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Mean length, age, and otolith weight as potential indicators of biomass depletion for Chatham Rise orange roughy

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Mean length, age, and otolith weight as potential indicators of biomass depletion for Chatham Rise orange roughy

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1 Executive Summary

The estimated mean length of fish in the major orange roughy spawning ground on the Chatham Rise has not declined in the way that might be expected given the estimated substantial decrease in biomass.

Simulations are used to show that neither mean age nor mean otolith weight would be more sensitive than mean length as indicators of biomass decline for orange roughy. Also, if recruitment had been constant, it is more likely than not that a change in mean length would have been detected ($P = 0.55$ to 0.8).

2 Introduction

The estimated mean length of fish in the major orange roughy spawning ground on the Chatham Rise has not declined in the way that might be expected given the substantial decrease in the biomass index (Francis *et al.* 1993). A possible explanation for this is that mean length is not a sensitive indicator of biomass decline.

In this paper we use simulations to calculate the sensitivity of mean length as an indicator under conditions of constant recruitment, and to determine whether mean age or mean otolith weight is more sensitive. These simulations are based on a set of length/age/otolith weight measurements for Tasmanian orange roughy and the estimated pattern of decline for the Chatham Rise population.

3 Materials and Method

3.1 The Otoliths

Sagittal otoliths were removed from orange roughy randomly sampled from commercial landings in Tasmania in 1992. Otoliths were stored dry in envelopes on which length (standard length to the nearest millimetre), sex, vessel, and area fished were recorded.

Otoliths were processed at the Central Ageing Facility, Queenscliff, Victoria. Each otolith was weighed to the nearest milligram. A comparison of left and right otoliths using a paired *t* test showed no significant difference at the 5% level. One otolith of each pair was sectioned using the methods described by Smith *et al.* (in press). Briefly, the method is as follows. Otoliths were embedded in a block of clear polyester resin and sectioned, longitudinally, along the anterior/posterior axis, using a Gemmasta circular saw with a diamond blade of 0.15 mm thickness. Sections were approximately 0.4 mm thick. No further preparation was required other than to mount them on slides with a clear mountant and cover slip. Three sections were taken through each otolith to ensure that one passed through the primordium.

Increments were counted using a compound microscope at magnifications of 40 to 100 times. Each otolith was read "blind", that is, without knowledge of fish size.

3.2 Model Data

For the model described below we need to know the means and variances of length (L) and otolith weight (O) at each age (A). To determine the means we fitted smooth curves to the L vs A and O vs A data (Figures 1A and B) using the lowess procedure (Becker *et al.* 1988).

To determine the variances, we examined the trimmed residuals (trimmed by removing the 5% of the residuals that were largest in absolute value) from these curves. For the L vs A relationship the variance of the residuals was independent of A (Figure 1B) so the variance of L at each age was taken to be the variance of the (trimmed) residuals. For the O vs A relationship the variance of the residuals increased with age (as is apparent from Figure 1D). However, this trend is removed when the residuals are standardised by dividing by A (Figure 1E). Thus, the variance of O at each age was taken as the variance of the standardised residuals multiplied by A^2 . The distributions of the residuals (for L vs A) and standardised residuals (for O vs A) are approximately symmetric (Figures 1C & F).

In the above calculations we restricted the data to fish of age 25 years or more, because there were few fish younger than this in the data set and this is approximately age of recruitment for orange roughy.

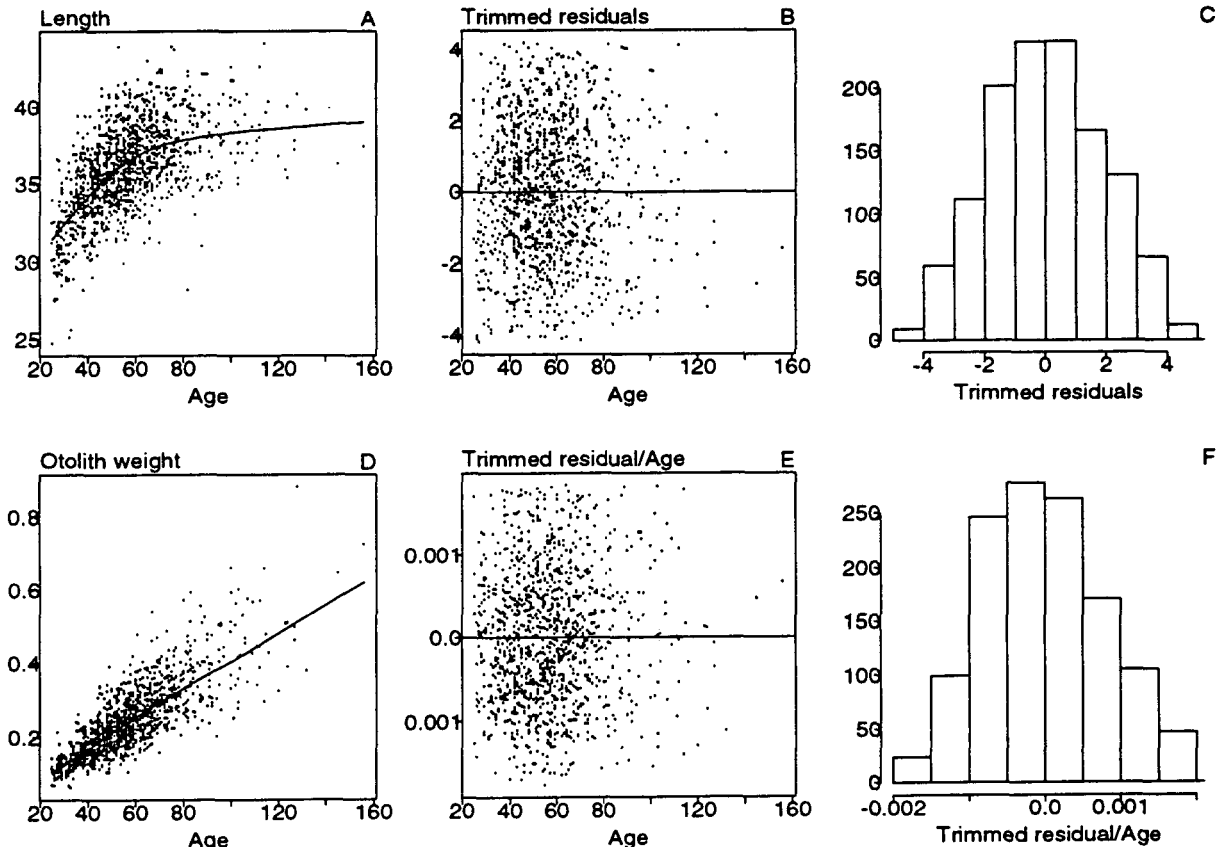


Figure 1. Plots of the orange roughy length (L), otolith weight (O), and age (A) data showing the L vs A relationship (panels A, B, C) and O vs A relationship (panels D, E, F).

Also needed for the model is a sequence of fishing mortalities (F). These were calculated using a standard age-structured population model (Francis 1993) and the catch history and biological parameters used in the 1993 assessment of Chatham Rise orange roughy (Francis *et al.* 1993) except that recruitment was assumed to be constant (*see* next section). The model was run (and sequences of F were calculated) for three values of B_0 (virgin biomass): 400 000 t, 500 000 t, and 600 000 t. These values of B_0 allowed us to consider a wide range of biomass depletion (*see* below). The sequences of F are shown in Figure 2.

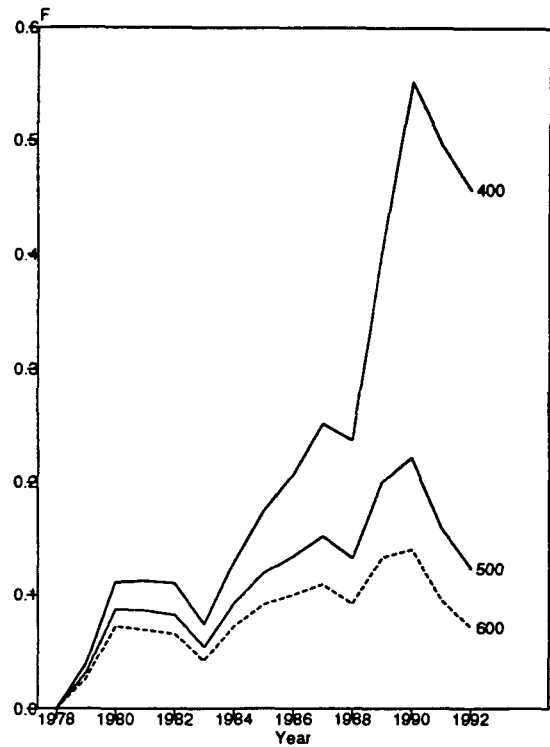


Figure 2. Sequences of fishing mortality, F (year^{-1}), for orange roughy on the Chatham Rise over the period of 1978 to 1992, calculated assuming constant recruitment and three levels of virgin biomass: 400 000 t, 500 000 t, and 600 000 t.

3.3 The Model

If F_i is the fishing mortality in year i (assumed to be zero for $i \leq 0$) and M is the natural mortality, then N_{ij} , the number of fish in the j th recruited cohort (age $24 + j$) at the end of year i , is given by

$$N_{ij} = R \exp \left[- \sum_{k=i-j+1}^i (F_k + M) \right]$$

where R is the number of recruits (at the beginning of the year) at age 25 (we assume that fishing mortality the same for all recruited (age ≥ 25) fish).

The mean values of A , L , and O in year i , are given by

$$\begin{aligned} \text{mean}(A)_i &= \sum_j (j N_{ij}) / \sum_j N_{ij} + 24 \\ \text{mean}(L)_i &= \sum_j (L_j N_{ij}) / \sum_j N_{ij} \\ \text{mean}(O)_i &= \sum_j (O_j N_{ij}) / \sum_j N_{ij} \end{aligned}$$

where L_j and O_j are the mean L and O for the j th cohort (from the curves in Figures 1A & B) and the summations are taken over 132 cohorts (up to age 156 – the oldest age in the sample data).

The standard deviations of A , L , and O in year i , are given by

$$s.d.(A)_i = \{\Sigma_j N_{ij}(j+24 - \text{mean}(A)_i)^2 / \Sigma_j N_{ij}\}^{0.5}$$

$$s.d.(L)_i = \{\Sigma_j N_{ij}[VL_j + (L_j - \text{mean}(L)_i)^2] / \Sigma_j N_{ij}\}^{0.5}$$

$$s.d.(O)_i = \{\Sigma_j N_{ij}[VO_j + (O_j - \text{mean}(O)_i)^2] / \Sigma_j N_{ij}\}^{0.5}$$

where VL_j and VO_j are the variances of L and O for the j th cohort (derived in the preceding section). (The two terms inside the square brackets in the equations for $s.d.(L)_i$ and $s.d.(O)_i$ are the within- and between-cohort components of variance.)

For orange roughy, (body) weight is proportional to $L^{2.71}$ (Francis *et al.* 1993). Thus the recruited biomass in year i , B_i , is proportional to

$$\Sigma_j (N_{ij} L_j^{2.71}) / R$$

3.4 Measuring Sensitivity

Two measures of sensitivity were calculated. First, an index of sensitivity, S_{rel} , was calculated for each indicator, and for each time period considered, as follows

$$S_{rel} = \frac{\text{mean}(X)_2 - \text{mean}(X)_1}{[s.d.(X)_1^2 + s.d.(X)_2^2]^{0.5}}$$

where X is L , O , or A , and the subscripts 1 and 2 refer to the first and last years, respectively, in the time period.

To understand why S_{rel} acts as an index of sensitivity, note that to say that an indicator is sensitive is the same as saying that there is a high probability that a test for a change in $\text{mean}(X)$ would give a statistically significant result.

The statistic for this test is

$$T = \frac{Y_2 - Y_1}{[s.e.(Y)_1^2 + s.e.(Y)_2^2]^{0.5}}$$

where Y_1 and Y_2 are our estimates of $\text{mean}(X)_1$ and $\text{mean}(X)_2$, and $s.e.(Y)_1$ and $s.e.(Y)_2$ are their estimated standard errors. We would conclude that there had been a significant change in $\text{mean}(X)$ if $|T| > 1.96$ (making the usual normality assumption).

From the form of T (a random variable, $Y_2 - Y_1$, divided by its standard error) we know that $s.d.(T) \approx 1$. Thus, the probability of obtaining a significant result depends on how big the expected value of T , $E(T)$, is. The bigger $E(T)$ is, the more likely it is that we would obtain a significant result.

To calculate $E(T)$, note that we may write

$$T = \frac{Y_2 - Y_1}{\left[\frac{s.d.(X)_2^2}{N_{eff}} + \frac{s.d.(X)_1^2}{N_{eff}} \right]^{0.5}} = \frac{N_{eff}^{0.5}(Y_2 - Y_1)}{[s.d.(X)_2^2 + s.d.(X)_1^2]^{0.5}}$$

where N_{eff} is the effective sample size (assumed to be (approximately) the same in both years) defined by $N_{eff} = [s.d.(X)_i / s.e.(Y)_i]^2$ for $i = 1$ and 2 (the effective sample size is much smaller than the actual sample size because of the complex sample structure, e.g., Francis *et al.* (1992) section 3.3.2).

Therefore,

$$E(T) = \frac{N_{eff}^{0.5} E(Y_2 - Y_1)}{[s.d.(X)_2^2 + s.d.(X)_1^2]^{0.5}} = N_{eff}^{0.5} S_{rel}$$

In comparing different indicators (say L vs A , or L vs O), we ignore sample size (assuming it to be the same for each indicator) and use S_{rel} as our index. The indicator with the biggest value of S_{rel} for the given time period will produce the biggest value of $E(T)$, and so be the most sensitive indicator.

S_{rel} measures relative sensitivity. For one of our indicators, $mean(L)$, we calculated absolute sensitivities, based on the Chatham Rise orange roughy length sampling regime. Our measure of absolute sensitivity was P_{sig} , the probability that, for a given time period, a significant change in $mean(L)$ would be detected (i.e., $P_{sig} = P(|T| > 1.96)$). For this sampling regime, Francis *et al.* (1993, section 4.4.3) estimated the coefficient of variation for mean length, is 0.66%. Thus, $s.e.(Y) = 0.23$ (= 0.66% of 35 cm), and so

$$E(T) = \frac{mean(L)_2 - mean(L)_1}{[0.23^2 + 0.23^2]^{0.5}}$$

For each time period we evaluated P_{sig} by calculating $E(T)$ and then using tables of the standard normal distribution.

4 Results

Two time periods were used in presenting estimates of biomass depletion and changes in the three indicators (Table 1). 1978 to 1992 is the period of the fishery (as analysed in the 1993

Table 1: Estimated declines in biomass, mean L (length), O (otolith weight), and A (age), and measures of sensitivity S_{rel} and P_{sig} , for three different levels of virgin biomass (B_0) and two time periods. (See text for details of calculations.)

		$B_0 = 400\ 000\ t$		$B_0 = 500\ 000\ t$		$B_0 = 600\ 000\ t$	
		1978-92	1984-90	1978-92	1984-90	1978-92	1984-90
Biomass	(%)	92	78	73	54	61	41
Mean L	(cm)	1.82	0.91	0.99	0.54	0.70	0.39
	(%)	5.3	2.6	2.8	1.6	2.0	1.1
	S_{rel}	0.47	0.22	0.24	0.13	0.17	0.09
	P_{sig}	1.00	0.80	0.86	0.39	0.57	0.23
Mean O	(g)	0.059	0.030	0.032	0.018	0.023	0.013
	(%)	29.2	15.1	16.1	9.0	11.4	6.5
	S_{rel}	0.45	0.21	0.23	0.12	0.16	0.09
Mean A	(year)	13.7	6.90	7.5	4.2	5.4	3.0
	(%)	28.1	14.4	15.4	8.7	11.0	6.3
	S_{rel}	0.47	0.22	0.24	0.13	0.17	0.09

assessment); 1984-90 is the period over which uncontroversial mean length data are available (there was no survey in 1991; for a discussion of the difficulties of interpretation of the 1992 mean length data see Francis *et al.* 1993).

In percentage terms the decreases in O and A for a given biomass depletion are approximately equal, and much larger than the decrease in L (Figure 3A). However, the index of sensitivity, S_{rel} , is approximately the same for each of the three indicators (Figure 3B).

The reason for this is illustrated in Figure 4 which shows how strongly skewed the distributions of A and O are. This means that although A and O decline more rapidly than L , a given sample size will result in much less precise estimates of A and O than of L .

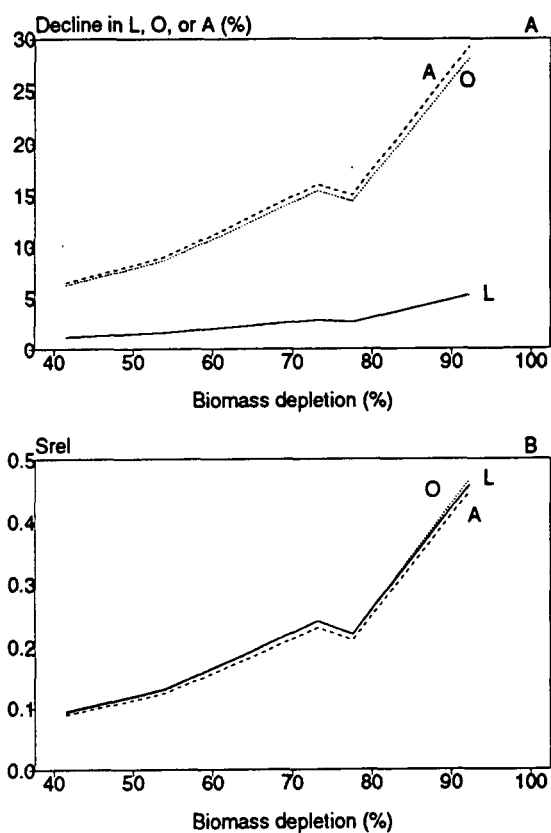


Figure 3. Plot of selected data from Table 1 as a function of biomass decline: A, percentage decline in mean length (L), otolith weight (O), and age (A); B, index of sensitivity, S_{rel} , for L , O , and A .

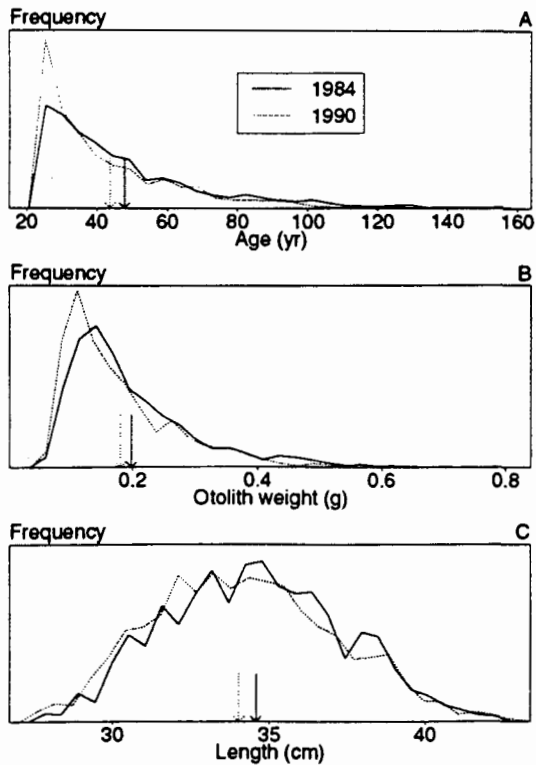


Figure 4. Simulated distributions for age, otolith weight, and length illustrating the change in these distributions between 1984 and 1990 for the case when $B_0 = 500\,000$ t. The arrows show the distribution means.

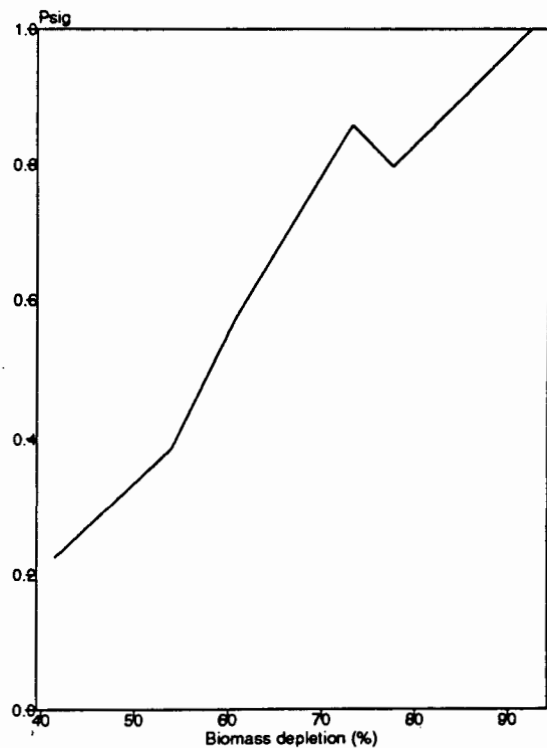


Figure 5. P_{sig} , the probability of detecting a significant change in mean length, plotted against biomass depletion (data from Table 1).

The probability that a change in mean length would be detected rises from 0.23 when the biomass is depleted by 40% to greater than 0.8 when the depletion exceeds 70% (Figure 5).

A stock reduction analysis using the 1993 data (but assuming constant recruitment, and thus ignoring the mean length data) gave a best estimate for B_0 of 408 000 t with 95% confidence interval 389 000 – 449 000 t. For these values of B_0 the biomass depletion between 1984 and 1990 was 70%, 75%, and 60%, respectively. From Figure 5 we see that the probability that a decline in mean length would have been detected lies between 0.55 and 0.8.

5 Discussion

The main result of this paper is that mean age or otolith weight are not more sensitive than mean length in detecting a decline in biomass. The three indicators are approximately equally sensitive given equal sample sizes (Figure 3B). However, on an equal cost basis, mean length is the most sensitive of the indicators because the cost of obtaining a length datum is so much lower than that for age or otolith weight.

This result was derived under the assumption of constant recruitment. However, it seems reasonable to assume that the relative sensitivities of the three indicators would be unchanged by a change in the pattern of recruitment.

A secondary result is that, had recruitment been constant, it is more likely than not that a decline in mean length between 1984 and 1990 would have been detected. This result can not be generalised to variable recruitment.

The assumption that fishing mortality is independent of size (for recruited fish) is probably not true. Anecdotal evidence suggests that fishers preferentially target larger fish. However, this type of targeting would tend to increase the decline in mean length rather than mask it. It is not clear what effect it would have on the relative sensitivities of the three indicators.

There are two factors of concern with regard to the (*L*, *A*, *O*) data used above. First, there is still uncertainty about the accuracy of the estimated ages. Smith *et al.* (in press) have shown that the age estimates are broadly consistent with those derived by Fenton *et al.* (1991) using radiometric methods, but the difficulty in interpreting otoliths of this species means that some ageing errors are still inevitable. Second, the data do not come from the Chatham Rise stock. However, the limited information available suggests that there are not gross differences in growth between these two stocks.

6 Acknowledgments

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