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

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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. *Johnies*, *Hotspot* and *Frankies* (to a lesser extent) are estimated to be heavily depleted if trends in resource abundance indices are ascribed entirely to the effects of removals by the fishery. However these results are not statistically compatible with absolute estimates of abundance from hydroacoustic surveys. If fishing alone is responsible for resource index trends, medium term sustainable yields for the fishery as a whole are likely in the 1 000–2 000 ton range; alternatively, if the extent of aggregation varies from year to year, such levels are likely higher in the 3 000–4 000 ton range (assuming 100% of the spawning stock collected at the aggregations in 1997).

Introduction

This paper updates assessments of the orange roughy resource at the various aggregations off Namibia presented by Brandão and Butterworth (2001), based upon a maximum penalised likelihood estimation approach. The assessments are carried out on a "fishing year" (July to June) instead of a calendar year basis as in previous assessments (the reasons for this are explained below), and the various standardised CPUE series presented by Brandão and Butterworth (2002) are considered. All available indices of abundance are taken into account, and deterministic projections under various levels of constant catch are reported.

Data

In previous analyses of the orange roughy resource, a "fishing year" was defined as a calendar year. However, both the hydroacoustic and the research swept area surveys are carried out around July when the fish aggregate to spawn. As the assessments assume that the fishery can be approximated as a pulse catch at the start of the “fishing year”, the logical choice for the start of this “fishing year” is July rather than January, particularly also as the bulk of the catches are made in July and nearby months. In the analyses presented in this paper a “fishing year” has therefore been taken to be the period July to June.

The commercial fishing database has recently been re-entered. This new database in its present (as at January 2002) state was used to calculate annual catch given in Table 1. The uncorrected and corrected hydroacoustic abundance (D Boyer and I Hampton, pers. commn) and research swept area (E Johnsen, 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, 2002) 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. 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 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:

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

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

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

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 year 1997 is taken as a standard, so that $x_{1997} = 1$ (i.e. it is assumed that all the fish aggregated in 1997).

Confidence intervals for the parameters estimated have been evaluated using the likelihood profile method.

Results

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 given by equation (2) is used, and applied to the results of each of six alternative (three for *Hotspot*) approaches to provide standardised CPUE series using a lognormal or a delta-lognormal (with binomial errors for the proportion positive) model in the GLM standardisation (Brandão and Butterworth 2002), and each of three methods ("zero", "same" or "proportional") for dealing with missing data in sub-aggregations in particular years. Tables 9 to 11 give results for two further models considered for each aggregation (except for *Hotspot*): the base case model without the penalty on q^{AC} and the base case model including a year aggregation factor x_y (in these cases the σ^{CPUE} value is fixed at 0.2 rather than estimated to prevent a tendency by the model to overweight the CPUE data). The model fits excluding the q^{AC} penalty are effectively assuming that the hydroacoustic estimates contain no information about abundance in absolute terms, and are reliable only as relative indices. The base case model was also fitted omitting the abundance indices for 2001, to ascertain the impact of data from the most recent year (i.e. essentially a "retrospective" analysis). 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 the case of the base case model amended to include a year aggregation factor x_y, two other CPUE analysis approaches were also considered: those, apart from the baseline interpretation, that provided the lowest and the highest depletion at the beginning of the fishing year 2001.

In terms of the base case model, the stock depletion at the beginning of the fishing year 2001 for *Johnies* is at 11% of the pre-exploitation abundance (Table 5). However having one more year of information has improved the estimate of the status of this stock (from a depletion of 6% of pre-exploitation biomass) (Table 9). The stock depletion under different CPUE scenarios ranges from 9% to 13% (Table 5). The results when no penalty function is applied to q^{AC} are not consistent with the assumptions concerning the precision of the acoustic indices as absolute measures of abundance. This is because the 95% confidence interval estimated for q^{AC} in this case does not overlap the 95% limits for the q^{AC}-systematic distribution of Table 4. This is also the case for the *Frankies* aggregation (Table 10). Including a relative multiplicative bias factor (for differential aggregation each year) in the base case model substantially improves the estimated state of the stock. In this case the stock depletion of orange roughy is at 80% of the pre-exploitation biomass. This is true under the baseline interpretation for the standardised CPUE series as well as for the most optimistic and the most pessimistic alternatives interpretations (Table 9). All the relative bias factors after 1997 are less than 1, which means that this approach infers that the proportions of the population that have aggregated in the years after 1997 have been substantially smaller than in 1997 (values exceeding 1 in earlier years, for which only CPUE data are available, imply that fishing was non-random and able to concentrate on higher density areas in these years).

The stock depletion at the beginning of the year 2001 for the *Frankies* aggregation is at 33% of the pre-exploitation abundance under the baseline interpretation for the standardised CPUE series (Table 6), and ranges from 31% to 35% under alternative CPUE interpretations. An extra year of information has slightly improved the estimated status of the resource from a stock depletion of 30% to 33% (Table 10). Including relative multiplicative bias factors (for differential aggregation) for each year for the biomass estimates, indicates that the population is substantially better (81% depletion for the base case scenario, 78% under the most pessimistic CPUE interpretation, and 90% under the most optimistic) than when the biomass indices are considered as comparable (Table 10). Again all the relative bias factors after 1997 are less than 1, with the same consequent implications as for *Johnies*.

The stock depletion at the beginning of the year 2001 is estimated at 74% 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 72% to 73%). An extra year's data has not changed the perceived state of the resource (Table 11). Placing no penalty on q^{AC} suggests that the population is more depleted (30% of initial biomass). 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 (81% stock depletion under all the standardised CPUE series interpretations considered).

The stock depletion at the beginning of the year 2001 for the *Hotspot* aggregation is estimated at 2% 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 3% when a delta-lognormal model is used for the commercial CPUE data, both when a lognormal and a binomial distribution is assumed for the proportion of positive catches (Brandão and Butterworth 2002). 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 is overly pessimistic.

Figures 1 to 7 show the observed and predicted values, as well as the standardised residuals 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. For the *Johnies* aggregation, the model does not fit the first observation in all the abundance indices, with the standardised residual greater than 2 for the first observation in the CPUE series and the research swept area series (Fig. 1 and 2). The first acoustic and research swept area index, and the 1996 CPUE index, for *Frankies* are not fitted well by the model (Fig. 3 and 4). The model fits to the data for *Rix* do not suggest any model misspecification (Fig. 5 and 6). For the *Hotspot* aggregation the 1994 CPUE index is not well fitted by the model.

Figures 8 and 9 show thirty five year deterministic projections of the orange roughy stock for the *Johnies* aggregation under the base case model and the differential aggregation model, 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 11% of initial biomass to 36%. A constant catch of 500 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 alternative scenario of the differential aggregation model, a 500 t constant catch involves no chance of stock depletion (which remains at 80%) and a constant catch of 1000 t after thirty five years reduces the stock depletion to only 64% of the pre-exploitation abundance.

Figures 10 and 11 show deterministic projections for the base case model and the differential aggregation model respectively, both for the baseline CPUE interpretation for the *Frankies* aggregation. A slight improvement in stock depletion to 39% of initial biomass is seen for the base case model for a constant catch of 250 t. The stock becomes extinct after twenty nine years under a constant catch of 500 t. Under the alternative differential aggregation model, a constant catch of 500 t reduces the stock depletion to only 75% of pre-exploitation abundance, and to 55% under a 1000 t constant catch.

Figures 12 to 13 show deterministic projections for the *Rix* aggregation under the base case and the differential 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 alternative differential aggregation model, a constant catch of 500 t for thirty five years reduces the stock to 68% of initial biomass and to 38% under a constant catch of 1000 t.

Figure 14 gives projections for the *Hotspot* aggregation for the base case model. A constant catch of 50 t renders the stock extinct within twenty three years. If no catches are taken for thirty five years, the resource improves from a depletion of 2% of initial biomass to 41%.

Discussion and Conclusions

The main assessment results obtained above may be summarised as follows:

- For the *Johnies*, *Hotspot* and *Frankies* (to a lesser extent) aggregations, the resource is estimated to be heavily depleted under the models that make no allowance for differential aggregation from year to year (i.e. the models that ascribe index trends entirely to the effect of fishing having reduced abundance).
- *Rix* is estimated to be well above MSYL at present; *Johnies* and *Frankies* are similarly assessed if models make allowance for differential aggregation from year to year.

- For the *Johnies* and *Frankies* aggregations, the models that ascribe abundance index trends entirely to the effect of fishing having reduced abundance are not statistically compatible with the precision accorded to hydroacoustic estimates of abundance in absolute terms.
- Data obtained during the 2001 season suggests resource status to be improved for the *Johnies*, *Frankies* and *Rix* aggregations from that estimated previously.

Taken together, these results suggest that the rapid decline in CPUE and survey estimates over the late 1990s cannot be ascribed to the effects of fishing alone. Rather, they provide increasing (albeit indirect) support for differential aggregation from year to year, together with early CPUE data having over-estimated abundance, probably because non-random fishing was then able to concentrate on denser aggregations.

In terms of future utilisation considerations, Table 12 provides a coarse summary. For the fishery as a whole, if declines are ascribed completely to fishing down, medium term annual sustainable yields would be in the 1 000–2 000 ton range, but in terms of the differential aggregation hypothesis this range would increase to 3 000–4 000 tons. This last statement is based upon the assumption that 100% of the spawning stock collected at the aggregations in 1997, and accordingly is likely to err on the conservative side.

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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 2001 is incomplete as data were available only until October.

Year	***Johnies***	***Frankies***	***Rix***	***Hotspot***	**Total**
1994	1 144	—	—	2 162	3 306
1995	3 379	1 246	301	892	5 818
1996	1 425	6 665	1 464	427	9 981
1997	5 026	2 473	2 035	194	9 728
1998	1 391	418	2 523	237	4 569
1999	1 195	35†	384	226	1 840
2000	540	11†	280	224	1 055
2001*	315	52†	140	36	543

* Incomplete
† Closed to normal commercial fishing

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*

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)	—

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*

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	5.663	0.030	5.096	1.159	6.614	0.049
1995	0.662	3.528	1.041	3.159	0.773	5.792
1996	0.343	0.941	0.782	1.680	0.400	1.545
1997	0.720	2.237	0.584	1.279	0.115	0.392
1998	0.141	0.376	0.114	0.215	0.022	0.066
1999	0.133	0.303	0.108	0.173	0.021	0.053
2000	0.118	0.357	0.095	0.204	0.019	0.063
2001	0.221	0.228	0.179	0.131	0.035	0.040

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	1.567	3.455	3.474	4.722	5.277	6.505
1996	3.353	2.153	2.556	1.887	1.224	0.417
1997	0.654	0.285	0.499	0.250	0.239	0.055
1998	0.300	0.085	0.229	0.074	0.109	0.016
1999	0.042	0.019	0.054	0.026	0.018	0.004
2000	—	—	0.081	0.022	0.001	0.001
2001	0.083	0.002	0.108	0.018	0.131	0.001

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	1.485	4.204	2.132	4.053	3.575	5.946
1996	0.329	0.227	1.347	0.931	0.791	0.322
1997	2.097	1.201	1.424	0.943	1.065	0.343
1998	1.293	0.780	0.878	0.612	0.656	0.222
1999	0.218	0.073	0.148	0.058	0.111	0.021
2000	0.575	0.375	0.390	0.295	0.292	0.107
2001	1.004	0.139	0.682	0.109	0.510	0.040

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	6.017	7.1989
1995	1.483	0.7806
1996	0.228	0.0108
1997	0.057	0.0020
1998	0.050	0.0027
1999	0.073	0.0028
2000	0.028	0.0016
2001	0.065	0.0007

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	—	$\sigma_{1998}^{AC} = 0.46$
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	—	$\sigma_{2001}^{AC} = 0.26$
q^{AC}-random ***Rix*** 1997	—	$\sigma_{1997}^{AC} = 0.25$
1998	—	$\sigma_{1998}^{AC} = 0.26$

Table 5. Estimates obtained when the base case model is 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). A vessel correction has been applied to the research swept area index of 2000 as a different vessel from that of 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 stock biomass (B_{2001}) and stock depletion (B_{2001}/B_0) at the beginning of the year 2001, the acoustic estimate bias (q^{AC}), the research swept area index catchability coefficient (q^{SA}) and the commercial CPUE index catchability coefficient (q^{CPUE}), the standard deviation of the standardised CPUE series (σ^{CPUE}), the maximum sustainable yield (MSY), the Maximum sustainable yield level (MSYL) and the negative of the log likelihood. The 95% confidence intervals are given for the parameter estimates.

Parameter estimates (95% confidence interval)	***Johnies***					
	"Zero" method		**"Same" method**		**"Proportional" method**	
	Lognormal model	**Delta-lognormal model**	**Lognormal model**	**Delta-lognormal model**	**Lognormal model**	**Delta-lognormal model**
B_0	13 268 (9 801; 16 215)	13 775 (10 820; 21 805)	12 728 (9 885; 13 795)	12 680 (10 401; 14 083)	12 915 (10 272; 13 824)	13 290 (9 837; 16 491)
M	0.054 (0.032; 0.106)	0.049 (0.028; 0.093)	0.060 (0.046; 0.111)	0.059 (0.046; 0.102)	0.055 (0.043; 0.101)	0.052 (0.033; 0.089)
B_{2001}	1 476	1 771	1 188	1 090	1 188	1 390
B_{2001}/B_0	0.111	0.129	0.093	0.085	0.091	0.105
q^{AC}	2.050 (1.639; 2.691)	1.982 (1.210; 2.600)	2.132 (1.855; 2.784)	2.144 (1.920; 2.737)	2.180 (1.862; 2.853)	2.052 (1.594; 2.766)
q^{SA}	3.292 (1.104; 8.520)	2.896 (0.053; 7.700)	3.841 (2.163; 10.074)	3.987 (2.984; 9.928)	3.740 (2.571; 10.997)	3.351 (0.888; 9.228)
q^{CPUE} $(\times 10^5)$	8.426 (3.788; 18.691)	9.157 (0.806; 20.347)	9.706 (7.099; 21.325)	14.102 (10.220; 27.553)	3.143 (2.293; 7.639)	4.197 (2.029; 10.406)
σ^{CPUE}	0.735 (0.705; 0.783)	1.464 (1.374; 1.729)	0.637 (0.436; 0.639)	0.409 (0.354; 0.421)	1.251 (0.877; 1.260)	1.358 (1.304; 1.410)
MSY	330	310	353	345	330	315
MSYL	0.244	0.246	0.243	0.243	0.244	0.245
-ln *L*	27.078	32.610	26.149	22.677	31.476	31.986

Table 6. Estimates obtained when the base case model is 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). The estimates shown are for the pre-exploitation orange roughy (recruited=mature) abundance (B_0), the natural mortality (M), the stock biomass (B_{2001}) and stock depletion (B_{2001}/B_0) at the beginning of the year 2001, the acoustic estimate bias (q^{AC}), the research swept area index catchability coefficient (q^{SA}) and the commercial CPUE index catchability coefficient (q^{CPUE}), the standard deviation of the standardised CPUE series (σ^{CPUE}), the maximum sustainable yield (MSY), the Maximum sustainable yield level (MSYL) and the negative of the log likelihood. The 95% confidence intervals are given for the parameter estimates.

Parameter estimates (95% confidence interval)	***Frankies***					
	"Zero" method		**"Same" method**		**"Proportional" method**	
	Lognormal model	**Delta-lognormal model**	**Lognormal model**	**Delta-lognormal model**	**Lognormal model**	**Delta-lognormal model**
B_0	13 882 (11 305; 18 744)	14 222 (11 380; 19 184)	13 604 (11 103; 18 296)	13 934 (11 332; 18 847)	14 203 (11 365; 19 160)	14 201 (11 364; 19 160)
M	0.042 (0.020; 0.074)	0.043 (0.022; 0.076)	0.042 (0.020; 0.073)	0.042 (0.020; 0.074)	0.043 (0.020; 0.075)	0.043 (0.020; 0.075)
B_{2001}	4 547	4 906	4 256	4 606	4 893	4 887
B_{2001}/B_0	0.328	0.345	0.313	0.331	0.345	0.344
q^{AC}	1.460 (0.713; 2.080)	1.386 (0.695; 1.970)	1.528 (0.721; 2.196)	1.447 (0.709; 2.066)	1.389 (0.696; 1.975)	1.390 (0.696; 1.977)
q^{SA}	1.558 (0.446; 2.505)	1.450 (0.440; 2.320)	1.659 (0.439; 2.693)	1.540 (0.443; 2.478)	1.454 (0.440; 2.329)	1.456 (0.440; 2.331)
q^{CPUE} $(\times 10^5)$	5.952 (2.505; 8.695)	1.978 (0.841; 2.873)	5.728 (2.138; 8.585)	2.402 (0.958; 3.599)	1.859 (0.761; 2.777)	0.407 (0.166; 0.608)
σ^{CPUE}	1.109 (0.940; 1.309)	2.189 (2.025; 2.380)	1.042 (0.841; 1.282)	1.607 (1.414; 1.834)	2.213 (2.066; 2.383	2.586 (2.411; 2.788)
MSY	267	277	260	269	278	277
MSYL	0.247	0.247	0.247	0.247	0.247	0.247
-ln *L*	20.675	24.671	20.960	23.855	26.031	27.123

Table 7. Estimates obtained when the base case model is 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). The estimates shown are for the pre-exploitation orange roughy (recruited=mature) abundance (B_0), the natural mortality (M), the stock biomass (B_{2001}) and stock depletion (B_{2001}/B_0) at the beginning of the year 2001, the acoustic estimate bias (q^{AC}), the research swept area index catchability coefficient (q^{SA}) and the commercial CPUE index catchability coefficient (q^{CPUE}), the standard deviation of the standardised CPUE series (σ^{CPUE}), the maximum sustainable yield (MSY), the Maximum sustainable yield level (MSYL) and the negative of the log likelihood. The 95% confidence intervals are given for the parameter estimates.

Parameter estimates (95% confidence interval)	*Rix*					
	"Zero" method		"Same" method		"Proportional" method	
	Lognormal model	Delta-lognormal model	Lognormal model	Delta-lognormal model	Lognormal model	Delta-lognormal model
B_0	23 226 (12 465; 41 688)	22 790 (12 049; 41 224)	21 813 (11 234; 39 987)	22 454 (11 755; 40 827)	22 219 (11 582; 40 486)	22 797 (12 043; 41 256)
M	0.050 (0.023; 0.096)	0.050 (0.023; 0.096)	0.050 (0.023; 0.095)	0.050 (0.023; 0.095)	0.050 (0.023; 0.095)	0.050 (0.023; 0.096)
B_{2001}	17 147	16 707	15 769	16 369	16 135	16 715
B_{2001}/B_0	0.738	0.733	0.723	0.729	0.726	0.733
q^{AC}	0.996 (0.606; 1.333)	1.009 (0.604; 1.357)	1.039 (0.606; 1.410)	1.019 (0.604; 1.375)	1.026 (0.606; 1.387)	1.008 (0.603; 1.357)
q^{SA}	0.058 (0.013; 0.101)	0.060 (0.013; 0.105)	0.063 (0.114; 0.688)	0.241 (0.070; 0.396)	0.328 (0.094; 0.541)	0.104 (0.031; 0.170)
q^{CPUE} ($\times 10^5$)	3.930 (1.246; 6.322)	2.306 (0.697; 3.756)	4.139 (1.138; 6.884)	2.407 (0.704; 3.956)	3.283 (0.944; 5.409)	1.042 (0.314; 1.699)
σ^{CPUE}	0.739 (0.723; 0.751)	1.195 (1.132; 1.247)	0.729 (0.636; 0.801)	1.214 (1.120; 1.290)	0.893 (0.810; 0.961)	1.586 (1.502; 1.655)
MSY	533	520	496	511	506	520
MSYL	0.245	0.245	0.245	0.245	0.245	0.245
-ln L	1.916	5.284	1.863	5.405	3.270	7.267

Table 8. Estimates obtained when the base case model is fitted to the available indices of Namibian orange roughy for the *Hotspot* aggregation, where the standardised CPUE series are obtained in various ways (Brandão and Butterworth 2002).. The estimates shown are for the pre-exploitation orange roughy (recruited=mature) abundance (B_0), the natural mortality (M), the stock biomass (B_{2001}) and stock depletion (B_{2001}/B_0) at the beginning of the year 2001, the commercial CPUE index catchability coefficient (q^{CPUE}), and the negative of the log likelihood. The 95% confidence interval are given for the parameter estimates.

Parameter estimates (95% confidence interval)	***Hotspot***		
	Lognormal model	**Delta-lognormal model (binomial errors)**	**Delta-lognormal model (lognormal errors)**
B_0	3 192 (2 759; 3 570)	3 223 (94; 7264)	3 258 (2 713; 4 044)
M	0.028 (0.016; 0.054)	0.043 (0.031; 0.088)	0.046 (0.038; 0.070)
B_{2001}	62	98	108
B_{2001}/B_0	0.019	0.030	0.033
$q^{CPUE}(\times 10^4)$	10.086 (3.667; 11.980)	0.561 (0.000678; 2.362)	12.559 (2.645; 18.413)
σ^{CPUE}	0.389 (0.278; 0.697)	1.867 (1.634; 2.490)	0.447 (;)
MSY	42	63	69
MSYL	0.250	0.247	0.246
-ln *L*	-4.638	6.198	-5.344

Table 9. Estimates obtained when various models are fitted to the available indices of Namibian orange roughy for the *Johnies* aggregation. A vessel correction has been applied to the research swept area index of 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 stock biomass (B_{2001}) and stock depletion (B_{2001}/B_0) at the beginning of the year 2001, the acoustic estimate bias (q^{AC}), the research swept area index catchability coefficient (q^{SA}) and the commercial CPUE index catchability coefficient (q^{CPUE}), the standard deviation of the standardised CPUE series (σ^{CPUE}), the relative multiplicative bias factor for the 1994, 1995, 1996, 1998, 1999, 2000 and 2001 estimates (x_{1994}, x_{1995}, x_{1996}, x_{1998}, x_{1999}, x_{2000}, x_{2001}), the maximum sustainable yield (MSY), the Maximum sustainable yield level (MSYL) and the negative of the log likelihood. The 95% confidence intervals are given for the parameter estimates in some cases.

Parameter estimates (95% confidence interval)	***Johnies***					
	Base case (with "zero" method and lognormal model)	**Variant (including x_y parameter)**	**Pessimistic variant ("same" method and delta-lognormal model)**	**Optimistic variant ("zero" method and delta-lognormal model)**	**Base case (no 2001 data)**	**Base case (no q^{AC} penalty)**
B_0	13 268	59 299	60 500	60 501	12 921	10 580
M	0.054	0.050	0.050	0.050	0.047	0.071
B_{2001}	1 476	47 390	48 591	48 592	817	581
B_{2001}/B_0	0.111	0.799	0.803	0.803	0.063	0.055
q^{AC}	2.050	0.953	0.953	0.953	2.127	9.991 (7.94; 17.04)
q^{SA}	3.292	0.765	0.858	0.858	3.681	9.063
q^{CPUE} ($\times 10^5$)	8.426	1.683	2.682	4.690	9.053	17.738
σ^{CPUE}	0.735	0.2	0.2	0.2	0.740	0.731
x_{1994}	—	5.673	0.714	0.011	—	—
x_{1995}	—	0.676	1.983	1.266	—	—
x_{1996}	—	0.371	1.115	0.357	—	—
x_{1998}	—	0.172	0.157	0.157	—	—
x_{1999}	—	0.133	0.108	0.108	—	—
x_{2000}	—	0.140	0.142	0.142	—	—
x_{2001}	—	0.283	0.118	0.118	—	—
MSY	330	1 367	1 395	1 395	279	350
MSYL	0.244	0.245	0.245	0.245	0.246	0.241
-ln *L*	27.078	-11.308	-10.407	-10.379	24.164	3.474

Table 10. 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 of 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 stock biomass (B_{2001}) and stock depletion (B_{2001}/B_0) at the beginning of the year 2001, the acoustic estimate bias (q^{AC}), the research swept area index catchability coefficient (q^{SA}) and the commercial CPUE index catchability coefficient (q^{CPUE}), the standard deviation of the standardised CPUE series (σ^{CPUE}), the relative multiplicative bias factor for the 1995, 1996, 1998, 1999, 2000 and 2001 estimates (x_{1995}, x_{1996}, x_{1998}, x_{1999}, x_{2000}, x_{2001}), the maximum sustainable yield (MSY), the Maximum sustainable yield level (MSYL) and the negative of the log likelihood. The 95% confidence intervals are given for the parameter estimates in some cases.

Parameter estimates (95% confidence interval)	*Frankies*					
	Base case (with "zero" method and lognormal model)	Variant (including x_y parameter)	Pessimistic variant ("same" method and delta-lognormal model)	Optimistic variant ("zero" method and delta-lognormal model)	Base case (no 2001 data)	Base case (no q^{AC} penalty)
B_0	13 882	46 171	40 492	87 303	13 441	10 254
M	0.042	0.050	0.050	0.050	0.041	0.041
B_{2001}	4 547	37 148	31 469	78 282	4 069	870
B_{2001}/B_0	0.328	0.805	0.777	0.897	0.303	0.08
q^{AC}	1.460	0.953	0.953	0.953	1.490	10.627
q^{SA}	1.558	0.706	0.727	0.352	1.728	9.597 (6.21; 16.15)
q^{CPUE} ($\times 10^5$)	5.952	1.616	1.598	0.255	8.142	22.296
σ^{CPUE}	1.109	0.2	0.2	0.2	1.038	0.669
x_{1995}	—	2.100	5.368	15.548	—	—
x_{1996}	—	4.614	4.070	9.824	—	—
x_{1998}	—	0.392	0.381	0.303	—	—
x_{1999}	—	0.082	0.12	0.080	—	—
x_{2000}	—	0.180	0.173	0.085	—	—
x_{2001}	—	0.164	0.231	0.024	—	—
MSY	267	1 065	934	2 013	253	195
MSYL	0.247	0.245	0.245	0.245	0.248	0.247
-ln L	20.675	-6.159	-10.406	28.3964	19.591	-0.234

Table 11. 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 of 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 stock biomass (B_{2001}) and stock depletion (B_{2001}/B_0) at the beginning of the year 2001, the acoustic estimate bias (q^{AC}), the research swept area index catchability coefficient (q^{SA}) and the commercial CPUE index catchability coefficient (q^{CPUE}), the standard deviation of the standardised CPUE series (σ^{CPUE}), the relative multiplicative bias factor for the 1995, 1996, 1998, 1999, 2000 and 2001 estimates (x_{1995}, x_{1996}, x_{1998}, x_{1999}, x_{2000}, x_{2001}), the maximum sustainable yield (MSY), the Maximum sustainable yield level (MSYL) and the negative of the log likelihood.

Parameter estimates (95% confidence interval)	***Rix***					
	Base case (with "zero" method and lognormal model)	**Variant (including x_y parameter)**	**Pessimistic variant ("same" method and delta-lognormal model)**	**Optimistic variant ("zero" method and delta-lognormal model)**	**Base case (no 2001 data)**	**Base case (no q^{AC} penalty)**
B_0	23 226	32 689	32 690	32 214	23 067	8 615
M	0.050	0.050	0.050	0.050	0.050	0.052
B_{2001}	17 147	26 617	26 617	26 141	16 987	2 562
B_{2001}/B_0	0.738	0.814	0.814	0.811	0.736	0.297
q^{AC}	0.996	0.953	0.953	0.953	1.001	3.558
q^{SA}	0.058	0.347	0.347	0.609	0.059	0.367
q^{CPUE} ($\times 10^5$)	3.930	7.524	5.109	4.420	3.707	16.723
σ^{CPUE}	0.739	0.2	0.2	0.2	0.779	0.754
x_{1995}	—	0.604	1.277	2.953	—	—
x_{1996}	—	0.135	0.814	0.161	—	—
x_{1998}	—	0.531	0.531	0.549	—	—
x_{1999}	—	0.108	0.108	0.062	—	—
x_{2000}	—	0.287	0.286	0.324	—	—
x_{2001}	—	0.501	0.502	0.120	—	—
MSY	533	754	753	742	528	205
MSYL	0.245	0.245	0.245	0.245	0.245	0.245
-ln *L*	1.916	-13.494	-13.494	-13.349	2.031	0.585

Table 12. Summary of deterministic projection information, giving MSY estimates and approximate medium term sustainable yield (SY) estimates based upon Figs. 8–14.

	Base case model (baseline CPUE)		**Differential aggregation model (baseline CPUE)**	
	MSY	**SY**	**MSY**	**SY**
Johnies	330	250–500	1 367	1 500 – 2 000
Frankies	267	250–400	1 065	1 000–1 500
Rix	533	500–750	754	500–750
Hotspot	42	50	(42+)?	(50+)?
Total	1 172	1 050–1 700	3 228+	3 050–4 300+

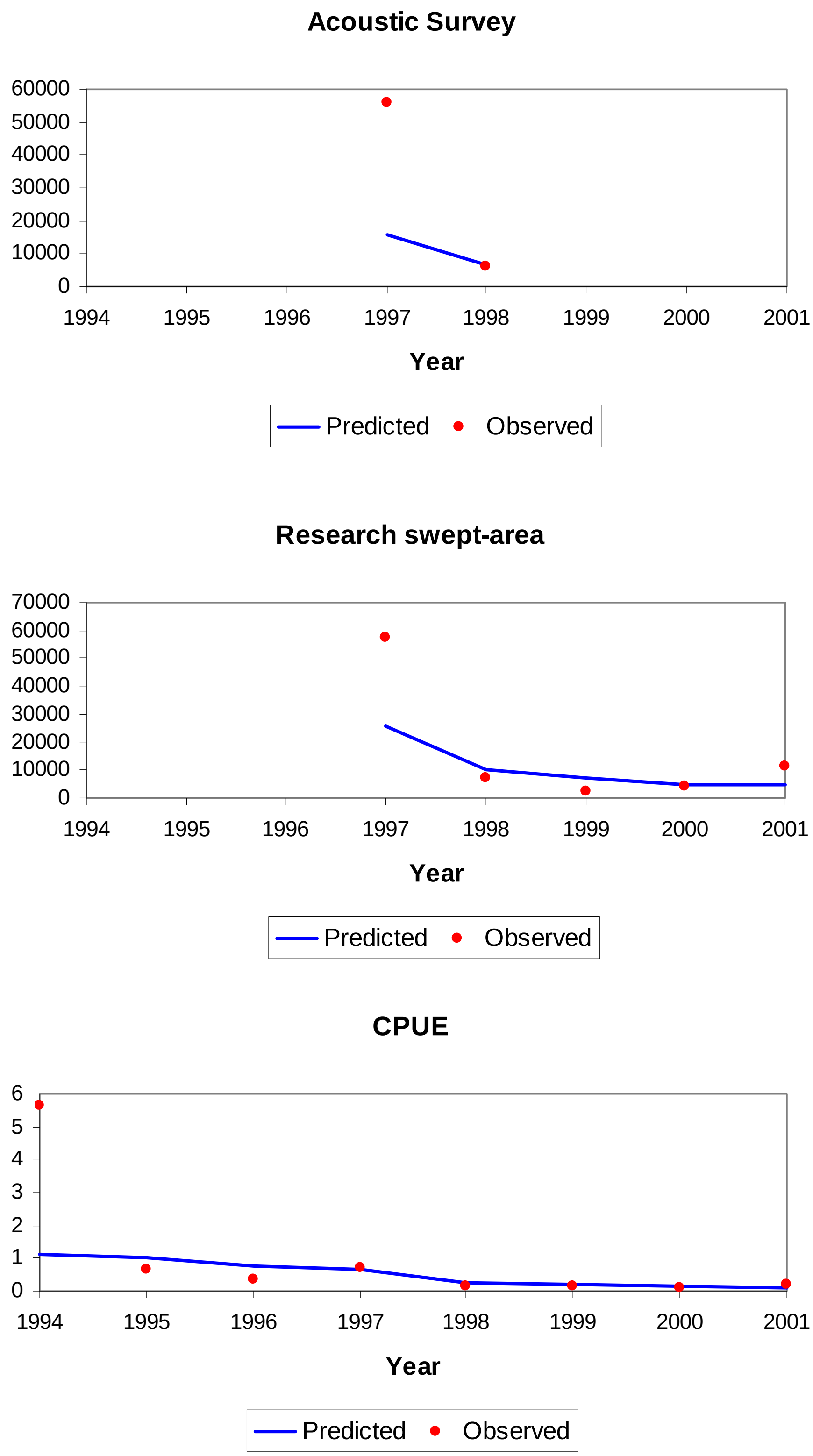
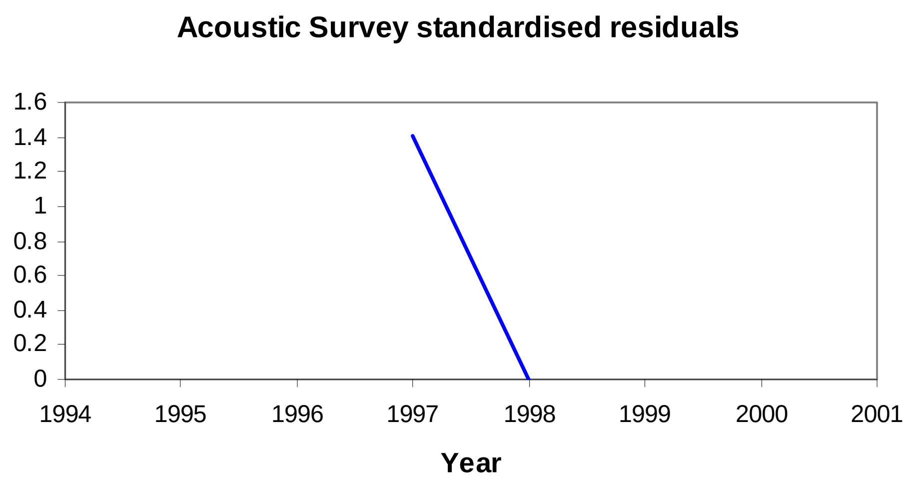
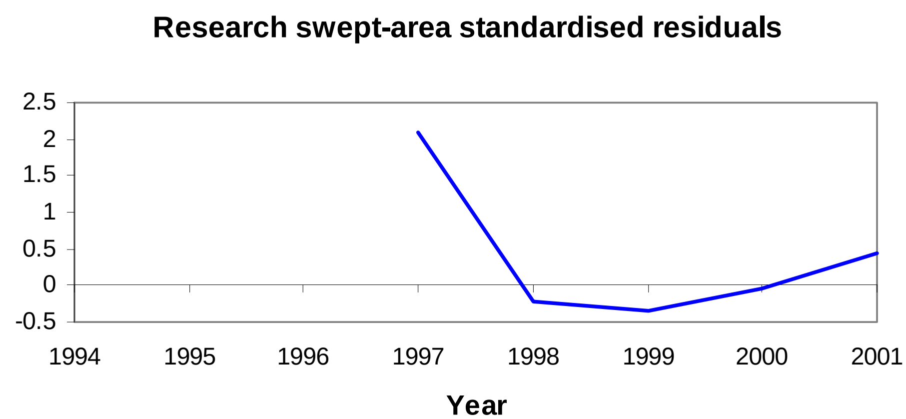


Figure 1. Observed and predicted values for each of the available indices of abundance of Namibian orange roughy for the *Johnies* aggregation when the base case model is fitted to data including the baseline standardised CPUE interpretation.





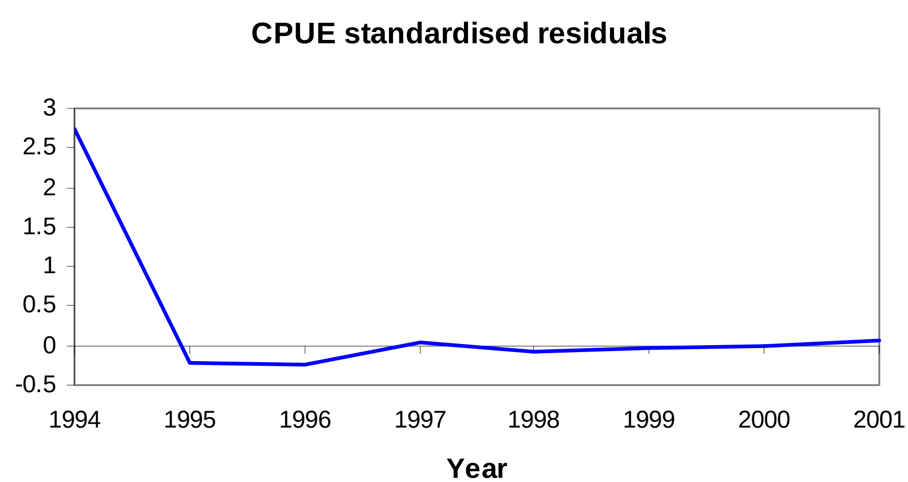


Figure 2. Standardised residuals for each of the available indices of abundance of Namibian orange roughy for the *Johnies* aggregation, when the base case model is fitted to data including the baseline standardised CPUE interpretation.

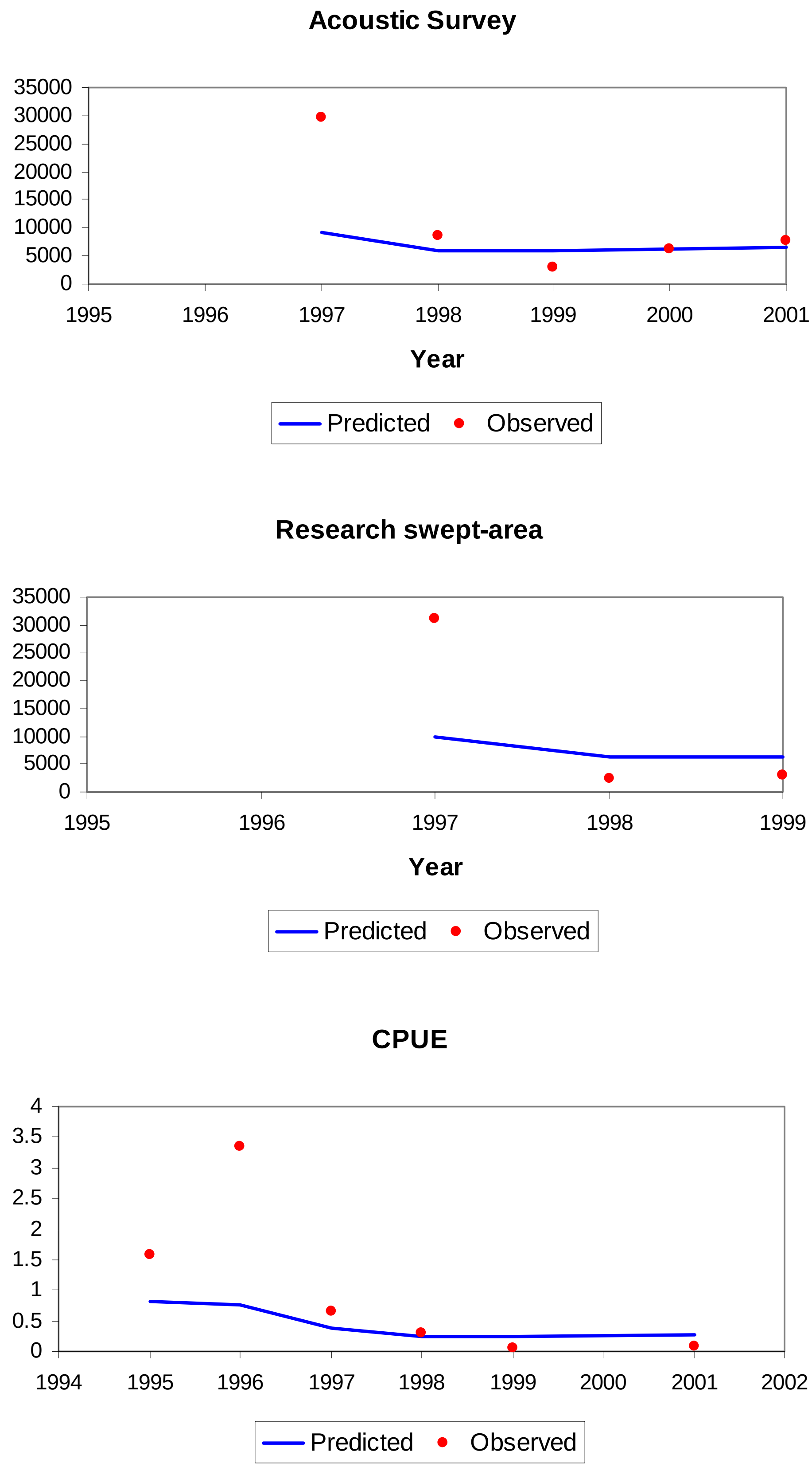
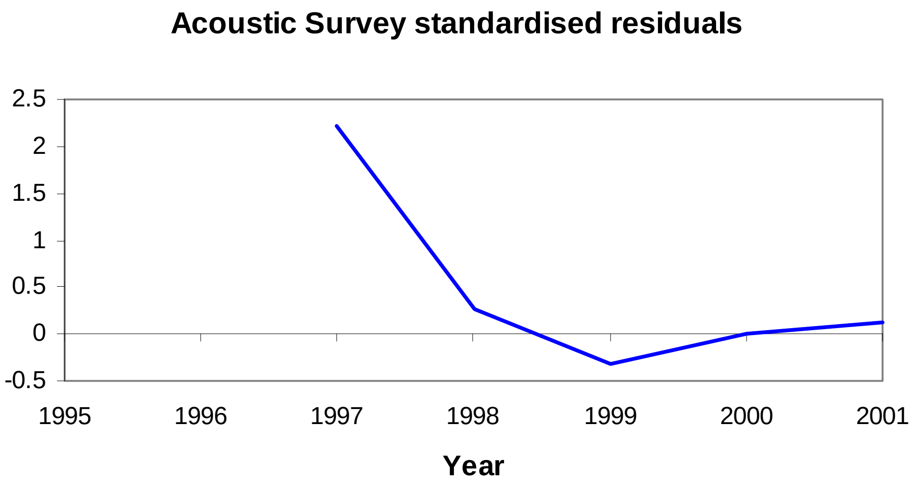
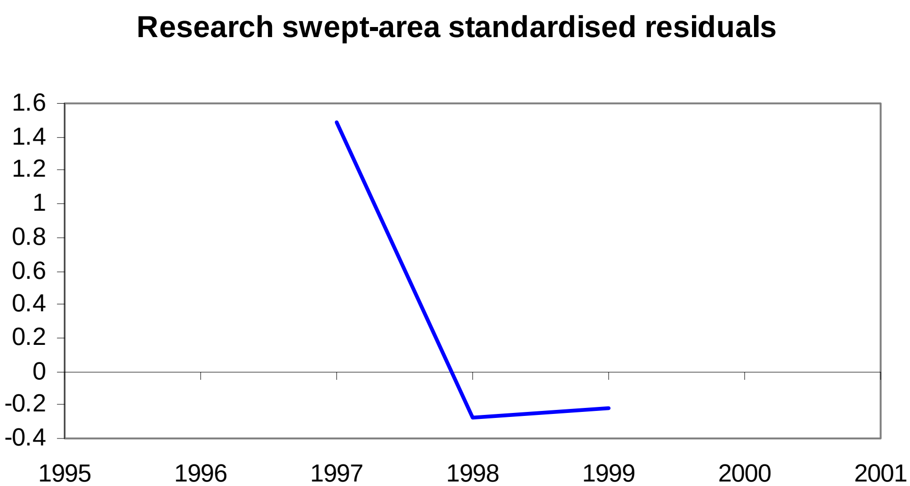


Figure 3. Observed and predicted values for each of the available indices of abundance of Namibian orange roughy for the *Frankies* aggregation, when the base case model is fitted to data including the beaseline standardised CPUE interpretation.





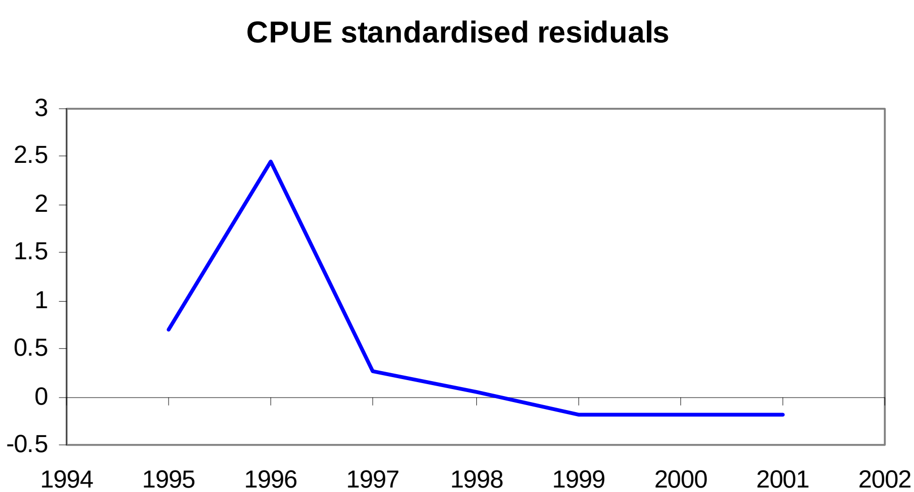
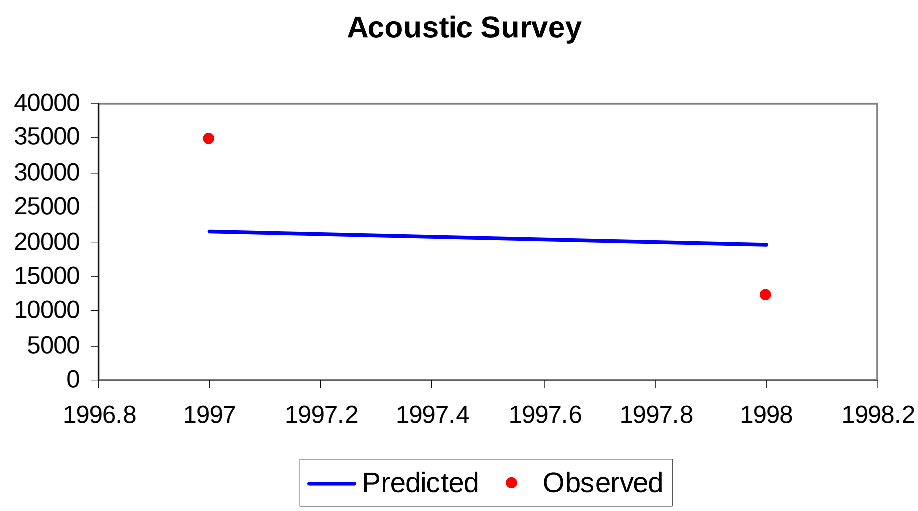


Figure 4. Standardised residuals for each of the available indices of abundance of Namibian orange roughy for the *Frankies* aggregation, when the base case model is fitted to data including the beseline standardised CPUE interpretation.



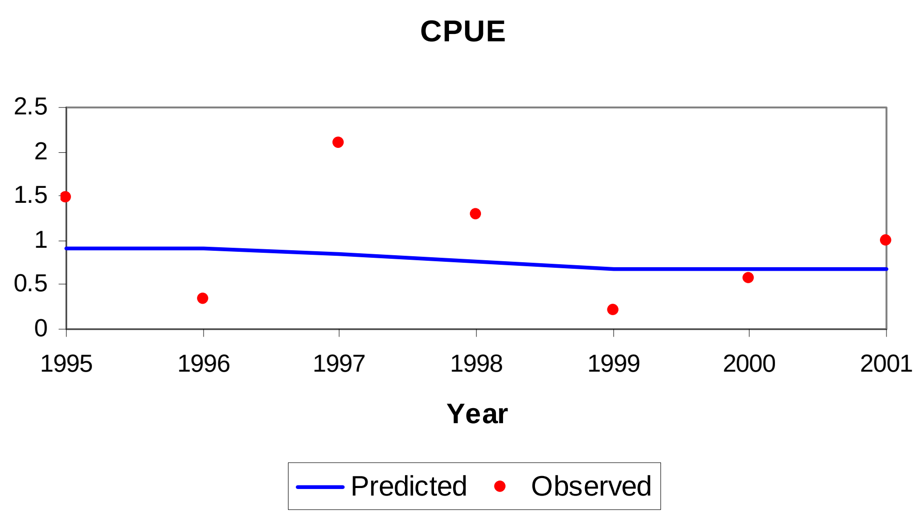
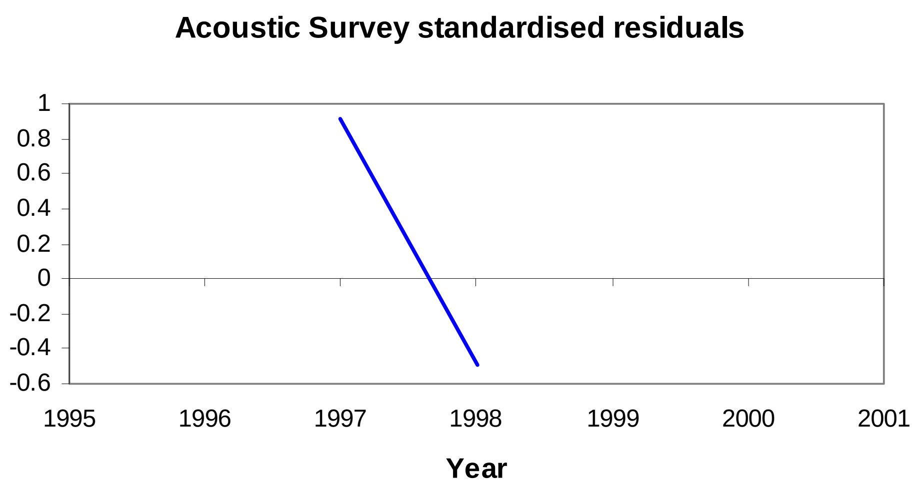


Figure 5. Observed and predicted values for each of the available indices of abundance of Namibian orange roughy for the *Rix* aggregation (there is only one value for the research swept area), when the base case model is fitted to data including the beseline standardised CPUE interpretation.



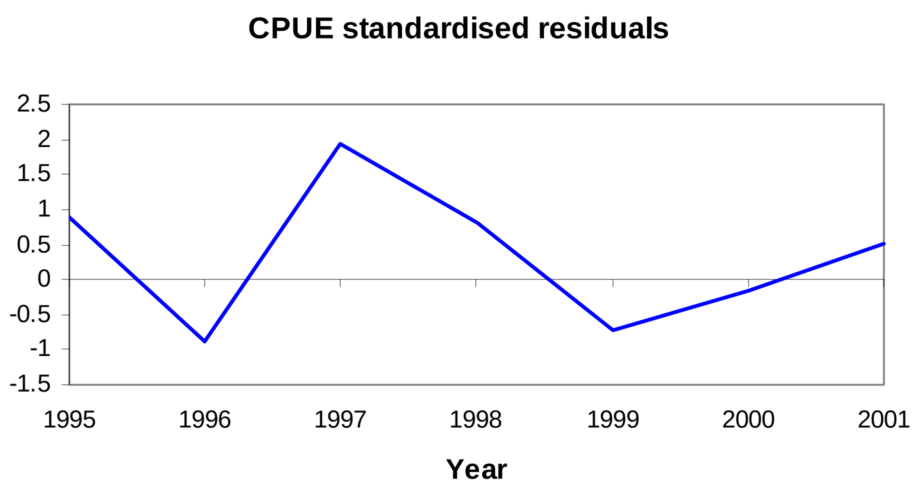
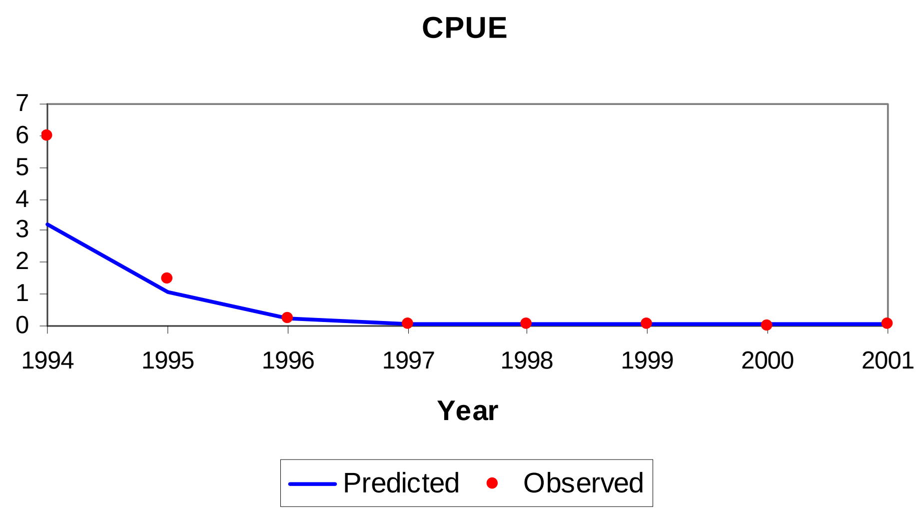


Figure 6. Standardised residuals for each of the available indices of abundance of Namibian orange roughy for the *Rix* aggregation (there is only one value for the research swept area), when the base case model is fitted to data including the baseline standardised CPUE interpretation.



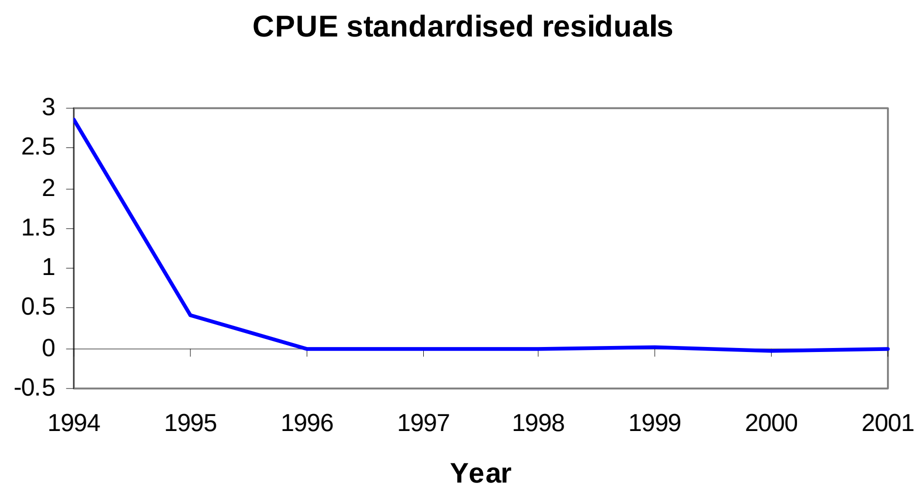


Figure 7. Observed and predicted values as well as standardised residulas for the available baseline CPUE index of abundance of Namibian orange roughy for the *Hotspot* aggregation, when the base case model is fitted.

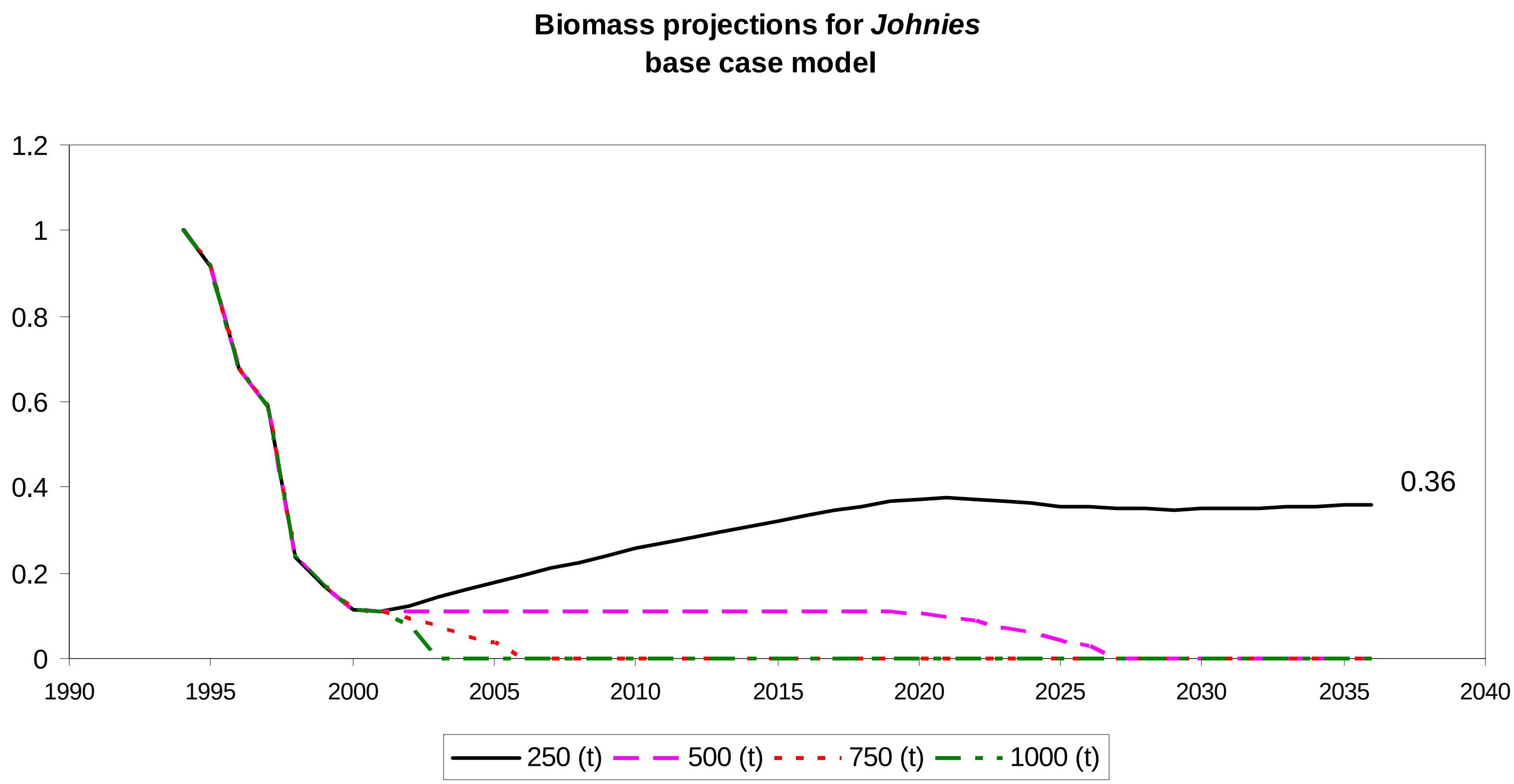


Figure 8. Thirty five year projections of the orange roughy stock for the *Johnies* aggregation under the scenario of the base case model and the baseline CPUE interpretation. Results for various levels of constant catch are shown. The value at the rightmost end of each projection is the value of depletion at that time.

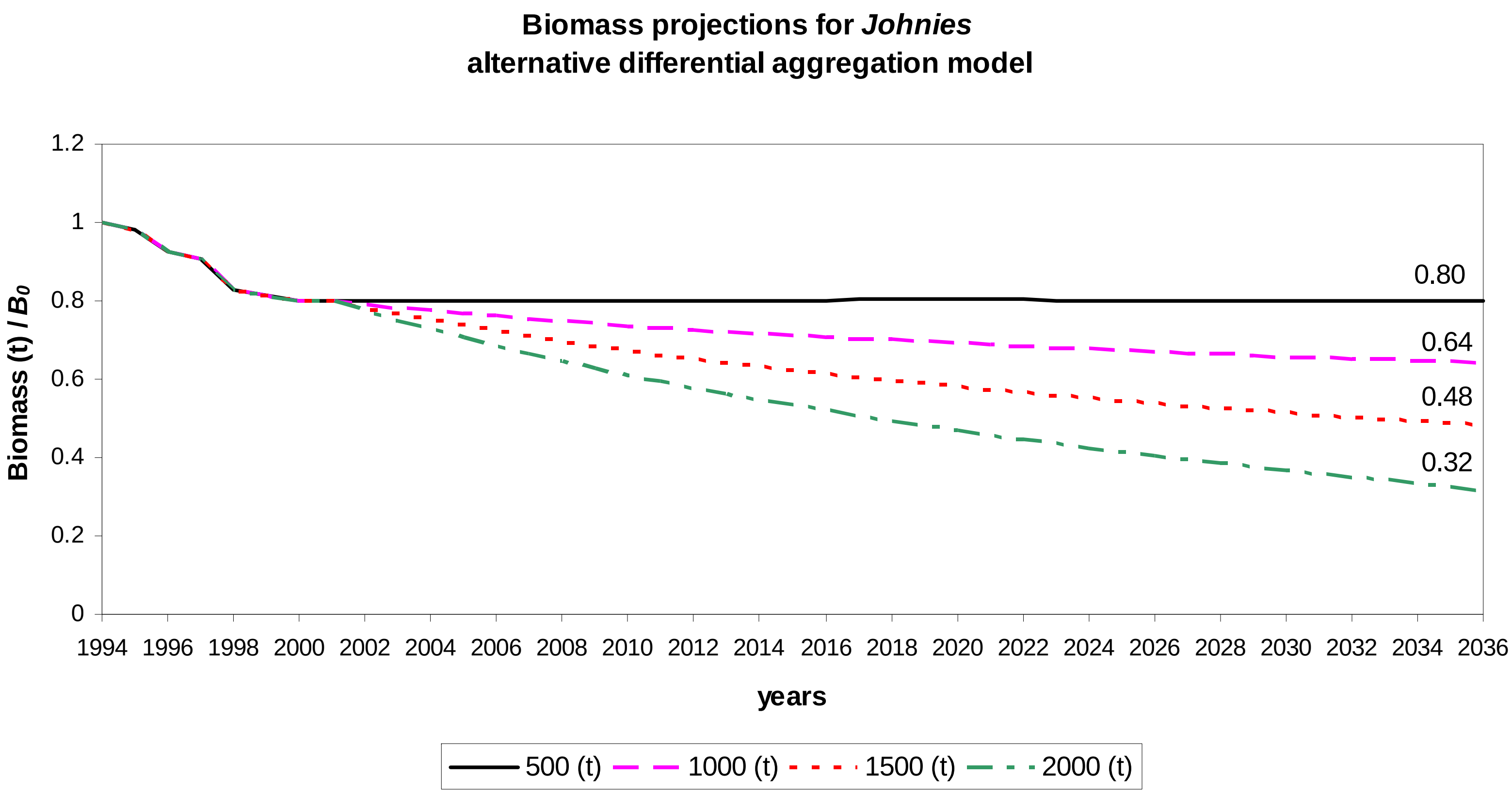


Figure 9. Thirty five year projections of the orange roughy stock for the *Johnies* aggregation under the scenario of the alternative differential aggregation model and the baseline CPUE interpretation. Results for various levels of constant catch are shown. The value at the rightmost end of each projection is the value of depletion at that time.

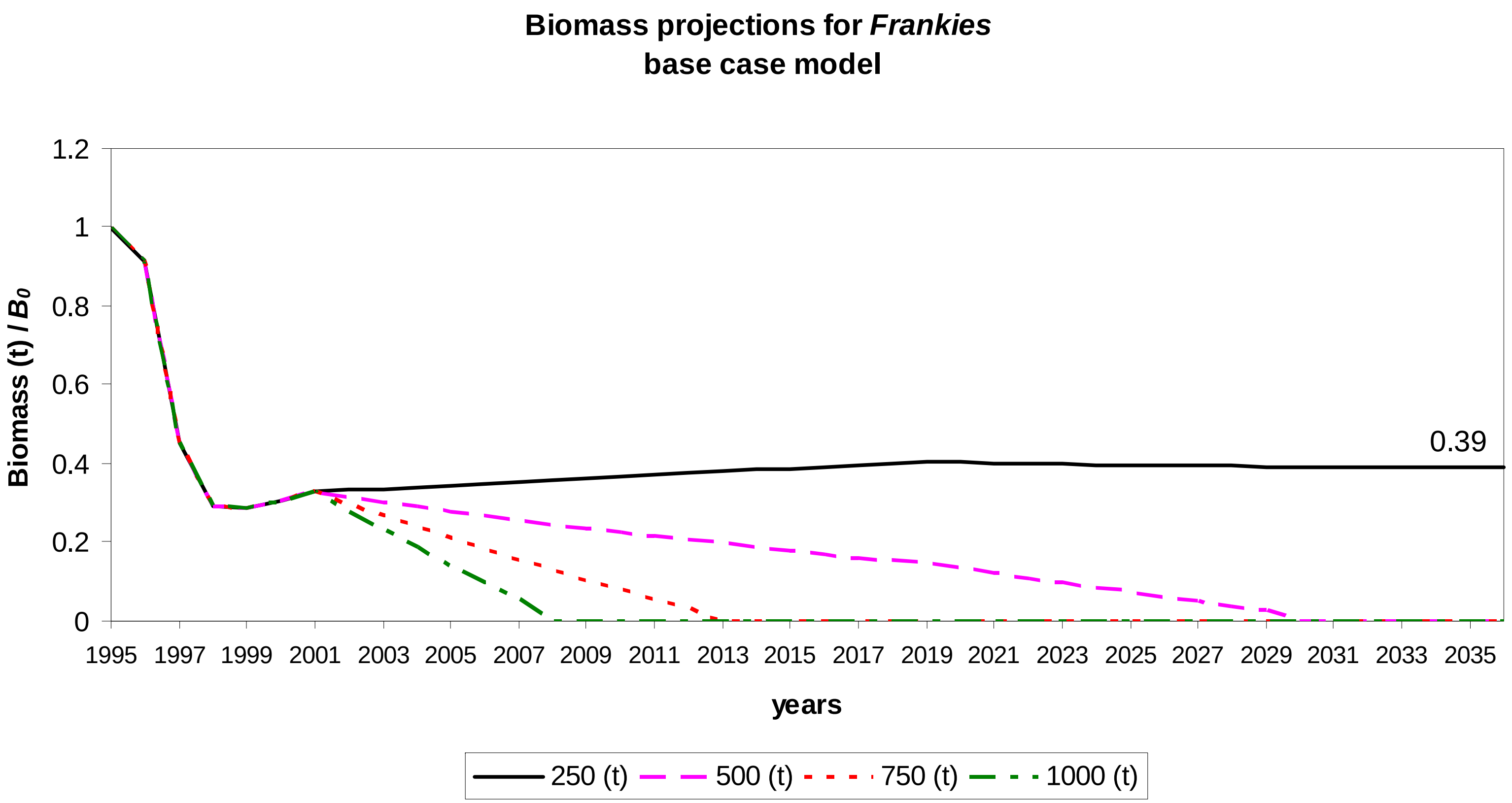


Figure 10. Thirty five year projections of the orange roughy stock for the *Frankies* aggregation under the scenario of the base case model and the baseline CPUE interpretation. Results for various levels of constant catch are shown. The value at the rightmost end of each projection is the value of depletion at that time.

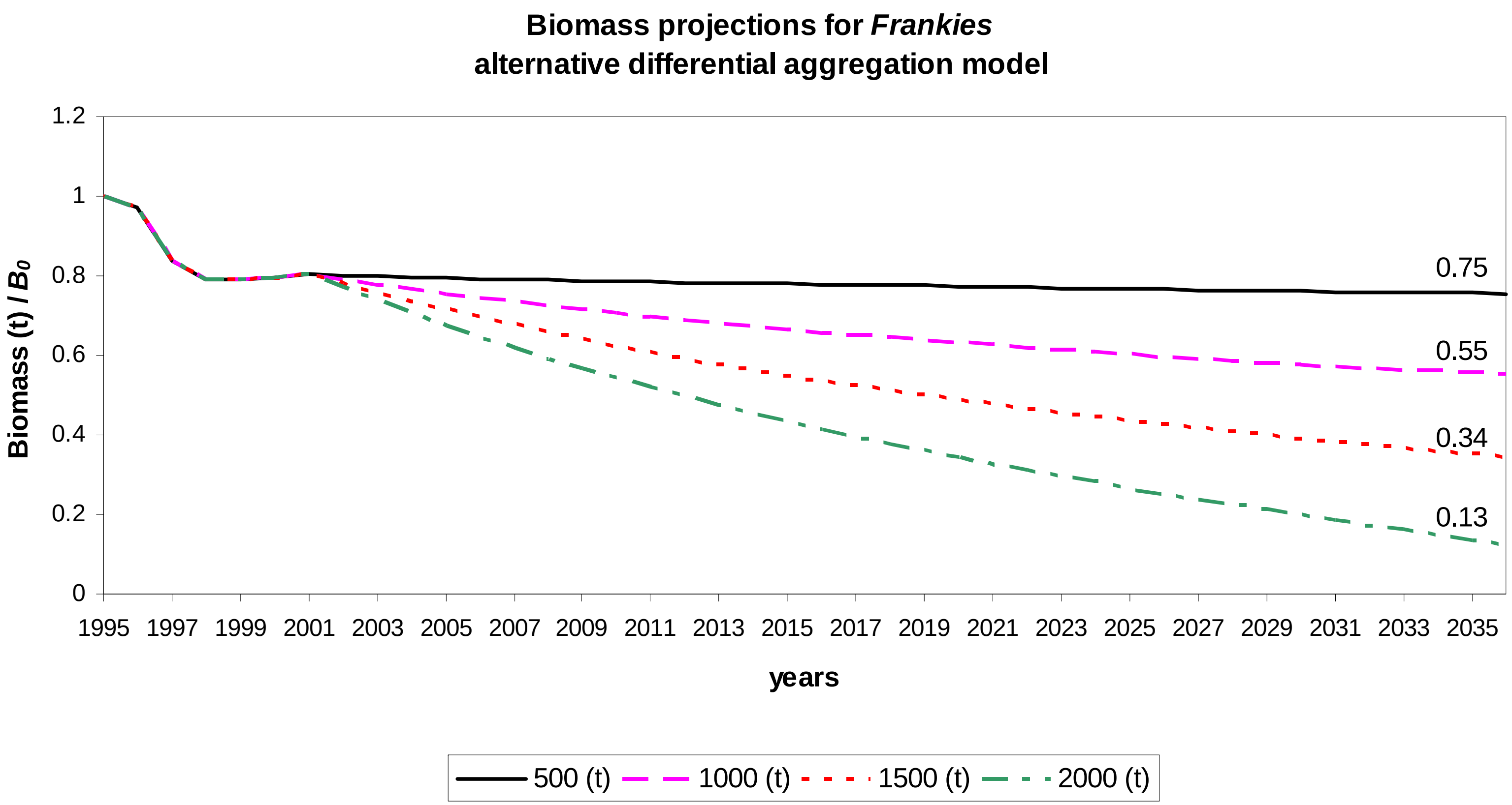


Figure 11. Thirty five year projections of the orange roughy stock for the *Frankies* aggregation under the scenario of the alternative differential aggregation model and the baseline CPUE interpretation. Results for various levels of constant catch are shown. The value at the rightmost end of each projection is the value of depletion at that time.

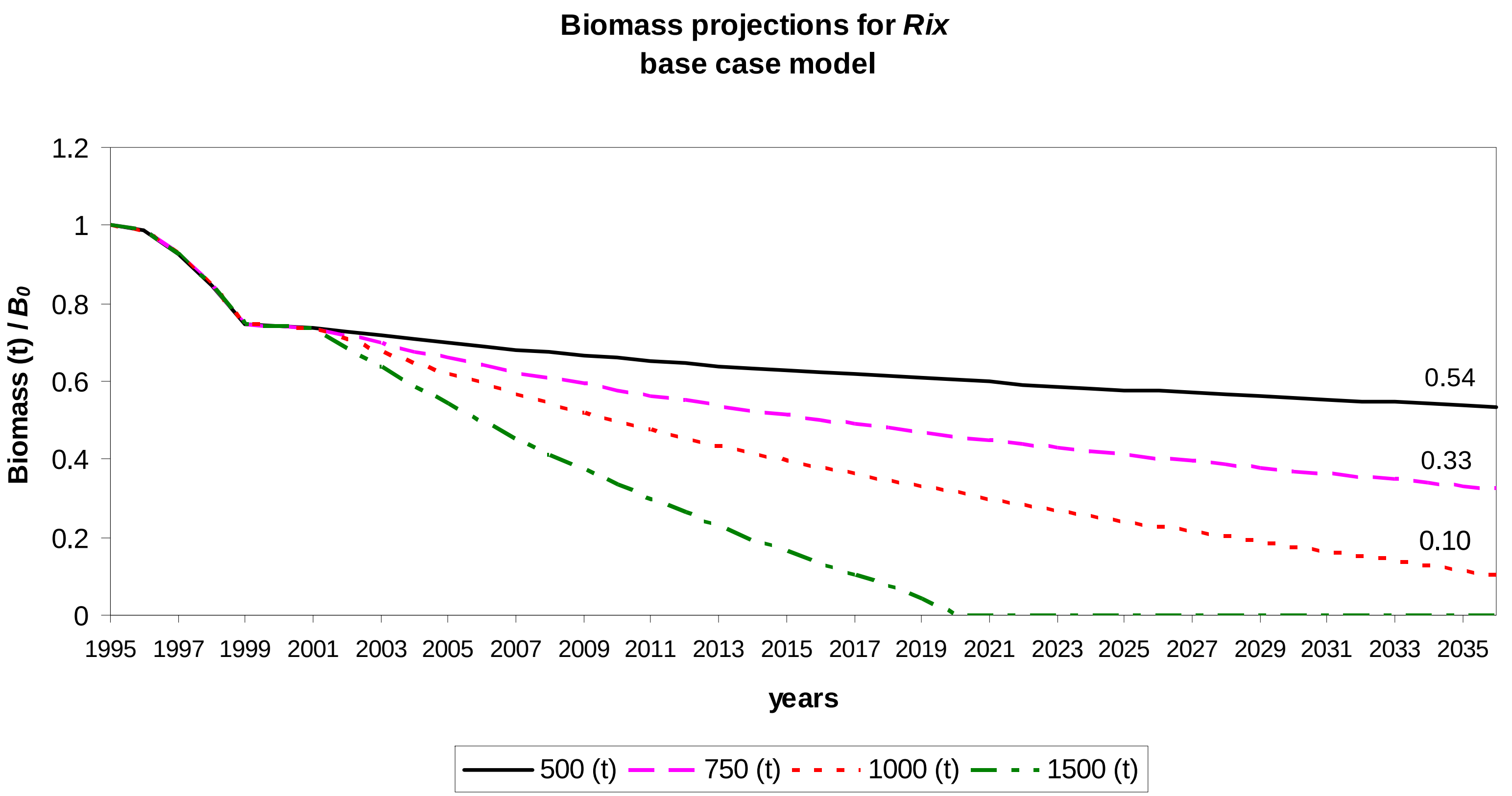


Figure 12. Thirty five year projections of the orange roughy stock for the *Rix* aggregation under the scenario of the base case model and the baseline CPUE interpretation. Results for various levels of constant catch are shown. The value at the rightmost end of each projection is the value of depletion at that time.

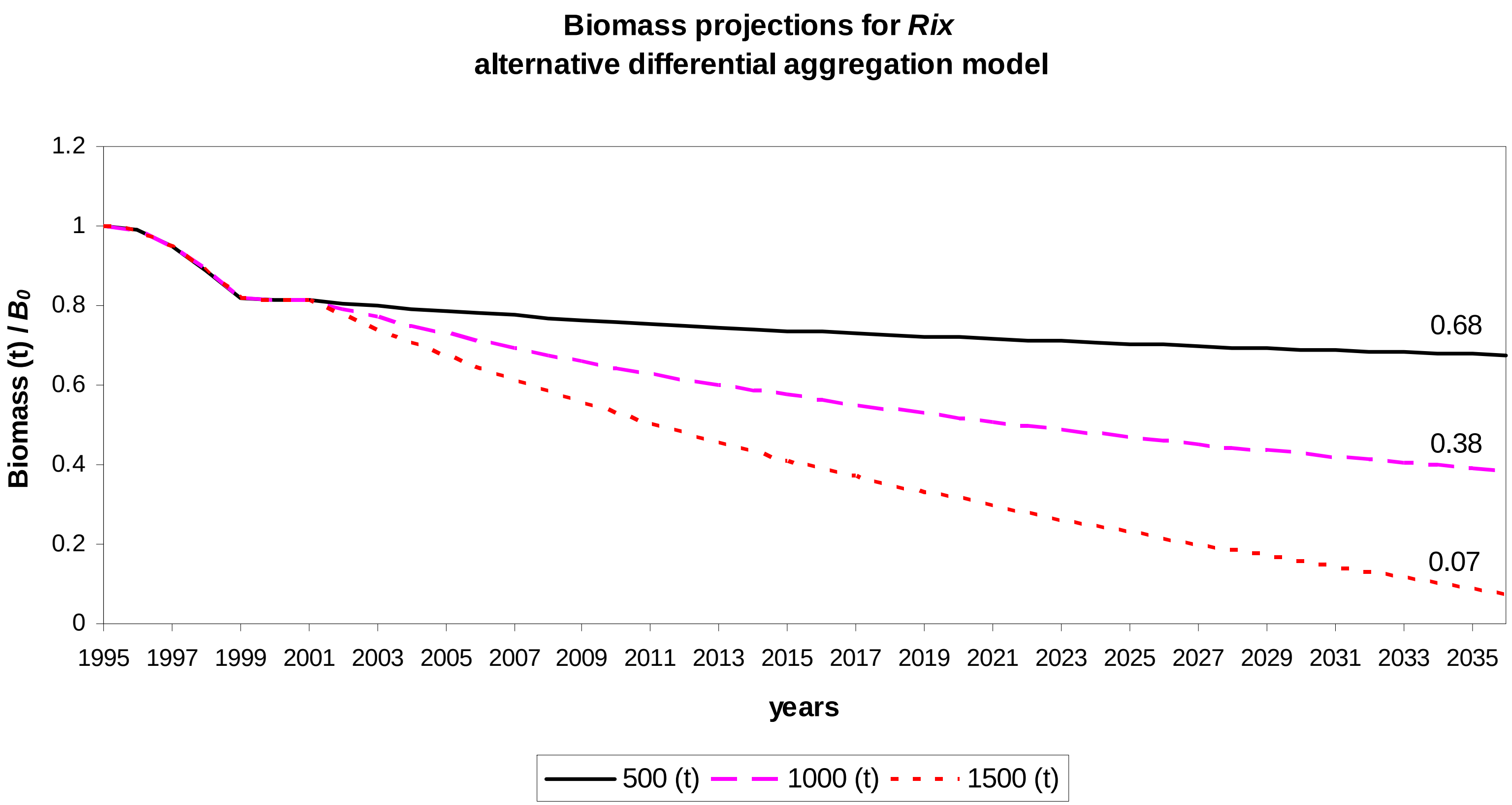


Figure13. Thirty five year projections of the orange roughy stock for the *Rix* aggregation under the scenario of the alternative differential aggregation model and the baseline CPUE interpretaation. Results for various levels of constant catch are shown. The value at the rightmost end of each projection is the value of depletion at that time.

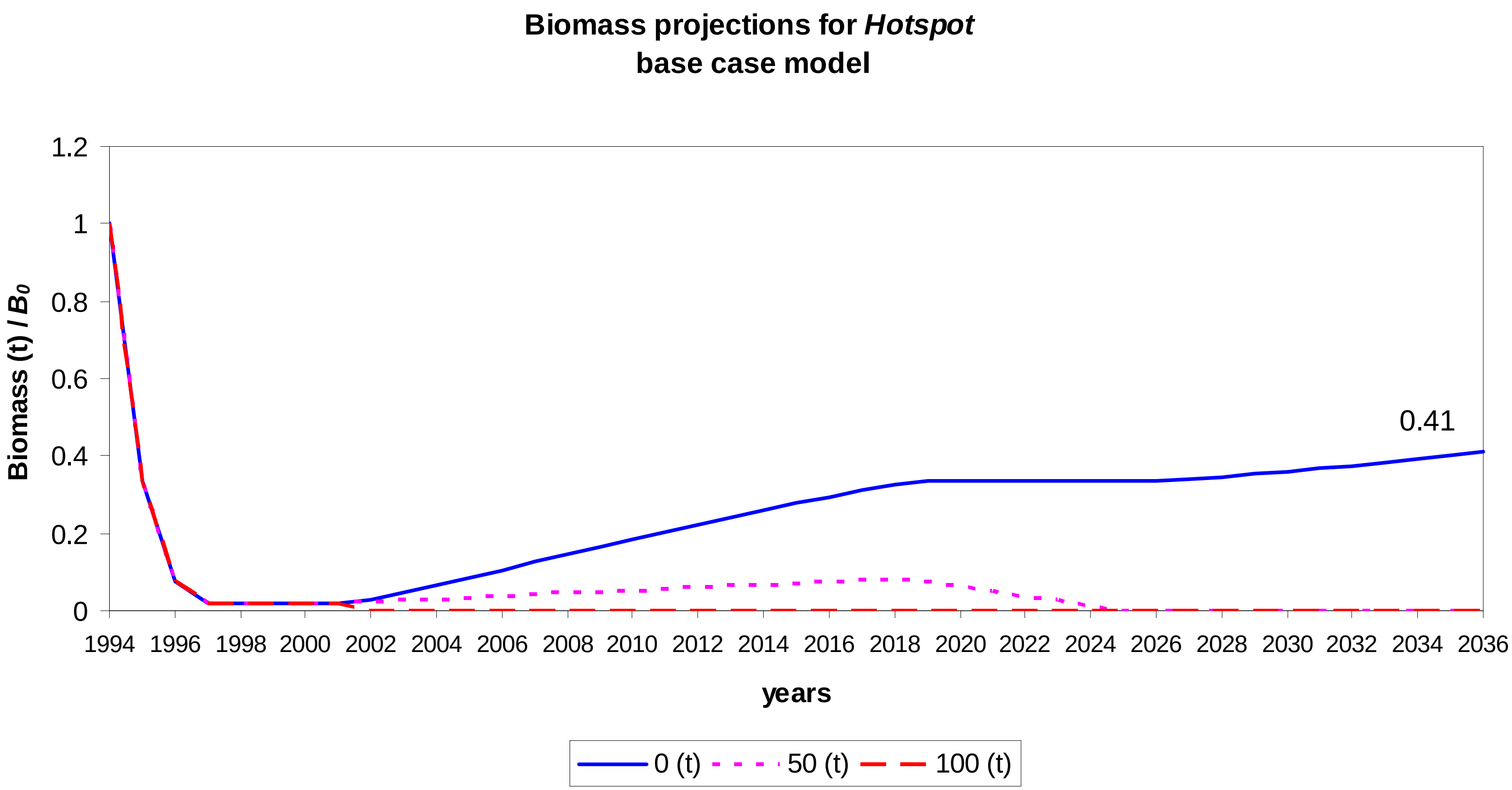


Figure 14. Thirty five year projections of the orange roughy stock for the *Hotspot* aggregation under the scenario of the base case model and the lognormal model fitted to the commercial CPUE data. Results for various levels of constant catch are shown. The value at the rightmost end of each projection is the value of depletion at that time.

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 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:

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

Rearranging equation (A2.12) gives:

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

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:

$$\gamma B_0^{sp} = R_0 = \frac{\alpha B_0^{sp}}{\beta + B_0^{sp}} \qquad \text{(A2.14)}$$

where:

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

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:

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

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.