# Stock assessment of Namibian orange roughy populations using an age-structured production model and all available indices of abundance from 1994 to 2002, and making allowance for annually variable aggregation of the stocks

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## Abstract

Updated assessments of the four orange roughy aggregations off Namibia, based upon a maximum penalised likelihood approach which uses all available indices of abundance, are presented, and projections under constant catch levels reported. Earlier methodology is extended to reflect the proportion of a stock present at the fishing aggregation each year governed by a beta distribution. This new methodology is argued to provide the most reliable assessment of the resource. It suggests that *Johnies*, *Frankies* and *Rix* are all presently at some 60% of their pre-exploitation level, but that *Hotspot* is perhaps much more depleted. Overall, medium term sustainable yields would seem to be in the 2 500 – 3 500 ton range. However, variable aggregation levels from year to year would lead to difficulties in making a catch of this size every year.

## Introduction

This paper updates assessments of the orange roughy resource at the various aggregations off Namibia presented by Brandão and Butterworth (2002a), based upon a maximum penalised likelihood estimation approach. Various standardised CPUE series presented by Brandão and Butterworth (2003) are considered. The assessments also consider the possibility of annually variable levels of aggregation of the stocks in the fishing areas. All available indices of abundance are taken into account, and deterministic projections under various levels of constant catch are reported.

## Data

In the analyses presented in this paper a "fishing year" has been taken to be the period July to June as used by Brandão and Butterworth (2002a).

In the previous assessment of Brandão and Butterworth (2002a), the commercial fishing database had recently been re-entered and used in its then state to calculate annual catches. Since that time, the database has been further updated to include missing records. The annual catches given in Table 1 have been recalculated based upon the most recent version of the database. The uncorrected and corrected hydroacoustic abundance and research swept area (A Staby, pers. commn) indices are listed in Table 2. In 2000 the *Emanguluko* (instead of the *Southern Aquarius*) performed the research swept area survey; therefore the research swept area value for 2000 has been corrected for a vessel effect (obtained from the General Linear Model applied to the commercial CPUE data), and this corrected value is used in all the assessments in this paper.

The standardised commercial CPUE data obtained when fitting different models and dealing with missing abundance indices in some years in sub-aggregations (Brandão and Butterworth, 2003) are given in Table 3.

## Methods

### Bias Factor Uncertainties

Appendix 1 lists the various bias factor distributions obtained from Boyer *et al*. (2000) that are appropriate to the acoustic estimates for each of the three aggregations where such surveys have taken place. As in the analyses conducted a year previously (Brandão and Butterworth 2002), a further bias factor distribution has been added to account for vessel calibration for acoustic surveys performed by a vessel other than the *Welwitchia*. The method of obtaining the bias $q$ (and its uncertainty) in the relationship:

$$I_y = q\,B_y \tag{1}$$

where $I$ is the corrected hydroacoustic estimate of abundance, and $B$ is the true resource biomass (the recruited = mature component thereof, in terms of the population model of Appendix 2) as explained in Brandão and Butterworth (2000). The one difference here is that the input data have now been standardised so that the same bias factor distributions apply for all years.

## Population Model Fitting

The age-structured production model (ASPM) of Brandão and Butterworth (2001) that includes all available indices of abundance in the fitting process is used. The negative of the penalised log likelihood (ignoring constants) which is minimised in the fitting procedure is thus:

$$
\begin{aligned}
-\ln L = {} & \frac{1}{2(\sigma_q^{AC})^2}\left(\ln q^{AC} - \ln q^{est}\right)^2 + \ln q^{AC} + \frac{1}{2\sigma_M^2}\left(\ln M - \ln M^{est}\right)^2 + \ln M \\
& + \sum_y^{AC} \frac{1}{2(\sigma_y^{AC})^2}\left(\ln I_y^{AC} - \ln\left(q^{AC} B_y\right)\right)^2 + \sum_y^{SA} \frac{1}{2(\sigma_y^{SA})^2}\left(\ln I_y^{SA} - \ln\left(q^{SA} B_y\right)\right)^2 \qquad (2) \\
& + \sum_y^{CPUE} \frac{1}{2(\sigma^{CPUE})^2}\left(\ln I_y^{CPUE} - \ln\left(q^{CPUE} B_y\right)\right)^2 + n_{CPUE}\left(\ln \sigma^{CPUE}\right),
\end{aligned}
$$

where

$q^{AC}$ is the remaining multiplicative bias of the acoustic abundance series, whose maximum likelihood estimate is given by:

$$
\ln \hat{q}^{AC} = \frac{\left(\sum_y^{AC} \frac{1}{\left(\sigma_y^{AC}\right)^2}\left(\ln I_y^{AC} - \ln \hat{B}_y\right)\right) - 1}{\left(\sum_y^{AC} \frac{1}{\left(\sigma_y^{AC}\right)^2}\right) + \frac{1}{\left(\sigma_q^{AC}\right)^2}},
$$

$q^{SA}$ is the catchability coefficient for the research swept area abundance indices, whose maximum likelihood estimate is given by:

$$
\ln \hat{q}^{SA} = \frac{\left(\sum_y^{SA} \frac{1}{\left(\sigma_y^{SA}\right)^2}\left(\ln I_y^{SA} - \ln \hat{B}_y\right)\right)}{\left(\sum_y^{SA} \frac{1}{\left(\sigma_y^{SA}\right)^2}\right)},
$$

$q^{CPUE}$ is the catchability coefficient for the standardised commercial CPUE abundance indices, whose maximum likelihood estimate is given by:

$$
\ln \hat{q}^{CPUE} = \frac{1}{n_{CPUE}} \sum_y^{CPUE}\left(\ln I_y^{CPUE} - \ln \hat{B}_y\right),
$$

$\sigma_q^{AC}$ is the standard deviation of the penalty function applied to $q^{AC}$, which is input; its value is the CV of the distribution of the product of the systematic bias factor distributions applied to the acoustic abundance indices,

$q^{est}$ is the mean of the penalty function applied to $q^{AC}$, whose value is taken to be equal to 1 as the distribution of the bias factors for the acoustic estimate have now been defined in such a way that the corrected acoustic estimate is intended to be an unbiased estimate of abundance,

$M$ is the natural mortality rate,

$M^{est}$ is the mean of the penalty function applied to $M$ (i.e. the prior distribution mean), which is input,

$\sigma_M$ is the standard deviation of the penalty function applied to $M$ (essentially the standard deviation of the prior for log $M$), which is input,

$\sigma_y^{AC}$ is the standard deviation of the log acoustic abundance estimate for year $y$, which is input and is given by:

$$\sigma_y^{AC} = \sqrt{\left(\mathrm{CV}_y^S\right)^2 + \left(\mathrm{CV}_y^R\right)^2}$$

where

$\mathrm{CV}_y^S$ is the CV of the sampling error distribution, and

$\mathrm{CV}_y^R$ is the CV of the distribution of the product of the random bias factor distributions applied to the acoustic abundance indices,

$\sigma_y^{SA}$ is the standard deviation of the log research swept area abundance index for year $y$, which is input and is given by the sampling CV of the research swept area index of relative abundance,

$\sigma^{CPUE}$ is the standard deviation of the standardised CPUE series, whose maximum likelihood estimate is given by:

$$\hat{\sigma}^{CPUE} = \sqrt{\frac{1}{n_{CPUE}} \sum_{y}^{CPUE} \left(\ln I_y^{CPUE} - \ln \hat{q}^{CPUE} \hat{B}_y\right)^2}$$

$I_y^{AC}$ is the acoustic series estimate for year $y$,

$I_y^{SA}$ is the research swept area series index for year $y$,

$I_y^{CPUE}$ is the standardised CPUE series index for year $y$,

$B_y$ is the population model biomass of the resource for year $y$, and

$n_{CPUE}$ is the number of data points in the standardised CPUE abundance series.

The estimable parameters of this model are $q^{AC}$, $q^{SA}$, $q^{CPUE}$, $B_0$, $\sigma^{CPUE}$ and $M$, where $B_0$ is the pre-exploitation mature biomass.

In an alternative model to test the comparability of the yearly index estimates of abundance within this framework (termed “variant”), an estimable multiplicative bias factor $x_y$ is included in the model, so that the various terms in equation (2) become:

$$\left(\ln I_y^{method} - \ln\left(x_y\, q^{method}\, B_y\right)\right)^2 \tag{3}$$

where *method* represents the type of abundance index in the likelihood; for example, *method* = *AC*, when dealing with the acoustic abundance index, and so on. This $x$ factor allows for the possibility that not all the orange roughy belonging to an aggregation collect at that site each year; the year 1997 is taken as a standard for “variant”, so that $x_{1997} = 1$ (i.e. it is assumed that all the fish aggregated in 1997).

The above method of dealing with differential aggregation assumes that 100% of the orange roughy stock aggregated in 1997 and the proportion of stock present in other years is then estimated relative to 1997. Results obtained from applying “variant” to the base case model gives results which seem to be over-optimistic and some estimates for $x_y$ which are greater than 1 (see Brandão and Butterworth 2002a) implying that more than 100% of the stock aggregated in that particular aggregation that year! The results of the hydroacoustic survey carried out in 2002 in *Frankies* (closed to commercial fishing since 1999) show an index of abundance for 2002 that is in the region of the 1997 estimate (Table 2a and b) indicating that the low indices of abundance observed in years subsequent to 1997 cannot be interpreted as purely fishing down of the population, but instead that variable aggregation of the stock occurs from year to year. This signal in one of the indices for the *Frankies* aggregation can be used to model variable aggregation of the orange roughy stock, without having to assume that $x_{1997} = 1$. A penalty function applied to the proportion of stock present ($x_y$) has also been introduced in the model for variable aggregation. As the $x_y$ proportions lie between 0 and 1, this penalty function implies the assumption that the $x_y$ proportions are assumed to follow a beta distribution which is restricted to this range. Therefore the following term is added to the negative of the log likelihood function given in equation (2) in which the various terms are given by equation (3):

$$-\left[N\left\{\ln\Gamma(\alpha+\beta)-\left[\ln\Gamma(\alpha)+\ln\Gamma(\beta)\right]\right\}+\sum_{y=1994}^{2002}\left\{(\alpha-1)\ln(x_y)+(\beta-1)\ln(1-x_y)\right\}\right] \tag{4}$$

where

$N$ is the total number of years considered in the assessment ($N = 2002 - 1994 + 1$),

$\alpha$ is a parameter of the beta distribution, such that $\alpha > 0$,

$\beta$ is a parameter of the beta distribution, such that $\beta > 0$.

Confidence intervals for the parameters estimated have been evaluated using the likelihood profile method. In a few cases where this was not possible, confidence intervals obtained from the Hessian matrix are given and are indicated in the tables with a "$^\dagger$".

## Results and Discussion

Table 4 gives the values of quantities input to equation (2) for the fitting process, including the values of the parameters of the lognormal distributions used to approximate the systematic and random uncertainty factors in the hydroacoustic estimates of abundance.

Tables 5 to 8 provide results for the population model fitting exercises for the four aggregations, *Johnies*, *Frankies*, *Rix* and *Hotspot*. The base case model corresponding to equation (2) is used, and applied to the results of each of three alternative (two for *Hotspot*) approaches to provide standardised CPUE series (Brandão and Butterworth 2003). The base case consists of using a lognormal model in the GLM standardisation and the "zero" method for dealing with missing data in sub-aggregations in particular years (Brandão and Butterworth 2002b). The pessimistic and optimistic cases were chosen as the two combination of GLM model (lognormal or a delta-lognormal (with binomial errors for the proportion positive) and method for dealing with missing data ("zero", "same" or "proportional") that provided the lowest and the highest depletion at the beginning of the fishing year 2002 respectively, when the base case model of equation (2) was applied to all six alternative approaches to provide standardised CPUE series ((Brandão and Butterworth 2002b and 2003) of the *Johnies* aggregation. These two combinations were then used in the other aggregations and designated as "pessimistic" or "optimistic" in terms of the depletion of the stock when the base case model was applied to these combinations for *Johnies*, even though these choices may not reflect these same two extremes for another aggregation.

Tables 5 to 8 also give results for the variant to the base case model used in last year's assessment ("variant") which includes a year aggregation factor $x_y$ (with $x_{1997}$ = 1) and the new variable aggregation model which is the base case model including a year aggregation factor $x_y$ (all estimated by the model) with a penalty on $x_y$ corresponding to the assumption that these values follow a beta distribution. Various fixed mean ($\mu_x$) and standard deviation ($\sigma_x$) values were used to specify the $\alpha$ and $\beta$ parameter values of the beta distribution penalty included in the variable aggregation model, and results obtained for the *Frankies* aggregation. From these results, a set of values ($\mu_x$, $\sigma_x$) were chosen that satisfied the condition that more than 80% of the stock was present in 1997 ($x_{1997} > 0.8$) and the negative of the log likelihood function be less than zero (the choice of "zero" is coincidental – it happens to be one that discriminates reasonably good fits to the data). From this set three options of ($\mu_x$, $\sigma_x$) were chosen that spanned a range of stock depletion: most, mid and least depletion. This set of three values for ($\mu_x$, $\sigma_x$) was then assumed to apply to the other aggregations as well. The reason for doing this is that the extent of fishing down and the proportions present at an aggregation are highly confounded for other than *Frankies*. Some discrimination is possible at *Frankies* as a result of the 2002 acoustic survey result. Hence we assume that the distribution governing the proportion present at *Frankies* each year applies also to the other aggregations. When fitting the variable aggregation model, the $\sigma^{CPUE}$ value is fixed at 0.3 (0.2 for *Hotspot*) rather than estimated, to offset a tendency by the model to overweight the CPUE data. However, the $\sigma^{CPUE}$ value is estimated in cases where this problem does not arise. These models are fitted only to the baseline CPUE interpretation (i.e. applied to the standardised CPUE series obtained from the “zero” method and a lognormal model).

In terms of the base case model, the stock depletion at the beginning of the fishing year 2002 for *Johnies* is at 20% of the pre-exploitation abundance (Table 5). The stock depletion under different CPUE scenarios ranges from 10% to 23%. Allowing for variable aggregation of the stock in the base case model substantially improves the estimated state of the stock. In this case the stock depletion of orange roughy ranges from 62% to 72% of the pre-exploitation biomass for the various mean and standard deviation values assumed for the penalty function on the proportion of stock present. Except for 1994, the proportion of the stock present in *Johnies* is much smaller in other years than in 1997 (for which this proportion ranges from 93% to 98%). This implies that for most years, less than 50% of the stock aggregated at *Johnies*.

The stock depletion at the beginning of the year 2002 for the *Frankies* aggregation is at 32% of the pre-exploitation abundance under the baseline interpretation for the standardised CPUE series (Table 6), and ranges from 27% to 29% under alternative CPUE interpretations. Including variable aggregation in the base case model indicates that the population is substantially better (between 60% to 69%) than when the biomass indices are considered as comparable from year to year. Over 80% of the stock aggregated in the years 1996, 1997 and 2002 with most others years having less than 50% of the stock aggregating (in some years as little as 23% for the set of ($\mu_x$, $\sigma_x$) corresponding to the greatest extent of depletion of the stock).

The stock depletion at the beginning of the year 2002 is estimated at 64% of the pre-exploitation biomass for the *Rix* aggregation under the base case scenario (Table 7). There is not much difference in the stock depletion under other standardised CPUE interpretations (ranging from 24% to 27%), but substantially worse state of the stock than that given by the base case model. By allowing for variable aggregation of the stock, the status of the resource is generally a little better than under the base case scenario (61% to 73% stock depletion). The highest stock aggregations at *Rix* occur after 1996, with all reflecting more than 50% of the stock aggregating for the choice for ($\mu_x$, $\sigma_x$) giving the greatest depletion of the stock, but most years having less than 50% aggregation under the ($\mu_x$, $\sigma_x$) choice giving the least depletion.

The stock depletion at the beginning of the year 2002 for the *Hotspot* aggregation is estimated at 10% of the initial biomass when the base case model is fitted to data in which the standardised CPUE series is obtained by fitting a lognormal model. This depletion is at 8% when a delta-lognormal model is used for the commercial CPUE data and a binomial distribution is assumed for the proportion of positive catches (Brandão and Butterworth 2003). By including relative bias factors (for differential aggregation) in the model, the status of the resource is less depleted than under the base case scenario (25% stock depletion) under the “variant” scenario with $x_{1997} = 1$. However, when a beta distribution is assumed for this differential aggregation and incorporated as a penalty function, stock depletion reduces to 9% of pre-exploitation levels. The least extent of aggregation occurs in 1997, with all others years having 50% and more of the stock aggregated at *Hotspot*.

Note that the *Hotspot* aggregation is the only one for which no survey estimates, and in particular no hydroacoustic estimates (see Table 2), are available, so that these assessment results are based entirely on the trend shown by the CPUE data. The pattern of results for the other aggregations suggests that these CPUE data are over-estimating the extent of decline, and therefore that this assessment of the status of the *Hotspot* aggregation may be overly pessimistic.

Figures 1 to 4 show the observed and predicted values for each of the available indices of abundance of orange roughy for each of the aggregations. Results shown are for the base case population model fitted to data including the baseline standardised CPUE interpretation and for the variable aggregation model for the set of ($\mu_x$, $\sigma_x$) giving a mid-depletion value. For the *Johnies* aggregation, neither the base case model nor the variable aggregation model provide a particularly good fit to the first (1997) observation in the hydroacoustic survey and the research swept area abundance indices. The variable aggregation model does however show a better fit to both the hydroacoustic survey and the CPUE abundance indices (though, naturally, it has the advantage of many more estimable parameters). Both models fit the research swept-area indices equally. For *Frankies* the base case model does not fit the 1997 or the 2002 acoustic index, while the variable aggregation model is able to fit both these high index values. The variable aggregation model also shows an overall better fit to the other indices. For both *Frankies* and *Rix* the base case model does not fit the first four observations in the CPUE abundance index, while the variable aggregation model shows a much better fit to the CPUE index. For *Hotspot* the variable aggregation model fits the CPUE index exactly, as there are as many estimable ($x_y$) parameters as data points, and in the absence of other abundance index series the penalty function has little influence.

Figure 5 shows the estimated proportion of orange roughy stock present in each year for each aggregation. For *Johnies* the highest proportions of the stock are present in 1994 and 1997. At *Frankies*, this occurs in 1996, 1997 and 2002, and at *Rix* in 1997, 1998 and 2000. At *Hotspot* the lowest proportion of the stock present occurs in 1997.

Figures 6 and 7 show thirty five year deterministic projections of the orange roughy stock for the *Johnies* aggregation under the base case model and the variable aggregation model for mid depletion of the stock, both for the baseline CPUE interpretation. For the base case model a constant catch of 250 t allows the resource to improve from a depletion of 20% of initial biomass to 52%, while a constant catch of 500 t improves it to only 26%. A constant catch of 750 t does not immediately deplete the resource, but after about sixteen years of a constant catch of this size, the resource abundance begins to drop and the stock becomes extinct within a few years. Under the variable aggregation model, a 500 t constant catch improves the stock depletion to 71% from 67% and a constant catch of 1000 t after thirty five years reduces the stock depletion to only 51% of the pre-exploitation abundance.

Figures 8 and 9 show deterministic projections for the base case model and the variable aggregation model respectively, both for the baseline CPUE interpretation for the *Frankies* aggregation. An improvement in stock depletion to 58% from 32% of initial biomass is seen for the base case model for a constant catch of 250 t and a constant catch of 500 t involves hardly any change in stock depletion (34%). The stock becomes greatly reduced (6%) after thirty five years under a constant catch of 750 t. Under the variable aggregation model, a constant catch of 500 t makes hardly any change in stock depletion (67% from 65%) and reduces it to 43% of pre-exploitation abundance under a 1000 t constant catch.

Figures 10 to 11 show deterministic projections for the *Rix* aggregation under the base case and the variable aggregation models fitted. For the former, a constant catch of 500 t reduces the stock to 54% of pre-exploitation biomass after 35 years. For the variable aggregation model, a constant catch of 500 t for thirty five years reduces the stock to 61% (from 69%) of initial biomass and to 28% under a constant catch of 1000 t.

Figure 12 and 13 give projections for the *Hotspot* aggregation for the base case model and the variable aggregation model. A constant catch of 50 t improves the stock depletion to 47% from 10% of initial biomass for the base case model and a constant catch of 100 t to 22%. If no catches are taken for thirty five years, the resource improves from a depletion of

10% of initial biomass to 70%. For the variable aggregation model, a constant catch of 50 t for thirty five years improves the stock depletion to 45% from 9% of initial biomass and to 20% under a constant catch of 100 t.

## Conclusions

Given the 2002 acoustic survey result at *Frankies* (Table 2) it would now seem clear that the premise that fishing down was the primary cause of the earlier drop in CPUE and other indices in at least this aggregation can no longer stand. The variable aggregation model therefore seems the best basis upon which to provide advice, and Table 9 presents a summary based on the “mid-depletion” version of this model. This indicates the three major aggregations (*Johnies*, *Frankies* and *Rix*) all to be reasonably healthy and in the 60%’s of their initial abundances. The combined MSY is about 2 700 tons, which varies up or down by about 400 tons depending upon which version of the variable aggregation model is used.

Projections using this mid-depletion version suggest an appropriate overall annual catch in the medium term to be in the 2 500 to 3 500 ton range. It is important, though, to bear in mind the variable aggregation effect suggests that in some years the extent of aggregation in the fishing areas will not be sufficient for such a level of catch to be made.

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## References

Branch, T.A. 1998. Assessment and adaptive management of orange roughy off southern Africa. MSc Thesis reprint TR 98/07, Department of Mathematics and Applied Mathematics, University of Cape Town, 204pp.

Brandão, A. and Butterworth, D.S. 2000. Are acoustic survey biomass estimates for orange roughy aggregations compatible with catch-induced depletion alone? Namibian Ministry of Fisheries and Marine Resources document WkShop/ORH/2000/ Doc. 11 (13pp).

Brandão, A. and Butterworth, D.S. 2001. Stock assessment of Namibian orange roughy using an age-structured production model and all available indices of abundance. Namibian Ministry of Fisheries and Marine Resources document DWFWG/WkShop/Mar07/ Doc. 2 (32pp).

Brandão, A. and Butterworth, D.S. 2002a. Stock assessment of Namibian orange roughy using an age-structured production model and all available indices of abundance from 1994 to 2001 and based on a fishing year of July to June. Namibian Ministry of Fisheries and Marine Resources document DWFWG/WkShop/Feb02/Doc. 2 (40pp).

Brandão, A. and Butterworth, D.S. 2002b. Standardised CPUE abundance indices of orange roughy off Namibia based on lognormal and delta-lognormal linear models. Namibian Ministry of Fisheries and Marine Resources document DWFWG/WkShop/Feb02/Doc. 1 (25pp).

Brandão, A. and Butterworth, D.S. 2003. Standardised CPUE abundance indices of orange roughy off Namibia based on lognormal and delta-lognormal linear models. Namibian Ministry of Fisheries and Marine Resources document DWFWG/WkShop/Mar03/Doc. 1 (25pp).

Boyer, D., Hampton, Staalesen, B. and Staby, A. 2000. Development of acoustic methods for assessment of orange roughy (*Hoplostetus atlanticus)* biomass off Namibia (Revised) (submitted to *S. Afr. J. Marine Science*).

Francis, R.I.C.C., Clark, M.R., Coburn, R.P., Field, K.D., and Grimes, P.J. 1995. Assessment of the ORH 3B orange roughy fishery for the 1994-95 fishing year. *New Zealand Fisheries Assessment Research Document* 95/4 (43pp).

**Table 1.** Yearly (fishing year) catches of orange roughy (in tons) taken from the aggregations considered in this paper. The notation of, for example, "1996" for year refers to the period July 1996 to June 1997. The year 2002 is incomplete as data were available only until September.

| **Year** | ***Johnies*** | ***Frankies*** | ***Rix*** | ***Hotspot*** | **Total** |
|---|---|---|---|---|---|
| 1994 | 1 145 | — | — | 2 169 | 3 315 |
| 1995 | 3 773 | 2 291 | 323 | 897 | 7 284 |
| 1996 | 2 062 | 8 736 | 1 861 | 477 | 13 136 |
| 1997 | 7 539 | 4 817 | 3 836 | 482 | 16 675 |
| 1998 | 1 917 | 650 | 3 921 | 358 | 6 845 |
| 1999 | 1 367 | 40† | 444 | 226 | 2 076 |
| 2000 | 667 | 11† | 307 | 224 | 1 209 |
| 2001 | 452 | 214† | 183 | 106 | 955 |
| 2002* | 285 | 15†† | 232 | 71 | 603 |

* Incomplete

† Closed to normal commercial fishing

†† Fishery partially reopened in September

**Table 2.** Abundance indices of orange roughy obtained from hydroacoustic surveys and research swept area surveys for the aggregations considered in this paper.

**a)** Target acoustic indices (uncorrected for biases) of absolute abundance in tons (CV). Note that these CV's correspond to the survey sampling variability only. These results are all given as standardised to the *Welwitchia*, against which the vessels that carried out the surveys have been calibrated.

| **Year** | ***Johnies*** | ***Frankies*** | ***Rix*** | **Survey vessel** |
|---|---|---|---|---|
| 1997 | 34 178 (0.21) | 17 925 (0.25) | 21 579 (0.15) | *Nansen* |
| 1998 | 3 570 (0.43) | 4 940 (0.38) | 7 572 (0.19) | *Nansen* |
| 1999 | — | 1 782 (0.25) | — | *Nansen* |
| 2000 | — | 3 756 (0.30) | — | *Conbaroya* |
| 2001 | — | 4 820 (0.16) | — | *Southern Aquarius* |
| 2002 | — | 15 802 (0.21) | — | *Southern Aquarius* |

**b)** Target acoustic indices (corrected for biases) of absolute abundance in tons (CV). Note that these CV's incorporate uncertainties in the survey bias factors as well as the survey sampling variability.

| **Year** | ***Johnies*** | ***Frankies*** | ***Rix*** |
|---|---|---|---|
| 1997 | 55 757 (0.35) | 29 567 (0.38) | 34 872 (0.32) |
| 1998 | 6 267 (0.54) | 8 478 (0.49) | 12 301 (0.35) |
| 1999 | — | 2 934 (0.38) | — |
| 2000 | — | 6 294 (0.44) | — |
| 2001 | — | 7 805 (0.34) | — |
| 2002 | — | 25 839 (0.37) | — |

**c)** Research swept area indices of relative abundance (CV), standardised for the Southern Aquarius.

| **Year** | ***Johnies*** | ***Frankies*** | ***Rix*** | **Survey vessel** |
|---|---|---|---|---|
| 1997 | 57 650 (0.27) | 30 995 (0.37) | — | *Southern Aquarius* |
| 1998 | 6 980 (0.25) | 2 400 (0.60) | — | *Southern Aquarius* |
| 1999 | 2 137 (0.40) | 3 055 (0.35) | 1 006 (0.59) | *Southern Aquarius* |
| 2000 | 4 365 (0.35) | — | — | |
| 2000 (uncorrected for vessel effect) | 3 330 (0.34) | — | — | *Emanguluko* |
| 2001 | 11 544 (0.46) | — | — | *Southern Aquarius* |
| 2002 | 10 148 (0.59) | — | — | *Southern Aquarius* |

**Table 3.** Abundance indices for orange roughy obtained from standardised commercial CPUE series, based on lognormal and delta-lognormal models, for the aggregations considered in this paper. For each of the models applied to the CPUE series, three methods ("zero", "same" and "proportional", see Brandão and Butterworth (2002) for a description of the methods) of dealing with cells (sub-aggregations) without data in particular years are considered.

**a)** Standardised commercial CPUE indices of relative abundance (normalised to their mean) for the *Johnies* aggregation.

| Year | "Zero" method | | "Same" method | | "Proportional" method | |
|---|---|---|---|---|---|---|
| | Lognormal model | Delta-lognormal model | Lognormal model | Delta-lognormal model | Lognormal model | Delta-lognormal model |
| **1994** | 2.209 | 2.878 | 2.485 | 2.921 | 5.020 | 5.407 |
| **1995** | 0.506 | 0.663 | 1.376 | 1.476 | 1.150 | 1.245 |
| **1996** | 0.643 | 0.734 | 1.465 | 1.522 | 1.461 | 1.378 |
| **1997** | 1.798 | 1.796 | 1.171 | 1.171 | 0.436 | 0.369 |
| **1998** | 0.998 | 0.876 | 0.650 | 0.572 | 0.242 | 0.180 |
| **1999** | 0.775 | 0.584 | 0.505 | 0.381 | 0.188 | 0.120 |
| **2000** | 0.818 | 0.665 | 0.533 | 0.434 | 0.199 | 0.137 |
| **2001** | 0.659 | 0.441 | 0.429 | 0.288 | 0.160 | 0.091 |
| **2002** | 0.594 | 0.362 | 0.387 | 0.236 | 0.144 | 0.074 |

**b)** Standardised commercial CPUE indices of relative abundance (normalised to their mean) for the *Frankies* aggregation.

| Year | "Zero" method | | "Same" method | | "Proportional" method | |
|---|---|---|---|---|---|---|
| | Lognormal model | Delta-lognormal model | Lognormal model | Delta-lognormal model | Lognormal model | Delta-lognormal model |
| **1995** | 0.453 | 0.578 | 2.487 | 2.329 | 4.544 | 4.028 |
| **1996** | 2.597 | 2.292 | 2.202 | 1.949 | 1.174 | 0.921 |
| **1997** | 1.190 | 1.117 | 1.009 | 0.950 | 0.538 | 0.449 |
| **1998** | 1.026 | 1.097 | 0.870 | 0.933 | 0.464 | 0.441 |
| **1999** | 0.392 | 0.333 | 0.385 | 0.327 | 0.190 | 0.142 |
| **2000** | | | 0.363 | 0.433 | 0.079 | 0.047 |
| **2001** | 0.342 | 0.583 | 0.342 | 0.540 | 0.182 | 0.259 |
| **2002** | | | 0.342 | 0.540 | 0.828 | 1.714 |

**Table 3 cont.** Abundance indices of orange roughy obtained from standardised commercial CPUE series, on lognormal and delta-lognormal models, for the aggregations considered in this paper. For each of the models applied to the CPUE series, three methods ("zero", "same" and "proportional", see Brandão and Butterworth (2002) for a description of the methods) of dealing with cells (sub-aggregations) without data in particular years are considered.

**c)** Standardised commercial CPUE indices of relative abundance (normalised to their mean) for the *Rix* aggregation.

| **Year** | **"Zero" method** | | **"Same" method** | | **"Proportional" method** | |
|---|---|---|---|---|---|---|
| | **Lognormal model** | **Delta-lognormal model** | **Lognormal model** | **Delta-lognormal model** | **Lognormal model** | **Delta-lognormal model** |
| **1995** | 0.511 | 0.705 | 1.788 | 1.822 | 2.040 | 2.464 |
| **1996** | 0.400 | 0.355 | 1.717 | 1.591 | 1.595 | 1.241 |
| **1997** | 2.729 | 2.493 | 1.730 | 1.648 | 1.680 | 1.543 |
| **1998** | 1.675 | 1.813 | 1.062 | 1.198 | 1.031 | 1.122 |
| **1999** | 0.602 | 0.639 | 0.382 | 0.422 | 0.371 | 0.396 |
| **2000** | 0.903 | 0.943 | 0.572 | 0.623 | 0.556 | 0.583 |
| **2001** | 0.578 | 0.520 | 0.366 | 0.343 | 0.356 | 0.322 |
| **2002** | 0.603 | 0.533 | 0.382 | 0.352 | 0.371 | 0.330 |

**d)** Standardised commercial CPUE indices of relative abundance (normalised to their mean) for the *Hotspot* aggregation. Note that for this aggregation, as there are no sub-aggregations, there are data available for all years and therefore only one method of obtaining the standardised CPUE series is used.

| **Year** | **Lognormal model** | **Delta-lognormal model** |
|---|---|---|
| **1994** | 3.806 | 4.148 |
| **1995** | 1.983 | 2.177 |
| **1996** | 0.832 | 0.675 |
| **1997** | 0.488 | 0.411 |
| **1998** | 0.561 | 0.469 |
| **1999** | 0.440 | 0.383 |
| **2000** | 0.303 | 0.277 |
| **2001** | 0.329 | 0.285 |
| **2002** | 0.258 | 0.174 |

**Table 4.** Parameters of distributions contributing to the various terms in the negative log likelihood of equation (2).

| **Factor** | **Central value** | **Standard deviation** |
|---|---|---|
| Natural mortality | $M^{est}$ = 0.055 | $\sigma_M = 0.30$ |
| $q^{AC}$-systematic | $q^{est}$ = 1.0 | $\sigma_q^{AC} = 0.22$ |
| $q^{AC}$-random ***Johnies*** 1997 | — | $\sigma_{1997}^{AC} = 0.28$ |
| 1998 | — | $\sigma_{1998}^{AC} = 0.48$ |
| $q^{AC}$-random ***Frankies*** 1997 | — | $\sigma_{1997}^{AC} = 0.32$ |
| 1998 | — | $\sigma_{1998}^{AC} = 0.43$ |
| 1999 | — | $\sigma_{1999}^{AC} = 0.31$ |
| 2000 | — | $\sigma_{2000}^{AC} = 0.38$ |
| 2001 | — | $\sigma_{2001}^{AC} = 0.26$ |
| 2002 | — | $\sigma_{2002}^{AC} = 0.29$ |
| $q^{AC}$-random ***Rix*** 1997 | — | $\sigma_{1997}^{AC} = 0.25$ |
| 1998 | — | $\sigma_{1998}^{AC} = 0.26$ |

**Table 5.** Estimates obtained when various models are fitted to the available indices of Namibian orange roughy for the *Johnies* aggregation. A vessel correction factor has been applied to the research swept area index for 2000 as a different vessel from that for other years was used for this survey. The estimates shown are for the pre-exploitation orange roughy (recruited=mature) abundance ($B_0$), the natural mortality ($M$), the current stock biomass ($B_{2002}$) and stock depletion ($B_{2002}/B_0$) at the beginning of the year 2002, the acoustic estimate multiplicative bias ($q^{AC}$), the research swept area index multiplicative bias ($q^{SA}$) and the commercial CPUE index catchability coefficient ($q^{CPUE}$), the standard deviation for the standardised CPUE series ($\sigma^{CPUE}$), the estimated proportion of the stock present each year ($x_{1994}$, $x_{1995}$, $x_{1996}$, $x_{1997}$, $x_{1998}$, $x_{1999}$, $x_{2000}$, $x_{2001}$, $x_{2002}$), the maximum sustainable yield (MSY), the maximum sustainable yield level (MSYL) and the negative of the log likelihood. The 95% confidence intervals (obtained by the profile likelihood method or using the Hessian matrix, indicated with "†") are given for the parameter estimates in some cases. Biomass units are tons.

| **Parameter estimates (95% confidence interval)** | ***Johnies*** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Base case (with "zero" method and lognormal model)** | **Pessimistic case ("proportional" method and delta-lognormal model)** | **Optimistic case ("same" method and lognormal model)** | **Variant (including $x_y$ parameter; $x_{1997}$=1)** | **Variable aggregation (most depletion; $\mu_x$=0.7, $\sigma_x$=0.2)** | **Variable aggregation (mid depletion; $\mu_x$=0.6, $\sigma_x$=0.2)** | **Variable aggregation (least depletion; $\mu_x$=0.55, $\sigma_x$=0.25)** |
| $B_0$ | 19 252<br>(13 965; 31 811) | 15 942<br>(13 388; 17 526) | 20 325<br>(17 712; 22 841) | 59 549<br>(24 334; 94 756)† | 40 607<br>(19 048; 83 858) | 46 779<br>(23 715; 97 894) | 55 813<br>(26 139; 129 777) |
| $M$ | 0.053<br>(0.026; 0.100) | 0.070<br>(0.043; 0.098) | 0.047<br>(0.024; 0.079) | 0.050<br>(0.023; 0.097) | 0.048<br>(0.023; 0.0915) | 0.049<br>(0.023; 0.0931) | 0.050<br>(0.023; 0.096) |
| $B_{2002}$ | 3 890 | 1 604 | 4 577 | 44 070 | 24 960 | 31 186 | 40 302 |
| $B_{2002}/B_0$ | 0.202 | 0.101 | 0.225 | 0.740 | 0.615 | 0.667 | 0.722 |
| $q^{AC}$ | 1.618<br>(1.036; 1.973) | 1.934<br>(1.752; 2.366) | 1.549<br>(1.406; 1.707) | 0.953<br>(0.661; 1.280) | 1.081<br>(0.694; 1.565) | 1.039<br>(0.680; 1.435) | 0.974<br>(0.666; 1.319) |
| $q^{SA}$ | 1.737<br>(0.053; 3.177) | 3.694<br>(2.382; 7.761) | 1.501<br>(1.047; 1.995) | 0.831<br>(0.225; 1.417)† | 0.728<br>(0.211; 1.468) | 0.705<br>(0.177; 1.339) | 0.707<br>(0.191; 1.309) |
| $q^{CPUE}$ ($\times 10^5$) | 11.523<br>(1.224; 25.531) | 8.573<br>(6.425; 15.473) | 9.469<br>(7.001; 12.100) | 5.418<br>(1.764; 14.867)† | 6.376<br>(1.601; 12.716) | 6.364<br>(1.610; 12.220) | 6.802<br>(1.604; 12.793) |
| $\sigma^{CPUE}$ | 0.666<br>(0.441; 0.942) | 0.607<br>(0.585; 0.728) | 0.155<br>(0.146; 0.187) | 0.419<br>(0.138; 0.700)† | 0.300 | 0.300 | 0.300 |
| $x_{1994}$ | — | — | — | 0.770 | 0.867 | 0.712 | 0.590 |
| $x_{1995}$ | — | — | — | 0.435 | 0.238 | 0.204 | 0.143 |
| $x_{1996}$ | — | — | — | 0.493 | 0.332 | 0.278 | 0.194 |
| $x_{1997}$ | — | — | — | 1.000 | 0.984 | 0.934 | 0.937 |
| $x_{1998}$ | — | — | — | 0.191 | 0.416 | 0.343 | 0.257 |
| $x_{1999}$ | — | — | — | 0.107 | 0.316 | 0.255 | 0.178 |
| $x_{2000}$ | — | — | — | 0.156 | 0.410 | 0.328 | 0.232 |
| $x_{2001}$ | — | — | — | 0.234 | 0.526 | 0.415 | 0.291 |
| $x_{2002}$ | — | — | — | 0.195 | 0.459 | 0.362 | 0.249 |
| **MSY** | 468 | 515 | 438 | 1 373 | 891 | 1 043 | 1 275 |
| **MSYL** | 0.245 | 0.241 | 0.246 | 0.245 | 0.246 | 0.246 | 0.245 |
| **-ln *L*** | 21.578 | 19.273 | 9.117 | -3.662 | 3.753 | 1.198 | -2.010 |

**Table 6.** Estimates obtained when various models are fitted to the available indices of Namibian orange roughy for the *Frankies* aggregation. A vessel correction has been applied to the research swept area index for 2000 as a different vessel from that for other years was used for this survey. The estimates shown are for the pre-exploitation orange roughy (recruited=mature) abundance ($B_0$), the natural mortality ($M$), the current stock biomass ($B_{2002}$) and stock depletion ($B_{2002}/B_0$) at the beginning of the year 2002, the acoustic estimate multiplicative bias ($q^{AC}$), the research swept area index multiplicative bias ($q^{SA}$) and the commercial CPUE index catchability coefficient ($q^{CPUE}$), the standard deviation for the standardised CPUE series ($\sigma^{CPUE}$), the estimated proportion of the stock present each year ($x_{1995}$, $x_{1996}$, $x_{1997}$, $x_{1998}$, $x_{1999}$, $x_{2000}$, $x_{2001}$, $x_{2002}$), the maximum sustainable yield (MSY), the maximum sustainable yield level (MSYL) and the negative of the log likelihood. The 95% confidence intervals (obtained by the profile likelihood method) are given for the parameter estimates in some cases. Biomass units are tons.

| **Parameter estimates (95% confidence interval)** | ***Frankies*** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Base case (with "zero" method and lognormal model)** | **Pessimistic case ("same" method and lognormal model)** | **Optimistic case ("proportional" method and delta-lognormal model)** | **Variant (including $x_y$ parameter; $x_{1997}$=1)** | **Variable aggregation (most depletion; $\mu_x$=0.7, $\sigma_x$=0.2)** | **Variable aggregation (mid depletion; $\mu_x$=0.6, $\sigma_x$=0.2)** | **Variable aggregation (least depletion; $\mu_x$=0.55, $\sigma_x$=0.25)** |
| $B_0$ | 19 706<br>(15 968; 25 280) | 18 849<br>(16 393; 22 494) | 18 348<br>(15 402; 23 575) | 37 618<br>(22 619; 65 519) | 33 775<br>(21 954; 54 829) | 38 252<br>(23 896; 65 974) | 42 929<br>(25 925; 96 967) |
| $M$ | 0.052<br>(0.025; 0.090) | 0.045<br>(0.022; 0.077) | 0.056<br>(0.028; 0.094) | 0.050<br>(0.023; 0.097) | 0.050<br>(0.023; 0.095) | 0.050<br>(0.023; 0.096) | 0.050<br>(0.023; 0.097) |
| $B_{2002}$ | 6 356 | 5 046 | 5 257 | 24 171 | 20 305 | 24 785 | 29 480 |
| $B_{2002}/B_0$ | 0.323 | 0.268 | 0.287 | 0.643 | 0.601 | 0.648 | 0.687 |
| $q^{AC}$ | 1.449<br>(0.751; 2.044) | 1.700<br>(1.022; 2.246) | 1.708<br>(0.849; 2.393) | 0.953<br>(0.567; 1.327) | 1.000<br>(0.575; 1.377) | 0.989<br>(0.583; 1.381) | 0.965<br>(0.586; 1.366) |
| $q^{SA}$ | 1.181<br>(0.398; 1.869) | 1.429<br>(0.676; 2.042) | 1.494<br>(0.417; 2.363) | 0.725<br>(0.297; 1.214) | 0.777<br>(0.347; 1.248) | 0.764<br>(0.334; 1.247) | 0.736<br>(0.316; 1.215) |
| $q^{CPUE}$ ($\times 10^5$) | 8.650<br>(4.115; 12.528) | 10.894<br>(6.011; 14.836) | 7.084<br>(2.979; 10.317) | 6.691<br>(2.723; 11.031) | 7.000<br>(3.134; 10.660) | 6.981<br>(3.174; 10.994) | 6.832<br>(3.053; 11.035) |
| $\sigma^{CPUE}$ | 0.725<br>(0.673; 0.782) | 0.363<br>(0.291; 0.460) | 0.993<br>(0.949; 1.084) | 0.300 | 0.300 | 0.300 | 0.300 |
| $x_{1995}$ | — | — | — | 0.180 | 0.227 | 0.199 | 0.162 |
| $x_{1996}$ | — | — | — | 1.096 | 0.942 | 0.820 | 0.842 |
| $x_{1997}$ | — | — | — | 1.000 | 0.957 | 0.837 | 0.802 |
| $x_{1998}$ | — | — | — | 0.463 | 0.575 | 0.458 | 0.377 |
| $x_{1999}$ | — | — | — | 0.188 | 0.228 | 0.186 | 0.153 |
| $x_{2000}$ | — | — | — | 0.284 | 0.419 | 0.331 | 0.246 |
| $x_{2001}$ | — | — | — | 0.281 | 0.343 | 0.280 | 0.231 |
| $x_{2002}$ | — | — | — | 1.122 | 0.952 | 0.829 | 0.833 |
| **MSY** | 471 | 390 | 475 | 867 | 774 | 877 | 988 |
| **MSYL** | 0.245 | 0.247 | 0.244 | 0.245 | 0.245 | 0.245 | 0.245 |
| **-ln $L$** | 20.543 | 15.633 | 23.385 | -3.820 | -0.333 | -1.319 | -3.389 |

**Table 7.** Estimates obtained when various models are fitted to the available indices of Namibian orange roughy for the *Rix* aggregation. A vessel correction has been applied to the research swept area index for 2000 as a different vessel from that for other years was used for this survey. The estimates shown are for the pre-exploitation orange roughy (recruited=mature) abundance ($B_0$), the natural mortality ($M$), the current stock biomass ($B_{2002}$) and stock depletion ($B_{2002}/B_0$) at the beginning of the year 2002, the acoustic estimate multiplicative bias ($q^{AC}$), the research swept area index multiplicative bias ($q^{SA}$) and the commercial CPUE index catchability coefficient ($q^{CPUE}$), the standard deviation for the standardised CPUE series ($\sigma^{CPUE}$), the estimated proportion of the stock present each year ($x_{1995}$, $x_{1996}$, $x_{1997}$, $x_{1998}$, $x_{1999}$, $x_{2000}$, $x_{2001}$, $x_{2002}$), the maximum sustainable yield (MSY), the maximum sustainable yield level (MSYL) and the negative of the log likelihood. The 95% confidence intervals (obtained by the profile likelihood method) are given for the parameter estimates in some cases. Biomass units are tons.

| **Parameter estimates (95% confidence interval)** | ***Rix*** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Base case (with "zero" method and lognormal model)** | **Pessimistic case ("same" method and lognormal model)** | **Optimistic case ("proportional" method and delta-lognormal model)** | **Variant (including $x_y$ parameter; $x_{1997}$=1)** | **Variable aggregation (most depletion; $\mu_x$=0.7, $\sigma_x$=0.2)** | **Variable aggregation (mid depletion; $\mu_x$=0.6, $\sigma_x$=0.2)** | **Variable aggregation (least depletion; $\mu_x$=0.55, $\sigma_x$=0.25)** |
| $B_0$ | 25 070<br>(14 542; 43 192) | 12 485<br>(11 189; 15 120) | 12 897<br>(11 495; 20 691) | 34 828<br>(17 281; 67 819) | 23 990<br>(13 598; 46 306) | 29 499<br>(15 963; 58 307) | 33 555<br>(16 028; 81 144) |
| $M$ | 0.050<br>(0.023; 0.096) | 0.040<br>(0.020; 0.067) | 0.041<br>(0.020; 0.077) | 0.050<br>(0.023; 0.097) | 0.048<br>(0.023; 0.093) | 0.049<br>(0.023; 0.094) | 0.050<br>(0.023; 0.096) |
| $B_{2002}$ | 15 949 | 2 992 | 3 448 | 25 720 | 14 814 | 20 353 | 24 432 |
| $B_{2002}/B_0$ | 0.636 | 0.240 | 0.267 | 0.738 | 0.618 | 0.690 | 0.728 |
| $q^{AC}$ | 0.980<br>(0.594; 1.273) | 1.703<br>(1.370; 1.857) | 1.653<br>(0.816; 1.798) | 0.953<br>(0.617; 1.332) | 1.071<br>(0.667; 1.516) | 1.013<br>(0.639; 1.424) | 0.977<br>(0.624; 1.376) |
| $q^{SA}$ | 0.064<br>(0.012; 0.114) | 0.329<br>(0.068; 0.438) | 0.289<br>(0.011; 0.381) | 0.164<br>(0.022; 0.336) | 0.114<br>(0.027; 0.253) | 0.115<br>(0.024; 0.248) | 0.142<br>(0.024; 0.299) |
| $q^{CPUE}$ ($\times 10^5$) | 4.232<br>(1.271; 6.853) | 14.661<br>(5.389; 17.673) | 12.926<br>(1.555; 15.571) | 9.790<br>(2.923; 17.569) | 7.847<br>(1.680; 14.337) | 7.669<br>(2.046; 13.920) | 8.897<br>(2.542; 16.120) |
| $\sigma^{CPUE}$ | 0.630<br>(0.612; 0.649) | 0.149<br>(0.141; 0.219) | 0.264<br>(0.236; 0.551) | 0.300 | 0.300 | 0.300 | 0.300 |
| $x_{1995}$ | — | — | — | 0.150 | 0.320 | 0.262 | 0.180 |
| $x_{1996}$ | — | — | — | 0.118 | 0.255 | 0.209 | 0.142 |
| $x_{1997}$ | — | — | — | 1.000 | 0.981 | 0.916 | 0.929 |
| $x_{1998}$ | — | — | — | 0.500 | 0.838 | 0.659 | 0.542 |
| $x_{1999}$ | — | — | — | 0.241 | 0.601 | 0.434 | 0.291 |
| $x_{2000}$ | — | — | — | 0.362 | 0.833 | 0.609 | 0.434 |
| $x_{2001}$ | — | — | — | 0.231 | 0.581 | 0.419 | 0.280 |
| $x_{2002}$ | — | — | — | 0.239 | 0.597 | 0.432 | 0.290 |
| **MSY** | 575 | 228 | 243 | 803 | 533 | 666 | 768 |
| **MSYL** | 0.245 | 0.248 | 0.248 | 0.245 | 0.246 | 0.246 | 0.245 |
| **-ln *L*** | 0.261 | -6.658 | -2.649 | -12.107 | -8.469 | -9.787 | -11.319 |

**Table 8.** Estimates obtained when various models are fitted to the available index of Namibian orange roughy for the *Hotspot* aggregation, where the standardised CPUE series are obtained in various ways (Brandão and Butterworth 2002 and 2003). The estimates shown are for the pre-exploitation orange roughy (recruited=mature) abundance ($B_0$), the natural mortality ($M$), the current stock biomass ($B_{2002}$) and stock depletion ($B_{2002}/B_0$) at the beginning of the year 2002, the commercial CPUE index catchability coefficient ($q^{CPUE}$), the standard deviation for the standardised CPUE series ($\sigma^{CPUE}$), the estimated proportion of the stock present each year ($x_{1994}$, $x_{1995}$, $x_{1996}$, $x_{1997}$, $x_{1998}$, $x_{1999}$, $x_{2000}$, $x_{2001}$, $x_{2002}$), the maximum sustainable yield (MSY), the maximum sustainable yield level (MSYL) and the negative of the log likelihood. The 95% confidence intervals (obtained by the profile likelihood method) are given for the parameter estimates in some cases. Biomass units are tons.

| **Parameter estimates (95% confidence interval)** | ***Hotspot*** | | | | | |
|---|---|---|---|---|---|---|
| | **Lognormal model** | **Delta-lognormal model (binomial errors)** | **Variant (including $x_y$ parameter; $x_{1997}=1$)** | **Variable aggregation (most depletion; $\mu_x=0.7$, $\sigma_x=0.2$)** | **Variable aggregation (mid depletion; $\mu_x=0.6$, $\sigma_x=0.2$)** | **Variable aggregation (least depletion; $\mu_x=0.55$, $\sigma_x=0.25$)** |
| $B_0$ | 4 268<br>(3 727; 4 848) | 4 237<br>(2 943; 4 914) | 5 145 | 4 273<br>(3 663; 4 868) | 4 286<br>(3 578; 5 057) | 4 294<br>(3 478; 6 254) |
| $M$ | 0.053<br>(0.031; 0.061) | 0.051<br>(0.028; 0.059) | 0.050 | 0.051<br>(0.025; 0.085) | 0.051<br>(0.024; 0.088) | 0.051<br>(0.024; 0.094) |
| $B_{2002}$ | 427 | 347 | 1 268 | 402 | 407 | 406 |
| $B_{2002}/B_0$ | 0.100 | 0.082 | 0.246 | 0.094 | 0.095 | 0.095 |
| $q^{CPUE}(\times 10^4)$ | 7.237<br>(4.209; 10.032) | 7.035<br>(1.931; 14.070) | 2.549 | 9.258<br>(1.401; 16.746) | 11.687<br>(3.900; 24.031) | 12.022<br>(1.192; 34.860) |
| $\sigma^{CPUE}$ | 0.222<br>(0.221; 0.237) | 0.316<br>(0.316; 0.319) | 0.200 | 0.200 | 0.200 | 0.200 |
| $x_{1994}$ | — | — | 2.902 | 0.919 | 0.736 | 0.729 |
| $x_{1995}$ | — | — | 2.547 | 0.925 | 0.745 | 0.739 |
| $x_{1996}$ | — | — | 1.440 | 0.679 | 0.523 | 0.494 |
| $x_{1997}$ | — | — | 1.000 | 0.537 | 0.415 | 0.388 |
| $x_{1998}$ | — | — | 1.401 | 0.864 | 0.669 | 0.648 |
| $x_{1999}$ | — | — | 1.268 | 0.916 | 0.725 | 0.714 |
| $x_{2000}$ | — | — | 0.924 | 0.799 | 0.611 | 0.587 |
| $x_{2001}$ | — | — | 1.059 | 0.932 | 0.750 | 0.749 |
| $x_{2002}$ | — | — | 0.798 | 0.728 | 0.558 | 0.538 |
| **MSY** | 104 | 98 | 119 | 101 | 100 | 100 |
| **MSYL** | 0.245 | 0.245 | 0.245 | 0.245 | 0.245 | 0.245 |
| **-ln $L$** | -11.989 | -8.806 | -17.430 | -22.380 | -21.723 | -19.464 |

**Table 9.** Summary of deterministic projection information, giving MSY estimates and approximate medium term sustainable yield (SY) estimates based upon Figs. 6–13, for the mid-depletion version of the variable aggregation model.

| | **Current depletion $B_{2002}/B_0$** | **Variable aggregation model (baseline CPUE)** | |
|---|---|---|---|
| | | **MSY** | **SY** |
| ***Johnies*** | 0.67 | 1 043 | 1 000 – 1 500 |
| ***Frankies*** | 0.65 | 877 | 1 000 |
| ***Rix*** | 0.69 | 666 | 500–1000 |
| ***Hotspot*** | 0.09 | 100 | 50 |
| **Total** | | 2 686 | 2 550–3 550 |

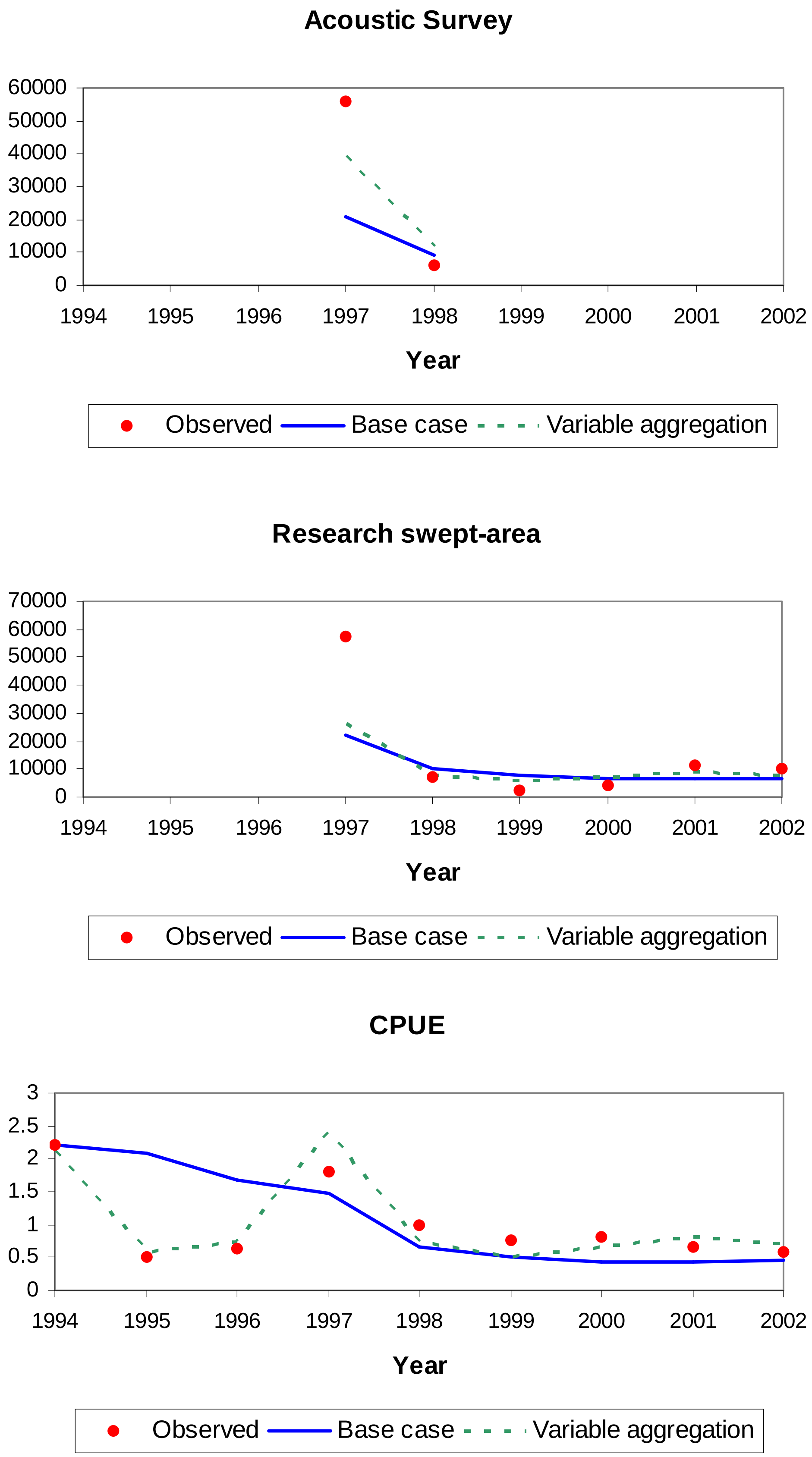
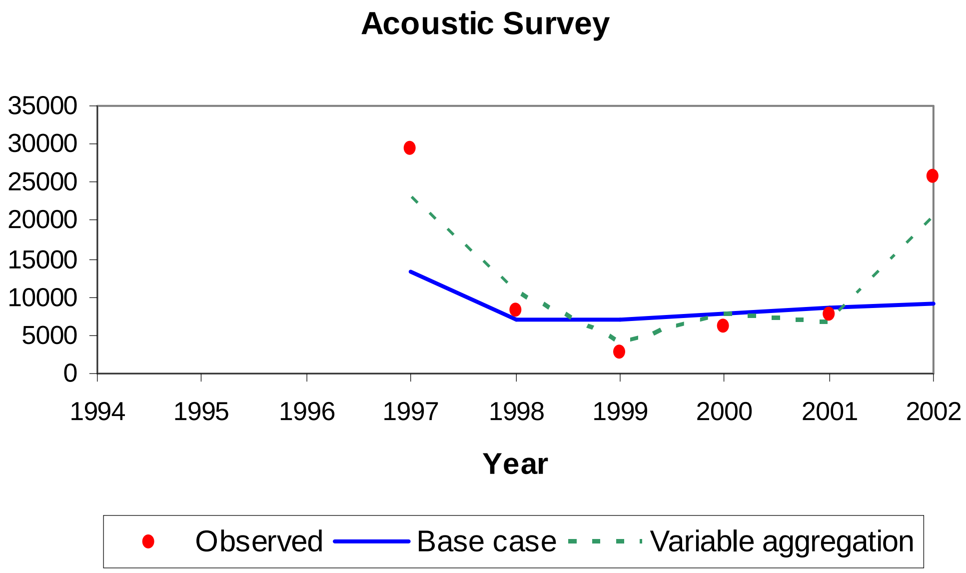
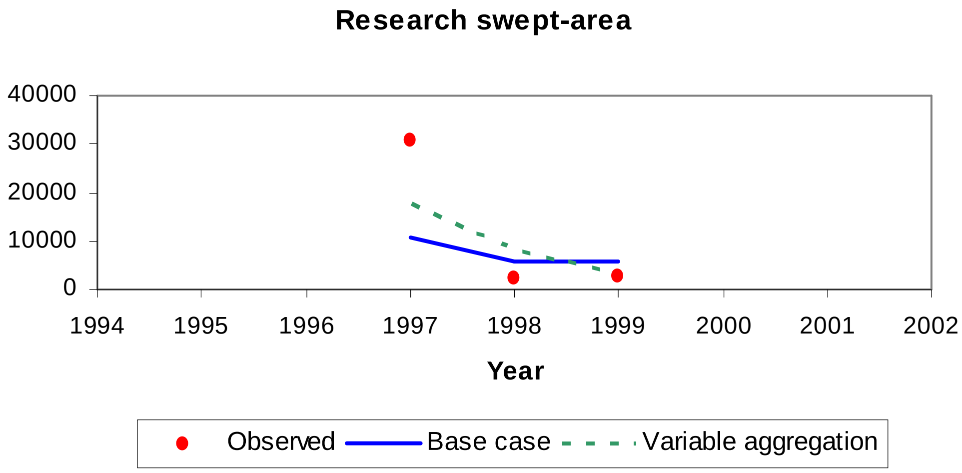


**Figure 1.** Observed and predicted values for each of the available indices of abundance of Namibian orange roughy for the *Johnies* aggregation when the base case model and the variable aggregation model are fitted to data including the baseline CPUE interpretation and the mid-depletion case.





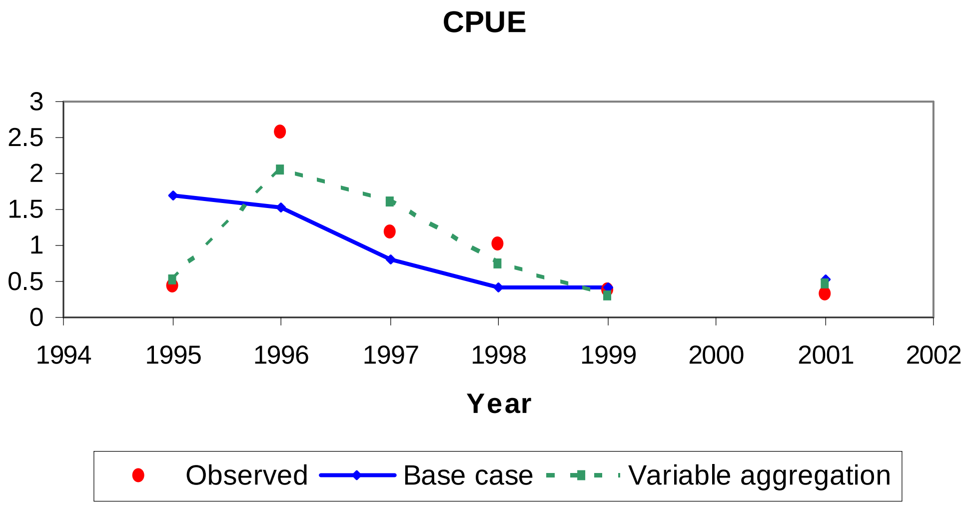


**Figure 2.** Observed and predicted values for each of the available indices of abundance of Namibian orange roughy for the *Frankies* aggregation when the base case model and the variable aggregation model are fitted to data including the baseline CPUE interpretation and the mid-depletion case.

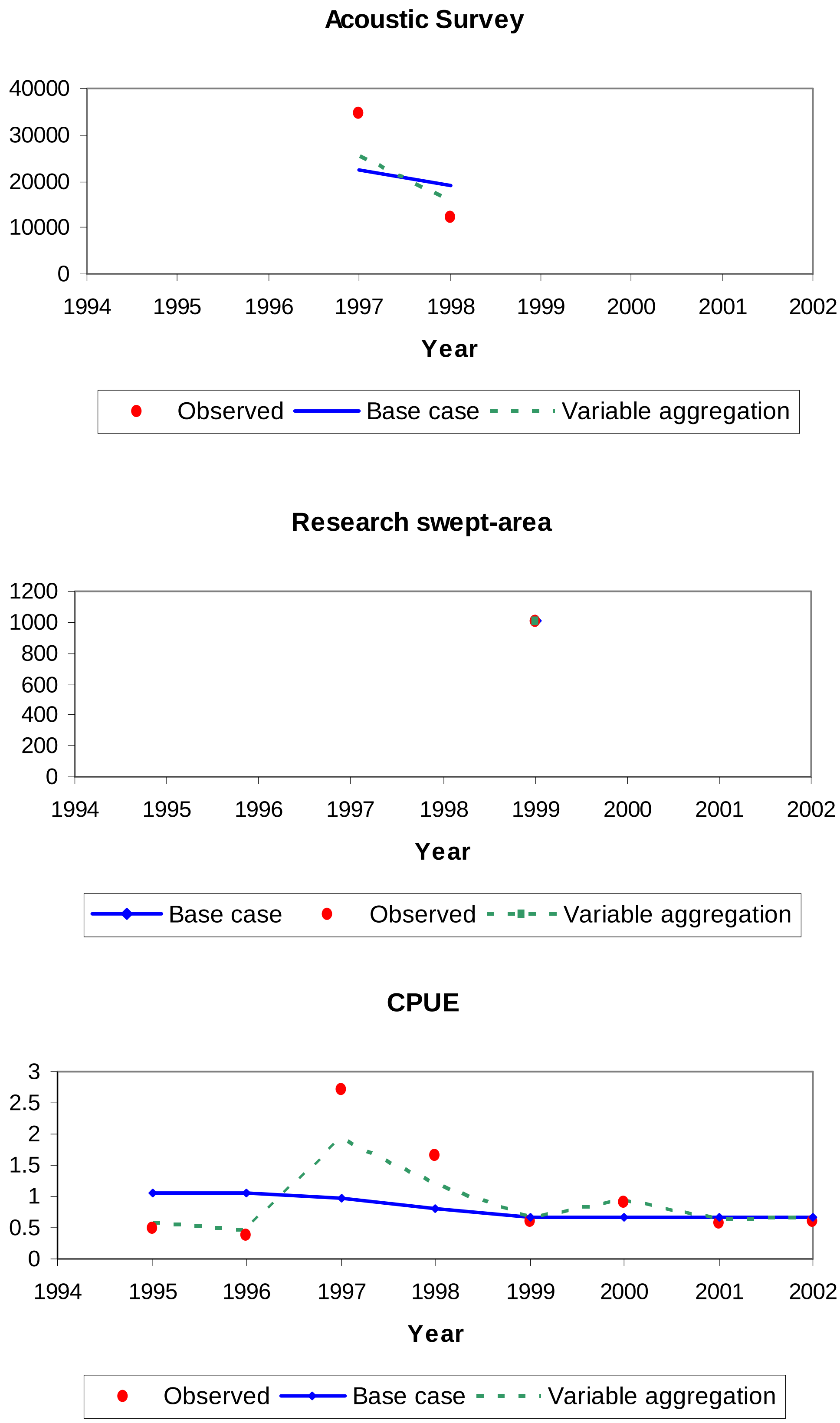


**Figure 3.** Observed and predicted values for each of the available indices of abundance of Namibian orange roughy for the *Rix* aggregation when the base case model and the variable aggregation model are fitted to data including the baseline CPUE interpretation and the mid-depletion case.

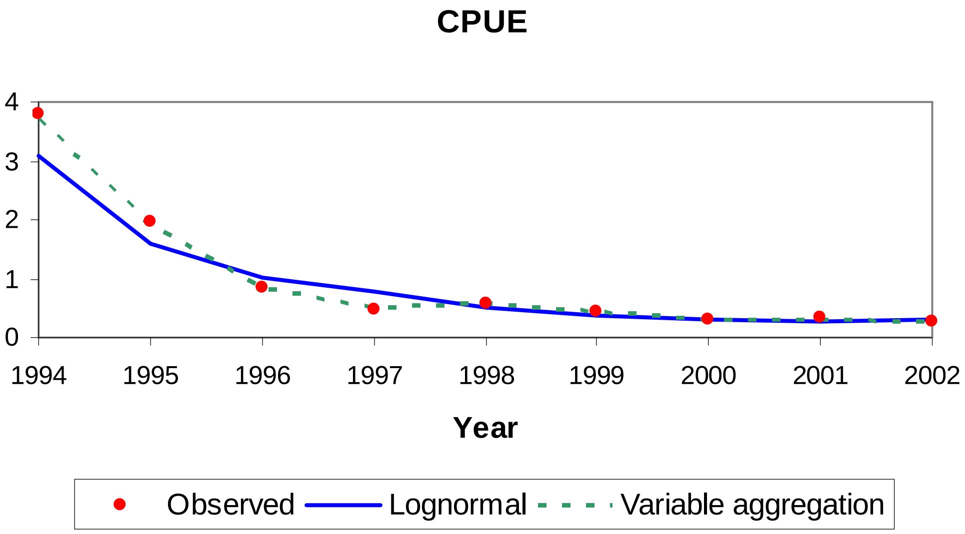


**Figure 4.** Observed and predicted values for each of the available indices of abundance of Namibian orange roughy for the *Hotspot* aggregation when the base case model and the variable aggregation model are fitted to data including the baseline CPUE interpretation and the mid-depletion case.

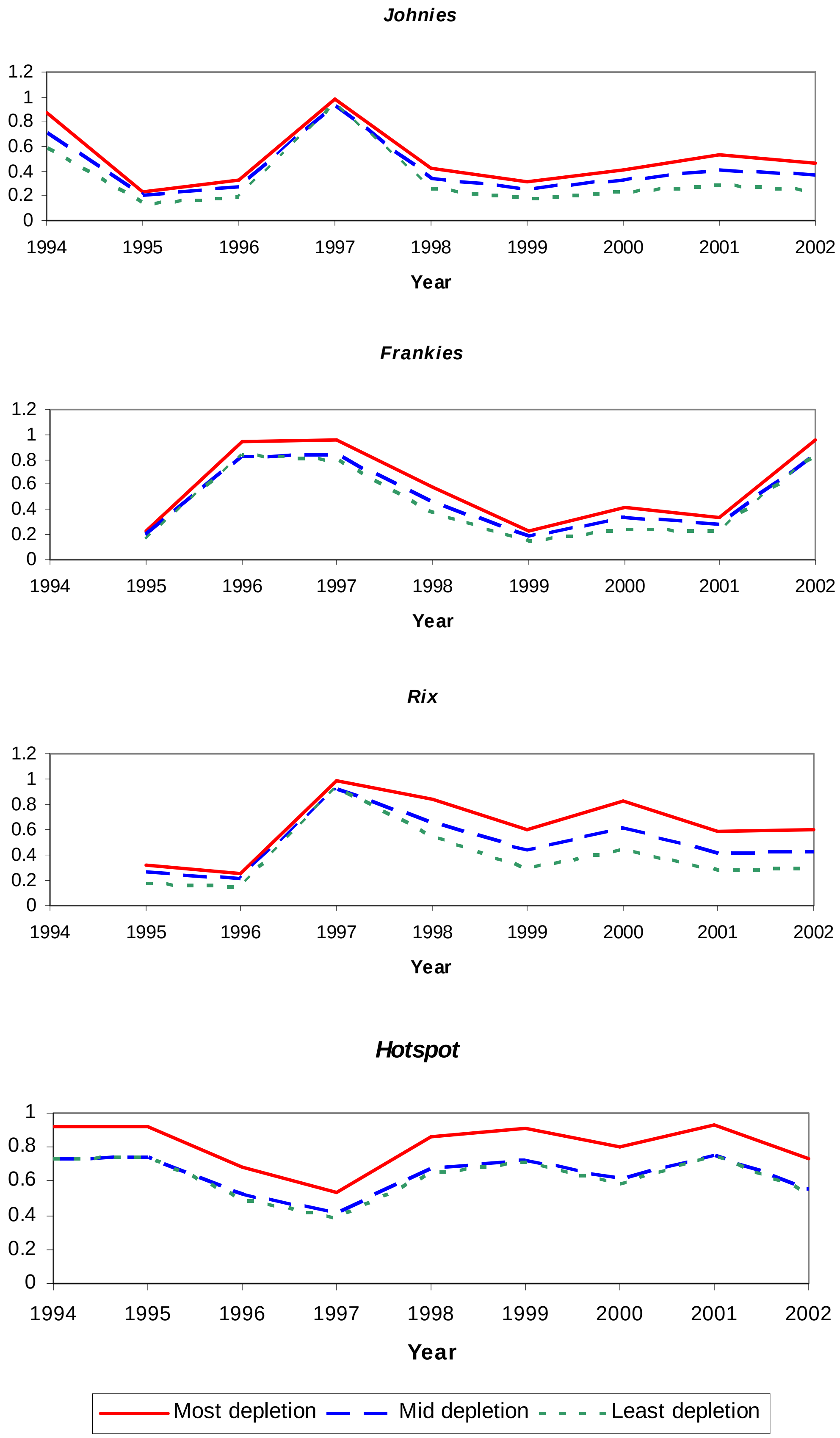


**Figure 5.** Estimated proportion of orange roughy stock present in each year for each aggregation ground. Estimates are given when the variable aggregation model is fit assuming different distribution parameters for the penalty on the proportion of stock present that give three possible levels of current stock depletion.

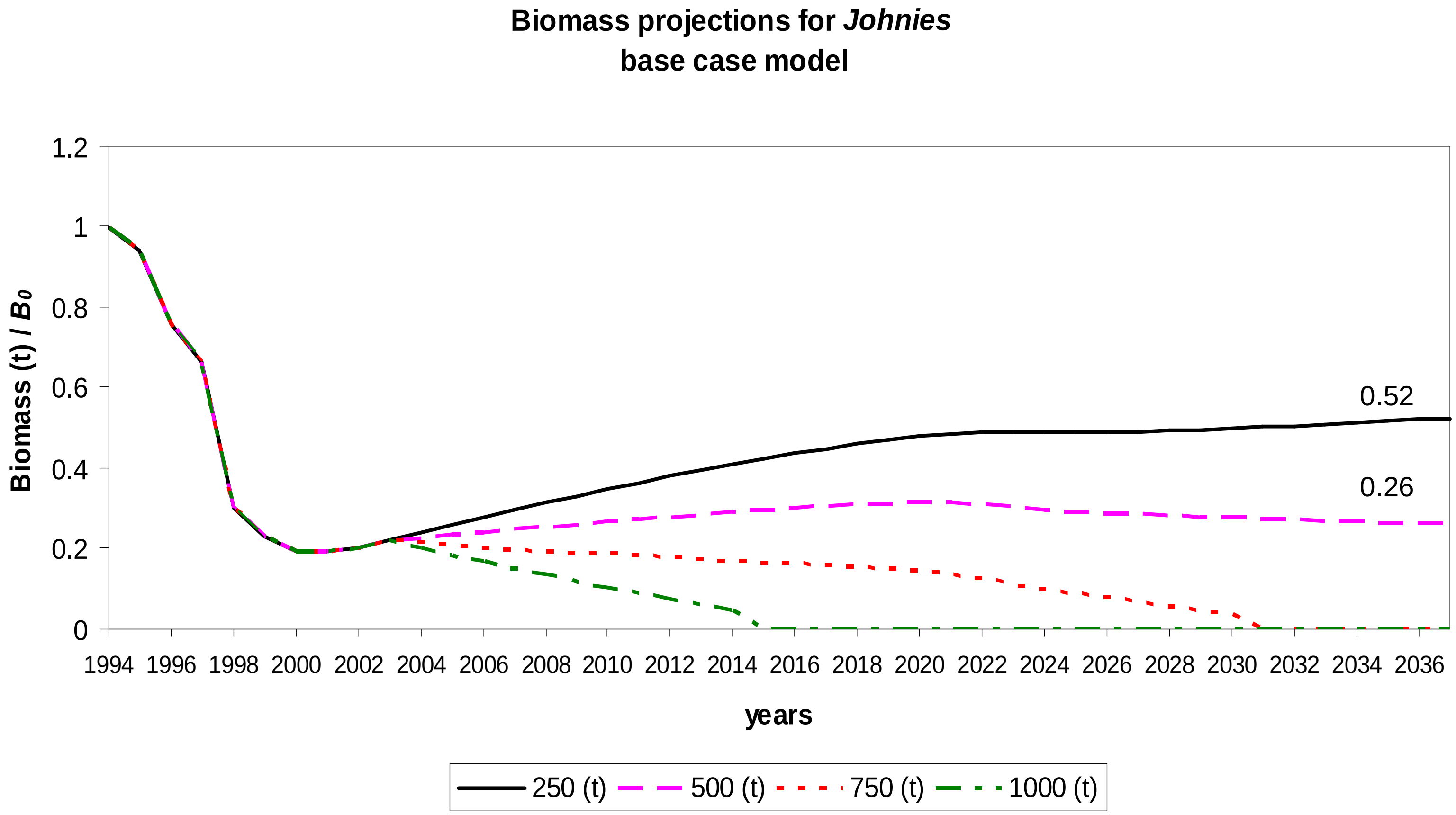


**Figure 6.** Thirty five year projections of the orange roughy stock for the *Johnies* aggregation under the scenario of the base case model and the base case CPUE scenario. Various levels of constant catch are shown. The figure at the right end of the trajectory is the stock depletion after 35 years.

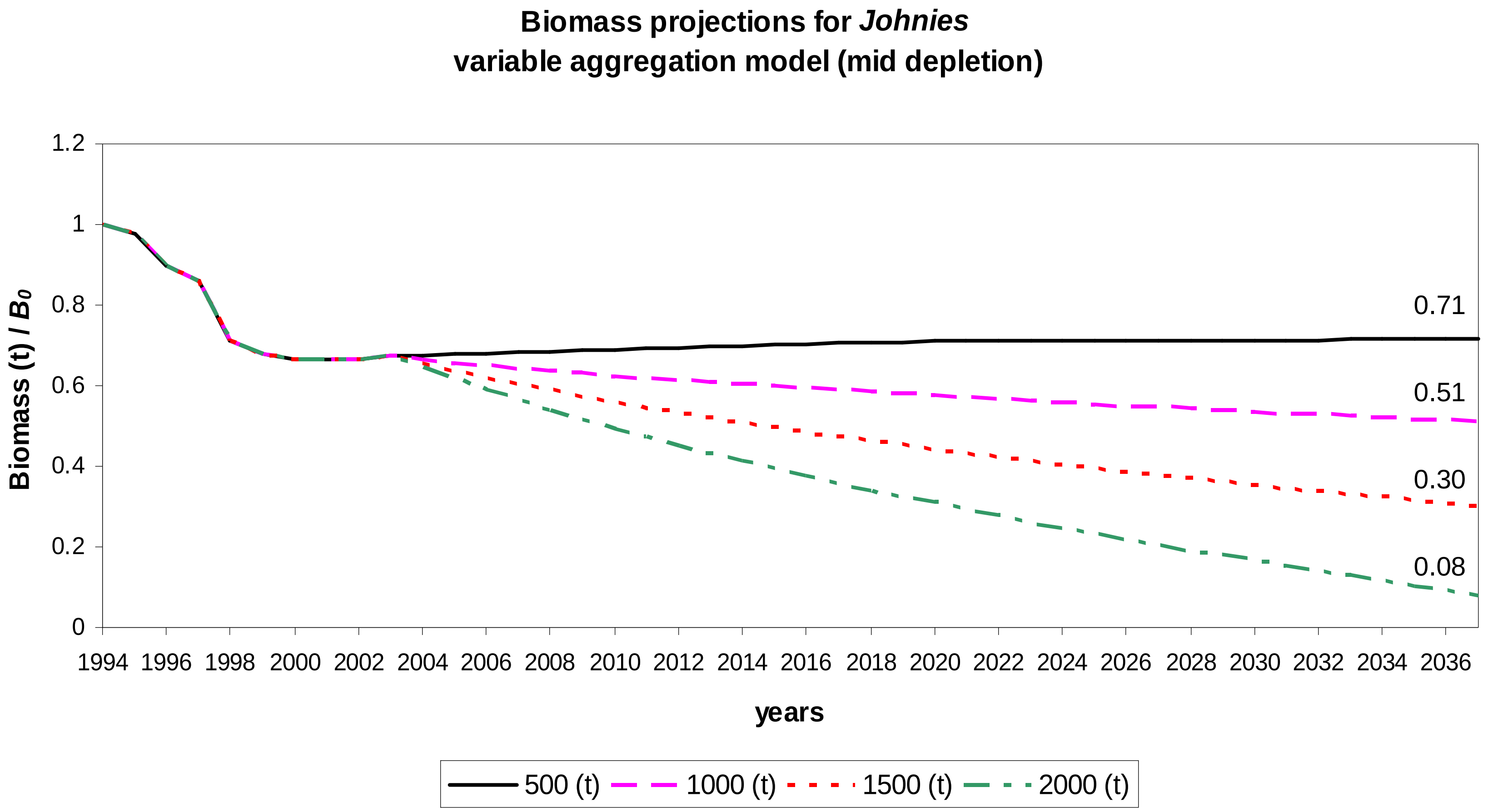


**Figure 7.** Thirty five year projections of the orange roughy stock for the *Johnies* aggregation under the scenario of the variable aggregation model and the base case CPUE scenario. Various levels of constant catch are shown. The figure at the right end of the trajectory is the stock depletion after 35 years.

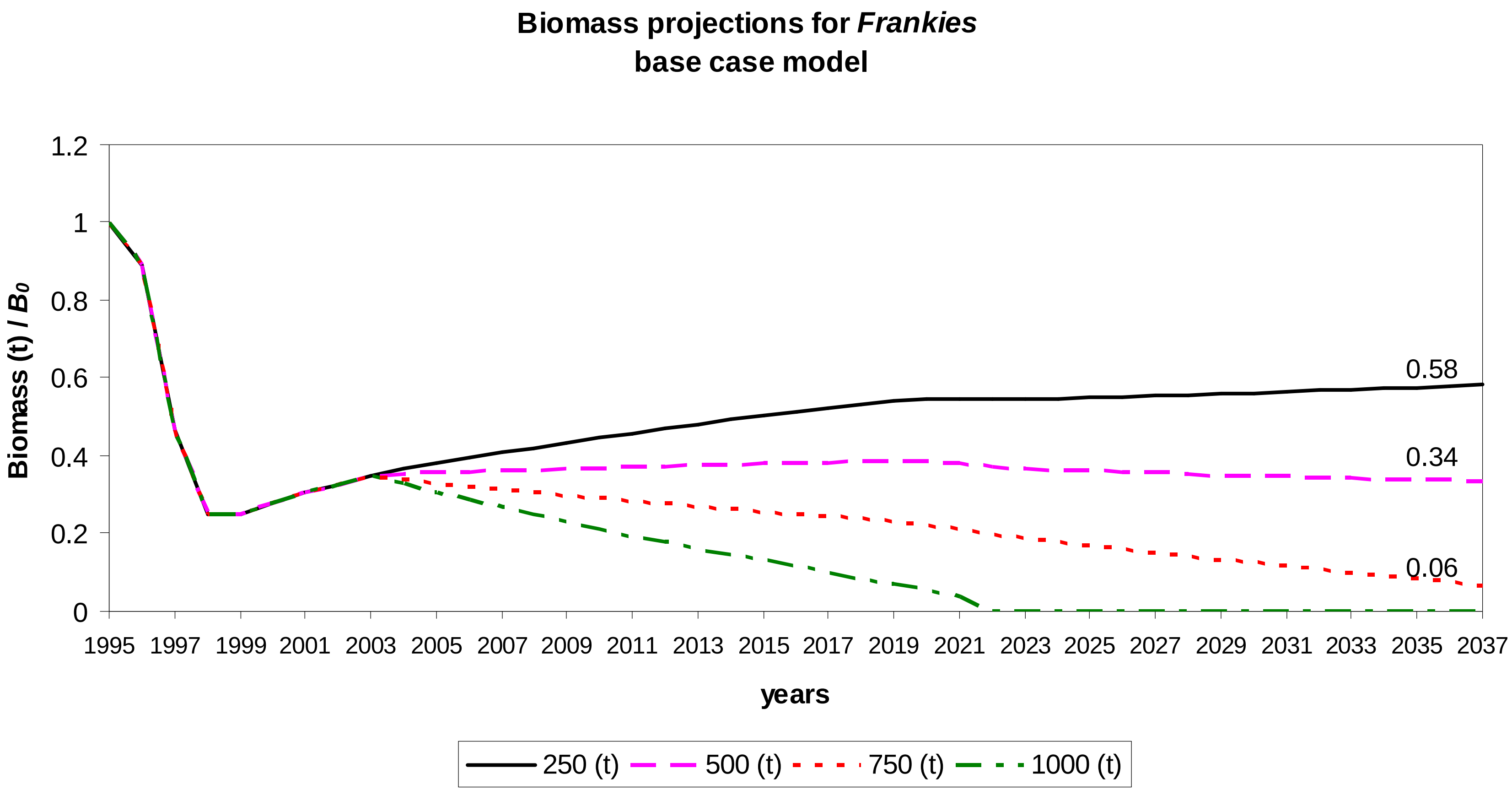


**Figure 8.** Thirty five year projections of the orange roughy stock for the *Frankies* aggregation under the scenario of the base case model and the base case CPUE scenario. Various levels of constant catch are shown. The figure at the right end of the trajectory is the stock depletion after 35 years.

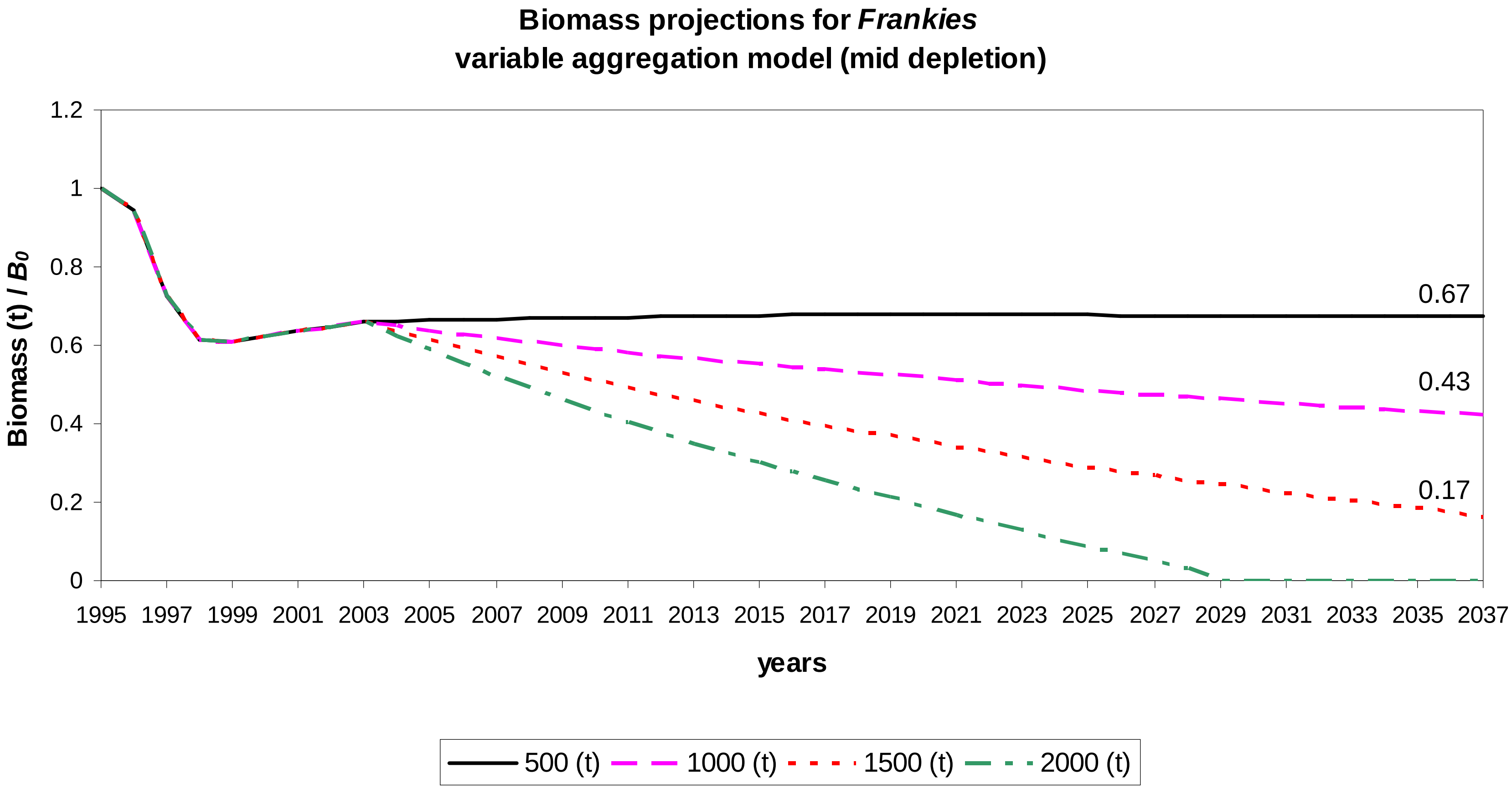


**Figure 9.** Thirty five year projections of the orange roughy stock for the *Frankies* aggregation under the scenario of the variable aggregation model and the base case CPUE scenario. Various levels of constant catch are shown. The figure at the right end of the trajectory is the stock depletion after 35 years.

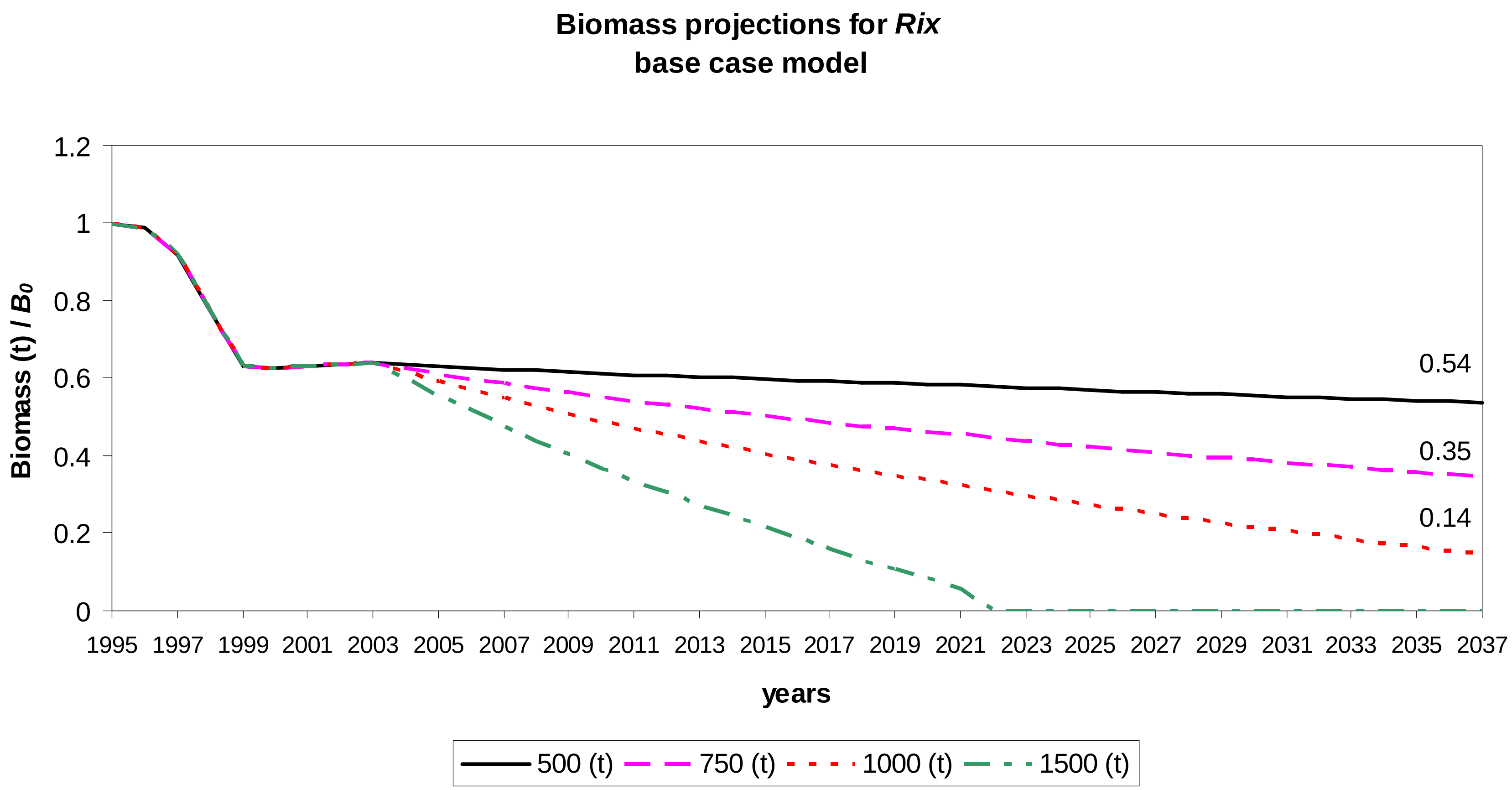


**Figure 10.** Thirty five year projections of the orange roughy stock for the *Rix* aggregation under the scenario of the base case model and the base case CPUE scenario. Various levels of constant catch are shown. The figure at the right end of the trajectory is the stock depletion after 35 years.

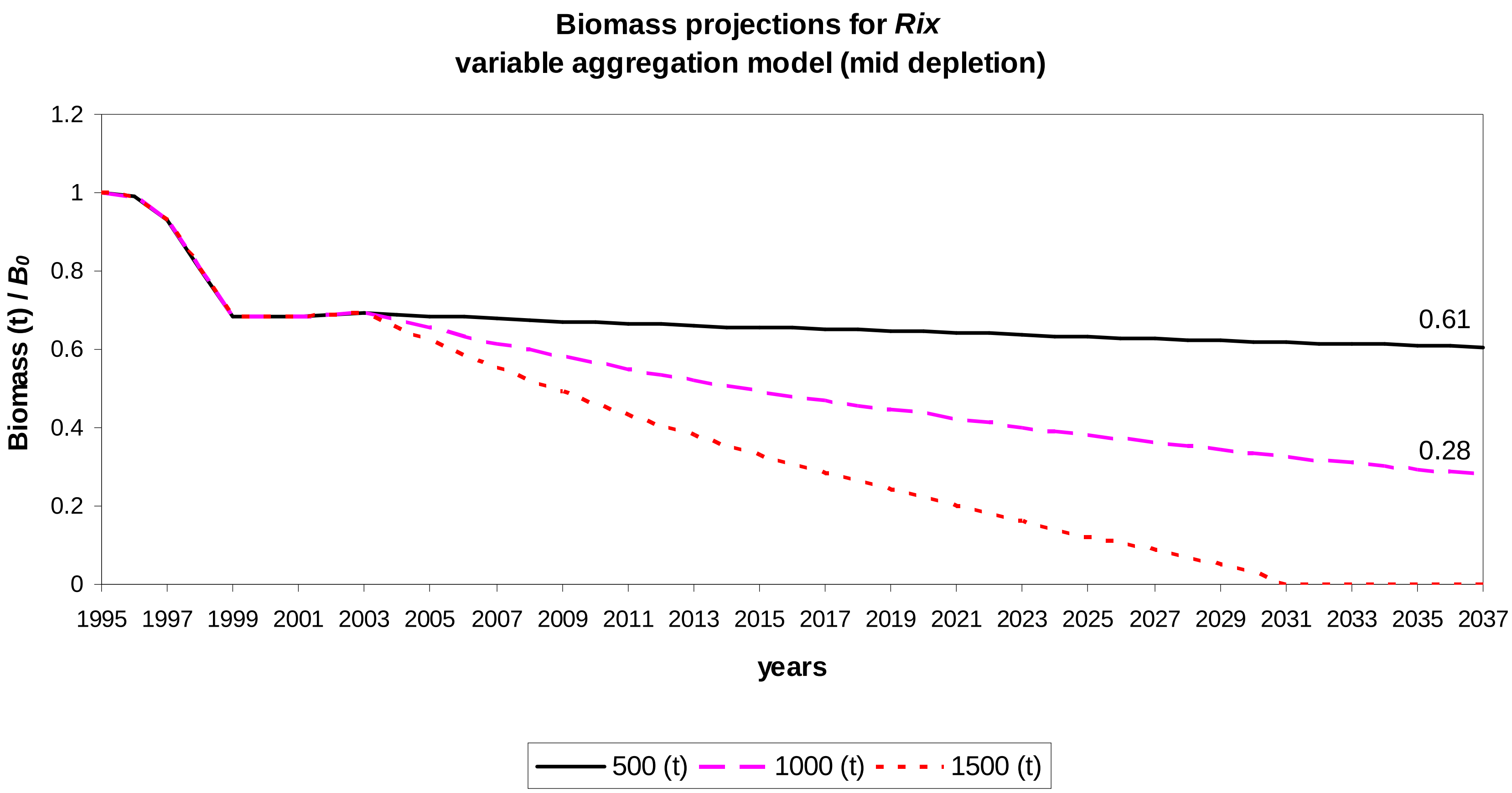


**Figure 11.** Thirty five year projections of the orange roughy stock for the *Rix* aggregation under the scenario of the variable aggregation model and the base case CPUE scenario. Various levels of constant catch are shown. The figure at the right end of the trajectory is the stock depletion after 35 years.

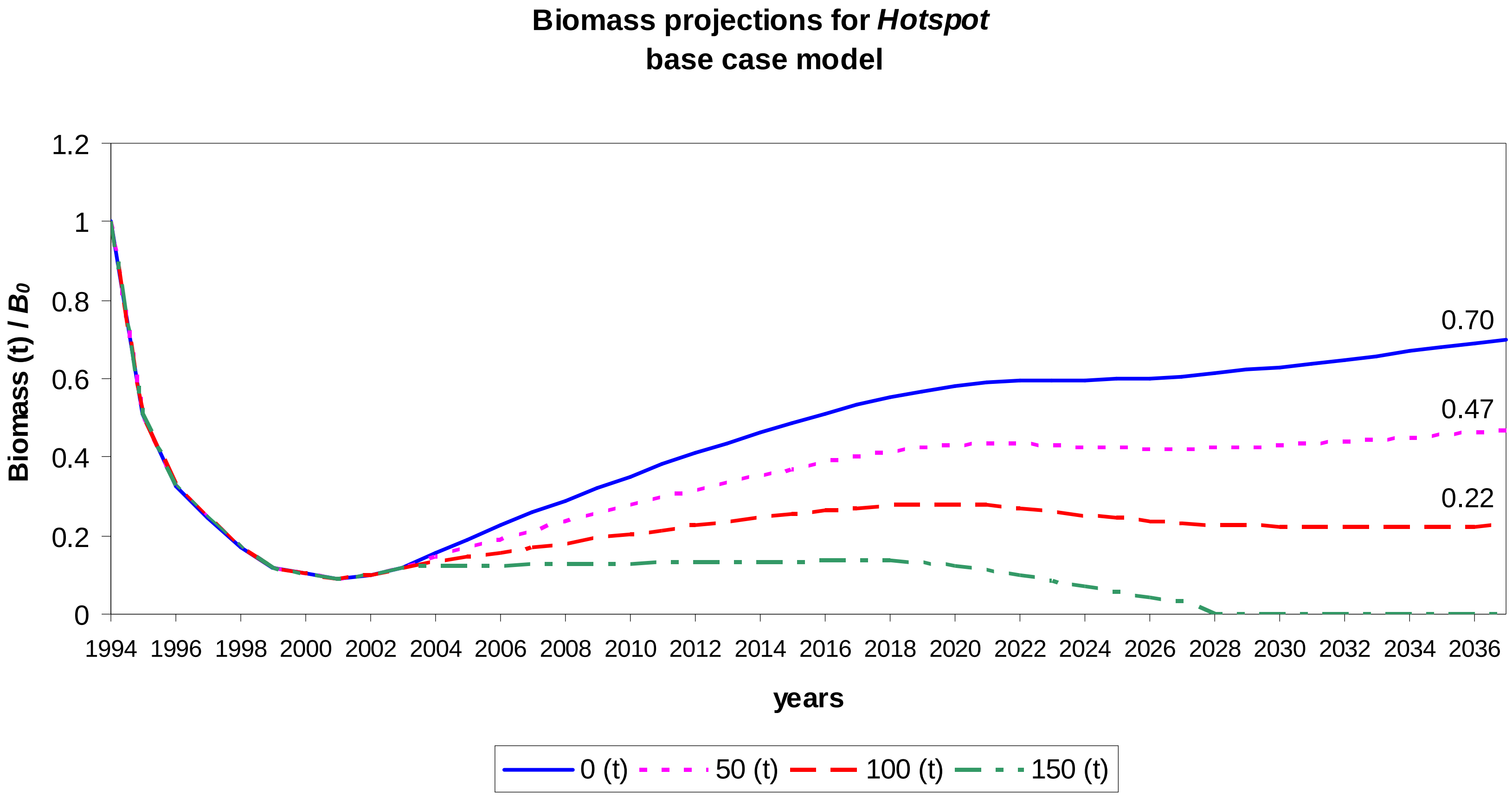


**Figure 12.** Thirty five year projections of the orange roughy stock for the *Hotspot* aggregation under the scenario of the base case model and the lognormal model fitted to the commercial CPUE data. Various levels of constant catch are shown. The figure at the right end of the trajectory is the stock depletion after 35 years.

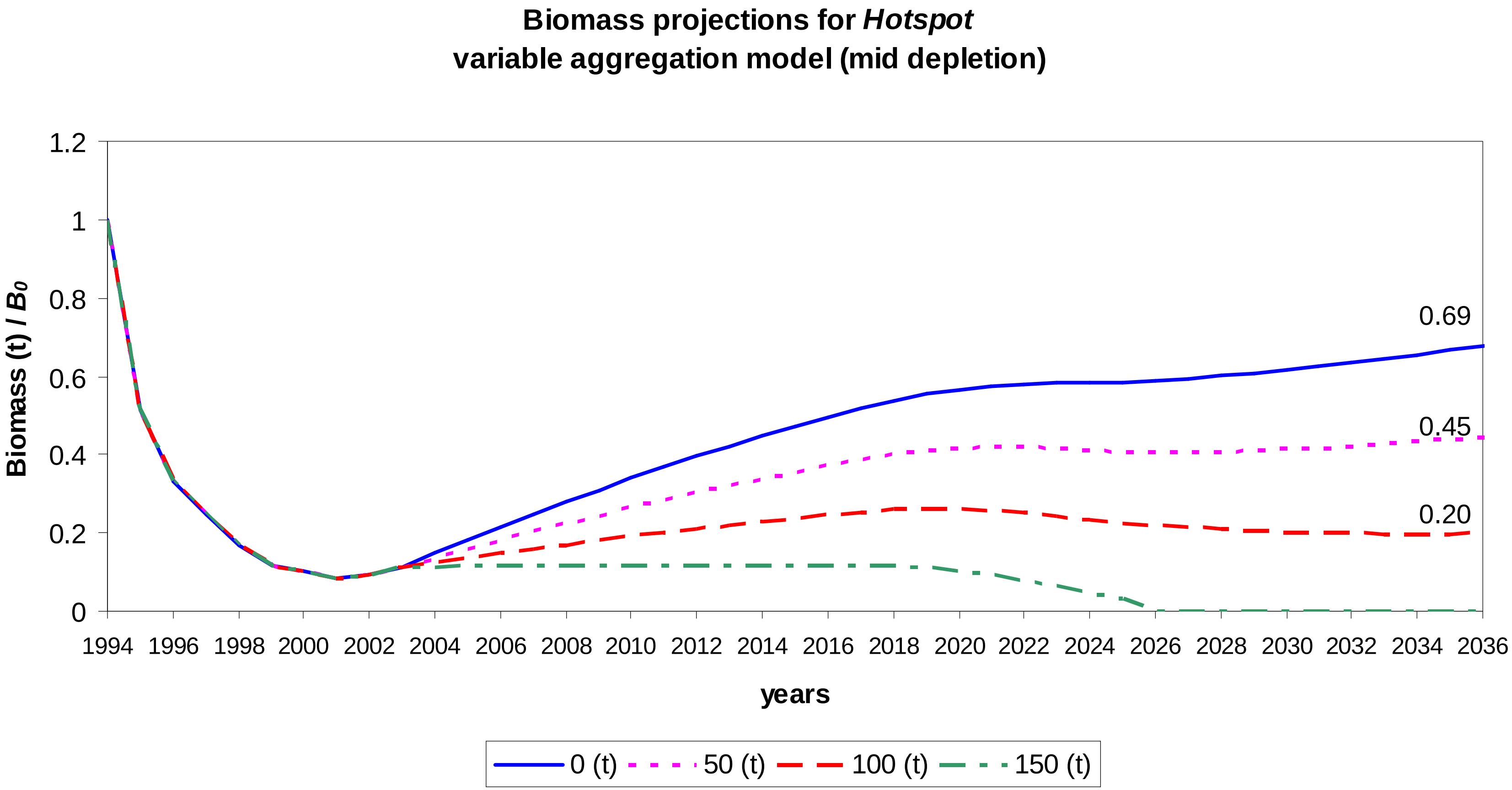


**Figure 13.** Thirty five year projections of the orange roughy stock for the *Hotspot* aggregation under the scenario of the variable aggregation model and the lognormal model fitted to the commercial CPUE data. Various levels of constant catch are shown. The figure at the right end of the trajectory is the stock depletion after 35 years.

# Appendix 1

## Bias factors applied to target acoustic indices of absolute abundance of orange roughy

The following table gives the latest bias factor distributions for the acoustic survey estimates of biomass (Boyer *et al*. 2000).

**Table A1.1** Bias factor distributions for the acoustic orange roughy survey.

| Factor | Minimum | Likely Range | Maximum | Nature |
|---|---|---|---|---|
| Target strength (experimental error) | 0.50 | 0.75 – 1.25 | 1.50 | Centred on 1.0. Systematic between years |
| Target strength (length dependency) | 1.00 | 1.10 – 1.20 | 1.30 | Centred on 1.15. Systematic between years |
| Dead zone (including bottom slope and transducer tilt) | 1.10 | 1.30 – 1.70 | 1.90 | Centred on 1.50. Random between years |
| Calibration (beam factor) | 0.80 | 0.90 – 1.10 | 1.25 | Centred on 1.0. Systematic between years |
| Calibration (on-axis sensitivity) | 0.90 | 0.95 – 1.05 | 1.10 | Centred on 1.0. Random between years |
| Absorption coefficient | 0.95 | 0.98 – 1.02 | 1.05 | Centred on 1.0. Systematic between years |
| Weather | 0.90 | 1.05 – 1.10 | 1.25 | Centred on 1.075. Random between years |
| Non-homogeneous aggregations | 0.50 | 0.85 – 0.95 | 1.00 | Centred on 0.75 Random between years |
| Vessel calibration (if not *Nansen*) | 0.8 | 0.90 – 1.10 | 1.20 | Centred on 1.0. Random between years |
| Sampling error (CV) |  | See Table 2a |  | Aggregation specific. Random between years |

# Appendix 2

## Deterministic population dynamics model for orange roughy

The model is based on the age-structured model presented in Francis *et al*. (1995), which was used to model the population dynamics of orange roughy on the Chatham Rise, New Zealand, and was applied previously to the Namibian orange roughy by, *inter alia*, Branch (1998).

## Population dynamics

$$N_{y+1,0} = R(B^{sp}_{y+1}) \qquad \text{(A2.1)}$$

$$N_{y+1,a+1} = (N_{y,a} - C_{y,a})e^{-M} \qquad 0 \le a \le m\text{-}2 \qquad \text{(A2.2)}$$

$$N_{y+1,m} = (N_{y,m} - C_{y,m})e^{-M} + (N_{y,m-1} - C_{y,m-1})e^{-M} \qquad \text{(A2.3)}$$

where:

$N_{y,a}$ is the number of orange roughy of age *a* at the start of year *y*,

$C_{y,a}$ is the number of orange roughy of age *a* taken by the fishery in year *y*,

$R(B^{sp})$ is the Beverton-Holt stock-recruitment relationship described by equation (A2.10) below,

$B^{sp}$ is the spawning biomass,

$M$ is the natural mortality of fish (assumed to be independent of age), and

$m$ is the maximum age considered (i.e. the “plus group”).

Given that natural mortality and fishing mortality are low, the fishery can be approximated in this manner as a single catch at the start of the year. This approximation simplifies the calculations without compromising accuracy.

The annual catch by mass ($C_y$) is given by:

$$C_y = \sum_{a=a_r}^{m} w_a C_{y,a} \qquad \text{(A2.4)}$$

where:

$w_a$ is the mass of a fish at age *a*, and

$a_r$ is the age at recruitment to the fishery (assumed equal to the age at maturity ($a_m$) for these orange roughy populations).

The mass-at-age is given by the combination of a von Bertalanffy growth equation $\ell(a)$ defined by constants $\ell_\infty$, $\kappa$ and $t_0$ and a relationship relating length to mass. Note that $\ell$ refers to standard length.

$$\ell(a) = \ell_\infty [1 - e^{-\kappa(a-t_0)}] \tag{A2.5}$$

$$w_a = c\ell(a)^d \tag{A2.6}$$

Given knife-edge recruitment to the fishery, and assuming uniform selectivity for ages $a \geq a_r$, the catch by mass is given by:

$$C_y = \sum_{a=a_r}^{m} w_a F_y N_{y,a} \tag{A2.7}$$

which can be re-written as:

$$F_y = \frac{C_y}{\sum_{a=a_r}^{m} w_a N_{y,a}} \tag{A2.8}$$

where:

$F_y$ = the proportion of the resource above age $a$ harvested in year $y$.

## Stock-recruitment relationship

The spawning biomass in year $y$ is given by:

$$B_y^{sp} = \sum_{a=a_m}^{m} w_a N_{y,a} \tag{A2.9}$$

where

$a_m$ = age at maturity (assumed to be knife-edge).

The number of recruits at the start of year $y$ is assumed to relate to the size of the spawner biomass, $B^{sp}$, by the Beverton-Holt stock-recruitment relationship (assuming deterministic recruitment):

$$R(B^{sp}) = \frac{\alpha B^{sp}}{\beta + B^{sp}}. \tag{A2.10}$$

The values of the parameters $\alpha$ and $\beta$ can be calculated given the initial spawning biomass $B_0^{sp}$ and the steepness of the curve *h*, using equations (A2.11)–(A2.15) below. If the initial (and pristine) recruitment is $R_0 = R(B_0^{sp})$, then steepness is the recruitment (as a fraction of $R_0$) that results when spawning biomass is 20% of its pristine level, i.e.:

$$hR_0 = R(0.2B_0^{sp}) \tag{A2.11}$$

from which it can be shown that:

$$h\frac{0.2(\beta + B_0^{sp})}{\beta + 0.2B_0^{sp}}. \tag{A2.12}$$

Rearranging equation (A2.12) gives:

$$\beta = \frac{0.2B_0^{sp}(1-h)}{h-0.2} \tag{A2.13}$$

and solving equation (A2.10) for $\alpha$ gives:

$$\alpha = \frac{0.8hR_0}{h-0.2}.$$

In the absence of exploitation, the population is assumed to be in equilibrium. Therefore $R_0$ is equal to the loss in numbers due to natural mortality when $B^{sp} = B_0^{sp}$, and hence:

$$\gamma B_0^{sp} = R_0 = \frac{\alpha B_0^{sp}}{\beta + B_0^{sp}} \tag{A2.14}$$

where:

$$\gamma = \left\{ e^{-Ma_m} \left( \sum_{a=a_m}^{m-1} w_a e^{-M(a-a_m)} + \frac{w_m e^{-M(m-a_m)}}{1-e^{-M}} \right) \right\}^{-1}. \tag{A2.15}$$

## Projections

Given a value for the pre-exploitation biomass of orange roughy recruited to the fishery ($B_0^{rec}$) from, say, the swept-area analyses, and the assumption that the initial age structure is at equilibrium, it follows that:

$$B_0^{rec} = R_0 e^{-Ma_r} \left( \sum_{a=a_r}^{m-1} w_a e^{-M(a-a_r)} + \frac{w_m e^{-M(m-a_r)}}{1-e^{-M}} \right) \tag{A2.16}$$

which can be solved for $R_0$. In this manner, $B_0^{sp}$ can be obtained from (A2.14) and (A2.15).

The initial numbers at each age $a$ are therefore given by:

$$N_{0,a} = \begin{cases} R_0 e^{-Ma} & 0 \le a \le m-1 \\ \dfrac{R_0 e^{-Ma}}{1-e^{-M}} & a = m \end{cases} \tag{A2.17}$$

Numbers-at-age for future years are then computed by means of equations (A2.1)-(A2.4) and (A2.7)-(A2.10) under the series of annual catches given. In cases where equation (A2.8) yields a value of $F_y > 1$, i.e. the available biomass is less than the proposed catch for that year, $F_y$ is restricted to 0.9, and the actual catch considered to be taken will be less than the proposed catch.