Updated stock assessment of Namibian orange roughy populations under the assumption of intermittent aggregation

A. Brandão and D. S. Butterworth

Marine Resource Assessment & Management Group (MARAM)
Department of Mathematics and Applied Mathematics
University of Cape Town
Rondebosch 7701, Cape Town

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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 and reflects the proportion of a stock present at the fishing aggregation each year, are presented, and projections under constant catch levels reported. Results suggest 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 2 500–2 750 ton range. Broadly speaking, MSY estimates are some 10% less than estimated a year previously. However, varying proportions of abundance present at aggregations 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 that allows for the possibility of annually variable levels of aggregation of the stocks in the fishing areas. Two standardised CPUE series presented by Brandão and Butterworth (2004) are considered. All available indices of abundance are taken into account, and deterministic projections under various levels of constant catch are reported. The results of two sensitivity tests are briefly discussed.

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).

Table 1 shows the total annual ("fishing year") catches of orange roughy for the different aggregations. 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 a delta-lognormal model and applying different methods of dealing with missing abundance indices in some years in sub-aggregations (Brandão and Butterworth, 2004) are given in Table 3.

The biological parameters used in the assessment are shown in Table 4.

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 2003), 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:

$$I_y = q\, B_y \qquad (1)$$

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 takes account of 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:

$$-\ln L = \frac{1}{2(\sigma_q^{AC})^2}\left(\ln q^{AC} - \ln q^{est}\right)^2 + \ln q^{AC} + \frac{1}{2\sigma_M^2}\left(\ln M - \ln M^{est}\right)^2 + \ln M$$

$$+ \sum_y^{AC} \frac{1}{2(\sigma_y^{AC})^2}\left(\ln I_y^{AC} - \ln\left(q^{AC} B_y\right)\right)^2 + \sum_y^{SA} \frac{1}{2(\sigma_y^{SA})^2}\left(\ln I_y^{SA} - \ln\left(q^{SA} B_y\right)\right)^2 \qquad (2)$$

$$+ \sum_y^{CPUE} \frac{1}{2(\sigma^{CPUE})^2}\left(\ln I_y^{CPUE} - \ln\left(q^{CPUE} B_y\right)\right)^2 + n_{CPUE}\left(\ln \sigma^{CPUE}\right),$$

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:

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

σ_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,

σ_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,

σ_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

CV_y^S is the CV of the sampling error distribution, and

CV_y^R is the CV of the distribution of the product of the random bias factor distributions applied to the acoustic abundance indices,

σ_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,

σ^{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, σ^{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, an estimable multiplicative bias factor x_y is included in the model, so that the various terms in equation (2) become:

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

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 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. Brandão and Butterworth (2003) used this signal in one of the indices for the *Frankies* aggregation to model intermittent aggregation of the orange roughy stock. A penalty function applied to the proportion of stock present (x_y) has also been introduced in the model for intermittent 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):

$$-\left[N\left\{\ln\Gamma(\alpha+\beta)-\left[\ln\Gamma(\alpha)+\ln\Gamma(\beta)\right]\right\}+\sum_{y=1994}^{2003}\left\{(\alpha-1)\ln(x_y)+(\beta-1)\ln(1-x_y)\right\}\right] \qquad (4)$$

where

- *N* is the total number of years considered in the assessment (*N* = 2003 - 1994 + 1),
- *α* is a parameter of the beta distribution, such that *α* > 0,
- *β* is a parameter of the beta distribution, such that *β* > 0.

Results and Discussion

Table 5 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 6 to 9 provide results for the population model fitting exercises for the four aggregations, *Johnies*, *Frankies*, *Rix* and *Hotspot*. The reference case model corresponding to equation (2) is used, and applied to the results of each of two alternative (one for *Hotspot*) approaches to provide standardised CPUE series (Brandão and Butterworth 2004). The reference case consists of using a delta-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).

Tables 6 to 9 also give results for the intermittent aggregation model which is the reference case model extended to include year aggregation factors x_y (all estimated by the model) with a penalty on x_y corresponding to the assumption that these values follow a beta distribution. Brandão and Butterworth (2003) considered various fixed mean (μ_x) and standard deviation (σ_x) values to specify the α and β parameter values of the beta distribution penalty included in the variable aggregation model for the *Frankies* aggregation. From these results, a set of values (μ_x, σ_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 (μ_x, σ_x) were chosen that spanned a range of stock depletion: most, mid and least depletion. The assumption is made that the distribution governing the proportion present at *Frankies* each year applies also to the other aggregations. All intermittent aggregation assessments carried out in this paper assume the mid-depletion option for (μ_x, σ_x), i.e. $\mu_x = 0.6$ and $\sigma_x = 0.2$. As a sensitivity test when fitting the intermittent aggregation model, the σ^{CPUE} value is fixed at 0.4 rather than estimated, to offset a tendency by the model to underweight the CPUE data. These models (with fixed σ^{CPUE}) are fitted only to the baseline CPUE interpretation (i.e. applied to the standardised CPUE series obtained from the "zero". The one exception is for *Rix*, where the intermittent aggregation model applied to the "proportional" method CPUE indices overweighted the CPUE data and so in this case the σ^{CPUE} value is also fixed at 0.4.

In terms of the reference case model, the stock depletion at the beginning of the fishing year 2003 for *Johnies* is at 3% of the pre-exploitation abundance (Table 6). Allowing for intermittent 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 64% to 66% of the pre-exploitation biomass for the two methods of standardising the CPUE series. The proportion of the stock present in *Johnies* is much smaller in other years than in 1997 (for which this proportion is 93%). This implies that for most years, less than 50% of the stock aggregated at *Johnies*, and only about 4% of the stock aggregated in 2003.

The stock depletion at the beginning of the year 2003 for the *Frankies* aggregation for the reference case model is in the region of 30–31% of the pre-exploitation abundance under alternative CPUE interpretations. Including intermittent aggregation in the reference case model indicates that the population is substantially better (65%) than when the biomass indices are considered as comparable from year to year. Over 80% of the stock aggregated in the years 1997 and 2002 with most others years having less than 50% of the stock aggregating (about 40% of the stock aggregated in 2003).

The stock depletion at the beginning of the year 2003 is estimated at 39% of the pre-exploitation biomass for the *Rix* aggregation under the reference case scenario (Table 8). Under the alternative CPUE interpretation, the stock is in a substantially worse state (6% of pre-exploitation biomass). By allowing for intermittent aggregation of the stock, the status of the resource is better than under the reference case scenario (60% to 64% stock depletion). For most years more than 50% of the stock aggregate in *Rix* prior to 2001. Since 2001, less than 50% of the stock has aggregated with only 22% aggregating in 2003 for the “zero” method interpretation of the CPUE series. Under the “proportional” method CPUE, the proportion of stock aggregated is rather less, with only 13% aggregating in 2003.

The stock depletion at the beginning of the year 2003 for the *Hotspot* aggregation is estimated at 4% of the initial biomass when the reference case model is fitted to data in which the standardised CPUE series is obtained by fitting a delta-lognormal model. By including relative bias factors (for differential aggregation) in the model, the estimated status of the resource scarcely changes. The least extent of aggregation occurs in 1997, 2000 and 2003, 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.

Fixing the σ^{CPUE} value to 0.4 for both the reference case and the intermittent aggregation model reflect the resource in all aggregations to be in a more depleted state than when this parameter is estimated; the only exceptions are for *Johnies* for the reference case and *Frankies* for the intermittent model. Thus giving more weight to the CPUE indices produces a bleaker view of the state of the resource.

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 reference case population model fitted to data and for the intermittent aggregation model including the baseline standardised CPUE interpretation. For the *Johnies* aggregation, neither the reference case model nor the intermittent aggregation model provide a particularly good fit to the first (1997) observation in the hydroacoustic survey and the research swept area abundance indices. The intermittent aggregation model does however show a better fit to both the research swept area abundance indices and the CPUE abundance indices in the earlier years, although neither fit the 1994 CPUE index. For *Frankies* the reference case model does not fit the 1997 or the 2002 acoustic index, while the intermittent aggregation model is able to fit both these high index values. The intermittent aggregation model also shows an overall better fit to the other indices. For both *Frankies* and *Rix* neither model fits the high observations in the CPUE series. For *Hotspot* both models fit the CPUE index for the later years, but not the first two years, although the intermittent aggregation model fits these better.

Figures 5 and 6 show thirty five year deterministic projections of the orange roughy stock for the *Johnies* aggregation under the reference case and the intermittent models, both for the baseline CPUE interpretation. For the reference case model a constant catch of 250 t does not immediately deplete the resource, but after about twenty five years of a constant catch of this size, the resource abundance begins to drop and the stock becomes extinct within a few years. Under a no catch scenario, the resource will recover to 39% after 35 years. Under the intermittent aggregation model, a 500 t constant catch improves the stock depletion from 64% to 68% whereas a constant catch of 1000 t after thirty five years reduces the stock depletion to 45% of the pre-exploitation abundance.

Figures 7 and 8 show deterministic projections for the reference case model and the intermittent aggregation model respectively, both for the baseline CPUE interpretation for the *Frankies* aggregation. An improvement in stock depletion to 56% from 31% of initial biomass is seen for the reference case model for a constant catch of 250 t and a constant catch of 500 t involves hardly any change in stock depletion (30%). The stock becomes depleted after thirty five years under a constant catch of 750 t. Under the intermittent aggregation model, a constant catch of 500 t makes hardly any change in stock depletion (66% from 65%) and reduces it to 40% of pre-exploitation abundance under a 1000 t constant catch.

Figures 9 to 10 show deterministic projections for the *Rix* aggregation under the reference case and the intermittent aggregation models fitted. For the former, a constant catch of 250 t improves the stock from 39% to 48% of pre-exploitation biomass after 35 years. For the intermittent aggregation model, a constant catch of 500 t for thirty five years reduces the stock to 53% (from 64%) of initial biomass and to 13% under a constant catch of 1000 t.

Figure 11 and 12 give projections for the *Hotspot* aggregation for the reference case model and the intermittent aggregation model. A constant catch of 50 t improves the stock depletion to 36% from 4% of initial biomass for the reference case model and a constant catch of 100 t to 9%. If no catches are taken for thirty five years, the resource improves from a depletion of 4% of initial biomass to 62%. For the intermittent aggregation model, a constant catch of 50 t for thirty five years improves the stock depletion to 38% from 4% of initial biomass and to 10% under a constant catch of 100 t.

Sensitivity tests

Several sensitivity tests have been performed on the assessment of the orange roughy stock by considering two different CPUE indices. The one case considered omitting the 1994 and 1995 commercial CPUE data. These values are usually very different from the other indices for other years and they may be reflecting different patterns in the fishery as the fishery was just starting.

The second case considered was to only use commercial CPUE data from the spawning season (taken here to be July–August) as this is the time when the fish will aggregate and the period that is therefore targeted.

Standardised CPUE indices for the above scenarios were obtained considering only the "zero" method of dealing with missing observations in the sub-aggregations. These indices are shown in Table 3 for the various aggregations. Both the reference case and the intermittent aggregation models were applied to these CPUE indices. All results for all aggregations were very similar to those when the "zero" method standardised CPUE indices obtained from the whole commercial database is used.

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 intermittent aggregation model therefore seems the best basis upon which to provide advice, and Table 10 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 2 400 tons, some 10% less than estimated a year previously by Brandão and Butterworth (2003).

Projections using the intermittent aggregation model suggest an appropriate overall annual catch in the medium term to be in the 2 500 to 2 750 ton range. It is important, though, to bear in mind the intermittent 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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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 2003 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	376	155††	350	336	1 217
2003*	299	125††	96	59	579

* Incomplete

† Closed to normal commercial fishing

†† Fishery partially reopened since September 2002

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*
2003	—	6 133 (0.27)	1 174 (0.51)	*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)	—
2003	—	10 126 (0.41)	2 133 (0.63)

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*
2003	943 (0.18)	—	—	*Southern Aquarius*

Table 3. Abundance indices for orange roughy obtained from standardised commercial CPUE series, based on a delta-lognormal model, for the aggregations considered in this paper. Two methods ("zero" 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	All data		Omitting 1994 and 1995	Spawning period only
	"Zero" method	"Proportional" method	"Zero" method	"Zero" method
1994	5.348	7.045		
1995	0.771	1.016		1.485
1996	1.089	1.435	2.284	2.695
1997	1.465	0.264	2.971	2.797
1998	0.536	0.097	1.108	0.730
1999	0.232	0.042	0.481	0.434
2000	0.198	0.036	0.409	0.257
2001	0.112	0.020	0.236	0.210
2002	0.141	0.026	0.287	0.207
2003	0.107	0.019	0.225	0.184

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

Year	All data		Omitting 1994 and 1995	Spawning period only
	"Zero" method	"Proportional" method	"Zero" method	"Zero" method
1995	1.309	6.785		
1996	4.007	1.271	4.166	0.981
1997	1.246	0.395	1.320	4.239
1998	0.594	0.188	0.628	0.553
1999	0.266	0.090	0.281	0.625
2000	—	0.043		
2001	0.412	0.155	0.434	0.450
2002	0.141	0.062	0.143	0.095
2003	0.026	0.012	0.028	0.056

Table 3 cont. Abundance indices for orange roughy obtained from standardised commercial CPUE series, based on a delta-lognormal model, for the aggregations considered in this paper. Two methods ("zero" 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	All data		Omitting 1994 and 1995	Spawning period only
	"Zero" method	"Proportional" method	"Zero" method	"Zero" method
1995	0.558	2.006		0.742
1996	0.665	2.392	0.617	2.126
1997	4.404	2.606	4.174	1.045
1998	1.862	1.102	1.781	3.258
1999	0.369	0.218	0.348	0.400
2000	0.383	0.227	0.359	0.452
2001	0.274	0.162	0.262	0.334
2002	0.287	0.170	0.271	0.378
2003	0.197	0.117	0.187	0.265

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	All data	Omitting 1994 and 1995	Spawning period only
1994	5.347		
1995	2.246		3.548
1996	0.800	2.6237	3.113
1997	0.289	0.9576	0.559
1998	0.459	1.5311	0.367
1999	0.240	0.8088	0.583
2000	0.093	0.3093	0.220
2001	0.155	0.5250	0.297
2002	0.327	1.0941	0.141
2003	0.044	0.1503	0.175

Table 4. Biological parameter values assumed for the assessments conducted. Note that for simplicity maturity is assumed to be knife-edge in age.

Parameter	Value
von Bertalanffy growth	
ℓ_∞ (cm)	29.5
κ (yr^{-1})	0.069
t_0 (yr)	-2.0
Weight length relationship	
a	0.1354
b	2.565
Age at maturity (yr)	23

Table 5. 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	—	$\sigma_{2002}^{AC} = 0.29$
2003	—	$\sigma_{2003}^{AC} = 0.35$
q^{AC}-random ***Rix*** 1997	—	$\sigma_{1997}^{AC} = 0.25$
1998	—	$\sigma_{1998}^{AC} = 0.26$
2003	—	$\sigma_{2003}^{AC} = 0.59$

Table 6. Estimates obtained when various models are fitted to the available indices of Namibian orange roughy for the *Johnies* aggregation where the standardised CPUE series are obtained in various ways (Brandão and Butterworth 2002 and 2004). 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_{2003}) and stock depletion (B_{2003}/B_0) at the beginning of the year 2003, 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 (σ^{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}, x_{2003}), the maximum sustainable yield (MSY), the maximum sustainable yield level (MSYL) and the negative of the log likelihood (as well as its different components). Biomass units are tons.

Parameter estimates	***Johnies***					
	Reference case ("zero" method) σ^{CPUE} estimated	**Reference case ("zero" method) σ^{CPUE} fixed**	**Reference case ("proportional" method)**	**Intermittent aggregation ("zero" method) σ^{CPUE} estimated**	**Intermittent aggregation ("zero" method) σ^{CPUE} fixed**	**Intermittent aggregation ("proportional" method)**
B_0	18 003	18 053	17 764	42 989	18 002	45 158
M	0.024	0.024	0.025	0.047	0.039	0.047
B_{2003}	551	610	395	27 509	1 794	29 700
B_{2003}/B_0	0.031	0.034	0.022	0.640	0.100	0.658
q^{AC}	1.766	1.760	1.790	1.126	1.896	1.112
q^{SA}	2.605	2.468	3.146	0.989	3.657	0.997
q^{CPUE} ($\times 10^5$)	13.532	13.070	5.043	4.450	18.101	1.361
σ^{CPUE}	0.504	0.400	0.839	0.754	0.400	1.349
x_{1994}	—	—	—	0.807	0.858	0.777
x_{1995}	—	—	—	0.583	0.322	0.712
x_{1996}	—	—	—	0.660	0.524	0.730
x_{1997}	—	—	—	0.934	0.948	0.926
x_{1998}	—	—	—	0.258	0.562	0.230
x_{1999}	—	—	—	0.118	0.353	0.097
x_{2000}	—	—	—	0.194	0.632	0.177
x_{2001}	—	—	—	0.355	0.716	0.408
x_{2002}	—	—	—	0.333	0.679	0.392
x_{2003}	—	—	—	0.039	0.173	0.034
MSY	199	200	206	928	323	981
MSYL	0.251	0.251	0.251	0.246	0.248	0.246
-ln *L*: Total	31.486	32.020	36.201	10.148	10.285	15.158
-ln *L*: CPUE	-1.851	-1.690	3.244	2.179	-3.844	7.993
-ln *L*: Acoustic survey	6.835	6.820	6.914	1.104	6.649	0.866
-ln *L*: Sweptarea	22.417	22.871	22.165	3.022	6.098	-2.112
-ln *L*: year bias	—	—	—	-6.503	0.892	-6.889
-ln *L*: prior on *M*	0.177	0.149	-0.203	-2.922	-2.596	-2.926
-ln *L*: prior on q^{AC}	3.908	3.869	4.081	0.263	4.869	0.224

Table 7. Estimates obtained when various models are fitted to the available indices of Namibian orange roughy for the *Frankies* aggregation where the standardised CPUE series are obtained in various ways (Brandão and Butterworth 2002 and 2004). 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_{2003}) and stock depletion (B_{2003}/B_0) at the beginning of the year 2003, 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 (σ^{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}, $x_{2002,}$ x_{2003}), the maximum sustainable yield (MSY), the maximum sustainable yield level (MSYL) and the negative of the log likelihood (as well as its different components). Biomass units are tons.

Parameter estimates	***Frankies***					
	Reference case ("zero" method) σ^{CPUE} estimated	**Reference case ("zero" method) σ^{CPUE} fixed**	**Reference case ("proportional" method)**	**Intermittent aggregation ("zero" method) σ^{CPUE} estimated**	**Intermittent aggregation ("zero" method) σ^{CPUE} fixed**	**Intermittent aggregation ("proportional" method)**
B_0	18 887	18 487	18 453	37 329	42 687	37 448
M	0.052	0.034	0.053	0.049	0.047	0.049
B_{2003}	5 898	4 152	5 563	24 176	29 412	24 293
B_{2003}/B_0	0.312	0.225	0.301	0.648	0.689	0.649
q^{AC}	1.630	2.011	1.726	1.011	1.096	1.021
q^{SA}	1.372	1.657	1.488	0.880	0.717	0.898
q^{CPUE} $(\times 10^5)$	6.179	7.569	2.915	3.516	3.569	1.569
σ^{CPUE}	1.182	0.400	1.362	1.272	0.400	1.468
x_{1995}	—	—	—	0.690	0.744	0.765
x_{1996}	—	—	—	0.744	0.900	0.718
x_{1997}	—	—	—	0.880	0.865	0.873
x_{1998}	—	—	—	0.326	0.364	0.311
x_{1999}	—	—	—	0.158	0.157	0.153
x_{2000}	—	—	—	0.337	0.258	0.313
x_{2001}	—	—	—	0.367	0.308	0.359
x_{2002}	—	—	—	0.813	0.467	0.814
x_{2003}	—	—	—	0.401	0.119	0.413
MSY	447	286	449	838	925	840
MSYL	0.245	0.249	0.245	0.246	0.246	0.246
-ln *L*: Total	24.773	44.757	26.763	6.001	21.527	8.019
-ln *L*: CPUE	5.335	22.754	7.282	5.922	11.196	7.956
-ln *L*: Acoustic survey	13.327	13.506	13.050	1.204	7.642	1.040
-ln *L*: Sweptarea	6.095	4.808	5.739	1.956	2.420	1.845
-ln *L*: year bias	—	—	—	0.151	-3.014	-0.094
-ln *L*: prior on *M*	-2.942	-2.052	-2.930	-2.941	-2.924	-2.941
-ln *L*: prior on q^{AC}	2.957	5.741	3.623	0.012	0.177	0.025

Table 8. Estimates obtained when various models are fitted to the available indices of Namibian orange roughy for the *Rix* aggregation where the standardised CPUE series are obtained in various ways (Brandão and Butterworth 2002 and 2004). 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_{2003}) and stock depletion (B_{2003}/B_0) at the beginning of the year 2003, 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 (σ^{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}, $x_{2002,}$ x_{2003}), the maximum sustainable yield (MSY), the maximum sustainable yield level (MSYL) and the negative of the log likelihood (as well as its different components). Biomass units are tons.

Parameter estimates	***Rix***					
	Reference case ("zero" method) σ^{CPUE} estimated	**Reference case ("zero" method) σ^{CPUE} fixed**	**Reference case ("proportional" method)**	**Intermittent aggregation ("zero" method) σ^{CPUE} estimated**	**Intermittent aggregation ("zero" method) σ^{CPUE} fixed**	**Intermittent aggregation ("proportional" method) σ^{CPUE} fixed**
B_0	15 492	12 807	10 612	25 294	23 423	22 958
M	0.043	0.038	0.029	0.048	0.047	0.047
B_{2003}	6 109	3 192	583	16 109	14 210	13 720
B_{2003}/B_0	0.394	0.249	0.055	0.637	0.607	0.598
q^{AC}	1.324	1.595	2.057	1.081	1.128	1.215
q^{SA}	0.164	0.300	0.971	0.125	0.184	0.295
q^{CPUE} ($\times 10^5$)	6.678	10.523	23.344	6.195	8.379	8.360
σ^{CPUE}	0.747	0.400	0.147	0.549	0.400	0.400
x_{1995}	—	—	—	0.488	0.358	0.790
x_{1996}	—	—	—	0.546	0.421	0.824
x_{1997}	—	—	—	0.926	0.938	0.920
x_{1998}	—	—	—	0.687	0.734	0.642
x_{1999}	—	—	—	0.502	0.388	0.250
x_{2000}	—	—	—	0.516	0.403	0.261
x_{2001}	—	—	—	0.411	0.299	0.190
x_{2002}	—	—	—	0.422	0.309	0.196
x_{2003}	—	—	—	0.216	0.190	0.134
MSY	309	224	142	556	508	492
MSYL	0.247	0.248	0.250	0.246	0.246	0.246
-ln *L*: Total	6.059	10.602	-3.299	-3.330	-3.152	-2.782
-ln *L*: CPUE	1.875	5.295	-12.756	-0.893	-3.391	-5.424
-ln *L*: Acoustic survey	5.921	5.113	4.641	1.935	1.907	1.359
-ln *L*: year bias	—	—	—	1.579	-0.987	-3.614
-ln *L*: prior on *M*	-2.829	-2.527	-1.281	-2.933	-2.925	-2.916
-ln *L*: prior on q^{AC}	1.092	2.721	6.097	0.141	0.270	0.586

Table 9. 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 2004). The estimates shown are for the pre-exploitation orange roughy (recruited=mature) abundance (B_0), the natural mortality (M), the current stock biomass (B_{2003}) and stock depletion (B_{2003}/B_0) at the beginning of the year 2003, the commercial CPUE index catchability coefficient (q^{CPUE}), the standard deviation for the standardised CPUE series (σ^{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}, x_{2003}), the maximum sustainable yield (MSY), the maximum sustainable yield level (MSYL) and the negative of the log likelihood (as well as its different components). Biomass units are tons.

Parameter estimates	*Hotspot*	
	Base case	**Intermittent aggregation**
B_0	4 266	4 236
M	0.049	0.050
B_{2003}	149	153
B_{2003}/B_0	0.035	0.036
q^{CPUE} ($\times 10^5$)	55.624	92.894
σ^{CPUE}	0.540	0.550
x_{1994}	—	0.791
x_{1995}	—	0.766
x_{1996}	—	0.654
x_{1997}	—	0.455
x_{1998}	—	0.694
x_{1999}	—	0.633
x_{2000}	—	0.407
x_{2001}	—	0.627
x_{2002}	—	0.755
x_{2003}	—	0.445
MSY	95	97
MSYL	0.246	0.245
-ln *L*: Total	-4.101	-11.744
-ln *L*: CPUE	-1.162	-4.336
-ln *L*: year bias	—	4.463
-ln *L*: prior on *M*	-2.939	-2.945

Table 10. Summary of deterministic projection information, giving MSY estimates and approximate medium term sustainable yield (SY) estimates based upon Figs. 5–12, for the intermittent aggregation model. Values in parentheses reflect results given a year previously in Brandão and Butterworth (2003).

	Current depletion B_{2003}/B_0 (B_{2003}/B_0)	**Intermittent aggregation model**	
		MSY	**SY**
Johnies	0.64 (0.67)	928 (1 043)	1 000 (1 000 – 1 500)
Frankies	0.65 (0.65)	838 (877)	1 000 (1 000)
Rix	0.64 (0.69)	556 (666)	500–750 (500–1000)
Hotspot	0.04 (0.09)	97 (100)	50 (50)
Total		2 419 (2 686)	2 550–2 800 (2 550–3 550)

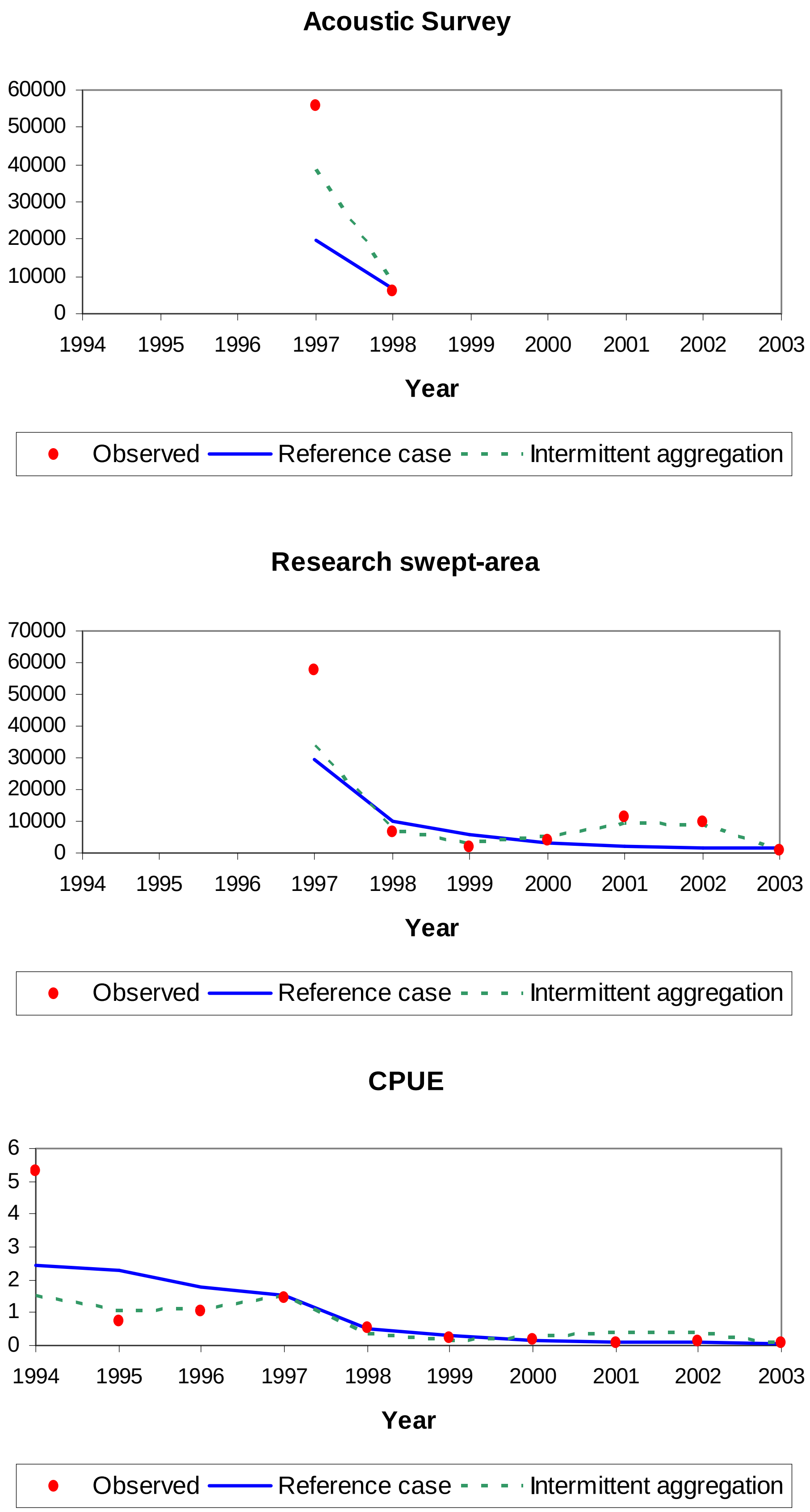

Figure 1. Observed and predicted values for each of the available indices of abundance of Namibian orange roughy for the *Johnies* aggregation when the reference case model and the intermittent aggregation model are fitted to data including the baseline (i.e. "zero" method) CPUE interpretation.

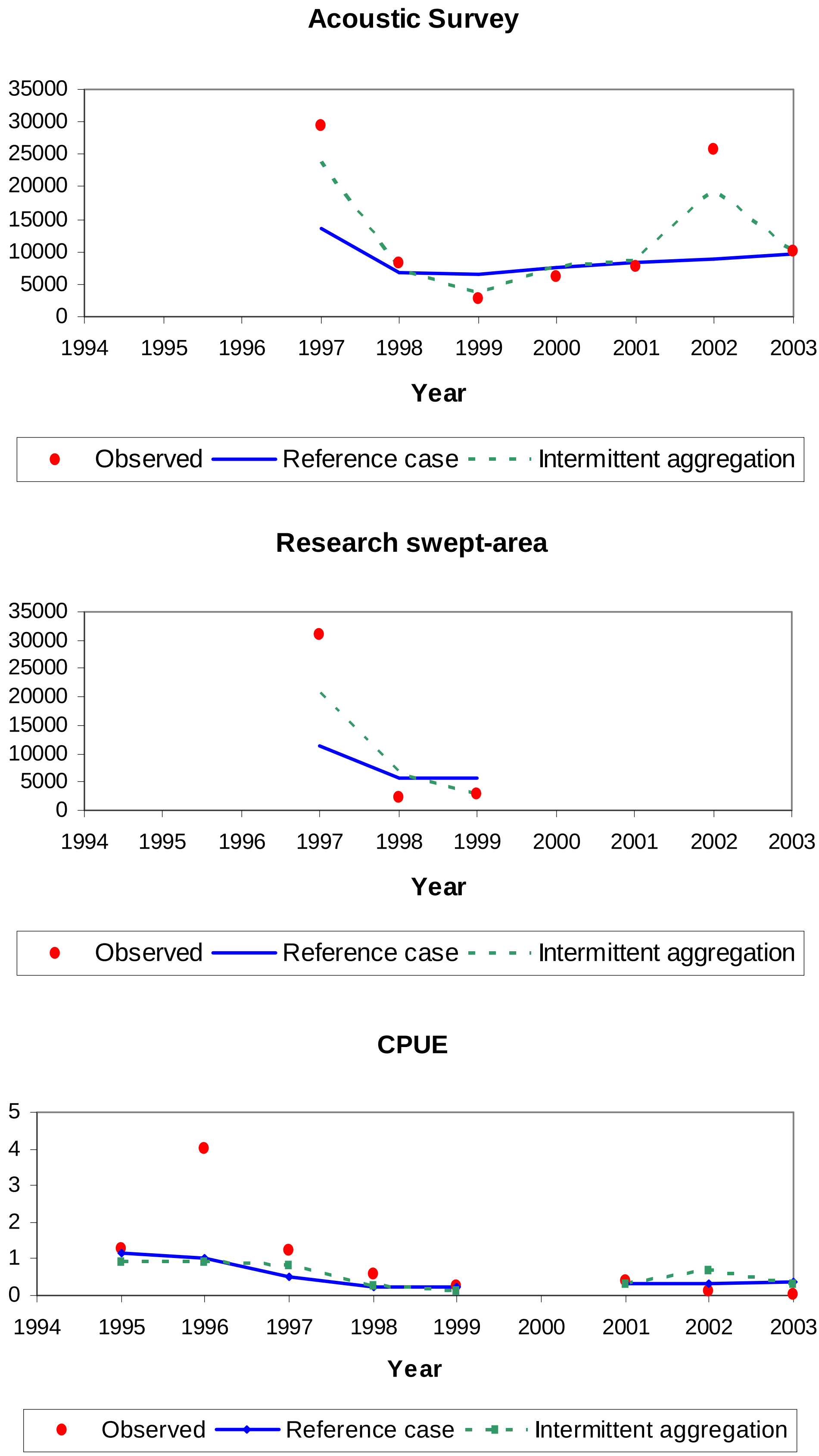

Figure 2. Observed and predicted values for each of the available indices of abundance of Namibian orange roughy for the *Frankies* aggregation when the reference case model and the intermittent aggregation model are fitted to data including the baseline (i.e. "zero" method) CPUE interpretation.

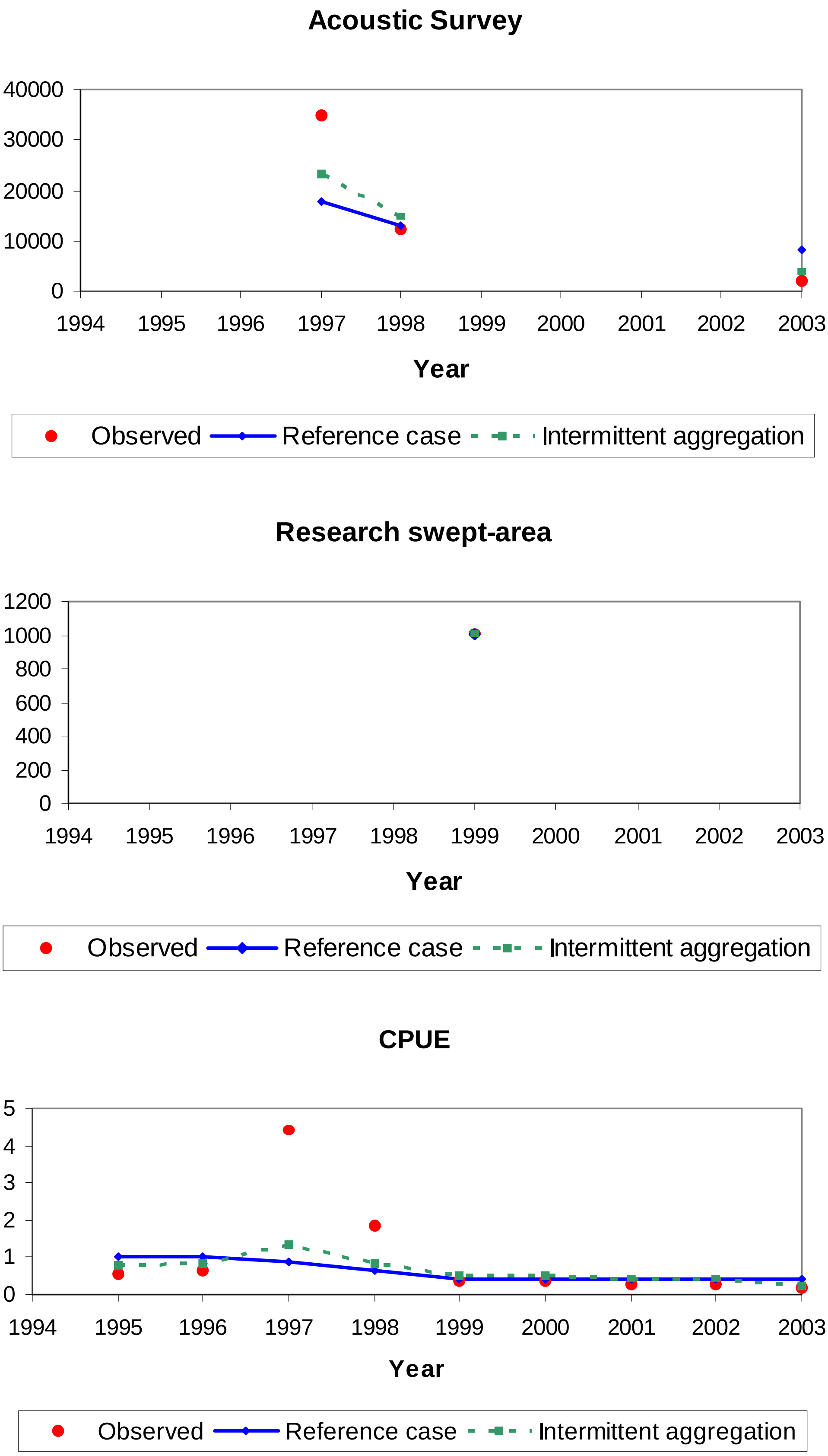

Figure 3. Observed and predicted values for each of the available indices of abundance of Namibian orange roughy for the *Rix* aggregation when the reference case model and the intermittent aggregation model are fitted to data including the baseline (i.e. “zero” method) CPUE interpretation.

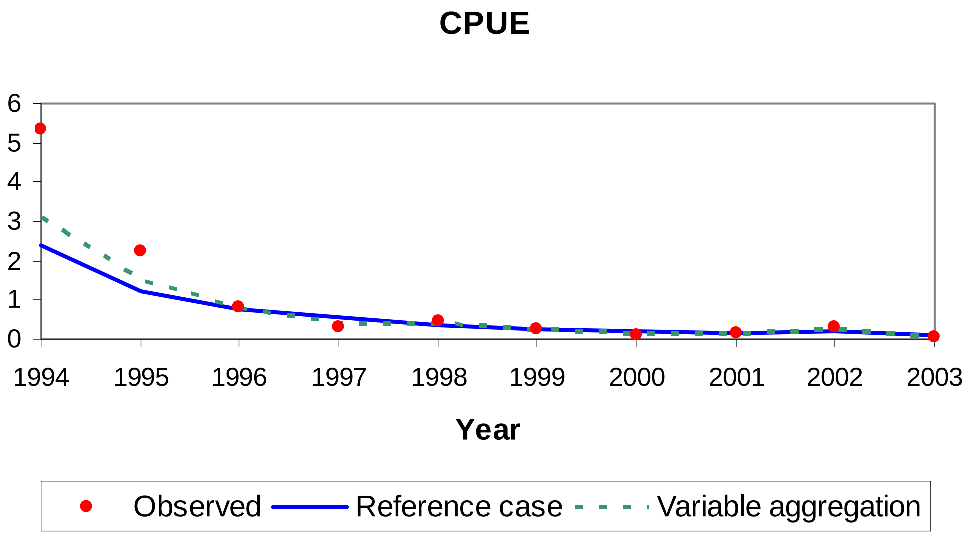

Figure 4. Observed and predicted values for the available index of abundance of Namibian orange roughy for the *Hotspot* aggregation when the reference case model and the intermittent aggregation model are fitted to the data.

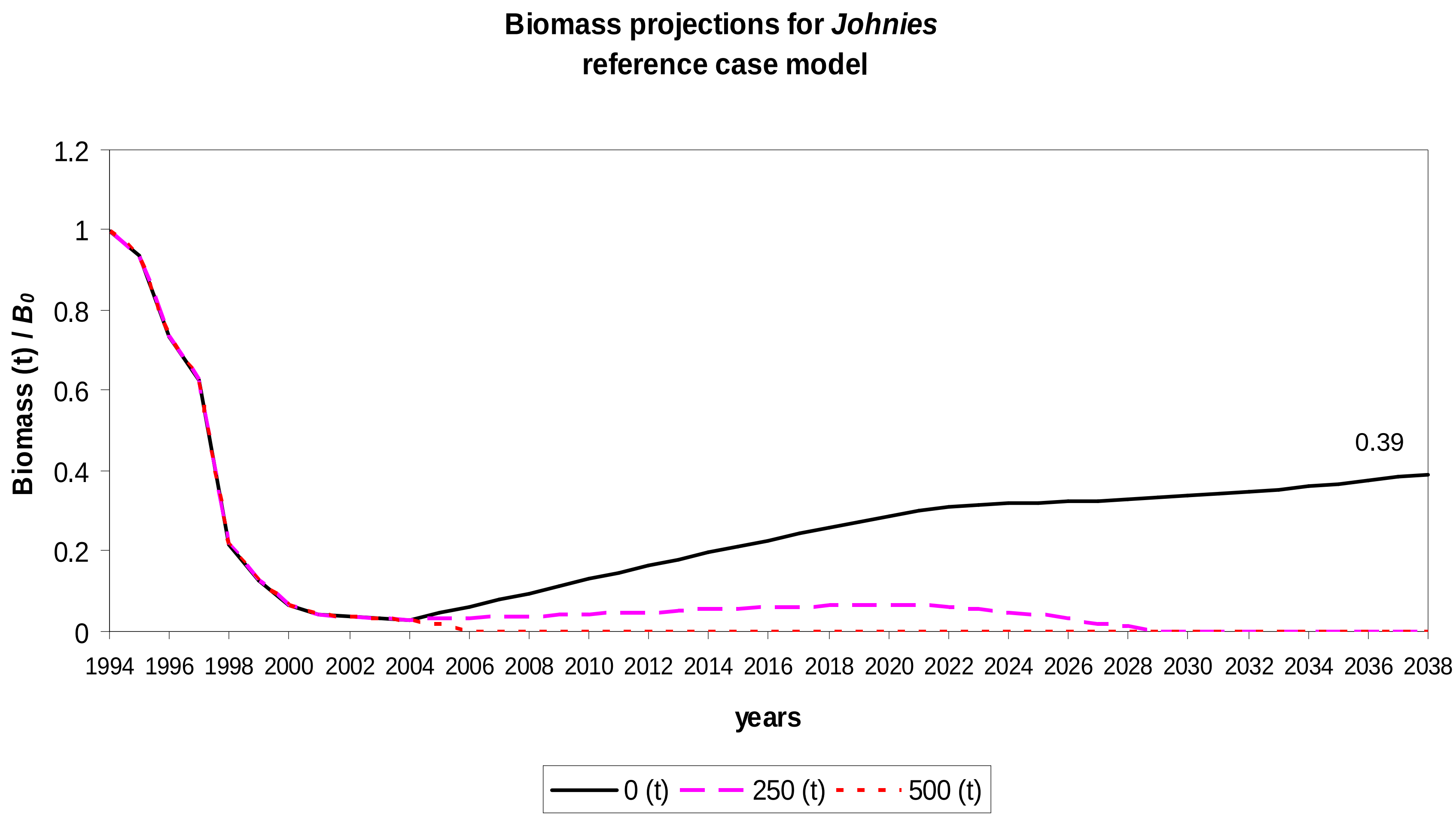

Figure 5. Thirty five year projections of the orange roughy stock for the *Johnies* aggregation under the scenario of the reference case model and the "zero" method CPUE scenario. Various levels of constant catch are shown. The figure at the right end of the trajectory is the stock depletion after 35 years.

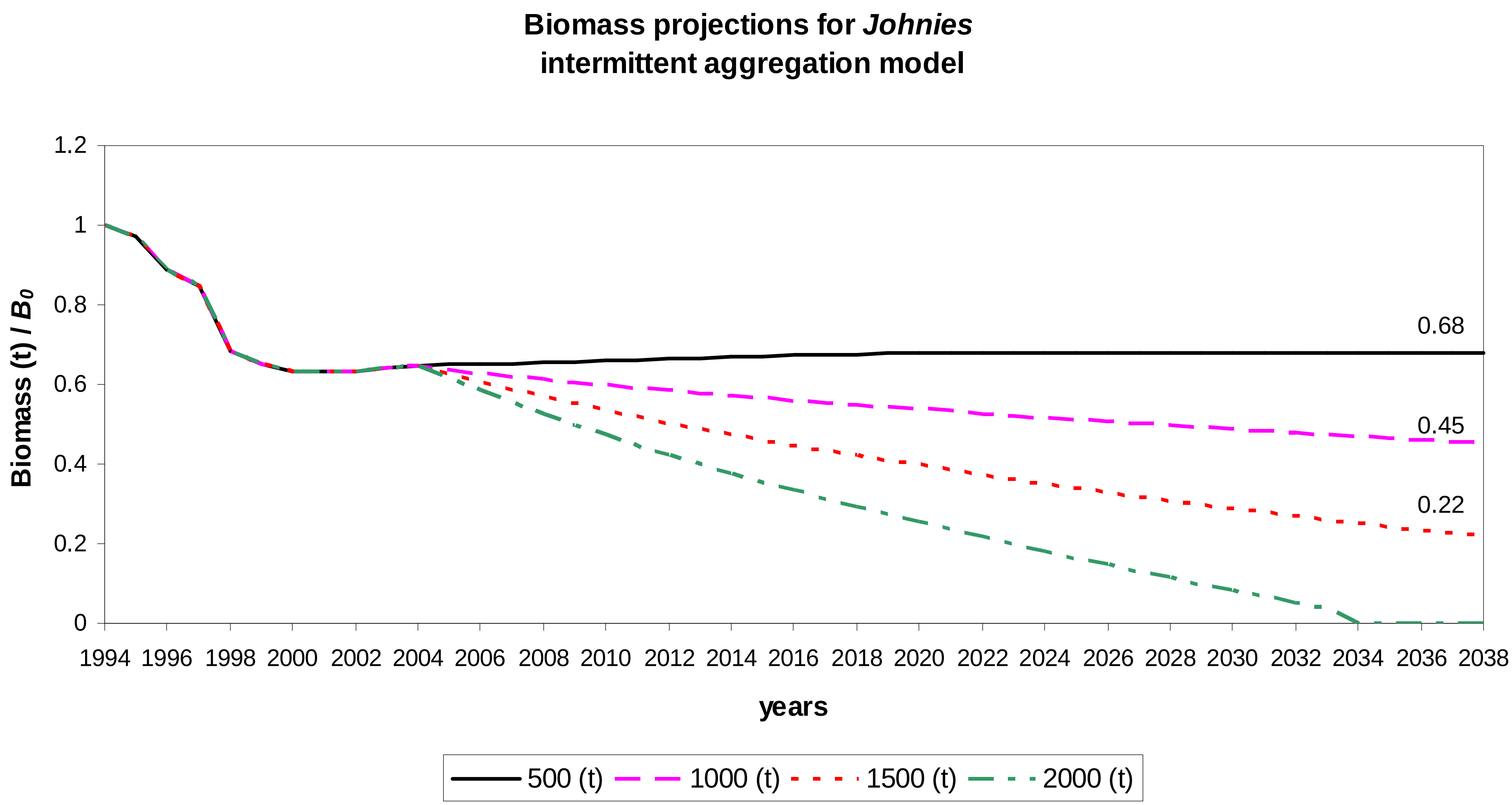

Figure 6. Thirty five year projections of the orange roughy stock for the *Johnies* aggregation under the scenario of the intermittent aggregation model and the "zero" method CPUE scenario. Various levels of constant catch are shown. The figure at the right end of the trajectory is the stock depletion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

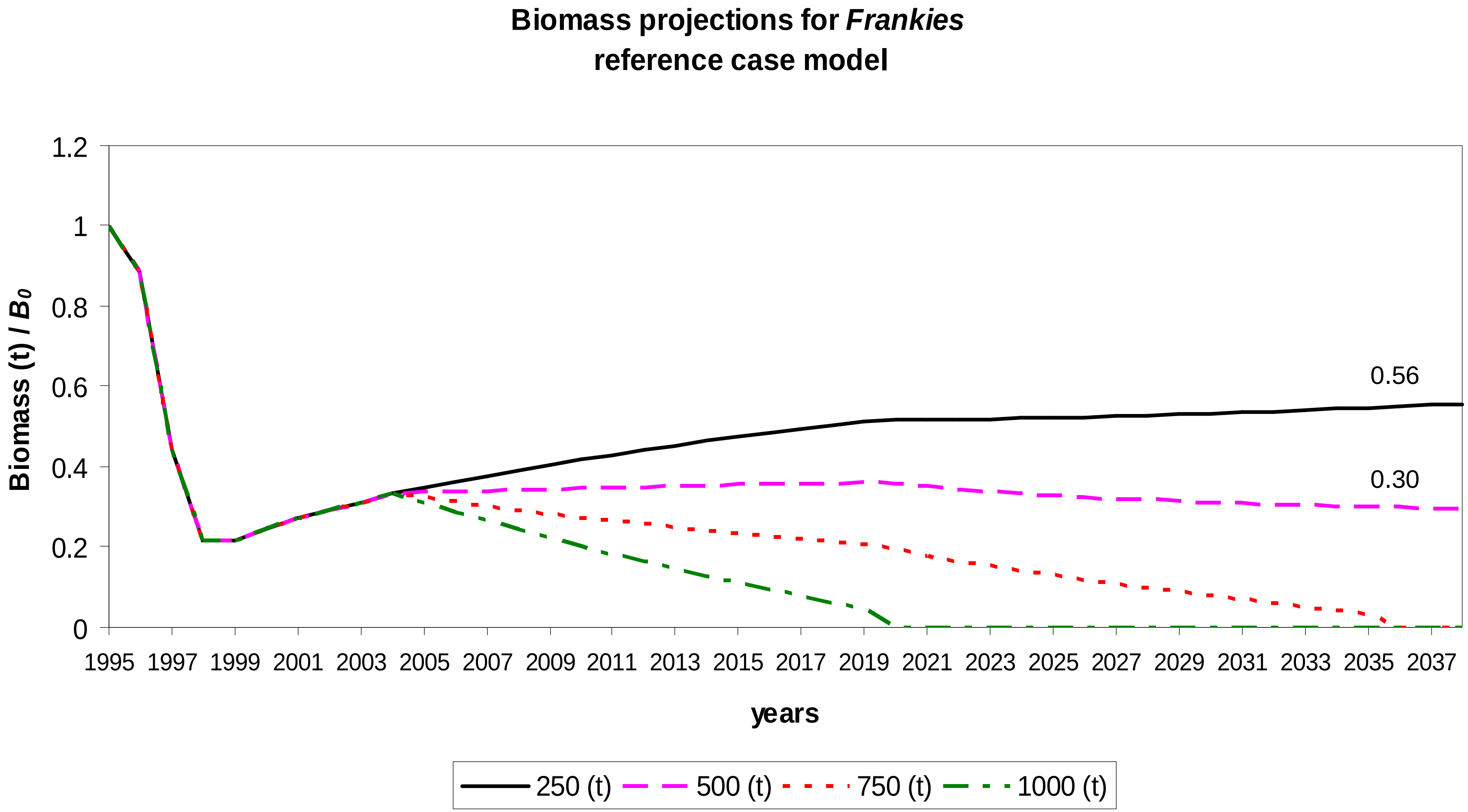

Figure 7. Thirty five year projections of the orange roughy stock for the *Frankies* aggregation under the scenario of the reference case model and the "zero" method CPUE scenario. Various levels of constant catch are shown. The figure at the right end of the trajectory is the stock depletion after 35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

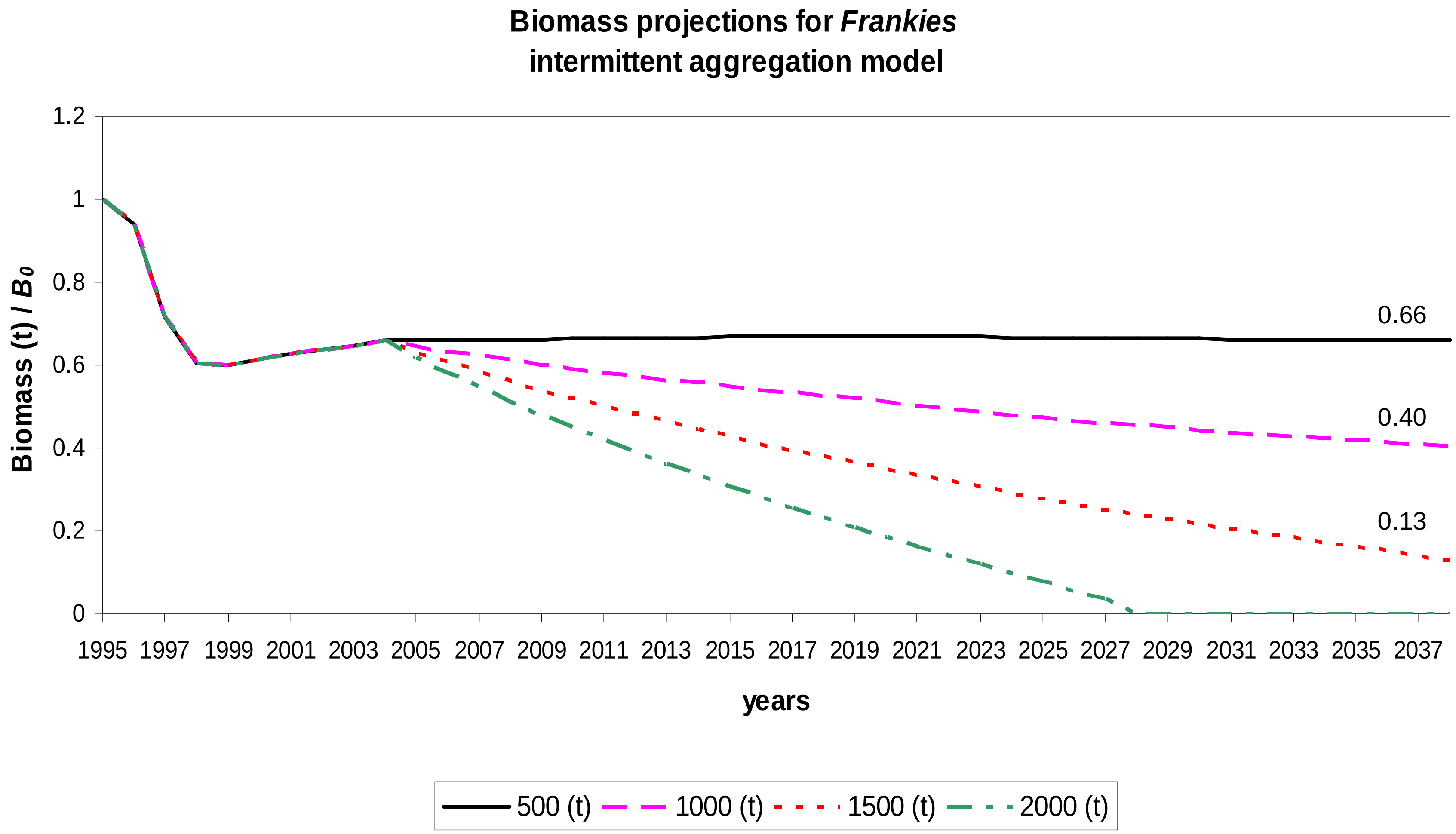

Figure 8. Thirty five year projections of the orange roughy stock for the *Frankies* aggregation under the scenario of the intermittent aggregation model and the "zero" method CPUE scenario. Various levels of constant catch are shown. The figure at the right end of the trajectory is the stock depletion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

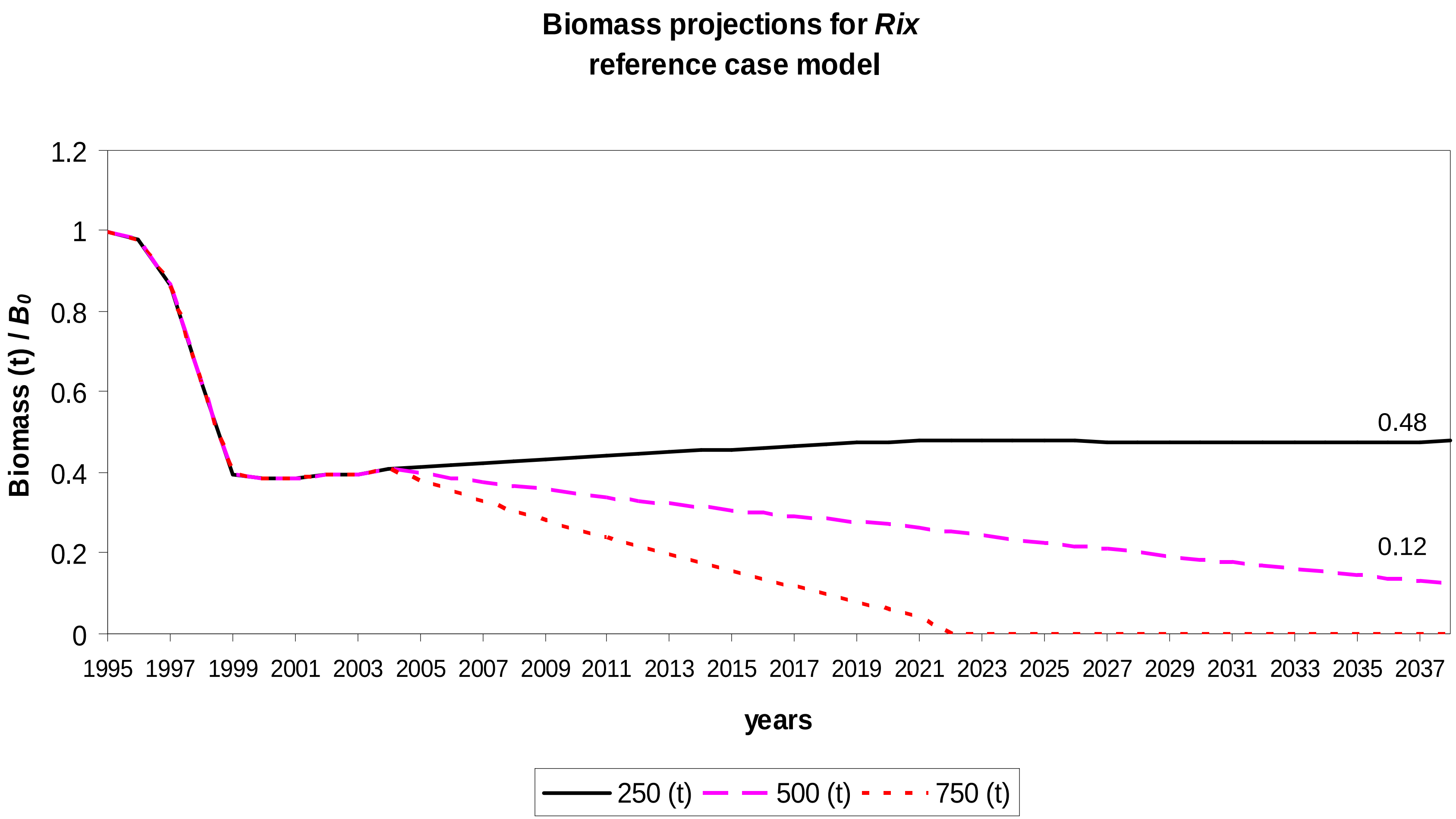

Figure 9. Thirty five year projections of the orange roughy stock for the *Rix* aggregation under the scenario of the base reference model and the "zero" method CPUE scenario. Various levels of constant catch are shown. The figure at the right end of the trajectory is the stock depletion after 35 years.

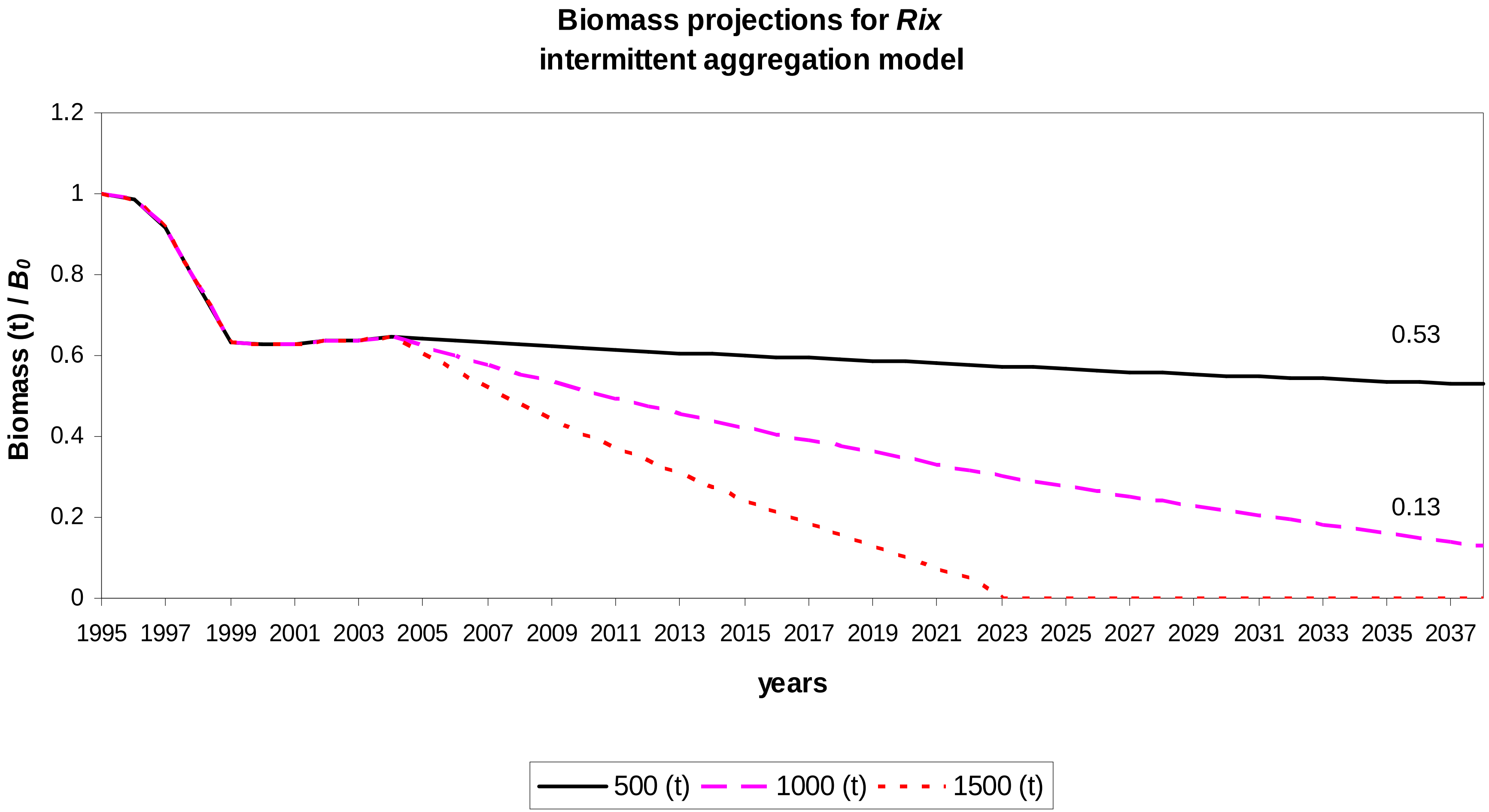

Figure 10. Thirty five year projections of the orange roughy stock for the *Rix* aggregation under the scenario of the intermittent aggregation model and the “zero” method CPUE scenario. Various levels of constant catch are shown. The figure at the right end of the trajectory is the stock depletion after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

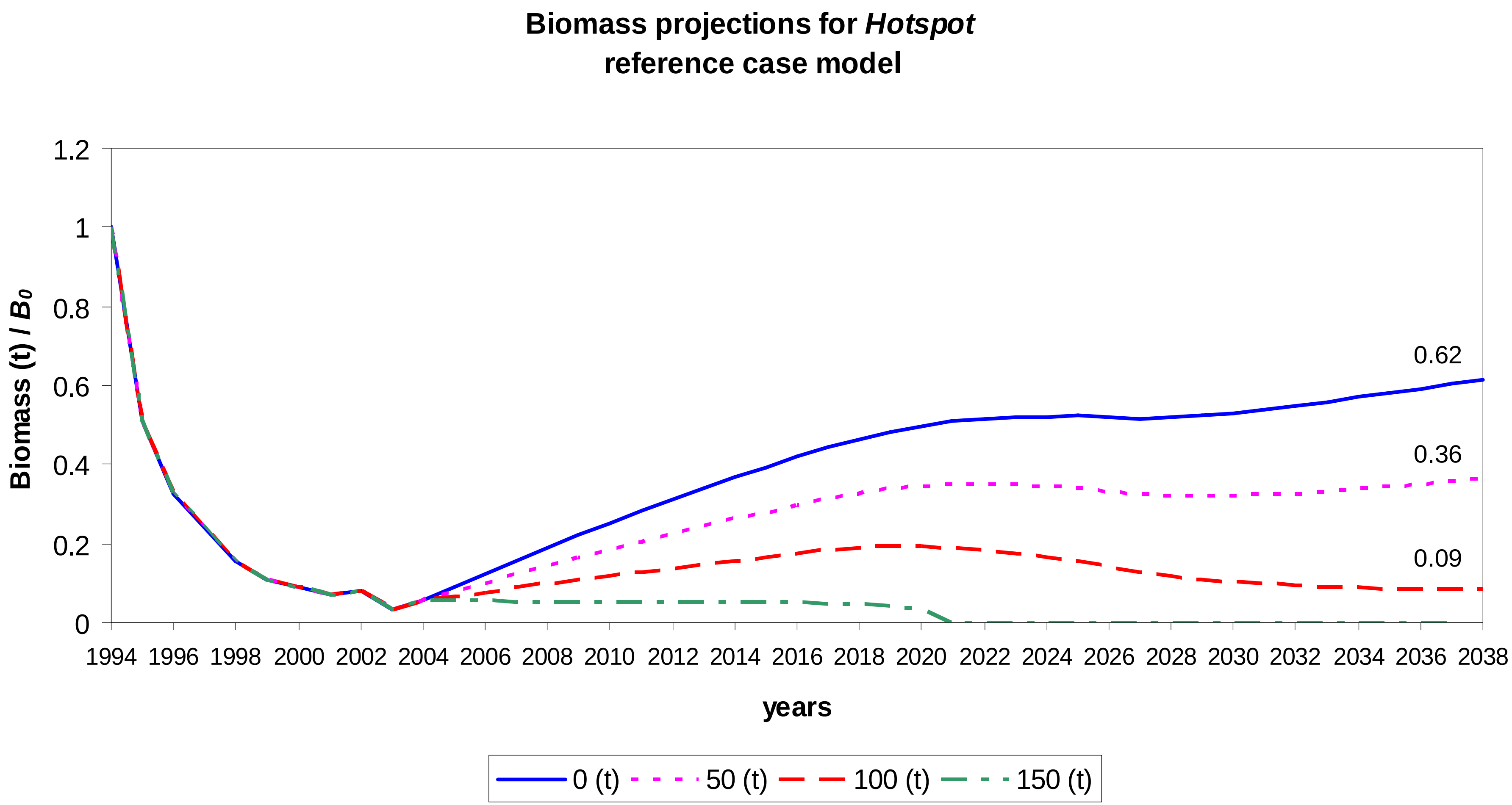

Figure 11. Thirty five year projections of the orange roughy stock for the *Hotspot* aggregation under the scenario of the reference case model and the delta-lognormal model fitted to the commercial CPUE data. Various levels of constant catch are shown. The figure at the right end of the trajectory is the stock depletion after 35 years.

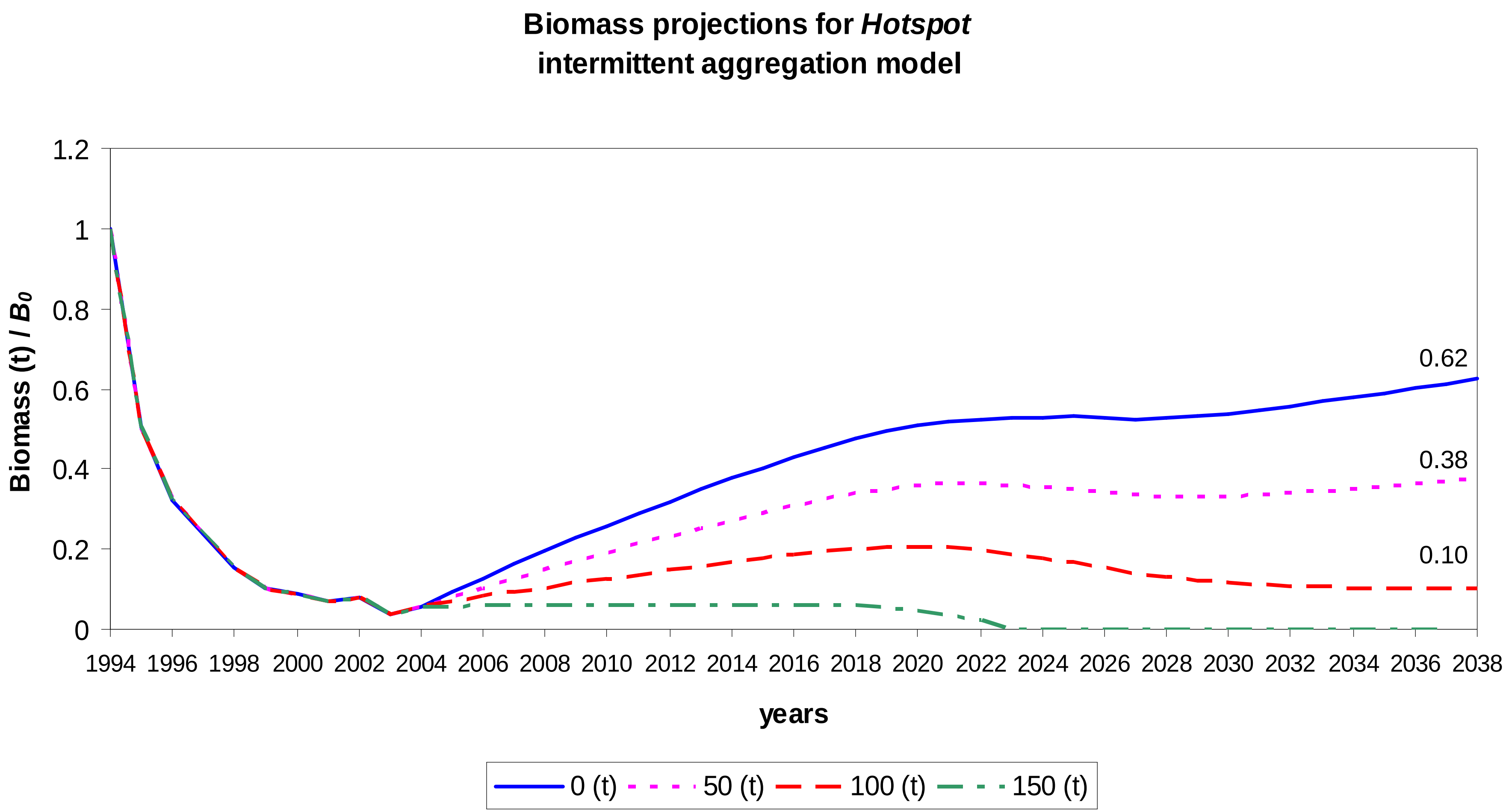

Figure 12. Thirty five year projections of the orange roughy stock for the *Hotspot* aggregation under the scenario of the intermittent aggregation model and the delta-lognormal model fitted to the commercial CPUE data. Various levels of constant catch are shown. The figure at the right end of the trajectory 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 and Hampton 2001).

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

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

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

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

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 ℓ_∞, κ and t_0 and a relationship relating length to mass. Note that ℓ 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 α and β 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 α 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:

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

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:

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

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.