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Trends in surplus production in New Zealand rock lobster stocks (*Jasus edwardsii*)

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EXECUTIVE SUMMARY

Breen, P.A. (2018). Trends in surplus production in New Zealand rock lobster stocks (*Jasus edwardsii*).

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For seven stocks of New Zealand red rock lobster (*Jasus edwardsii*), annual surplus production was calculated from total catch, standardised CPUE and catchability. Catchability and total catch estimates were taken from recent stock assessments made with length-based models. In an extended model, errors in CPUE and catchability estimates were incorporated. Surplus production showed downward trends in all stocks from 1979–2015. A general parabolic model was fitted to predict observed production as a function of biomass and mean annual sea surface temperature (SST) specific to each stock at a variety of assumed lags between the years of temperature and production.

For most stocks, both temperature and biomass explained some of the variability in annual production. Temperature effects were negative for five of the seven stocks (higher temperature reduced productivity). The residuals from the biomass and temperature model were regressed against year to assess the residual trends in production. For 1979–2015, annual production showed negative trends in all stocks except CRA 5, and trends from 1990–2015 were negative in five of the seven stocks and positive in one stock.

This study shows declining lobster productivity over time, some but not all of which is explained by changes in biomass and temperature. Whatever the cause, this has implications for industry, stock assessment and management.

1. INTRODUCTION

Simple surplus-production analyses have been made for lobsters in the past for several reasons, even after the development of biologically detailed length-based models such as MSLM (Haist et al. 2009) and LSD (Webber et al. 2017). For instance, Breen (2009) used a surplus-production model as an operating model to develop a voluntary management procedure for CRA 5. He compared results from this approach with those from the length-based model (Breen 2011) and found that the approach was defensible. Breen & Starr (2010) calculated annual surplus production from several stocks to compare with puerulus settlement indices and a variety of environmental indices.

A summary of the method is given by Hilborn (2001) for survey data: it assumes that the survey index is proportional to abundance and that catches are known. These assumptions are the same as those used by the length-based models. Hilborn suggests that this simple approach can lead to robust conclusions, and he recommends:

> *... that agencies should calculate the surplus production using the method described in this paper in addition to any other stock assessment models being used.*

Using this method, rather than exploring production trends using the stock assessment model, has two advantages. By using the simple model, one can explore all the stocks with the most recent data. Stock assessments are usually done for one or two stocks, at most three stocks each year, so the stock assessments are always out of date by three or four years for some stocks. Second, the stock assessment model is almost always changed in some way each year; these changes are documented but the results for different stocks assessed at different times may not be strictly comparable: using the simple model ensures that the same method is used for all stocks and that their trends are comparable.

A common theme in the fisheries literature is that catchability (q) can change over time, usually increasing because of changes in technology or the environment (see, for instance, the review by Eigaard et al. 2014). For lobsters, this was a major concern for management in Western Australia when management was based on pot limits. The pioneering work of Brown et al. (1995) showed that GPS and sounders had caused large increases in pot efficiency. Hall & Chubb (2001) assumed a 1–2% annual increase in gear efficiency in the Western Australian fishery. deLestang et al. (2012) compared standardised CPUE from fishermen's data with catch rates from fishery-independent breeding surveys and estimated annual increases in effort efficiency of 0.5 to 4.0%. They also used the in-season depletion analysis described by Wright et al. (2006) and estimated annual increases from 2.3 to 8.1%, with high uncertainties. Wright et al. (2006) had estimated a roughly 7% annual increase in catchability but ascribed some of this to decreased total effort, with less competition among pots, rather than technological changes.

There is no comparable work on fishing power changes for New Zealand rock lobsters, but it seems likely that catchability has increased since 1979 because of improved fishing technology (including faster and more capable boats), decreased competition among pots, decreased competition among fishermen and increased lobster abundance that allows fishing to concentrate on the more abundant areas. This study assumed an arbitrary annual catchability increase of 1.5%, based on a literature survey (Breen unpublished).

Breen & Starr's (2010) exploration of correlations between annual productivity and a variety of environmental indices followed indices used by Hurst et al. (2012): the southern oscillation index, the interdecadal Pacific oscillation, Kidson climate regimes (Kidson 2000) and sea surface temperatures obtained from NOAA satellites (Mark Hadfield, NIWA, pers. comm.). The only substantial results were negative correlations between SST and estimated annual productivity in CRA 3 and CRA 4 with lags of 0 to 4 years. In this study, only sea surface temperature (SST) was explored. Instead of calculating production and then making correlations with SST, SST effects were included in the model that predicted production from biomass. Thus the confounding effects of biomass (if any), SST (if any) and time could be estimated and separated.

This study explored the effects of uncertainty in catchability, taken from the stock assessments, and in CPUE, taken from the standardisation model. The standard errors of catchability and annual CPUE were used to produce 999 randomised sets of CPUE, each with a randomised *q*, and the model was fit to the single non-randomised data set and the 999 randomised sets; quantities of interest were based on distributions of 1000 model results.

There is also, of course, uncertainty in commercial and non-commercial catches. Non-commercial catches are especially poorly known: the illegal catch is thought to be the largest segment of this but there is no documented methodology for, and much variation in, the various estimates that have been provided by the Ministry over time. Recent recreational catches and their uncertainty are reasonably well estimated (e.g. Wynne-Jones et al. 2014), but long-term trends and scales of uncertainty around illegal and recreational catches are unknown; thus there is no formal way to address catch uncertainty in the model.

2. DATA

Input data were catch, CPUE, catchability and sea surface temperature (SST) for each of stocks CRA 1 through CRA 5, CRA 7 and CRA 8 (see Figure 1 for stocks). There has never been a length-based CRA 6 stock assessment, so CRA 6 was not analysed in this study. For CRA 9, CPUE is not considered reliable because of the few vessels fishing and the very large size of the area, so CRA 9 was not addressed.

As in the stock assessment, data were collated by fishing year, running from 1 April through 31 March; viz. “1992” refers to the 1992–93 fishing year.

2.1 Catch

Paul Starr (Starrfish, pers. comm.) provided annual commercial catch for CRA 1 through CRA 8 in September 2017. Non-commercial catch trajectories were taken from the most recent assessment for each stock:

- CRA 1: Webber & Starr (2015)
- CRA 2: assessed 2017: Paul Starr (Starrfish) and D’Arcy Webber (Quantifish), pers. comm.
- CRA 3: Haist et al. (2015)
- CRA 4: Breen et al. (2017)
- CRA 5: Starr & Webber (2016)
- CRA 7 and CRA 8: Haist et al. (2016).

Stock assessments used the Bayesian length-based model MSLM (Haist et al. 2009) or (CRA 2) the analogous LSD model of Webber et al. (2017). Total catch was the sum of commercial and non-commercial catches. Non-commercial catches for the period after the most recent assessment were provided by Paul Starr (Starrfish, pers. comm.) in June 2016, simply extended from the last year of estimates. Total catches are shown in Table 1 and Figure 2.

2.2 CPUE

Paul Starr (pers. comm.) provided standardised annual CPUE estimates by stock (Table 2 and Figure 2) in September 2017, based on a September extract of the 2016–17 data and collated with the F2-LFX algorithm (see Starr 2017 for description of the collation and standardisation of data). Estimated standard errors (Table 3) of the year effects were also provided.

2.3 Catchability

For each stock the catchability coefficient, q, was taken as the median of the base case posterior from the most recent stock assessment (Table 4) and its standard error was based on the standard deviation of the posterior distribution. Where there were two base cases, the mean of the two medians and the higher of the two standard errors were used. For CRA 2, the q used here was the MPD estimate from a fit that was comparable to those made in other years (Paul Starr, Starrfish, and D'Arcy Webber, Quantifish, pers. comm; the actual 2017 stock assessment used a more complex procedure). For CRA 2 the s.e. of q was taken as the mean s.e. from the other stocks.

2.4 Temperature

NOAA satellite SST was obtained by Mark Hadfield (NIWA, pers. comm.) for September 1981 through June 2016 for the one-degree rectangle of sea surface adjacent to the coast for each stock (Table 5). The data were summarised by month by Mark Hadfield. For each stock, the average SST for each complete fishing year was calculated, 1982 through 2015 (Table 6), then for each year for each stock the anomaly was calculated as the annual mean minus the overall mean. For fishing years 1979–81, for which there was no mean annual SST, the mean of 1982–84 was assumed as the mean SST.

SST showed an increasing trend in all stocks (Table and Figure 3), with regressions predicting an increase of 0.2 to 1.0° C between the 1982 and 2015 fishing years.

3. BASIC MODEL

For each stock for each year, CPUE was assumed to be proportional to mid-season stock biomass B_y^{mid} (the stock index is suppressed):

$$B_y^{mid} = I_y / q_y$$

where I_y is the standardised annual CPUE and q_y is the catchability coefficient in year y. The value of catchability obtained from the stock assessment, q^{med}, was applied to 1997 for each stock; 1997 was chosen so that mean q_y in 1979–2016 was near exp(q^{med}). For years before 1997:

$$q_y = q_{y+1} / 1.015$$

and for years after 1997:

$$q_y = 1.015 q_{y-1}$$

Biomass at the start of a season was calculated in the basic model as:

$$B_y^{start} = B_y^{mid} + 0.5 C_y$$

where C_y is the total catch in year y. "Observed" annual production P_y was calculated as change in biomass plus the catch:

$$P_y = B_{y+1}^{start} - B_y^{start} + C_y$$

This is the same method as described by Hilborn (2001) except that a survey index was replaced by CPUE and (as in the stock assessment) CPUE was assumed to be related to mid-season biomass. An empirical relation was fit between production and start-of-season biomass using a purely descriptive polynomial:

$$\hat{P}_y = a + bB_y^{start} - c\left(B_y^{start}\right)^2$$

where $\hat{P}_y$ is the predicted production in year *y*. This polynomial does not assume any relation between production and biomass: if *a* is the mean production and *b* and *c* are zero then the relation is a flat line, and nothing prevents the polynomial from being convex upwards instead of downwards. This relation was extended to include the effect of SST:

$$\hat{P}_y = \exp\left(d\left(T_{y-Tlag} - \bar{T}\right)\right)\left[a + bB_y^{start} - c\left(B_y^{start}\right)^2\right]$$

where T_y is the SST in year *y*, $\bar{T}$ is the mean SST for the time series, *Tlag* is the assumed lag between SST and production and *d* is the estimated parameter for the effect of temperature. This descriptive model was fit assuming that the error is normal and estimating its magnitude:

$$-LL_y = \ln\sigma^P + 0.5\left(\frac{P_y - \hat{P}_y}{\sigma^P}\right)^2$$

where $-LL_y$ is the negative log-likelihood and σ^P is the estimated standard deviation of error. Initial values were set at *a* = mean production, *b* = *c* = *d* = 0 and σ^P = 50. The model was coded in AD ModelBuilder (Fournier et al. 2012).

The deviance explained by biomass and temperature, separately and together, was calculated by comparing the mean squared error from the various models with the deviance obtained when only the intercept was fitted. These comparisons used the values of *Tlag* that gave the best fit for each stock.

4. EXTENDED MODEL

The extended model explored uncertainty in the catchability coefficient and annual CPUE. Except for CRA 2, uncertainty in q^{med} was available as the standard deviation of the posterior median of ln(*q*) (Table 3) and for CRA 2 the mean from the other stocks was used.

The extended model was fitted to 1000 different sets of CPUE and *q*. In the first set there was no random uncertainty; for each of the next 999 draws, random noise was added to catchability and CPUE as described below.

4.1 Uncertainty in catchability

For each of the 999 draws, noise was added to q^{med} and applied to 1997:

$$q'_{k,1997} = \exp\left(\ln\left(q^{med}\right) + \varepsilon_k s.e.^q - 0.5\left(s.e.^q\right)^2\right)$$

where $q'_{k,1997}$ is the resulting catchability for 1997 in the *k*th draw, $\ln\left(q^{med}\right)$ is the median reported from the stock assessment, $s.e.^q$ is the reported standard error and ε_k is a random normal deviate for the *k*th draw. This value was then used to determine the $q_{k,y}$ values within the draw as described above.

4.2 uncertainty in CPUE

Uncertainty in estimated CPUE used the reported standard errors from the year effect in natural log space; for examples see Starr (2017) but the values used here are not yet published. In each of the 999 random draws, CPUE for each year was randomly chosen based on the reported value and its standard error:

$$I'_{k,y} = \exp\left(\ln\left(I_y\right) + \varepsilon_{k,y} s.e._y^I - 0.5\left(s.e._y^I\right)^2\right)$$

where $I'_{k,y}$ is the randomly drawn CPUE for year *y* in draw *k*, $\ln\left(I_y\right)$ is the natural log of estimated CPUE for year *y*, $\varepsilon_{k,y}$ is the random normal deviate for year *y* in the *k*th draw and $s.e._y^I$ is the standard error for CPUE in year *y*.

Mid-season biomass for the *y*th year in the *k*th draw became:

$$B_{k,y}^{mid} = I'_{k,y} / q'_{k,y}$$

start-of-season biomass became:

$$B_{k,y}^{start} = B_{k,y}^{mid} + 0.5C_y$$

and production was calculated as:

$$P_{k,y} = B_{k,y+1}^{start} - B_{k,y}^{start} + C_y$$

4.3 comparison with MSLM estimates

The distributions of annual production calculated with the extended model were compared with the surplus production posteriors for each stock. For this comparison to be comparable with MSLM, the extended model was run with no assumed increase in catchability.

5. INDICATORS AND RUNNING PROCEDURES

The basic model was run for each stock both with and without estimated SST effects, using a range of assumed lags (*Tlag*) from 0 to 5 when SST effects were estimated. Indicators included the parameters of the fitted model, *a, b, c* and σ^P, the SST effect *d* and the log-likelihood function (*-LL*). The trend in productivity that was not explained by changes in biomass and SST was explored by calculating the slope of a regression of the residuals against time. This was done for 1979–2015, the whole series of productivity estimates available, and also for 1990–2015, which comprises the period of management with the Quota Management System (QMS). The slope has units of tonnes per year, and this was divided by the mean P_y for the period to give a percentage annual change in productivity, which was called *anndec79* for 1979–2015 and *anndec90* for 1990–2015. The percentage effect on productivity of a 1° C increase in SST from the mean, *1degree*, was calculated as:

$$1degree = 100\left(\exp\left(d\right) - 1\right)$$

The effect of the assumed annual change in catchability was explored using the basic model and the best lag (the value of *Tlag* giving the minimum function value) for each stock.

The value of *Tlag* giving the best function value was then used in extended model runs to explore the effect of uncertainty on model results.

6. RESULTS

6.1 Basic model

Basic calculated production, ignoring uncertainty in catchability and CPUE, is shown in Table 7 and Figure 4. In all stocks, annual production showed a decreasing trend over time (Table 8), with predicted decreases from 1979–2015 from 32 t (CRA 1) to 720 t (CRA 8).

There was limited correlation in production between adjacent stocks. CRA 4 showed significant correlations in production with both adjacent stocks CRA 3 and CRA 5 (Table 9). CRA 7 and CRA 8 were significantly correlated but no other adjacent stocks were significantly correlated. Some non-adjacent stocks were significantly correlated: CRA 3 and CRA 5, CRA 8 with CRA 3, CRA 4 and CRA 5.

In the basic model fits using biomass and SST, all the estimated parabolas are dome shaped (positive *b*, negative *c*) (Table 10). Compared with estimating only the effect of biomass, estimating the effect of SST improved the fit only slightly (less than 2 likelihood units) for CRA 1, CRA 5 and CRA 7, but improved the fit by 8 to 14 units in the other stocks. At the best lag (the one with the smallest likelihood value) for each stock, the effect of increased SST was negative except in CRA 1 and CRA 7. The best lags varied from zero in CRA 3 to 4 years in CRA 1 and CRA 8; they were 1 or 2 years in the other stocks. The estimated *1degree* was usually greatest at the best lag and varied from -34% (CRA 3) to 72% (CRA 7).

The deviance explained by the basic models is shown in Table 11. Biomass and temperature explained a substantial part of the variation except in CRA 1 and CRA 7. Temperature explained more deviation than biomass in CRA 2, CRA 3 and CRA 4. In CRA 8, using both explained more deviance than the sum of deviances explained by these variables separately.

At the best lag value for each stock, the production residuals from 1979–2015 declined even when biomass and temperature were used, except in CRA 5 (Table 12 and Figure 5). The residual decline ranged roughly from 0.3% to 1.7% annually.

The effect of changing *qmult*, the assumed annual increase in catchability, is shown in Table 13. Effects on the likelihood and the SST effects were not great. In some stocks, but not all, increasing *qmult* was associated with increasing percentage decline in production from 1979–2015. Effects on *1degree* were small. Thus, model results do not appear to be driven by the assumed rate of change in catchability.

To summarise:

- calculated production declined in all stocks from 1979–2015
- the biomass model explained some of the decline in production
- SST to the model also explained some of the change in production
- the best lag between SST and production varied from 0 to 4 years
- at the best lag, the effect of increasing SST was negative except in CRA 1 and CRA 7
- except in CRA 5, there was residual decline in annual production not explained by biomass and SST

6.2 Extended model

The distributions of estimated and derived parameters from the extended model, using the best lag for each stock are summarised in Table 14. Except for the intercept parameter *a*, medians of distributions were reasonably close to the basic model results. All distributions of *anndec79* were negative, indicating that declining production was not all explained by biomass and SST, except for CRA 5. Median annual declines were less than 0.5% per year in CRA 1, CRA 2 and CRA 5, but were greater than 0.5% in the remaining stocks. As in the basic model, SST effects were negative in all stocks except CRA 1 and CRA 7.

The distribution of *anndec90* was positive in CRA 2 and straddled zero in CRA 7; in all the other stocks the annual change was negative, although very small in CRA 5.

All the fitted parabolas were dome-shaped except for 22 in CRA 1, 30 in CRA 4 and 1 in CRA 7. The fitted curves are summarised in Figure 6. For all stocks the curves tended to have zero production near zero biomass and near or just beyond the highest biomass observed. In other words, they were similar to a symmetric Schaeffer curve. The exception to this was CRA 4, where the curves suggest that highest production would occur beyond nearly all the observed biomass values. Thus for most stocks, variation in biomass explained some of the variation in production. For all stocks, the estimated SST effect was also substantial, suggesting that SST also had a strong signal.

Surplus production posteriors from the MSLM models for four stocks – the two with the best and two with the worst comparisons – are compared with the distributions from the extended model in Figure 7. Trends were very similar. Because the MSLM model is an observation-error time series model, biomass and thus production tends to be smoothed compared to the extended model.

7. DISCUSSION

Stock assessments compare the current state of the stock with previous states, and management procedure evaluations (MPEs) predict the performance of harvest strategies based on recent stock behaviour. These activities implicitly assume that the past is a good indicator of the future, but especially for MPEs this assumption is not a good one. Vert-pre et al. (2013) suggest that

> *Fisheries management agencies need to recognize that irregular changes in productivity are common and that harvest regulation and management targets may need to be adjusted whenever productivity changes.*

Estimated annual production varied considerably in the seven stocks. The effect of biomass was estimated in a way that did not assume a relation between biomass and production, as surplus-production models do. The simple parabola could estimate zero for *a* and *c*, resulting in a flat relation between biomass and production, or even a bowl-shaped curve. The fitted curves were predominantly dome-shaped and resembled surplus-production models except in CRA 4.

This set of simple analyses suggests that annual production declined between 1979 and 2015 in all New Zealand rock lobster stocks, from 0.35% per year in CRA 1 to 2.72% in CRA 3. Except for CRA 5, changes in biomass and temperature explain some but not all of this (see Table 11).

The simple method used here makes simple assumptions: that CPUE reflects biomass through a proportionality constant *q* and that catches are known. These assumptions are also made by the stock assessment models, although the relation between biomass and CPUE is more sophisticated in the stock assessment models and involves sex- and length-based size selectivity of the fishery, sex-based seasonal changes in vulnerability and modification by the MLS and berried female protections. The simple approach has two advantages over the length-based models: it can be used for all stocks at any time, whereas length-based assessments will always be one to four years out of date for some stocks. The simple model is also consistent for all stocks whereas length-based models are often modified to some extent from year to year.

CPUE is widely questioned as an index of abundance (e.g. Harley et al. 2001; van Poorten et al. 2016). Problems include noise, which is addressed here by using the extended model. Changes in fishing power affect catchability, addressed here by assuming a 1.5% annual increase. Pauly & Palomars (2010) suggest that effective effort increases annually by 1 to 3%. A 3% annual increase in effective capacity was suggested as realistic by the European Commission (2008, cited in Eigaard et al. 2014). Hall &

Chubb (2001), assumed a 1 to 2% annual increase in gear efficiency in the Western Australian fishery. de Lestang et al. (2012) estimated annual rates of increase in effort efficiency of 0.5 to 4.0% in that fishery. The assumption of 1.5% made here is arbitrary but seems reasonable (perhaps conservative) in light of these published values, and the sensitivity trial (Table 12) suggests that the assumption does not affect model conclusions. Changes in fishing pattern involving month and statistical area are addressed in a simple way by the standardisation model (Starr 2017). Hyperdepletion or hyperstability were not addressed here (and are usually not by the length-based models).

Neither this simple model nor the length-based models address uncertainty in catches. Catches are not known accurately, although the reported commercial catches are well reported from 1991 onwards. Commercial catches are generally the largest component of the assumed total catch, but non-commercial catches are a substantial proportion in the northern stocks. Under-estimating the non-commercial catch will lead to under-estimated production and vice-versa. Very little is known about trends in non-commercial catches.

Predicting the effects of climate change, especially warming, has become an increasingly popular area of study (e.g. Marzloff et al. 2016), extending even to claiming that marine reserves can mitigate the risks (Ling & Johnson 2012). Nothing in the results from this study should be taken as a conclusion on the effects of climate change. First, the study involved temperature changes over a short period only, 1982–2015. Shears & Bowen (2017) state that "there was no evidence of annual warming in northeastern New Zealand [boundary currents]" based on SST at Leigh from 1969. Their figure 2 shows that SST has an increasing trend if the period 1982–present is used.

Second, SST was included in the study because of significant correlations found by Breen & Starr (2010) in an essentially shotgun approach involving many index/lag combinations, thus with a high propensity to find spurious relations. The SST effects were positive for most stocks but negative in two, and the best lags varied from zero to four years; underscoring the possibility of a spurious relation. Dunn et al. (2009) explored data for correlations between environmental and climate indices and year-class strengths in a wide variety of New Zealand fisheries. These authors also discuss the possibility of spurious correlations that arise from the numbers of series being compared, and the need for development of hypotheses.

If temperature is indeed implicated in productivity, it might be an alias for another oceanic process such as currents, and the effects may be indirect through ecological factors rather than through direct effects on recruitment, growth or mortality. Hurst et al. (2012) suggest that

> *Any relationships are likely to be highly complex and variable and may change over time in response to regime shifts, climate change, and fishing pressure. Impacts of climate variability and change on fish populations are likely to show response lags or step-like changes that are difficult to predict. Significantly long time series are required to develop relationships that are statistically robust...*

There are many other candidates for mechanisms to explain the observed residual declines in surplus production. These include ocean climate changes not reflected in SST, ocean acidification, sedimentation of the nearshore coastal reefs (Desmond et al. 2015; Lowe et al. 2015), alienation of commercial lobster habitat by marine reserves and mataitai, terrestrial chemical runoff, dredge spoil dumping and other nearshore modifications, habitat changes caused by invasive species such as *Undaria*, seismic oil surveys, increasing toxic algal blooms, etc. See reviews by Baird et al. (2012) and MacDiarmid et al. (2012).

Whatever the causes of declining productivity, the trends cause problems for management. Empirical reference points have been used, based on a biomass level in the past. If there are persistent downward trends in productivity, then these are not realistic. Management procedure evaluations also need to address the changing levels of expected production.

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Table 1: Total catch (t) by fishing year (FY) for each stock.

FY	CRA 1	CRA 2	CRA 3	CRA 4	CRA 5	CRA 7	CRA 8
1979	177.7	380.7	551.6	604.2	491.1	446.1	1917.2
1980	260.6	562.9	705.6	731.4	623.6	339.4	1672.1
1981	286.6	520.1	696.6	781.1	621.9	322.6	1692.6
1982	321.3	432.1	882.4	1065.8	801.7	160.4	1818.8
1983	333.2	365.0	916.4	1164.1	765.6	136.4	1845.4
1984	303.7	356.2	851.8	1071.0	911.1	233.7	1874.3
1985	316.5	443.5	788.2	1055.1	912.3	385.0	2248.4
1986	305.2	364.1	689.8	1174.0	795.5	393.5	1934.3
1987	275.1	337.9	439.0	1149.5	634.3	356.6	2011.5
1988	266.8	301.5	353.8	951.3	460.4	259.9	1281.0
1989	259.0	355.2	475.1	943.9	413.5	127.3	1520.5
1990	217.2	365.2	639.1	709.5	532.6	184.6	906.3
1991	194.6	335.2	563.5	660.5	508.3	226.7	1052.0
1992	158.1	274.9	466.9	568.6	482.4	178.3	983.3
1993	180.3	319.7	355.4	585.1	480.3	177.7	1002.9
1994	198.1	343.5	236.6	606.7	407.7	153.0	962.4
1995	207.6	351.9	261.3	610.3	413.4	104.0	912.5
1996	258.3	418.4	339.8	641.2	388.9	90.6	962.2
1997	258.0	427.1	325.5	639.2	397.1	64.8	884.3
1998	252.4	425.3	462.6	659.0	401.3	88.6	905.7
1999	237.3	432.5	501.9	726.7	454.9	87.6	806.2
2000	254.1	402.4	441.6	729.9	453.9	110.9	787.5
2001	258.8	367.1	397.5	711.2	458.9	93.1	644.1
2002	245.5	338.5	394.7	714.7	464.2	97.2	626.9
2003	239.6	320.1	332.6	703.7	471.3	90.1	625.8
2004	256.1	327.7	278.2	675.6	463.7	102.9	659.5
2005	250.4	350.4	287.0	596.2	475.5	103.7	658.0
2006	266.2	360.2	295.6	532.5	471.3	128.9	808.0
2007	270.7	357.1	289.5	400.1	472.2	128.8	803.9
2008	257.8	352.8	307.7	341.8	467.5	129.0	1015.8
2009	263.9	346.1	283.4	367.0	479.9	145.2	1066.4
2010	258.7	329.2	286.7	520.6	472.9	83.5	1064.8
2011	254.5	331.8	290.3	580.0	481.5	54.4	1006.0
2012	270.4	332.3	323.5	589.3	484.8	62.5	1007.0
2013	256.9	329.2	355.4	613.8	471.5	52.7	1012.1
2014	260.4	286.7	386.2	572.0	472.0	74.7	1010.8
2015	259.6	256.3	386.6	535.6	472.9	106.3	1010.6
2016	260.8	221.6	386.6	442.8	472.7	106.3	1010.9

Table 2: Standardised annual fishing year (FY) CPUE for each stock in kg/potlift (Paul Starr, pers. comm.)

FY	CRA 1	CRA 2	CRA 3	CRA 4	CRA 5	CRA 7	CRA 8
1979	0.821	0.519	0.772	0.829	0.600	0.961	1.960
1980	0.986	0.624	0.856	0.803	0.730	0.845	1.705
1981	0.925	0.520	0.845	0.861	0.652	0.719	1.641
1982	1.000	0.433	0.914	0.927	0.719	0.464	1.404
1983	0.951	0.355	0.835	0.841	0.643	0.401	1.058
1984	0.883	0.343	0.676	0.763	0.651	0.537	1.024
1985	0.825	0.397	0.645	0.729	0.534	0.716	1.212
1986	0.806	0.359	0.560	0.775	0.470	0.819	1.077
1987	0.752	0.313	0.398	0.677	0.393	0.691	1.132
1988	0.661	0.341	0.410	0.571	0.343	0.406	0.848
1989	0.691	0.349	0.445	0.562	0.351	0.327	0.832
1990	0.600	0.475	0.423	0.517	0.353	0.422	0.808
1991	0.682	0.419	0.284	0.520	0.295	0.975	0.793
1992	0.601	0.391	0.240	0.499	0.286	0.392	0.673
1993	0.665	0.432	0.495	0.546	0.328	0.619	0.896
1994	0.852	0.520	0.963	0.696	0.356	0.455	0.798
1995	1.173	0.731	1.533	0.918	0.399	0.290	0.861
1996	1.004	0.938	1.920	1.234	0.520	0.245	0.806
1997	0.977	1.090	2.432	1.437	0.725	0.177	0.688
1998	1.064	1.102	2.054	1.637	0.857	0.256	0.703
1999	0.896	0.854	1.926	1.476	0.936	0.224	0.752
2000	1.155	0.757	1.338	1.382	1.198	0.341	0.914
2001	1.192	0.549	1.019	1.183	1.394	0.498	0.989
2002	1.122	0.430	0.674	1.217	1.571	0.602	1.154
2003	1.055	0.437	0.554	1.252	1.751	0.595	1.721
2004	1.336	0.513	0.444	0.954	1.348	0.881	1.890
2005	1.362	0.476	0.550	0.819	1.362	1.279	2.307
2006	1.709	0.556	0.555	0.675	1.400	1.755	2.797
2007	1.776	0.558	0.576	0.589	1.441	1.553	3.059
2008	1.720	0.514	0.660	0.744	1.661	1.786	4.108
2009	1.722	0.445	0.869	1.040	2.097	1.084	3.942
2010	1.521	0.397	1.186	1.038	2.041	0.803	3.231
2011	1.504	0.378	1.718	1.257	1.899	0.687	3.182
2012	1.701	0.410	2.392	1.409	1.769	0.680	3.316
2013	1.482	0.364	2.235	1.199	1.639	2.059	3.422
2014	1.343	0.331	2.047	1.049	1.793	2.094	3.253
2015	1.346	0.281	1.781	0.754	1.566	2.059	3.449
2016	1.191	0.296	1.777	0.653	1.735	2.782	3.858

Table 3: Standard errors in natural log space associated with the CPUE estimates presented above.

FY	CRA 1	CRA 2	CRA 3	CRA 4	CRA 5	CRA 7	CRA 8
1979	0.037	0.022	0.021	0.020	0.024	0.031	0.019
1980	0.039	0.021	0.021	0.019	0.026	0.033	0.020
1981	0.042	0.021	0.021	0.020	0.027	0.033	0.021
1982	0.040	0.021	0.020	0.019	0.025	0.037	0.020
1983	0.040	0.022	0.020	0.019	0.025	0.038	0.020
1984	0.039	0.022	0.019	0.019	0.025	0.037	0.020
1985	0.038	0.022	0.020	0.019	0.025	0.036	0.020
1986	0.038	0.023	0.021	0.019	0.026	0.038	0.021
1987	0.038	0.024	0.021	0.020	0.026	0.040	0.022
1988	0.044	0.026	0.024	0.020	0.029	0.046	0.026
1989	0.047	0.046	0.022	0.020	0.033	0.047	0.026
1990	0.044	0.029	0.024	0.020	0.031	0.042	0.026
1991	0.042	0.029	0.022	0.020	0.032	0.054	0.024
1992	0.047	0.033	0.023	0.019	0.036	0.048	0.024
1993	0.043	0.033	0.033	0.020	0.037	0.058	0.026
1994	0.045	0.036	0.045	0.022	0.039	0.055	0.026
1995	0.053	0.040	0.049	0.025	0.045	0.056	0.029
1996	0.059	0.046	0.054	0.030	0.043	0.065	0.029
1997	0.065	0.044	0.053	0.032	0.044	0.064	0.027
1998	0.063	0.044	0.049	0.032	0.049	0.064	0.030
1999	0.065	0.043	0.049	0.032	0.047	0.071	0.032
2000	0.058	0.038	0.042	0.031	0.054	0.063	0.034
2001	0.059	0.035	0.042	0.029	0.061	0.066	0.041
2002	0.058	0.034	0.034	0.027	0.059	0.069	0.038
2003	0.060	0.034	0.034	0.026	0.053	0.075	0.042
2004	0.069	0.037	0.036	0.025	0.051	0.094	0.042
2005	0.064	0.035	0.036	0.026	0.048	0.110	0.045
2006	0.061	0.034	0.034	0.024	0.046	0.092	0.045
2007	0.058	0.036	0.038	0.027	0.045	0.084	0.042
2008	0.067	0.038	0.042	0.031	0.047	0.107	0.044
2009	0.062	0.034	0.044	0.031	0.049	0.075	0.040
2010	0.059	0.035	0.046	0.027	0.049	0.084	0.041
2011	0.057	0.035	0.048	0.028	0.051	0.081	0.038
2012	0.056	0.035	0.050	0.029	0.055	0.092	0.037
2013	0.058	0.034	0.050	0.030	0.053	0.130	0.041
2014	0.062	0.037	0.040	0.028	0.054	0.126	0.041
2015	0.063	0.036	0.039	0.027	0.054	0.118	0.038
2016	0.073	0.038	0.040	0.027	0.057	0.102	0.040

Table 4: Catchability coefficients (*q*) and their standard errors for each stock.

Stock	CRA 1	CRA 2	CRA 3	CRA 4	CRA 5	CRA 7	CRA 8
q	-6.35	-6.646	-5.964	-6.321	-6.912	-6.090	-6.870
s.e.	0.145	0.135	0.144	0.194	0.122	0.134	0.072

Table 5: Co-ordinates for the point used as the basis for SST for each stock, regression coefficients for a simple regression of mean SST against fishing year and the increase in predicted annual SST from 1982–2015 (C).

	CRA 1	CRA 2	CRA 3	CRA 4	CRA 5	CRA 7	CRA 8
longitude E	174.5	177.5	178.5	176.5	174.5	170.5	167.5
latitude S	35.5	37.5	38.5	40.5	42.5	46.5	44.5
slope	0.0147	0.0104	0.0260	0.0305	0.0243	0.0063	0.0172
intercept	-11.51	-3.10	-35.39	-45.89	-35.29	-1.99	-20.31
1982–2015	0.486	0.343	0.858	1.007	0.803	0.209	0.567

Table 6: Mean annual SST (C) by stock and complete fishing year (FY) (Mark Hadfield, NIWA, pers. comm.).

FY	CRA 1	CRA 2	CRA 3	CRA 4	CRA 5	CRA 7	CRA 8
1982	17.71	17.39	15.13	13.59	12.29	10.58	13.22
1983	17.53	17.39	15.75	14.19	12.38	10.52	13.38
1984	18.21	18.22	16.66	14.95	13.02	11.14	13.97
1985	17.79	17.71	16.34	14.41	13.15	11.01	14.64
1986	17.59	17.58	16.40	14.75	13.12	10.74	14.09
1987	17.58	17.30	16.47	15.26	13.49	10.36	13.68
1988	18.11	17.74	16.59	14.83	13.20	9.93	13.84
1989	18.36	18.18	17.10	15.30	13.45	10.83	14.87
1990	17.76	17.73	16.83	15.50	13.22	10.33	13.64
1991	17.12	17.00	16.06	14.63	12.99	10.37	13.39
1992	16.77	16.55	15.37	14.44	12.89	10.35	13.44
1993	17.28	17.06	15.63	14.11	12.67	10.64	13.74
1994	17.32	17.21	16.03	14.48	13.08	10.42	13.43
1995	18.01	17.71	16.71	15.43	13.52	10.52	13.83
1996	17.78	17.43	16.33	14.55	13.23	10.66	13.72
1997	17.96	17.70	16.72	15.44	13.62	10.42	13.82
1998	18.86	18.44	17.27	15.41	13.50	10.66	14.38
1999	18.41	18.19	17.25	15.60	13.39	10.81	14.81
2000	18.02	17.82	16.85	15.08	13.39	10.92	14.26
2001	18.25	18.12	17.25	15.63	13.55	11.41	15.07
2002	17.92	17.77	16.91	15.77	13.79	10.70	13.84
2003	17.91	17.84	17.13	16.03	13.83	10.51	13.96
2004	17.34	17.24	16.53	15.19	13.22	10.26	13.40
2005	18.34	18.14	17.31	16.20	13.76	10.78	14.26
2006	17.77	17.55	16.88	15.18	13.53	10.52	14.06
2007	18.19	17.96	17.14	15.66	13.72	10.23	14.04
2008	17.88	17.77	17.01	15.75	13.93	10.38	14.21
2009	17.92	17.53	16.52	14.69	12.90	10.44	14.03
2010	18.23	17.84	16.79	14.83	13.28	10.80	14.27
2011	18.02	17.72	16.52	14.88	13.12	10.47	13.86
2012	17.92	17.55	16.48	15.47	13.61	10.83	14.23
2013	17.99	17.91	17.05	15.48	13.68	11.25	14.40
2014	18.27	17.96	16.91	15.59	13.77	11.33	14.69
2015	18.27	17.86	16.43	15.01	13.60	10.67	14.25

Table 7: Calculated production (t) by stock and fishing year (FY).

FY	CRA 1	CRA 2	CRA 3	CRA 4	CRA 5	CRA 7	CRA 8
1979	331.7	568.0	664.6	640.8	713.8	318.6	1441.2
1980	218.4	430.7	689.6	788.6	509.4	253.2	1572.9
1981	347.9	384.8	816.5	960.3	783.2	94.6	1441.4
1982	282.1	318.6	855.3	1046.7	677.0	110.7	1396.0
1983	260.9	344.8	803.1	1056.2	835.7	254.6	1801.6
1984	261.6	445.0	800.9	1032.9	760.2	399.6	2260.8
1985	289.7	363.7	695.6	1137.1	768.2	436.8	1916.8
1986	246.2	305.4	487.4	1091.1	617.2	303.4	2016.3
1987	203.9	339.7	398.8	976.3	482.7	158.9	1315.5
1988	275.8	330.7	427.3	936.8	440.9	151.4	1369.8
1989	173.8	463.6	544.7	793.9	468.7	200.0	1174.3
1990	252.0	297.4	539.5	681.7	451.1	469.6	950.6
1991	119.6	276.5	494.8	597.8	480.8	-81.6	880.1
1992	203.1	325.7	514.8	600.0	521.9	281.3	1211.4
1993	295.2	397.5	483.5	678.6	467.6	85.4	870.5
1994	384.6	508.8	471.6	729.3	449.6	50.5	987.4
1995	124.3	538.3	444.5	796.6	518.1	75.2	871.1
1996	234.2	528.6	520.5	742.7	591.9	45.9	798.3
1997	296.3	422.9	235.2	746.8	519.1	109.8	899.0
1998	142.6	231.4	422.2	593.0	491.9	73.0	892.5
1999	380.0	336.6	242.5	666.4	693.3	147.0	935.7
2000	266.9	225.8	295.3	605.2	624.7	165.5	771.3
2001	205.3	261.8	265.9	721.1	606.9	134.6	769.4
2002	199.0	329.6	317.3	717.9	611.5	87.4	1111.0
2003	384.2	372.3	264.0	530.9	78.8	206.7	766.5
2004	256.3	308.5	316.7	562.1	463.9	254.0	991.1
2005	421.8	404.2	290.4	488.5	489.0	292.4	1116.0
2006	289.2	354.3	296.6	420.4	489.3	42.2	988.9
2007	223.8	321.2	323.5	440.0	638.9	207.5	1730.1
2008	249.7	299.7	360.6	486.8	819.1	-132.1	857.1
2009	153.9	303.2	382.4	435.5	404.3	6.3	455.2
2010	238.3	315.0	450.9	642.5	336.3	23.0	959.2
2011	342.1	347.9	508.6	643.7	355.7	52.2	1072.8
2012	153.6	299.3	280.3	500.3	353.8	533.9	1051.9
2013	186.9	285.3	303.9	520.4	573.0	65.0	846.9
2014	252.2	239.1	297.9	421.3	277.1	68.1	1118.8
2015	184.9	244.8	377.8	442.3	583.6	336.3	1270.3

Table 8: Slopes of annual production against time (t/year) for each stock, and the predicted change (t) from 1979 to 2015.

	CRA 1	CRA 2	CRA 3	CRA 4	CRA 5	CRA 7	CRA 8
slope	-0.881	-3.618	-12.392	-15.335	-6.463	-3.423	-20.000
intercept	2,012	7,578	25,203	31,324	13,447	7,005	41,099
1979–2015	-31.7	-130.2	-446.1	-552.1	-232.7	-123.2	-720.0

Table 9: Matrix of correlations in production among stocks from the basic model; bold indicates significance at 0.05.

	CRA 1	CRA 2	CRA 3	CRA 4	CRA 5	CRA 7	CRA 8
CRA 1	1.000	0.292	0.063	0.100	0.029	0.079	0.122
CRA 2		1.000	0.349	0.282	0.107	0.052	0.153
CRA 3			1.000	**0.690**	**0.474**	0.210	**0.617**
CRA 4				1.000	**0.457**	0.238	**0.640**
CRA 5					1.000	0.082	**0.493**
CRA 7						1.000	**0.532**
CRA 8							1.000

Table 10: From the basic model: for each stock, estimated and derived parameter estimates for a run without the effect of SST estimated, and with 6 lags between SST and annual production. Function values in bold are the smallest; grey indicates a quantity not estimated.

QMA	Tlag	*a*	*b*	*c*	*σ*	*d*	*-LL*	*anndec79*	*anndec90*	*1degree*
1	0	1.78	0.738	-5.220E-04	73.2	0.000	177.37	-0.26%	-0.14%	0.00%
1	0	-70.95	0.927	-6.401E-04	73.0	-0.067	177.25	-0.20%	-0.09%	-6.47%
1	1	-11.87	0.773	-5.427E-04	73.2	-0.026	177.35	-0.24%	-0.12%	-2.56%
1	2	-7.61	0.744	-5.140E-04	71.9	-0.151	176.66	-0.15%	0.02%	-13.99%
1	3	6.33	0.726	-5.140E-04	72.8	-0.076	177.14	-0.19%	0.01%	-7.29%
1	**4**	-36.83	0.847	-5.959E-04	70.5	0.193	**175.97**	-0.44%	-0.55%	21.31%
1	5	19.23	0.704	-5.085E-04	71.3	0.182	176.38	-0.39%	-0.40%	19.97%
2	0	-7.67	1.036	-6.477E-04	76.5	0.000	178.96	-0.42%	-0.21%	0.00%
2	0	12.09	0.957	-5.777E-04	75.8	-0.079	178.64	-0.36%	-0.01%	-7.61%
2	1	-41.05	1.116	-6.885E-04	67.0	-0.260	174.10	-0.17%	0.40%	-22.90%
2	**2**	19.23	0.964	-6.184E-04	60.3	-0.330	**170.15**	-0.29%	0.20%	-28.10%
2	3	59.60	0.867	-5.738E-04	68.3	-0.270	174.77	-0.44%	-0.06%	-23.66%
2	4	-7.31	1.056	-6.804E-04	76.1	-0.070	178.79	-0.41%	-0.17%	-6.72%
2	5	37.87	0.842	-4.658E-04	75.4	0.138	178.43	-0.47%	-0.33%	14.79%
3	0	-230.15	2.247	-1.614E-03	153.1	0.000	204.65	-2.38%	-2.25%	0.00%
3	**0**	-131.04	1.867	-1.339E-03	104.2	-0.422	**190.42**	-1.05%	-0.88%	-34.43%
3	1	-78.99	1.729	-1.257E-03	112.5	-0.375	193.25	-1.11%	-0.94%	-31.24%
3	2	94.39	1.183	-8.837E-04	114.7	-0.378	193.98	-1.17%	-0.73%	-31.45%
3	3	86.30	1.291	-1.012E-03	128.6	-0.337	198.19	-1.32%	-0.97%	-28.59%
3	4	-34.27	1.690	-1.293E-03	130.8	-0.307	198.82	-1.29%	-1.12%	-26.43%
3	5	-237.89	2.337	-1.747E-03	127.4	-0.332	197.84	-1.05%	-1.21%	-28.22%
4	0	-174.15	1.454	-4.891E-04	161.9	0.000	206.72	-1.47%	-1.37%	0.00%
4	0	-269.91	1.734	-6.834E-04	133.2	-0.207	199.50	-0.78%	-1.01%	-18.71%
4	**1**	-26.92	1.230	-4.445E-04	125.2	-0.236	**197.20**	-0.72%	-0.94%	-21.05%
4	2	179.29	0.780	-2.179E-04	130.3	-0.241	198.69	-0.78%	-0.90%	-21.44%
4	3	380.59	0.349	-4.410E-06	129.8	-0.266	198.54	-0.75%	-0.92%	-23.32%
4	4	-43.64	1.418	-6.370E-04	132.0	-0.256	199.17	-0.78%	-0.98%	-22.61%
4	5	-227.19	1.838	-8.593E-04	136.8	-0.234	200.49	-0.77%	-0.82%	-20.89%
5	0	-102.45	1.314	-5.747E-04	118.9	0.000	195.30	-0.42%	-0.21%	0.00%
5	0	-85.87	1.247	-5.370E-04	114.0	-0.144	193.73	-0.10%	-0.12%	-13.42%
5	1	-76.93	1.226	-5.286E-04	112.8	-0.158	193.35	-0.06%	-0.14%	-14.58%
5	**2**	-59.62	1.188	-5.117E-04	112.8	-0.161	**193.34**	-0.07%	-0.19%	-14.88%
5	3	-62.43	1.200	-5.179E-04	115.3	-0.126	194.17	-0.16%	-0.26%	-11.86%
5	4	-55.03	1.181	-5.082E-04	116.2	-0.117	194.44	-0.22%	-0.30%	-11.05%
5	5	-101.65	1.311	-5.734E-04	118.9	-0.003	195.30	-0.41%	-0.21%	-0.29%
7	0	31.26	0.767	-8.394E-04	144.0	0.000	202.39	-1.62%	0.70%	0.00%
7	0	-10.26	0.994	-1.094E-03	140.8	0.549	201.54	-1.64%	-0.11%	73.11%
7	**1**	15.30	0.844	-9.207E-04	140.7	0.540	**201.52**	-1.69%	-0.09%	71.53%
7	2	47.08	0.681	-7.454E-04	143.2	0.342	202.19	-1.64%	0.16%	40.75%
7	3	48.09	0.673	-7.372E-04	141.8	0.438	201.80	-1.51%	0.21%	54.92%
7	4	81.30	0.480	-5.277E-04	141.5	0.572	201.74	-1.51%	0.28%	77.19%
7	5	35.56	0.762	-8.632E-04	141.5	0.577	201.74	-1.30%	0.97%	78.02%
8	0	-823.15	1.909	-4.000E-04	305.8	0.000	230.25	-1.41%	-0.93%	0.00%
8	0	-801.68	1.882	-3.933E-04	304.4	-0.057	230.08	-1.31%	-0.76%	-5.58%
8	1	-749.47	1.822	-3.796E-04	299.9	-0.122	229.53	-1.19%	-0.67%	-11.52%
8	2	-749.95	1.820	-3.808E-04	276.0	-0.253	226.46	-0.91%	-0.41%	-22.35%
8	3	-751.01	1.803	-3.759E-04	263.0	-0.340	224.68	-0.76%	-0.32%	-28.84%
8	**4**	-870.74	1.935	-4.044E-04	246.2	-0.353	**222.23**	-0.63%	-0.44%	-29.75%
8	5	-976.94	2.039	-4.258E-04	249.3	-0.341	222.69	-0.56%	-0.63%	-28.92%

Table 11: At the value of *Tlag* giving the best fit for each stock, the calculated deviance explained by biomass, temperature and combined biomass and temperature.

explained	**CRA 1**	**CRA 2**	**CRA 3**	**CRA 4**	**CRA 5**	**CRA 7**	**CRA 8**
biomass	3.0%	19.7%	22.6%	37.7%	42.2%	8.1%	38.5%
lag	4	2	0	1	2	1	4
temperature	6.1%	36.0%	45.3%	43.4%	21.9%	3.5%	14.5%
both	10.1%	50.1%	64.1%	62.8%	48.0%	8.2%	60.2%

Table 12: Average annual residual decline, 1979–2015, in production from regressions involving the calculated production, the basic model using biomass only and the basic model with both biomass and SST.

Stock	**Calculated production**	**Biomass model**	**Model plus SST**
CRA 1	-0.35%	-0.26%	-0.44%
CRA 2	-1.02%	-0.42%	-0.29%
CRA 3	-2.72%	-2.38%	-1.05%
CRA 4	-2.19%	-1.47%	-0.72%
CRA 5	-1.20%	-0.42%	-0.07%
CRA 7	-2.02%	-1.62%	-1.69%
CRA 8	-1.73%	-1.41%	-0.63%

Table 13: From the basic model: for each stock, estimated and derived parameter estimates for runs with best lag and varying values for the assumed annual increase in catchability, *qmult*.

QMA	*qmult*	*Tlag*	*a*	*b*	*c*	σ^P	*d*	*LL*	*anndec79*	*anndec90*	*1degree*
1	1.000	4	29.42	0.679	-4.598E-04	73.7	0.202	177.62	-0.21%	-0.24%	22.44%
1	1.005	4	13.38	0.722	-5.004E-04	72.4	0.200	176.93	-0.25%	-0.33%	22.17%
1	1.010	4	-12.33	0.790	-5.553E-04	71.3	0.197	176.36	-0.32%	-0.43%	21.77%
1	1.015	4	-36.83	0.847	-5.959E-04	70.5	0.193	175.97	-0.44%	-0.55%	21.31%
1	1.020	4	3.07	0.701	-4.826E-04	70.2	0.192	175.80	-0.55%	-0.66%	21.14%
1	1.025	4	130.76	0.297	-1.843E-04	69.8	0.199	175.58	-0.51%	-0.62%	21.97%
2	1.000	2	-0.88	1.044	-6.816E-04	63.4	-0.342	172.06	-0.72%	-0.36%	-28.93%
2	1.005	2	-22.63	1.103	-7.189E-04	61.5	-0.335	170.93	-0.55%	-0.13%	-28.50%
2	1.010	2	-12.58	1.067	-6.917E-04	60.5	-0.331	170.28	-0.40%	0.06%	-28.21%
2	1.015	2	19.23	0.964	-6.184E-04	60.3	-0.330	170.15	-0.29%	0.20%	-28.10%
2	1.020	2	63.02	0.822	-5.178E-04	60.7	-0.331	170.42	-0.22%	0.27%	-28.15%
2	1.025	2	111.37	0.665	-4.055E-04	61.6	-0.333	170.95	-0.18%	0.30%	-28.35%
3	1.000	0	-232.71	2.285	-1.655E-03	94.7	-0.367	186.86	-0.73%	-0.31%	-30.71%
3	1.005	0	-230.74	2.275	-1.667E-03	97.2	-0.384	187.84	-0.85%	-0.63%	-31.88%
3	1.010	0	-191.01	2.114	-1.544E-03	101.0	-0.405	189.26	-0.97%	-0.83%	-33.30%
3	1.015	0	-131.04	1.867	-1.339E-03	104.2	-0.422	190.42	-1.05%	-0.88%	-34.43%
3	1.020	0	-68.24	1.606	-1.116E-03	105.9	-0.431	191.01	-1.08%	-0.82%	-35.03%
3	1.025	0	-12.19	1.372	-9.138E-04	106.1	-0.432	191.08	-1.06%	-0.69%	-35.10%
4	1.000	1	-414.58	2.313	-1.144E-03	139.1	-0.285	201.10	-1.00%	-1.58%	-24.82%
4	1.005	1	-229.77	1.802	-8.164E-04	135.3	-0.274	200.08	-0.92%	-1.36%	-23.99%
4	1.010	1	-103.67	1.448	-5.864E-04	130.4	-0.257	198.70	-0.83%	-1.14%	-22.67%
4	1.015	1	-26.92	1.230	-4.445E-04	125.2	-0.236	197.20	-0.72%	-0.94%	-21.05%
4	1.020	1	17.34	1.106	-3.656E-04	120.3	-0.215	195.74	-0.62%	-0.76%	-19.31%
4	1.025	1	41.05	1.045	-3.297E-04	116.2	-0.194	194.44	-0.52%	-0.60%	-17.62%
5	1.000	2	64.89	0.925	-3.556E-04	127.1	-0.172	197.77	0.02%	0.21%	-15.76%
5	1.005	2	28.02	1.003	-4.026E-04	121.5	-0.160	196.09	0.00%	0.09%	-14.76%
5	1.010	2	-12.90	1.090	-4.544E-04	116.7	-0.155	194.60	-0.03%	-0.04%	-14.37%
5	1.015	2	-59.62	1.188	-5.117E-04	112.8	-0.161	193.34	-0.07%	-0.19%	-14.88%
5	1.020	2	-113.42	1.298	-5.739E-04	109.7	-0.182	192.33	-0.13%	-0.36%	-16.63%
5	1.025	2	-169.52	1.407	-6.331E-04	107.8	-0.222	191.68	-0.22%	-0.54%	-19.92%
7	1.000	1	63.50	0.584	-5.541E-04	154.0	0.587	204.88	-0.92%	1.16%	79.77%
7	1.005	1	37.02	0.724	-7.275E-04	147.8	0.574	203.35	-0.99%	0.93%	77.61%
7	1.010	1	13.61	0.854	-9.006E-04	143.1	0.564	202.16	-1.21%	0.55%	75.76%
7	1.015	1	15.30	0.844	-9.207E-04	140.7	0.540	201.52	-1.69%	-0.09%	71.53%
7	1.020	1	70.09	0.517	-5.642E-04	139.9	0.482	201.32	-2.24%	-0.83%	61.94%
7	1.025	1	131.45	0.133	-1.206E-04	138.6	0.449	200.97	-2.37%	-1.22%	56.63%
8	1.000	4	-529.24	1.569	-2.968E-04	259.5	-0.290	224.17	-0.30%	0.10%	-25.16%
8	1.005	4	-640.14	1.692	-3.336E-04	250.6	-0.298	222.89	-0.33%	0.00%	-25.76%
8	1.010	4	-776.02	1.839	-3.756E-04	244.5	-0.318	221.98	-0.42%	-0.17%	-27.24%
8	1.015	4	-870.74	1.935	-4.044E-04	246.2	-0.353	222.23	-0.63%	-0.44%	-29.75%
8	1.020	4	-757.22	1.796	-3.750E-04	262.1	-0.392	224.54	-0.95%	-0.78%	-32.41%
8	1.025	4	-409.34	1.395	-2.809E-04	282.9	-0.402	227.37	-1.20%	-0.99%	-33.07%

Table 14: For each stock, a summary of estimated and derived parameters from the extended model; the first line for each stock shows the basic model estimates for comparison.

	QMA	**lag**	***a***	***b***	***c***	σ^P	***d***	***LL***	***anndec79***	***anndec90***	***1degree***
MPD	1	4	-36.8	0.847	-0.000596	70.5	0.193	176.0	-0.44%	-0.55%	21.3%
5%			-315.6	0.412	-0.001375	62.5	0.089	171.5	-0.52%	-0.78%	9.3%
median			-82.5	1.013	-0.000727	83.5	0.189	182.7	-0.34%	-0.36%	20.8%
95%			123.0	1.738	-0.000309	107.0	0.303	193.1	-0.12%	0.02%	35.5%
MPD	2	2	19.2	0.964	-0.000618	60.3	-0.330	170.2	-0.29%	0.20%	-28.1%
5%			-48.9	0.718	-0.000906	52.1	-0.422	164.8	-0.36%	0.04%	-34.5%
median			22.9	0.959	-0.000613	64.3	-0.335	172.5	-0.29%	0.18%	-28.5%
95%			78.7	1.262	-0.000408	80.4	-0.261	180.8	-0.22%	0.29%	-23.0%
MPD	3	0	-131.0	1.867	-0.001339	104.2	-0.422	190.4	-1.05%	-0.88%	-34.4%
5%			-205.7	1.417	-0.001738	102.3	-0.436	189.7	-1.14%	-1.13%	-35.3%
median			-122.8	1.843	-0.001315	107.6	-0.421	191.6	-1.05%	-0.88%	-34.4%
95%			-35.4	2.235	-0.000904	113.4	-0.407	193.6	-0.91%	-0.65%	-33.4%
MPD	4	1	-26.9	1.230	-0.000444	125.2	-0.236	197.2	-0.72%	-0.94%	-21.0%
5%			-189.7	0.754	-0.000647	113.3	-0.275	193.5	-0.83%	-1.34%	-24.1%
median			-42.2	1.246	-0.000454	128.0	-0.239	198.0	-0.73%	-0.97%	-21.3%
95%			162.6	1.577	-0.000073	142.1	-0.196	201.9	-0.62%	-0.70%	-17.8%
MPD	5	2	-59.6	1.188	-0.000512	112.8	-0.161	193.3	-0.07%	-0.19%	-14.9%
5%			-208.4	0.965	-0.000751	98.5	-0.209	189.3	-0.17%	-0.38%	-18.9%
median			-89.4	1.261	-0.000542	126.2	-0.142	197.9	-0.04%	-0.14%	-13.3%
95%			28.8	1.567	-0.000367	159.5	-0.060	207.5	0.10%	0.10%	-5.8%
MPD	7	1	15.3	0.844	-0.000921	140.7	0.540	201.5	-1.69%	-0.09%	71.5%
5%			-87.9	0.329	-0.001714	119.0	0.329	196.0	-2.38%	-1.42%	39.0%
median			1.4	0.932	-0.001012	145.4	0.551	202.9	-1.52%	0.12%	73.5%
95%			97.4	1.464	-0.000307	178.2	0.777	211.4	-0.45%	1.91%	117.4%
MPD	8	4	-870.7	1.935	-0.000404	246.2	-0.353	222.2	-0.63%	-0.44%	-29.7%
5%			-1043.5	1.687	-0.000503	231.3	-0.393	219.9	-0.75%	-0.61%	-32.5%
median			-875.9	1.944	-0.000407	257.4	-0.351	223.9	-0.62%	-0.41%	-29.6%
95%			-715.4	2.217	-0.000323	290.1	-0.302	228.3	-0.47%	-0.20%	-26.1%

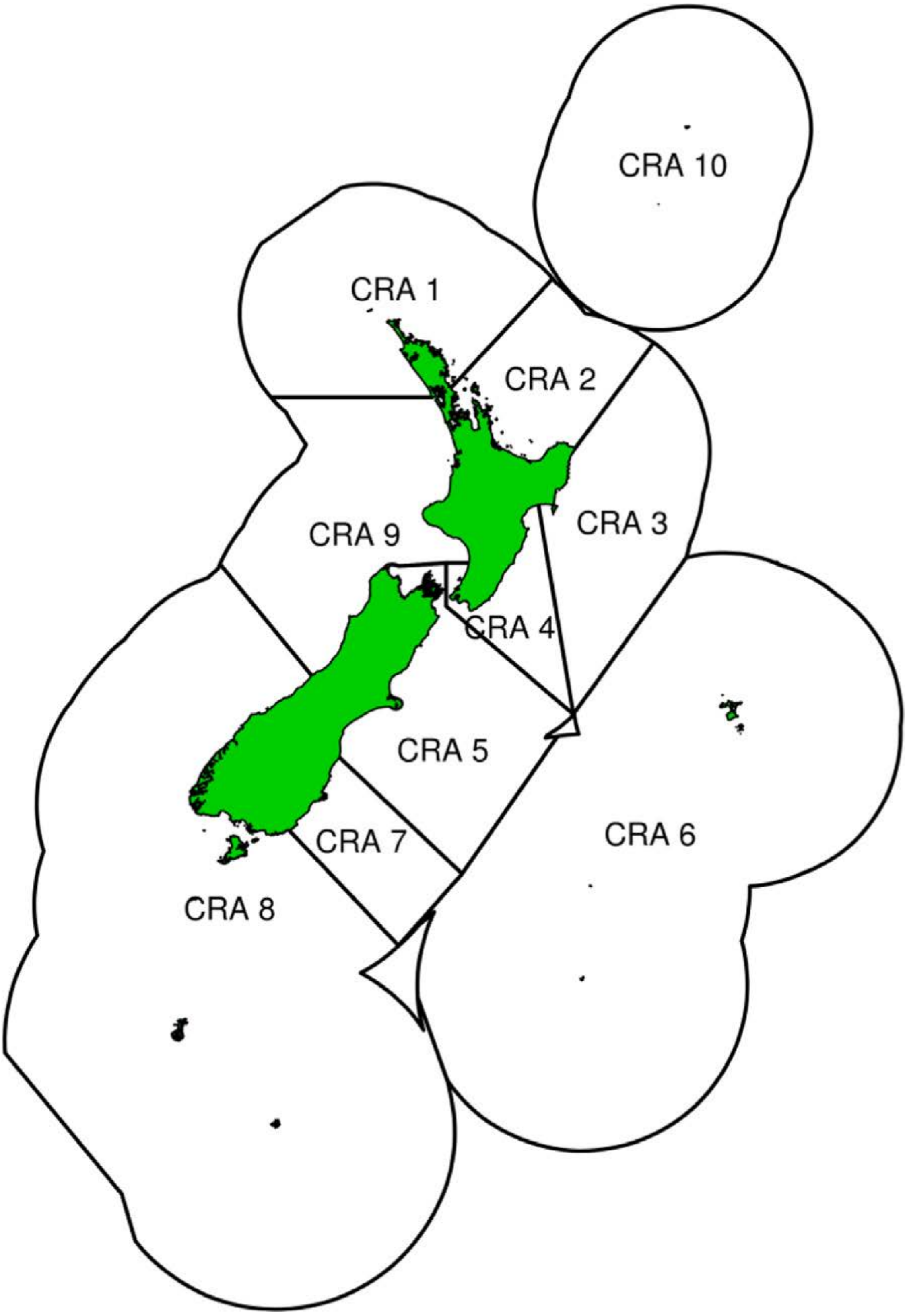

Figure 1: Rock lobster Quota Management Areas.

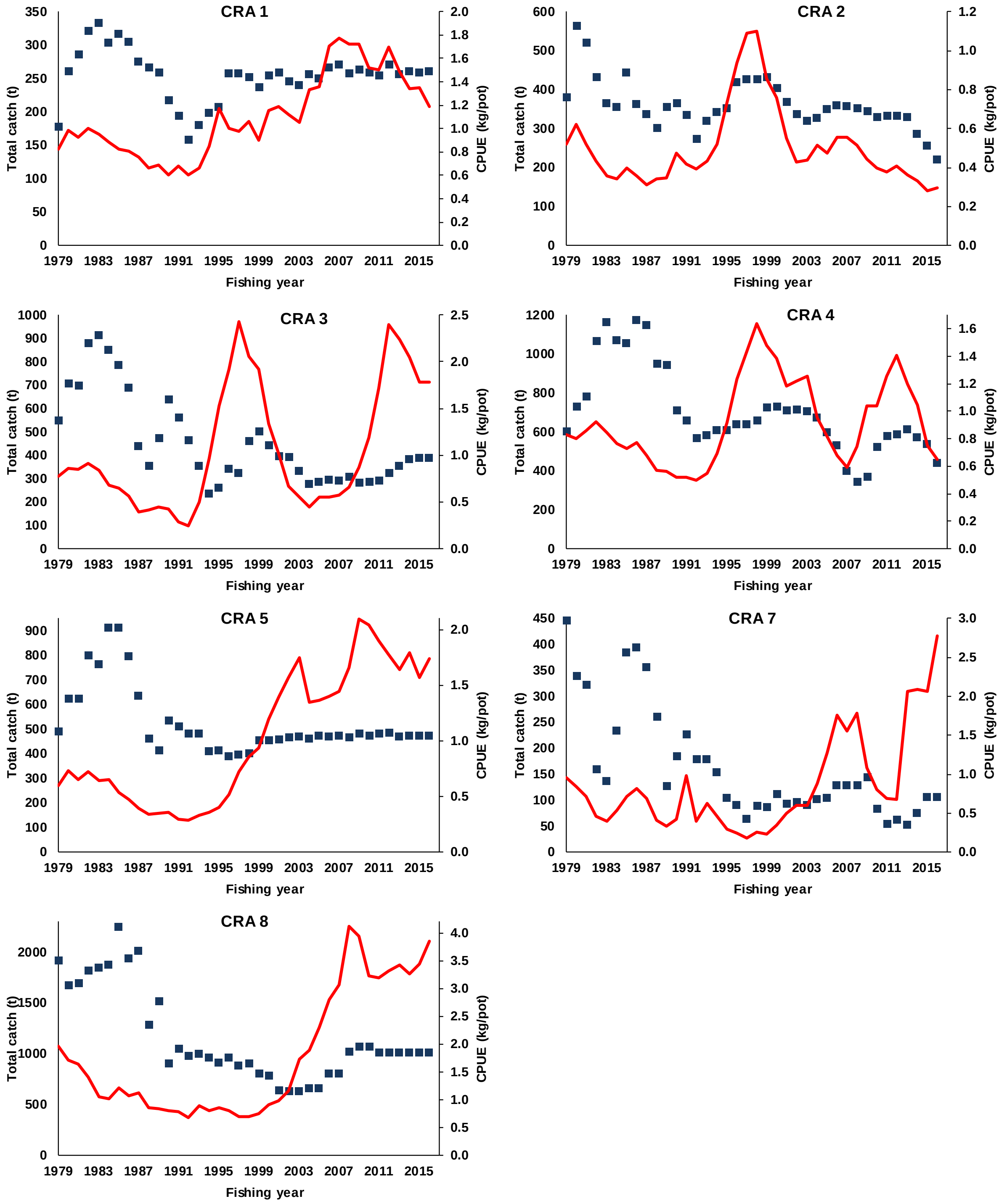

Figure 2: For each stock, total annual catch by fishing year (t, blue squares) and CPUE (kg/potlift, red line).

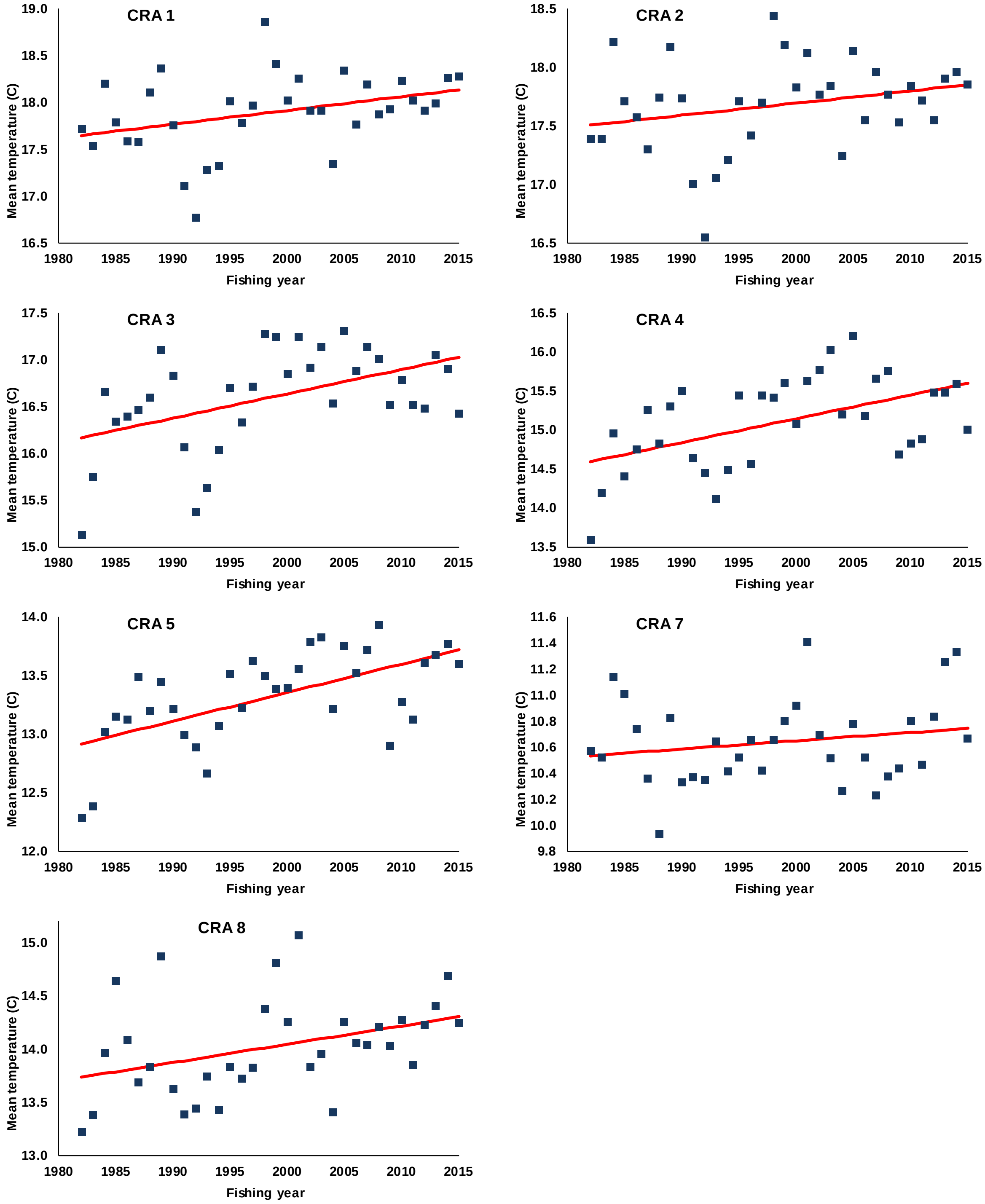

Figure 3: For each stock, mean annual SST and a simple regression against year for 1982–2015; the y-axes are truncated and vary among stocks.

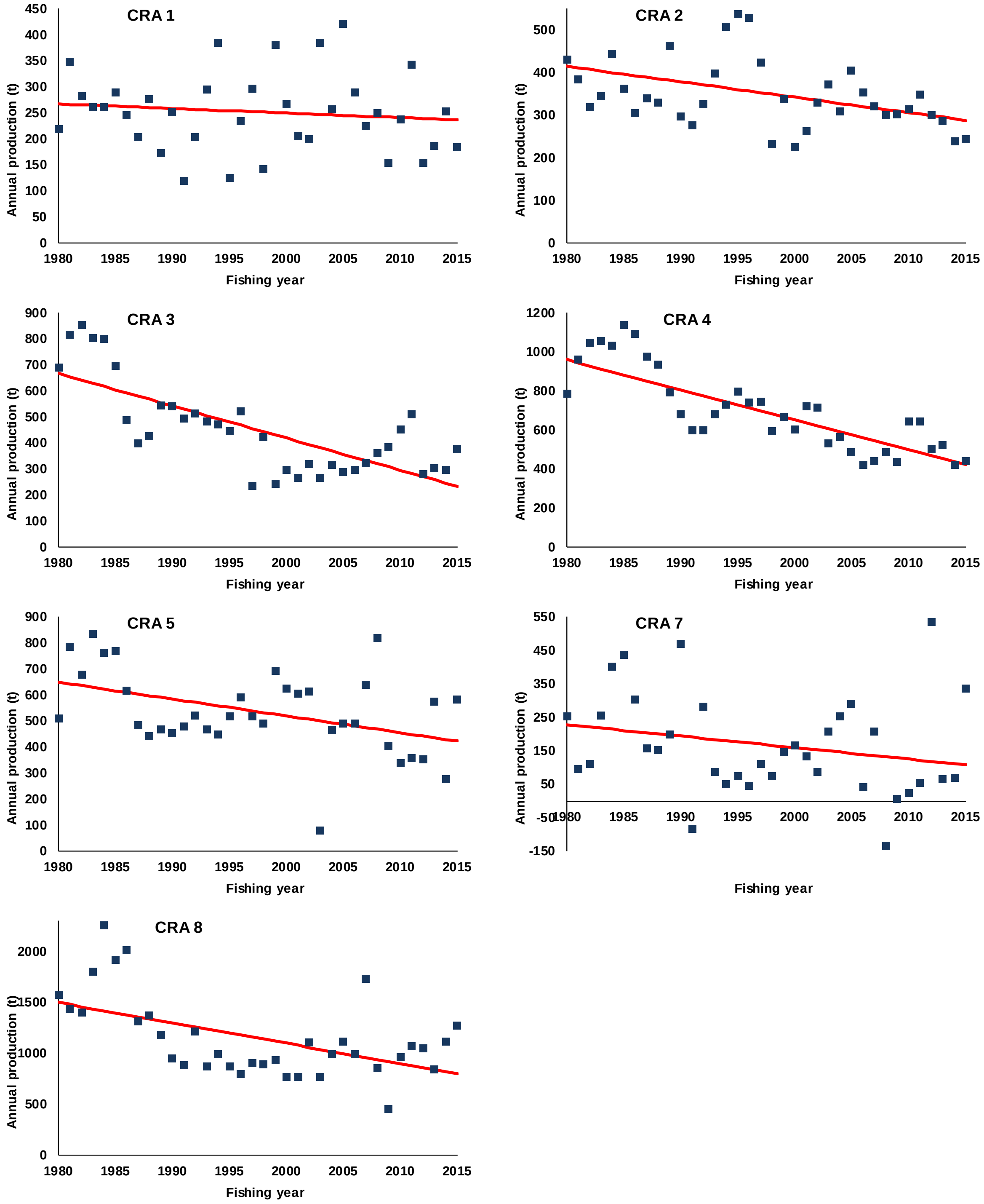

Figure 4: Calculated annual production (t) for each stock, and a simple regression against time for 1979–2015.

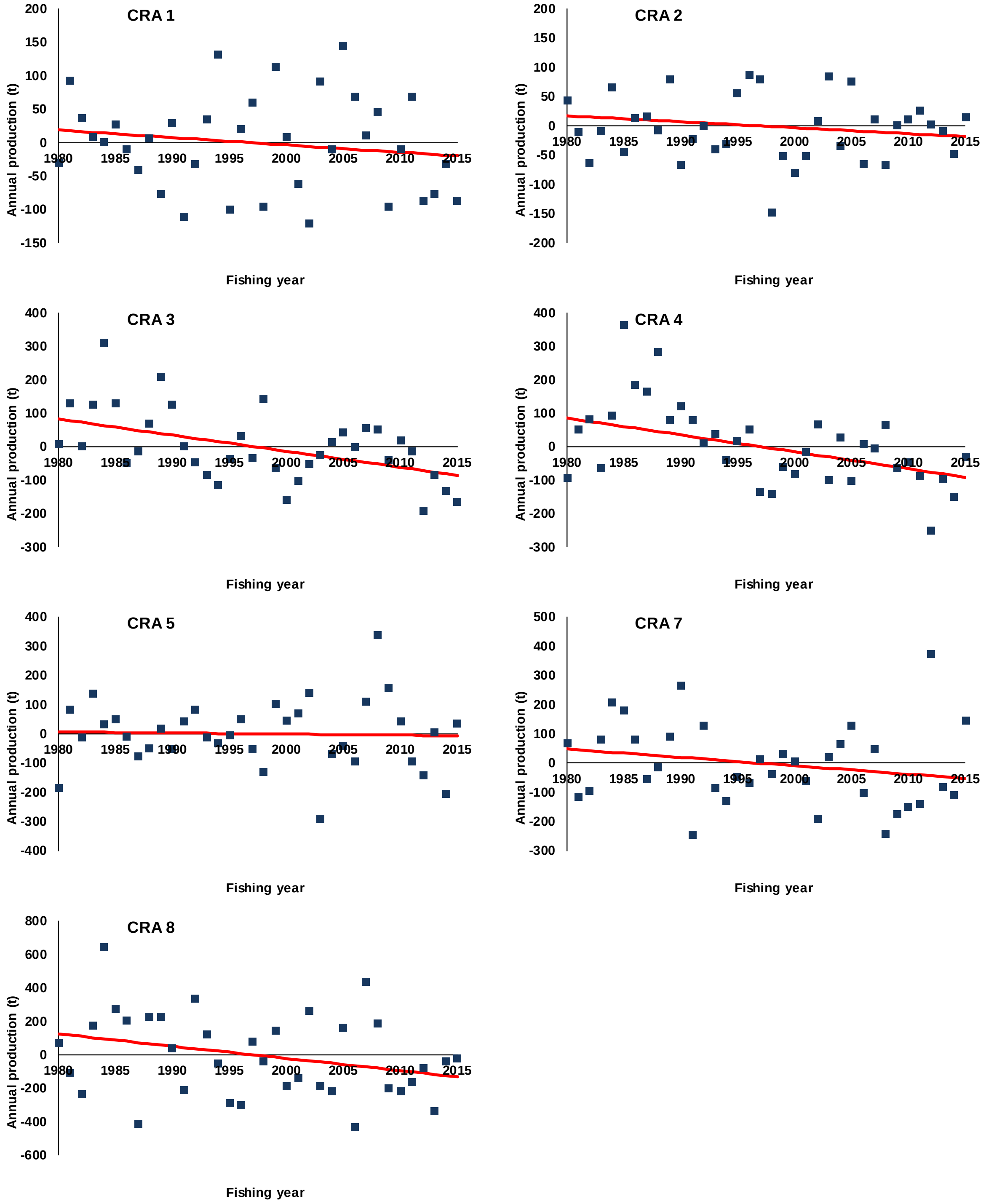

Figure 5: For each stock, residuals from the basic model fitted to observed production using biomass and SST, and a simple regression against year, 1979–2015.

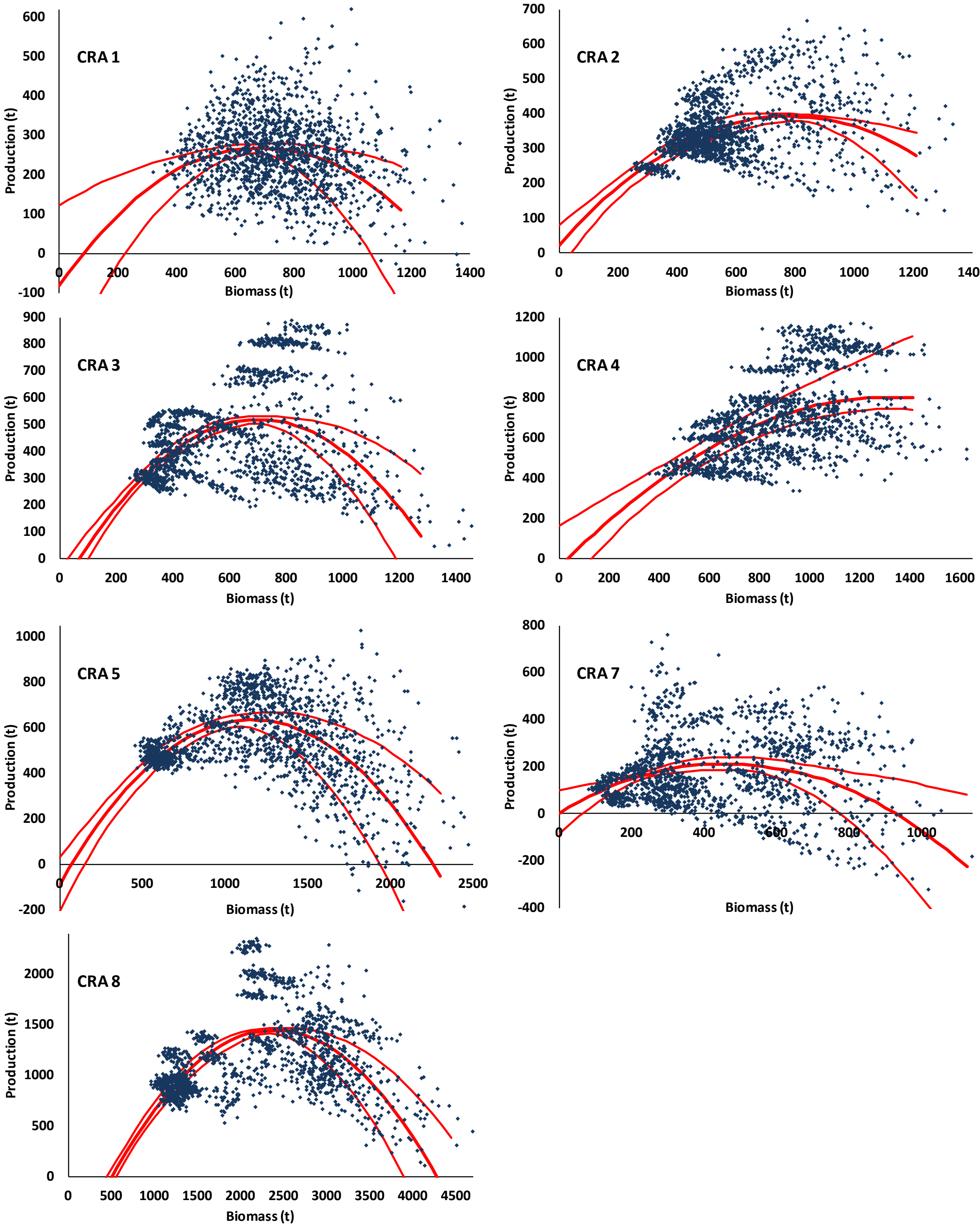

Figure 6: For each stock, a sample of randomised biomass/production pairs (blue diamonds), the median of production predicted from the extended model (heavy red line) and the 5th and 95th quantiles (lighter red lines).

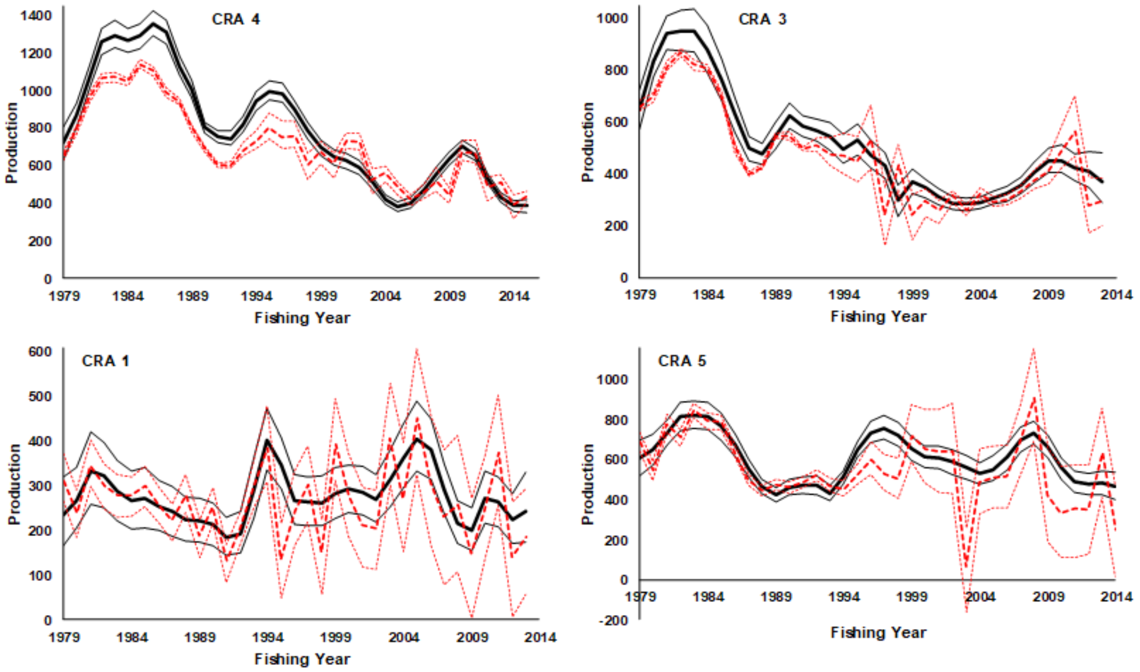

Figure 7: Estimated surplus production from the MSLM (black lines) and extended (red lines) models (median: heavy line; 5th and 95th quantiles: lighter lines), for CRA 4, where the comparison was the best CRA 3, CRA 5 and the worst comparison, CRA 1.