Namibian orange roughy age-structured production model assessments and projections for 2006

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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 *Frankies* and *Rix* are presently at some 60% of their pre-exploitation level, but that *Hotspot* is perhaps much more depleted at about 10%. Estimates for *Johnies* range between these extremes, depending on the relative weight accorded survey and CPUE indices of abundance. Overall, medium term sustainable yields would seem to be in the vicinity of 1750 to 2 500 tons. Broadly speaking, MSY estimates are some 5–30% 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 (2005), 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 (2006) are considered. All available indices of abundance are taken into account, and deterministic projections under various levels of constant catch are reported.

Data

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

Table 1 shows the total annual (“fishing year”) landed catches of orange roughy for the different aggregations. Landed records split into aggregations were not obtained in time do perform the assessments presented in this paper and therefore the catches for 2004 and 2005 represent captains’ estimates.

The uncorrected and corrected hydroacoustic abundance (I Hampton, pers. commn) and research swept area 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 was 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. In 2004 and 2005 the *Conboroya Quarto* performed the research swept area survey. At the present time it has not been clarified whether the 2004 estimate has been standardised to the *Southern Aquarius* and the 2005 value has not been standardised.

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, 2006) are given in Table 3. There were not enough records for the 2005 fishing year to obtain reliable estimates from the GLM analyses and therefore no 2005 CPUE index is available at this time.

The biological parameters used in the assessment are shown in Table 4. Note that different values are used for the *Hotspot* aggregation, as these are considered more appropriate for the larger orange roughy which occur there.

Methods

Bias Factor Uncertainties

Appendix 1 lists the various bias factor distributions obtained from Boyer and Hampton (2001) that are appropriate to the acoustic estimates for each of the three aggregations where such surveys have taken place. 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 fundamental ASPM methodology applied is as in Brandão and Butterworth (2003) (see Appendix 2), and the basic biological parameter values remain unchanged, except that more appropriate biological parameters for the *Hotspot* aggregation have been used (see Table 4). Brandão and Butterworth (2004) concluded that given the 2002 acoustic survey result at *Frankies* (Table 2), 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, and therefore that the intermittent aggregation model seemed the best basis upon which to provide advice. For this reason, this paper concentrates only on the assessment of the Namibian orange roughy resource under the intermittent model.

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*. Results are for the intermittent aggregation model which includes 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. The chosen values for the 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 remain the same as suggested by Brandão and Butterworth (2003) (viz. μ_x = 0.6 and σ_x = 0.2; these choices ensure that more than 80% of the resource biomass was present at each of *Johnies*, *Frankies* and *Rix* in 1997). As a general sensitivity test, the σ^{CPUE} value is fixed at 0.4 rather than estimated, to offset a possible tendency by the model to underweight the CPUE data. These models (with fixed σ^{CPUE}) are fitted to the baseline CPUE interpretation only (i.e. applied to the standardised CPUE series obtained from the “zero” method).

The stock depletion at the beginning of the fishing year 2005 for *Johnies* is estimated at 10–12% of the pre-exploitation abundance (Table 6). These results are similar to those obtained in the previous year’s assessment when more weight was given to the CPUE index (i.e. fixing the σ^{CPUE}

value to 0.4). In the present assessment, the estimated σ^{CPUE} value is 0.52, i.e. more weight is being given to the CPUE indices than in previous assessments. The proportion of the stock present in *Johnies* is smaller in other years than in 1997 (for which this proportion is 95%), though not by as large an extent as in previous assessments. The reason for these changed results is that now more weight is being given to the CPUE results than the hydroacoustic, with the multiplicative bias q^{AC} for the latter being estimated at 1.88, i.e. much above the median of 1 for the associated "prior", implying that there was severe positive bias in the absolute estimate for the 1997 acoustic survey estimate for Johnies. To show the consequences of this, a further sensitivity was run fixing q^{AC} to 1.07, which is the mean of the estimates of q^{AC} obtained for *Frankies* and R*i*x in the previous assessment. In this case the current depletion estimate becomes 63%, i.e. close to that estimated previously.

The stock depletion at the beginning of the year 2005 for the *Frankies* aggregation is estimated in the region of 64–66% of the pre-exploitation abundance under alternative CPUE interpretations (Table 7). The model estimates that in 1997, 90% of the stock aggregated, while 51% aggregated in 2005.

The stock depletion at the beginning of the year 2005 is estimated at 56–58% of the pre-exploitation biomass for the *Rix* aggregation (Table 8). For most years more than 50% of the stock aggregated in *Rix* prior to 2001. Since 2001, however, less than 50% of the stock has aggregated with only 19% aggregating in 2003 and 30% in 2005. Convergence problems were encountered when the model was fitted to the proportional CPUE interpretation (i.e. applied to the standardised CPUE series obtained from the "proportional" method). Due to the lateness of the acquisition of the data, there was not enough time to try to resolve this issue satisfactorily in the present assessment. Note nevertheless that stock status assessments in the past have been based on results from the "zero" method, as available in this paper.

The stock depletion at the beginning of the year 2005 for the *Hotspot* aggregation is estimated at 8% of the initial biomass. The extent of aggregation estimated varies between 50% and 80%. Problems were encountered with convergence issues for *Hotspot* when fixing the σ^{CPUE} value. Due to the lateness of the acquisition of the data, there was not enough time to try to resolve this issue in the present assessment and therefore no sensitivity results are given for fixed values of σ^{CPUE}.

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 the CPUE data are over-estimating the extent of decline, and therefore that this assessment of the status of the *Hotspot* aggregation may be overly pessimistic.

Figures 1 to 4 show the observed and predicted values for each of the available indices of abundance of orange roughy for each of the aggregations. Results shown are for the intermittent aggregation model including the baseline standardised CPUE interpretation and σ^{CPUE} estimated. For the *Johnies* aggregation, the model does not provide a particularly good fit to the first (1997) observation in the hydroacoustic survey and the research swept area abundance indices, nor the 1994 CPUE index. For the sensitivity (Fig. 1b) which fixes q^{AC} = 1.07, fits to the acoustic and research trawl surveys are generally improved, but that to the CPUE series deteriorates. The fit to the higher research swept area abundance indices for the years 2001, 2002 and 2004 is not very good. For *Frankies* the model struggles somewhat to fit the acoustic index for 1997 and 2002, and the 1997 research swept area index. The fit to the CPUE series is not very good. For *Rix* the model does not fit the high observations in the CPUE series. For *Hotspot* the model fits the CPUE index for the later years reasonably, but not that for the first year.

Figures 5 to 8 show 35-year deterministic projections of the orange roughy stock for each of the aggregations under the intermittent model for the baseline CPUE interpretation and σ^{CPUE} estimated. For the *Johnies* aggregation a 250 t constant catch improves the stock depletion from 11% to 24% whereas a zero constant catch improves the stock depletion after 35-years to 58% of the pre-exploitation abundance. However, if q^{AC} is fixed at 1.07, results are much more optimistic (Fig. 5b). For the *Frankies* aggregation, a constant catch of 500 t makes hardly any change to stock depletion (from 64 to 63%), but this is reduced to 35% of pre-exploitation abundance under a 1 000 t constant catch.

Deterministic projections for the *Rix* aggregation (Figure 7) show a reduction of the stock to 41% (from 58%) of initial biomass under a constant catch of 500 t for 35 years and to 17% under a constant catch of 750 t. For the *Hotspot* aggregation, a constant catch of 50 t improves the stock depletion to 41% from 8% of initial biomass, but to only 17% for a constant catch of 100 t. If no catches are taken for 35-years, the resource improves from a depletion of 8% of initial biomass to 63%.

Conclusions

Table 10 presents a summary based on the baseline results for the intermittent aggregation model. This indicates two of the major aggregations (*Frankies* and *Rix*) to be reasonably healthy and at about 60%'s of their initial abundances, but *Hotspot* at about 10% to be well below MSYL. Estimates for *Johnies* range between these two extremes, with acoustic and swept area survey results favouring the more optimistic interpretation, and CPUE data the more pessimistic. Depending on these alternative interpretations for *Johnies*, the combined MSY estimates range from about 1 600 to 2 100 tons, some 5–30% less than estimated a year previously by Brandão and Butterworth (2005).

Projections using the intermittent aggregation model suggest an appropriate overall annual catch in the medium term to be in the vicinity of 1 750 to 2 500 tons, again depending on the interpretation for *Johnies*. It is important, though, to bear in mind that 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 2005 is incomplete as data were available only until July.

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	430	158	124	129	841
2004*	87	54	13†††	42	191
2005*	10	1	0†††	0	11

* These catches are based on captains' estimates of catches as the land catch records received did not split the catches into the separate aggregations

† Closed to normal commercial fishing

†† Fishery partially reopened since September 2002

††† Closed to normal commercial fishing on 1st August 2004

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*
2004	—	4 066* (0.27)	—	*Conbaroya Quarto*
2005	—	4 817* (0.47)	2 104 (0.31)	*Conbaroya Quarto*

***** The 2005 acoustic index has not been standardised to the *Welwitchia* and at the present time it is not clear whether the 2004 value was so standardised.

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)
2004	—	6 720 (0.41)	—
2005	—	8 667 (0.59)	3 514 (0.43)

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

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*
2004	5 865* (0.73)	—	—	*Conbaroya Quarto*
2005	2 132* (0.64)	—	—	*Conbaroya Quarto*

***** The 2005 swept area index has not been standardised to the *Southern Aquarius* and at the present time it is not clear whether the 2004 value was so standardised.

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 (2002b) 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	"Proportional" method
1994	5.756	7.627
1995	0.868	1.151
1996	1.218	1.614
1997	1.608	0.294
1998	0.587	0.107
1999	0.261	0.048
2000	0.224	0.041
2001	0.126	0.023
2002	0.158	0.029
2003	0.134	0.024
2004	0.059	0.042

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

Year	"Zero" method	"Proportional" method
1995	1.362	7.461
1996	4.305	1.447
1997	1.361	0.457
1998	0.649	0.218
1999	0.292	0.104
2000	—	0.050
2001	0.432	0.172
2002	0.151	0.071
2003	0.428	0.015
2004	0.020	0.003

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 (2002b) 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	"Proportional" method
1995	0.956	3.116
1996	0.717	2.337
1997	4.709	2.547
1998	2.042	1.105
1999	0.404	0.218
2000	0.419	0.226
2001	0.300	0.162
2002	0.300	0.162
2003	0.154	0.083
2004	—	0.044

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 and there are data available for all years, the different methods of dealing with zero cells need not be considered.

Year	"Zero" method
1994	5.782
1995	2.463
1996	0.871
1997	0.314
1998	0.493
1999	0.261
2000	0.102
2001	0.167
2002	0.352
2003	0.093
2004	0.101

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	
	***Johnies*, *Frankies* and *Rix* aggregations**	***Hotspot* aggregation**
von Bertalanffy growth		
ℓ_∞ (cm)	29.5	37.2
κ (yr^{-1})	0.069	0.065
t_0 (yr)	-2.0	-0.5
Weight length relationship		
a (gm/cm^b)	0.1354	0.1354
b	2.565	2.565
Age at maturity (yr)	23	29
Steepness parameter (h)	0.75	0.75

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	—	$\sigma_{1997}^{AC} = 0.31$
1998	—	$\sigma_{1998}^{AC} = 0.44$
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	—	$\sigma_{2003}^{AC} = 0.35$
2004	—	$\sigma_{2004}^{AC} = 0.35$
2005	—	$\sigma_{2005}^{AC} = 0.55$
q^{AC}-random ***Rix*** 1997	—	$\sigma_{1997}^{AC} = 0.25$
1998	—	$\sigma_{1998}^{AC} = 0.26$
2003	—	$\sigma_{2003}^{AC} = 0.59$
2005	—	$\sigma_{2005}^{AC} = 0.37$

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 2002b and 2006). 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_{2005}) and stock depletion (B_{2005}/B_0) at the beginning of the year 2005, 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_{2005}), 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. See text for motivation of sensitivity which fixes the value of q^{AC}.

Parameter estimates	**Intermittent aggregation ("zero" method) σ^{CPUE} estimated**	**Intermittent aggregation ("zero" method) σ^{CPUE} fixed at 0.4**	**Intermittent aggregation ("proportional" method)**	**Intermittent aggregation ("zero" method) σ^{CPUE} estimated, q^{AC} fixed**
B_0	18 259	18 034	18228	40591
M	0.035	0.034	0.037	0.045
B_{2005}	2 050	1 710	2229	25569
B_{2005}/B_0	0.112	0.095	0.122	0.630
q^{AC}	1.882	1.902	1.921	**1.070**
q^{SA}	3.624	3.769	4.129	0.906
q^{CPUE} ($\times 10^5$)	17.780	19.686	5.990	4.090
σ^{CPUE}	0.515	**0.400**	0.944	0.902
x_{1994}	0.829	0.857	0.815	0.792
x_{1995}	0.405	0.332	0.715	0.641
x_{1996}	0.590	0.535	0.756	0.690
x_{1997}	0.950	0.947	0.944	0.947
x_{1998}	0.543	0.563	0.463	0.301
x_{1999}	0.336	0.371	0.239	0.139
x_{2000}	0.646	0.688	0.551	0.237
x_{2001}	0.791	0.782	0.793	0.466
x_{2002}	0.754	0.762	0.734	0.442
x_{2003}	0.180	0.223	0.134	0.046
x_{2004}	0.414	0.377	0.636	0.244
x_{2005}	0.460	0.499	0.400	0.190
MSY	291	279	307	838
MSYL	0.249	0.249	0.249	0.247
-ln *L*: Total	11.741	11.923	16.133	14.312
-ln *L*: CPUE	-1.790	-3.889	4.862	4.363
-ln *L*: Acoustic survey	6.486	6.667	6.555	1.708
-ln *L*: Sweptarea	6.171	8.093	3.200	4.720
ln *L*: year bias *x*	-1.705	-1.801	-1.139	6.285
-ln *L*: prior on *M*	-2.183	-2.057	-2.400	-2.879
-ln *L*: prior on q^{AC}	4.762	4.910	5.054	0.115

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 2002b and 2006). The estimates shown are for the pre-exploitation orange roughy (recruited=mature) abundance (B_0), the natural mortality (M), the current stock biomass (B_{2005}) and stock depletion (B_{2005}/B_0) at the beginning of the year 2005, 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_{1995}, …, x_{2005}), 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	Intermittent aggregation ("zero" method) σ^{CPUE} estimated	Intermittent aggregation ("zero" method) σ^{CPUE} fixed at 0.4	Intermittent aggregation ("proportional" method)
B_0	34 823	36745	35 029
M	0.048	0.045	0.048
B_{2005}	22 389	24098	22 608
B_{2005}/B_0	0.643	0.656	0.645
q^{AC}	1.022	1.140	1.023
q^{SA}	0.924	0.806	0.937
q^{CPUE} ($\times 10^5$)	3.980	4.280	1.283
σ^{CPUE}	1.188	**0.400**	1.796
x_{1995}	0.692	0.746	0.748
x_{1996}	0.753	0.903	0.713
x_{1997}	0.895	0.896	0.891
x_{1998}	0.357	0.426	0.340
x_{1999}	0.174	0.185	0.169
x_{2000}	—	—	0.358
x_{2001}	0.404	0.362	0.399
x_{2002}	0.837	0.543	0.847
x_{2003}	0.514	0.436	0.477
x_{2004}	0.292	0.095	0.315
x_{2005}	0.508	0.451	0.504
MSY	762	764	769
MSYL	0.246	0.247	0.246
-ln L: Total	6.174	20.730	10.854
-ln L: CPUE	6.048	10.824	10.854
-ln L: Acoustic survey	1.833	7.854	1.657
-ln L: Sweptarea	2.120	2.711	1.993
ln L: year bias x	-0.924	1.918	-0.746
-ln L: prior on M	-2.931	-2.887	-2.932
-ln L: prior on q^{AC}	0.027	0.310	0.029

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 by the “zero” method (Brandão and Butterworth 2002b and 2006). The estimates shown are for the pre-exploitation orange roughy (recruited=mature) abundance (B_0), the natural mortality (M), the current stock biomass (B_{2005}) and stock depletion (B_{2005}/B_0) at the beginning of the year 2005, 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_{1995}, …, x_{2005}), 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.

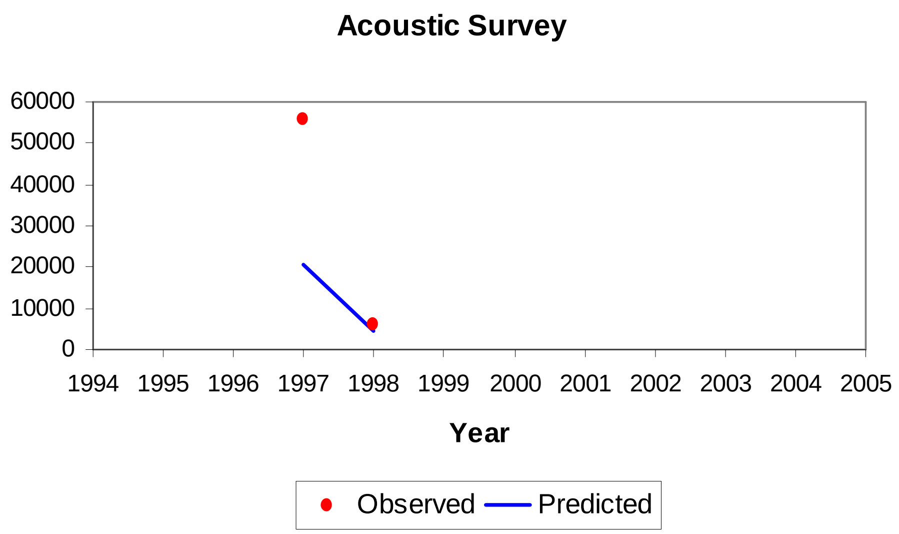
Parameter estimates	**Intermittent aggregation (“zero” method) σ^{CPUE} estimated**	**Intermittent aggregation (“zero” method) σ^{CPUE} fixed at 0.4**
B_0	20 919	19 817
M	0.046	0.045
B_{2005}	12 180	11 045
B_{2005}/B_0	0.582	0.557
q^{AC}	1.183	1.229
q^{SA}	0.177	0.222
q^{CPUE} ($\times 10^5$)	9.050	1.090
σ^{CPUE}	0.479	**0.400**
x_{1995}	0.581	0.516
x_{1996}	0.489	0.416
x_{1997}	0.937	0.943
x_{1998}	0.765	0.790
x_{1999}	0.490	0.433
x_{2000}	0.505	0.450
x_{2001}	0.393	0.338
x_{2002}	0.389	0.334
x_{2003}	0.193	0.175
x_{2004}	—	—
x_{2005}	0.302	0.319
MSY	440	411
MSYL	0.246	0.247
-ln *L*: Total	-3.436	-3.385
-ln *L*: CPUE	-2.118	-3.523
-ln *L*: Acoustic survey	2.431	2.494
ln *L*: year bias *x*	-1.309	-0.116
-ln *L*: prior on *M*	-2.899	-2.885
-ln *L*: prior on q^{AC}	0.459	0.645

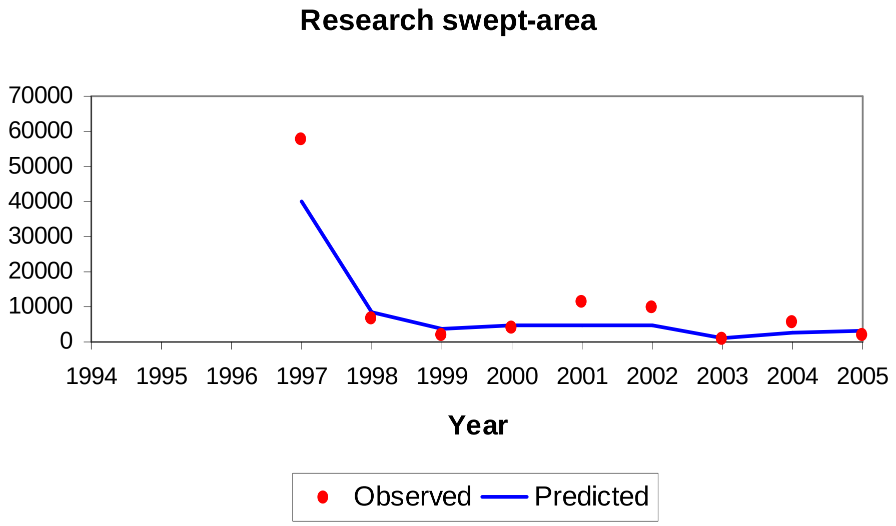
Table 9. Estimates obtained when various models are fitted to the available index of Namibian orange roughy for the *Hotspot* aggregation, where the standardised CPUE series are equivalent to the "zero" method as there are no gaps in the data (Brandão and Butterworth 2002b and 2006). The estimates shown are for the pre-exploitation orange roughy (recruited=mature) abundance (B_0), the natural mortality (M), the current stock biomass (B_{2005}) and stock depletion (B_{2005}/B_0) at the beginning of the year 2005, 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_{2004}), 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	Intermittent aggregation σ^{CPUE} estimated
B_0	4 182
M	0.050
B_{2005}	320
B_{2005}/B_0	0.076
q^{CPUE} ($\times 10^5$)	100.0
σ^{CPUE}	0.379
x_{1994}	0.796
x_{1995}	0.766
x_{1996}	0.717
x_{1997}	0.646
x_{1998}	0.681
x_{1999}	0.630
x_{2000}	0.528
x_{2001}	0.586
x_{2002}	0.656
x_{2003}	0.516
x_{2004}	0.527
x_{2005}	—
MSY	100
MSYL	0.240
-ln *L*: Total	-14.362
-ln *L*: CPUE	-5.174
ln *L*: year bias *x*	-6.243
-ln *L*: prior on *M*	-2.945

Table 10. Summary of deterministic projection information, giving MSY estimates and approximate medium term sustainable yield (SY) estimates based upon Figs. 5–8, for the intermittent aggregation model. The SY estimates reflect depletion to about 0.4 after 35 years for resources estimated to be above MSYL, and maintaining current abundance for those below MSYL. Values in parentheses reflect results given a year previously in Brandão and Butterworth (2005).

	Current depletion B_{2005}/B_0 (B_{2004}/B_0)	**Intermittent aggregation model**	
		MSY	**SY**
Johnies	0.11 (0.60)	291 (811)	250 (1 000)
***Johnies* (*q^{AC}* fixed)**	0.63 (0.60)	838 (811)	1 000 (1 000)
Frankies	0.64 (0.63)	762 (755)	900 (900)
Rix	0.58 (0.65)	440 (557)	500 (700)
Hotspot	0.08 (0.04)	100 (91)	100 (50)
Total		1 593 (2 214)	1 750 (2 650)
Total (*q^{AC}* fixed for Johnies)		2 140 (2 214)	2 500 (2 650)





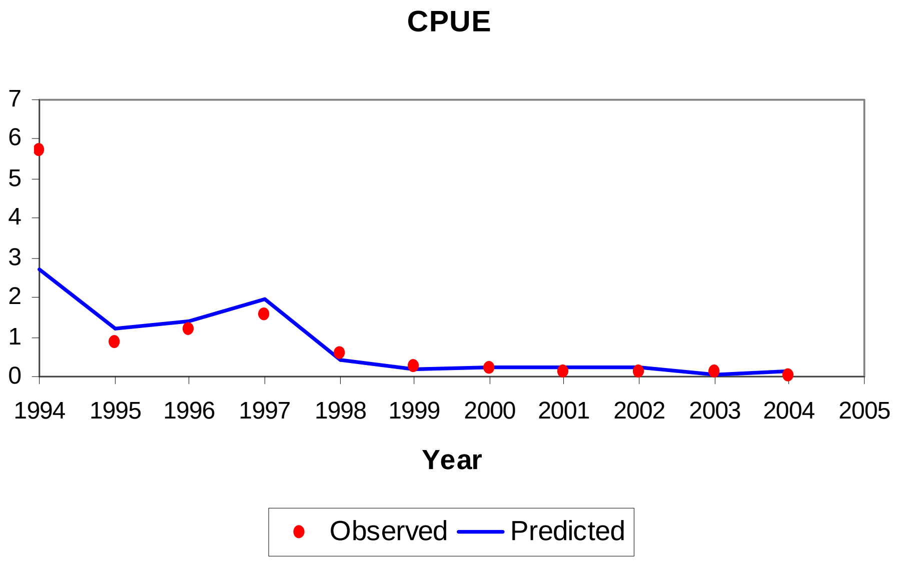
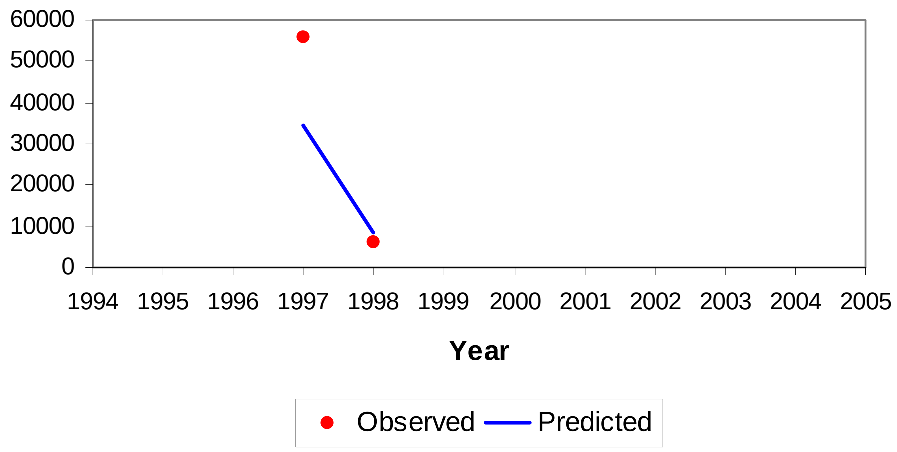
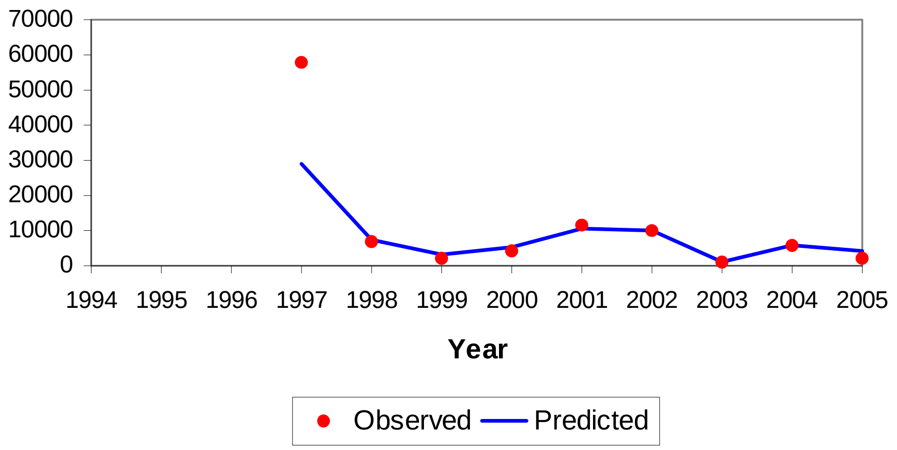


Figure 1a. Observed and predicted values for each of the available indices of abundance of Namibian orange roughy for the *Johnies* aggregation when the intermittent aggregation model is fitted to data including the baseline (i.e. "zero" method) CPUE interpretation and σ^{CPUE} is estimated.

Acoustic Survey



Research swept-area



CPUE

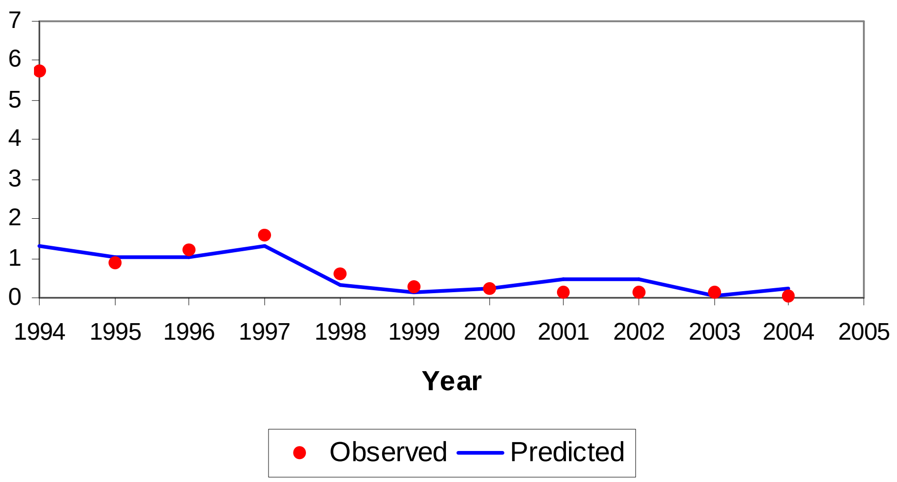


Figure 1b. Observed and predicted values for each of the available indices of abundance of Namibian orange roughy for the *Johnies* aggregation when the intermittent aggregation model is fitted to data including the baseline (i.e. "zero" method) CPUE interpretation, σ^{CPUE} is estimated and q^{AC} is fixed at 1.07 which is the mean of the estimates of q^{AC} obtained for *Frankies* and R*ix* in the previous assessment.

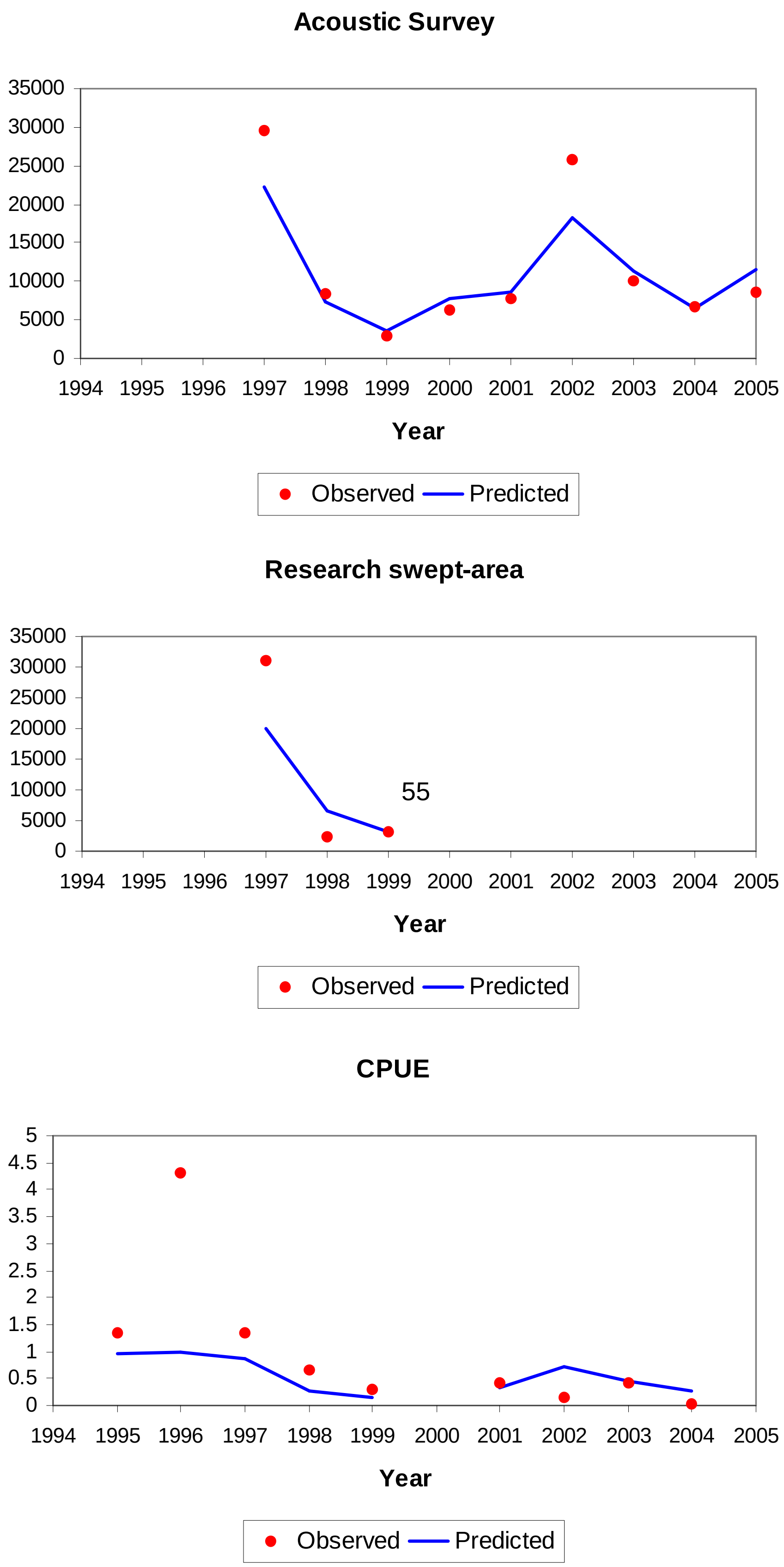


Figure 2. Observed and predicted values for each of the available indices of abundance of Namibian orange roughy for the *Frankies* aggregation when the intermittent aggregation model is fitted to data including the baseline (i.e. “zero” method) CPUE interpretation and σ^{CPUE} is estimated.

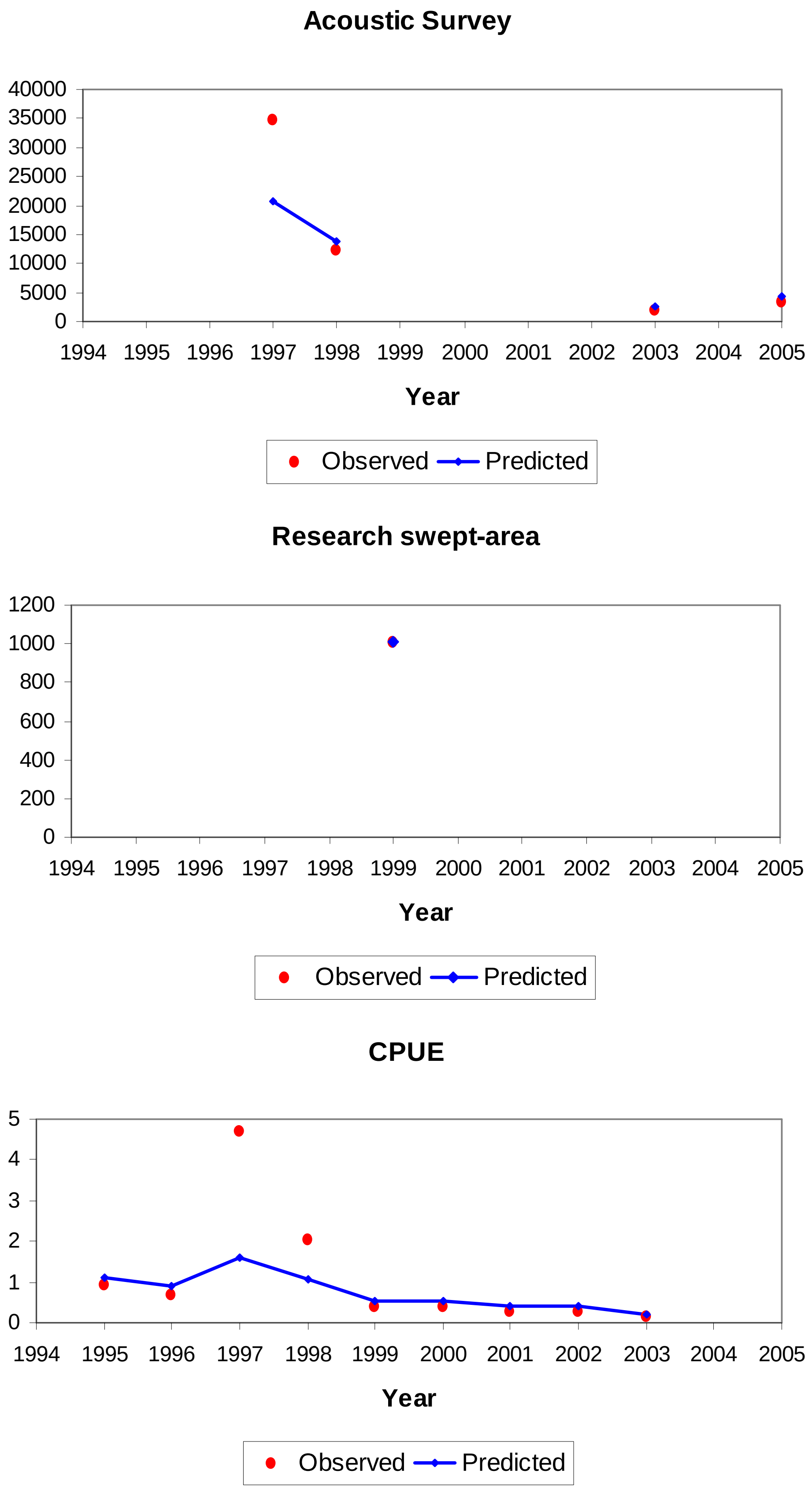


Figure 3. Observed and predicted values for each of the available indices of abundance of Namibian orange roughy for the *Rix* aggregation when the intermittent aggregation model is fitted to data including the baseline (i.e. “zero” method) CPUE interpretation and σ^{CPUE} is estimated. Note that given only one research swept area estimate, the model estimates the corresponding q^{SA} value so that the observed and predicted values match exactly.

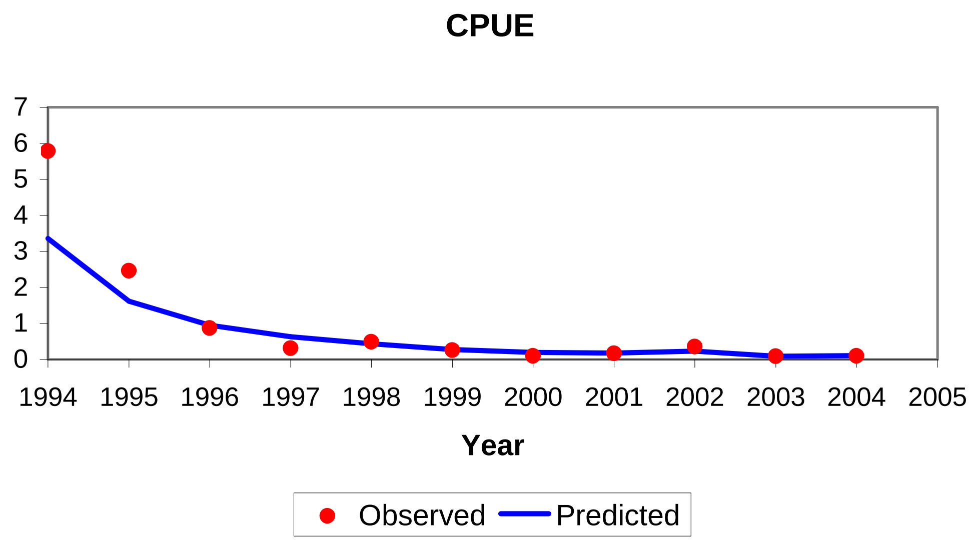


Figure 4. Observed and predicted values for the available index of abundance of Namibian orange roughy for the *Hotspot* aggregation when the intermittent aggregation model is fitted to the data.

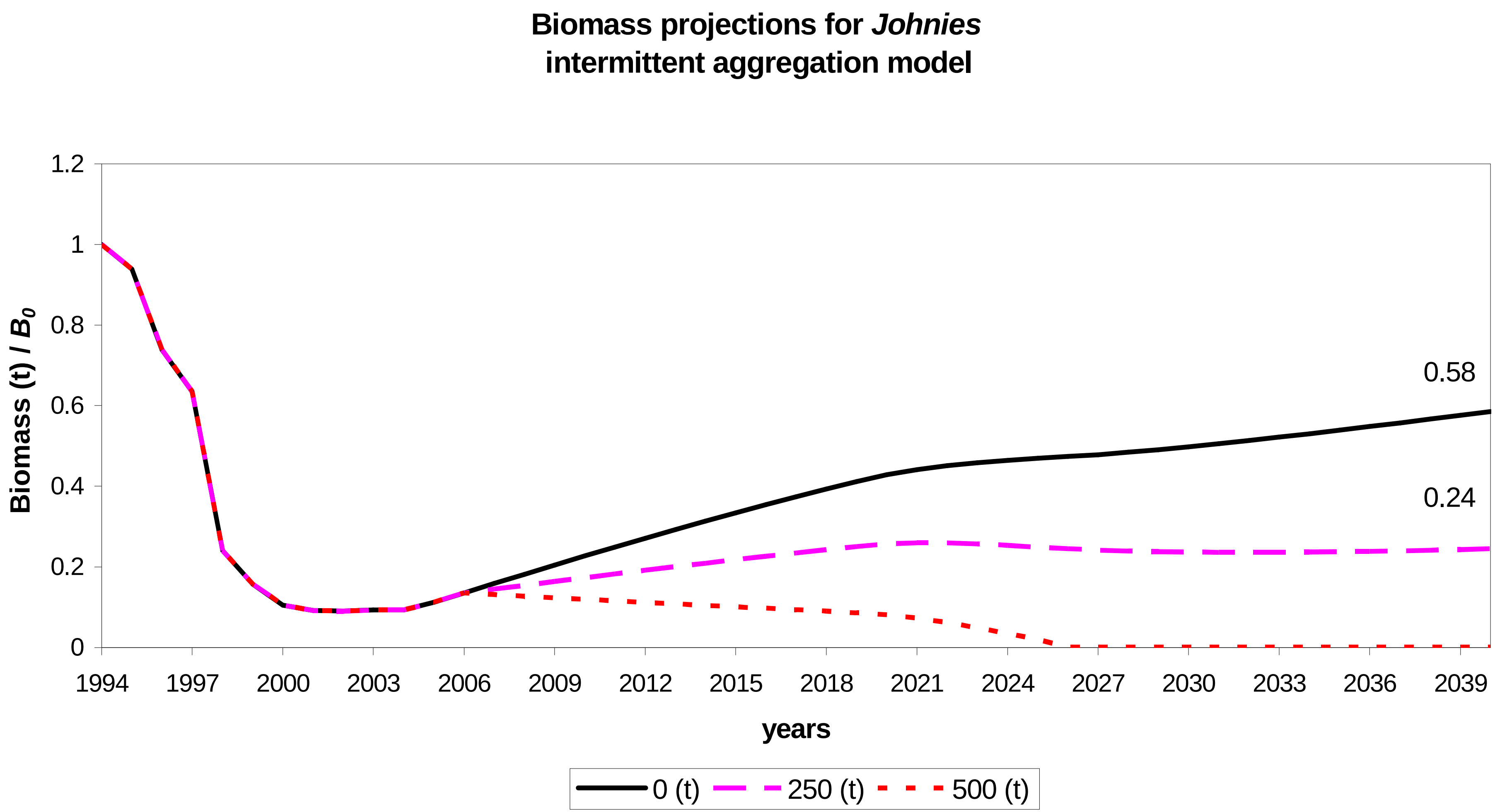


Figure 5a. Thirty five year projections of the orange roughy stock for the *Johnies* aggregation under the scenario of the intermittent aggregation model, the "zero" method CPUE scenario and σ^{CPUE} estimated. Results for various levels of future constant catch are shown. The figure at the right end of a trajectory is the stock depletion after 35 years.

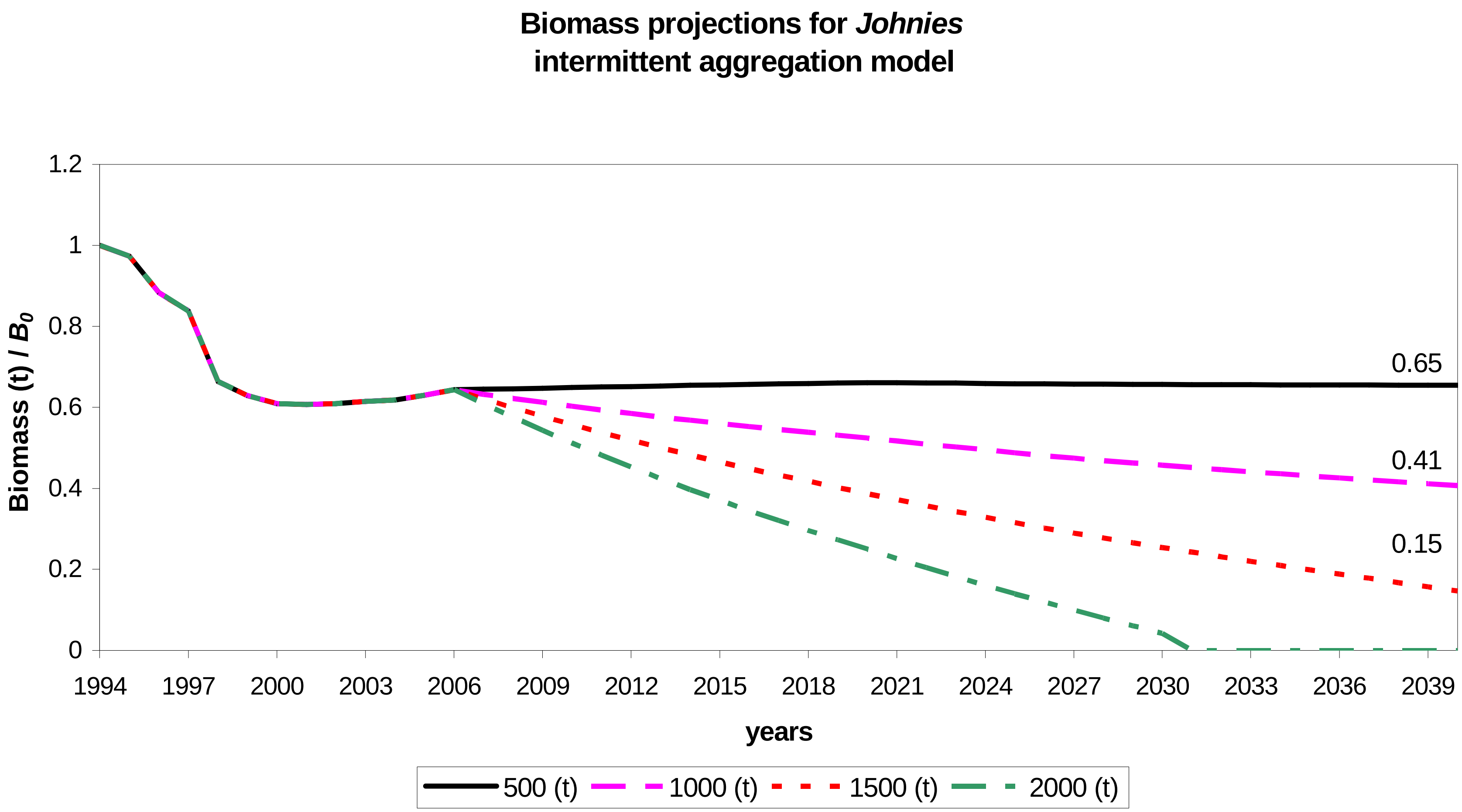


Figure 5b. Thirty five year projections of the orange roughy stock for the *Johnies* aggregation under the scenario of the intermittent aggregation model, the "zero" method CPUE scenario, σ^{CPUE} estimated and q^{AC} fixed at 1.07. Results for various levels of future constant catch are shown. The figure at the right end of a trajectory is the stock depletion after 35 years.

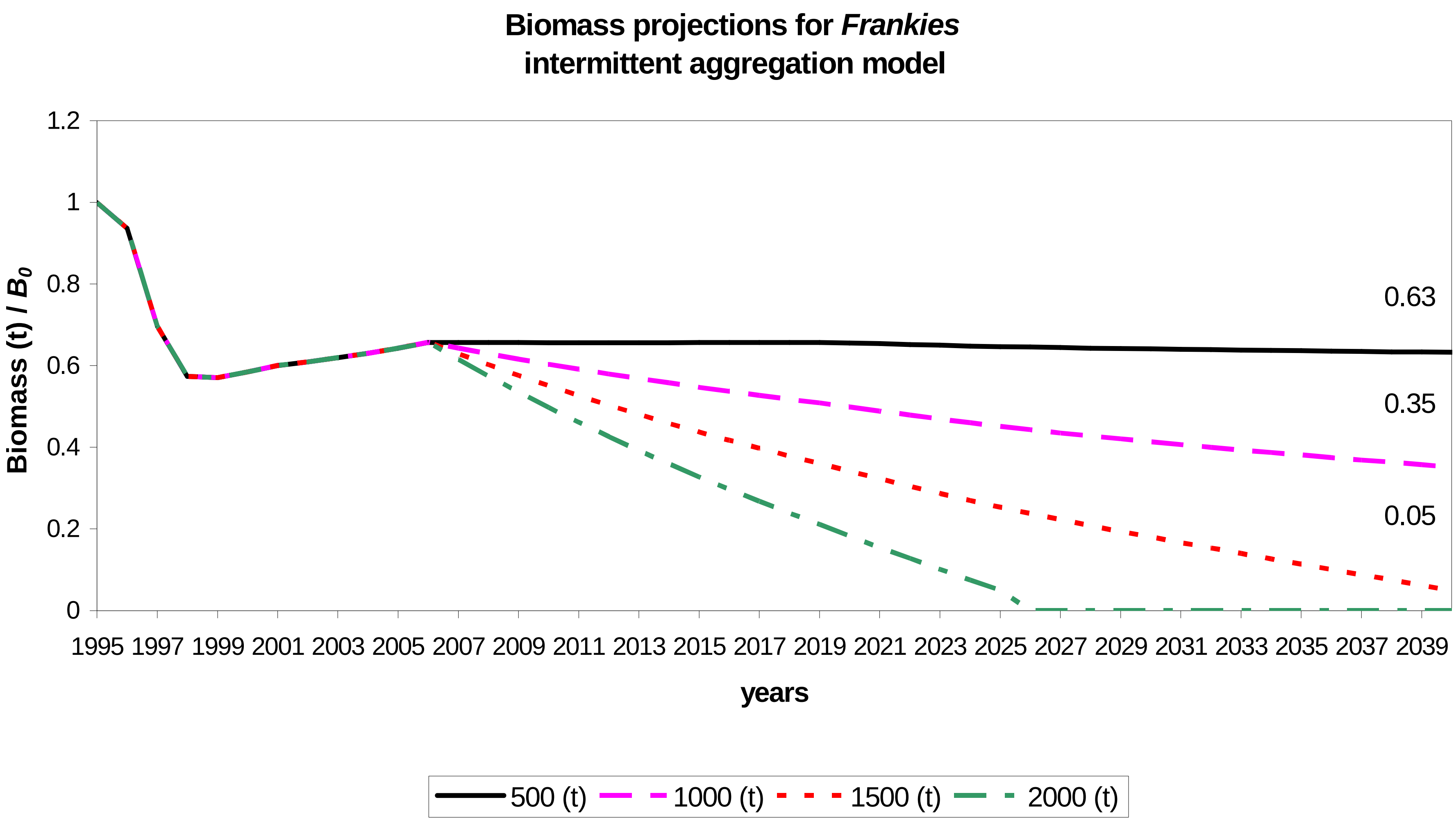


Figure 6. Thirty five year projections of the orange roughy stock for the *Frankies* aggregation under the scenario of the intermittent aggregation model, the "zero" method CPUE scenario and σ^{CPUE} estimated. Results for various levels of future constant catch are shown. The figure at the right end of a trajectory is the stock depletion after 35 years.

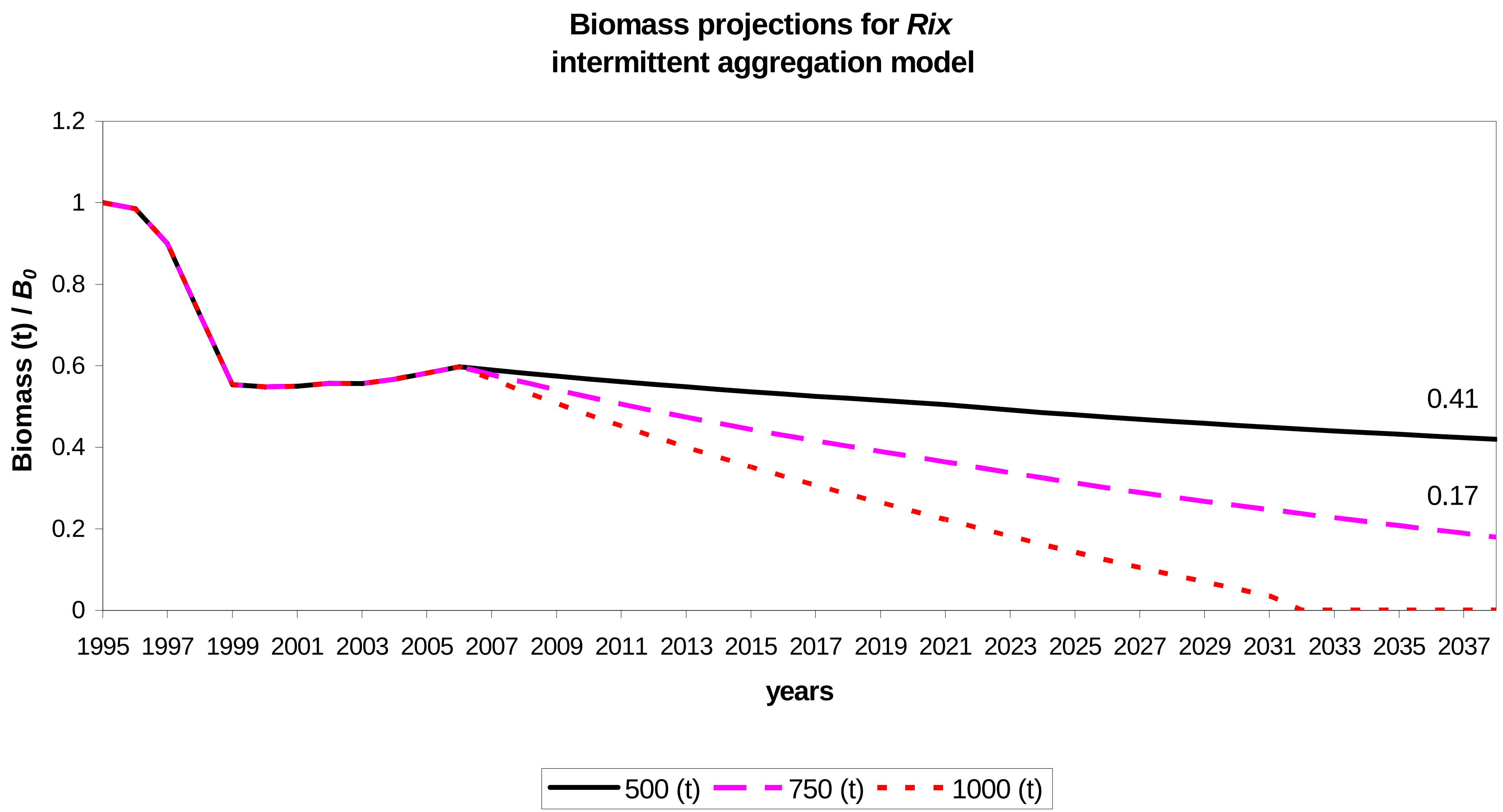


Figure 7. Thirty five year projections of the orange roughy stock for the *Rix* aggregation under the scenario of the intermittent aggregation model, the "zero" method CPUE scenario and σ^{CPUE} estimated. Results for various levels of future constant catch are shown. The figure at the right end of a trajectory is the stock depletion after 35 years.

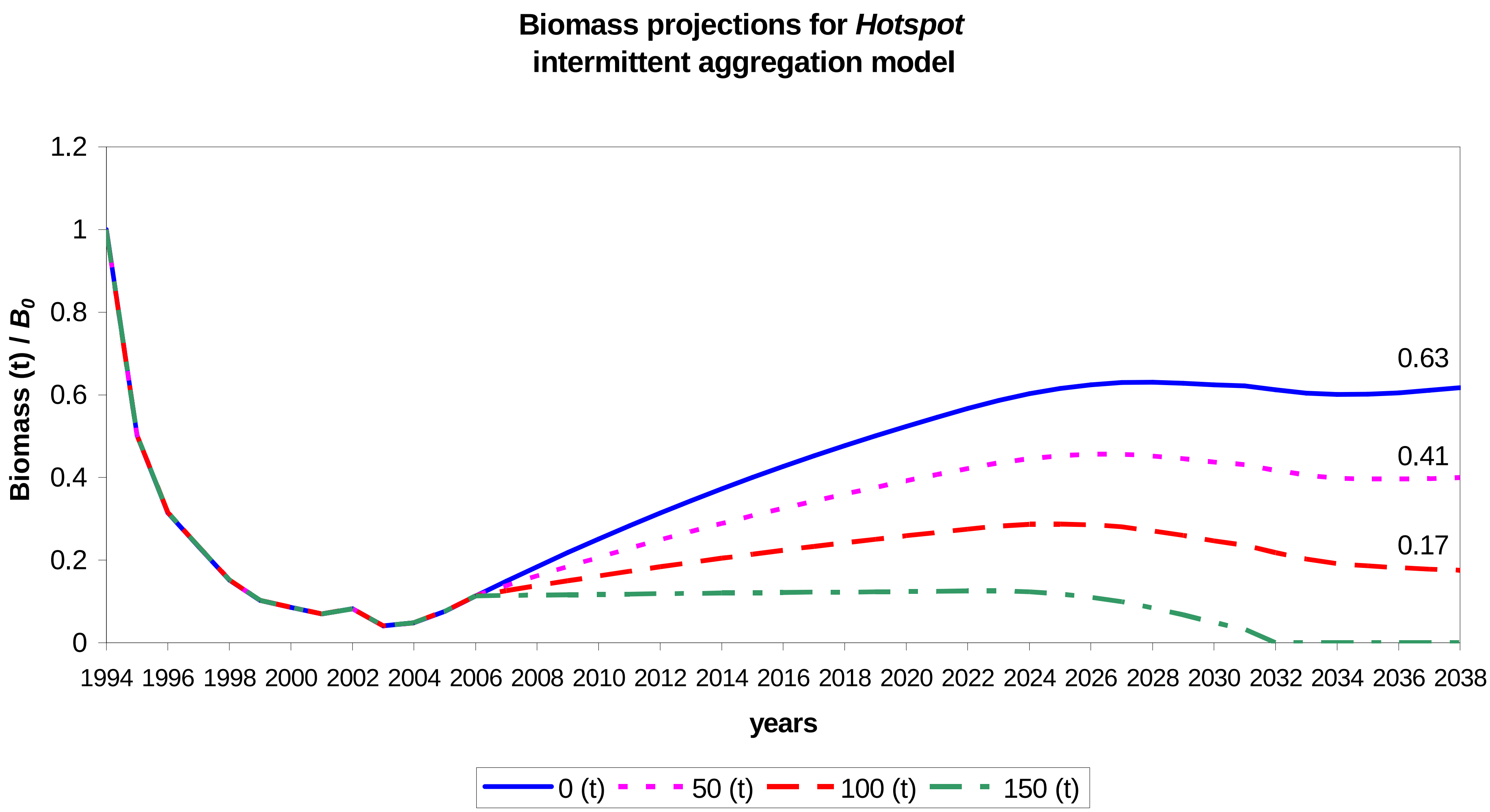


Figure 8. Thirty five year projections of the orange roughy stock for the *Hotspot* aggregation under the scenario of the intermittent aggregation model, the delta-lognormal model fitted to the commercial CPUE data and σ^{CPUE} is estimated. Results for various levels of future constant catch are shown. The figure at the right end of a 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 Age Structured Production Model (ASPM) 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 at the start of year *y*,

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

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

Note that in the interests of simplicity this approximates the fishery as a pulse fishery at the start of the year. Given that orange roughy is relatively long-lived with low natural mortality, such an approximation would seem adequate.

The number of fish of age *a* caught in year *y* is given by:

$$C_{y,a} = N_{y,a} S_a F_y \qquad \text{(A2.4)}$$

where:

F_y is the proportion of the resource above age *a* harvested in year *y*, and

S_a is the commercial selectivity at age *a* (assumed to be knife-edge so that $S_a = 0$ for $a < a_r$ and $S_a = 1$ for $a \geq a_r$.

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.

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

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

where:

w_a is the mass of a fish at age a.

Given knife-edge recruitment to the fishery, and assuming uniform selectivity for ages $a \geq a_r$, the total catch by mass (C_y) in year y is given by:

$$C_y = \sum_{a=a_r}^{m} w_a C_{y,a} = \sum_{a=a_r}^{m} w_a F_y N_{y,a} \quad \text{(A2.7)}$$

where:

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

Equation (A2.7) can be re-written as:

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

Stock-recruitment relationship

The spawning biomass in year y is given by:

$$B_y^{sp} = \sum_{a=1}^{m} w_a f_a N_{y,a} = \sum_{a=a_m}^{m} w_a N_{y,a} \quad \text{(A2.9)}$$

where

f_a is the proportion of fish of age a that are mature (assumed to be knife-edge at age a_m).

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

$$R(B_y^{sp}) = \frac{\alpha B_y^{sp}}{\beta + B_y^{sp}}. \quad \text{(A2.10)}$$

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:

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

Past stock trajectory and future projections

Given a value for the pre-exploitation spawning biomass (B_0^{sp}) of orange roughy, and the assumption that the initial age structure is at equilibrium, it follows that:

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

which can be solved for R_0.

The initial numbers at each age *a* for the trajectory calculations, corresponding to the deterministic equilibrium, are 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 subsequent 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.

The model estimate of the exploitable component of the biomass is given by:

$$B_y^{\exp} = \sum_{a=0}^{m} w_a S_a N_{y,a} = \sum_{a=a_r}^{m} w_a N_{y,a} \tag{A2.18}$$

The likelihood function

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 likelihood is calculated assuming that the observed abundance indices are lognormally distributed about their expected value:

$$I_y^{method} = \widehat{I}_y^{method} e^{\varepsilon_y} \text{ or } \varepsilon_y = \ln\left(I_y^{method}\right) - \ln\left(\widehat{I}_y^{method}\right), \tag{A2.19}$$

where

I_y^{method} is the abundance index of type *method* for year *y*, where for example, *method* = *AC*, when dealing with the acoustic abundance index, and so on,

$\widehat{I}_y^{method} = \widehat{q}^{method} \widehat{B}_y^{\exp}$ is the corresponding model estimate, where

$\widehat{B}_y^{\exp}$ is the model estimate of exploitable biomass of the resource for year *y*, and

q^{method} is the catchability coefficient for the abundance indices of type *method*, and

ε_y is normally distributed with mean zero and standard deviation σ (assuming homoscedasticity of residuals).

The negative of the penalised log likelihood (ignoring constants) which is minimised in the fitting procedure is thus:

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

$$+\sum_y^{AC}\frac{1}{2(\sigma_y^{AC})^2}\left(\ln I_y^{AC} - \ln\left(q^{AC}\,B_y^{\exp}\right)\right)^2 + \sum_y^{SA}\frac{1}{2(\sigma_y^{SA})^2}\left(\ln I_y^{SA} - \ln\left(q^{SA}\,B_y^{\exp}\right)\right)^2 \qquad \text{(A2.20)}$$

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

where

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

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

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

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

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:

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

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, 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 (A2.20) become:

$$\left(\ln I_y^{method} - \ln\left(x_y\ q^{method}\ B_y^{\exp}\right)\right)^2 \qquad \text{(A2.21)}$$

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 (A2.20) in which the various terms are given by equation (A2.21):

$$-\left[N\{\ln\Gamma(\alpha+\beta)-[\ln\Gamma(\alpha)+\ln\Gamma(\beta)]\}+\sum_{y=1994}^{2004}\{(\alpha-1)\ln(x_y)+(\beta-1)\ln(1-x_y)\}\right] \qquad \text{(A2.22)}$$

where:

N is the total number of years considered in the assessment (*N* = 2005 - 1994 + 1),

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

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