuals of sex g that grow from size-class s to size-class s' in season p
$V_{s,g}$	Vulnerability of an individual of sex g and size s
Q_s	Probability that a female at size s will mature in one time step
$\mathbf{Q}$	Vector of the probability of females maturing at size
$W_{s,g}$	Weight of an individual of size s and sex g
State variables	
$N_t^{s,g}$	Numbers of sex g and size s at the start of time step t
$\dot{N}_t^{s,g}$	Numbers of sex g and size s after fishing and natural mortality during time step t
R_t	Total recruitment in time step t
$R_t^{s,g}$	Recruitment to sex g and size s in time step t
B_t^{legal}	Biomass vulnerable to legal fishing in time step t
$B_t^{illegal}$	Biomass vulnerable to illegal fishing in time step t
u_t^{legal}	Legal exploitation rate in time step t
$u_t^{illegal}$	Illegal exploitation rate in time step t
Likelihoods	
ε_y	Recruitment residual in year y
σ^ε	Standard deviation of recruitment residuals
σ^s	Standard deviation of proportional catches at size and sex
q	Catchability coefficient.
σ^I	Standard deviation of legal biomass indices
k	Scalar for puerulus settlement indices
σ^P	Standard deviation of puerulus indices
e	Years between settlement and recruitment to the model

A1.1 Initial size structure

The population is assumed to be at equilibrium in an unexploited state at the start of the period being modelled. The number of each sex, in each size class, is the equilibrium function of the product of the growth transition matrices for each season, recruitment and natural mortality,

Eq 1

$$\mathbf{N}_{0,male} = \left[1+\mathbf{X}^{AW}_{male}\delta\right]\left[\mathbf{R}_0\left(\mathbf{I}-\mathbf{X}^{AW}_{male}\mathbf{X}^{SS}_{male}\delta^2\right)'\right]$$

$$\mathbf{N}_{0,female} = \left[1+\mathbf{X}^{AW}_{female}\delta(1-\mathbf{Q})\right]\left[\mathbf{R}_0\left(\mathbf{I}-\mathbf{X}^{AW}_{female}\mathbf{X}^{SS}_{female}\delta^2(1-\mathbf{Q})^2\right)'\right]$$

$$\mathbf{N}_{0,femmat} = \left[1+\mathbf{X}^{AW}_{female}\delta\right]\left[\mathbf{R}_0\left(\mathbf{I}-\mathbf{X}^{AW}_{female}\mathbf{X}^{SS}_{female}\delta^2\right)'\right]-\mathbf{N}_{0,female}$$

where the vector $\mathbf{R}_{0,g}$ is derived from the multiplication of R_0 and the equilibrium recruitment proportions calculated as in Eq 4; $\mathbf{X}^{SS}_g$ and $\mathbf{X}^{AW}_g$ are growth transition matrices for spring-summer and autumn-winter for sex g; δ is the natural survival rate in one time step, $\delta = e^{-M/2}$.

A1.2 Recruitment

The numbers of lobsters recruiting to the model is assumed to be equal for both sexes and is divided equally over the two seasons. Recruitment residuals are estimated for those years likely to have information on the strength of recruitment,

Eq 2

$$R^g_t = 0.5R_0\, e^{\left[\varepsilon_y - \frac{(\sigma^\varepsilon)^2}{2}\right]}$$

where ε_y are estimated assuming that they are normally distributed with mean zero and standard deviation σ^ε. The term $-\frac{(\sigma^\varepsilon)^2}{2}$ corrects for the log-normal bias associated with different values of σ^ε.

Recruitment is dispersed over the size-classes following a normal distribution that is truncated at the smallest size class,

Eq 3

$$R_s = \frac{\exp\left(-(\bar{S}_s-\phi)^2 \big/ (\gamma)^2\right)}{\sum_s \exp\left(-(\bar{S}_s-\phi)^2 \big/ (\gamma)^2\right)}$$

A1.3 Growth

Moult based growth is modelled explicitly using a two part model. The first part estimates the moult increment of a lobster in size class $\bar{S}_s$,

Eq 4

$$i_s = \begin{cases} b(\bar{S}_s - S^{\infty}) & if\ \bar{S}_s \le S^{\infty} \\ 0 & if\ \bar{S}_s > S^{\infty} \end{cases}$$

Variability in the growth increment is assumed to be normally distributed with a fixed standard deviation,

Eq 5

$$\varepsilon \sim N(0, \varphi)$$

The second part defines the probability of moulting. Each sex has a primary moulting season during which all size classes moult. For males the primary moulting season is at the end of autumn-winter and for females it is at the end of spring summer. During the secondary moulting season only animals below an estimated size, S^m, moult,

Eq 6

$$m_s = \begin{cases} 1 & if\ \bar{S}_s \le S^m \\ 0 & if\ \bar{S}_s > S^m \end{cases}$$

That is, lobsters in size classes above, S^m, have no growth in the secondary season.

From this growth model the transition matrix is generated as follows. The expected size of an individual of size s in the following seasonal time period is

Eq 7

$$\hat{S}_{s,t+1} = \bar{S}_{s,t} + i_s m_s$$

However, due to the variability in growth, not all individuals move into the size class to which $\hat{S}_s$ belongs. Some individuals move into size classes above and below this size depending upon the magnitude of φ. For each size class, s, the probability over one time step of an individual growing into each of the other size classes, s', is calculated by integrating over a normal distribution with mean, $\hat{S}_s$ and standard deviation, φ. The largest size group is cumulative, that is no animals grow out of this group, so the integration is done from the smallest size in that size class, $\breve{S}_{s'}$ to ∞.

Eq 8

$$X_{s,s'} = \begin{cases} \displaystyle\int_{\breve{S}_{s'}}^{\bar{S}_{s'}} \frac{1}{\sqrt{2\pi}\varphi} \exp\left(-\frac{\left(S - \hat{S}_s\right)^2}{2\varphi^2} \right) \partial S & if\ s' < s_{\max} \\ \displaystyle\int_{\breve{S}_{s'}}^{\infty} \frac{1}{\sqrt{2\pi}\varphi} \exp\left(-\frac{\left(S - \hat{S}_s\right)^2}{2\varphi^2} \right) \partial S & if\ s' = s_{\max} \end{cases}$$

Moulting in this model occurs at the end of each period. Growth is applied to the numbers of lobster remaining in each size class after fishing in each time step. Along with the addition of recruitment this updates numbers in each size class before fishing in the next time step.

Eq 9

$$N_{t+1}^{s',g} = \sum_s \left(X_{s,s',p}^{g} \dot{N}_t^{s,g} \right) + R_{t+1}^{s',g}$$

A1.4 Selectivity and relative vulnerability

The ascending and descending limbs of the selectivity curve are modelled using normal curves with common means but different variances. A logistic selectivity curve can be approximated by setting the variance for the right hand limb to a large number. The relative vulnerability of each sex by season is determined by the parameter r_g^p.

Eq 10

$$V_{s,g}^{p} = r_g^{p} \begin{cases} \exp\left\{\dfrac{-\left(\bar{S}_s - \eta_g\right)^2}{v_g^l}\right\} & for \quad \bar{S}_s \le \eta_g \\ \exp\left\{\dfrac{-\left(\bar{S}_s - \eta_g\right)^2}{v_g^r}\right\} & for \quad \bar{S}_s > \eta_g \end{cases}$$

The estimates for η_g, v_g^l, and v_g^r are constrained to be the same for both mature and immature females. It is assumed that the maximum relative vulnerability is for males in spring-summer($r_{male}^{SS} = 1$). It is also assumed that the relative vulnerability of mature females is only different from immature females in the autumn-winter when the former are in berry (i.e. $r_{mature\,fem}^{SS} = r_{immature\,fem}^{SS}$).

Separate estimates of v_g^l are made for each period having a distinct escape-gap regulation. For instance, in all areas there was a change in escape gap regulations in 1993, so separate estimates of the ascending limb of the selectivity curve are made before and after this year.

A1.5 Maturity

The probability of a female maturing during one period is modelled as a logistic curve

Eq 11

$$Q_s = \frac{1}{1 + \exp\left[-\ln(19)\left(\bar{S}_s - m_{50}\right) \big/ \left(m_{95} - m_{50}\right)\right]}$$

where m_{95} is constrained to be greater than m_{50}. Female maturation is modelled as occurring after growth.

A1.6 Exploitation rates

The exploitation rates for the legal and illegal fisheries for each period are calculated as the ratio of the catch to the available biomass. The available biomass for each fishery is the sum across all size classes of the product of the number of individuals, their weight and the proportion that are vulnerable. For the legal fishery this biomass total is further adjusted by whether the size class is above the size limit for that sex and the assumption that all mature females in the autumn-winter season are prohibited from capture due to the carrying of eggs. Note that these equations assume that the vulnerabilities are the same for legal and illegal catches and that the only difference between these two categories is the type of lobster retained.

Eq 12 $$u_t^{legal} = \frac{C_t^{legal}}{B_t^{legal}}$$

Eq 13 $$B_t^{legal} = \sum_g \sum_s N_t^{s,g} W_{s,g} V_{s,g} L_{s,g}$$

Eq 14 $$u_t^{illegal} = \frac{C_t^{illegal}}{B_t^{illegal}}$$

Eq 15 $$B_t^{illegal} = \sum_g \sum_s N_t^{s,g} W_{s,g} V_{s,g}$$

The legal status is determined by the minimum legal size limit,

$$L_{s,g} = \begin{cases} 0 & \overline{S}_s \le l_g \\ 1 & \overline{S}_s > l_g \end{cases}$$

and is zero for mature females by the when the season is autumn-winter,

$$L_{s,femat} = 0$$

The weight of individuals in each size class is determined by,

Eq 16 $$W_{s,g} = a_g \left(\overline{S}_s\right)^{b_g}$$

Note that the a_g and b_g parameters are assumed to be the same for both immature and mature females.

A1.7 Mortality

Fishing, natural, and handling mortality are applied simultaneously. Given the assumption that all mature females in the autumn-winter season are berried and hence not legal, legal fishing mortality is applied in the same manner to both males and females. Handling (discard – *d*) mortality is applied in proportion to the rate of legal fishing mortality.

Eq 17 $$N_{t+1}^{s,g} = N_t^{s,g} \delta \left[1 - U_t^{legal} V_{s,g} \left(L_{s,g} + (1 - L_{s,g}) d\right)\right]\left[1 - U_t^{illegal} V_{s,g}\right]$$

A1.8 Catch-at-size likelihood

The observed relative catch-at-size ($p_y^{s,g}$) for each sex category of males, immature females, and mature females are fitted separately but not independently as the proportions for all three categories sum to one. The model predictions for the relative frequencies of each of these categories are

Eq 18

$$\hat{p}_t^{s,g} = \frac{V_{s,g} N_t^{s,g}}{\sum_g \sum_s V_{s,g} N_t^{s,g}}$$

We adopt the robust normal likelihood formulation proposed by Fournier et al. (1990) for fitting the model predictions to the observed catch compositions. The variance is assumed to be multinomial and is weighted by the effective sample size used to determine the proportional catch-at-size (κ_t),

Eq 19

$$L(\hat{p}_t^{s,g} \mid \theta) = \frac{1}{\sqrt{2\pi p_t^{s,g}(1-p_t^{s,g}) + 0.1/\Omega}} \exp\left(\frac{-\kappa_t(\hat{p}_t^{s,g} - p_t^{s,g})^2}{2(p_t^{s,g}(1-p_t^{s,g}) + 0.1/\Omega)} \right) + 0.01$$

where Ω is the number of proportions observed in the catch-at-size data.. The robust likelihood eliminates the influence of observed outliers that have either high or low predicted probability. The 0.01 term in the second part of the likelihood equation reduces the influence for observations more than three standard deviations from the predicted eliminating the influence of outliers. The $0.1/\Omega$ term prevents the variance from tending to zero as the predicted value tends to zero avoiding influence of observed outliers with small predicted probability (Fournier et al. 1990).

A1.9 Likelihood of tag size increments

The predicted size of a tagged lobster at the time of recapture is calculated by simulating each moult during the time at liberty. A normal likelihood function is used to compare predicted ($\hat{S}_i$) and observed (S_i) sizes at recapture,

Eq 20

$$L(S_i \mid \theta) = \frac{1}{\sqrt{2\pi\varphi}} \exp\left(-\frac{(S_i - \hat{S}_i)^2}{2\varphi^2} \right)$$

where the standard deviation φ is assumed and is constant for all observations.

A1.10 Likelihood of legal biomass indices

A predicted biomass index is calculated as a proportion of legal biomass,

Eq 21

$$\hat{I}_t = qB_t^{legal}$$

where the catchability coefficient is calculated analytically,

Eq 22

$$q = \exp\left[\frac{\sum_{t=1}^{n_t} \log\left(\frac{I_t}{B_t^{legal}} \right)}{n_t} \right]$$

where n_t is the number of time steps for which an observed biomass index is available.

A log-normal likelihood function is used to compare predicted ($\hat{I}_t$) and observed (I_t) biomass indices,

Eq 23

$$L(\hat{I}_y \mid \theta) = \frac{1}{\sigma^I \sqrt{2\pi}} \exp\left[\frac{-(\ln(I_t) - \ln(\hat{I}_t))^2}{2(\sigma^I)^2}\right]$$

where the variance σ^I is assumed and is constant for all observations.

A1.11 Likelihood of puerulus settlement indices

Annual puerulus settlement indices are fitted in a similar manner to legal biomass indices. Predicted puerulus settlement is calculated as a proportion of the estimated recruitment, lagged by the assumed number of years, e, between settlement and recruitment to the model,

Eq 24

$$\hat{P}_y = kR_{y+e}$$

where the scaling parameter k is calculated analytically by,

Eq 25

$$k = \exp\left[\frac{\sum_{y=1}^{n_y} \log\left(\frac{P_y}{R_y}\right)}{n_y}\right]$$

where n_y is the number of years for which a settlement index is available.

A log-normal likelihood function is used to compare predicted ($\hat{P}_t$) and observed (P_t) settlement indices,

Eq 26

$$L(\hat{P}_y \mid \theta) = \frac{1}{\sigma^P \sqrt{2\pi}} \exp\left[\frac{-(\ln(P_t) - \ln(\hat{P}_t))^2}{2(\sigma^P)^2}\right]$$

where the standard deviation of puerulus settlement indices, σ^P, is assumed and is constant for all observations.

A1.12 Likelihood of recruitment residuals

Annual recruitment deviations are penalised from moving away from average recruitment using a normal likelihood function, Eq 27

$$L(\varepsilon_y \mid \theta) = \frac{1}{\sigma^{\varepsilon}\sqrt{2\pi}} \exp\left[\frac{-(\varepsilon_y)^2}{2(\sigma^{\varepsilon})^2}\right]$$

A1.13 Performance indicators

Since there are changes in the legal biomass between seasons, due to seasonal differences in vulnerabilities and the legal status of females, all performance indicators are expressed in terms of B^{total}. That is, the total biomass of males and females, above their respective size limit.

Projections are done using stochastic recruitment with a mean equal to the recruitment in an unexploited population, R_0, and the assumed recruitment variation, σ^{ε}. The projected catch is split between seasons based on the split in the catch observed in the last year, 1998. The biomass at maximum sustainable yield (B_{MSY}) is calculated for a given set of parameters by maximising the yield from the population in equilibrium with a fixed exploitation rate of legal fishing. The exploitation rate is applied between seasons based on the ratio of exploitation rates that the model predicts in the last year, 1998. B_{MSY} is also in terms of B^{total}.

APPENDIX 2. Tables of input data used in assessments

Table 18: Legal and illegal catch data and CPUE biomass indices used for the NSS assessment. All catches are in kilograms. Catches are reported by calendar year up to 1978. From 1979 onwards, catches are reported by fishing year, 1 April to 31 March.

Fishing year	Season[1]	Sequential season number	Commercial reported[2]	Commercial unreported[3]	Recreational legal[4]	Reported illegal[5]	Unreported illegal[6]
1945	1	1	92 138	0	402	0	0
1945	2	2	110 159	0	3 617	0	0
1946	1	3	78 232	0	449	0	0
1946	2	4	93 533	0	4 043	0	0
1947	1	5	77 260	0	497	0	0
1947	2	6	92 371	0	4 469	0	0
1948	1	7	88 043	0	544	0	0
1948	2	8	105 263	0	4 894	0	0
1949	1	9	239 394	0	591	0	0
1949	2	10	286 216	0	5 320	0	0
1950	1	11	338 729	0	638	0	0
1950	2	12	404 979	0	5 745	0	0
1951	1	13	431 377	0	686	0	0
1951	2	14	515 748	0	6 171	0	0
1952	1	15	585 527	0	733	0	0
1952	2	16	700 047	0	6 597	0	0
1953	1	17	1 039 209	0	780	0	0
1953	2	18	1 242 464	0	7 022	0	0
1954	1	19	1 735 022	0	828	0	0
1954	2	20	2 015 219	0	7 448	0	0
1955	1	21	1 978 001	0	875	0	0
1955	2	22	2 312 329	0	7 873	0	0
1956	1	23	2 023 414	0	922	0	0
1956	2	24	2 749 445	0	8 299	0	0
1957	1	25	1 794 636	0	969	0	0
1957	2	26	1 989 795	0	8 724	0	0
1958	1	27	1 251 567	0	1 017	0	0
1958	2	28	1 992 065	0	9 150	0	0
1959	1	29	777 276	0	1 064	0	0
1959	2	30	2 014 868	0	9 576	0	0
1960	1	31	759 888	0	1 111	0	0
1960	2	32	1 777 284	0	10 001	0	0
1961	1	33	632 619	0	1 159	0	0
1961	2	34	1 914 501	0	10 427	0	0
1962	1	35	495 877	0	1 206	0	0
1962	2	36	2 331 169	0	10 852	0	0
1963	1	37	1 105 332	0	1 253	0	0
1963	2	38	2 299 668	0	11 278	0	0

Continues

Fishing year	Season[1]	Sequential season number	Commercial reported[2]	Commercial unreported[3]	Recreational legal[4]	Reported illegal[5]	Unreported illegal[6]
1964	1	39	815 367	0	1 300	0	0
1964	2	40	2 050 633	0	11 704	0	0
1965	1	41	779 756	0	1 348	0	0
1965	2	42	2 244 244	0	12 129	0	0
1966	1	43	554 208	0	1 395	0	0
1966	2	44	2 526 792	0	12 555	0	0
1967	1	45	424 787	0	1 442	0	0
1967	2	46	2 336 213	0	12 980	0	0
1968	1	47	463 751	0	1 490	0	0
1968	2	48	2 265 249	0	13 406	0	0
1969	1	49	341 649	0	1 537	0	0
1969	2	50	2 207 351	0	13 831	0	0
1970	1	51	318 603	0	1 584	0	0
1970	2	52	2 633 397	0	14 257	0	0
1971	1	53	446 649	0	1 631	0	0
1971	2	54	2 359 351	0	14 683	0	0
1972	1	55	321 064	0	1 679	0	0
1972	2	56	1 671 936	0	15 108	0	0
1973	1	57	734 137	0	1 726	0	0
1973	2	58	1 793 863	0	15 534	0	0
1974	1	59	558 734	73 576	1 773	0	0
1974	2	60	1 365 266	179 783	15 959	0	0
1975	1	61	505 590	126 127	1 821	0	0
1975	2	62	1 235 410	308 191	16 385	0	0
1976	1	63	563 961	112 574	1 868	0	0
1976	2	64	1 378 039	275 074	16 811	0	0
1977	1	65	504 719	133 374	1 915	0	0
1977	2	66	1 233 281	325 900	17 236	0	0
1978	1	67	666 833	187 041	1 962	0	0
1978	2	68	1 629 406	457 036	17 662	0	0
1979	1	69	625 628	53 663	2 010	1 758	1 289
1979	2	70	1 632 816	140 053	18 087	4 588	3 365
1980	1	71	459 199	59 310	2 010	2 375	1 742
1980	2	72	1 381 386	178 419	18 087	7 144	5 239
1981	1	73	538 131	0	2 010	4 036	2 959
1981	2	74	1 154 352	0	18 087	8 657	6 348
1982	1	75	535 507	0	2 010	5 032	3 690
1982	2	76	1 152 978	0	18 087	10 834	7 945
1983	1	77	391 397	0	2 010	4 492	3 294
1983	2	78	1 267 503	0	18 087	14 547	10 667
1984	1	79	629 386	0	2 010	7 955	5 833
1984	2	80	1 128 060	0	18 087	14 257	10 455
1985	1	81	934 644	0	2 010	10 801	7 921
1985	2	82	1 261 884	0	18 087	14 583	10 694
1986	1	83	621 781	0	2 010	8 992	6 594

Continues

Fishing year	Season[1]	Sequential season number	Commercial reported[2]	Commercial unreported[3]	Recreational legal[4]	Reported illegal[5]	Unreported illegal[6]
1986	2	84	1 352 951	0	18 087	19 566	14 348
1987	1	85	553 342	0	2 010	8 951	6 564
1987	2	86	1 408 116	0	18 087	22 779	16 705
1988	1	87	317 619	0	2 010	8 909	6 533
1988	2	88	943 934	0	18 087	26 476	19 416
1989	1	89	500 037	0	2 010	14 443	10 592
1989	2	90	851 523	0	18 087	24 595	18 037
1990	1	91	266 093	0	2 010	11 738	8 608
1990	2	92	701 722	0	18 087	30 954	22 700
1991	1	93	347 147	0	2 010	15 606	11 445
1991	2	94	794 987	0	18 087	35 740	26 209
1992	1	95	356 518	0	2 010	21 220	15 562
1992	2	96	651 532	0	18 087	38 780	28 438
1993	1	97	535 963	0	2 010	29 007	21 272
1993	2	98	498 048	0	18 087	26 955	19 767
1994	1	99	453 958	0	2 010	24 140	17 702
1994	2	100	522 480	0	18 087	27 783	20 374
1995	1	101	353 882	0	2 010	13 507	9 905
1995	2	102	553 062	0	18 087	21 109	15 480
1996	1	103	316 115	0	2 010	15 399	11 293
1996	2	104	607 651	0	18 087	29 601	21 707
1997	1	105	295 789	0	2 010	16 200	11 880
1997	2	106	525 850	0	18 087	28 800	21 120
1998	1	107	274 261	0	2 010	14 280	10 472
1998	2	108	590 017	0	18 087	30 720	22 528

[1] 1, autumn/winter season; 2, spring/summer season

[2] These are the total reported commercial catches from catch statistics. Seasonal splits calculated as reported in Section 4.3.1.

[3] The estimate for unreported commercial catch is calculated from a comparison of total reported commercial catch with published export statistics (Breen 1991). The appropriate seasonal split from the commercial fishery was applied.

[4] Recreational catch has been set to 20% of the current estimate in 1945. This value is then increased linearly to 100% which is reached in 1980. The current recreational catch estimate is the mean of all available recreational catch estimates in numbers of lobster. The conversion to catch in weight is based on 1993–96 commercial logbook data. The seasonal split was obtained by assuming a 90%-10% split between the spring/summer and autumn/winter fisheries

[5] This is the fraction of illegal catch which is thought to have been processed through normal legal channels by the Ministry of Fisheries Compliance Unit. This value is subtracted from the total reported commercial catch when calculating the total legal catch in order to avoid double counting of catch. This value has only been estimated in the most recent years (1996) and this fraction has been applied retrospectively to the period of illegal catch estimates.

[6] This is the remaining fraction of illegal catch which is thought to have been processed through other channels by the Ministry of Fisheries Compliance Unit. The total illegal catch is the sum of these two illegal components.

Table 19: CPUE biomass indices, settlement indices and male and female size limits used for the NSS assessment. All CPUE are reported by fishing year, 1 April to 31 March.

Fishing year	Season[1]	Sequential season number	Commercial CPUE[2]	Historical CPUE[3]	Settlement Indices[4]	Male size limit[5]	Female size limit[5]
1945	1	1	0.000	0	0	0	0
1945	2	2	0.000	0	0	0	0
1946	1	3	0.000	0	0	0	0
1946	2	4	0.000	0	0	0	0
1947	1	5	0.000	0	0	0	0
1947	2	6	0.000	0	0	0	0
1948	1	7	0.000	0	0	0	0
1948	2	8	0.000	0	0	0	0
1949	1	9	0.000	0	0	0	0
1949	2	10	0.000	0	0	0	0
1950	1	11	0.000	0	0	47	49
1950	2	12	0.000	0	0	47	49
1951	1	13	0.000	0	0	47	49
1951	2	14	0.000	0	0	47	49
1952	1	15	0.000	0	0	51	53
1952	2	16	0.000	0	0	51	53
1953	1	17	0.000	0	0	51	53
1953	2	18	0.000	0	0	51	53
1954	1	19	0.000	0	0	51	53
1954	2	20	0.000	0	0	51	53
1955	1	21	0.000	0	0	51	53
1955	2	22	0.000	0	0	51	53
1956	1	23	0.000	0	0	51	53
1956	2	24	0.000	0	0	51	53
1957	1	25	0.000	0	0	51	53
1957	2	26	0.000	0	0	51	53
1958	1	27	0.000	0	0	51	53
1958	2	28	0.000	0	0	51	53
1959	1	29	0.000	0	0	53	56
1959	2	30	0.000	0	0	53	56
1960	1	31	0.000	0	0	53	56
1960	2	32	0.000	0	0	53	56
1961	1	33	0.000	0	0	53	56
1961	2	34	0.000	0	0	53	56
1962	1	35	0.000	0	0	53	56
1962	2	36	0.000	0	0	53	56
1963	1	37	0.000	282	0	53	56
1963	2	38	0.000	292	0	53	56
1964	1	39	0.000	207	0	53	56
1964	2	40	0.000	214	0	53	56
1965	1	41	0.000	150	0	53	56
1965	2	42	0.000	156	0	53	56

Continues

Fishing year	Season[1]	Sequential season number	Commercial CPUE [2]	Historical CPUE [3]	Settlement Indices [4]	Male size limit [5]	Female size limit [5]
1966	1	43	0.000	102	0	53	56
1966	2	44	0.000	185	0	53	56
1967	1	45	0.000	100	0	53	56
1967	2	46	0.000	154	0	53	56
1968	1	47	0.000	73	0	53	56
1968	2	48	0.000	115	0	53	56
1969	1	49	0.000	58	0	53	56
1969	2	50	0.000	109	0	53	56
1970	1	51	0.000	78	0	53	56
1970	2	52	0.000	130	0	53	56
1971	1	53	0.000	86	0	53	56
1971	2	54	0.000	100	0	53	56
1972	1	55	0.000	67	0	53	56
1972	2	56	0.000	86	0	53	56
1973	1	57	0.000	0	0	53	56
1973	2	58	0.000	0	0	53	56
1974	1	59	0.000	0	0	53	56
1974	2	60	0.000	0	0	53	56
1975	1	61	0.000	0	0	53	56
1975	2	62	0.000	0	0	53	56
1976	1	63	0.000	0	0	53	56
1976	2	64	0.000	0	0	53	56
1977	1	65	0.000	0	0	53	56
1977	2	66	0.000	0	0	53	56
1978	1	67	0.000	0	0	53	56
1978	2	68	0.000	0	0	53	56
1979	1	69	1.070	0	0	53	56
1979	2	70	1.749	0	0	53	56
1980	1	71	0.974	0	0	53	56
1980	2	72	1.461	0	0	53	56
1981	1	73	1.092	0	0	53	56
1981	2	74	1.325	0	0	53	56
1982	1	75	0.892	0	0	53	56
1982	2	76	1.313	0	0	53	56
1983	1	77	0.630	0	0	53	56
1983	2	78	1.176	0	0	53	56
1984	1	79	0.715	0	0	53	56
1984	2	80	1.009	0	0	53	56
1985	1	81	0.826	0	0	53	56
1985	2	82	0.966	0	0	53	56
1986	1	83	0.565	0	1.0	53	56
1986	2	84	0.980	0	1.0	53	56
1987	1	85	0.597	0	53.3	53	56
1987	2	86	0.960	0	53.3	53	56
1988	1	87	0.469	0	49.1	54	58

Continues

Fishing year	Season[1]	Sequential season number	Commercial CPUE [2]	Historical CPUE [3]	Settlement Indices [4]	Male size limit [5]	Female size limit [5]
1988	2	88	0.737	0	49.1	54	58
1989	1	89	0.552	0	67	54	56
1989	2	90	0.791	0	67	54	56
1990	1	91	0.465	0	35.5	54	57
1990	2	92	0.883	0	35.5	54	57
1991	1	93	0.552	0	37.9	54	57
1991	2	94	0.957	0	37.9	54	57
1992	1	95	0.493	0	13.5	54	57
1992	2	96	0.733	0	13.5	54	57
1993	1	97	0.559	0	5.3	54	57
1993	2	98	0.918	0	5.3	54	57
1994	1	99	0.551	0	90.5	54	57
1994	2	100	0.912	0	90.5	54	57
1995	1	101	0.571	0	19	54	57
1995	2	102	0.989	0	19	54	57
1996	1	103	0.435	0	37.6	54	57
1996	2	104	0.961	0	37.6	54	57
1997	1	105	0.397	0	47.3	54	57
1997	2	106	0.815	0	47.3	54	57
1998	1	107	0.409	0	5.1	54	57
1998	2	108	0.865	0	5.1	54	57

[1] 1, autumn/winter season; 2, spring/summer season

[2] These CPUE indices are standardised CPUE indices scaled to the 1980 unstandardised index to preserve the units of kilogram per potlift

[3] CPUE indices in kilogram per day from Annala & King (1983)

[4] Annual settlement indices from Chalky Inlet (Booth et al. 2000)

[5] In units of tail width (TW [mm]) converted using parameters provided in Section 4.3.2