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## EXECUTIVE SUMMARY

Francis, R.I.C.C. 2001: Stock assessment of orange roughy on the South Chatham Rise.

*New Zealand Fisheries Assessment Report 2001/27. 25 p.*

The fishery for orange roughy on the South Chatham Rise developed in the early 1980s, with annual catches of about 5000 t through until the early 1990s, when TACCs started to fall. In recent years the annual catch has averaged 1400 t, with about 60% of this coming from the eastern end of the South Rise, near the hill complex Big Chief.

This is the first time that orange roughy in this area have been assessed separately. Previously they were assessed as part of a single Chatham Rise stock. The only input to this assessment, apart from catches and biological parameters, is commercial catch per unit effort (CPUE) for four sectors of the catch (one sector contains all tows on the flat; the other three sectors contain hill tows from three subareas of the South Rise). In the assessment model these four sectors are treated as distinct, because a more complicated model, that allowed migration between sectors, did not provide a substantially better fit to the data.

The assessment suggests that the current stock size is about 24% of the virgin size ( $B_0$ ) of 95 000 t. This is less than  $B_{MSY}$  (which, for orange roughy stocks, is normally interpreted as the mean biomass under a CAY policy — 30%  $B_0$ ). There is no separate catch limit for this area, but recent catches are similar to the estimated MCY and CAY, which suggests that they are sustainable and likely to move the stock towards  $B_{MSY}$ .

There is some doubt as to whether the stock biomass is rebuilding (as the stock assessment model suggests) because none of the four CPUE series show any such rebuild.

This report addresses objective 6 of Ministry of Fisheries project ORH2000/02: *To develop a stock assessment model and undertake a stock assessment of orange roughy for the South Chatham Rise, including estimating biomass and sustainable yield, if a relative abundance index is available from Objective 3.*

# 1. INTRODUCTION

The South Chatham Rise lies within Quota Management Area ORH 3B. For the purposes of this assessment it comprises the area shown in Figure 1. This area, which is the same as used by Francis (2001) does not correspond exactly to that defined by the Minister of Fisheries, but the differences are of little consequence (Francis 2001).

This is the first time that orange roughy in this area have been assessed separately. Before 1997 they were assessed as part of a single Chatham Rise stock (the last such assessment was described by Francis et al. 1995). They have not been assessed since 1995.

The work described in this report addresses objective 6 of Ministry of Fisheries project ORH2000/02: *To develop a stock assessment model and undertake a stock assessment of orange roughy for the South Chatham Rise, including estimating biomass and sustainable yield, if a relative abundance index is available from Objective 3.*

I first describe stock structure (Section 2), the fishery (Section 3), and the model inputs (Section 4), which include four CPUE indices derived by Francis (2001) under Objective 3 of ORH2000/02. I then show (Section 5) that a model that includes various types of migration, as well as habitat modification, is no better at assessing this fishery than a simple model that treats as independent the four strata associated with the CPUE indices. Finally, I assess the fishery using the simple model (Section 6) and discuss the management implications of this assessment (Section 7).

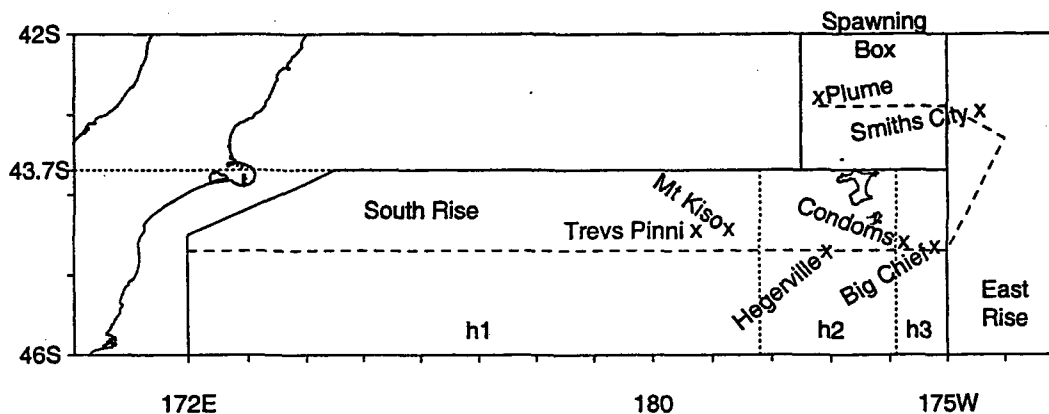


Figure 1: The Chatham Rise, showing the boundaries of the South Rise, East Rise and Spawning Box (solid lines), the boundaries between the three hill strata, h1, h2, and h3 in South Rise (vertical dotted lines at longitudes 178.2° W and 175.9° W), the nominal spawning migration route (broken line — an extension of the “longitude” axis defined by Francis 2001) and the location of five major hills in South Rise and two spawning areas (Plume and Smiths City) outside South Rise.

## 2. STOCK STRUCTURE

There is evidence that orange roughy on the Chatham Rise are genetically distinct from those in other areas (Annala et al. 1998), but the genetic data are equivocal about stock boundaries within the Chatham Rise (Francis et al. 1995). Because spawning occurs simultaneously in the northwest Rise and the Spawning Box, and a post-spawning migration from the latter appears to be eastward (Coburn & Doonan 1994), it seems reasonable to separate the northwest from the rest of the Chatham Rise.

However, further subdivision is problematic. Outside the northwest Rise, major spawning aggregations have been found only in the Spawning Box and the northeast Rise (Smiths City and Camerons). A boundary between these aggregations is inappropriate because the above-mentioned post-spawning migration from the Spawning Box passes the other spawning areas.

It is unlikely that the South Rise forms a separate stock because no major spawning aggregations have been found in this area.

## 3. THE FISHERY

The description of the fishery given here summarises the more detailed description given by Francis (2001).

Major trends in the fishery are shown in Figure 2. It developed in the early 1980s, with annual catches of about 5000 t through until the early 1990s, when catches started to fall; since 1995 they have fluctuated about a mean of 1400 t. Effort increased rapidly to a peak of 2808 tows in 1989 but has averaged about 800 tows per year in recent years. Around 1991 (when more accurate position fixing became available) there was a sudden change from mainly long tows over relatively flat terrain to mainly short tows on hills. Currently about two-thirds of tows are on hills. Catch rates of targeted flat tows peaked at about 6 t/h in 1983 (ignoring the 1979 value, which is based on very little effort), gradually declined to about 1 t/h, but rose to more than 3 t/h in 2000. On hills, the catch rate of targeted tows is now about 2 t/tow, which is about half the level when the hill fishery first developed around 1991. 82% of the total catch is from target tows.

The method of limiting catches in this fishery has changed several times. A TAC was first imposed in 1981–82, and this applied to the whole of ORH 3B. It was initially set at 23 000 t, rose in three steps to 38 065 t in 1986–87, then gradually dropped (in six steps) to its current level of 12 700 t in 1995–96. Since 1992–93 there have been a series of agreements, between the Minister and industry, partitioning the ORH 3B TAC amongst several subareas, one of which was the South Rise. The catch limit for this area was 6000 t in both 1992–93 and 1993–94, and then fell to 2000 t in the following year. In 1995–96 a limit of 4950 t was agreed for the area formed by combining this area with the East Rise and the Spawning Box. This limit is still in force.

The South Rise fishery has historically been spread across all months except the time of peak spawning in July. In recent years it has been mostly confined to the first 8 months of the fishing year: October to June.

Oreos are an important bycatch. Their importance decreases from west to east and has increased with time, from 30% in the early 1980s to 65% in the late 1990s (calculated as the oreo catch as a percentage of the combined catch of oreos and orange roughy, for targeted tows only).

Most of the catch from this fishery has been taken from the neighbourhoods of five major hills, all of which are east of longitude 180° (see Figure 1). The focus of the fishery moved gradually further to the east; since 1992, 60% of the catch has come from the extreme eastern end of the South Rise, near Big Chief.

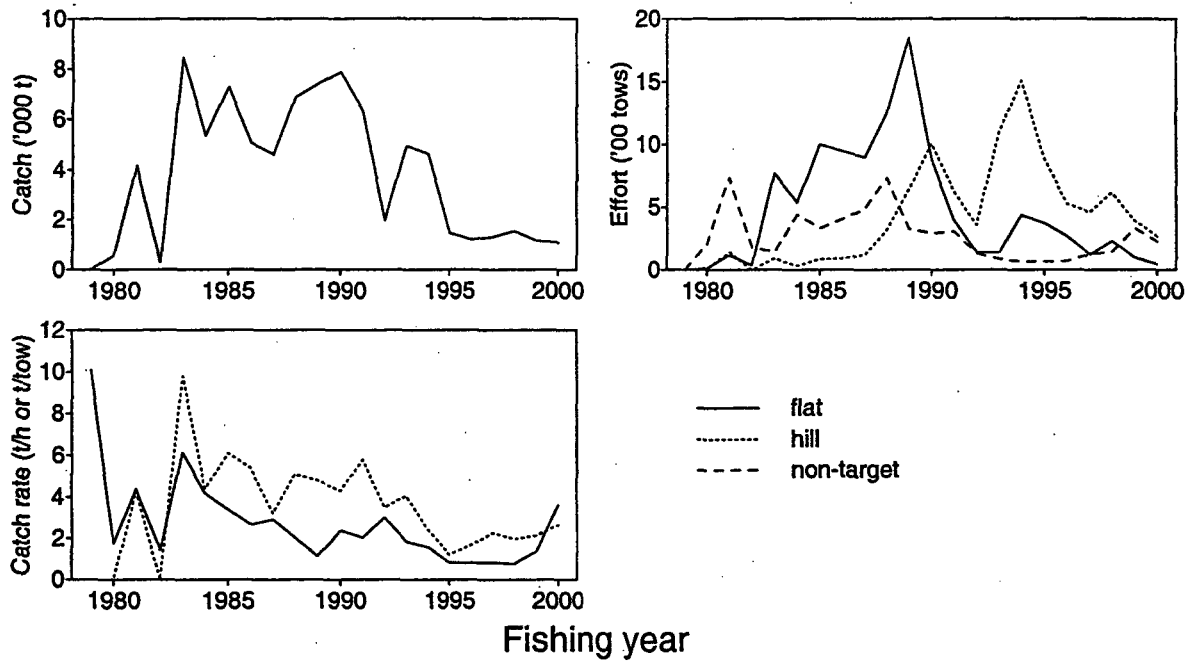


Figure 2: Catch, effort (number of tows), and catch rate by fishing year. Tows of less than 30 minutes are designated “hill” tows and their catch rates are calculated as  $t/tow$  (total tonnes divided by total tows); tows of longer duration are designated “flat” tows and their catch rates are  $t/h$  (total tonnes divided by total hours).

#### 4. MODEL INPUTS

There are three types of model inputs: biological parameters, CPUE indices, and catches (and numbers of tows).

##### 4.1 Biological parameters

There are no estimates of biological parameters specifically for the South Rise. In this assessment I use those given by Annala et al. (2000) for the Chatham Rise (Table 1), which derive mostly from northeast Chatham Rise data.

Table 1: Orange roughy biological parameters for the Chatham Rise. –, not estimated.

Parameter	Symbol	Male	Female	Both sexes
Natural mortality	$M$	–	–	$0.045 \text{ yr}^{-1}$
Age of recruitment	$A_r$	–	–	$=A_m$
Gradual recruitment	$S_r$	–	–	$=S_m$
Age at maturity	$A_m$	–	–	29 yr
Gradual maturity	$S_m$	–	–	3 yr
von Bertalanffy parameters	$L_\infty$	36.4 cm	38.0 cm	–
	$k$	$0.070 \text{ yr}^{-1}$	$0.061 \text{ yr}^{-1}$	–
	$t_0$	$-0.4 \text{ yr}$	$-0.6 \text{ yr}$	–
Length-weight parameters	$a$	–	–	0.0921
$[W(g) = a L(\text{cm})^b]$	$b$	–	–	2.71
Recruitment variability	$\sigma_R$	–	–	1.1
Recruitment steepness		–	–	0.75

## 4.2 CPUE indices

Francis (2001) analysed CPUE in South Rise and concluded that it was not possible to derive a single series of CPUE indices that was representative of trends in the whole fishery. Instead, he stratified the fishery by tow type and area into four strata: f1, containing all tows on the flat; and h1, h2, and h3, containing hill tows in three subareas (see Figure 1). A standardised CPUE index was calculated for each stratum (Table 2).

Coefficients of variation (c.v.s) for these indices were calculated by adapting the recommendation of Francis et al. (2001) that default c.v.s for CPUE indices in stock assessments should be between 0.15 and 0.2. These c.v.s may be thought of as a sum of two components: sampling error and (annual variation in) catchability. For most CPUE indices (including those on which this recommendation was based) the latter component will be dominant because sampling error in CPUE indices is usually small — typically less than 0.1 (Francis 1999b). Thus we can infer that the c.v. due to catchability should be around 0.15 to 0.17 (if the sampling error c.v. were very small, say 0.02, then the catchability c.v. could not be much less than 0.15; if the sampling c.v. were as high as 0.1 then a catchability c.v. much higher than 0.17 would produce an overall c.v. greater than 0.2). Now, the above recommendation does not apply directly to the present CPUE indices because their sampling c.v.s are much higher than usual (range 0.07 to 0.25, median 0.13) (the reason some of these c.v.s are so high is that an interaction with year was allowed in the CPUE model, and this meant that some index values are based on comparatively small sample sizes). However, we can adapt the recommendation by assuming a catchability c.v. of 0.16 (the mean of 0.15 and 0.17) and “adding” this to the sampling-error c.v.s estimated by Francis (2001) (bearing in mind that c.v.s “add” as squares, so 0.16 “added” to 0.13 is  $\sqrt{(0.16^2 + 0.13^2)} = 0.21$ ). This was done, and the resultant c.v.s range from 0.17 to 0.29, with median 0.21 (Table 2).

**Table 2: CPUE indices (with c.v.s in parentheses) for four strata (f1, h1, h2, and h3) in South Rise. —, not estimated.**

	f1		h1		h2		h3	
1981	—	—	5.11	(0.19)	—	—	—	—
1983	4.38	(0.21)	5.23	(0.21)	—	—	—	—
1984	2.95	(0.19)	6.30	(0.19)	—	—	—	—
1985	3.18	(0.17)	4.33	(0.19)	—	—	—	—
1986	3.04	(0.18)	4.54	(0.19)	—	—	—	—
1987	3.64	(0.18)	3.44	(0.23)	3.68	(0.22)	—	—
1988	1.64	(0.18)	1.35	(0.19)	2.54	(0.18)	—	—
1989	0.46	(0.18)	0.83	(0.23)	1.41	(0.18)	2.25	(0.21)
1990	0.40	(0.19)	1.09	(0.23)	1.59	(0.18)	3.43	(0.18)
1991	0.68	(0.24)	1.23	(0.23)	1.31	(0.22)	4.19	(0.18)
1992	—	—	—	—	1.28	(0.21)	2.92	(0.19)
1993	—	—	1.81	(0.24)	1.43	(0.21)	2.59	(0.18)
1994	0.70	(0.22)	0.63	(0.21)	0.74	(0.19)	1.65	(0.17)
1995	0.23	(0.28)	—	—	0.28	(0.22)	1.15	(0.19)
1996	0.61	(0.27)	—	—	0.28	(0.26)	0.83	(0.21)
1997	—	—	0.56	(0.28)	0.25	(0.28)	0.76	(0.22)
1998	—	—	—	—	0.35	(0.23)	0.43	(0.22)
1999	—	—	—	—	0.27	(0.28)	0.64	(0.21)
2000	—	—	—	—	—	—	0.42	(0.29)



### 4.3 Catches and numbers of tows

The catches and numbers of tows used in this assessment are all for October–September years and were calculated as follows. First, ratios were calculated by dividing the official catches for ORH 3B by those in the TCEPR database (Table 3). Next, these ratios were converted, where necessary, to October–September years by taking weighted averages. For example, the ratio for 10/81–9/82 was taken as 0.5 times the ratio for 4/81–3/82 plus 0.5 times the ratio for 4/82–3/83, because half of the year 10/81–9/82 lies in 4/81–3/82 and half in 4/82–3/83. Finally, TCEPR catches and numbers of tows for the flat and hill strata (for October–September years) were multiplied by the October–September ratios and rounded to give the values in Table 4. The tows counted were all those that either caught or targeted orange roughy. (The way that numbers of tows could be used as a model input is discussed in Section 5.1.2.)

TCEPR catches are usually a few percent less than the official catches so the ratios in Table 4 are typically slightly greater than 1 (median 1.074). The most extreme ratios are in 1989 and 1990 (1.225 and 1.386, respectively), when a sizeable proportion of the TCEPR data was lost after the Fisheries Statistics Unit was disestablished.

**Table 3: Comparison of “official” catches for ORH 3B (taken from Table 1 on p. 272 of Annala et al. 2000, with an update for 1999–2000) with those in the TCEPR database for the same years (both in t). Also shown is the ratio of the catches (official/TCEPR). (Note the change in fishing year, from the original March–April year to the current October–September year, with two transitional 15-month years).**

Year	4/79-3/80	4/80-3/81	4/81-3/82	4/82-6/83	7/83-9/84	10/84-9/85	10/85-9/86	10/86-9/87
Official	11 800	31 100	28 200	32 605	32 535	29 340	30 075	30 689
TCEPR	12 080	29 089	22 150	35 636	29 115	27 036	28 750	29 955
Ratio	0.977	1.069	1.273	0.915	1.117	1.085	1.046	1.025
Year	10/87-9/88	10/88-9/89	10/89-9/90	10/90-9/91	10/91-9/92	10/92-9/93	10/93-9/94	10/94-9/95
Official	24 214	32 785	31 669	21 521	23 269	20 048	16 960	11 891
TCEPR	24 497	26 754	22 855	19 947	22 133	18 216	15 651	11 040
Ratio	0.988	1.225	1.386	1.079	1.051	1.101	1.084	1.077
Year	10/95-9/96	10/96-9/97	10/97-9/98	10/98-9/99	10/99-9/00			
Official	12 501	9 278	9 638	9 372	8 663			
TCEPR	11 668	8 621	9 596	8 998	8 356			
Ratio	1.071	1.076	1.004	1.042	1.037			

**Table 4: Catches (t) and numbers of tows used in the stock assessment model, together with the ratios used to calculate them from TCEPR catches (all are for October–September years, which are labelled by the end year — so 10/98–9/99 is labelled 1999).**

Catches (t)											
	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
f1	17	494	1230	290	3885	3147	5013	2675	2955	2865	2562
h1	0	87	3639	33	4295	2849	2888	2441	1088	912	1316
h2	0	0	0	0	0	0	14	179	663	2962	3871
h3	0	0	0	0	0	0	0	0	0	59	1353
All	17	581	4869	323	8180	5996	7915	5295	4706	6798	9102
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
f1	806	413	180	119	244	93	202	101	78	136	85
h1	1280	1357	416	677	288	152	171	197	160	157	117
h2	2364	657	506	511	755	288	218	318	281	280	381
h3	6489	4429	987	4134	3721	1063	706	795	1041	651	551
All	10939	6856	2089	5441	5008	1596	1297	1411	1560	1224	1134

**Table 4, continued**

Numbers of tows											
	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
f1	2	175	354	193	527	609	1062	846	999	1217	1607
h1	0	57	807	43	435	517	462	621	410	377	539
h2	0	0	0	0	0	3	11	30	126	670	989
h3	0	0	0	0	0	0	0	1	0	5	306
All	2	232	1161	236	962	1129	1535	1498	1535	2269	3441
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
f1	654	236	85	100	234	256	196	126	153	201	124
h1	453	307	173	282	335	218	207	160	132	130	102
h2	808	231	218	178	459	402	276	173	316	240	160
h3	1095	662	184	884	1152	550	244	298	391	281	170
All	3010	1436	660	1444	2180	1426	923	757	992	852	556
Ratios											
	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
	0.977	1.023	1.171	1.094	0.966	1.117	1.085	1.046	1.025	0.988	1.225
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
	1.386	1.079	1.051	1.101	1.084	1.077	1.071	1.076	1.004	1.042	1.037

## 5. MIGRATION MODEL

The simplest way to model this stock would be to treat the four CPUE strata (f1, h1, h2, and h3) as containing discrete populations, and then to combine the biomass trajectories estimated for each stratum. This appears undesirable because it ignores fish movement between strata, and such movement seems very likely (particularly between the flat and hill strata). However, it would be acceptable if the inclusion of migration in the assessment model did not provide a markedly better fit to the data and (more importantly) a significantly different assessment of the status of the stock. In this section I develop a new model that includes migration and is thus capable of assessing the stock as a single entity. I then show that it provides an assessment that is no better than that deriving from the simple approach described in the first sentence of this paragraph.

This is the first attempt to explicitly model migration for a New Zealand orange roughy stock. It was intended to allow us to make inferences about the nature and extent of migration in South Rise. The four CPUE strata are treated as being four separate areas and each CPUE index is assumed to be proportional to the abundance in that area. In most models there are four processes that contribute to annual changes in abundance: recruitment, growth, natural mortality, and fishing mortality. In this model we include migration between areas as a fifth process. We can, as a special case of the model, set migration to zero. This is equivalent to modelling the four areas separately. Note that migration has not been totally ignored in other orange roughy assessments. For example, the timing and areal coverage of most surveys (trawl, acoustic, and egg) are based on an understanding of an annual spawning migration. However, the migration itself has not been modelled before.

### 5.1 Model description

The model description given here is mostly verbal. A full mathematical description is given in Appendix 1.

Because the focus of the model was migration, other aspects of the model were simplified. There is no age or sex structure and growth and natural mortality were combined in a single survival parameter,  $S$ , which was set to  $1-M$  (where  $M$  is the instantaneous natural mortality from Table 1).

This means that all but one of the parameters in Table 1 were ignored. At the beginning of each year the biomass in each area is reduced by multiplication by  $S$  and then increased by the addition of recruitment. Next, the biomasses are adjusted to allow for migration between areas. Finally, the catch is removed, with the proviso that no more than two-thirds of the biomass can be caught in any area.

Recruitment is deterministic and the total recruitment is the same each year (because the age at recruitment is greater than the duration of the fishery, there is no need to consider a stock-recruit relationship). The recruitment to each area is proportional to its carrying capacity,  $K$ .

The within-year structure of the model (first natural mortality, growth, and recruitment, then migration, and then fishing mortality) is clearly simplistic and not intended to be realistic. We make such a simplification for two reasons. First, the time span of primary interest to us in stock assessment is multi-year; we are not particularly interested in what happens within a year. Therefore we ignore within-year structure. The above ordering of processes is purely arbitrary. Second, it is not clear that our data are sufficient to allow inferences about within-year processes, even if we wanted to make them. We ignore movement within areas and assume there is no net movement into or out of the entire South Rise.

### 5.1.1 Migration

Two alternative types of migration are modelled: *diffusion* and *spawning*. In the diffusion model a fish can migrate only to an adjacent area, and will tend to migrate only if the adjacent area is, in a sense I will define shortly, more attractive than its current area. In the spawning migration model it is assumed that a certain proportion,  $p_{sp}$ , of fish leave their current area each year to spawn outside the South Rise (in the East or North Chatham Rise) but then return to whichever of the four areas is most attractive. The movement outside the South Rise is not modelled explicitly; we model only between-area migration within the South Rise, but we use the idea of a spawning migration to the east to help us define which areas are most attractive to fish. The spawning model is motivated by the fact that there are no known major spawning concentrations in South Rise. With this model we will assume that the migration is either to the Plume in the Spawning Box (42.8°S, 177.2°W) or to Smiths City (43°S, 174.4°W) (see Figure 1).

The attractiveness, or *allure*, of each area, denoted  $A$ , is assumed to be a function of its current biomass,  $B$ , and its carrying capacity,  $K$ . Two alternative functions are modelled. In the first,  $A = 1 - B/K$ . The idea here is that if one area is half full ( $B = 0.5K$ , so  $A = 0.5$ ) it will be more attractive to fish than one which is three-quarters full ( $B = 0.75K$ , so  $A = 0.25$ ), presumably because more resources (e.g., food, space) would be available in the former area. In the second alternative, allure is defined by  $A = K - B$ . Here, I assume that the allure of an area is equal to the biomass of fish that would need to immigrate there before its biomass reached carrying capacity. In other words, an area that has room for an additional 500 t of fish ( $K - B = 500$ ) is more attractive than one that has room for only 300 t more ( $K - B = 300$ ). Both versions of allure are based on the idea of spare capacity. The former depends on relative spare capacity and the latter on absolute spare capacity. Thus, as a shorthand, I will refer to these two versions of allure as *relative* and *absolute*, respectively. Whichever version is used, fish are assumed to migrate towards areas of higher allure.

In the spawning migration model I introduce a further factor into the calculation of allure: the distance,  $D$ , from the spawning ground. I will assume that allure is inversely proportional to  $D^d$ , where  $d$  is some positive number to be estimated (this allows the inverse proportionality to be non-linear). We can remove the relationship with distance by setting  $d = 0$ . The distance  $D$  is measured in kilometres along the route shown in Figure 1, which corresponds roughly to a depth contour. Calculated distances are given in Table 5. For the hill strata, these are measured to the main hill in the area (Mt Kiso in h1, Hegerville in h2, and Big Chief in h3). Distances to f1 were taken as being the same as to h1 because the approximate centroid of all flat tows in South Rise is very close to the

longitude of Mt Kiso. (The centroid was calculated as the weighted average of the start-of-tow longitudes, weighting by catches; this centroid shows no strong trend with time).

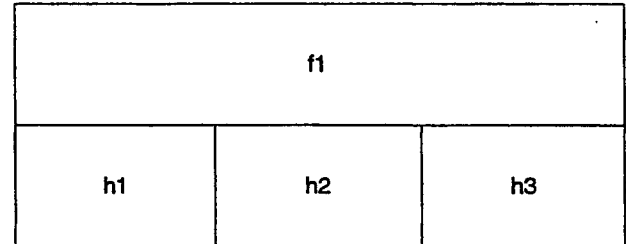
**Table 5: Distances (km) from stratum centres to each of the two spawning locations, measured along the migration route of Figure 1.**

Spawning location	Stratum			
	f1	h1	h2	h3
Plume	742	742	611	465
Smiths City	516	516	385	239

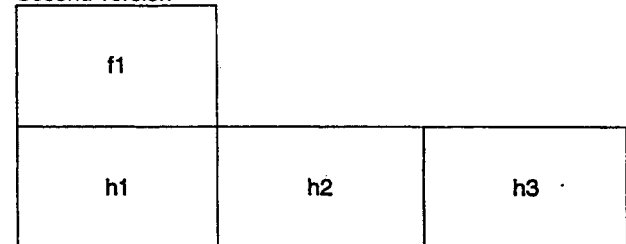
The details of the calculation of the extent of migration in each year are a little complicated (see Appendix 1 for equations) but the concepts underlying them are straightforward. Migration takes place from areas with lower allure towards those of higher allure. If there were no constraints then all areas would have equal allure after each annual migration. When there are some constraints it may not be possible to achieve equal allure, so the effect of each year's migration may simply be to reduce (rather than remove) between-area differences in allure. For the spawning model, the only constraint was that non-spawning fish may not migrate (recall that it is assumed that the same fraction of the biomass,  $p_{sp}$ , spawns each year). For the diffusion model two constraints were applied: no more than a given fraction,  $p_{migr}$ , of the biomass in an area may emigrate in any one year; and migration may take place only between adjacent areas. Two slightly different versions of "adjacency" were considered (Figure 3).

In the first version, area f1 was assumed to be adjacent to all the hill areas so the only pair of areas between which migration may not occur is h1 and h3. In the second version (which is motivated by the near coincidence of the centroids of fishing in strata f1 and h1), migration to (or from) f1 can occur only from (or to) h1.

First version



Second version



**Figure 3: Pictorial representation of the two versions, in the diffusion model, of which pairs of strata are adjacent.**

### 5.1.2 Habitat modification

It is known that the benthic fauna in some areas of intense fishing for orange roughy (hills in particular) have been substantially changed by fishing activity. However, it is not clear whether this has changed the carrying capacity of these areas (for orange roughy) and, if so, whether the change is positive (an enhancement) or negative (a degradation). This part of the model allows for such changes.

The carrying capacity,  $K$ , of an area is determined by the cumulative number of tows in that area and depends on two parameters,  $h_{max}$  and  $r_{hab}$ . Initially (before fishing), it is equal to the virgin biomass,  $B_0$ ; as the amount of fishing increases it tends to an asymptotic value of  $(1 + h_{max})B_0$  (Figure 4).

Thus  $h_{\max}$  determines the maximum change that is possible and its sign indicates the direction of change:  $h_{\max} = 0$  means that no modification is possible;  $h_{\max} = -1$  means that the carrying capacity can be reduced to zero; and  $h_{\max} = 1$  means that it can be doubled. The second parameter,  $r_{\text{hab}}$ , is an exponential rate coefficient (analogous to  $k$  in the von Bertalanffy equation) which determines how fast  $K$  approaches its asymptote (a large value indicates a rapid approach).

Another feature of the equation is that it is scaled so that the amount of change caused by a given number of tows depends on the initial carrying capacity,  $B_0$ . Thus, for example, number of tows required to change the carrying capacity of an area by, say, 20% is proportional to the initial carrying capacity of the area (for given values of  $h_{\max}$  and  $r_{\text{hab}}$ ).

Some deficiencies of this part of the model are discussed at the end of Section 5.2.

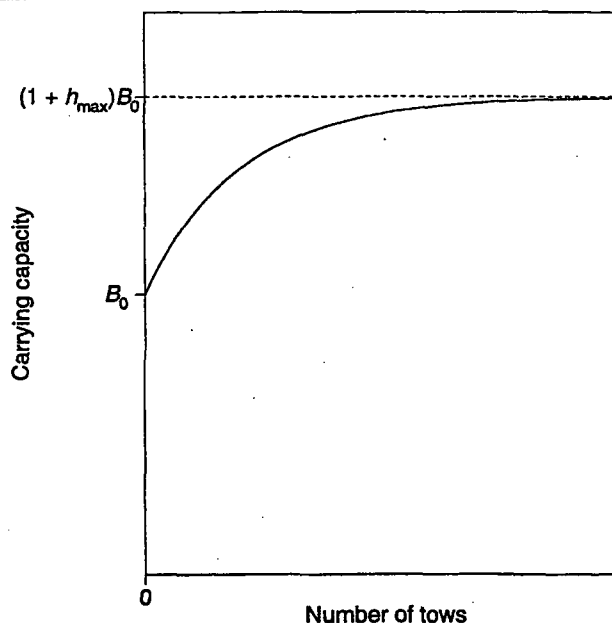


Figure 4. Illustration of the habitat-modification portion of the migration model: the relationship between the cumulative number of tows in an area and the carrying capacity of that area. Note that additional tows can either enhance the carrying capacity (if  $h_{\max} > 0$ ), or degrade it (if  $h_{\max} < 0$ ).

### 5.1.3 Fitting criteria

The model was fitted by maximum likelihood, assuming that the CPUE indices were lognormally distributed with the c.v.s given in Table 2. A penalty was added to the likelihood whenever the biomass in an area was too low to allow the observed catch to be taken. The penalty was made large enough so that the observed catch was always taken in all model fits. Some parameters were constrained to lie within specified bounds (Table 6).

Table 6: Parameters of the migration models.

Parameter	Description	Bounds	Comments
$B_{0a}$	Virgin biomass in stratum $a$	1 000, 75 000	One parameter for each of the four strata
$q_a$	CPUE catchability in stratum $a$	none	One parameter for each of the four strata
$p_{\text{migr}}$	Proportion of full migration	0,1	Only in diffusion model; no migration when $p_{\text{migr}} = 0$
$p_{\text{sp}}$	Proportion spawning	0.5,0.5	Only in spawning model; not estimated
$d$	Spawning distance exponent	0.1,10	Only in spawning model
$h_{\max}$	Extent of max. habitat modification	-0.9,0.9	No habitat modification when $h_{\max} = 0$
$r_{\text{hab}}$	Modification rate constant	0.1,100	Has no effect when $h_{\max} = 0$

## 5.2 Fits to migration model

The starting point for the investigation of the migration model was to see how well the model fits when the migration and habitat modification parts of the model are switched off. Note that when there is no migration (i.e.,  $p_{migr} = 0$  for the diffusion model, or  $p_{sp} = 0$  for the spawning model) the diffusion and migration models are equivalent and there is no difference between relative and absolute allure. The model fit appears moderately good (Figure 5, left panels) and it estimates a total  $B_0$  of 74 000 t and a current biomass of 25% of this (see fit 1 in Table 7).

**Table 7: Details of six fits to the migration model. The total negative log-likelihood is followed, in parentheses, by the values for each area. \*, parameter held fixed; -, not used.**

Fit	Model type		Parameter estimates				Goodness of fit	Biomass	
	Migration	Allure	$p_{migr}/p_{sp}$	$d$	$h_{max}$	$r_{hab}$	Negative log-likelihood	$B_0$ (‘000 t)	$B_{curr}$ (% $B_0$ )
1	either	either	0*	-	0*	-	84.3 (24.5,26.8,25.6,7.4)	74	25
2	diffusion	either	0	-	-0.9	10.0	51.2 (13.2,24.3,13.0,0.7)	74	25
3	spawning	relative	0.5*	0.21	0*	-	147.2(39.9,26.3,17.0,63.8)	71	21
4	spawning	absolute	0.5*	0.10	0*	-	140.5 (38.6,24.1,9.6,68.3)	126	56
5	spawning	relative	0.5*	1	-0.9	10.3	93.5(34.3,25.0,17.3,16.8)	78	14
6	spawning	absolute	0.5*	10	-0.9	5.8	57.7 (16.3,20.1,8.3,12.9)	71	21

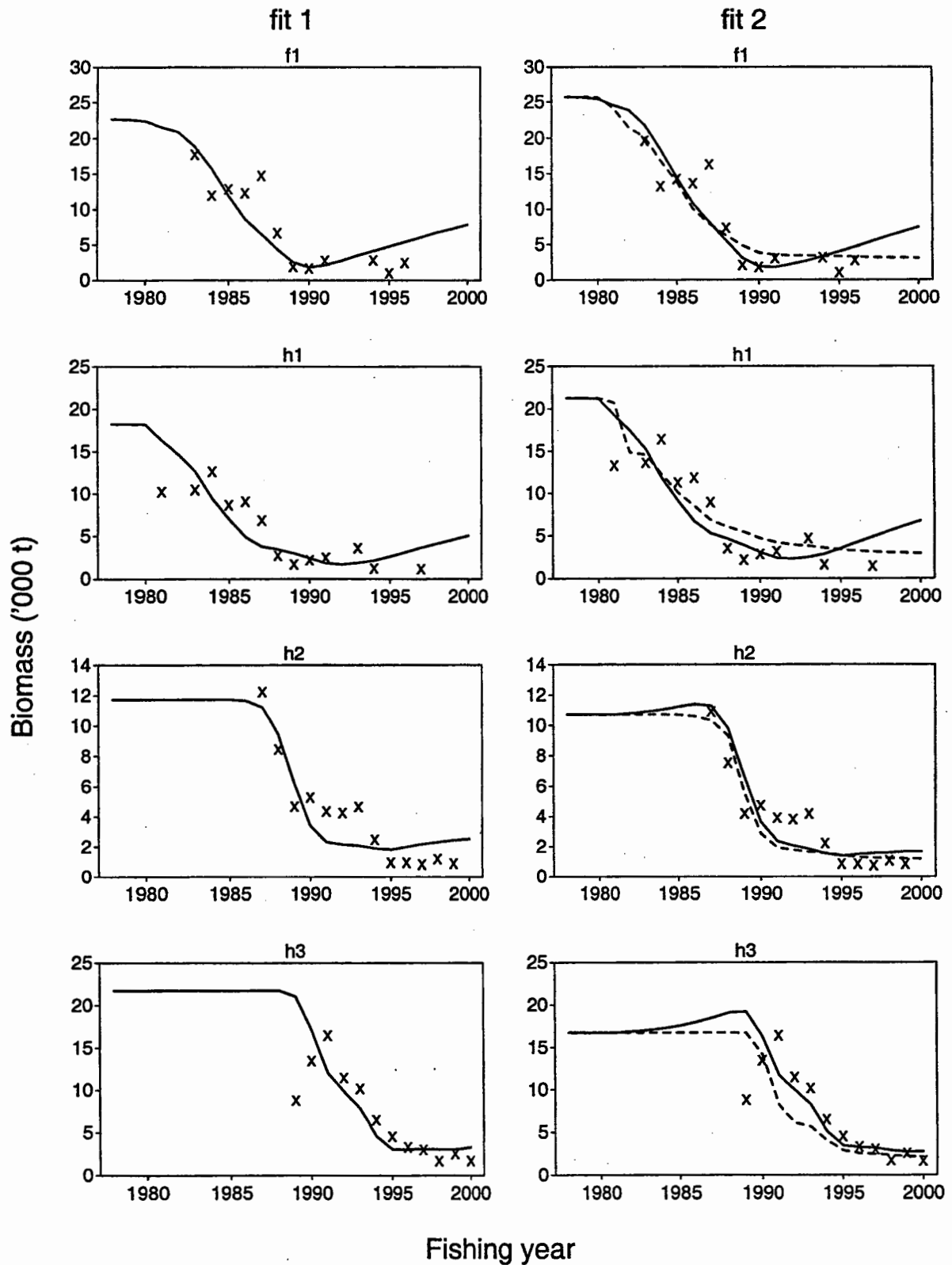
Next I considered the diffusion model. When no habitat modification was allowed ( $h_{max} = 0$ ) this model was unable to achieve a better fit than fit 1. That is, when  $h_{max} = 0$  the best value of  $p_{migr}$  is zero. When  $h_{max}$  was allowed to vary, the optimal value was found to be at the lower limit of  $-0.9$  and again the best value of  $p_{migr}$  was zero. The effect of such a low value of  $h_{max}$  is that the biomass trajectory in each area is similar to that for the carrying capacity (Figure 5, right panels). In terms of log-likelihood this fit (fit 2) is markedly better than fit 1; however, it is virtually identical in terms of total virgin and current biomass (Table 7). Results with the diffusion model were independent of which of the two versions of adjacency (as described in Figure 3) was used.

For the spawning model without habitat modification ( $h_{max} = 0$ ) the fits are much worse regardless of whether relative or absolute allure is used (Table 7, fits 3 and 4). With relative allure (fit 3) the estimated virgin and current biomasses are slightly less than those for fits 1 and 2; with absolute allure the biomasses are much higher because that for stratum h3 hits the upper bound of 75 000 t (Figure 6).

When habitat modification was allowed in the spawning model the optimum value of  $h_{max}$  was again at the lower limit of  $-0.9$ , for both types of allure, and the biomass and carrying capacity trajectories were similar (Figure 7). The fit was better with absolute allure (Table 7).

The preceding results for the spawning model use the distances to the Spawning Box (see Table 5). When distances to Smiths City were used instead, the results (in terms of log-likelihood and estimated biomass) were almost identical.

Figure 8 provides some insights into how the model is working. This shows the nett annual change in biomass in each area that is due to two factors: recruitment and migration. In fit 1 there is no migration and the recruitment (which is proportional to the original stock size in each area) does not change from year to year because there is no habitat modification. In fit 2 there is still no migration but the (only) effect of the habitat modification is that areas h2 and h3 get more recruitment (and f1 and h1 get less) in the early middle years of the fishery. The annual changes in fit 6, where we have both habitat modification and migration, are highly variable from year to year. These fluctuations are caused by migration (the recruitment component alone — not plotted — looks very much like that for fit 2, except that the changes over time in each area are smaller) and do not seem plausible.



**Figure 5: Illustration of fit 1 (left panels) and fit 2 (right panels) to the migration model (see Table 7 for description of these fits). Each panel shows the estimated biomass trajectory (solid line) and the CPUE data ('x', scaled up by the estimated catchability) for one of the four CPUE strata, f1, h1, h2, and h3. For fit 2 (where the carrying capacity was allowed to vary) the broken lines show the estimated carrying capacity for each stratum.**

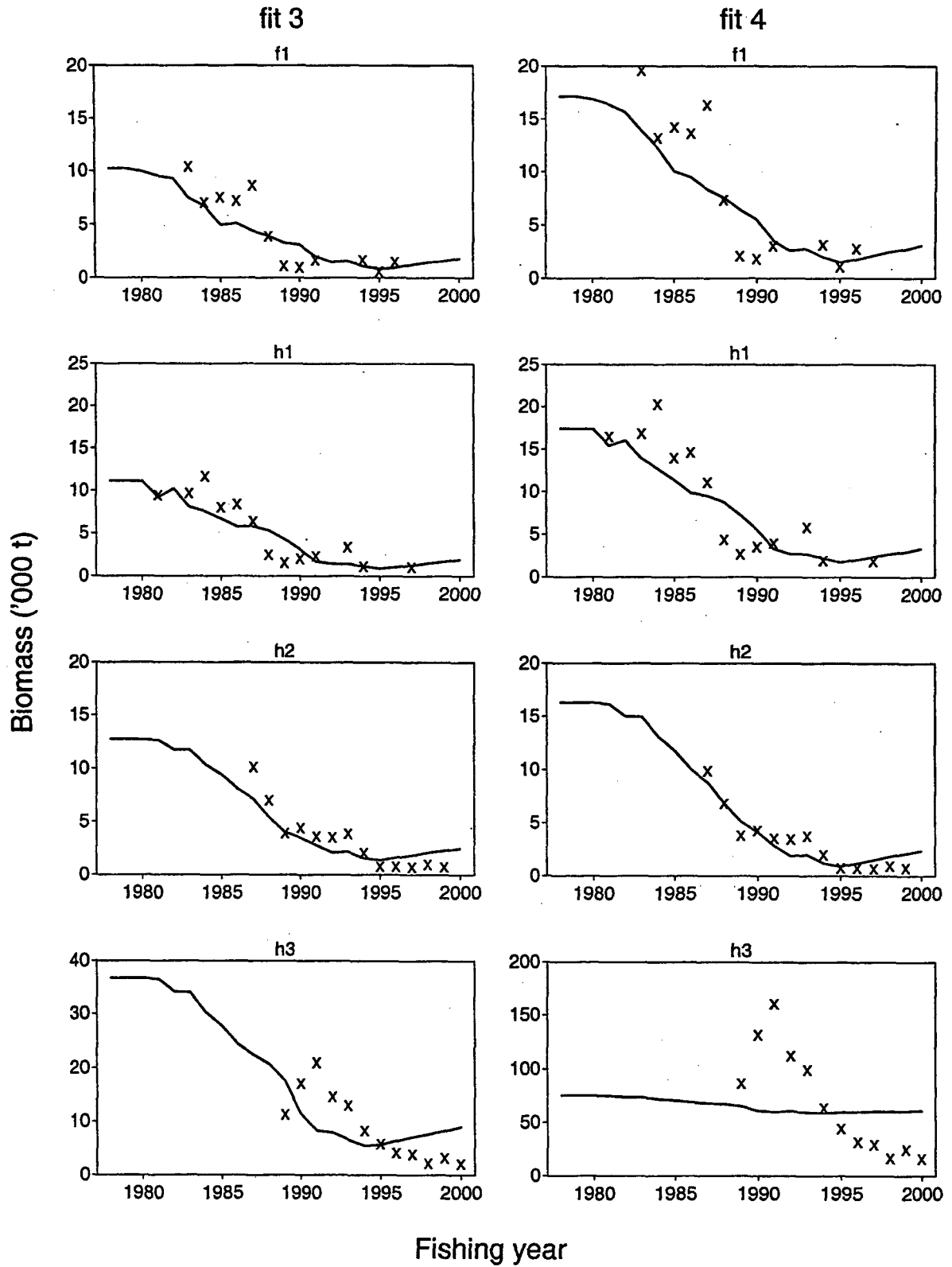


Figure 6: Illustration of fit 3 (left panels) and fit 4 (right panels) to the migration model (see Table 7 for description of these fits). Each panel shows the estimated biomass trajectory (solid line) and the CPUE data ('x', scaled up by the estimated catchability) for one of the four CPUE strata, f1, h1, h2, and h3.



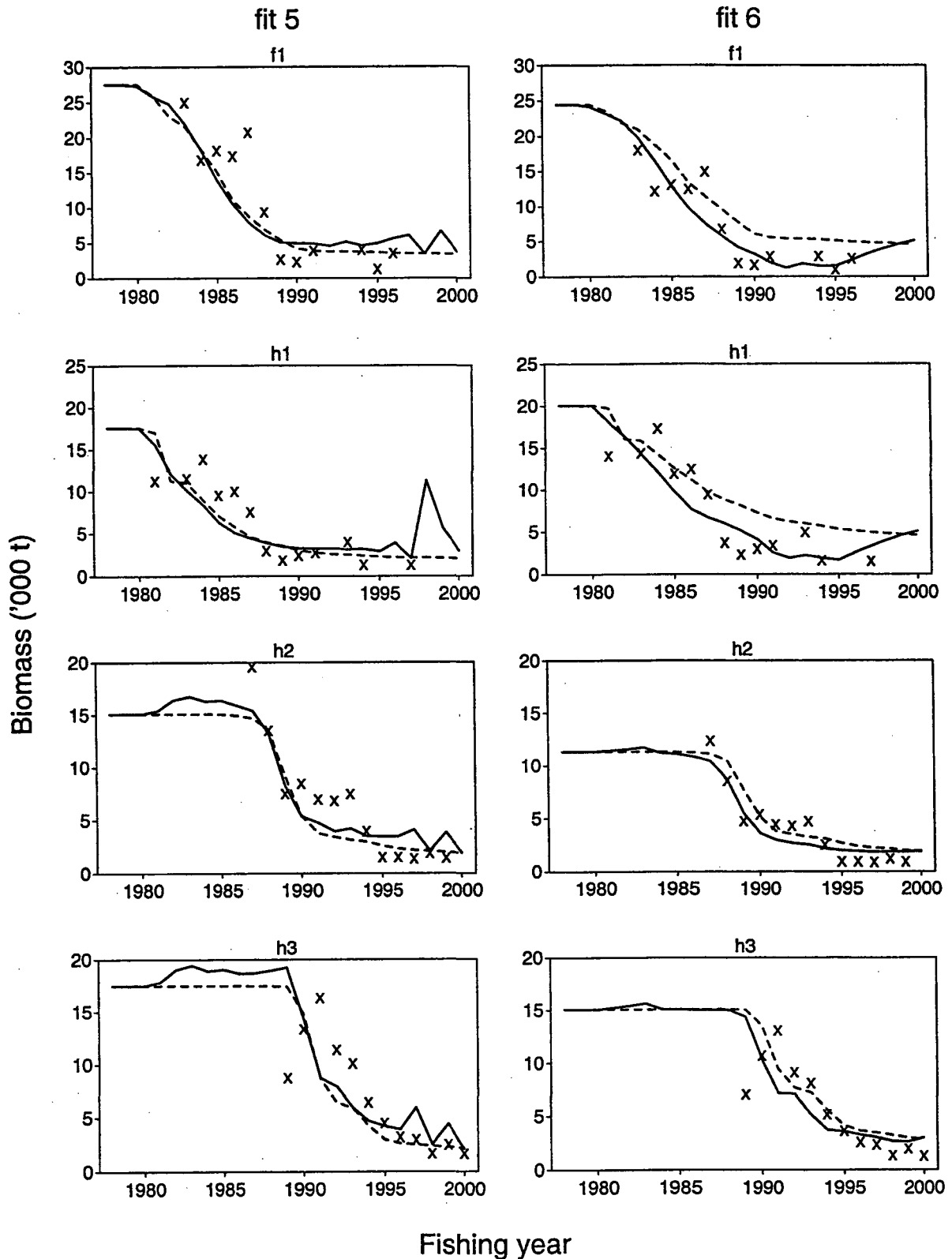


Figure 7: Illustration of fit 5 (left panels) and fit 6 (right panels) to the migration model (see Table 7 for description of these fits). Each panel shows the estimated biomass trajectory (solid line) and the CPUE data ('x', scaled up by the estimated catchability) for one of the four CPUE strata, f1, h1, h2, and h3. For fit 2 (where the carrying capacity was allowed to vary) the broken lines show the estimated carrying capacity for each stratum.

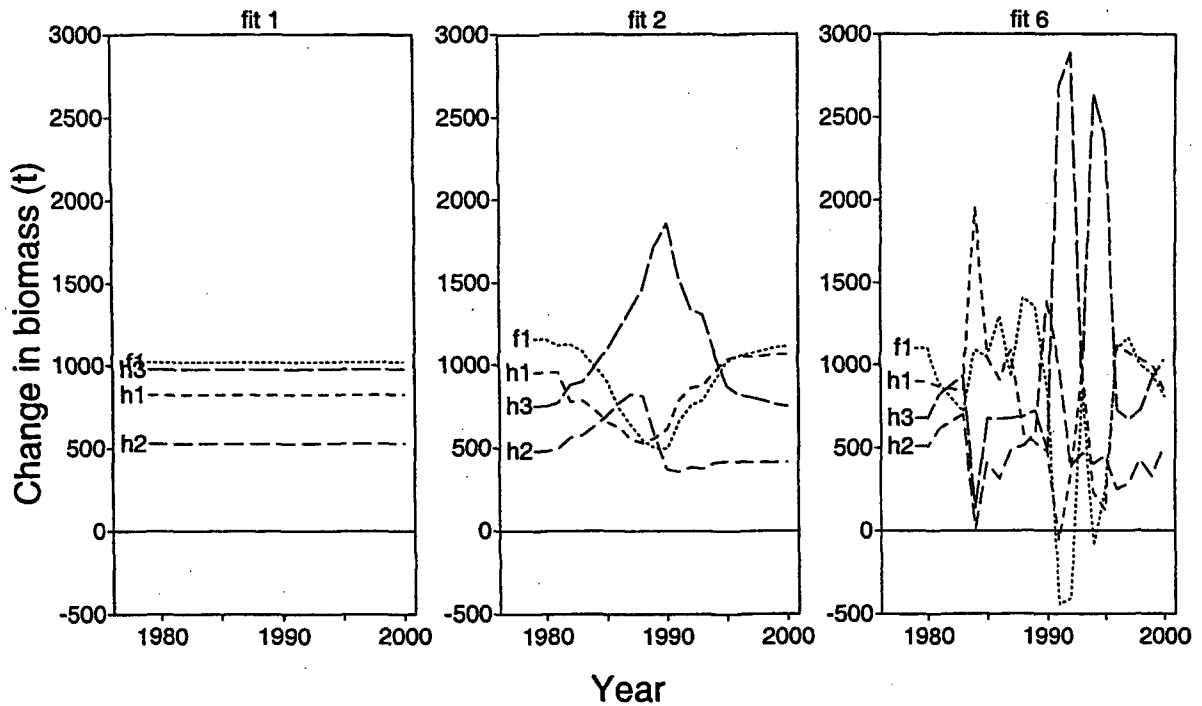


Figure 8: Annual changes in biomass, by area and year, caused by the combined effects of recruitment and migration in model fits 1, 2, and 6 (the three best fits).

A referee has pointed that there is no mechanism in the migration model to stop the biomass in any area exceeding its carrying capacity. This is discouraged (by setting to zero the allure of any area where this happens), but it is not prevented. In fact, the total biomass exceeds twice the total carrying capacity in fits 2 and 5. Nor is there any mechanism that would allow the stock to rebuild to a level higher than its pre-fishing level if trawling has increased carrying capacity. There are two ways in which these weaknesses in the model might have been avoided. One way would be to make the total recruitment for the South Rise in any year proportional to the total carrying capacity in that year (rather than to the original carrying capacity). Another possibility would be to allow an additional mortality on the recruited fish when there was insufficient carrying capacity for the current biomass (this might be called a *Lebensraum* mortality). These ideas certainly merit consideration but will have to await a future project. For the present model we should perhaps think of the quantity  $I$  as being a *relative* carrying capacity. Its role in the model is to modify both the way that recruitment is allocated between areas and also the direction and volume of migration between areas.

On the basis of the results in Table 7 I conclude that the migration and habitat modification components of this model are of no help in assessing the South Rise fishery. By themselves, neither type of migration (diffusion or spawning) improves the fit of our simple model (fit 1). Whenever the habitat modification component is included the estimated modification is implausibly extreme ( $h_{\max} = -0.9$ ), with biomass and carrying-capacity trajectories being similar. With this extreme modification the migration component of the model is dominated by changes in carrying capacity that are caused by habitat degradation. Further, the best fit (fit 2) is virtually identical, in terms of total estimated biomass, to that of the simple model.

### 5.3 The effect of catch overruns

In assessments of orange roughy on the Chatham Rise it is the usual practice to increase reported catches by an overrun factor (which is high for the early catches and low for recent catches — see below). Because of an oversight this was not done in the evaluation of the migration model that has just been described. However, when the stock assessment described in Section 6 (where catch

overruns were assumed) was repeated without overruns, the model fits were qualitatively very similar (though the biomass scale was changed). Thus it seems unlikely that the evaluation of the migration model would have been materially different had overruns been included.

## 6. STOCK ASSESSMENT

### 6.1 Model and assumptions

Having shown that the migration model (including habitat modification) is not useful for this assessment I revert to the simple model in which each of the CPUE strata is assessed separately and the resulting biomass trajectories are summed to produce an overall trajectory for the whole South Rise. For consistency I use the same population model (including age and sex structure) that has been used for the assessment of other orange roughy stocks. This uses all the biological parameters of Table 1 and has sometimes been applied with deterministic recruitment (i.e.,  $\sigma_R = 0$ , e.g., Francis & Bull 2000) and sometimes with stochastic recruitment (e.g., Francis 1999a).

Deterministic recruitment was assumed for the present assessment. Using stochastic recruitment would produce a somewhat better fit to the CPUE data. However, it seems inappropriate to use this more sophisticated model given that we are ignoring movement between our four strata (such movement undoubtedly happens but we have been unable to model it). Also, it is not possible with the present model to link recruitment in the four strata.

The catches used in the assessment were those of Table 4, multiplied by the estimated overruns in Table 8, which are the same as have been used in the northeast Chatham Rise (the Deepwater Working Group felt that there was no evidence to support the use of different overrun figures for the South Rise). To take the assessment up to the present year (2000–01) it was assumed that the catches in this year would be the same as those in the previous year.

Table 8: Catch overruns (%) by fishing year.

Year	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Overrun	30	30	30	30	30	30	30	28	26	24
Year	1989	1990	1991	1992	1993	1994	1995 & subsequently			
Overrun	22	20	15	10	10	10	5			

The model was applied separately to each of the four CPUE strata (f1, h1, h2, and h3) and the resulting biomass trajectories were combined to provide a trajectory for the whole fishery. It was fitted by maximum likelihood, with the CPUE indices being assumed to be lognormally distributed (see Appendix Section A.3 for equations).

### 6.2 Model estimates

The model fitted the four CPUE series moderately well (Figure 9), with biomass estimates ranging from 15 000 t to 30 000 t for virgin biomass ( $B_0$ ), and 15 % to 32% of  $B_0$  for current biomass (mid-year biomass in 2000–01) (Table 9) (the estimates of  $B_0$  are markedly higher than for fit 1 because of the inclusion of catch overruns — see Section 5.3). For stratum f1,  $B_0 = B_{\min}$ , which means that the exploitation rate in this stratum almost reached the maximum allowed level of 0.67 (in 1989). The maximum exploitation rates were also high in the other strata (0.46 in 1991 for h1, 0.51 in 1990 for h2, and 0.53 in 1994 for h3), but all current exploitation rates are estimated to be much lower (between 0.01 in f1 and 0.14 in h3).

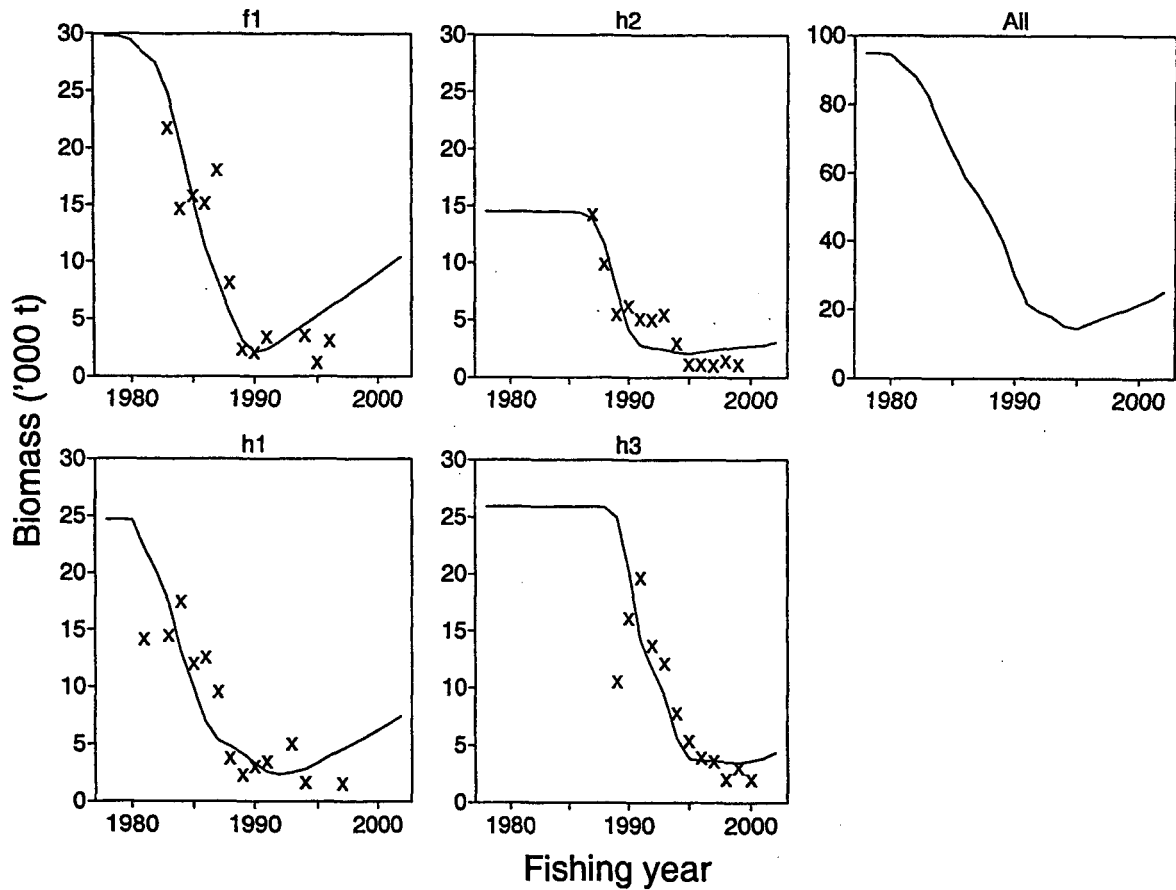


Figure 9: Estimated biomass trajectories, from the assessment model, for each of the CPUE strata (f1, h1, h2, and h3) and for all areas combined. Also plotted (as 'x') are the CPUE indices for each strata, scaled by the estimated catchabilities.

For all strata combined,  $B_0$  is estimated to be 95 000 t; the biomass is estimated to have reached a minimum of 14 400 t (15%  $B_0$ ) in 1995; and to have subsequently rebuilt to 23 100 t (24%  $B_0$ ) in 2000–01.

A bootstrap procedure (Cordue & Francis 1994) was used to estimate bootstrap distributions for each stratum, and these were summed (which assumes that CPUE sampling error is independent between strata) to produce a 95% confidence interval of (93 200,97 900) for  $B_0$ . These bounds are clearly too narrow to accurately reflect the uncertainty in this assessment (as is typical when the deterministic model is used for stocks that have been reduced to low levels).

Table 9: Model fits and estimated biomasses for the assessment model.

Stratum	Negative log-likelihood	Catchability	$B_0$ ('000 t)	$B_{2000-01}$	
				('000 t)	(% $B_0$ )
f1	19.2	$2.02 \times 10^{-4}$	30	9.6	32
h1	23.9	$3.62 \times 10^{-4}$	25	6.8	28
h2	22.1	$2.59 \times 10^{-4}$	15	2.8	19
h3	5.7	$2.13 \times 10^{-4}$	26	3.9	15
All	70.9	N.A.	95	23.1	24

It is reasonable to ask whether we should expect there to be as much variation in catchabilities as is seen in Table 9. However, there does not seem to be an easy answer to this question. The CPUE indices were all standardised to represent the expected catch rate for an "average" vessel fishing at a

“typical depth” in the given area (Francis 2001). Thus, the catchabilities may be thought of as being the proportion of the current biomass that would be caught by such a vessel fishing at the given depth (it is an assumption of the stock assessment that this proportion does not change over time or with changes in biomass). There is a difference in units of catch rate between f1 (t/hour) and the other areas (t/tow) so it is not sensible to compare catchabilities between f1 and the hill areas. Within the hill areas we have no difficulty with units but it’s not obvious how much variation in catchability is plausible. In a simple (and simplistic) model of a fishery we could think of fish as being evenly spread over the area and assume that the net caught all fish that it encountered. In this model the catchability would be equal to the area swept by the net divided by the stock area. If the net catches only a fraction of the fish it encounters then the catchability would be reduced by multiplication by this fraction. In a more realistic model, in which fish density varies throughout the area, the catchability will depend partly on how much the density varies and partly on how successful fishers are in targeting the areas of maximum density. We don’t know enough about these matters to come to any precise conclusion about how much catchability might vary between areas.

### 6.3 Yield estimates

Estimates of MCY, CAY, and MAY were calculated using the method of Francis (1992) (and allowing for assumed future catch overruns of 5%). MCY and CAY estimates are similar to South Rise catch levels in the five years since catch limits were last changed (range, 1134 to 1560 t) (Table 10). (Since 1995–96 the TAC for ORH 3B has been 12 700 t and the catch in the area comprising the Spawning Box, the East Rise, and the South Rise has been limited, by an agreement between the Minister of Fisheries and industry, to 4950 t.)

Table 10: Yield estimates (t).

MCY	CAY <sub>2001-02</sub>	MAY
1360	1540	1800

## 7. MANAGEMENT IMPLICATIONS

This assessment suggests that the current stock size is about 24% of the virgin size ( $B_0$ ) of 95 000 t. This is less than  $B_{MSY}$  (which, for orange roughy stocks, is normally interpreted as the mean biomass under a CAY policy — 30%  $B_0$ ). There is no separate catch limit for this area, but recent catches are similar to the estimated MCY and CAY, which suggests that they are sustainable and likely to move the stock towards  $B_{MSY}$ .

There is some doubt as to whether the stock biomass is rebuilding (as the model shows it to be) because none of the four CPUE series show any rebuild (see Figure 9).

Attempts to include a migration component in the assessment model (to allow movement amongst the four CPUE strata) were unsuccessful. However, because the model fits the data moderately well it seems unlikely that the addition of a migration component would radically change the assessment of the stock.

It is unlikely (see Section 2) that orange roughy within the South Rise constitute a distinct stock (as has been implicitly assumed for this assessment). However, the assessment would still be valid if we were to make the less stringent assumption that, although there may be interchange between the South Rise and the East Rise, the nett flow of fish is negligible. There is no information to either support or contradict this assumption but it seems defensible on pragmatic grounds (and is implicit in the assessment of northeast Chatham Rise orange).

## 8. ACKNOWLEDGMENTS

I am grateful to Ralph Coburn, on whose idea the spawning migration model is based, and to Dave Gilbert, for a most useful review of a draft of this report. This work was funded by Ministry of Fisheries research project ORH2000/02.

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## Appendix 1: Migration model equations

This appendix contains a complete mathematical description of the migration model (of Section 5) and how it was fitted. I first describe the main model equations, then those associated with migration and habitat modification, and finally the likelihood equations used in fitting the model. The likelihood equations are the same as are used in fitting the assessment model (of Section 6).

### A.1 Main equations

The main equations of the model are very simple. Let  $B_{0a}$  be the virgin biomass in area  $a$  and denote the biomass in that area at the  $i$ th stage of year  $y$  by  ${}_iB_{ya}$ . We will use three stages in each year:  $i = 1$  and 2 refer to the immediate pre- and post-migration periods;  $i = 3$  denotes the end of year (post-migration and post-catch).  ${}_2B_{ya}$  is calculated below, in the migration section; the other biomasses are calculated as follows.

The pre-migration biomass is given by

$${}_1B_{ya} = \begin{cases} B_{0a}S + R_{1a} & \text{if } y = 1 \\ {}_3B_{y-1,a}S + R_{ya} & \text{if } y > 1 \end{cases}$$

where  $S$  is a factor containing contributions from both natural mortality and growth,  $R_{ya}$  is recruitment, which is given by

$$R_{ya} = K_{ya} (1 - S) \frac{\sum_{a'} B_{0a'}}{\sum_{a'} K_{ya'}}$$

and  $K_{ya}$  is the carrying capacity of area  $a$  in year  $y$  (defined in the habitat modification section below). No stock recruit relationship is used because the duration of the fishery is less than the age at maturity of orange roughy (estimated to be 29 y on the Chatham Rise).

We need to distinguish between the reported ( ${}_{\text{rep}}C_{ya}$ , as in Table 4) and actual ( ${}_{\text{act}}C_{ya}$ ) catches. Often these will be the same, but  ${}_{\text{act}}C_{ya}$  will be less than  ${}_{\text{rep}}C_{ya}$  when there is insufficient biomass to support the latter. Thus,

$${}_{\text{act}}C_{ya} = \min({}_{\text{rep}}C_{ya}, {}_2B_{ya} E_{\text{max}}),$$

where  $E_{\text{max}}$  is the assumed maximum exploitation rate.

Finally, the end-of-year biomass is given by

$${}_3B_{ya} = {}_2B_{ya} - {}_{\text{act}}C_{ya}.$$

### A.2 Migration

In this Section we show how migration is modelled, or, in other words, how post-migration biomass,  ${}_2B_{ya}$ , is calculated from pre-migration biomass,  ${}_1B_{ya}$ . Because all the calculations take place within the same year we drop the year subscript in the Section. It is not straightforward, for either type of migration model, to calculate the optimum migration rates to maximise allure. Instead we take an approximate approach.

For the diffusion migration model we need to define the neighbourhood of each area to be the union of the area itself and all areas that are adjacent to it. Thus, for example, the neighbourhood of h1 is the union of h1, f1, and h2. Let  ${}_{nb}K_a$  and  ${}_{nb}B_a$  denote the carrying capacity and pre-migration biomass and, respectively, for the neighbourhood of area  $a$ .

Now, the pre-migration allure of area  $a$ , is given by

$${}_1A_a = \begin{cases} 1 - {}_1B_a/K_a & \text{for relative allure} \\ K_a - {}_1B_a & \text{for absolute allure} \end{cases}$$

(if the calculated allure is negative (because  ${}_1B_a$  exceeds  $K_a$ ) then it is set to zero).

Suppose, for the moment, that migration were restricted to the neighbourhood of area  $a$ . If there were no constraints on migration then, after the migration, all areas within this neighbourhood would have the same allure,  ${}_{eq}A_a$ . Given that the post-migration biomasses in this area must sum to  ${}_{nb}B_a$  (remember, we are, for the moment restricting migration to this neighbourhood) it is straightforward to show that

$${}_{eq}A_a = \begin{cases} 1 - {}_{nb}B_a/{}_{nb}K_a & \text{relative} \\ ({}_{nb}K_a - {}_{nb}B_a)/b_a & \text{absolute} \end{cases}$$

where  $b_a$  is the number of areas in the neighbourhood of area  $a$ . It follows, from the definitions of allure, that the post-migration biomass in area  $a$  that would make the allure equal to  ${}_{eq}A_a$  is given by

$${}_{eq}B_a = \begin{cases} (1 - {}_{eq}A_a)K_a & \text{relative} \\ K_a - {}_{eq}A_a & \text{absolute} \end{cases}$$

We can repeat this calculation for all areas, so that we end up with a value of  ${}_{eq}B_a$  for each area  $a$ . Now, all these biomasses are calculated on the assumption that there were no constraints on migration. We assume that, with partial migration, the post-migration biomass in area  $a$  will lie between  ${}_{eq}B_a$  and  ${}_1B_a$ . Specifically, we define

$${}_2B_a = p_{migr} ({}_{eq}B_a) + (1 - p_{migr}) {}_1B_a.$$

Thus, with no migration ( $p_{migr} = 0$ ) the allure of area  $a$  will remain unchanged at  ${}_1A_a$ ; with full migration ( $p_{migr} = 1$ ) it will change to  ${}_{eq}A_a$ .

There are two complications. First, it may turn out that  ${}_{eq}B_a$  is negative (this can happen only with absolute allure). When this happens we set it equal to 1 t. Second, we must make sure that biomass is conserved (i.e., no biomass gets lost or created!). We achieve this by re-scaling  ${}_2B_a$  by multiplying it by  $(\sum_{a'} {}_1B_{a'}) / (\sum_{a'} {}_2B_{a'})$ .

For the spawning migration model, the pre-migration allure is defined by

$${}_1A_a = \begin{cases} (1 - {}_1B_a/K_a)/D'_a & \text{relative} \\ (K_a - {}_1B_a)/D'_a & \text{absolute} \end{cases}$$



where  $D'_a = D_a^d / \sum_{a'} D_{a'}^d$ ,  $D_a$  is the distance from area  $a$  to the spawning ground, and  $d$  is a parameter to be estimated. Again, any negative allure is set equal to zero. If there were no constraints on migration then all areas would achieve the same allure,  ${}_{\text{eq}}A$ , given by

$${}_{\text{eq}}A = \begin{cases} (\sum_a K_a - \sum_{a'} B_{a'}) / \sum_a (K_a D'_a) & \text{relative} \\ (\sum_a K_a - \sum_{a'} B_{a'}) / \sum_a D'_a & \text{absolute} \end{cases}$$

The minimum post-migration biomass in area  $a$  is given by  ${}_{\text{min}}B_a = (1 - p_{\text{sp}})B_a$ . The amount of biomass that would have to be added to this to achieve allure equal to  ${}_{\text{eq}}A$  is given by

$${}_{\text{add}}B_a = \begin{cases} K_a (1 - {}_{\text{eq}}AD'_a) - {}_{\text{min}}B_a & \text{relative} \\ K_a - {}_{\text{eq}}AD'_a - {}_{\text{min}}B_a & \text{absolute} \end{cases}$$

Because the biomass in each area cannot fall below  ${}_{\text{min}}B_a$  we set  ${}_{\text{add}}B_a$  equal to zero in any areas in which it is negative. Then we calculate  ${}_2B_a$  as

$${}_2B_a = {}_{\text{min}}B_a + {}_{\text{add}}B_a (p_{\text{sp}} \sum_{a'} B_{a'}) / (\sum_{a'} {}_{\text{add}}B_{a'})$$

(the final ratio in this equation re-scales  ${}_{\text{add}}B_a$  so that it sums to the total spawning biomass).

### A.3 Habitat modification

The habitat modification part of the model determines how the carrying capacity of each area,  $K_{ay}$ , is changed by fishing. It is controlled by two parameters:  $h_{\text{max}}$  and  $r_{\text{hab}}$ .

The carrying capacity is calculated as

$$K_{ay} = \left[ 1 + h_{\text{max}} \left( 1 - e^{-r_{\text{hab}} N_{ay} / B_{0a}} \right) \right] B_{0a}$$

where  $N_{ay}$  is the total number of tows in area  $a$  in the years preceding (but not including) year  $y$ .

### A.4 Model fitting

The likelihood equations described in this Section apply both to the migration model (Section 5) and the assessment model (Section 6).

If  $I_{ay}$  is the CPUE index for area  $a$  in year  $y$ , and  $B_{ya}$  is the corresponding biomass (assumed equal to  ${}_2B_{ya} - 0.5_{\text{act}}C_{ya}$  in the migration model), then we assume that  $I_{ay}$  is lognormally distributed with mean  $q_a B_{ya}$  and c.v.  $c_{ay}$ , where the  $c_{ay}$  are assumed known but the catchabilities,  $q_a$ , are to be estimated. It is convenient to let  $\mu_{ay}$  and  $\sigma_{ay}$  denote the mean and s.d. of  $\exp(I_{ay})$ , which means that  $\sigma_{ay} = \sqrt{\ln(1 + c_{ay}^2)}$  and  $\mu_{ay} = \ln(q_a B_{ya}) - 0.5 \sigma_{ay}^2$ .

Now, the negative log-likelihood,  $\lambda$ , is given by

$$\lambda = \sum_{ay} \ln(\sigma_{ay} I_{ay}) + 0.5 \sum_{ay} \left( \frac{\ln(I_{ay}) - \mu_{ay}}{\sigma_{ay}} \right)^2$$

$$\text{so } \lambda = \sum_{ay} \ln(\sigma_{ay} I_{ay}) + 0.5 \sum_{ay} \left( \frac{\ln(I_{ay}/B_{ay}) - \ln(q_a) + 0.5\sigma_{ay}^2}{\sigma_{ay}} \right)^2 \quad (\text{A1})$$

(ignoring constants). For a given set of  $B_{ay}$  we can calculate the maximum likelihood estimate of  $q_a$  by: differentiating by  $q_a$ , setting the derivative equal to zero, and solving for  $\ln(q_a)$ . This leads to

$$\ln(q_a) = \frac{\sum_y \left( \frac{\ln(I_{ay}/B_{ay})}{\sigma_{ay}^2} \right) + 0.5n_a}{\sum_y \sigma_{ay}^{-2}} \quad (\text{A2})$$

where  $n_a$  is the number of years in which there is a CPUE index in area  $a$ .

Given a set of model parameter values (that is, values of  $\{B_{0a}, p_{\text{migr}}, h_{\text{max}}, r_{\text{hab}}\}$  for the diffusion migration model, or of  $\{B_{0a}, d, h_{\text{max}}, r_{\text{hab}}\}$  for the spawning migration model, or of  $\{B_{0a}\}$  for the assessment model) and the known  $c_{ay}$  (from which we calculate the  $\sigma_{ay}$ ) we can calculate  $\ln(q_a)$  using equation (A2), and then  $\lambda$  using equation (A1). The models are fitted by searching for sets of parameter values that maximise  $\lambda$ .