CRA 9 management procedure evaluations

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EXECUTIVE SUMMARY

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This report describes work towards development of a management procedure for CRA 9. CRA 9 catch and CPUE data from 1963 are presented and discussed: these were used to estimate annual production using simple assumptions. The total catch vector was developed according to agreements made by the Rock Lobster Fishery Assessment Working Group, which involved assumptions for generating a trajectory of recreational catch.

Next, a simple assessment is described that involved fitting a production model to the data. This was implemented in AD Model Builder, and posterior distributions of estimated parameters were obtained from Markov chain–Monte Carlo simulations.

This model was then used as the basis for an operating model, with stochastic variation in annual production and stochastic CPUE observation error, both based on patterns observed in the simple assessment. A family of harvest control rules was defined, a standard set of indicators was defined, and simple explorations were made to explore the productivity characteristics of the model. A set of 204 harvest control rules was explored with the base case operating model; these were narrowed to 44 by screening out rules that failed to meet simple criteria.

Two robustness trials were made with the 44 screened rules: one with an alternative recreational catch series and another with reduced operating model productivity. Rules performed as well under the first trial as they had in the base case, and less well with reduced productivity. The use of these trials in choosing a final rule is discussed.

The next step in this project will be to discuss the results with the CRA 9 stakeholders and determine what they want to obtain from a management procedure and what they expect from the major tradeoffs seen among rules tested.

1. INTRODUCTION

The CRA 9 (Westland) fishery for red rock lobsters (*Jasus edwardsii*) is the least studied of the nine New Zealand rock lobster fisheries. CRA 9 is geographically large, extending from Bruce Bay in Westland to the Kaipara Harbour in west coast Northland (Figure 1), but it has the smallest TACC of any region, just over 47 t. Commercial lobster fishing in CRA 9 is limited to the northwest coast of the South Island and the Taranaki coastline.

No formal stock assessment has ever been done for CRA 9. No TAC has been set for this fishery; the TACC of 47 t set in 1992 has remained unchanged and has been fully caught each year (Table 1). CPUE increased more than two-fold from 1999 to 2006, and since then has declined by 32%.

There are no estimates of customary catch for the CRA 9 fishery, but there are uncertain estimates of the recreational catch. There are 23 quota share owners, but in the 2009–10[1] fishing year only six commercial vessels reported CRA 9 landings (Starr 2011). Value of the landed catch is estimated from average port price to be $2.6 million (National Rock Lobster Management Group (NRLMG) 2010).

The study reported here addressed the possibility of a management procedure for CRA 9. Management procedures are extensively simulated-tested decision rules: see Johnston & Butterworth (2005) for discussion of a management procedure used to manage rock lobsters in South Africa. Management procedures are now a major part of New Zealand rock lobster management (Breen et al. 2009b). They have been used to rebuild the depleted CRA 7 and CRA 8 stocks in New Zealand; a voluntary management procedure was used to govern ACE shelving in CRA 4 to rebuild a badly depleted stock (Breen et al. 2009c), and has now been adopted by the Minister of Fisheries as a TACC-adjusting rule; a voluntary management procedure was adopted by CRA 5 to govern ACE shelving to maintain high abundance (Breen 2009a); a management procedure was adopted for CRA 3 in 2010. A more functional management procedure was explored for CRA 5 in 2010 (Haist et al. 2011) and management procedures for CRA 6 were explored in 2009 (Breen 2009b).

This study used an approach similar to that of Breen (2009a; 2009b). Productivity of the stock was first explored using a variation of the method described by Hilborn (2001) (see also Walters et al. 2008). Next, a simple stock assessment was performed with a surplus-production model. A family of harvest control rules was defined. Forward projections were made with different harvest control rules, and a set of fishery indicators was defined for use in evaluating rules.

Preliminary explorations were made to scope out the productivity characteristics of the operating model. Then a series of evaluations were made to identify suitable harvest control rules that could be used in a CRA 9 management procedure. A smaller set of these were then evaluated in two robustness trials.

2. CRA 9 DATA

Data were compiled for 1963–2009. The earliest year with any abundance index was 1963, and the last year of data was 2009. Some holes in the catch data were handled as described below.

[1] The fishing year runs from April through March, and is properly named 2009–10. The convention used in this report is to name the year by its major portion; thus 2009–10 is "2009".

2.1 Catch data

CRA 9 commercial catch data were taken from the CRACE database (Bentley et al. 2005). These come from Annala & King (1983), Annala & Esterman (1986), annual FSU reports by Brian Sanders (e.g., Sanders 1983), Booth et al. (1994) and the FSU and QMR/MHR databases. Commercial catches are shown in Table 1 and Figure 2. Commercial catches for 1988 and 1989 were suspiciously lower than the adjoining catches: these were years in which the Ministry of Agriculture and Fisheries changed its data collection and lost data in the process. Catches for these two years were set to the mean of 1987 and 1990 catches. Commercial catches are unknown for 1974–78.

Non-commercial catches are poorly known. Nothing is known of customary catch, and 1 t was assumed for the whole series. Recent catches reported under Section 111 of the Fisheries Act, allowing commercial fishers to take a recreational bag limit, extracted from the CRACE database (Bentley et al. 2005), rose from 0.0 t in 2001 to 2.25 t in 2009 (Table 1; Paul Starr, pers. comm.).

In 1994 and 1995, recreational catches were estimated as 6000 and 26000 fish respectively (Table 2

Table 2) (Bradford 1997, 1998). These were converted to weight by assuming a mean weight of 750 g based on summaries of voluntary logbook length frequencies supplied by Nokome Bentley (Trophia, pers. comm.), giving 4.5 and 19.5 t respectively, with a mean of 12 t.

The Rock Lobster Fishery Assessment Working Group (RLFAWG) agreed that these 1994 and 1996 estimates should be used for recreational catch, and that the approach used in the 2010 assessment of CRA 5 (Haist et al. 2011) should be followed to produce the trajectory. This involves assuming that recreational catch was proportional to CPUE after 1978 and calculating the proportionality from the average CPUE for 1994–96 and the estimated mean recreational catch in 1994 and 1996 of 12 t. Catch was assumed to have been 20% of the 1979 value in 1945, with a straight-line interpolation between those dates. The resulting recreational catch vector is shown in Table 1 and Figure 2.

Illegal catches were estimated by MFish Compliance for 1990–96 (Table 1). The following algorithm was used by Paul Starr (pers. comm.) to prepare the series of illegal catches (Table 1 and Figure 2).

1. Starting with the estimates of export discrepancies for all of New Zealand for the period 1974 to 1980 (J. McKoy, NIWA, unpub. data), the CRA 9 illegal catches for each of these seven years were estimated from the ratio of the reported commercial catch in CRA 9 to the total New Zealand reported commercial catch for the same years.
2. The average ratio in CRA 9 of the export discrepancy catch to reported commercial catch was calculated for the period 1974–80. This ratio was used to generate an illegal catch estimate for all years with no data (1945 through 1973 and 1981 through 1989) by multiplying the reported catch by the average ratio.
3. Beginning with 1990, which is the first year that estimates were provided by QMA, illegal catch was based on MFish Compliance estimates (see Table 1). For years without Compliance estimates, the level of illegal catch was interpolated (see Table 1).

Because commercial catches were unavailable for 1974–78, total catch was interpolated for this period (Table 1 and Figure 2) from a regression based on the six years before and six years after this. Total annual catch averaged 93 t since 1963, with a maximum of 238 t in 1965 and minimum 59 t in 1963.

2.2 CPUE data

Monthly catch and effort (days fishing) data from 1963 through 1973 were summarised by Annala & King (1983) and used to calculate unstandardised catch per day for each calendar year from 1963 to 1973. Paul Starr (pers. comm.) extracted these from the CRACE database. CPUE was available in standardised kg per pot lift for 1979 through 2009 (Starr 2011). The methods of standardising and grooming were as described by Bentley et al. (2005) and Starr (submitted), using the B4 algorithm.

For CRA 9 it is a problem that statistical area 929 straddles CRA 9 and CRA 8 (Figure 1). With the current algorithms for extracting data from the CELRs, some CRA 9 catch and effort in this area may be lost. This does not affect the catch data from the QMR/MHR database.

CPUE estimates are shown in Table 1 and in Figure 3. Catch per pot showed a minimum of 0.71 in 1985 and a maximum of 2.3 in 2004.

3. OBSERVED PRODUCTION

The data in Table 1 can be used to estimate production if catchability is assumed. Biomass can be estimated as

(1) $$B_t = \frac{I_t}{q}$$

where B_t is biomass in year t, I_t is CPUE in year t and q is an assumed catchability coefficient. Once biomass is estimated, production is the change in biomass plus the catch:

(2) $$P_t = B_{t+1} - B_t + C_t = \frac{I_{t+1} - I_t}{q} + C_t$$

where C_t is the total catch in year t. This method is a variant of that described by Hilborn (2001), and was used to estimate production patterns in CRA 5 (Breen 2009a) and CRA 6 (Breen 2009b).

Using estimates of catchability from the surplus production model described below, 9.17×10^{-5} for catch per day and 2.79×10^{-6} for kg/pot, biomass and production estimates for CRA 9 are shown in Figures 4 and 5.

Production is shown plotted against biomass in Figure 6. Production shows high variability in the biomass range that comprised most of the period; there are three negative production estimates.

Exploitation rate (observed catch divided by estimated biomass) is shown in Figure 7. This peaked at 39% in 1986 and the minimum was 9.6% in 2004. However, exploitation rate estimated by this method is sensitive to the assumed catchability.

4. SURPLUS-PRODUCTION MODEL

A simple surplus-production model was fitted to these data. The model predicts production as a function of biomass:

(3) $$P_t = \frac{r}{p} B_t \left(\left(\frac{B_t}{K} \right)^p \right)$$

where the maximum rate of increase r, shape parameter p and carrying capacity K are parameters of the model. The biomass *Bmsy* that produces maximum sustainable yield (*MSY*) is given by:

(4) $$Bmsy = K \left(\frac{\quad}{p} \right)^{\frac{1}{p}}$$

and *MSY* is obtained by substituting (4) into (3).

The model was fitted using an "observation error time series" approach (see Hilborn & Walters 1992). The 1963 biomass was an estimated parameter, *Binit*, and subsequent biomass was modelled with a rearrangement of (2):

(5) $$B_{t+} = \quad + \quad -$$

The model was fitted by predicting CPUE with an estimated catchability:

(6a) $\hat{I}_{t,day} =$ for catch per day, 1963 through 1973

(6b) $\hat{I}_{t,pot} =$ for catch per pot, 1979 through 2009

Predicted and observed CPUE values were compared with robust log-normal likelihood (Bull et al. 2008):

(7) $$- \quad = \quad - \left(\left(\left(\quad \right) \right) \right)$$

where σ was an estimated parameter. The likelihood for catch per pot was analogous. Normalised residuals were:

(8) $$residual_{t,day} = \frac{\ln I \, / \, \hat{I}}{\sigma} +$$

The model was implemented in both Excel™ and AD Model Builder. The two abundance index data sets were given equal weight. Each of the eight estimated parameters was given a uniform prior with wide bounds (Table 3).

The fits between observed and predicted CPUE from the mode of the joint posterior distribution (MPD) are shown in Figures 8Figure 8 and 9. The fit to kg/day was good, at least after the first four years, and the fit to kg/pot was good but had trouble tracking the most recent years. The catchability for kg/day was 32.9 times that for kg/pot.

"Observed" production from the simple procedure described above and "predicted" production from the surplus production model are compared over time in Figure 10 and as functions of biomass in Figure 11. When looking at these, the reader should remember that the model is not fitting to production. These plots suggest that biomass did not explain much of the variation in production.

These estimates are the mode of the joint posterior distribution (MPD). The MPD results (Figures 10 and 11) suggest that production is not very sensitive to biomass over the range estimated from 1963 to 2009, and that variability in production is high; biomass appears to be a poor determinant of annual production.

Uncertainty in the parameter estimates was estimated using Markov chain–Monte Carlo simulations (McMC). After some experimentation, an McMC chain of 10^9 simulations was made, saving 2500 samples. For the McMC, the estimated *sigma*s were fixed at their MPD values. Diagnostic plots for the estimated parameters are shown in Figures 12 through 17, and for three key derived parameters in Figures 18 through 20. While the likelihoods and most parameters were converged, *Binit* and *p* were not converged even after a billion simulations; most of the derived parameters were converged, but the standard deviation of normalised residuals (sdnr) for the first abundance index and the catchability coefficient for the second abundance series were not well converged. However, *Binit* was not correlated with any of the derived parameters except *sdnr1* (Table 4), and *p* affected only current biomass as a proportion of *K*. The lack of convergence does not appear fatal to the use of this model in an operating model to test management procedures.

The posterior distributions of estimated and derived parameters are summarised in Table 5. Current biomass was estimated to be well above *Bmin* (all runs were above *Bmin)*, at about half of *K* (5% to 95% range 54% to 69%) and 48% above *Bmsy* (31% to 65%). *MSY* was estimated at 93 t (88 to 98 t), close to the average estimated total catches of 95 t. Current surplus production was estimated as 79 t (76 t to 87 t).

According to this model, current biomass is above *Bmsy* with 99% probability. Both the *MSY* of 93 t and the current surplus production (*CSP*) of 80 t are higher than the current total catch of 68 t. The model estimates that exploitation rate has never been very high (maximum 39% in 1987) and that recent exploitation rate has been low: median 10.4% in 2009, compared with a median equilibrium exploitation rate at *Bmsy* of 21%.

A form of the "snail trail" plot recently introduced to New Zealand stock assessments is shown in Figure 21. The stock in 1967 was well above *Bmsy* and fishing was below the rate associated with *MSY*; for the next 20 years the stock decreased as fishing pressure increased. Maximum fishing pressure occurred in 1987 and stock reached its lowest value in 1988. After CRA 9 was placed into the QMS, the stock increased and fishing pressure decreased: for 16 years fishing mortality from all sources has been less than the rate associated with *Bmsy*, and for 12 years mean biomass has been above *Bmsy*.

5. HARVEST CONTROL RULES

Three harvest control rule families were used in this study. The first two were used only for exploratory runs, and the third was used in actual evaluations. Harvest control rules determined TAC, and TACC was determined by subtracting the assumed non-commercial catches as described below.

The rule 1 family has a constant TACC, which can be zero, and non-commercial fishing is simulated. The rule 2 family uses a constant multiplier on CPUE to obtain TACC, using CPUE from the current (not previous) year, and using the predicted CPUE before observation error is applied; thus using perfect information about the stock. Non-commercial fishing is simulated in rule 2.

Rule 3 generates an annual TACC, and is a simplified version of the generalised harvest control rule used in evaluations for CRA 8 (Breen et al. 2008), CRA 7 (Breen 2010) and CRA 3 (Breen et al. 2009a).

Parameters are shown in Table 6 and an example with the major rule options in Figure 22. The rule has three major sections.

- A "rebuilding phase" between zero CPUE and a CPUE level determined by *par3*. In this phase, a decrease or increase in CPUE results in decreased or increased TACC. The TACC becomes zero at a point determined by *par2*, and the line describing the rule output between *par2* and *par3* can be curved: its shape is determined by *par6*.
- A plateau, where the TACC does not change as CPUE changes. The upper and lower CPUE boundaries are determined by *par3* and *par4* and plateau height by *par5*. Unlike the rebuilding phase, the plateau phase is optional, and can be averted by making *par3* equal to *par4*.
- An ascending phase above the plateau, whose slope is *par7* times the slope between *par2* and *par3*. This phase is also optional, and can be averted by making *par4* very large, or by making *par7* zero.

If *T* is the TACC (or voluntary catch limit) for a specific fishing year and *I* is input CPUE, observed in the previous fishing year, the rule is defined by:

(9) $T =$ for $I <$

(10) $T = \left(\quad - \quad \right)$ for $par2 \leq \quad <$

(11) $T =$ for $par3 \leq \quad \leq$

(12) $T = \quad + \quad - \quad 5/par3$ for $I >$

The *min* and *max* parameters determine the relative minimum and maximum change thresholds. The change proposed by the basic rule is defined as:

(13) $\Delta = \frac{T}{I_y} -$

If the rule would make a change with absolute value less than *min*, then no change is made; if the rule would make a change with absolute value greater than *max*, then the change is limited to *max*.

The *latent switch* controls whether a latent year operates. Zero defines no latent year. One defines a simple latent year: no change can be made if a change in catch limit was made in the previous year. Two defines an asymmetric latent year: if a change was made in the previous year, the catch limit can be decreased but not increased.

All rule parameters except the *latent switch* must be positive (*latent switch* can be 0; *par2* can be negative); *par2* must not be greater than *par3*; *par4* must not be greater than *par3*; *par7* would not rationally be less than 0.

6. PROJECTIONS

Projections were made by running the dynamics forward (equation (5)). One run was made from each of the 2500 samples from joint posterior distribution of parameters.

For catch, separate terms were used for commercial, recreational and other non-commercial catches. For commercial catch, the current TACC of 47 t was used for 2010; in subsequent years the TACC was determined by the harvest control rule being tested. Recreational catch was projected by first calculating, for each year from 1979 through 2009 in each run, the recreational exploitation rate as recreational catch divided by model biomass, and obtaining the mean. Recreational catch was then determined from the mean recreational exploitation rate and model biomass for each projection year. The other non-commercial catches were constant at 4.255 t (1 t illegal, 1 t customary and 2.255 t section 111 catch).

CPUE used as input to the harvest control rule was determined from model biomass and estimated catchability. Stochastic observation error was added based on the CPUE residuals in each run. The CPUE observation error deviations were:

(14) $$I_y^{dev} = \quad + \quad I_y^{dev} + \overline{\quad - \quad} \quad {}^{Idev}\varepsilon_y$$

where μ is the mean of CPUE residuals in log space in the run:

(15) $$\mu = \sum^{y} \quad \frac{ed}{31}$$

ρ is the amount of autocorrelation between successive years, σ is the standard deviation of CPUE residuals in log space in the run, and $\varepsilon \cong$. The value of ρ was set to 0.6118, the median of CPUE log-space residual autocorrelations in the McMC.

The projected CPUE, $\hat{I}_y^{proj}$, was:

(16) $$\hat{I}_y^{proj} = q_{y,pot} B_y \exp \; I_y^{dev}$$

The projection dynamics incorporated production deviations. In the pre-projection years, these were calculated as

(17) $$P_t^{dev} = P_t - P_t$$

where $\hat{P}_t$ is production estimated from the surplus production model (equation (3)) and P_t is estimated by equation (2). The base case MPD production deviations are shown in Figure 23. In projections, production deviations were calculated for each sample of the joint posterior distribution and resampled from 1979 onwards. In the McMC, the median autocorrelation in these deviations was 0.05, so no autocorrelation was simulated.

Negative deviations can exceed biomass, so low biomass was arbitrarily truncated at 1 t. When the total catch exceeded 75% of biomass, it was truncated to 75% of biomass, and each catch component was reduced proportionally.

Runs were made for 50 years, through 2061. For each set of runs for a harvest control rule, projections were made from each of the 2500 samples from the joint posterior distribution that had been obtained from the McMC simulations.

7. INDICATORS

Indicators were defined for risk, yield, abundance, and stability of catch limit. Indicators from each run were as follows:

- *minBio*: the minimum of biomass during the run from 2011 through 2060
- *meanBio*: the average biomass during the run
- *minTACC*: the minimum TACC during the run
- *minComm*: the minimum commercial catch during the run
- *meanComm*: the average commercial catch during the run
- *minRec*: the minimum recreational catch during the run
- *meanRec*: the average recreational catch during the run
- *meanTotal*: the average total catch during the run
- *minCPUE*: minimum of CPUE during the run
- *meanCPUE*: the average CPUE during the run
- *AAVH*: the average annual change in TACC
- %<*Bmin*: the percentage of years in which biomass was less than *Bmin*
- %<*Bmsy*: the percentage of years in which biomass was less than *Bmsy*
- %<20*K*: the percentage of years in which biomass was less than 20% *K*
- sumcollapse: the number of runs in which at some stage the biomass became less than 1 t

AAVH was calculated as:

(18) $$AAVH = \sum_{y=}^{y} \frac{|TACC \quad - \quad |}{TACC_y + }$$

Indicators were written from each run, and were summarised for a set of 2500 runs by the median of the posterior distribution except for the three percentage indicators and sumcollapse, which were all based on the sum from each set of runs.

8. PRELIMINARY EXPLORATIONS

Sets of runs were made with the rule 1 and rule 2 families: rule 1 with various constant TACCs from zero through 152 t, and rule 2 with multipliers that gave TACCs from zero to 152 t at CPUE = 1.0, with linearly proportional TACCs at other CPUE values.

Summaries are shown in Table 7 for rule 1 and Table 8 for rule 2.

A maximum median total catch of 90.2 t was obtained with a constant TAC of 72 t under rule 1, and this was associated with a median mean CPUE of 1.19 kg/pot and mean biomass of 481 t. For rule 2, the maximum catch was 94.0 t, obtained with a multiplier of 72 t and associated with mean CPUE of 1.04 kg/pot and mean biomass of 420 t.

These values, if taken as indicators of *MSY* and *Bmsy*, compare pretty well with results from the surplus production model's deterministic MPD and McMC results, as shown in the text table below. The exploitation rate at *Bmsy* for rules 1 and 2, *Umsy*, was calculated by simply dividing the median *MSY* by the median *Bmsy*, not from their posteriors.

	***MSY* (t)**	***Bmsy* (t)**	***Umsy***
base case MPD	91.7	412.8	22.2%
McMC median	93.2	457.9	20.9%
rule1	90.2	480.6	18.8%
rule 2	94.0	419.7	22.4%

For these exploratory rules, some indicators are plotted against the median total catch in Figures 24 and 25. The first two panels in Figure 24 show the higher total catch available from rule 2 for a given level of average biomass or CPUE. The bottom left panel shows that minimum TACC in rule 1 increases even though total catch decreases, whereas minimum TACC decreases at high catch (low abundance) under rule 2. The last panel shows that mean commercial catch increases in proportion with total catch, but at high fishing intensity the proportion of commercial catch in the total catch increases because recreational catch decreases as abundance decreases.

Figure 25 shows some safety indicators plotted against mean total catch: in each case rule 2 shows higher safety than rule 1; rule 1 has higher percentages of collapse and years less than a reference for any given level of mean catch. This is also shown in the table below, where the values are the highest mean total catch that remains below the threshold shown for each indicator. The 50%<*Bmsy* threshold is met near the *MSY* catch under rule 2; all other indicator thresholds are met with lower catches.

These two rules illustrate that maximum yield is a function of the harvest strategy and that a constant rate strategy outperforms a constant yield strategy.

indicator	**threshold**	**rule 1**	**rule 2**
%<*Bmin*	5%	73.5	84.4
%<*Bmsy*	50%	89.1	94.0
%<20%*K*	5%	83.1	92.1
%collapse	5%	70.2	92.1

9. PRODUCTION RUNS

Based on results of the preliminary explorations described above, a set of production runs was made with Rule 3. These were made in two sets: a set of simple rules and a set of plateau rules. For the simple rules, the harvest control rule parameters used to define 108 rules were:

name	par	value 1	value 2	value 3	value 4	value 5	value 6
rule type	*par1*	3					
close fishery threshold	*par2*	0.00	0.25	0.50			
plateau left	*par3*	1					
plateau right	*par4*	1					
plateau height	*par5*	35	40	45	50	55	60
rebuilding shape	*par6*	1.0	1.2				
upper slope	*par7*	1					
min	*par8*	10%					
max	*par9*	50%					
latent switch	*par10*	0	1	2			

For the plateau rules, the parameters used to define 96 rules were:

name	par	value 1	value 2	value 3	value 4
rule type	*par1*	3			
close fishery threshold	*par2*	0.00	0.25		
plateau left	*par3*	1.00	1.25		
plateau right	*par4*	1.75	2.00		
plateau height	*par5*	42	47	52	57
rebuilding shape	*par6*	1.0			
upper slope	*par7*	1			
min	*par8*	10%			
max	*par9*	50%			
latent switch	*par10*	0	1	2	

Results from the 204 harvest control rules were then screened: first for safety, then stability, then yield. Eighty-eight rules were discarded because the percentage of collapsed runs exceeded 5%; from the remainder, 8 were discarded because %<*Bmin* was greater than 5%; of the remainder, all had less than 5% of years less than 20%*K.* Stability ranged from *AAVH* of 5 to 26% in the original set of 204 rules, and from the remaining rules after safety screening 12 were discarded with AAVH greater than 15%. From the remaining rules, 16 were discarded because mean commercial catch was less than the 1990–2009 average of 46.6 t. From the remainder, 36 rules were discarded because the median of minimum TACC was less than 30 t.

This left 44 rules, all of which were plateau rules. Most of the simple rules failed the criterion that the median of minimum TACC be 30 t or greater. The range of indicator values and their medians across the 44 rules are shown in Table 9, while the parameters for and results from the 44 screen-surviving rules are shown in Table 10. The effects of the various parameter values are compared in Table 11. The surviving rules were reasonably well distributed with respect to rule parameters except that plateau heights tended to be mostly 47 or 52. Of the five parameters that were varied, only plateau height had much effect, with a higher plateau height associated with higher commercial and total catch, lower CPUE and recreational catch.

The major trade-off in this set of 44 rules was that between abundance and yield (Figure 26): there was nearly an exact relation between average CPUE and commercial catch. However, the range of CPUE was narrow (1.55 to 1.71 kg/pot) compared with the range of commercial catch (46 to 57 t). There was also a strong relation between safety and yield (Figure 27), but no relation between stability and yield among these 44 surviving rules (Figure 28), nor between stability and abundance (Figure 29). There was a strong relation between safety and abundance (Figure 30), but no relation between safety and stability Figure 31).

Because the recreational catch in the operating model was related to abundance, which is inversely related to commercial catch, there is a strong negative relation between recreational and commercial catches (Figure 32). Again, the range of recreational catch was small (19.5 to 21.5 t) compared with the range of commercial catch in this relation.

10. ROBUSTNESS TRIALS

The 44 screen-surviving rules were used in two robustness trials: 1) using a different recreational catch and 2) as for the base case but with arbitrarily reduced productivity.

The alternative recreational catch series was based on the average of the 2000 and 2001 surveys (see Table 2), 37.125 t; all other procedures for calculating the recreational catch vector were the same as for the base case. This alternative vector was substantially higher than in the base case (Figure 33). Table 12 compares MPD estimates from the base case and this trial: estimated current biomass was roughly the same, but *K* was 70% larger and *Binit* was 45% smaller; *MSY* was 45% larger and *Bmsy* 70% larger. Whereas in the base case the current stock was estimated at well above *Bmsy*, in this trial it was close to *Bmsy*. Thus the operating model was more productive, but the status of the stock was closer to *Bmsy* than in the base case.

The second robustness trial was based on the base case McMC, but the projected production for each year was reduced to 75% of what it would otherwise have been.

Robustness trials were run in the same way as the base case trials. The medians of results from the 44 rules for each trial are shown in Table 13. The first robustness trial gave higher biomass, catch and CPUE, slightly higher AAVH, slightly lower risk indicators except that the percentage of years less than *Bmsy* was higher than in the base case, but all rules were less than 50%.

Conversely, the second robustness trial gave a lower biomass by about 17%, a lower mean commercial catch by 9% and lower total catch by 11%. There was a substantial increase in years with biomass less than *Bmin* and smaller increases in other risk indicators.

Thus, rules in the first robustness trial gave better results than they had in the base case. In the second trial, although production declined by 25%, the rules gave catches that reduced by only 10% (commercial and total catch) or 20% (recreational), and biomass declined by 17% overall. The major indicator of interest was %<*Bmin*: only three of the 44 rules had a value less than 5% in the second robustness trial, and these were among the most conservative (lowest catch, highest abundance) of the rules.

Between the base case and second robustness trial, there was substantial variation among rules in the way that the decrease in catch was related to the increased risk: this is illustrated in Figure 34. For a given level of loss of catch, there is a range of increases in risk, so there is a "choice frontier" (Bentley et al. 2003) along the lower edge of the figure: one interpretation of the "best" rule is the one that for a given catch has the minimum increase in risk.

Under this approach, the 17 rules along the choice frontier were identified as the set of final rules that could be considered. Their performance in the second robustness trial is shown in Table 14.

11. DISCUSSION

Although this study was not a stock assessment, the operating model was based on a primitive version of a stock assessment. An actual stock assessment would take size information into account as well as catch and CPUE, and would use the length-based model of Haist et al. (2009).

The base case surplus production analysis, based on CPUE and estimated total catch, was a Bayesian procedure. The diagnostics were reasonably good except that two model parameters, *Binit* and *p*, were not converged even after one billion McMC simulations. This analysis suggested that the CRA 9 stock trajectory is similar to that in CRA 5 (Haist et al. 2011): the stock was overfished when the QMS was introduced in the early 1990s and then rebuilt steadily to a stock now well above *Bmsy* with current fishing intensity well below that associated with *MSY*. Such an interpretation is consistent with the large fish observed in logbook sampling (NZ RLIC Ltd., unpublished data).

A major uncertainty in this analysis is the level of non-commercial catch, and particularly recreational catch. The base case analysis assumed that the 1994–96 surveys were accurate and that recreational catch is proportional to stock abundance, reflected in CPUE. An alternative analysis assumed that the 2000–01 surveys were accurate, leading to much larger recreational catch (and thus total catch) estimates. This alternative analysis suggests a stock near *Bmsy*.

Another uncertainty is caused by statistical area 929's straddling CRA 8 and CRA 9 (Figure 1); this has an unexplored potential effect on CRA 9 CPUE estimates.

Both analyses assume that CPUE is a linear index of abundance. The relation between stock size and CPUE is unknown for any stock, and the base case assessments for other lobster stocks assume a linear relation (e.g. Haist et al. 2011).

This study explored two types of harvest control rules: simple rules such as those adopted by CRA 7 in 2008 and CRA 4 in 2007 and plateau rules such as those adopted by CRA 8 in 2008 and CRA 3 in 2010. None of the 108 simple rules survived the basic screening that was used, with most failing the arbitrary criterion that the median of minimum TACC be 30 t or greater.

By contrast, 44 of the 96 plateau rules survived this screening. The major tradeoffs were those between abundance and yield, and between safety and yield or abundance. Except for plateau height, which affected catch and abundance, there was no substantial pattern in the other parameters among the surviving rules, so the main consideration for a choice of specific rule would be plateau height.

Because all the screened rules had passed arbitrary safety criteria, the important tradeoff for industry to consider is that between mean commercial yield and CPUE. This is essentially a difficult economic decision that should be approached only by industry. The relation between recreational catch and the commercial catch is negative because of the abundance tradeoff, but the scale of change in recreational catch is much smaller than the scale of choice of average commercial catch. Any choice of management procedure should take this into account.

The performances of rules in the first robustness trial, which involved using much larger assumed recreational catches in both the model fitting and projections, were as good as or better than those in the base case except for the percentage of years with biomass less than *Bmsy*. This statistic decreased, but in

all rules was less than 50%. Thus this robustness trial is not useful for distinguishing among the rules, except for noting that if the base case used an under-estimate of recreational catch, this did not prejudice rule performance.
The second robustness trial explored the effect of decreased operating model productivity on rule performance. As expected, performance was degraded. If the same screening criteria were applied to these results, only three rules would pass the 5% threshold for the percentage of years with biomass less than *Bmin*, and these rules are among the most conservative (low catch, high abundance) of the 44 rules. It is probably unrealistic to require that an adopted rule must pass basic criteria in robustness trials, because with rules continually reviewed after 5 years, a regime shift in recruitment or productivity would be detected and the rule exchanged for a more conservative version before any serious damage had been done.

To choose among rules taking the second robustness trial into account, there are at least two approaches: 1) choose a short list of rules from the base case performance and then inspect their performance in the second robustness trial, or 2) choose a short list of rules from those that lie along the choice frontier in Figure 34.

This work is now at the stage where input is needed from the CRA 9 stakeholders. Major tradeoffs have been identified and exemplified among a set of final rules, but the decision about what targets are desirable and what direction should be taken on a specific tradeoff are a matter for stakeholders. The work suggests that management procedures are feasible for this stock.

A serious uncertainty involves the use of a simple surplus production model for the operating instead of a more realistic and complex model. The simple model assumes that production is related to biomass and that CPUE is related to abundance. The more complex length-based model MSLM (Haist et al. 2009) explicitly considers lobster sex, size and maturity, considers the minimum legal size and models the different way the illegal and customary fisheries operate compared with the recreational and commercial fisheries; it considers the effects of season and uses finer-scale data and much more data than used here. Does a simple model do an adequate job for the purposes of an operating model? This question can be answered only by using a simple model in parallel with the MSLM model.

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13. REFERENCES

Annala, J.H.; Esterman, D.B. (1986). Yield estimates for the New Zealand rock lobster fishery. *In* Jamieson, G.S.; Bourne, N. (Eds.), North Pacific Workshop on Stock Assessment and Management of Invertebrates, pp. 347–358. *Canadian Special Publication of Fisheries and Aquatic Sciences 92.*

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.

Bentley, N.; Breen, P.A.; Starr, P.J.; Sykes, D.R. (2003). Development and evaluation of decision rules for management of New Zealand rock lobster stocks. *New Zealand Fisheries Assessment Report 2003/29.* 14 p.

Bentley, N.; Starr, P.J.; Walker, N.A.; Breen, P.A. (2005). Catch and effort data for New Zealand rock lobster fisheries. *New Zealand Fisheries Assessment Report 2005/49*. 49 p.

Booth, J.D.; Robinson, M.; Starr, P.J. (1994). Recent research into New Zealand rock lobsters, and a review of recent rock lobster catch and effort data. New Zealand Fisheries Assessment Document 94/7. 58 p. (Unpublished report held in NIWA 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. (Unpublished report held in NIWA Library, Wellington.)

Bradford, E. (1998). Harvest estimates from the 1996 national marine recreational fishing surveys. New Zealand Fisheries Assessment Research Document 98/16. 27 p. (Unpublished report held in NIWA Library, Wellington.)

Breen, P.A. (2009a). A voluntary harvest control rule for a New Zealand rock lobster (*Jasus edwardsii*) stock. *New Zealand Journal of Marine and Freshwater Research 43(3)*: 941–951.

Breen, P.A. (2009b). CRA 6 Management procedure evaluations. *New Zealand Fisheries Assessment Report 2009/60*. 56 p.

Breen, P.A. (2010). Exploration of alternative management procedures for CRA 7 rock lobsters (*Jasus edwardsii*). Final Research Report for CRA2009–01, 2010–11, Objective 5. Ministry of Fisheries, Wellington. 30 September 2010. 31 p.

Breen, P.A.; Haist, V.; Smith, A.N.H.; Starr, P.J. (2008). Review of the NSS decision rule for stocks CRA 7 and CRA 8 and development of new operational management procedures. *New Zealand Fishery Assessment Report 2008*/55. 71 p.

Breen, P.A.; Haist, V.; Starr, P.J.; Kendrick, T.H. (2009a). Development of a management procedure for the CRA 3 stock of rock lobsters (*Jasus edwardsii*). Final Research Report for CRA2006–01, 2008–09, Objective 4. Ministry of Fisheries, Wellington. 30 November 2009. 50 p.

Breen, P.A.; Starr, P.J.; Haist, V. (2009b). New Zealand decision rules and management procedures for rock lobsters. *New Zealand Fisheries Assessment Report 2009/43*. 18 p.

Breen, P.A.; Sykes, D.; Starr, P.J.; Haist, V.; Kim, S. (2009c). A voluntary reduction in the commercial catch of rock lobster (*Jasus edwardsii*) in a New Zealand fishery. *New Zealand Journal of Marine and Freshwater Research 43(1)*: 511–523.

Haist, V.; Breen, P.A.; Starr, P.J. (2009). A new multi-stock length-based assessment model for New Zealand rock lobsters (*Jasus edwardsii*). *New Zealand Journal of Marine and Freshwater Research 43(1):* 355–371.

Haist, V.; Breen, P.A.; Starr, P.J.; Kendrick, T.H. (2011). The 2010 stock assessment of red rock lobsters (*Jasus edwardsii*) in CRA 5, and development of an operational management procedure. *New Zealand Fisheries Assessment Report 2011/12.* 68 p.

Hilborn. R. (2001). Calculation of biomass trend, exploitation rate, and surplus production from survey and catch data. *Canadian Journal of Fisheries and Aquatic Sciences 58*: 579–584.

Hilborn, R.; Walters, C.J. (1992). Quantitative fisheries stock assessment. Choice, dynamics and uncertainty. Chapman & Hall, New York. xv + 570 pp.

Johnston, S.J.; Butterworth, D.S. (2005). Evolution of operational management procedures for the South African West Coast rock lobster (*Jasus lalandii*) fishery. *New Zealand Journal of Marine and Freshwater Research 39*: 687–702.

Ministry of Fisheries. (2010). Report from the Mid-year Plenary. Unpublished report, Wellington.

National Rock Lobster Management Group. (2010). NRLMG 2010 Annual Report to the Minister of Fisheries, Hon. Phil Heatley. Unpublished report, Wellington. 13 December 2010. 195 p.

Sanders, B.M. (1983). The 1981 New Zealand rock lobster landings. *Fisheries Research Division Occasional Publication: Data Series No. 12.* 31 p.

Starr, P.J. (2011). Rock lobster catch and effort data: summaries and CPUE standardisations, 1979–80 to 2009–10. *New Zealand Fisheries Assessment Report.*

Walters, C.J.; Hilborn, R.; Christensen, V. (2008). Surplus production dynamics in declining and recovering fish populations. *Canadian Journal of Fisheries and Aquatic Sciences 65(11)*: 2536–2551.

Table 1: Commercial catch (all catches in t), section 111 catch, estimated recreational catch, estimated illegal catch (actual MFish estimates in bold), customary catch, total catch and CPUE for CRA 9, 1963–2009. Total catch was interpolated for 1974-78 and commercial catch was interpolated for 1987–88 (little grey cells). The CPUE in kg/pot is standardised (Starr 2011).

Year	TACC	comm. catch	s. 111 catch	rec. catch	illegal catch	cust. catch	total catch	CPUE kg/day	CPUE kg/pot
1963		43.3		9.1	5.7	1.0	59.0	45.95	
1964		72.1		9.4	9.4	1.0	91.9	84.98	
1965		201.2		9.8	26.3	1.0	238.3	123.27	
1966		174.4		10.1	22.8	1.0	208.4	105.90	
1967		93.2		10.5	12.2	1.0	116.9	62.34	
1968		95.2		10.8	12.5	1.0	119.5	60.63	
1969		126.9		11.1	16.6	1.0	155.7	48.25	
1970		44.9		11.5	5.9	1.0	63.2	38.94	
1971		118.0		11.8	15.5	1.0	146.3	54.97	
1972		87.9		12.2	11.5	1.0	112.6	43.38	
1973		101.0		12.5	13.2	1.0	127.7	42.47	
1974				12.9		1.0	111.4		
1975				13.2		1.0	109.1		
1976				13.5		1.0	106.7		
1977				13.9		1.0	104.4		
1978		42.4		14.2	11.1	1.0	68.7		
1979		89.0		14.6	7.7	1.0	112.3		1.186
1980		97.1		15.7	11.1	1.0	124.9		1.278
1981		72.0		12.1	9.4	1.0	94.5		0.983
1982		59.1		10.1	7.7	1.0	78.0		0.824
1983		70.6		10.6	9.2	1.0	91.4		0.859
1984		80.8		10.0	10.6	1.0	102.3		0.813
1985		79.2		8.8	10.4	1.0	99.4		0.719
1986		93.3		10.2	12.2	1.0	116.7		0.834
1987		92.7		10.5	12.1	1.0	116.3		0.854
1988		69.0		10.2	3.4	1.0	83.6		0.828
1989		69.0		9.2	3.5	1.0	82.7		0.746
1990	54.7	45.3		10.2	12.8	1.0	69.3		0.830
1991	50.2	47.5		10.6	31.0	1.0	90.1		0.860
1992	47.0	45.7		11.7	18.0	1.0	76.4		0.954
1993	47.0	45.5		13.7	12.0	1.0	72.2		1.115
1994	47.0	45.2		10.9	12.0	1.0	69.1		0.885
1995	47.0	45.4		13.3	10.2	1.0	69.8		1.081
1996	47.0	46.9		11.9	8.3	1.0	68.1		0.966
1997	47.0	46.7		10.2	6.5	1.0	64.4		0.832
1998	47.0	46.9		13.5	4.7	1.0	66.0		1.096
1999	47.0	47.0		11.2	2.8	1.0	62.0		0.911
2000	47.0	47.0		13.2	1.0	1.0	62.2		1.073
2001	47.0	46.8	0.0	12.8	1.0	1.0	61.6		1.044
2002	47.0	47.0	0.9	15.1	1.0	1.0	65.0		1.227
2003	47.0	45.9	1.0	21.6	1.0	1.0	70.5		1.761
2004	47.0	47.0	1.6	28.2	1.0	1.0	78.8		2.294
2005	47.0	46.6	2.1	25.8	1.0	1.0	76.5		2.099
2006	47.0	47.0	1.2	26.5	1.0	1.0	76.7		2.157
2007	47.0	47.0	1.5	22.2	1.0	1.0	72.7		1.810
2008	47.0	47.0	1.6	15.1	1.0	1.0	65.7		1.232
2009	47.0	46.6	2.3	18.1	1.0	1.0	68.9		1.473

Table 2: Recreational catch estimates for CRA 9 from four surveys (Ministry of Fisheries 2010, table 6), with numbers of fish converted to weight by assuming a mean weight of 0.75 kg.

year	fish	weight (kg)
1994	6000	4500
1996	26000	19500
2000	65000	48750
2001	34000	25500

Table 3: Lower (lb) and upper (ub) bounds for each estimated parameter in the surplus production model.

parameter	lb	ub
K	5.00E+04	1.00E+08
Binit	5.00E+04	1.00E+08
r	0.01	1.5
p	0.01	5
$\ln(q_{day})$	-20	-3
$\ln(q_{pot})$	-20	-3
σ_{day}	0.1	2
σ_{pot}	0.01	2

Table 4: Correlation coefficients among the estimated and derived parameters in the McMC. Grey shows absolute values greater than 0.50. Sdnr1 and sdnr2 refer to the standard deviations of normalised residuals for the catch pre day and catch pre pot indices respectively.

	Binit	*K*	*r*	*p*	ln(*q1*)	ln(*q2*)	sdnr1	sdnr2	B09	*B09 /K*	*Bmin*	*Bmsy*	*B09/ Bmsy*	*MSY*	*CSP*	*Bmsy /K*
Binit	1.00															
K	-0.17	1.00														
r	-0.11	-0.64	1.00													
p	-0.32	0.14	0.55	1.00												
ln(*q1*)	-0.12	-0.26	0.47	0.10	1.00											
ln(*q2*)	0.13	-0.63	0.36	-0.35	0.51	1.00										
sdnr1	0.90	-0.31	0.09	-0.25	-0.04	0.23	1.00									
sdnr2	0.12	0.04	-0.17	-0.14	-0.48	-0.43	0.10	1.00								
B2009	-0.24	0.84	-0.34	0.46	-0.22	-0.84	-0.33	0.14	1.00							
B09/K	-0.09	-0.47	0.76	0.52	0.22	-0.17	0.05	0.15	0.05	1.00						
Bmin	-0.12	0.66	-0.40	0.34	-0.59	-0.96	-0.23	0.49	0.85	0.11	1.00					
Bmsy	-0.26	0.94	-0.39	0.46	-0.21	-0.68	-0.35	-0.01	0.91	-0.24	0.70	1.00				
B09/Bmsy	0.25	-0.63	0.23	-0.47	0.11	0.18	0.30	0.30	-0.41	0.50	-0.23	-0.72	1.00			
MSY	-0.21	0.57	0.06	0.33	0.38	-0.28	-0.21	-0.08	0.63	0.12	0.24	0.62	-0.20	1.00		
CSP	-0.21	0.79	-0.38	0.23	0.08	-0.14	-0.29	-0.34	0.52	-0.60	0.17	0.79	-0.84	0.56	1.00	
Bmsy/K	-0.33	0.15	0.54	1.00	0.11	-0.35	-0.25	-0.14	0.47	0.51	0.34	0.47	-0.48	0.33	0.24	1.00

Table 5: Summaries of posterior distributions (5th and 95th quantiles, mean and median) of estimated and derived parameters from the McMC, and the MPD estimates; sdnr is the standard deviation of normalised residuals. Biomass and yields in t.

	5%	mean	median	95%	MPD
function value	39.81	41.85	42.19	45.75	38.71
likelihood for kg/day	45.48	46.55	46.73	48.82	45.00
likelihood for kg/pot	-6.22	-4.86	-4.54	-1.76	-6.29
Binit	1040	3285	5388	16400	1285
K	912	1050	1088	1330	1116
r	0.212	0.276	0.276	0.343	0.224
p	0.039	0.307	0.338	0.769	0.010
ln(*q*) for kg/day	-9.64	-9.37	-9.38	-9.16	-9.30
ln(*q*) for kg/pot	-13.20	-12.90	-12.91	-12.67	-12.79
sigma for kg/day	0.158	0.158	0.158	0.158	0.158
sigma for kg/pot	0.182	0.182	0.182	0.182	0.182
sdnr for kg/day	1.774	3.387	3.606	6.217	1.130
sdnr for kg/pot	1.015	1.050	1.061	1.148	0.997
B2009	547.3	656.4	668.5	819.6	619.2
B09/K	0.543	0.620	0.619	0.691	0.555
Bmin	240.3	316.9	328.4	453.4	274.8
Bmsy	350.2	445.2	457.9	583.1	412.8
B09/Bmsy	1.308	1.479	1.477	1.652	1.500
MSY	88.6	92.7	93.2	98.3	91.7
CSP	74.6	79.2	80.1	87.4	81.7
Bmsy/K	0.375	0.418	0.420	0.476	0.370

Table 6: parameters for the generalised harvest control rule family.

par	name
par1	rule type
par2	close fishery threshold
par3	plateau left
par4	plateau right
par5	plateau height
par6	rebuilding shape
par7	upper slope
par8	min
par9	max
par10	latent switch

Table 7: Rule 1: Medians of indicators for various constant catches (*par2*, t) from exploratory runs with the operating model; Bio: biomass (t), Comm: commercial catch (t), Rec: recreational catch (t), Total: total catch (t); AAVH: average annual TACC variation as a percentage; %<*Bmin*: the percentage of years in which biomass was less than *Bmsy*; %coll: the percentage of runs in which biomass fell to 1 t or less. CPUE in kg/pot.

	min	*mean*	*min*	*min*	*mean*	*min*	*mean*	*mean*	*min*	*mean*	%	%	%	%	%
par2	*Bio*	*Bio*	*TACC*	*Comm*	*Comm*	*Rec*	*Rec*	*Total*	*CPUE*	*CPUE*	*AAVH*	*<Bmin*	*<Bmsy*	*<20%K*	*coll*
0	596	898	0.0	0.0	0.0	18.5	27.8	32.1	1.252	2.216	0.0	0.2	0.5	0.0	0.1
0	596	898	0.0	0.0	0.0	18.5	27.8	32.1	1.252	2.216	0.0	0.2	0.5	0.0	0.1
4	588	883	4.0	4.0	4.0	18.1	27.4	35.6	1.229	2.180	0.0	0.2	0.6	0.1	0.2
8	577	867	8.0	8.0	8.0	17.9	26.9	39.2	1.203	2.143	0.0	0.3	0.7	0.1	0.4
12	565	851	12.0	12.0	12.0	17.5	26.4	42.7	1.175	2.103	0.0	0.4	0.9	0.1	0.4
16	552	835	16.0	16.0	16.0	17.1	26.0	46.2	1.146	2.062	0.0	0.5	1.1	0.1	0.6
20	537	820	20.0	20.0	20.0	16.7	25.4	49.7	1.117	2.021	0.0	0.6	1.5	0.2	0.8
24	522	803	24.0	24.0	24.0	16.2	24.9	53.2	1.088	1.980	0.0	0.8	1.9	0.3	0.9
28	505	785	28.0	28.0	28.0	15.6	24.4	56.6	1.054	1.936	0.0	1.1	2.5	0.4	1.2
32	485	767	32.0	32.0	32.0	15.1	23.8	60.1	1.018	1.891	0.0	1.4	3.3	0.5	1.6
36	465	747	36.0	36.0	36.0	14.5	23.2	63.5	0.980	1.844	0.0	2.0	4.4	0.8	2.2
40	444	727	40.0	40.0	40.0	13.7	22.6	66.8	0.937	1.791	0.0	2.7	5.9	1.2	3.2
44	420	705	44.0	44.0	44.0	13.0	22.0	70.2	0.892	1.741	0.0	3.7	7.8	1.8	4.7
48	394	682	48.0	48.0	48.0	12.2	21.3	73.5	0.841	1.688	0.0	5.0	10.2	2.5	6.4
52	365	657	52.0	52.0	52.0	11.4	20.6	76.8	0.786	1.629	0.0	6.9	13.5	3.8	9.9
56	333	628	56.0	56.0	56.0	10.3	19.8	80.0	0.726	1.560	0.0	9.5	17.5	5.3	13.1
60	297	599	60.0	60.0	60.0	9.2	18.9	83.1	0.646	1.485	0.0	12.9	22.2	7.6	18.8
64	252	563	64.0	64.0	64.0	7.9	17.8	86.0	0.550	1.405	0.0	17.0	27.7	10.8	25.8
68	191	525	68.0	68.0	68.0	6.0	16.5	88.5	0.429	1.310	0.0	21.9	33.9	14.6	34.3
72	79	481	72.0	53.9	71.6	1.8	15.0	90.2	0.182	1.193	0.0	27.5	40.5	19.3	43.6
76	1	433	76.0	0.7	71.8	0.0	13.4	89.1	0.003	1.079	0.0	33.4	46.9	24.1	53.9
80	1	386	80.0	0.7	71.5	0.0	11.9	87.0	0.002	0.963	0.0	39.2	53.1	29.5	62.6
84	1	344	84.0	0.7	70.8	0.0	10.4	85.0	0.002	0.848	0.0	45.0	58.8	34.8	71.1
88	1	308	88.0	0.7	70.0	0.0	9.2	82.6	0.002	0.757	0.0	50.6	64.2	40.0	78.6
92	1	275	92.0	0.7	69.3	0.0	8.2	80.8	0.002	0.679	0.0	56.0	69.0	45.1	85.2
96	1	249	96.0	0.7	68.6	0.0	7.4	79.3	0.002	0.615	0.0	60.8	73.2	49.8	90.2
100	1	228	100.0	0.7	67.9	0.0	6.7	77.6	0.002	0.564	0.0	65.0	76.7	54.2	93.4
104	1	208	104.0	0.7	67.2	0.0	6.2	76.5	0.002	0.521	0.0	68.8	79.6	57.9	95.6
108	1	193	108.0	0.7	66.8	0.0	5.7	75.2	0.002	0.487	0.0	72.0	82.0	61.4	97.4
112	1	181	112.0	0.7	66.3	0.0	5.3	74.3	0.002	0.457	0.0	74.9	84.0	64.4	98.4

	min	mean	min	min	mean	min	mean	mean	min	mean	%	%	%	%	%
par2	*Bio*	*Bio*	*TACC*	*Comm*	*Comm*	*Rec*	*Rec*	*Total*	*CPUE*	*CPUE*	*AAVH*	*<Bmin*	*<Bmsy*	*<20%K*	*coll*
116	1	172	116.0	0.7	66.0	0.0	5.0	73.6	0.002	0.433	0.0	77.3	85.6	67.0	99.0
120	1	163	120.0	0.7	65.7	0.0	4.7	72.8	0.002	0.411	0.0	79.2	86.9	69.3	99.3
124	1	156	124.0	0.7	65.5	0.0	4.4	72.2	0.002	0.392	0.0	80.8	88.1	71.4	99.4
128	1	150	128.0	0.7	65.1	0.0	4.2	71.7	0.002	0.376	0.0	82.3	89.0	73.1	99.7
132	1	145	132.0	0.7	64.9	0.0	4.0	71.2	0.002	0.363	0.0	83.6	89.8	74.6	99.8
136	1	140	136.0	0.7	64.8	0.0	3.8	70.8	0.002	0.351	0.0	84.7	90.5	75.8	99.9
140	1	136	140.0	0.7	64.6	0.0	3.7	70.3	0.002	0.342	0.0	85.6	91.1	77.0	100.0
144	1	133	144.0	0.7	64.3	0.0	3.5	70.1	0.002	0.333	0.0	86.4	91.5	78.0	100.0
148	1	129	148.0	0.7	64.2	0.0	3.4	69.8	0.002	0.324	0.0	87.1	92.1	79.0	100.0
152	1	126	152.0	0.7	64.2	0.0	3.3	69.5	0.002	0.317	0.0	87.7	92.4	79.8	100.0

Table 8: Rule 2: Medians of indicators for various multipliers (*par2*, t) from exploratory runs with the operating model; see caption for Table 7.

	min	mean	min	min	mean	min	mean	mean	min	mean	%	%	%	%	%
par2	*Bio*	*Bio*	*TACC*	*Comm*	*Comm*	*Rec*	*Rec*	*Total*	*CPUE*	*CPUE*	*AAVH*	*<Bmin*	*<Bmsy*	*<20%K*	*coll*
0	596	898	0.0	0.0	0.0	18.5	27.8	32.1	1.252	2.216	0.0	0.2	0.5	0.0	0.1
4	578	865	5.8	5.8	8.7	17.9	26.9	39.8	1.205	2.136	8.4	0.2	0.6	0.1	0.2
8	553	834	11.2	11.2	16.8	17.2	25.9	47.0	1.153	2.060	8.7	0.3	0.9	0.1	0.4
12	530	803	16.0	16.0	24.2	16.4	24.9	53.4	1.098	1.982	9.1	0.4	1.2	0.1	0.4
16	504	773	20.2	20.2	31.1	15.6	24.0	59.4	1.047	1.908	9.4	0.6	1.8	0.1	0.5
20	475	744	23.9	23.9	37.4	14.7	23.1	64.8	0.996	1.836	9.8	0.8	2.5	0.2	0.8
24	446	715	27.0	27.0	43.2	13.9	22.2	69.7	0.942	1.766	10.2	1.1	3.7	0.3	1.0
28	418	687	29.5	29.5	48.4	13.0	21.4	74.1	0.886	1.696	10.6	1.6	5.4	0.4	1.2
32	391	659	31.6	31.6	53.1	12.1	20.5	77.9	0.831	1.631	11.1	2.1	7.5	0.6	1.5
36	364	633	33.0	33.0	57.3	11.3	19.7	81.3	0.778	1.564	11.6	3.0	10.3	0.9	2.0
40	336	606	33.8	33.8	61.1	10.4	18.9	84.4	0.727	1.502	12.1	4.1	13.7	1.3	2.8
44	309	580	34.3	34.3	64.5	9.6	18.1	86.9	0.673	1.440	12.7	5.6	17.7	1.8	3.8
48	283	555	34.3	34.3	67.4	8.9	17.3	89.1	0.617	1.379	13.4	7.5	22.3	2.6	5.4
52	256	531	33.8	33.8	69.8	8.0	16.6	90.7	0.563	1.318	14.1	9.6	27.3	3.5	7.0
56	231	507	32.7	32.7	72.0	7.2	15.9	92.1	0.511	1.262	14.9	12.2	32.7	4.6	9.3
60	205	485	31.2	31.2	73.7	6.4	15.2	93.2	0.462	1.204	15.7	15.2	38.1	6.1	12.0
64	180	462	29.1	29.1	75.0	5.6	14.5	93.7	0.409	1.150	16.8	18.5	43.6	7.9	15.0
68	156	441	26.5	26.5	75.9	4.9	13.8	94.0	0.354	1.095	17.8	22.1	49.1	10.0	19.5

	min	*mean*	*min*	*min*	*mean*	*min*	*mean*	*mean*	*min*	*mean*	%	%	%	%	%
par2	*Bio*	*Bio*	*TACC*	*Comm*	*Comm*	*Rec*	*Rec*	*Total*	*CPUE*	*CPUE*	*AAVH*	*<Bmin*	*<Bmsy*	*<20%K*	*coll*
72	132	420	23.8	23.8	76.4	4.1	13.2	94.0	0.301	1.043	19.1	25.9	54.3	12.3	24.4
76	108	399	20.3	20.3	76.8	3.3	12.5	93.6	0.242	0.993	20.6	29.9	59.0	14.7	29.2
80	83	380	16.6	16.6	77.0	2.6	11.9	93.2	0.187	0.943	22.3	34.0	63.5	17.4	33.9
84	57	361	12.2	12.2	76.9	1.8	11.3	92.5	0.133	0.898	24.3	38.3	67.5	20.1	38.8
88	31	343	7.0	7.0	76.5	1.0	10.7	91.4	0.077	0.855	26.5	42.4	71.1	23.0	43.9
92	6	326	1.2	0.9	75.9	0.1	10.2	90.4	0.011	0.813	28.9	46.6	74.3	25.9	50.0
96	1	310	0.3	0.0	75.5	0.0	9.7	89.4	0.003	0.775	31.4	50.6	77.2	28.9	55.8
100	1	296	0.3	0.0	75.0	0.0	9.2	88.5	0.003	0.737	33.6	54.4	79.7	31.9	61.3
104	1	282	0.3	0.0	74.3	0.0	8.8	87.3	0.002	0.704	36.1	58.0	81.9	34.9	66.4
108	1	269	0.3	0.0	73.6	0.0	8.4	86.1	0.002	0.671	38.2	61.4	83.7	37.8	70.7
112	1	258	0.3	0.0	72.9	0.0	8.0	85.0	0.002	0.643	40.5	64.5	85.4	40.6	74.7
116	1	246	0.3	0.1	72.4	0.0	7.7	84.0	0.002	0.615	42.7	67.3	86.9	43.5	78.2
120	1	235	0.3	0.1	71.6	0.0	7.4	82.9	0.002	0.588	44.8	70.1	88.1	46.2	81.5
124	1	226	0.3	0.1	70.7	0.0	7.0	81.7	0.002	0.563	46.9	72.5	89.2	48.8	84.7
128	1	216	0.3	0.1	70.1	0.0	6.7	80.7	0.002	0.542	48.6	74.7	90.1	51.3	86.9
132	1	208	0.3	0.1	69.4	0.0	6.5	79.8	0.002	0.520	50.4	76.7	91.0	53.7	88.7
136	1	200	0.3	0.1	68.7	0.0	6.2	78.8	0.002	0.500	52.5	78.6	91.7	56.0	90.6
140	1	193	0.4	0.1	68.1	0.0	6.0	77.9	0.002	0.481	54.4	80.3	92.4	58.2	92.4
144	1	186	0.4	0.1	67.6	0.0	5.8	77.1	0.002	0.464	56.1	81.8	92.9	60.3	93.9
148	1	180	0.4	0.1	67.0	0.0	5.6	76.3	0.002	0.448	57.8	83.1	93.4	62.2	94.4
152	1	174	0.4	0.1	66.4	0.0	5.4	75.6	0.002	0.433	59.4	84.3	93.9	64.0	95.3

Table 9: Of the 44 rules that survived screening in production runs, the minimum, maximum and median values of each indicator; catch and biomass indicators expressed in t.

indicator	min	max	median
minBio	335.8	410.6	374.1
meanBio	625.8	690.4	661.2
minTACC	30.0	40.2	34.8
minComm	30.0	40.2	34.8
meanComm	46.5	57.2	51.7
minRec	10.4	12.8	11.6
meanRec	19.5	21.5	20.6
meanTot	72.3	81.1	76.7
minCPUE	0.723	0.876	0.801
meanCPUE	1.550	1.710	1.636
%AAVH	5.90	11.80	8.41
%<*Bmin*	2.19	4.90	3.44
%<*Bmsy*	6.52	13.29	9.45
%<20%*K*	0.70	1.86	1.21
%collapse	1.80	4.92	3.10

Table 10: Parameter values and indicators from the 44 rules that survived screening; catch and biomass indicators expressed in t.

serial	*par2*	*par3*	*par4*	*par5*	*par10*	*min TACC*	*min Comm*	*mean Comm*	*mean Rec*	*mean Tota*	*min CPUE*	*mean CPUE*	*%AAVH*
3201	0	1	1.75	42	0	36.3	36.3	48.1	21.2	73.6	0.855	1.689	11.2
3202	0	1	1.75	42	1	37.9	37.9	52.4	20.4	77.2	0.850	1.688	8.2
3203	0	1	1.75	42	2	36.6	36.6	48.1	21.2	73.7	0.865	1.704	9.0
3204	0	1	1.75	47	0	38.3	38.3	52.5	20.4	77.1	0.795	1.624	10.7
3205	0	1	1.75	47	1	36.7	36.7	46.9	21.4	72.7	0.791	1.620	7.9
3206	0	1	1.75	47	2	38.3	38.3	51.3	20.6	76.4	0.805	1.640	8.6
3209	0	1	1.75	52	2	39.1	39.1	55.5	19.8	79.7	0.741	1.574	8.4
3216	0	1	2	47	0	34.4	34.4	48.0	21.2	73.5	0.821	1.663	7.7
3217	0	1	2	47	1	34.8	34.8	52.2	20.4	77.0	0.817	1.659	5.9
3218	0	1	2	47	2	33.9	33.9	56.2	19.6	80.3	0.826	1.672	6.3
3221	0	1	2	52	2	34.9	34.9	48.0	21.2	73.6	0.764	1.605	6.1
3226	0	1.25	1.75	42	1	35.5	35.5	52.2	20.4	77.0	0.876	1.710	8.5
3228	0	1.25	1.75	47	0	35.0	35.0	46.8	21.5	72.6	0.823	1.651	11.3
3229	0	1.25	1.75	47	1	35.3	35.3	51.1	20.6	76.2	0.820	1.649	8.5
3230	0	1.25	1.75	47	2	34.9	34.9	55.1	19.9	79.4	0.830	1.668	9.3
3231	0	1.25	1.75	52	0	31.3	31.3	50.8	20.7	75.8	0.767	1.588	11.2
3232	0	1.25	1.75	52	1	32.4	32.4	54.7	20.0	79.0	0.764	1.588	8.4
3233	0	1.25	1.75	52	2	30.8	30.8	46.5	21.5	72.3	0.778	1.607	9.3
3236	0	1.25	1.75	57	2	32.4	32.4	50.8	20.7	75.8	0.723	1.550	9.4
3240	0	1.25	2	47	0	33.5	33.5	54.6	20.0	78.9	0.843	1.681	8.6
3241	0	1.25	2	47	1	31.7	31.7	49.7	21.0	75.1	0.840	1.682	6.7
3242	0	1.25	2	47	2	32.8	32.8	53.6	20.2	78.2	0.849	1.693	7.3
3243	0	1.25	2	52	0	33.4	33.4	57.2	19.5	81.1	0.788	1.621	8.6
3244	0	1.25	2	52	1	39.1	39.1	49.8	20.9	75.1	0.785	1.619	6.6
3245	0	1.25	2	52	2	39.4	39.4	50.0	20.9	75.2	0.796	1.633	7.2
3246	0	1.25	2	57	0	39.4	39.4	49.2	21.0	74.6	0.731	1.556	8.8
3248	0	1.25	2	57	2	40.2	40.2	53.5	20.2	78.2	0.740	1.572	7.4

serial	*par2*	*par3*	*par4*	*par5*	*par10*	*min* *TACC*	*min* *Comm*	*mean* *Comm*	*mean* *Rec*	*mean* *Total*	*min* *CPUE*	*mean* *CPUE*	*%AAVH*
3249	0.25	1	1.75	42	0	36.3	36.3	49.7	21.0	75.0	0.857	1.691	11.8
3250	0.25	1	1.75	42	1	35.9	35.9	54.0	20.1	78.5	0.851	1.690	8.6
3251	0.25	1	1.75	42	2	37.1	37.1	49.8	20.9	75.1	0.866	1.705	9.4
3252	0.25	1	1.75	47	0	37.4	37.4	54.0	20.1	78.5	0.798	1.628	11.4
3253	0.25	1	1.75	47	1	36.8	36.8	49.0	21.1	74.4	0.793	1.624	8.4
3254	0.25	1	1.75	47	2	36.2	36.2	53.3	20.3	78.0	0.806	1.645	9.2
3255	0.25	1	1.75	52	0	32.0	32.0	48.6	21.2	74.1	0.735	1.563	11.2
3257	0.25	1	1.75	52	2	33.1	33.1	52.7	20.4	77.4	0.745	1.583	9.1
3264	0.25	1	2	47	0	33.6	33.6	56.6	19.6	80.5	0.822	1.666	8.3
3265	0.25	1	2	47	1	33.2	33.2	48.6	21.2	74.1	0.817	1.661	6.3
3266	0.25	1	2	47	2	34.6	34.6	52.7	20.4	77.4	0.828	1.676	6.9
3267	0.25	1	2	52	0	32.3	32.3	47.9	21.3	73.5	0.760	1.599	8.2
3268	0.25	1	2	52	1	33.4	33.4	52.0	20.6	76.9	0.756	1.597	6.2
3269	0.25	1	2	52	2	34.1	34.1	55.8	19.8	79.9	0.766	1.613	6.7
3289	0.25	1.25	2	47	1	30.0	30.0	48.3	21.2	73.8	0.846	1.688	7.3
3292	0.25	1.25	2	52	1	30.5	30.5	52.3	20.5	77.0	0.791	1.627	7.4
3295	0.25	1.25	2	57	1	30.7	30.7	55.8	19.8	79.9	0.733	1.569	7.7

Table 11: Mean indicator values as a function of the rule parameter values shown; catch and biomass indicators expressed in t.

par	value	n	*min* *TACC*	*min* *Comm*	*mean* *Comm*	*mean* *Rec*	*mean* *Total*	*min* *CPUE*	*mean* *CPUE*	*%AAVH*
par2	0.00	27	35.0	35.0	51.5	20.6	76.4	0.803	1.637	8.4
	0.25	17	34.7	34.7	51.5	20.6	76.5	0.798	1.637	8.5
par3	1.00	25	36.8	36.8	51.1	20.7	76.1	0.805	1.643	8.5
	1.25	19	32.4	32.4	52.1	20.5	76.9	0.796	1.629	8.4
par4	1.75	23	34.8	34.8	51.4	20.6	76.4	0.806	1.638	9.5
	2	21	35.0	35.0	51.6	20.6	76.5	0.796	1.636	7.3
par5	42	7	35.0	35.0	47.5	21.3	73.1	0.860	1.697	9.5
	47	19	35.3	35.3	50.2	20.8	75.4	0.820	1.657	8.2
	52	14	34.9	34.9	53.9	20.1	78.4	0.767	1.601	8.2
	57	4	32.9	32.9	56.3	19.7	80.3	0.732	1.562	8.3
par10	0	13	34.7	34.7	51.8	20.5	76.7	0.800	1.632	9.9
	1	15	34.3	34.3	51.0	20.7	76.0	0.809	1.645	7.5
	2	16	35.6	35.6	51.7	20.5	76.7	0.796	1.634	8.1

Table 12: Comparison of MPD estimates from the base case MPD and the robustness trial 1 MPD; catch and biomass indicators expressed in t.

	base case	robustness trial 1
K	1118.7	1922.1
Binit	1281.8	694.5
r	0.224	0.187
p	0.010	0.010
ln(q1)	-9.296	-9.139
ln(q2)	-12.792	-12.835
sigma1	0.164	0.253
sigma2	0.181	0.175
f	38.721	38.008
Bcurrent	619.2	676.9
Bcurr/K	0.555	0.352
Bmsy	412.8	710.6
Bcurrent/Bmsy	1.500	0.953
CSP	81.7	131.6
MSY	91.7	131.7
MSY/Bmsy	0.222	0.185
Bmsy/K	0.370	0.370
ERate09	0.111	0.151

Table 13: Medians of indicators from the 44 rules run in the base case and two robustness trials; robust1: alternative recreational catch series, robust2: reduced productivity; catch and biomass indicators expressed in t.

	base median	robust1 median	robust2 median
minBio	374.1	591.8	300.7
meanBio	661.2	986.9	548.5
minTACC	34.8	42.1	26.7
minComm	34.8	42.1	26.7
meanComm	51.7	57.2	46.8
minRec	11.6	41.6	9.3
meanRec	20.6	68.1	17.1
meanTot	76.7	129.6	68.2
minCPUE	0.801	1.001	0.642
meanCPUE	1.636	1.906	1.355
%AAVH	8.41	9.75	7.35
%<Bmin	3.44	2.30	8.06
%<Bmsy	9.45	27.38	23.64
%<20%K	1.21	1.72	2.70
%collapse	3.10	2.28	4.52

Table 14: Indicators from the 17 runs on the choice frontier based on robustness trial 2; catch and biomass indicators expressed in t.

						min	*min*	*mean*	*mean*	*mean*	*min*	*mean*	%	%	%	%	%
serial	*par2*	*par3*	*par4*	*par5*	*par10*	*TACC*	*Comm*	*Comm*	*Rec*	*Total*	*CPUE*	*CPUE*	*AAVH*	*<Bmin*	*<Bmsy*	*<20%K*	*collapse*
3203	0	1	1.75	42	2	30.6	30.6	43.1	18.2	65.8	0.721	1.445	6.50	5.47	17.02	1.72	3.00
3218	0	1	2	47	2	31.0	31.0	46.1	17.4	67.7	0.652	1.376	4.92	8.08	22.36	2.81	4.76
3226	0	1.25	1.75	42	1	26.7	26.7	42.0	18.5	64.9	0.752	1.469	7.21	4.31	14.57	1.32	2.20
3228	0	1.25	1.75	47	0	26.2	26.2	45.5	17.5	67.3	0.687	1.389	9.75	6.35	20.28	1.98	3.36
3229	0	1.25	1.75	47	1	27.3	27.3	45.4	17.5	67.3	0.680	1.390	7.54	6.56	20.40	2.15	3.92
3230	0	1.25	1.75	47	2	26.6	26.6	44.9	17.7	66.9	0.700	1.408	8.27	5.62	18.74	1.70	2.80
3231	0	1.25	1.75	52	0	25.9	25.9	48.5	16.5	69.3	0.612	1.310	10.39	9.30	27.22	3.19	5.04
3232	0	1.25	1.75	52	1	26.9	26.9	48.3	16.5	69.1	0.607	1.313	8.02	9.53	27.20	3.45	6.16
3233	0	1.25	1.75	52	2	26.5	26.5	47.8	16.7	68.9	0.628	1.330	8.80	8.22	25.11	2.69	4.48
3236	0	1.25	1.75	57	2	26.0	26.0	50.1	15.8	70.2	0.561	1.259	9.49	11.46	31.72	4.10	6.96
3242	0	1.25	2	47	2	27.0	27.0	44.2	17.9	66.4	0.711	1.425	6.76	5.30	17.54	1.59	2.64
3249	0.25	1	1.75	42	0	26.5	26.5	43.3	18.1	65.9	0.716	1.438	8.74	5.11	16.95	1.47	2.40
3251	0.25	1	1.75	42	2	27.2	27.2	42.9	18.3	65.5	0.727	1.455	7.26	4.51	15.52	1.23	1.80
3264	0.25	1	2	47	0	25.7	25.7	46.1	17.4	67.7	0.653	1.378	7.04	7.33	21.84	2.26	3.60
3266	0.25	1	2	47	2	26.3	26.3	45.5	17.6	67.4	0.664	1.395	5.93	6.42	20.12	1.87	2.84
3289	0.25	1.25	2	47	1	23.8	23.8	44.0	18.0	66.2	0.712	1.430	7.24	4.90	16.82	1.44	2.16
3295	0.25	1.25	2	57	1	22.6	22.6	49.1	16.2	69.6	0.582	1.289	9.09	9.71	28.64	3.29	5.20

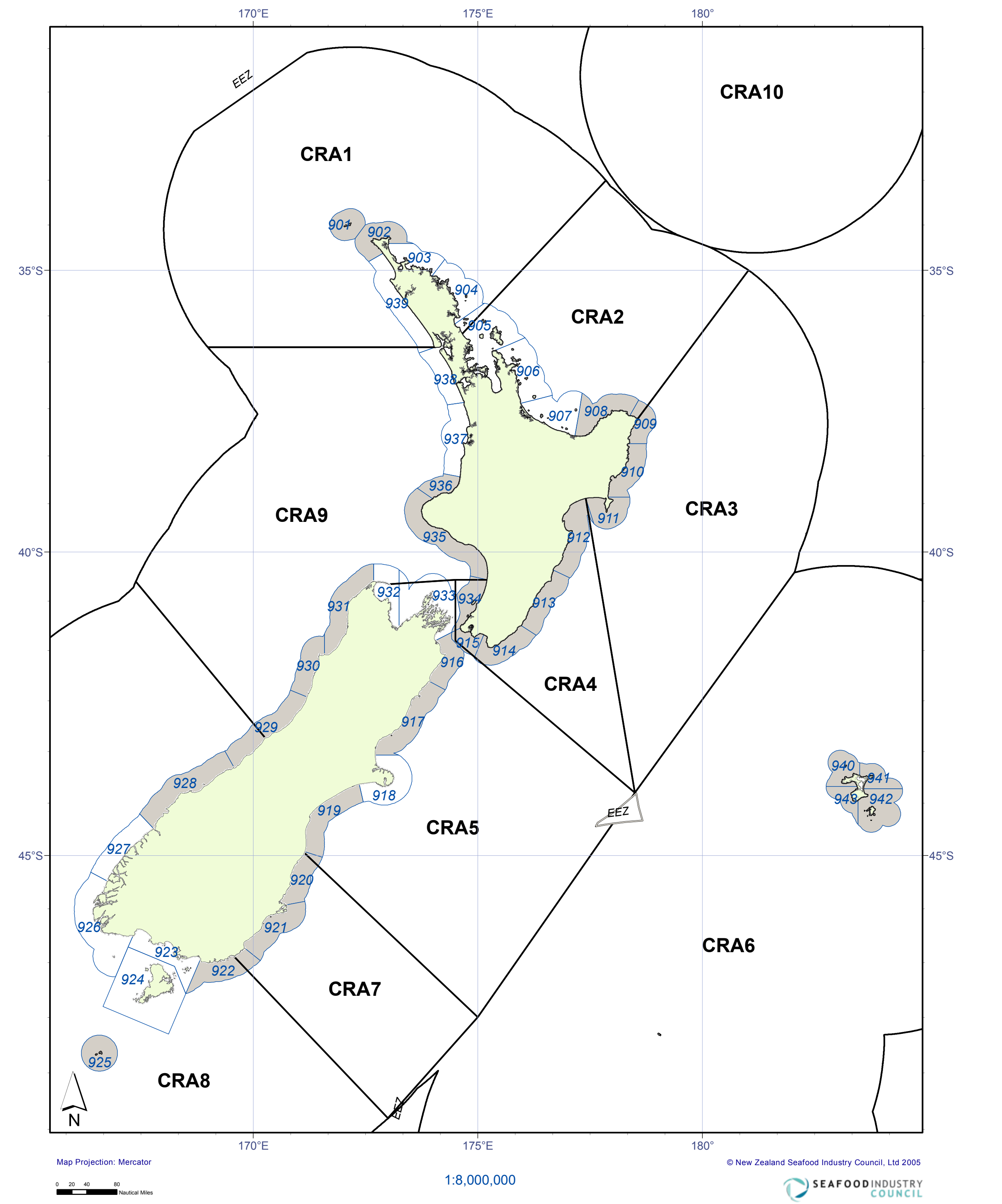

Figure 1: New Zealand rock lobster QMAs and statistical areas (courtesy of the New Zealand Seafood Industry Council).

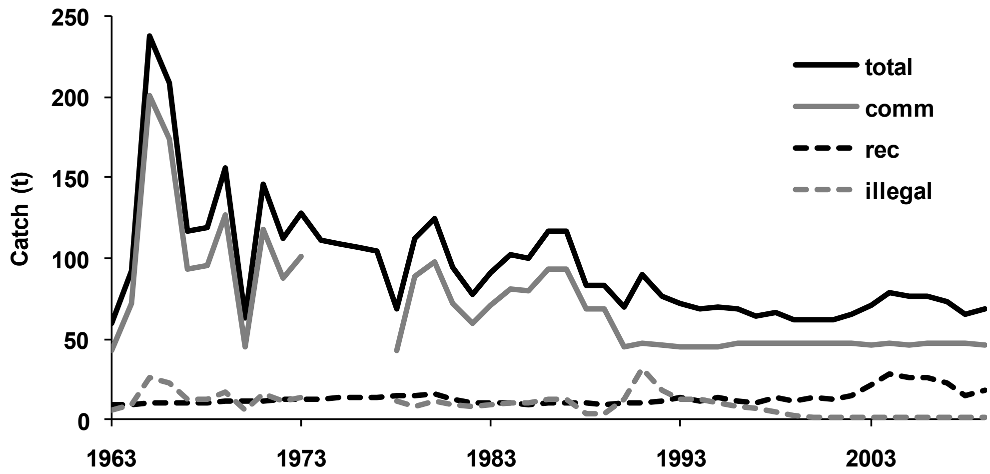

Figure 2: Total, commercial, estimated recreational and illegal catch vectors from CRA 9, 1963–2009.

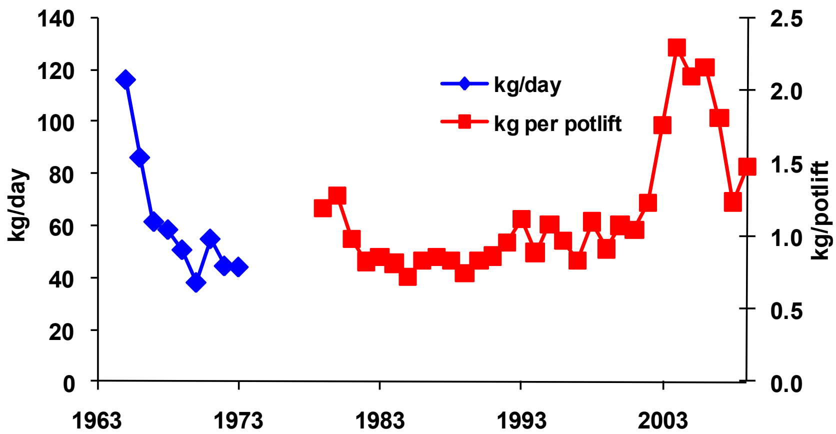

Figure 3: Catch per day diamonds) and standardised catch per potlift from CRA 9.

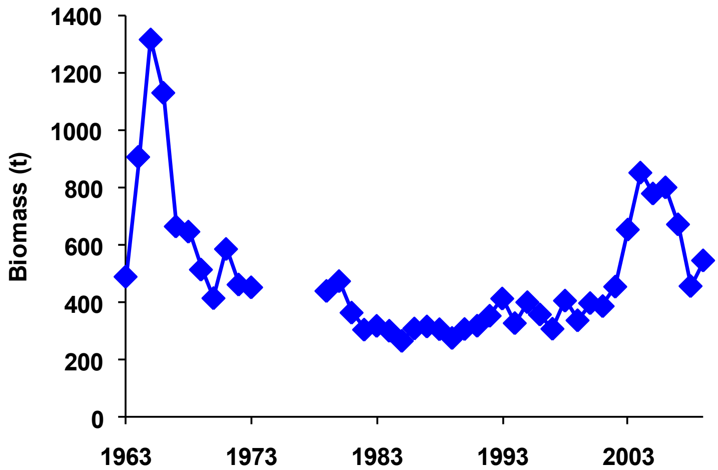

Figure 4: CRA 9 biomass estimated from the simple method described in the text.

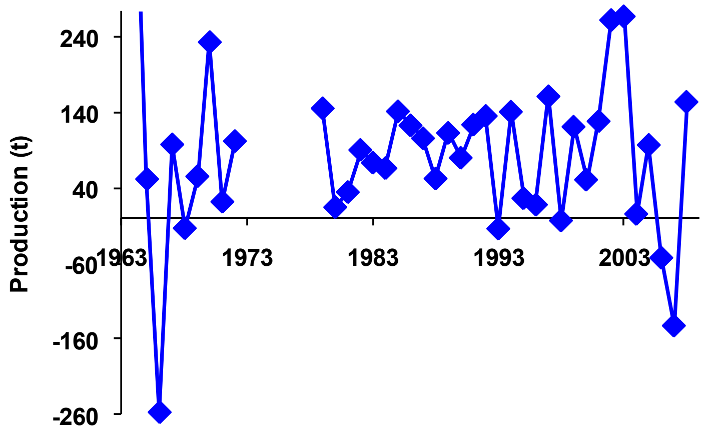

Figure 5: Annual CRA 9 production estimated from the simple method described in the text.

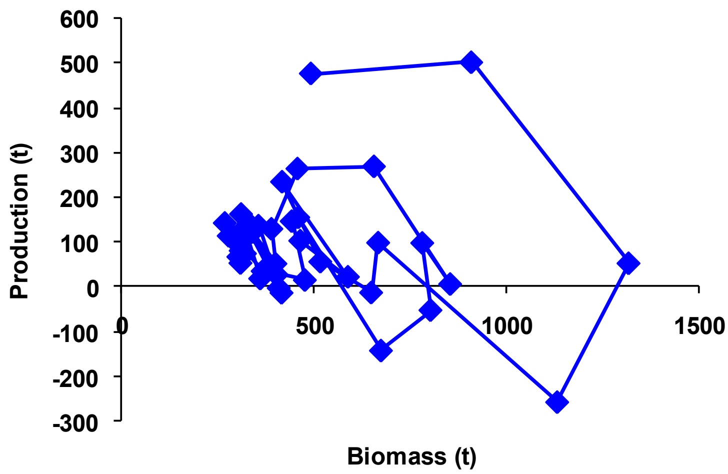

Figure 6: Estimated annual CRA 9 production plotted against estimated biomass, 1963-2009.

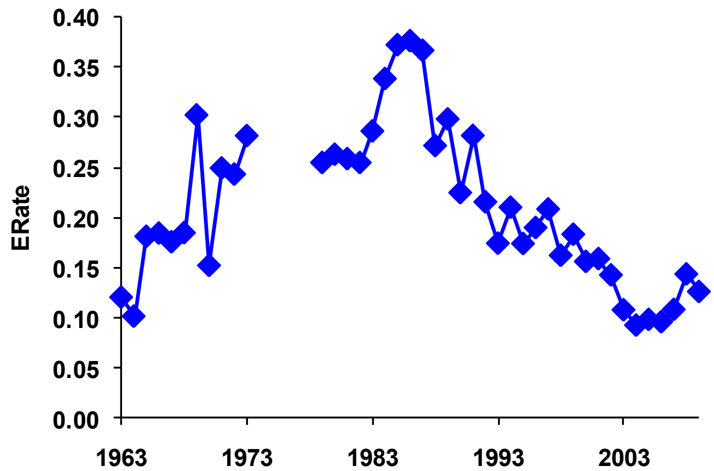

Figure 7: CRA 9 exploitation rate estimated from the simple method described in the text.

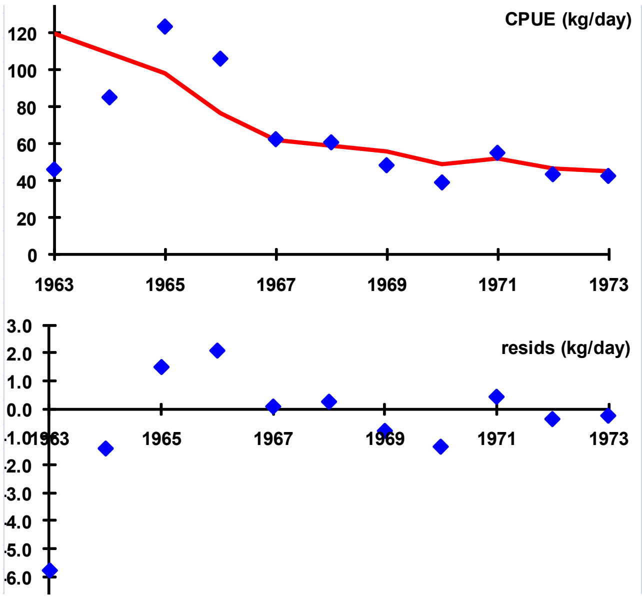

Figure 8: The fit to CPUE (kg/day) (upper) from the base case MPD fit with the surplus production model: diamonds are the observed and the line is the predicted CPUE; and normalised residuals from the fit (lower).

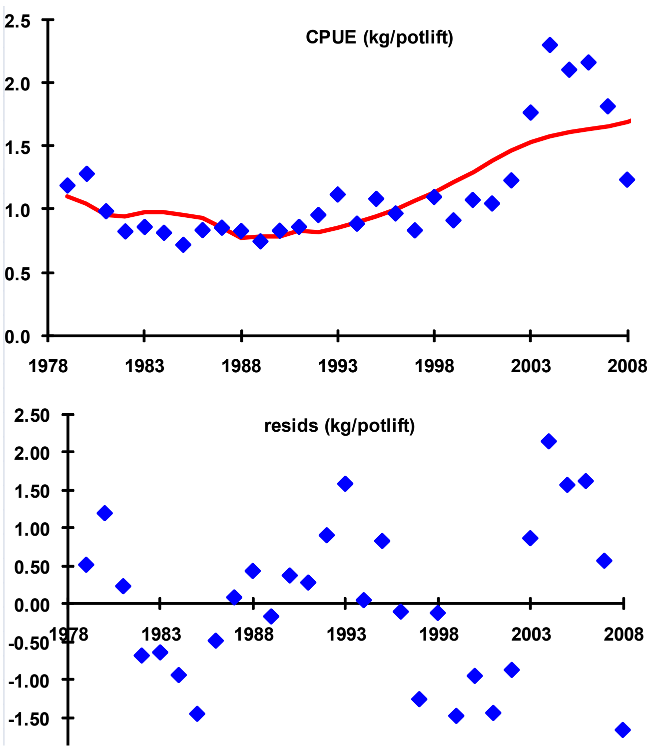

Figure 9: The fit to CPUE (kg/pot) (upper) from the base case MPD fit with the surplus production model: diamonds are the observed and the line is the predicted CPUE; and residuals from the fit (lower).

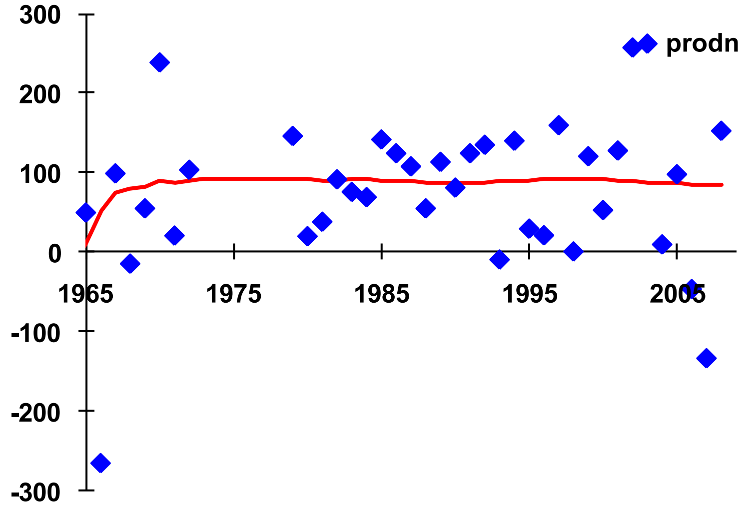

Figure 10: The relation between observed (diamonds) and predicted (line) production trajectories (t) from the base case MPD fit with the surplus production model. Two very high production values are off the scale and not shown.

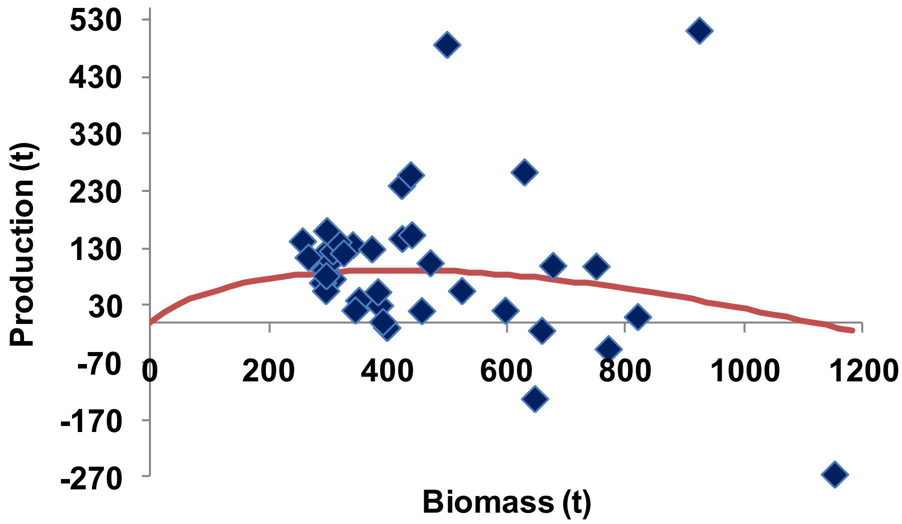

Figure 11: From the base case MPD fit with the surplus production model, comparing observed production (diamonds) and predicted production (line) as functions of biomass.

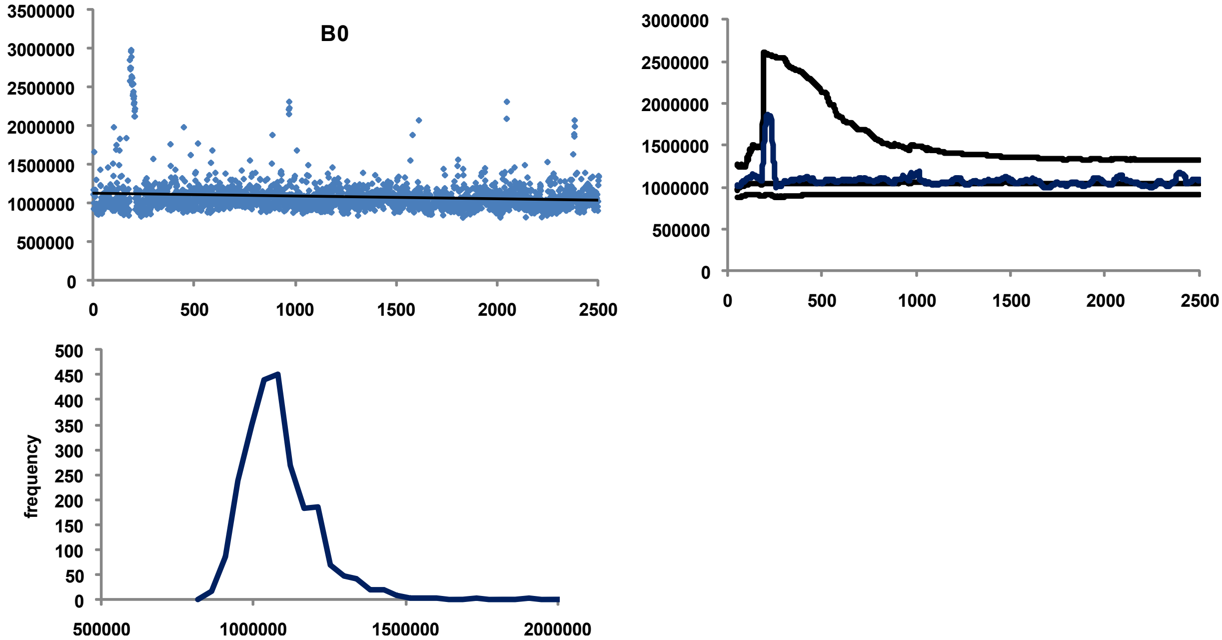

Figure 12: Diagnostic plots for *K*: top left shows the trace and a trendline; top right shows a running median with 5th and 85th quantiles (outside lines and smoother central lines) and a moving average over 50 samples (jagged central line); the bottom plot shows the posterior distribution.

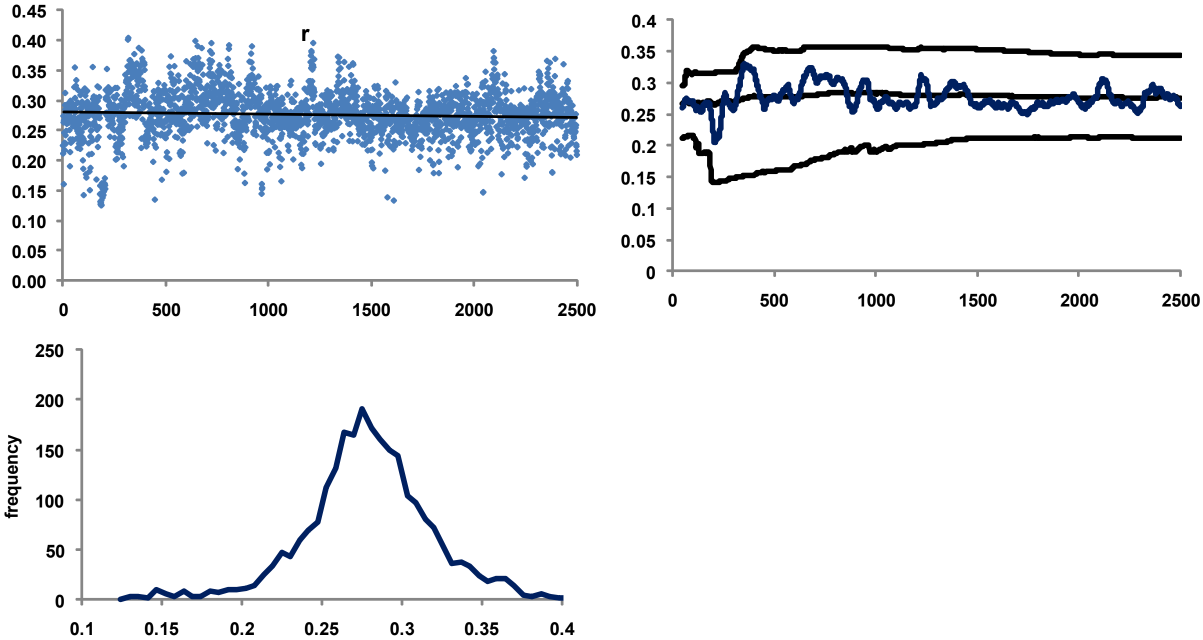

Figure 13: Diagnostic plots for *r* : top left shows the trace and a trendline; top right shows a running median with 5th and 85th quantiles (outside lines and smoother central lines) and a moving average over 50 samples (jagged central line); the bottom plot shows the posterior distribution.

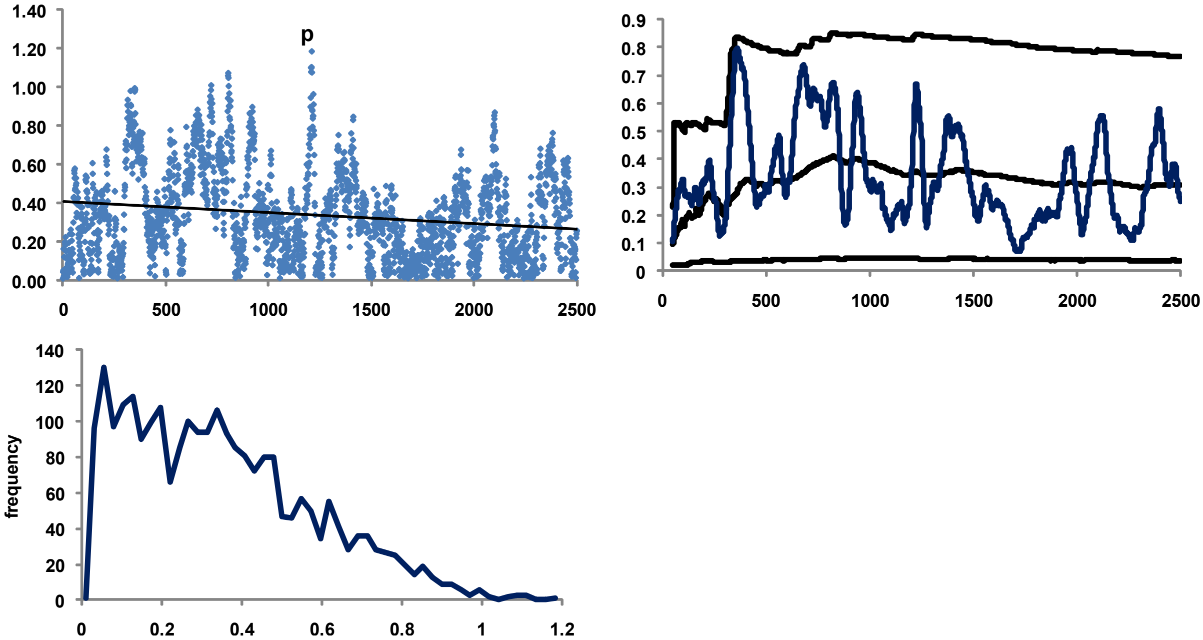

Figure 14: Diagnostic plots for *p* : top left shows the trace and a trendline; top right shows a running median with 5th and 85th quantiles (outside lines and smoother central lines) and a moving average over 50 samples (jagged central line); the bottom plot shows the posterior distribution.

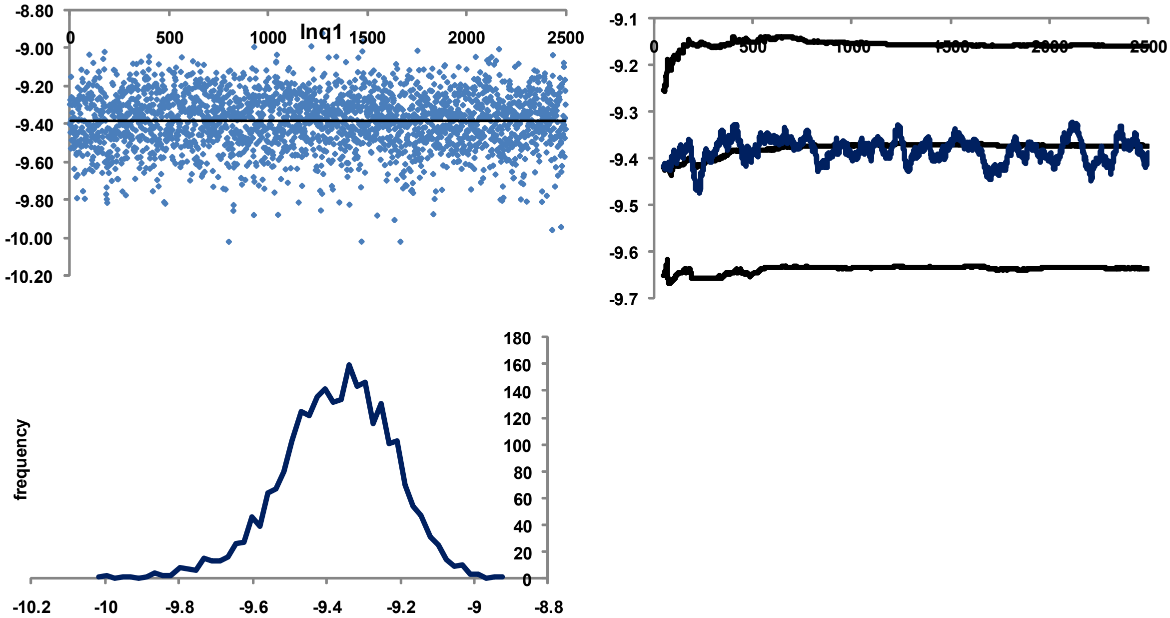

Figure 15: Diagnostic plots for ln(*q1*): top left shows the trace and a trendline; top right shows a running median with 5th and 85th quantiles (outside lines and smoother central lines) and a moving average over 50 samples (jagged central line); the bottom plot shows the posterior distribution.

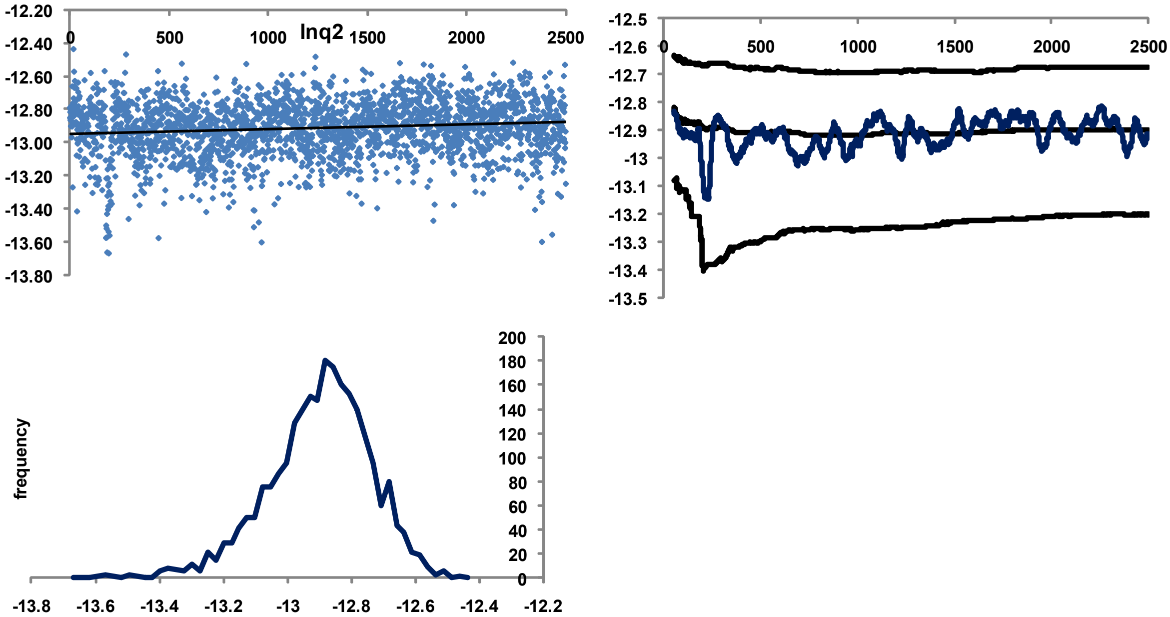

Figure 16: Diagnostic plots for ln(*q2*): top left shows the trace and a trendline; top right shows a running median with 5th and 85th quantiles (outside lines and smoother central lines) and a moving average over 50 samples (jagged central line); the bottom plot shows the posterior distribution.

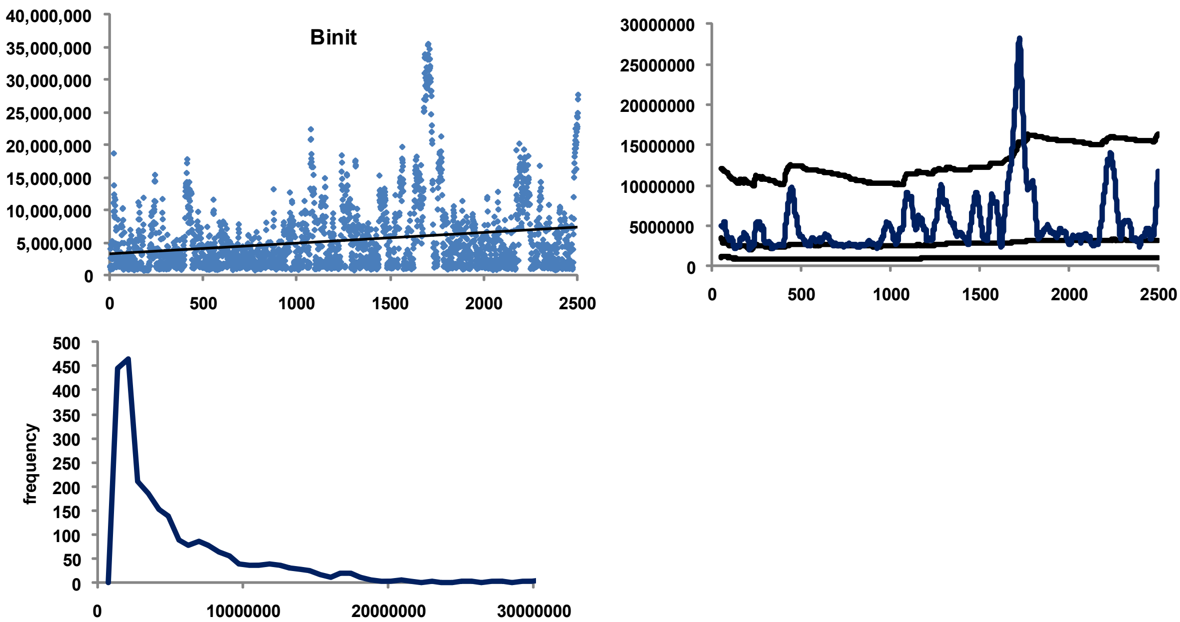

Figure 17: Diagnostic plots for *Binit* : top left shows the trace and a trendline; top right shows a running median with 5th and 85th quantiles (outside lines and smoother central lines) and a moving average over 50 samples (jagged central line); the bottom plot shows the posterior distribution.

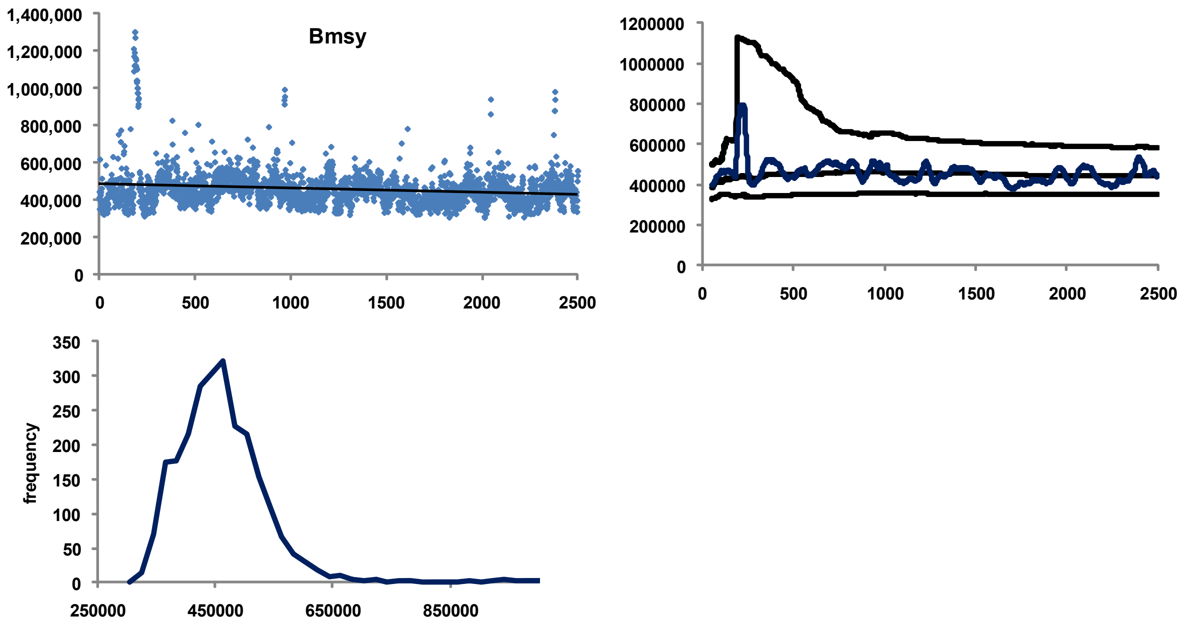

Figure 18:Diagnostic plots for *Bmsy* : top left shows the trace and a trendline; top right shows a running median with 5th and 85th quantiles (outside lines and smoother central lines) and a moving average over 50 samples (jagged central line); the bottom plot shows the posterior distribution.

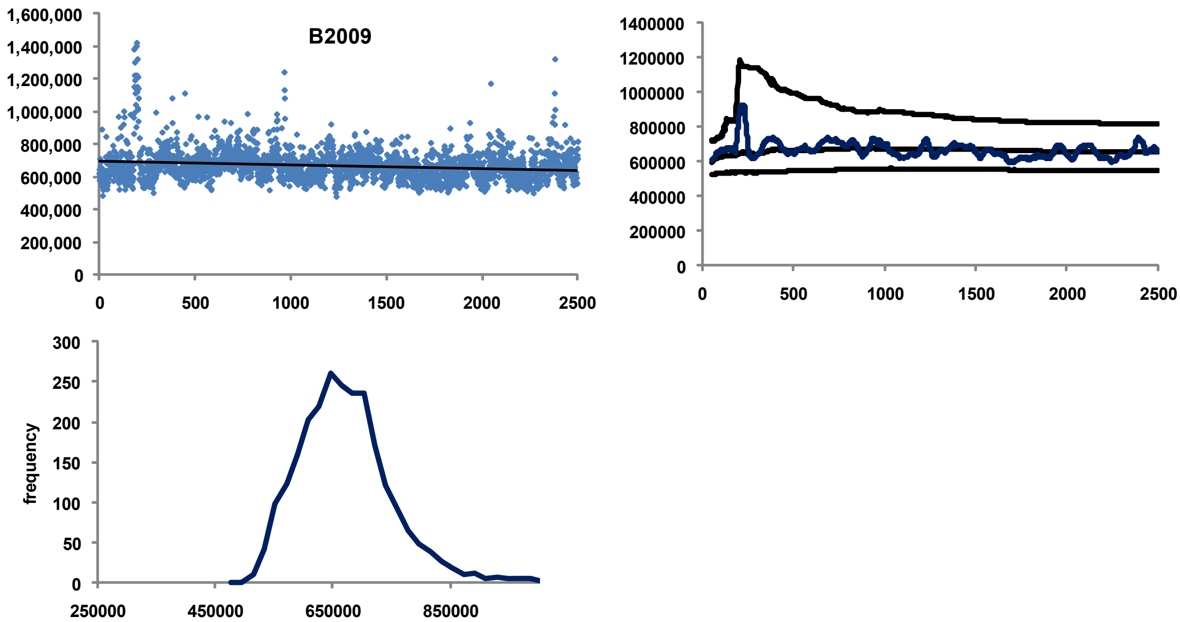

Figure 19: Diagnostic plots for *B2009* : top left shows the trace and a trendline; top right shows a running median with 5th and 85th quantiles (outside lines and smoother central lines) and a moving average over 50 samples (jagged central line); the bottom plot shows the posterior distribution.

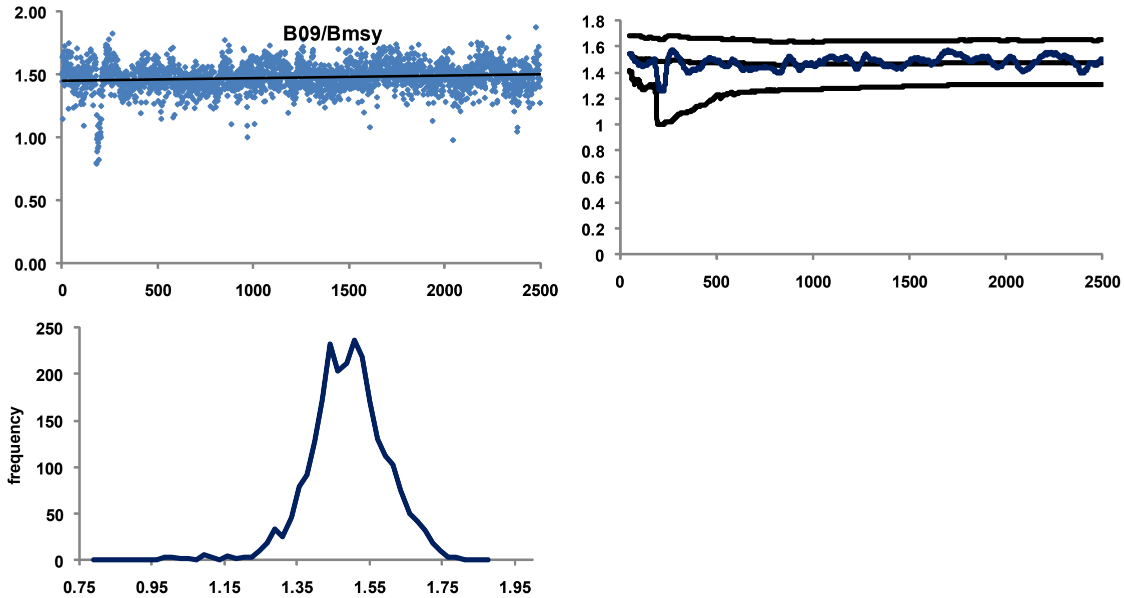

Figure 20: Diagnostic plots for *B2009/Bmsy* : top left shows the trace and a trendline; top right shows a running median with 5th and 85th quantiles (outside lines and smoother central lines) and a moving average over 50 samples (jagged central line); the bottom plot shows the posterior distribution.

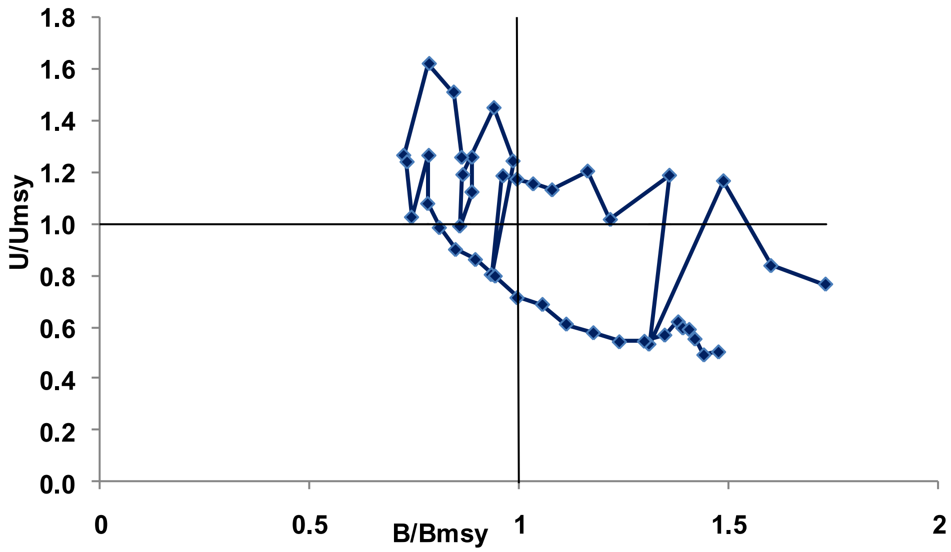

Figure 21: Snail trial of the CRA 9 fishery: the x-axis is the mean of the posterior distribution of biomass as a proportion of *Bmsy*; the y-axis is the mean of the posterior of exploitation rate as a proportion of equilibrium exploitation rate at *Bmsy*; the horizontal line is 1.0 (equilibrium exploitation rate at *Bmsy*); the vertical line is the median of *B/Bmsy*. Current values are on the lower right. The point at upper right is 1967; the point at lower right is 2009.

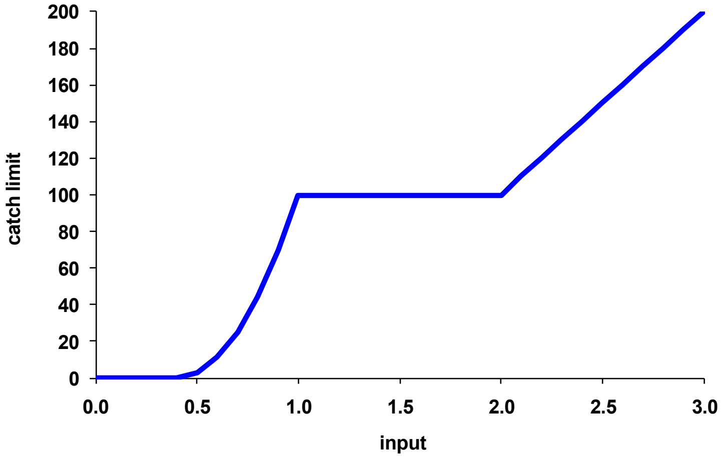

Figure 22: A hypothetical example of the generalised harvest control rule.

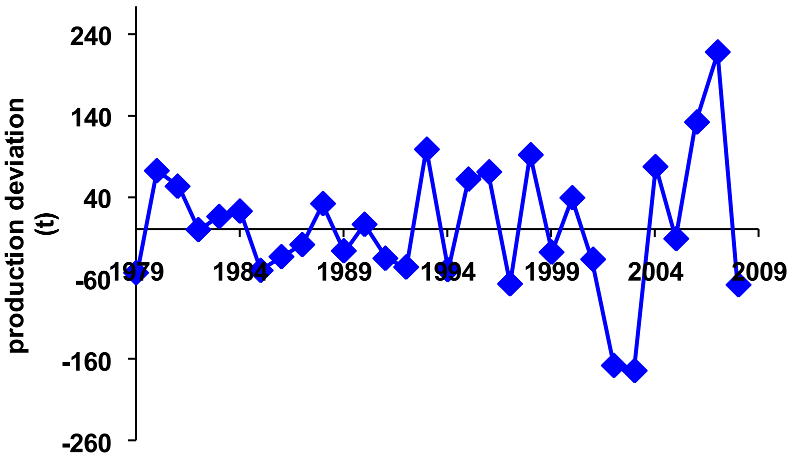

Figure 23: Production deviations from the MPD of the surplus production model.

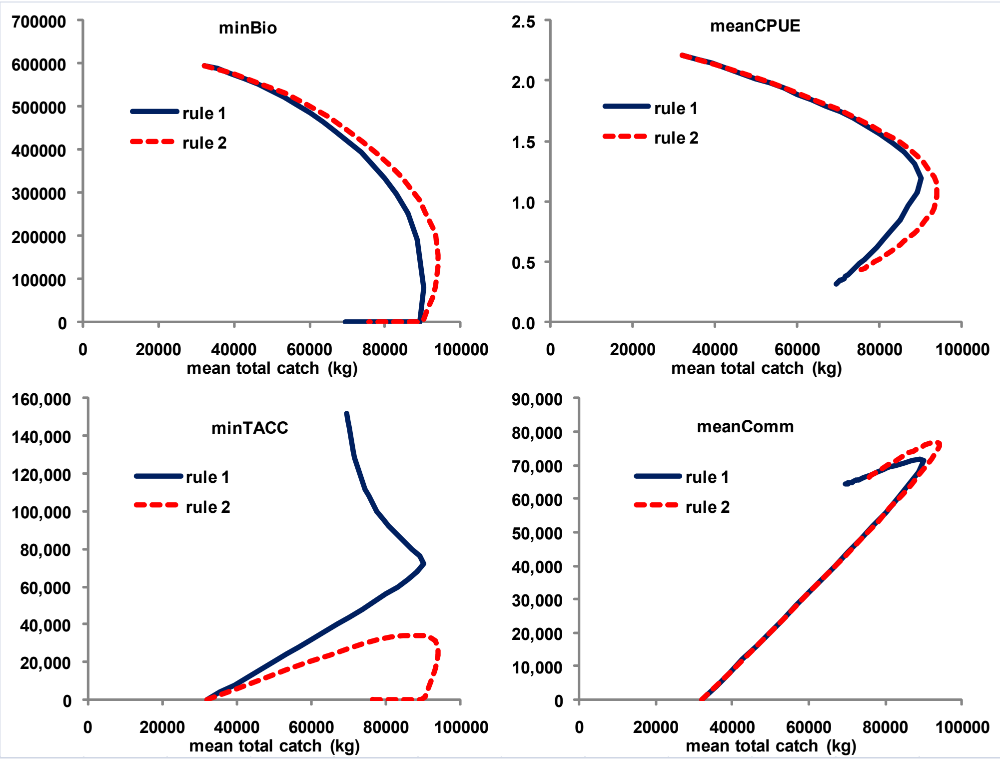

Figure 24: Some indicator summaries from preliminary explorations with the operating model using rule 1 with constant TACs (sold line) and rule 2 with CPUE multipliers (dashed line).

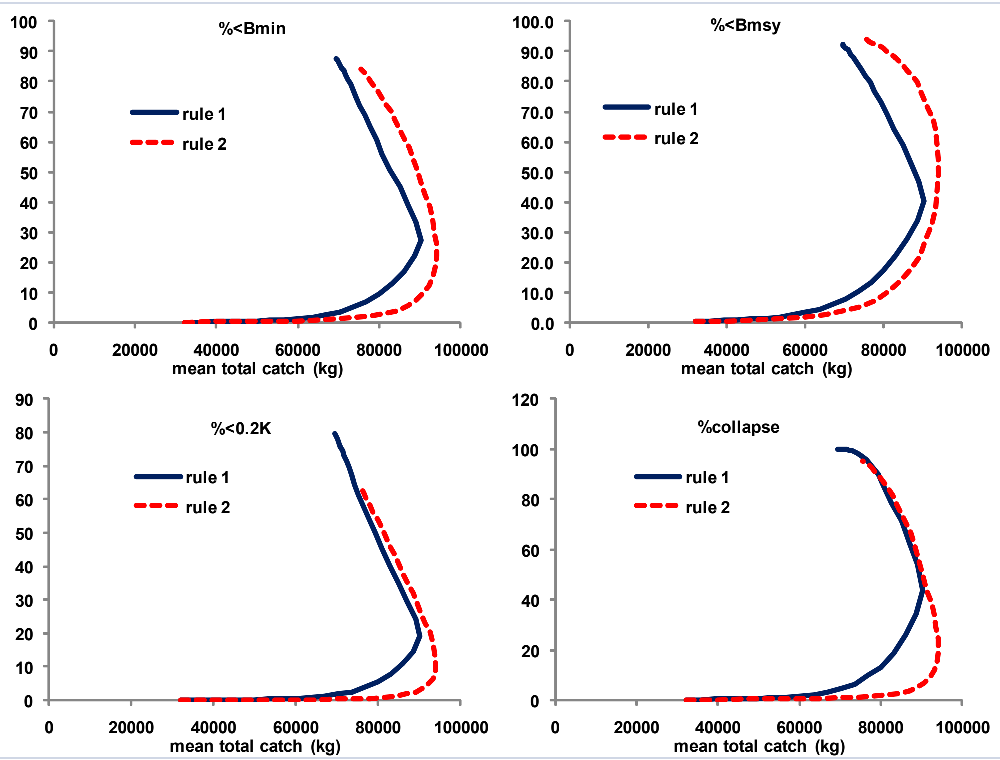

Figure 25: Some indicator summaries from preliminary explorations with the operating model using rule 1 with constant TACs (solid line) and rule 2 with CPUE multipliers (dashed line).

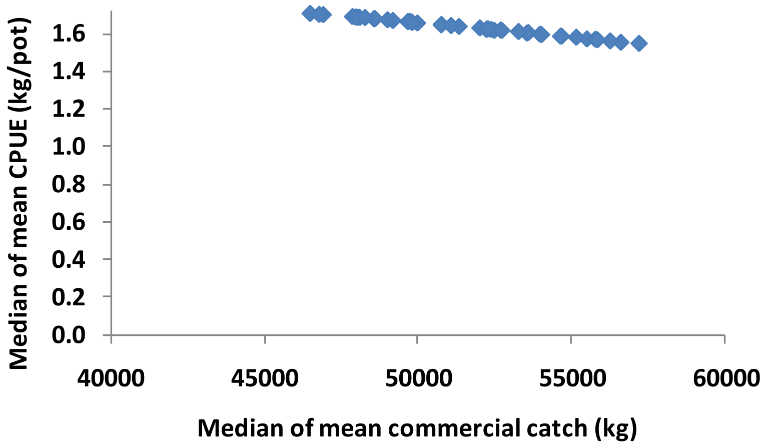

Figure 26: Average CPUE vs. average commercial catch in the 44 harvest control rules that survived screening.

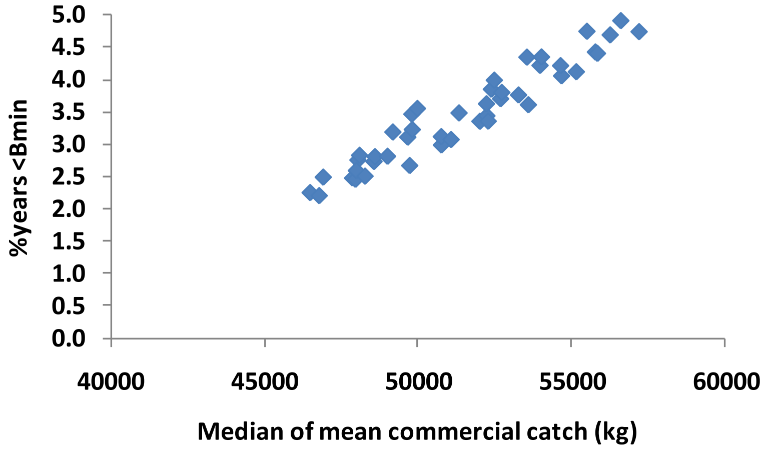

Figure 27: Percentage of years with biomass less than *Bmin* vs. average commercial catch in the 44 harvest control rules that survived screening.

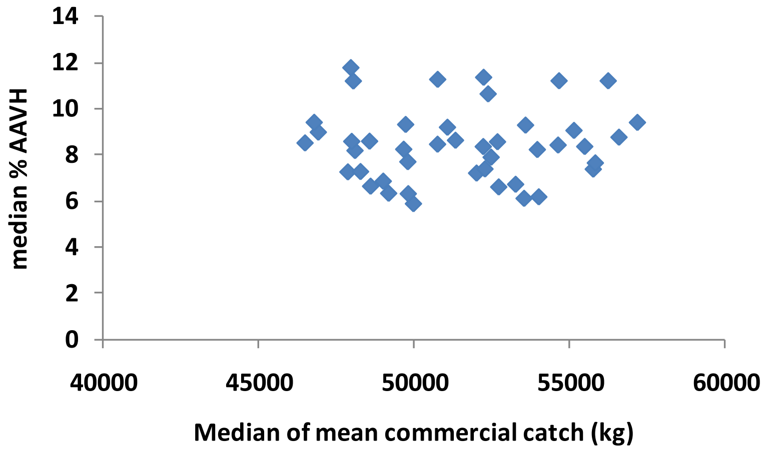

Figure 28: Median percentage AAVH vs. average commercial catch in the 44 harvest control rules that survived screening.

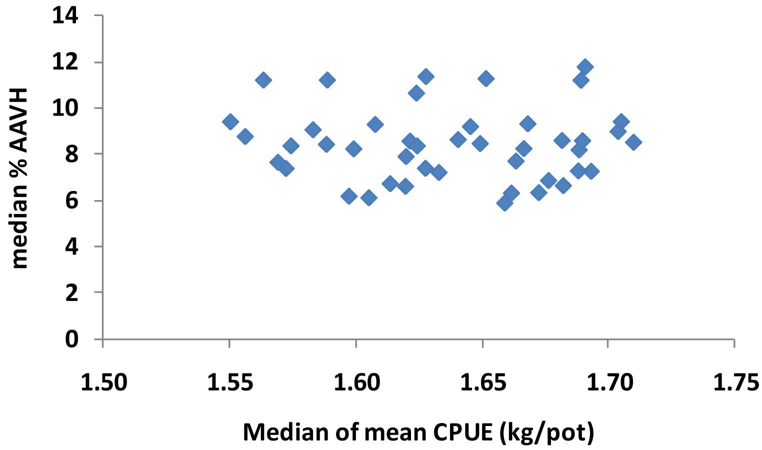

Figure 29: Median percentage AAVH vs. average CPUE in the 44 harvest control rules that survived screening.

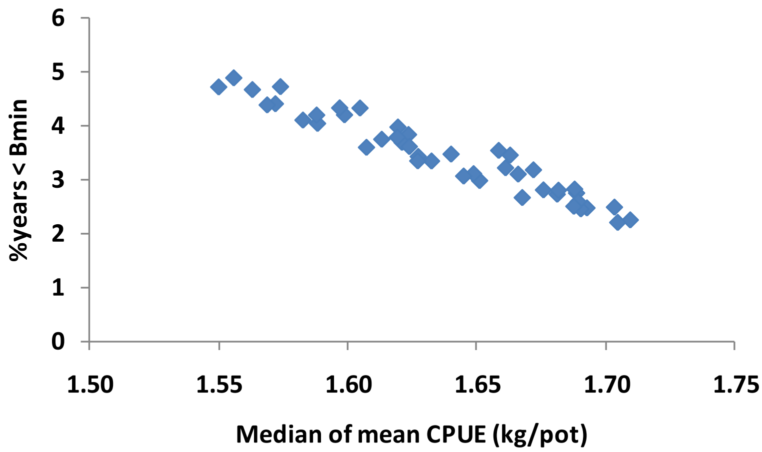

Figure 30: Percentage of years with biomass less than *Bmin* vs. average CPUE in the 44 harvest control rules that survived screening.

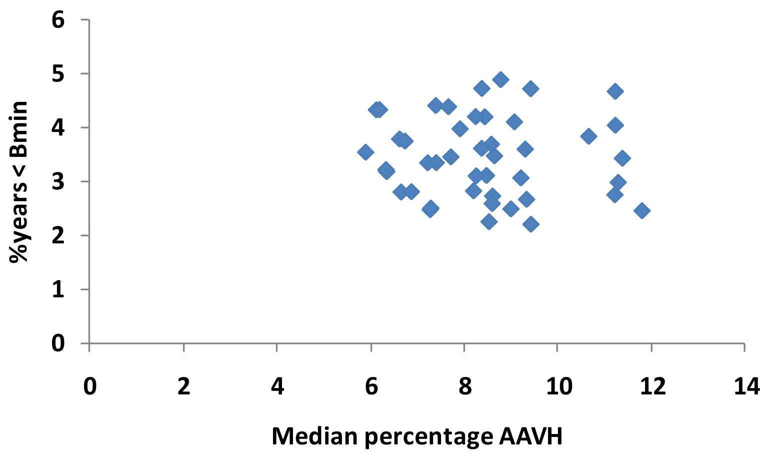

Figure 31: Percentage of years with biomass less than *Bmin* vs. average AAVH in the 44 harvest control rules that survived screening.

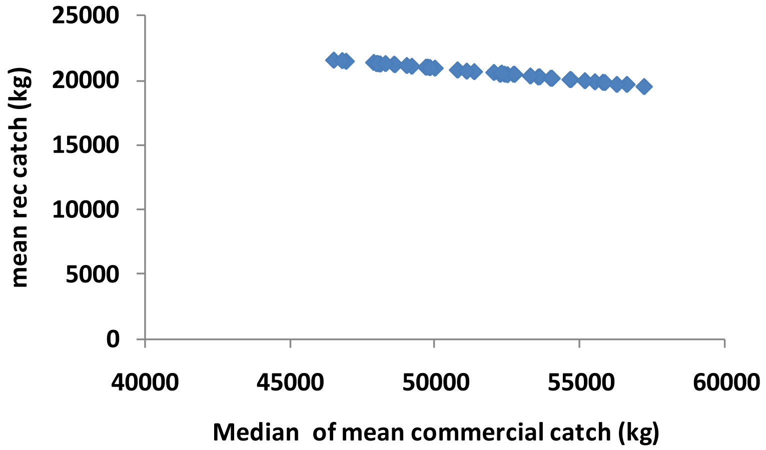

Figure 32: Average recreational catch vs. average commercial catch in the 44 harvest control rules that survived screening.

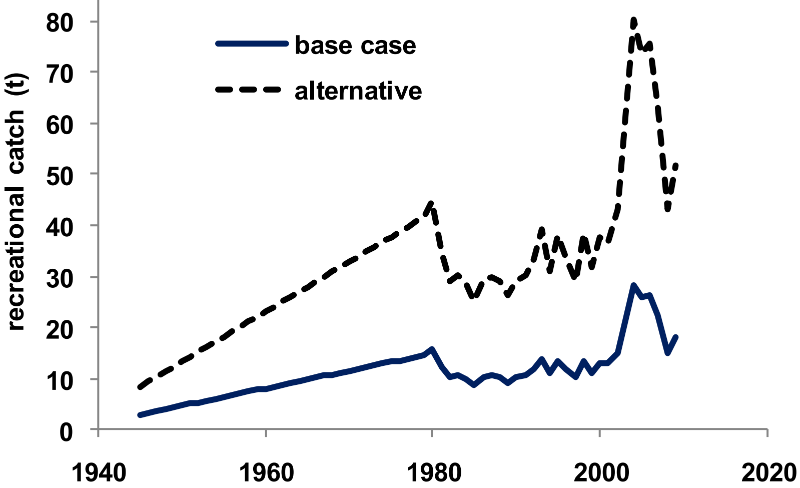

Figure 33: Comparison of the assumed recreational catch in the base case (solid line), based on 1994 and 1996 surveys, and robustness trial 1, based on 2000-01 surveys (dashed line).

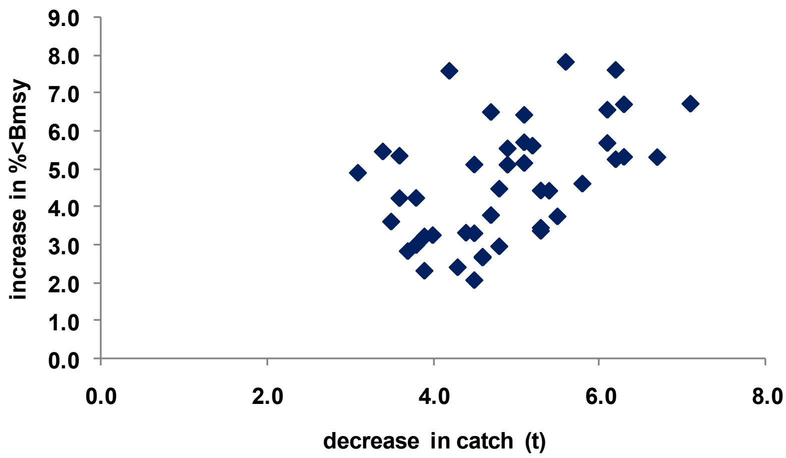

Figure 34: From the second robustness trial, the increase in *%<Bmsy* plotted against the decrease in median commercial catch when compared with the base case.