Assessment And Adaptive Management Of Orange Roughy Off Southern Africa

by

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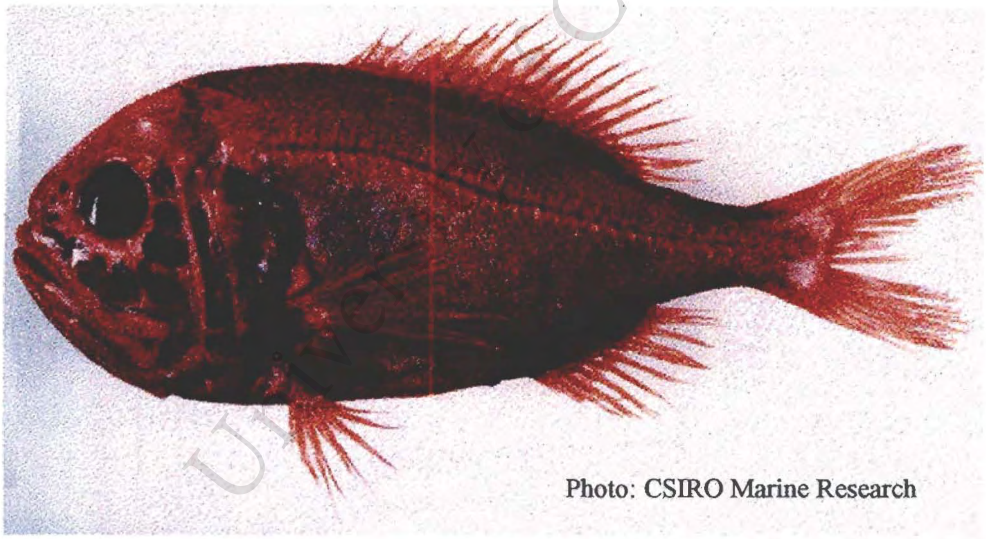

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Assessment And Adaptive Management Of Orange Roughy Off Southern Africa

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When Jesus had finished speaking, he said to Simon, “Put out into deep water, and let down the nets for a catch.”

Simon answered, “Master, we’ve worked hard all night and haven’t caught anything. But because you say so, I will let down the nets.”

When they had done so, they caught such a large number of fish that their nets began to break.

Luke 5 v 4–6

Abstract

Exploratory fishing off southern Africa for deepwater fish species (at depths > 500 m) started in earnest in 1994. The most sought after of these species is the orange roughy (*Hoplostethus atlanticus*), which has provided the basis for lucrative trawl fisheries in New Zealand and Australia. Orange roughy form dense aggregations, especially during the spawning season, from which catch rates may reach 50 tonnes per minute of trawling with the net on the seabed. Orange roughy have many features of a K-selected species: extreme longevity (> 100 years), slow growth rate, low fecundity and poor productivity, although some of these estimates are controversial. All of these factors conspire to make orange roughy easily susceptible to over-fishing.

Discoveries of fishable aggregations of orange roughy were made off Namibia in January 1995. In a short period of time, the annual catch became the second greatest in the world after New Zealand, and management advice for this fishery was urgently needed. In the absence (at that time) of scientific surveys that typify management in the more established fisheries off Australia and New Zealand, another approach was needed at the onset of the fishery.

A swept-area methodology was developed which could be applied to the available commercial data. Swept-area biomass estimates were made and then corrected for the most factors thought to introduce bias, for example adjustment for the directed nature of the commercial data. Open discussion was held during two meetings in Namibia in January 1997 to decide on the values for these bias factors. Representatives of the exploratory fishing company and the Namibian fisheries ministry, and two international scientists were present at these meetings. Two final sets of specifications gave median biomass estimates of 306 000 t (CV = 34%) and 321 000 t (CV = 29%). An estimated 38–42% of this biomass was found inside four high-density aggregations, while the remainder was sparsely distributed around the Namibian coast.

The swept-area methodology was later used in South Africa to assess their stocks of orange roughy (estimated median biomass 18 200 t; CV = 73%), and, with some changes in the bias factors, their stocks of oreo dories (mainly warty oreo dory, *Allocyttus verrucosus*) (39 200 t; CV = 90%). Oreo dories have similar population parameters to orange roughy, sharing their longevity and low productivity. There are few indications of the potential for a substantial fishery off South Africa in either case.

The Namibian results were taken further, using a population model to simulate a fishing-down period of 14 years, comprising seven years of constant catches followed by a linear decline in catches to the MSY. Advice was given about the risk to the fishery of different levels of catches in the first seven years. This simple approach did not take into account the learning that would result from planned future acoustic surveys. An adaptive management approach based on Smith (1993) was therefore investigated, with different decision rules which used a simulated series of acoustic indices, to estimate pristine biomass and to decide on appropriate catch levels. This approach is shown to reduce the estimated risk of over-fishing substantially. A number of different decision rules were modelled before two were chosen. Performance criteria included total catch, risk to the fishery and year-to-year fluctuation in catches.

The advice given on the basis of the swept-area methodology played an important role in setting the 12 000 t TAC for Namibian orange roughy in the 1997–98 fishing season, and in the development of a management policy for deepwater species off South Africa. Nevertheless, independent biomass estimates from techniques such as the planned acoustic surveys would greatly increase the reliability of the estimates presented here. Acoustic surveys would also be ideal inputs for an adaptive management approach to the fishery. The assessment methodology (Chapters 3–7) and the long-term adaptive management approach (Chapter 8) are certain to continue to play a central role in the future management of Namibian orange roughy.

1. Introduction

This species is an oddity. That is probably the most apt description that can be made of orange roughy (*Hoplostethus atlanticus*). Orange roughy are thought to be extremely long-lived (> 100 years), only reaching maturity after 30 years. In addition, they form dense aggregations where catches of 40–50 t are possible for just a few minutes of bottom time. These two attributes alone make orange roughy susceptible to over-fishing. On top of that, orange roughy are slow-growing and have very low fecundity, which delays the recovery of stocks that have been heavily fished.

The market price for orange roughy is extremely high: with fillets currently selling for US$8.80–9.20 per kilogram (New Zealand Fishing Industry Board 1996; G. Patchell, pers. comm.), or US$2 750 per greenweight tonne (G. Patchell, Sealord Group, New Zealand, pers. comm.). These prices drive a lucrative fishery. Orange roughy aggregations therefore represent untapped sources of wealth, which have fuelled extensive exploratory fishing off New Zealand, Australia and southern Africa. Fishers use advanced technology to locate and exploit the stocks because of the great depths (500–1 500 m) and hard rocky grounds occupied by orange roughy. Once aggregations are found, they can be exploited easily, especially because the catch rates are so high.

Exploratory permits were issued in both Namibian and South African waters in 1994–95. Little orange roughy has been discovered off South Africa, but the Namibian findings are considerable, and the fishery there is the second-largest in the world after New Zealand. There was therefore an urgent need to manage that resource in a responsible manner. Paralleling the orange roughy discovery off Namibia was the discovery of commercial quantities of warty oreo dory (*Allocyttus verrucosus*) off South Africa, which also required assessment advice.

1.1 History of orange roughy fisheries

Major orange roughy trawl fisheries have developed in New Zealand (1979), Australia (1989), North-east Atlantic (1991) and Namibia (1994).

New Zealand

Fishing by the USSR of orange roughy off New Zealand started in the late 1970s, but the domestic fleet now controls that fishery. Exploitation focused in the "Spawning Box" on the Chatham Rise for the first few years of the fishery, but has spread to a number of other areas around New Zealand as new grounds have been found at regular intervals (Clark 1995a). Annual reported catches from 1983–84 to 1989–90 were 40 000–55 000 t, but had fallen below 21 000 t by 1995–96 (Figure 1.1). The target biomass level in New Zealand is 30% of the pristine biomass (Annala & Sullivan 1997), but many stocks are already thought to have fallen below this level, including the Mid-east Coast, North-east Chatham Rise, Puysegur, Challenger Plateau and Cook Canyon stocks (Annala & Sullivan 1997).

Australia

After limited success from 1985–88, a major spawning aggregation was discovered off eastern Tasmania in 1989 and further non-spawning aggregations were located off southern Tasmania in 1990. Catches ranged from 26 000–54 000 t per year from 1989–92 (Figure 1.1) before management action, including the imposition of TACs, halted the orange roughy rush. The reduction to 4 120 t in 1996 (Figure 1.1) was required to satisfy the Australian management objective: to maintain the spawning biomass of orange roughy above 30% of the 1988 spawning biomass. A rebuilding strategy is underway since there is already a 52–87% probability that the biomass of orange roughy is below 20% of the pristine biomass (Bax 1997).

North-east Atlantic

No high-density aggregations have been discovered in this region, but orange roughy is landed as a bycatch to other fisheries (J.D. le Garrec, Glomar Fishing, Namibia, pers. comm.). French vessels landed over 3 000 t of orange roughy in 1991 (Clark 1996a), but catches have subsequently fluctuated around 2 500 t per year (J.D. le Garrec, Glomar Fishing, Namibia, pers. comm.).

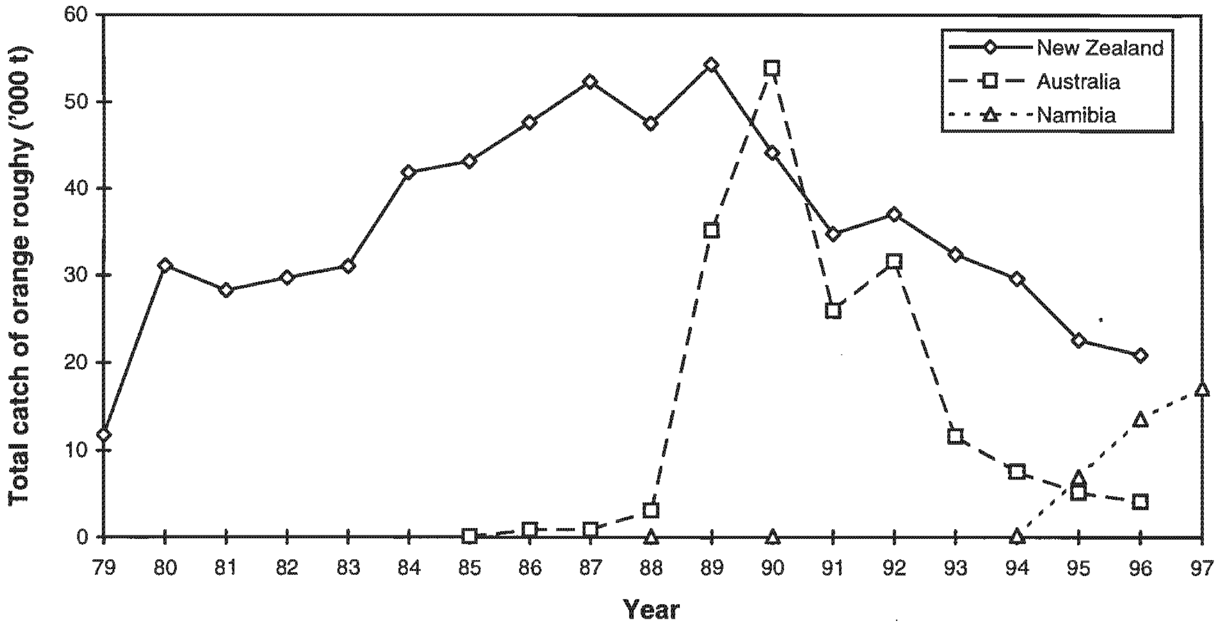

Figure 1.1 Catch history for orange roughy off New Zealand, Australia and Namibia. Catches elsewhere in the world are smaller and more sporadic. The New Zealand fishing season ran from 1 April to 30 March from 1978–79 to 1983–84, and from 1 October to 30 September thereafter; the catches shown here correspond to the year in which each season ended. Australian and Namibian data are for calendar years. Overruns are not incorporated for New Zealand or Namibia, but are included for Australia. For assessment purposes, the New Zealand overruns are assumed to be 30% until 1983–84; gradually reduced to 10% in 1991–92 and reduced further to 5% after 1994–95 (Annala & Sullivan 1997). Namibian catches do not include those made in December 1997. In addition, information is not yet available from all trips in 1996 and 1997. An estimated 2 131 t in 1996, and 2 138 t in 1997, were made during these trips; these catches have been added to reported catches for Namibia in 1996 and 1997 respectively. Data for New Zealand are from Annala & Sullivan (1997); for Australia, Bax (1997); and for Namibia, from a database collated by R.D. Roberts (UCT, South Africa) which was used in the 1998 Namibian stock assessments.

Namibia

Only small catches were made before 1994 when an exploratory permit was issued for orange roughy. Substantial catches were made only after the discovery of the Hotspot and Johnies aggregations in 1995, and Rix and Frankies regions in 1996 (which were further extended in 1997). Total catches in 1995–97 were 6 976 t, 13 617 t and 17 144 t (Figure 1.1). The 1996 catches were worth about US$40 million (MFMR 1996), constituting 2.6% by value of the total Namibian exports in that year (Namibian Ministry of Trade and Industry 1997). These figures underline the importance of orange roughy to the Namibian economy. The exploratory phase of the fishery ended in April 1997 when a TAC of 12 000 t was set for the 1997–98 season. Fishing effort has been kept deliberately low throughout the development of the fishery, with the number of vessels never exceeding five.

1.2 Survey methods: their advantages and disadvantages

Surveys can be used in one of two ways: as an estimate of absolute biomass, or as a relative index of abundance. A survey result can be used as an absolute estimate if it is close to the true biomass value (i.e. accurate). This information is most useful near the start of a fishery, as an initial estimate of pre-exploitation biomass (B_0). A relative index, on the other hand, needs to be precise (indicated by a low CV) and capable of reliably tracking changes in the biomass as catches are made. A relative index is related to the true biomass by some (hopefully constant) factor, usually denoted by q. Given a series of relative indices, a biomass model, and the catch history, it is possible to estimate the values of q and B_0; the resource depletion can then be estimated in turn. Egg surveys and acoustic surveys are generally regarded as providing reliable absolute estimates of biomass; while trawl surveys, acoustic surveys and catch-per-unit-effort analysis have been used as relative indices. A review of survey techniques in New Zealand is provided by Clark (1996b); his review provides the backbone of this section.

Trawl surveys

Trawl surveys have been extensively used for orange roughy, particularly in New Zealand. They are used only as relative estimates of abundance, primarily because the reaction of orange roughy to trawling gear is poorly understood. Clark (1996b) reports the results of 24 trawl surveys off New Zealand; Evans & Pullen (1986) and Bulman *et al.* (1994) describe two trawl surveys off Australia. A two-phase stratified random survey is usually used on flatter areas because it provides estimates with low CVs (Francis 1984); on seamounts, the methodology involves tows in random directions starting on the hilltops (Clark 1994). Trawl surveys have shown strong trends in biomass on the Chatham Rise and Challenger Plateau, with CVs generally from 11% to 27% (Clark 1996b). However, the two most recent trawl surveys on the Chatham Rise had CVs of 34% (1992) and 67% (1994), perhaps because of very low biomass levels (Clark 1995a; Francis *et al.* 1995) or because fishing, which may disrupt the stability of orange roughy aggregations (Clark & Tracey 1991), was markedly reduced. Trawl surveys on the Chatham Rise have therefore been discontinued. An additional problem on the Chatham Rise was that the trawl surveys were restricted to a small area (the Spawning Box) which was thought to index the whole of the Chatham Rise. However, this assumption is no longer believed to be valid (Annala & Sullivan 1997). Trawl survey series elsewhere in New Zealand have been difficult to interpret, because different vessels were used in different years. For example, the East Coast surveys from 1986 to 1991 are not used in stock assessments because they were not regarded as comparable (Field *et al.* 1994). Off Australia, trawl surveys have produced unreliable results, primarily because little trawling was done on rough ground. For example, Bulman *et al.* (1994) estimated orange roughy biomass at 5 044 t in a region where an aggregation with a pristine biomass of about 100 000 t was later discovered (Kloser *et al.* 1996). Trawl surveys have therefore been viewed in an unfavourable light by both industry and scientists in Australia (Ross & Smith 1997).

Trawl surveys do, however, have a number of advantages: the methodology is well-established, results are quickly calculated, and specialised equipment and vessels are not required. They also provide a method for assessing biomass outside the dense aggregations, which egg and acoustic surveys are unable to do. However, the range of bottom types can cause problems: orange roughy may be present on flat grounds, on the tops and sides of seamounts, and near deep canyons. Gear performance and fish catchability (*q*) can vary on these different features. The very high densities can also cause gear saturation, and provide problems with processing time in the short time available for the surveys.

CPUE analysis

In any fishery, a vast amount of commercial data is available for analysis. Usually, some form of catch-per-unit-effort (CPUE) analysis provides a relative index of abundance that is presumed to track changes in abundance. A method of standardising these indices for vessel type, power and nationality was developed by Doonan (1991), but the pattern of change is generally similar for standardised and unstandardised (e.g. t/tow) measures of CPUE (Clark 1996b). CPUE indices for New Zealand indicate dramatic declines in biomass, with stocks fished down to 2–8% of the initial biomass for the Chatham Rise, Challenger Plateau, Ritchie Banks and Cook Canyon (Clark 1992; Clark & Tracey 1994; Field *et al.* 1994; Clark & Field 1995). Such declines are more precipitous than those estimated by stock reduction analyses, and have not proven very reliable for estimating orange roughy stock size in either New Zealand or Australia (Clark 1996b; Koslow *et al.* 1997). A number of other factors combine to cast doubt on the validity of using CPUE data other than as a general indicator of the health of the fishery (Clark 1996b; Clark 1996a). Nevertheless, this technique is used to provide assessment advice for orange roughy south of Tasmania, Australia (Koslow *et al.* 1997).

Egg surveys

Egg surveys have been used off New Zealand and Australia to estimate spawning stocks of orange roughy. Two methods are in use: the daily fecundity reduction method (DFRM) developed by Lo *et al.* (1992) and the annual egg production method (AEPM) (Saville 1964).

The DFRM has been used to assess the New Zealand Ritchie Banks and East Cape spawning grounds. The Ritchie Banks estimate was 45 000 t with a CV of 40% (Field *et al.* 1994), but this was later revised to 30 000 t after a number of additional aspects were incorporated in the estimate (Clark 1996b). In the Eastern Cape, the DFRM estimate was successfully used to obtain a biomass estimate with a CV of 46%, which proved to be of great importance in reducing the total allocable catch in that fishery (Zeldis *et al.* 1997). The AEPM method was applied to the Australian St Helens aggregation, obtaining an estimate congruent with acoustic and stock reduction analyses, with a CV of 41–47% (Koslow et al. 1995a). It is likely that the AEPM method is more robust because it does not require assumptions about fish turnover in the aggregations, but it requires the whole spawning period to be covered, needing up to six weeks of vessel time (Clark 1996b).

Egg surveys are thought to give good estimates of absolute biomass, but typically have very high variance, making them unsuitable as a basis for relative indices. Survey design and data analysis can also be complicated. Specialised equipment and experienced staff are required, and sampling must be intensive in and around the core area (Clark 1996b).

Acoustic surveys

Since orange roughy form dense aggregations, they appear to be ideal candidates for acoustic surveys. Acoustic equipment is described in Do & Coombs (1989) and Kloser *et al.* (1996). Acoustic surveys provide excellent relative indices of abundance, but there are a number of factors which make their estimates of absolute abundance questionable.

The Chatham Rise was acoustically assessed in 1986 and 1995. Estimates of 266 000 t (CV = 66%) (Do & Coombs 1989) and 20 000 t (CV = 34%) (Clark 1996b) were obtained, but the former survey was intended as a pilot project only. The St Helens aggregation off Australia was assessed from 1990 to 1993, with very low sampling CVs (7–15%), making them ideal for relative indices of abundance there.

There are many potential sources of bias when attempting to estimate absolute biomass from acoustic surveys. Because of these biases, CVs of around 40% were assigned to the St Helens estimates for stock assessments (A.D.M. Smith, pers. comm.). Problems with target strength[1] are notorious—orange roughy have low target strength due to their swim bladders being oil-filled instead of gas-filled (Do & Coombs 1989). Estimates of target strength have altered from -36.0 dB, based on dead orange roughy in a tank (Do & Coombs 1993), to -41 dB using the reduction in mean backscatter during commercial fishing (Elliott & Kloser 1993) to final values of -47.2 dB (using modelling) or -53 dB (tethered at depth) (Kloser *et al.* 1997). Dominant modes *in situ* at -50 dB have been partially attributed to orange roughy (Kloser *et al.* 1997), and unpublished work by McClatchie *et al.* also supports a target strength of -50 dB. Attempts to obtain target strengths of single fish *in situ* have been unsuccessful because the fish display marked avoidance (Koslow *et al.* 1995b).

Another major problem is the acoustic dead-zone[2] for orange roughy. This region may be 7–24 m at the centre of the beam on hills with slopes of 10–20° (Cordue 1996a), but reduces to 2–6 m when deep-towed transducers are used. On St Helens, the mean shadow zone was up to 24–32 m on the steepest regions, but a deep-towed transducer reduced this zone to a maximum of 14–16 m (Kloser 1996; Kloser *et al.* 1996). A vessel-mounted transducer could underestimate biomass by a factor of 1.4–2.0 (Kloser *et al.* 1996). On flat ground the dead zone is much reduced.

Acoustic backscatter cannot always be attributed to orange roughy, since other species may also be associated with orange roughy aggregations (Do & Coombs 1989; Elliott & Kloser 1993). This problem is exacerbated by the low target strength of orange roughy: Kloser *et al.* (1997) estimate that a single 50 cm morid cod may have an effect equivalent to 79 orange roughy. Trawling must therefore accompany acoustic surveys to determine the composition of aggregations of fish. Trawling is not an ideal way to address this fault:

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[1] Target strength is the ratio of the reflected (echo) intensity at 1 m from the organism to the intensity that strikes it.

[2] The dead zone is a zone just above the sea bottom where fish cannot be detected because their echoes are obscured by the arrival of the leading edge of the bottom echo.

problems of avoidance (Koslow *et al.* 1995b) and herding (Kloser *et al.* 1997) may bias trawl compositions. Multi-species aggregations may occur on untrawlable ground, thwarting the determination of species composition—this problem prevents acoustic surveys being used in feeding aggregations south of Tasmania, Australia (Koslow *et al.* 1997).

Despite all these problems, the extensive acoustic series on St Helens provides absolute estimates of biomass which concur with estimates obtained from an egg survey, and with stock reduction analyses. Acoustic estimates appear to be the best available method to monitor orange roughy stocks.

1.3 Assessments of southern African deepwater fisheries

The orange roughy fishery off Namibia had become quite lucrative by mid-1996, with a single exploratory permit granting rights to a fishing company called Gendor Fishing. There was pressure from other fishing companies to open up the fishery, and also pressure from the Namibian fisheries ministry to ensure that orange roughy was used sustainably in their waters. There was particular concern given the history of rapid over-exploitation that characterised the Australian orange roughy fishery and, to a lesser extent, the New Zealand fishery. At that time, no surveys had been performed in southern Africa, nor were there plans to start a survey series. The only data available came from the commercial vessels operating under Gendor.

Against that background, this thesis focuses on the development and application of a swept-area methodology. In Chapter 2 the biology and stock structure of orange roughy is outlined to provide context for the rest of the thesis. In Chapter 3 the swept-area technique is described. This technique was designed to provide the best possible advice on the basis of limited (commercial) data. This technique was then applied to the Namibian orange roughy fishery to obtain bias-corrected swept-area estimates (Chapter 4).

Concurrently with these developments, there was pressure in South Africa to open up the fishery to more than the existing two permit-holders (Suidor Fishing and Atlantic Fishing) (Tilney 1997). Despite the virtual absence of orange roughy there, 1 700 t of oreo dories had been landed, mainly warty oreo dory (*Allocyttus verrucosus*). The methodology developed for the Namibian orange roughy assessment in Chapters 3–4 was applied to South African orange roughy (Chapter 5) and South African oreo dories (Chapter 6). These analyses indicated that the South African deepwater species could not support a major fishery unless aggregations of orange roughy were discovered. Accordingly, the South African assessments were not taken further.

The Namibian stocks showed greater promise, and therefore required more in-depth management advice. Further analyses were undertaken (Chapter 7) to explore the effect of various types of simple fishing-down strategies on the biomass estimates obtained in Chapter 4. with the aim of providing better management recommendations for the fishery. These simple fixed trajectories were conservative since they did not allow for learning from future surveys, and the initial risk assessment was therefore unduly pessimistic. Further work was done to develop a more sophisticated "adaptive management" approach which incorporates a simulated future time series of acoustic indices of abundance (Chapter 8). That chapter provides a more realistic indication of the risks of alternative catch control laws. The first actual acoustic survey in the series was performed in July 1997 (Huse *et al.* 1997).

1.4 Overall aims

The aims of this thesis were two-fold. First, to provide the best possible estimates of biomass for deepwater species off Namibia and South Africa, given the absence of surveys at that time. Secondly, to use these estimates to provide management advice for their developing fisheries.

This thesis also performs a subsidiary function as an historical record of the assessment process used for orange roughy (and oreo dories) off southern Africa. The historical bias in the thesis has been variously described as "tedious and repetitive in places" and as "most interesting and informative". Readers who might become bored with these historical details should feel free to skip over (in particular) Sections 4.4–4.7 and 7.3–7.7.

1.5 Commonly used terms and abbreviations

Throughout this thesis, the following terms are used in a consistent manner. To avoid confusion, definitions are included here.

Biomass: spawning biomass, excluding the biomass of juvenile fish. In this thesis, since the age at recruitment to the fishery is assumed to be the same as the age at maturity, it is also the fishable biomass.

Collapse: refers to any case where the fishable biomass is less than the TAC for that year.

Deepwater: this term is used throughout to describe the orange roughy and oreo dory fisheries, which occur in mid-slope waters.

DWFWG: the (Namibian) Deep Water Fisheries Working Group.

MSY: Maximum Sustainable Catch.

MSYL: biomass level at which the MSY is obtained.

NatMIRC: the (Namibian) National Marine Information and Research Centre.

Pdf: Probability density function, a function for which the total area under the curve is exactly 1. If representing a biomass estimate, the area under the curve between two specific biomass values gives the probability that the biomass lies between those two values.

Probability interval (or "credibility interval"): a region in parameter space delimited by upper and lower bounds within which there is a specified probability that the parameter (or parameters) fall. This (Bayesian) term is distinct from "confidence interval" which is obtained using standard sampling theory.

SFRI: the (South African) Sea Fisheries Research Institute.

Significant: always refers to statistical significance at the 5% level.

Southern Africa: in the context of this thesis, South Africa and Namibia.

Strata-name: the names of the swept-area strata are italicised. However, when Hotspot, Rix, Frankies and Johnies refer to fishing grounds, and not narrowly defined strata, they are not italicised.

Surveys (absolute or relative estimates): surveys may give a point estimate of biomass (absolute estimate, e.g. 200 000 t) or may only estimate changes in the biomass (relative estimate, e.g. survey results of 1.00, 0.80 and 0.63 indicate that the biomass declined by 37% over the course of the surveys).

TAC: Total Allowable Catch.

2. Review of the biology and stock structure of orange roughy

This section provides a brief summary of research on the biology and stock structure of orange roughy. Oreo dories are not the main focus of this thesis, but the resource off South Africa is assessed in Chapter 6, which includes a short summary of their biology (Section 6.2). Salient features of orange roughy biology include their very low fecundity, slow development and extreme longevity. These characteristics, combined with their habit of forming extremely dense aggregations, make them potentially susceptible to over-fishing.

2.1 Habitat and identification

Orange roughy are found world-wide at depths of 500–1 800 m (Paulin 1979; Bell *et al.* 1992). Commercial exploitation occurs at depths of 800–1 200 m off Australia, New Zealand and Britain (Merrett & Wheeler 1983; Coburn & Doonan 1994; Ross & Smith 1997), but at 600–800 m off Namibia (Clark 1997). Throughout their distribution, orange roughy occur in water temperatures of 3–9°C but most large catches are recorded in 4.5–6.5°C water, typical of Antarctic Intermediate Water (Clark 1997; this study). The water temperature, and not the depth, may therefore be an important factor affecting their distribution. Aggregations are usually found on topographical features (e.g. seamounts or canyons) on hard ground, but dispersed orange roughy are also caught in areas of soft bottom. The fish is bright orange. Adults typically have a standard length (SL) of 20–40 cm (Paulin 1979), although this varies from region to region, and specimens up to 60 cm have been reported in the North-east Atlantic (Merrett 1989; Du Boit 1995). Despite these length differences, orange roughy stocks world-wide constitute a single species—*Hoplostethus atlanticus* Collett 1896—in the family Trachichthyidae within the order Beryciformes. A formal description and identification key for the trachichthyids off New Zealand is included in Paulin (1979). None of the other *Hoplostethus* species is of commercial interest.

2.2 Reproduction and egg development

Orange roughy are synchronous spawners which form dense aggregations within which spawning occurs over a period of 2–3 weeks, usually starting in mid-July in the Southern Hemisphere (Pankhurst & Conroy 1987; Pankhurst *et al.* 1987; Pankhurst 1988; Bell *et al.* 1992; Zeldis 1993). Occasionally, spawning starts in June (Bell *et al.* 1992). There is separation of the sexes in these spawning aggregations, with some indications that the females remain in deeper water than the males (Pankhurst 1988; Francis 1996). Not all mature females spawn every year—during the spawning season, up to one-half of the adult population remains outside the aggregations (Bell *et al.* 1992; Zeldis *et al.* 1997).

Absolute fecundity is low around Australia and New Zealand, with reported means ranging between 28 180 and 49 530 eggs/female. Similarly, relative fecundity is also low: 22 000–49 000 eggs/kg body mass (Pankhurst & Conroy 1987; Clark *et al.* 1994; Koslow et al. 1995c). Higher absolute fecundities of 70 000–380 000 eggs/female have been reported for larger individuals (SL 43–53 cm) in the North-east Atlantic (Du Buit 1995), which translates to a similar 28 000–88 000 eggs/kg body mass. There has been no evidence of a fecundity increase to compensate for over-fishing on the Challenger Plateau (Clark *et al.* 1994), although fecundity increased significantly off eastern Tasmania after a decline in stock size (Koslow et al. 1995c). There appears to be a slight decline in fecundity after the age of 60 (Koslow et al. 1995c), but this relationship is weak.

Orange roughy eggs usually have a single big bright-orange oil droplet, with a diameter of 2.0–2.5 mm (Pankhurst & Conroy 1987; Bulman & Koslow 1995; Du Boit 1995), larger than that of 82 of the 84 fish species listed in Pauly & Pullin (1988). The eggs are highly buoyant and rise to about 200 m at estimated rates of 12.5–23.8 $m.h^{-1}$ (Bulman & Koslow 1995; Zeldis *et al.* 1995). Most egg development occurs at this depth before the eggs lose their buoyancy and sink, probably hatching near the ocean bottom (Bulman & Koslow 1995; Zeldis *et al.* 1995). Egg distribution is extremely patchy, decreasing to 1/1000th of the density just 10–15 km from spawning centres (Zeldis 1993). Time to hatching has been estimated at 175 h under natural conditions (Bulman & Koslow 1995), and in the laboratory is 312 h at 7°C (Bulman & Koslow 1995) and 235 h at 10°C (Zeldis *et al.*

1995). The hatched orange roughy do not start feeding for about a month (Grimes & Zeldis 1993). Orange roughy in the 0+ and 1+ cohorts have only been found on the North Chatham Rise, 50–175 km from the main spawning aggregation (Zeldis *et al.* 1995), and also recently at Frankies off Namibia (B.I. Staaleson, pers. comm.). Young orange roughy have extremely slow growth rates, with validated standard lengths of 3.1, 5.5 and 7.6 cm for ages 1, 2 and 3 years (Mace *et al.* 1990).

2.3 Ageing studies: a continuing controversy

A wide range of ages has been ascribed to orange roughy, and there has been continued controversy in this area of research. For assessment purposes, orange roughy are usually presumed to be extremely long-lived (Lyle 1994; Annala & Sullivan 1997; this thesis). To some extent, this presumption is based on a precautionary approach (FAO 1997), since an extremely long-lived species would be much more susceptible to over-fishing than a shorter-lived one. A number of ageing methods have been applied to orange roughy: circuli in scales, microincrements in otoliths, annuli in whole otoliths and sectioned otoliths, and radiometric dating. Ages obtained from scales (7–8 years) and otolith microincrements (< 18 years) are the youngest, while sectioned otoliths and radiometric dating give the oldest maximum ages (> 100 years). A major problem with ageing methods applied to orange roughy is the lack of validation past the first three years, a problem in common with many other fish ageing studies world-wide (Beamish & McFarlane 1983).

Gauldie *et al.* (1991) examined the chemistry of orange roughy scales and discovered matching peaks and troughs in calcium and fluorine, from the spiny external to the smooth internal part of each scale. If the peaks and troughs in fluorine were annual, then the fish examined had a maximum age of 7–8 years. The number of circuli (visible rings) in one scale was 76, but it was presumed that these did not represent annual rings.

A technique of ageing based on microincrements in orange roughy otoliths was developed by Gauldie (1989). Microincrements are presumed daily rings which are 1–5 µm wide in orange roughy (Gauldie & Nelson 1988; Gauldie *et al.* 1995). Applications of this technique to orange roughy have yielded maximum ages of 15–18 years (Gauldie *et al.* 1989; Gauldie 1990a,b). A plausible mechanism for daily growth rings is developed by Gauldie & Nelson (1988), and microincrements in the trevally (*Caranx georgianus*) are shown to be obligatory and laid down daily (Gauldie & Radtke 1990). Gauldie *et al.* (1995) indicated that strontium variation in orange roughy otoliths had a similar periodicity to microincrements, but that there were an average of 253 microincrements between peaks in microincrement width. Fusion of microincrements into checks could account for about 16% of the difference between 253 and 365 (if the peaks were annual), but this mechanism alone is not sufficient to explain the discrepancy.

Various check rings and marks are visible on orange roughy otoliths, and this mechanism has been used to assign ages to orange roughy under the presumption that these rings are annual. Early attempts either ended in failure to age the otoliths (Linkowski & Liwoch 1986), or concluded that age estimates resulting from whole otoliths were not reliable (Gauldie 1987; Gauldie 1988). Ring counts from thin sections of otoliths did not correspond to ring counts from whole otoliths (Gauldie 1987; Gauldie 1988), although Gauldie (1987) conceded that the diffuse check rings visible in thin sections were the most likely candidate for an annual ring. Validation of the annuli (in whole otoliths) has been successful up to three years, using modal analysis of length-frequency distributions of small juveniles (Mace *et al.* 1990). The validation was used to extrapolate a maximum age in excess of 50 years. The relationship between whole and sectioned otolith counts was examined by Smith *et al.* (1995). They showed similar counts until about 20 annuli; after this age, counts on sectioned otoliths were much higher. Whole otoliths gave maximum age as 38, while sectioned otoliths put maximum age at 125 years (Smith *et al.* 1995). A similar age was obtained for sectioned otoliths (21–156 years) by CSIRO (1995). In rockfish, *Sebastes alutus* and *S. diploproa*, maximum ages of 50–80 years have been inferred from sectioned otoliths and only 25 years from whole otoliths (Bennett *et al.* 1982; Stanley 1986), a result akin to that for orange roughy.

Radiometric ageing is the latest ageing method to be used for orange roughy. This method had been developed for *Sebastes diploproa* and *S. mentella*. In those species it showed that sectioned otoliths give a more accurate age estimate than whole otoliths (Bennett *et al.* 1982; Campana *et al.* 1990), confirming longevities of 75–80 years for these species. However, radiometric ageing does not always support ages from sectioned otoliths: in three species of tropical snapper (Lutjanidae), the whole otolith ring count agreed better with the radiometric ageing (Milton *et al.* 1995). The radiometric method relies on the incorporation of ^{226}Ra in the otolith, where it decays to ^{210}Pb. The radium isotope has a much longer half-life (1 600 years) than the lead isotope (22.3 years), so that the ratio of ^{210}Pb: ^{226}Ra provides a measure of the time elapsed since the ^{226}Ra was incorporated into the otolith. A maximum age of 149 ± 12 years for orange roughy was obtained using this method (Fenton *et al.* 1991). The extreme longevity proved controversial, and West & Gauldie (1994) attacked a number of assumptions made in the analysis of Fenton *et al.* (1991), concluding that uncontrolled errors might invalidate the approach they used. West and Gauldie (1994) had three principal concerns: (1) it is probable that one of the intermediate products (^{222}Rn) diffuses out of the otolith; (2) the sources and sinks of ^{210}Pb, ^{226}Ra, and other intermediates, have not been quantified; (3) an assumed otolith-mass growth model uses "ages" produced by other ageing methods, and is potentially tautological. Little has been done to address the first two concerns, but the third concern is considered by Francis (1995), who provides two approaches to avoid the problem of circular reasoning. He re-estimates maximum age as having a lower bound of 84 years, with a "most likely" value of 194 years for one of the samples. Smith *et al.* (1995) also attempt to address the problem of the mass-growth model, incorporating estimates about growth rate from sectioned otoliths. They conclude that maximum age is either 101 or 125 years, depending on the assumptions made. Further controversy is introduced by Whitehead & Ditchburn (1996) who demonstrate that excess ^{210}Pb is incorporated into the outer layers of otoliths from old fish—artificially inflating age estimates. Nevertheless, the overall conclusion from the radiometric data is that the maximum age of orange roughy is at least 84 years, and probably well over 100 years.

2.4 Aggregating behaviour

Orange roughy form dense aggregations on hard ground, often on features like seamounts and canyons. Catch rates on these aggregations can be astoundingly high—reported rates off New Zealand, Australia and Namibia have exceeded 10 tonnes per minute of bottom time (Pankhurst 1988; Clark 1995a; Koslow 1997; Koslow *et al.* 1997; present study), and may reach 50 tonnes per minute of bottom time (Ross & Smith 1997). The St Helens aggregation off Australia, which encompasses only 10 km², had vessels queuing for a shot on one of three major tow lines on the hill in 1990. In that year, up to 47 vessels were fishing on the hill in a single week (Lyle *et al.* 1990). Aggregations form primarily for spawning and feeding, but may also aid in the avoidance of predators. Non-spawning aggregations in New Zealand are most dense in spring and summer (Clark 1995a). Spawning aggregations appear to be made up of fish which migrate in for spawning during winter, and then return to their normal locale (Bell *et al.* 1992; Coburn & Doonan 1994). Densities are highest on these grounds during this time, but a resident population remains throughout the year (Bell *et al.* 1992), presumably for feeding. The density inside aggregations is so high that it cannot be maintained just by the productivity of the water column occupied (Koslow 1997). However, the currents around the topographic features are strong (0.1–0.4 m/s) and may import organisms (Koslow 1997). These features may therefore represent regions of food abundance.

The aggregations may serve a subsidiary purpose as a predator-avoidance mechanism. Orange roughy aggregations display marked avoidance behaviour, reacting to acoustic cameras as much as 130 m away and to an iron bar (30×8×1 cm) at a distance of 60 m (Koslow *et al.* 1995b). Aggregations dispersed at least 30–40 m when these objects were detected. Orange roughy have a pronounced lateral line (Paulin 1979) and a high degree of visual specialisation (Pankhurst 1987); these adaptations may allow them to detect movements of adjacent fish and respond quickly (Koslow 1996).

In the aggregations, there is marked sexual segregation: individual tows rarely catch equal proportions of males and females (Pankhurst 1988; Lyle *et al.* 1990; Bulman *et al.* 1994; Francis 1996; A. Rees, unpublished data). The sex ratios depend strongly on when and where the catches were made (Francis 1996). In some areas (e.g. South Chatham Rise), females dominate throughout the fishery (Francis 1996), while in others (e.g. Johnies in Namibia) males dominate (A. Rees, unpublished data). On some grounds (e.g. Ritchie Bank), catches were initially male dominated and later female dominated (Francis 1996).

2.5 Diet and feeding

Orange roughy are opportunistic predators which consume a wide variety of invertebrate and fish species. The main prey includes fish, squid, amphipods, mysids and decapods; their proportions in the diet apparently depend on the local abundance of these prey items (Liwoch & Linkowski 1986; Gordon & Duncan 1987; Rosecchi *et al.* 1988; Bulman & Koslow 1992; Lesch 1995; A. Rees unpublished data). Food consumption rates have been estimated at 0.91% (juveniles) and 1.15% (adults) of body mass per day (Bulman & Koslow 1992).

It is likely that the orange roughy starves during the spawning season—the proportion of empty stomachs increases during this period, and feeding only re-commences at the end of the spawning season (Liwoch & Linkowski 1986; Bulman & Koslow 1992; Lesch 1995; A. Rees, unpublished data). Feeding is most intense during March and mid-April, when the gonads are developing (Liwoch & Linkowski 1986). Outside the spawning season, there is some indication that the incidence of feeding is greater in the aggregations (Bulman & Koslow 1992), which may explain the existence of a resident population of orange roughy at those grounds.

Orange roughy metabolism is high—0.11 ℓ O_2 kg^{-1} wet wt h^{-1} for juveniles and 0.14 for adults—similar to active mesopelagic fish, and this leads to exceptionally poor growth efficiencies of about 5% (Bulman & Koslow 1992; Koslow 1997). The high metabolic rates in adults may be related to their strong locomotory ability and avoidance response to perceived threats (Koslow *et al.* 1995b; Koslow 1996).

2.6 An oily delicacy

Orange roughy command high prices in the US market, primarily because of their firm flesh, ability to take a sauce and the wide variety of ways in which they can be cooked. Their flesh contains large quantities of lipids, which are almost entirely (98–100%) wax esters (Bakes *et al.* 1995). Most fish, including the closely related *Hoplostethus mediterraneus*, have a large proportion of triacylglycerols in their flesh (Sargent *et al.* 1983), so that the orange roughy is unusual in this respect. The wax esters are not harmful to pigs and are therefore presumed to be perfectly safe for human consumption (James *et al.* 1986). A number of studies have focused on the properties and composition of the wax esters in orange roughy.

Wax esters are contained primarily in the muscles, belly flap, liver, pyloric caeca, cranial cavity and swim bladder of orange roughy (Sargent *et al.* 1983). The swim bladder is not gas-filled—instead, it contains 82–90% wax ester (Bakes *et al.* 1995) which may play a role in maintaining neutral buoyancy in the cold waters that they inhabit (Phleger & Grigor 1990). The lipid content in orange roughy muscles is quite high, and also varies from region to region. Off New Zealand, the range is 3.9–9.7% (Hayashi & Takagi 1980; Grigor *et al.* 1983; Vlieg & Body 1988; Phleger & Grigor 1990); in the North Atlantic, 7.5–10.4% (Sargent *et al.* 1983; Sigurgisladóttir & Pálmadóttir 1993; Bakes *et al.* 1995); and off Australia, 27% of wet weight (Bakes *et al.* 1995). The wax esters in muscles may be used as metabolic reserves, or aid in insulation (Bakes *et al.* 1995).

The composition of fatty acids in the wax esters of orange roughy is extremely anomalous. Fish species normally have large quantities of polyunsaturated fatty acids, especially eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which belong to the ω-3 fatty acid family. These fatty acids are thought to prevent coronary heart disease and other related diseases (Iacono & Dougherty 1993). But orange roughy seem to have the lowest concentrations of EPA and DHA of any marine fish. For example, Sigurgisladóttir & Pálmadóttir (1993) found that EPA and DHA comprised only 3.3% of the fatty acids in orange roughy, the next lowest concentration in 34 other species examined being 6.2%. Similarly, Bakes *et al.* (1995) found a total concentration of 2.3%, compared to the next lowest of 13.6% in seven species of oreos (family Oreosomatidae), many of which share the unusual ecological features of orange roughy (Koslow 1996; Koslow 1997). Even *Hoplostethus mediterraneus* has considerably greater quantities of EPA and DHA than orange roughy (Sargent *et al.* 1983).

Not only are EPA and DHA sparse in orange roughy, but so are the other polyunsaturated fatty acids—monounsaturated fatty acids comprise 82–94% of fatty acids in orange roughy (Hayashi & Takagi 1980; Grigor *et al.* 1983; Sargent *et al.* 1983; Vlieg & Body 1988; Sigurgisladóttir & Pálmadóttir 1993; Bakes *et al.* 1995), compared to a mean of 31% (SD 11.8%) for 34 other species listed in Sigurgisladóttir & Pálmadóttir (1993).

Explanations of the anomalous fatty acid composition and presence of wax esters in orange roughy have focused on two possible causes: diet, and *de novo* synthesis of these compounds (Grigor *et al.* 1990; Phleger & Grigor 1990; Bakes *et al.* 1995). The diet of orange roughy is varied but includes a number of species rich in wax esters (Grigor *et al.* 1990). Species like oreos, which are conspecific with orange roughy, have a large proportion of salps in their diet (Clark *et al.* 1989), which do not contain wax esters. Oreos do not have high levels of wax esters in their flesh, so that it is likely that the anomalous lipid composition in orange roughy is due at least partly to diet.

2.7 Genetics and stock structure

Research on orange roughy stock structure has produced equivocal results. On the one hand, studies which have focused on environmental characteristics of the fish have generally found differences between stocks (Table 2.1). On the other hand, most genetic studies have not found differences between even very widely separated regions (Table 2.1). A tagging study would be an ideal way of resolving this discrepancy. Tagging

Table 2.1 Summary of stock structure results in different studies on orange roughy. Different stocks are represented by the same letter if that study found no difference between the stocks. Study types are arranged from those which easily discriminate between stocks, to those which do not.
Abbreviations for different areas are: a) *New Zealand*: Eastern Cape, Bay of Plenty, Ritchie Bank (RB), Wairarapa (Wa), Cook Strait (CS), Kaikoura (Ka), Chatham Rise (CR), Waitaki (Wi), Puysegur Bank (PB), West Coast (WC), Challenger Plateau (Ch), Lord Howe Rise (LH), b) *Australia*: Western Australia (We), Great Australian Bight (GA), South Australia (So), Western Tasmania (WT), Maatsuyker (Ma), Cascade Plateau (Ca), Eastern Tasmania (ET), St Helens (SH), New South Wales (NS), c) *Other*: South Africa (SA) and British Isles (BI).

		New Zealand												Australia									SA	BI
Study	Method	EC	BP	RB	Wa	CS	Ka	CR	Wi	Pu	WC	Ch	LH	We	GA	So	WT	Ma	Ca	ET	SH	NS		
Elliott et al. (1995)	Morphometrics													a	b		c	d	e	f	g	h		
Haddon & Willis (1995)	Morphometrics									a			b											
CSIRO (1995)	Otolith chemistry													b	c	a				a		d		e
Edmonds et al. (1991)	Otolith chemistry													a		b	c							
CSIRO (1995)	Otolith shape															a				b				
Lester *et al*. (1988)	Parasite analysis					b		a				c			d	a	e		a	f		g		
Ward & Elliott (1993)	Standard length													a	b/c			b	a		c	d		
Bell *et al*. (1992)	Fecundity, spawning time, length at maturity															a	a			a		b		
Smith *et al*. (1996)	Mitochondrial DNA restrictions			a				a	b	b	a	a												
Elliot *et al*. (1994)	Mitochondrial DNA restrictions														a	a	a			a		a		b
Smolenski *et al*. (1993)	Mitochondrial DNA restrictions							a						a	a	a	a			a		b	a	
Ovenden *et al*. (1989)	Mitochondrial DNA restrictions																a			b				
Baker *et al*. (1995)	Mitochondrial DNA cytochrome *b* sequencing			a				a		a		a	a				a						a	
Smith & Benson (1997)	Allozymes (11 loci)	a	a	a	a		a	b																
Elliot *et al*. (1994)	Allozymes (11 loci)													a	a			a	a		a	a		b
Ward & Elliott (1993)	Allozymes (11 loci)													a	a			a	a		a	a		
Elliott & Ward (1992)	Allozymes (11 loci)				a		a	a				a		a	a			a	a		a	a		
Smith (1986)	Allozymes (22 loci)				a		a	a				a												a
Baker *et al.* (1992)	DNA fingerprints							a					a											
Smith *et al*. (1994)	Random amplified polymorphic DNA			a	a		a		a															

has been attempted using break-away hooks on other deepwater species including alfonsino (*Beryx splendens*) (Grimes *et al.* 1983; Horn 1989). Unfortunately, this approach is inappropriate for orange roughy because they are not caught by long-liners (CSIRO 1995).

Environmental characteristics depend on the surroundings of the fish during its life. Studies on trace elements in otoliths (Edmonds *et al.* 1991; CSIRO 1995), otolith structure (CSIRO 1995), morphometric differences (Elliott *et al.* 1995; Haddon & Willis 1995) and parasite analysis (Lester *et al.* 1988) have found significant differences among virtually every stock examined (Table 2.1). The standard length of adult orange roughy may also be significantly different from one aggregation to the other (Ward & Elliott 1993; Elliott *et al.* 1995; Huse *et al.* 1997; A. Rees unpublished data). Orange roughy off New South Wales even have a different time of spawning, greater fecundity and a smaller length at maturity than other populations off Australia (Bell *et al.* 1992). All of these studies suggest that adult orange roughy are relatively sedentary, and that stocks are fairly isolated from one another.

Genetic studies reveal inheritance patterns, but have generally failed to discriminate between stocks (Table 2.1). Restriction site analysis of mitochondrial DNA has been used with the most success. For example, this technique has shown that the Waitaki and Puysegur Bank stocks are different from other New Zealand stocks (Smith *et al.* 1996); that New South Wales orange roughy form a different stock to other Australian orange roughy (Smolenski *et al.* 1993); and that orange roughy off the British Isles are distinct from those off Australia (Elliott *et al.* 1994). The technique has also been used to show that Eastern Tasmania and Western Tasmania orange roughy are different stocks (Ovenden *et al.* 1989). Other genetic methods have proved less successful: including direct sequencing of the mitochondrial cytochrome *b* gene (Baker *et al.* 1995), analysis of polymorphic allozymes (Smith 1986; Elliott & Ward 1992; Ward & Elliot 1993; Elliott *et al.* 1994), examination of DNA fingerprints (Baker *et al.* 1992) and random amplified polymorphic DNA (RAPDs) (Smith *et al.* 1994). One allozyme study could not even distinguish New Zealand orange roughy from those off South Africa (Smith 1986). However, one allozyme study on New Zealand orange roughy managed to find differences between adjacent East Coast and Chatham Rise stocks, and even showed genetic heterogeneity within the Chatham Rise (Smith & Benson 1997). An intriguing study by Smith *et al.* (1991) on New Zealand orange roughy reported a reduction in genetic diversity on the Chatham Rise, the Challenger Plateau, and the east coast between 1982–83 and 1988. The authors postulated that this may be caused by higher mortality of larger fish, which might be more heterozygous. However, Ward & Elliott (1993) found no evidence for a link between mean length and levels of heterozygosity in Australian populations of orange roughy. A later study (Smith & Benson 1997) found no significant decline in heterozygosity between 1982 and 1994 on the sites studied by Smith *et al.* (1991).

Of the genetic techniques used, mitochondrial-DNA restriction-site analysis provides the best discriminatory power, and appears to echo the finding from environmental characteristics that stock differences may be present over distances of less than 500 km (Edmonds *et al.* 1991; Elliott *et al.* 1995). Genetic data may have poor discriminatory power because of the extreme longevity (> 100 y) of orange roughy, which has two important consequences. First, genetic changes accumulate very slowly in long-lived species, and second, the number of migrants per year must be extremely small to allow genetic divergence. For example, Smith *et al.* (1996), estimated that the effective number of migrants must be less than two per generation between the northern and southern sites off New Zealand, to allow the observed genetic separation between these regions.

3. Swept-area assessments: obtaining estimates and accounting for biases

3.1 Rationale for using the swept-area method

Exploratory fishing for deepwater species off southern Africa started in earnest in 1994, and their assessment became a priority at the start of 1996. In New Zealand and Australia, assessment of deepwater species is based on trawl surveys, CPUE indices, egg surveys and acoustic surveys. The advantages and disadvantages of these techniques are examined in Section 1.2. In 1996, however, none of these standard assessment techniques could be applied to the southern African stocks: no surveys had been performed[3], and only commercial catch data were available. There was little point in performing a CPUE analysis as the time series was too short to provide meaningful trends. In addition, CPUE analyses in New Zealand are not thought to track changes in biomass very reliably (Clark 1996b).

Despite these problems, it was still considered vital to get an indication of the absolute biomass of commercially important species before large-scale fishing began. The swept-area technique has been used as a relative index only, to obtain biomass estimates from trawl surveys off New Zealand and Australia (Clark 1996b). A time series of such indices, together with a catch history, can be used to give an estimate of virgin biomass (i.e. "stock reduction analysis", Annala & Sullivan 1997). However, this time series must extend for a number of years before an estimate can be considered to be reliable.

In principle though, a swept-area estimate from a single trawl survey could be used to provide an absolute estimate of biomass, if the constant factor relating the relative index to the absolute biomass is known. Estimates of this factor (termed catchability[4]) can be made from time series on the Chatham Rise off New Zealand, where trawl surveys were

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[3] A trawl survey had been performed by the Japanese vessel *Matsuyama Maru* in Namibian waters in 1995 (Lesch 1995). However, no tows were placed inside the aggregations and the vessel and fishing gear were not designed for deepwater fishing (see Appendix B for a more complete critique). Their results were therefore considered to be inappropriate for biomass estimation.

[4] "Catchability" is generally defined to be the gradient of the (assumed linear) relationship between catch rate and fish density. In the swept-area estimate, it is the ratio between estimated density and true density, assuming that the net catches all the fish in the area covered by the trawl.

conducted from 1984 to 1994. In the absence of trawl survey tows off southern Africa, it was decided to apply this method to the commercial tows off southern Africa, to obtain an estimate of absolute abundance.

The swept-area estimate is affected by a number of biases. These 'bias factors' include catchability, the use of commercial data instead of trawl survey data, herding effects, estimates of the extent of the aggregations, the use of 'windows' in the sides of nets, the choice of an appropriate depth range and the presence of "zero catches" recorded in the database where in fact very small catches had been made. An important part of the assessment method is taking these bias factors into account. The point estimate of biomass obtained by the swept-area method is then converted into a probability density function, or pdf (defined in Section 1.5) for biomass. The resulting pdf therefore incorporates uncertainty about the estimate, which plays a central role in assessing the long-term risks of both different fixed catch levels (Chapter 7) and adaptive management strategies (Chapter 8).

It is important to realise that estimates obtained during this process rest heavily on the range of values assigned to the different bias factors. Although every effort was made to develop realistic values for the bias factors, it is possible that some of the assigned ranges are too narrow, or are themselves biased. In some cases, very little information was available to determine probable ranges for their values, which makes the resulting estimates quite uncertain. It is also possible, although unlikely, that additional biases exist which were not taken into account. The overall methodology used here has not been validated using independent data, and the results cannot yet be regarded as highly reliable. Instead, estimates should rather be seen as the start of an attempt to place bounds on the possible biomass level, in the absence of systematic surveys[5].

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[5] Note that the swept-area estimates for Namibia were presented at meetings in January 1997, and hence data from the acoustic survey in July 1997 (Huse *et al.* 1997) could not be incorporated. No surveys have yet been performed off South Africa.

3.2 Swept-area methodology

Data sources

Separate analyses have been performed for South Africa and Namibia, primarily because the countries have separate management structures. Data were obtained from Gendor for the Namibian assessment and from the Sea Fisheries Research Institute and Suidor for the South African assessment. Typically, the data included the following information about each tow: shot position, bottom position and haul position[6], based on Global Positioning System (GPS); and the mass (or number of cases) of each species caught. Obvious typographical errors were corrected using positional information from the same tow, or from preceding and subsequent tows. Where possible, dubious entries were double-checked against the original trawl sheets.

Exclusion of tows from analyses

Tows were excluded from the analyses for a variety of reasons:

1. Incomplete (e.g. equipment failure, coming fast on the bottom).
2. Performed outside the EEZ's of Namibia and South Africa.
3. Not targeted on deepwater species[7].
4. Bottom distance of a tow could not be calculated or estimated.

Positioning of strata

The corrected database was converted so that it could be visualised using a Geographical Information System (GIS): Arc/Info for UNIX. The spatial distribution of the tows was examined to determine where strata should be positioned[8]. In the absence of official governmental agreement, the maritime boundary between South Africa and Namibia was taken to be a line equidistant from the boundary on the shores of the two countries.

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[6] The shot position is where the trawl commences, the bottom position is where the trawl gear first touches the bottom, and the haul position is where the trawl gear lifts off the bottom.

[7] Such tows were recorded only in South African waters, since the exploratory permit in Namibia restricted fishing to waters deeper than 500 m.

[8] Post-stratification of this nature can result in biased estimates of variance, and would not be used for the rigorous analysis of a survey. However, the aim of this analysis is merely to provide ballpark figures for biomass.

Obvious areas of high catches and fishing intensity were defined as 'aggregations', and were delimited on the GIS by enclosing the bottom and haul positions of these tows in a tight polygon with minimal acute angles. Other strata were defined between 500 m and 1 000 m depth intervals, because > 90% of all tows were between these depths. Where tows would have been placed marginally outside these strata, the strata were widened sufficiently to just include those tows.

The possibility was entertained that the depth range chosen for the strata may be positively biasing the abundance estimates. This may occur as a result of the fish and fishing effort both being concentrated in a narrower depth range. The high density of this depth range would not be representative of the total area considered. In an Australian estimate of biomass in 1988–89 using swept-area methods, each stratum was subdivided into 100-m intervals (Bulman *et al.* 1994). This approach was not possible for Namibia because depth intervals in some strata had been inadequately sampled by the exploratory trawls. However, off South Africa, there was sufficient sampling density to allow for this possibility. There, each stratum was divided into five bands, each of 100-m depth, ranging from 500 m to 1 000 m, and the tows assigned to the appropriate depth band using information in the database. Tows outside these depth intervals were assigned to the nearest depth interval. When depth-stratification was performed, point estimates of biomass decreased by 2% for South African orange roughy (the overall CV decreased from 50% to 19%) and by 11% for South African oreo dories (the overall CV increased from 23% to 24%).

Baseline biomass estimation

The swept-area technique requires knowledge of four factors: the catch by each tow, the distance each tow spent on the bottom (bottom distance), the effective width of the trawling equipment, and the area of suitable habitat. The average density in each stratum is estimated as follows[9], where the summation is over all the tows in the stratum:

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[9] The formula used here is equivalent to an average of the catch rates for individual tows, weighted according to effort, appropriate when Poisson-like sampling variance is assumed to be the main cause of variability.

$$density[t.km^{-2}] = \frac{\sum catch[t]}{\sum (bottom\ distance[km] \times width\ of\ trawling\ gear\ [km])} \quad (3.1)$$

The total biomass estimate is then given by the following summation, where the summation is over all the strata:

$$biomass[t] = \sum (density[t.km^{-2}] \times area\ of\ stratum[km^2]) \quad (3.2)$$

The estimate obtained using these formulae is regarded as a "baseline estimate" since it does not take any of the bias factors into account. For example, the explicit assumption is made that 100% of the fish in the vertical column of water both above and below the path of the net are caught; this is unrealistic, and more plausible alternatives are introduced later. The formulae used in calculating CVs are included in Appendix A.

Reported catches were converted to greenweight tonnes. Where necessary, a conversion factor of 2.0 was used for the data from the *Nicola* and *Iris* off South Africa (R. Tilney, pers. comm.), and 2.2 for all other vessels (A. James & A. Rees, pers. comm.), to back-calculate greenweight tonnes from product-weight tonnes.

The bottom distance of each tow was calculated as the straight line distance between the bottom position and the haul position. Some tows did not contain the bottom position and the haul position, so that estimates of the bottom distance were sometimes necessary. For the Namibian analysis, the estimated bottom distance was taken to be 51% of the distance from shot position to haul position. This estimate was obtained from Namibian tows, with SE = 13%, and it was applied to 116 (7%) of the tows there. A slightly more sophisticated estimation procedure was used for the South African analyses, applying regression analysis to 1454 tows with complete information performed off both South Africa and Namibia:

$$\begin{cases} if\ total < 6\,km, & bottom\ distance = 0.476 \times total\ distance - 0.845 \\ if\ total \geq 6\,km, & bottom\ distance = 1.024 \times total\ distance - 3.876 \end{cases} \quad (3.3)$$

These estimates were applied to 17 (5%) of the tows in the South African orange roughy analysis, and to 20 (4%) of the tows in the South African oreo dory analysis. In the latter analysis, a further problem arose with data from SFRI for the *Iris*, which lacked detailed positional information. Bottom distances were therefore inferred from the time the tow spent on the bottom, using the following formula:

$$\textit{bottom distance}[km] = 6.03 \times \textit{bottom time}[h] + 0.106 \tag{3.4}$$

This regression was obtained from 2042 tows off southern Africa where both bottom distance and bottom time were available. Tows for which the average speed was greater than 8 km/h, or less than 4 km/h, were excluded from this regression as these estimates of speed are unrealistic and were presumed to result from erroneous information in the database.

The net width (wingspread distance) was taken to be 14.8 m for the *Southern Aquarius* and 11.5 m for the *Whitby* (A. Rees, pers. comm.), 14.8 m for other vessels off Namibia, and 20 m for other vessels operating off South Africa (A. Rees, pers. comm.; Clark & Tracey 1993).

The areas of the strata were calculated automatically by the GIS software. Where the strata were separated into 100-m depth intervals, each depth interval was assumed to have equal area, as accurate bathymetry was not available to this level of resolution.

3.3 Undiscovered aggregations of orange roughy

A major problem in assessing the biomass of orange roughy stocks is that new aggregations may subsequently be discovered, which will increase biomass estimates. Four aggregations had been discovered off Namibia at the time of the analysis there (January 1997), and none off South Africa. The problem of estimating the number of undiscovered aggregations is akin to placing a small coin on the surface of a large table. What is the probability that the coin will remain untouched by n pencils placed onto the table at random? The table represents a stratum, the coin an undiscovered aggregation, and the pencils represent the trawls made in that stratum. Two assumptions must be made. First, trawls in a stratum are independent of one another. Secondly, the trawls are conducted at random with respect to resource distribution.

Using these assumptions, an attempt was made to estimate the number of undiscovered aggregations. Given the trawling effort, there was a 50% probability that nine aggregations[10] could remain undiscovered off Namibia (Branch 1996), and two to five off South Africa (Branch 1997). However, neither of the underlying assumptions is likely to hold since the data come from directed fishing operations. Work on this aspect was accordingly discontinued, and is not presented in this thesis.

3.4 Bias factors affecting the swept-area estimate

Major sources of potential bias in the baseline estimates are presented below. In Section 3.5, a methodology is developed for taking these sources of bias into account. Some bias factors are thought to affect estimates inside and outside aggregations to different degrees; subscripts "agg" and "out" are appended to the symbols for bias factors where this is necessary.

Catchability (C_{agg}, C_{out})

The swept-area method assumes that all fish in the path of the net are caught (i.e. all fish above and below the net are herded into the net). In reality, some pass over and some pass under the net. Orange roughy, in particular, may also attempt to avoid the net.

Non-random trawls (R_{agg}, R_{out})

Data from commercial tows were used in preparing the baseline estimates. This is thought to inflate estimates when compared to a random trawl survey, especially outside the aggregations. Some tows are placed randomly; in others (directed tows), skippers use bathymetric or echo-sounder cues.

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[10] 'Probability' is used here in the following sense: if an additional nine aggregations were in fact off Namibia, there is a 50% probability that at least one of them would have been discovered by the exploratory trawling.

Herding (*H*)

The doors on either side of the trawl net may herd orange roughy into the net. The swept-area method assumes that the area covered by the net is the net width multiplied by the bottom distance covered by the tow. Doors may effectively increase the area that the nets sweep, inflating the estimates.

Extent of the aggregations (*E*)

The areal extent of the aggregations of orange roughy off Namibia was defined on the basis of trawls performed before July 1996. Subsequent exploratory effort has shown the extent of the aggregations to be considerably larger.

Lost catch (*L*)

In the initial phase of exploratory fishing, fish in excess of a pre-set bag size were forced out of the nets through 'windows' in the sides of the nets. This factor arises for large catches, and hence only affects estimates for the aggregations.

Depth ranges chosen for strata (*O*)

The strata outside aggregations were conservatively defined between depths of 500 m and 1 000 m. Orange roughy do occur outside these depths (down to 1 800 m off New Zealand), so that the biomass estimate for outside the aggregations needs to be adjusted upwards. In addition, strata did not cover the northern reaches of Namibia or the east coast of South Africa, where no deepwater tows had been undertaken.

Erroneous zeros (*Z*)

Catches smaller than one case (up to 44 kg) were recorded as zeros in the databases used. This factor can have a large impact on the estimates if the number of "zero" tows in a particular stratum is large.

Biased CVs (CV_{agg}, CV_{out})

CVs for the baseline estimate are likely to be negatively biased, because the directed trawls are neither random nor independent—instead, positive correlation seems likely. As a crude initial adjustment, an additional term with a 10% CV was added to the variances originally estimated.

Undiscovered aggregations

It is possible that a number of additional aggregations remain to be discovered off both South Africa and off Namibia. However, it was deemed premature by management authorities in both countries to base decisions on resources whose existence had not yet been confirmed. For this reason, undiscovered aggregations are not taken into account as a bias factor.

Migratory behaviour

There is circumstantial evidence that orange roughy migrate into aggregations from the surrounding areas, particularly during the spawning season. The baseline estimate may be positively biased if aggregations are sampled more often during the spawning season, and other areas are sampled more frequently outside the spawning season. There was no evidence for this bias in the Namibian data, so that it is consequently ignored.

3.5 Correcting for bias in the baseline estimates

Baseline biomass estimates inside the aggregations (B_{agg}) and outside the aggregations (B_{out}) are obtained using the swept-area methodology. If the values of the various biases were exactly known, the bias-corrected biomass $\hat{B}$ would be given by Equation 3.5, where ε_{agg} and ε_{out} are random numbers drawn from normal distributions with mean 0 and standard deviations σ_{agg} and σ_{out} respectively[11].

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[11] In the equations, sampling variability is assumed to be log-normally distributed. The $-\frac{\sigma^2}{2}$ term is an adjustment to ensure that the mean of the distribution is equal to the point estimate.

$$\hat{B} = \frac{B_{agg}}{C_{agg}} \times R_{agg} \times H \times E \times L \times e^{\varepsilon_{agg} - \frac{\sigma_{agg}^2}{2}} + \frac{B_{out}}{C_{out}} \times R_{out} \times H \times O \times Z \times e^{\varepsilon_{out} - \frac{\sigma_{out}^2}{2}} \tag{3.5}$$

For the South African estimates, no aggregations had been discovered. In addition, the factors H and C were merged. The bias-corrected biomass $\hat{B}$ therefore simplifies to Equation 3.6:

$$\hat{B} = \frac{B}{C} \times R \times O \times Z \times e^{\varepsilon - \frac{\sigma^2}{2}} \tag{3.6}$$

Values for σ are obtained from the adjusted CV of the baseline estimates:

$$\sigma^2 = \ln(1 + CV^2) \tag{3.7}$$

The formulation in Equations 3.5 and 3.6 assumes that the biases are known exactly, but in reality their values are only poorly known. Each factor was therefore ascribed a range of likely values, with a pdf specified over this range. Values with high associated probability densities were generated more often than those with low associated densities, using a Monte Carlo procedure. In this process, 5 000 realisations (all equally likely values) of $\hat{B}$ were generated for each scenario considered.

A smoothed pdf for the biomass level was obtained from the 5 000 $\hat{B}$ realisations, using a normal kernel. This requires the application of Equation 3.8, which (in essence) converts each realisation of $\hat{B}$ into a tiny normal curve and then adds the values for each tiny curve, producing the smoothed pdf:

$$f(B) = \frac{1}{S_{\max}} \sum_{S=1}^{S_{\max}} \frac{1}{\sigma\sqrt{2\pi}} \times e^{-\frac{(B - \hat{B}_s)^2}{2\sigma^2}} \tag{3.8}$$

In Equation 3.8, S counts the realisations of $\hat{B}$ up to a maximum of $S_{\max} = 5\,000$. The value of σ that was chosen to yield a smooth curve added 2–3% to the standard deviation of the realisations. Thus the smoothing process did not widen the distribution appreciably.

Biomass estimates were given as the median values in the 5 000 realisations of biomass produced in the Monte Carlo simulations; 90% probability intervals were obtained by discarding the highest 5% and the lowest 5% of these realisations.

3.6 Obtaining likely ranges for the bias factors

Plausible specifications for the bias factors were obtained from a number of sources. Initial estimates were gleaned from the literature and from available data in southern Africa. There was extensive discussion over these specifications at two meetings in January 1997 between representatives (including scientists) from industry, independent consultants and the Namibian fisheries authorities. At the conclusion of these meetings, close agreement had been reached on the specifications. The values obtained at those meetings were used (with a few modifications) for the South African assessments of orange roughy and oreo dories.

Each bias factor was specified by a pdf, characterised by minimum and maximum values and the most likely range for that factor. The pdf was taken to be uniform (and maximum) over the most likely range. Parabolas (and not straight lines) were fitted from the lower most likely value to the minimum value, and from the upper most likely value to the maximum value, such that the slope of the pdf was zero at both the maximum and the minimum (this shape is best illustrated by Figures 4a-j). Parabolic tails were intentionally chosen to ensure that the bulk of the probability is in the "most likely" range. The actual values chosen are motivated and reported in Chapters 4–6.

4. Swept-area results for Namibian orange roughy

The swept-area methodology outlined in Chapter 3 was developed as an assessment technique for the Namibian orange roughy fishery and the results were presented and refined at two meetings in January 1997 in Swakopmund, Namibia.

4.1 Data

In total, 1 644 tows were considered for this analysis. The database included all known deepwater tows off Namibia up until July 1996, except those from a Japanese trawler, the *Matsuyama Maru*. That vessel conducted a transect trawl survey off the Namibian coast in 1995, but tow data were unavailable at the time of the swept-area analysis.

4.2 Strata definition

There were four obvious areas of high fishing intensity, which are termed 'aggregations': *Hotspot*, *Rix*, *Frankies* and *Johnies* (Figure 4.1). Collectively, 1 329 (81%) of the tows were inside these aggregations, with 623 (38%) of the tows in the *Hotspot*. Additional strata 'outside aggregations' were defined between depths of 500 and 1 000 m (Figure 4.1). Ground names were assigned to these strata for descriptive purposes—but they are not necessarily the names used by the fishers. In the *South Namibia* stratum, initial estimates were 60 times higher than in the other strata, due to the presence of small areas in which high catches of orange roughy had been recorded. The *South Namibia* stratum was therefore further subdivided to keep obvious areas of higher catches of orange roughy (> 2 t) separate from those of low catches. In all, 15 strata were defined, ranging in size from 5 km² for the *Frankies* aggregation, to 8 700 km² for a swathe in North Namibia containing only four trawls. The total area included in strata was 31 000 km². The area of the aggregations was 133 km², which was 0.43% of the total area of the strata.

4.3 Swept-area results

Baseline estimates of biomass were obtained using the swept-area technique outlined in Chapter 3. A detailed breakdown of the biomass estimates for orange roughy in each

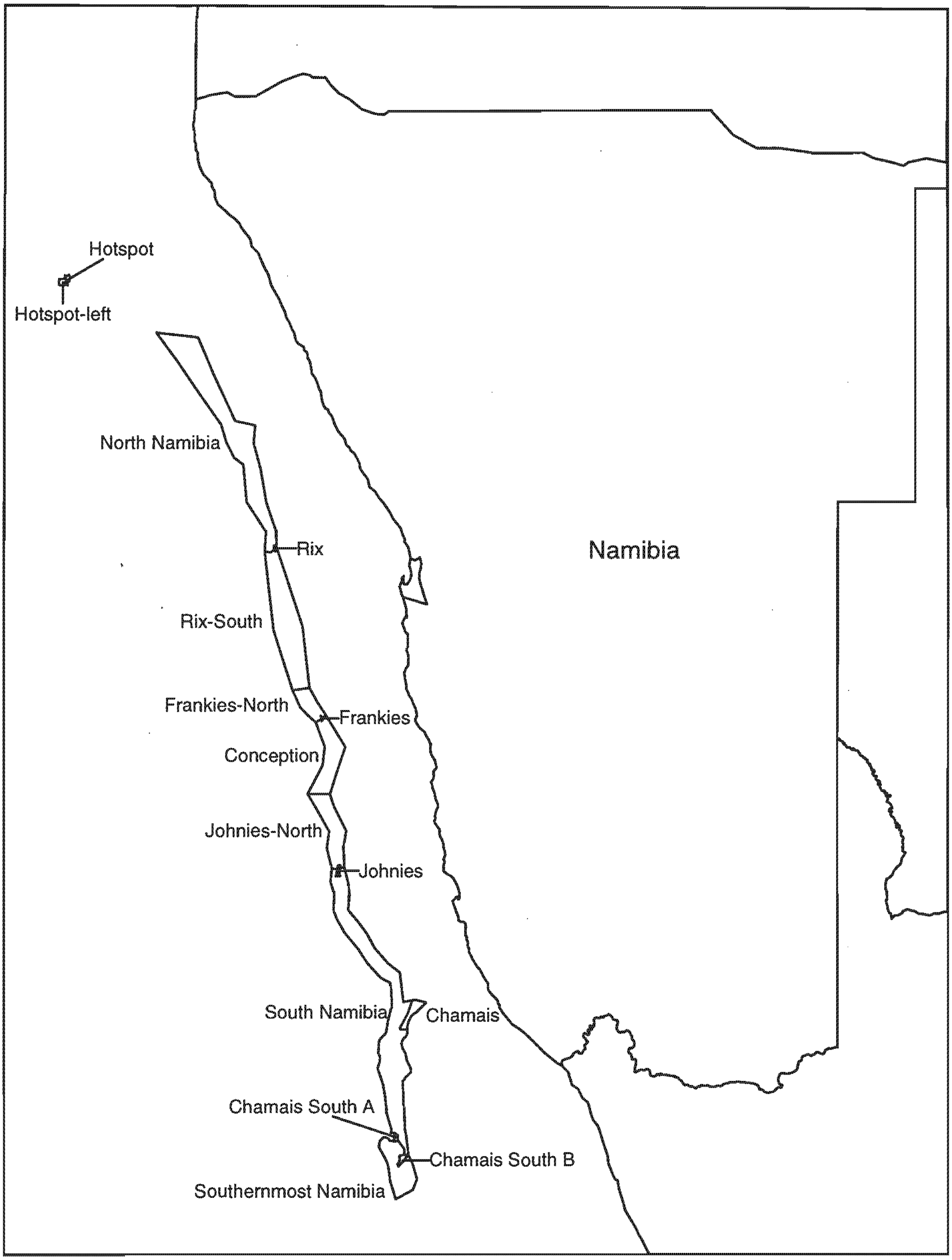

Figure 4.1 An overview of the strata used in the baseline swept-area assessment for orange roughy off Namibia. Four strata are defined as aggregations: *Hotspot, Rix, Frankies* and *Johnies*.

stratum is contained in Table 4.1. The overall estimate for Namibia is 243 000 t (CV = 21%) (Table 4.2), most of which is outside the aggregations. An estimated 32 000 t (CV = 5%), or 13% of the total biomass, is contained inside the aggregations. The density of orange roughy in the known aggregations is 280.7 t/km², 25 times greater than that outside known aggregations (11.0 t/km²) (Table 4.2).

4.4 First attempt at specifying values for the bias factors

Several sources were used to obtain initial pdfs for each of the bias factors considered; brief explanations are given below. A summary of the values used for each bias factor, and the directional effect of each on the biomass estimates, is given in Table 4.3. The pdfs themselves are shown in Figures 4.2a-j.

Catchability inside the aggregations (C_{agg})

The nets used do not catch all the fish in their path, so that catchability necessarily falls between 0 and 1 (note that herding, which has the opposite effect, is considered separately later). Inside the aggregations, plumes of fish often occur which extend off the bottom, and only a small fraction of these fish is available to the gear. Sex ratios for catches made by the *Southern Aquarius* are consistently biased towards males (Table 4.4a), with a mean male:female ratio of 2.15:1 (A. Rees, unpublished data). It seems likely that the females occur higher in the water column, where fewer are available to the gear (G. Patchell, pers. comm.). If this is true, and the overall sex ratio is 1:1, then an upper bound for C_{agg} is given by $(1 + r)/(2r)$ where r is the male:female sex ratio in the catches. This gives a bound of 0.73 for a 2.15:1 sex ratio.

One indirect way in which to estimate C_{agg} is by using data from the New Zealand orange roughy fishery. Trawl surveys (Francis *et al.* 1995) from the Chatham Rise between 1984 and 1992 give swept-area biomass indices which can be compared to back-calculated biomass estimates (using a stock reduction analysis). Francis *et al.* (1995) estimated the biomass in 1978 as 453 000 t, and the biomass in 1993–1994 as between 10 and 17% of B_0 (B_0—the average level prior to exploitation—is estimated to be 405 000 t). Biomass in

Table 4.1 Estimated swept-area biomass (in tonnes) of orange roughy for each stratum off Namibia (strata are arranged from North to South). No bias factors are taken into account in these estimates. Asterisks denote the strata considered to be aggregations. Densities are calculated by dividing the total catch in a stratum by the total area trawled in that stratum.

Ground Name	Area (km²)	Number of trawls	Density (t/km²)	Biomass (t)	CV
Hotspot-left	66	4	0.0	0	–
*Hotspot**	61	623	186.2	11 372	10%
North Namibia	8 702	4	3.6	31 289	47%
Rix-South	5 461	20	6.9	37 953	82%
*Rix**	13	164	89.4	1 196	16%
North-Frankies	962	9	0.6	589	52%
*Frankies**	5	166	641.3	3 255	9%
Conception	2 334	5	11.2	26 218	66%
Johnies-North	2 154	9	2.0	4 250	40%
*Johnies**	54	376	307.5	16 574	8%
South Namibia	8 492	169	10.7	91 119	37%
Chamais	396	6	39.0	15 454	27%
Chamais South A	44	42	22.5	998	26%
Southernmost Namibia	2 042	19	0.7	1 410	77%
Chamais South B	84	28	14.5	1 224	41%
TOTAL	30 871	1,644	–	243 000	21%

Table 4.2 Summary of swept-area biomass estimates for orange roughy in Namibian waters. No biases have been taken into account in these estimates. Aggregations are taken to be *Hotspot, Rix, Johnies* and *Frankies.*

	Area (km²)	Number of trawls	Density (t/km²)	Biomass (t)	CV
Inside aggregations	133	1 329	280.7	32 000	5%
Outside aggregations	30 737	315	11.0	211 000	24%
Namibia (total)	30 871	1 644	–	243 000	21%

Table 4.3 Bias factors that are taken into account in this document. The most likely values for each bias factor are indicated, together with its qualitative effects on biomass estimates inside and outside aggregations.

					Effect on biomass estimate	
Bias factor	Symbol	Minimum	Most likely range	Maximum	Inside aggregations	Outside aggregations
Catchability inside the aggregations	C_{agg}	0.27	0.40 – 0.50	0.73	Increase	–
Catchability outside aggregations	C_{out}	0.50	0.58 – 0.68	0.76	–	Increase
Directed fishing inside aggregations	R_{agg}	0.50	0.70 – 0.80	0.90	Decrease	–
Directed fishing outside aggregations	R_{out}	0.05	0.10 – 0.12	0.20	–	Decrease
Revised R_{out} (excluding *M. Maru* survey)	R_{out}	0.20	0.40 – 0.60	0.80	–	Decrease
Herding by the doors	H	0.75	1.00 – 1.00	1.00	Decrease	Decrease
Increase in known extent of aggregations	E	1.4	3.0 – 4.0	5.0	Increase	–
Loss of catch	L	1.00	1.04 – 1.07	1.10	Increase	No effect
Fish outside defined strata	O	1.20	1.22 – 1.24	1.30	–	Increase
As-yet undiscovered aggregations	M	1	5 – 7	10	Increase	–

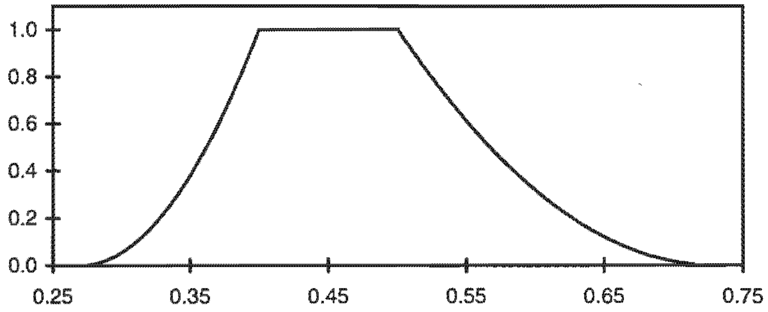

Figure 4.2a Catchability inside aggregations *(C_{agg})*

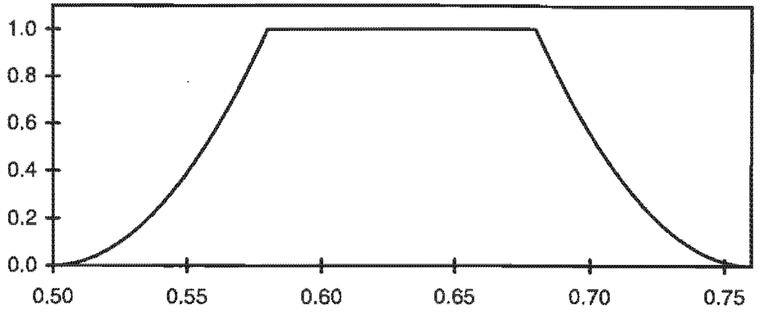

Figure 4.2b Catchability outside aggregations *(C_{out})*

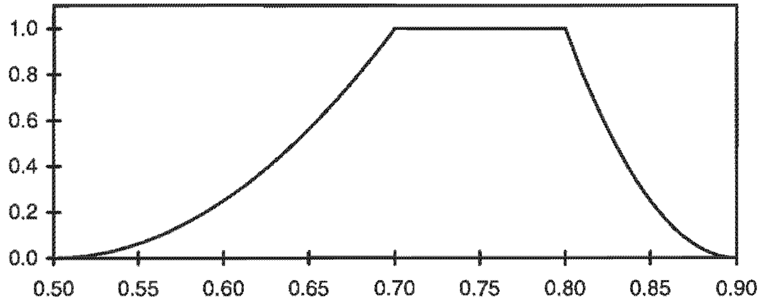

Figure 4.2c Directed exploratory trawls inside the aggregations *(R_{agg})*

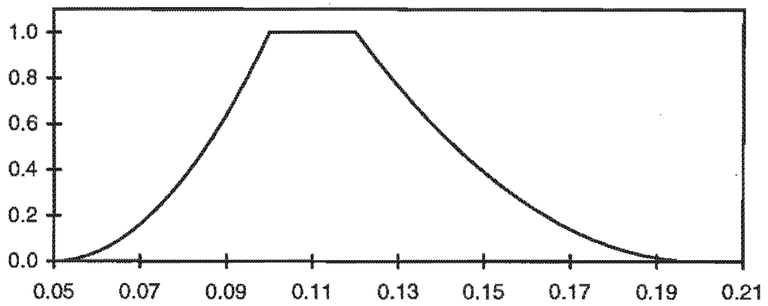

Figure 4.2d Directed exploratory trawls outside the aggregations *(R_{out})*, based on the *Matsuyama Maru* survey

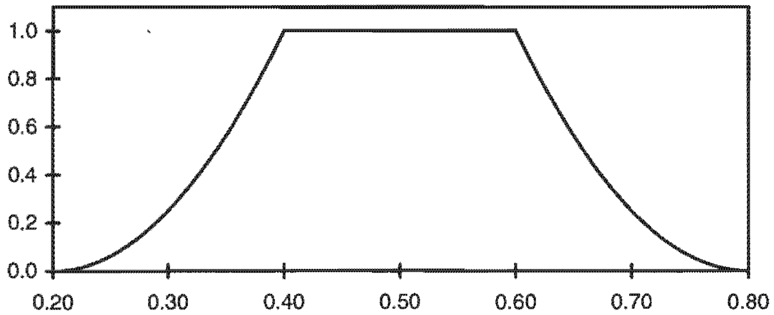

Figure 4.2e *R_{out}* estimates not derived directly from the *Matsuyama Maru* survey.

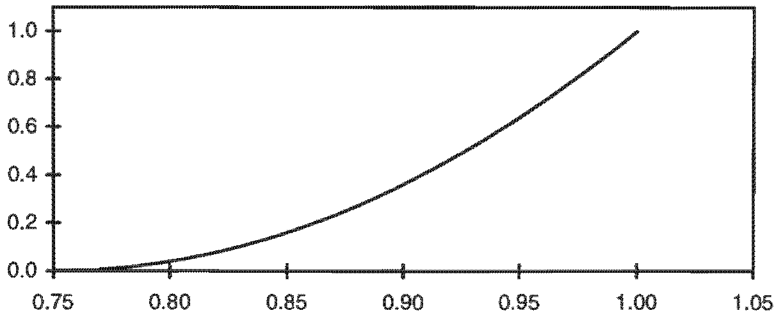

Figure 4.2f Herding by the doors *(H)*

Figure 4.2a-f Original pdfs for the bias factors, before the two meetings in January 1997. Considerable revision of these pdfs was made during those meetings; final values for the bias factors are presented in Table 4.12.

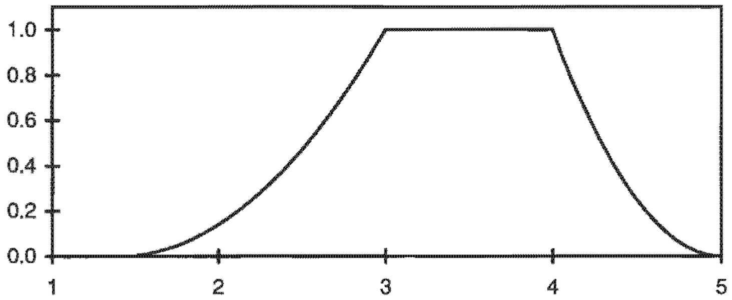

Figure 4.2g Extent of the aggregations *(E)*

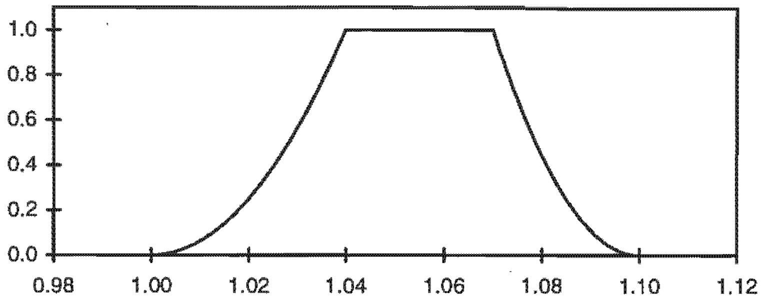

Figure 4.2h Loss of catch *(L)*

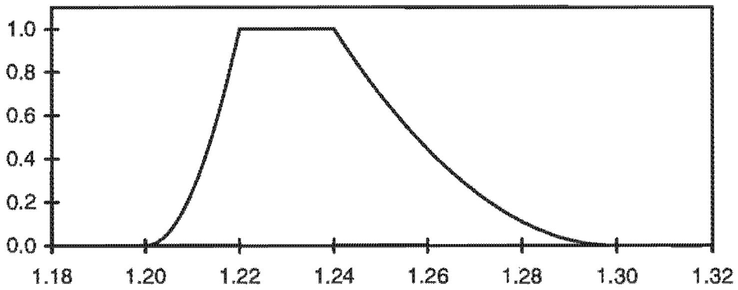

Figure 4.2i Outside strata *(O)*

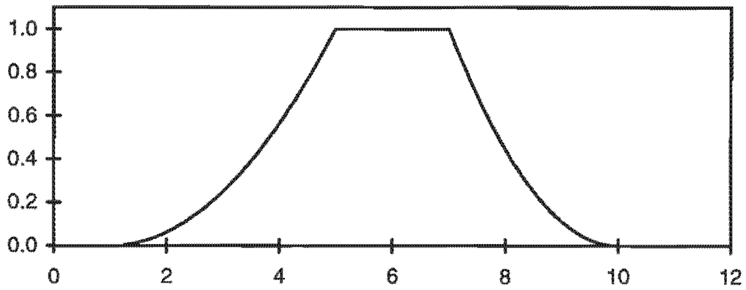

Figure 4.2j Undiscovered aggregations *(M)*

Figure 4.2g-j Original pdfs for the bias factors, before the two meetings in January 1997. Considerable revision of these pdfs was made during those meetings; final values for the bias factors are presented in Table 4.12.

Table 4.4a Mean sex ratios of orange roughy in tows made inside aggregations by the *Southern Aquarius*. Associated upper bounds for catchability inside aggregations (C_{agg}) are calculated under the assumptions that the tows under-sample females, and that the true sex ratio is 1:1. Based on unpublished data from A. Rees.

Dates	Sex ratio (male : female)	Upper catchability bound
June-July 1995	2.2 : 1	0.73
August-September 1995	2.4 : 1	0.71
November 1995	2.1 : 1	0.74
January-March 1996	1.9 : 1	0.76
Mean	2.15 : 1	0.73

Table 4.4b Sex ratios from four tows conducted by the *Southern Aquarius* outside the aggregations. Associated upper bounds for catchability outside aggregations (C_{out}) are calculated under the assumptions that the tows under-sample females, and that the true sex ratio is 1:1. Based on unpublished data from A. Rees.

Date	Sex ratio (male : female)	Upper catchability bound
6/27/95	1.9 : 1	0.77
6/30/95	2.0 : 1	0.74
8/2/95	0.2 : 1	–
9/11/95	3.3 : 1	0.65
Mean	1.9 : 1	0.77

1993–1994 is therefore 40 500–68 900 t. Three versions of a simple dynamic surplus production model ($B_{i+1} = B_i + F(B_i) - C_i$ where B is biomass and C annual catch) were used to calculate biomass values in the years between 1978 and 1994 to compare to the swept-area estimates to obtain a catchability estimate for each such survey. These models assumed: (a) exponential growth $F(B) = rB$, (b) constant surplus production $F(B) = P$, and (c) logistic growth $F(B) = rB(1-B/K)$ where K was set equal to the biomass estimate for 1978. The value of the unknown parameter (r or P) was determined by requiring that the model, on input of the 1978 biomass estimate and the known catch history, yielded the requisite value for the biomass in 1994. The resultant estimates for catchability were: (a) mean 0.40–0.45, range 0.29–0.53; (b) mean 0.44–0.49, range 0.32–0.57; (c) mean 0.44–0.49, range 0.32–0.57. G. Patchell (pers. comm.) used a similar approach to estimate catchability between 0.27 and 0.45. More recent estimates of catchability have involved the use of four sets of data, "using various trawl survey and length options" (M. Clark, pers. comm.). This method gives mean values for catchability lying between 0.45 and 0.63, with an overall range from 0.35 to 0.90. R.I.C.C. Francis (pers. comm.) draws attention to a major problem with the use of New Zealand data for estimating catchability in Namibia. The New Zealand catchability estimates are essentially a product of three factors: vertical availability (height of the plumes), vulnerability (proportion of fish in the path of the net that is caught)[12] and areal availability (proportion of the population inside the survey area). The first two factors may be reasonably assumed to have similar values in Namibia, but the third factor may be quite different, as it depends on the specific area covered by the trawl surveys. However, in the absence of other information, New Zealand catchability estimates still represent the most valuable source of information on which to draw inferences about catchability.

The minimum value of the associated pdf was taken to be 0.27 (from Patchell's estimate), and the maximum as 0.73 (from the sex ratio data), with the most likely range between 0.40 and 0.50 (Figure 4.2a).

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[12] Note that this implies that New Zealand catchability estimates include "herding" effects.

Catchability outside the aggregations (C_{out})

Data for catchability outside the aggregations are scant. Some of the fish in the path of the net will escape, either over or under the net opening. Male:female ratios in catches outside the aggregations have a mean of 1.9:1 (Table 4.4b), which corresponds to an upper bound for catchability of 0.77. Plumes are uncommon outside the aggregations, so that it may be surmised that catchability is higher than inside the aggregations. A plausible range was therefore chosen as 0.50 to 0.76, with the middle third of this range (0.58–0.68) selected as the most likely portion (Figure 4.2b).

Non-random positioning of trawls inside the aggregations (R_{agg})

Fish inside the aggregations are very dense, and the number of feasible tow lines is limited by the bottom topography. Potential future trawl surveys would probably have to be conducted along the same tow lines as those for the current fishery, and catches would presumably be large, possibly as great as for the directed exploratory fishing. However, no comparative survey data were available for Namibia to contrast commercial and survey catch rates inside aggregations at the time of the analysis. In Australia, the speculated virgin biomass of orange roughy at Mount St Helens, based on commercial catches, were an order of magnitude greater than indicated by later trawl, acoustic and egg surveys (Koslow *et al.* 1997). This initial estimate was obtained by extrapolating catch per volume swept by the volume of acoustic marks on the hill, without allowing for the effects of herding of fish in the water column down into the nets (A.D.M. Smith, pers. comm.). However, the swept-area method used here explicitly assumes that all fish above the net are caught, thus avoiding this problem. Minimum and maximum values specified were 0.50 and 0.90 under the expectation that the fishery may still concentrate on areas of temporarily higher density within the aggregations; the highest probability density was specified between 0.70 and 0.80 (Figure 4.2c).

Non-random positioning of trawls outside the aggregations (R_{out})

The experience of the skippers is thought to contribute to increased catch rates compared to those which a random survey would yield when fishing occurs outside aggregations.

Trawls are placed over regions with favourable bottom characteristics, where there are marks on echo-sounders, and at particular depths within 500–1 000 m. Approximately 20% of the bottom ground off Namibia at suitable depths is muddy, and thought to be unsuitable habitat for orange roughy; this area is not currently targeted by the skippers (A. Rees, pers. comm.). A comparison between directed fishing and a systematic survey trawl series can be made using data from the Japanese trawler, the *Matsuyama Maru* (Lesch 1995). This vessel performed 43 trawls directed at orange roughy every 30 minutes of latitude from 24°30′S to 29°00′S, and at depths of 750, 850, 950, 1 000 and 1 100 m. Trawls attempted at depths between 750 and 1 000 m were selected for comparison with directed fishing catches. The net width was presumed to be 27 m (V. Helgason, pers. comm.). Average densities of orange roughy were calculated for the following strata: *North Frankies*, *Conception*, *Johnies-North*, *South Namibia* and *Chamais*, and are contrasted with density estimates from directed fishing in Table 4.5. Two tows with erroneous bottom distances in the Gendor database were corrected to the mean in their strata for this comparison. Estimates for R_{out} range between 0.014 and 0.66 (Table 4.5), with a mean of 0.10. Values for R_{out} in *Conception* and *South Namibia* (containing the highest number of trawls by the *Matsuyama Maru*) were 0.13 and 0.11 respectively. The *Chamais* stratum is problematic, because the consistently high commercial catches were obtained at much shallower depths than the catches in the survey trawls. If the *Chamais* results are excluded, the overall mean would be 0.12. The consequential range of values specified for R_{out} is 0.05 to 0.20, with greatest probability density between 0.10 and 0.12 (Figure 4.2d).

These values for R_{out} are almost exclusively reliant on the survey trawls by the *Matsuyama Maru*. However, the results from this survey may be problematic, for several reasons, mainly relating to the type of gear used, and relative inexperience in targeting deepwater species (for a fuller discussion, see Appendix B). An alternative range of plausible values for R_{out} was therefore argued as follows. An upper limit is set at 0.80, since 20% of the ground at suitable depth is muddy and unfavourable to orange roughy. A lower limit is set at 0.20 since the net height of the *Matsuyama Maru* was 3 m (Lesch 1995), compared to

Table 4.5 A comparison of density estimates from the *Matsuyama Maru* and those from directed fishing in the same areas. The *Matsuyama Maru* conducted a systematic trawl survey off Namibia in November 1995 (Lesch 1995). The mean densities are weighted by the number of survey tows in each stratum. The ratio between the density estimate from the survey data and the directed fishing, represents the bias due to directed fishing on the catches *(R_{out})* outside the aggregations.

	Survey data		Directed fishing		
Strata	Number of trawls	Density (t/km²)	Number of tows	Density (t/km²)	Density ratio
North Frankies	2	0.40	9	0.61	0.66
Conception	8	1.51	5	11.20	0.13
Johnies-North	4	1.36	9	5.89	0.23
South Namibia	18	1.18	169	10.70	0.11
Chamais	2	0.55	6	39.00	0.01
Mean	–	1.19	–	11.56	0.10

6 m in vessels conducting directed trawling (A. Rees, pers. comm.). If the assumption is made that a 6-m net height would have doubled the efficiency of the *Matsuyama Maru*, then the mean value obtained from the *Matsuyama Maru* would be 0.20. The most likely range for R_{out} is then defined as the middle third of this range, i.e. 0.40–0.60 (Figure 4.2e).

Herding (H)

Herding was assumed to be identical inside and outside the aggregations. Bulman *et al.* (1994) made no adjustment for herding in their swept-area estimates for orange roughy off Australia. Skippers operating off Namibia believe that little herding by the doors occurs (A. James, pers. comm.). The effects of herding on the estimate are inter-linked with catchability estimates, so that the influence of this factor in isolation is therefore difficult to assess. H was therefore presumed to be close to 1.0 (Figure 4.2f), with a parabolic tail tapering down to a minimum value of 0.75.

Extent of the aggregations (E)

The areal extent of the aggregations in the baseline estimate was developed on the basis of the placement of the trawls in the aggregations. The bathymetry of the aggregations was not taken into account. In addition, during the spawning season in 1996, the known extent of three of the aggregations increased substantially. Bathymetry charts and data stored in Seaplot, at the Gendor offices, were examined to estimate the increase in the known extent of the grounds since June 1996. Two methods were used: first, a simple rectangle was drawn around all catches and areas where echo-sounder marks had been located; secondly, a more complex and tightly-fitting polygon was drawn around the catches and marks. The increase in overall area was 7.6 times using the box method and 3.4 times using the polygon method[13] (Table 4.6a). When this increase in area was applied to the biomass estimates for each aggregation, the total biomass estimate increased by 9.5 times for the box method and 4.9 times for the polygon method (Table 4.6b). The polygon method seems the more accurate of the two methods. One problem with the increased extent of the

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[13] Note that the area of the strata outside the aggregations was not adjusted downwards to compensate for this increase in the area of the aggregations. The decrease would have been 1–2% , which was considered negligible compared to the increase in the area of the strata (O), and other bias factors.

Table 4.6a Increase in the area of the aggregations *(E),* due to an expansion in the known extent of the aggregations during the recent spawning season. The box method entails drawing a rectangle around the new area; the polygon method encloses the aggregations in a more tightly-fitting, and complicated, polygon.

Aggregation	Baseline area (km²)	Box area (km²)	Increase (box)	Polygon area (km²)	Increase (polygon)
Hotspot	61	181	3.0	95	1.6
Rix	13	439	32.8	125	9.3
Frankies	5	343	67.6	179	35.3
Johnies	54	51	0.9	51	0.9
Total	133	1014	7.6	450	3.4

Table 4.6b Increase in the biomass inside the aggregations *(E),* due to an expansion in the known extent of the aggregations during the recent spawning season. Baseline biomasses are multiplied by the increase in the extent of the aggregations to obtain the revised biomass estimate. The box method entails drawing a rectangle around the new area; the polygon method encloses the aggregations in a more tightly-fitting, and complex, polygon.

Aggregation	Baseline biomass (t)	Box biomass (t)	Increase (box)	Polygon biomass (t)	Increase (polygon)
Hotspot	11,300	33,700	3.0	17,700	1.6
Rix	1,200	39,200	32.7	11,100	9.3
Frankies	3,300	220,000	66.7	114,800	34.8
Johnies	16,600	15,700	0.9	15,700	0.9
Total	32,400	308,600	9.5	159,300	4.9

aggregations is that these now larger areas are unlikely to contain uniform densities of orange roughy. It seems reasonable to expect that the additional area would contain some sections of much lower density than the aggregation as originally defined. Accordingly, the polygon estimates of biomass increase were treated as upper limits; the modal increase was presumed to lie between 3.0 and 4.0, with a range from 1.4 to 5.0 (Figure 4.2g).

Lost catch (*L*)

In certain circumstances, not all of the catch is retained in the nets. Catch may be lost when bags burst, or when fish are forced out through 'windows'—large holes in the side of the net through which fish pass when the catch exceeds a certain limit. Incomplete trawls were not included in the analysis, so that lost catch may be considered to occur only through the windows. Net windows were set at a 20 t bag (A. Rees, pers. comm.), so that it may be assumed that all bags greater than 20 t lost some fish through the windows. Inside the aggregations, 238 tows (18%) yielded more than 20 t, while only four tows (1.3%) outside the aggregations made catches greater than this. If it is assumed that every catch greater than 20 t lost 10% of the fish through the windows, then a re-analysis of the data shows that the overall biomass estimates would increase by 5.8%; if each of these trawls lost 25% of the catch through the windows, then the overall estimates would increase by 14.6%. A. Rees (pers. comm.) considers it likely that less than 10% of the catch is lost through the windows in a 20 t bag. In the future, lost catches will be negligible because newly installed net monitors make the windows obsolete and will effectively prevent lost catch. In the early phases of the St Helens fishery, burst bags were common due to catches of up to 100 t/tow, and additional mortality was estimated at 30% (A.D.M. Smith, pers. comm.). New Zealand analyses of biomass in the Chatham Rise assumed an "overrun" (i.e. lost catch) of 10% for the seasons from 1991–1992 to 1993–1994 and 5% thereafter (Annala & Sullivan 1997). Given current technology (including windows and net sensors), the overrun figures for Namibia are also likely to be lower than 10%. Most likely values were chosen to be between 1.04 and 1.07, with a range from 1.00 to 1.10 (Figure 4.2h).

Depth ranges chosen for the strata (*O*)

The strata outside aggregations were defined between the 500 and 1 000-m depth contours. However, orange roughy have been caught in both shallower and deeper waters. In addition, as defined, the strata do not extend completely to the northern border of Namibia. Average catches per tow made at different depths by the *Matsuyama Maru* are shown in Table 4.7a. The average catch over the 750–1 000 m range was 92.1 kg/tow, while at 1 100 m the average catch was 82.9 kg/tow. If the catch from 750–1 000 m is extrapolated to the 500–750 m range, and the catch at 1 100 m applied to the depth range 1 000–1 200 m, then 32% of the orange roughy biomass would fall outside the defined 500–1 000 m range[14]. Catches outside the aggregations in the Gendor database were analysed to obtain mean catches at various depth ranges (Table 4.7b), based on the haul position. According to these calculations, an estimated 10% of orange roughy could be outside the depth ranges defined. The Gendor data are more extensive and probably a better indication of the percentage of biomass that lies outside the defined depth ranges. The northern reaches of Namibia, not included in the original strata due to the absence of trawls in that area, add 12% to the area outside the aggregations. The range of estimates for this factor is therefore set between 20% and 30%, with the highest probability density assigned to the 22–24% range (Figure 4.2i)

Erroneous zeros (*Z*)

Many "zeros" in the Gendor database are actually catches that were less than one case (44 kg greenweight) of orange roughy. All zero catches in the database were replaced with 22 kg catches, and the baseline estimates re-calculated. There were 267 (20%) zero catches inside the aggregations, and modification of the values increased the estimates by 19.2 t (0.06%). Outside the aggregations, there were 107 (34%) zero catches recorded in the database, and correction increased the biomass estimates by 1617 t (0.8%). This factor was therefore considered to have a negligible impact on the results, and was not considered further for the Namibian analysis.

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[14] This assumes that the areal extent of each 100-m interval off the coast of Namibia is approximately the same.

Table 4.7a Average catches per tow of orange roughy made by the *Matsuyama Maru,* at different depths outside the aggregations. The estimated fraction of orange roughy biomass outside the 500–1 000 m depths is calculated by applying the average catch per tow in 750–1 000 m depths to the depth range 500–1 000 m, and by applying the average catch per tow at 1 100 m to the range 1 000–1 200 m.

Depth (m)	Tows (n)	Average catch (kg)
750	9	21.5
850	10	61.3
950	5	193.0
1 000	10	136.0
750–1 000	34	92.1
1 100	8	82.9

Fraction outside 1 000 m	0.32

Table 4.7b Average catches per tow of orange roughy during directed exploratory fishing, in different depth ranges outside the aggregations. The estimated fraction of biomass outside 500–1 000 m is obtained by applying average catches per tow to the depth ranges in which they were recorded.

Depth (m)	Tows (n)	Average catch (kg)
500–1 000	261	1789.4
1 001–1 050	20	959.3
1 051–1 100	10	96.8
1 101–1 150	5	396.0
1 151–1 300	4	88.0

Fraction outside 1 000 m	0.10

Biased CVs (CV_{agg}, CV_{out})

Since tows were neither independent nor random, it seems likely that they were positively correlated, and the CVs therefore negatively biased. As a crude initial adjustment, an additional term with a 10% CV was added to the variances originally estimated. In consequence, the CV for the aggregations was adjusted upwards from 5% to 11%, and the CV outside the aggregations was raised from 24% to 26%.

Number of aggregations

The baseline estimates were based on four aggregations, but an additional aggregation (*21 Jump Street*) close to the *Frankies* aggregation was subsequently discovered inside the Namibian EEZ. A strong possibility existed that further aggregations would be discovered as the exploratory fishing operation extended. Earlier evaluations outlined in Branch (1996) placed an upper limit of 8.6 on the number of undiscovered aggregations, though the assumptions underlying this estimate were likely in error. Based on suitable habitat, a suggested upper limit on the number of additional aggregations that remain to be discovered is ten (A. James, pers. comm.). Outer limits for this value were chosen to be one and ten, with the most likely range between five and seven (Figure 4.2j).

Migratory behaviour

The migratory behaviour of orange roughy is poorly known, and it would be foolhardy to speculate on the influence of this factor. Circumstantial evidence, in the form of modes in the length-frequency records, indicate that orange roughy migrate into the aggregations over the spawning period to supplement a resident population (A. Rees, pers. comm.). This supports evidence in New Zealand from commercial CPUE data over the period 1979–1988 that fish move into the spawning area on the Chatham Rise from the north-east and the east (Coburn & Doonan 1994). Off Australia, there is also evidence from changes in the proportion of non-spawning fish which supports this contention (Bell *et al.* 1992). The extent to which these spawning movements affect the swept-area estimates is unclear. In Australia, for example, a trawl survey found only small quantities of orange roughy (Bulman *et al.* 1994), although later a spawning hill, St Helens, was discovered in the same region. It is evident that the fish which migrated to the spawning hill were not detected in the earlier trawl survey outside the spawning aggregation. Most directed trawling in Namibia has occurred outside the spawning season. Given the poor knowledge on migration patterns, no attempt was made to account for the possible influence of this factor.

4.5 Preliminary results

The specifications developed above were intended as first-cut estimates of the bias factors. They were presented for debate at an initial meeting between representatives from the Namibian ministry of fisheries and representatives of the fishing company conducting exploratory fishing, on the 14th January 1997. The results presented there were intended to be preliminary and to serve as a focus for discussion at that meeting.

Estimates

Point estimates for biomass are given as the median values in the 5 000 realisations of biomass produced in the Monte Carlo simulations; 90% probability intervals are obtained by discarding the highest 5% and lowest 5% of these realisations. A summary of the estimates is contained in Table 4.8a-c. The total biomass was estimated at 214 000 t (CV = 24%), with a 90% probability interval of 141 000–313 000 t (Figure 4.3a). Most of the biomass (median 77%) was estimated to be inside the aggregations: 164 000 t (CV = 30%) with a 90% probability interval of 97 000–262 000 t (Figure 4.3b). Only a relatively small proportion of the biomass was estimated to fall outside the aggregations: 47 000 t (CV = 34%), with a 90% probability interval of 26 000–81 000 t (Figure 4.3c). These results reverse the impression gained from the point baseline estimates in Section 4.3 that most of the biomass is contained outside the aggregations.

The values for the influence of directed fishing on catch rates outside the aggregations (R_{out}) upon which the results above are based are derived from the *Matsuyama Maru* survey. However, there is concern that the results of that survey are not directly comparable to trawls conducted by the exploratory deepwater fishing vessels (see

Table 4.8a Preliminary estimates of *total* biomass: medians, CVs and 90% probability intervals. Four cases are presented; depending on whether additional, as-yet undiscovered aggregations are taken into account, and whether the bias for directed fishing (R_{out}) is derived directly from the *Matsuyama Maru* survey or not.

Aggregations	R_{out} derived from *M. Maru* survey?	Median	CV	Lower limit	Upper limit
Known	Yes	214 000	24%	141 000	313 000
Undiscovered	Yes	447 000	30%	270 000	732 000
Known	No	362 000	24%	242 000	536 000
Undiscovered	No	600 000	26%	386 000	917 000

Table 4.8b Preliminary estimates of biomass *inside* aggregations: medians, CVs and 90% confidence limits. The estimates are based on either known aggregations, or by incorporating the number of currently undiscovered aggregations.

	Median	CV	Lower limit	Upper limit
Known aggregations only	164 000	30%	97 000	262 000
Including as-yet undiscovered aggregations	397 000	34%	221 000	677 000

Table 4.8c Preliminary estimates of biomass *outside* the aggregations: medians, CVs and 90% probability intervals. Two cases are presented: one in which the estimated bias due to directed fishing (R_{out}) was derived from a survey by the *Matsuyama Maru*, and the other case where the *Matsuyama Maru* survey was not used to estimate R_{out} directly.

	Median	CV	Lower limit	Upper limit
R_{out} derived from *Matsuyama Maru* survey	47 000	35%	26 000	81 000
R_{out} derived independently	192 000	36%	105 000	335 000

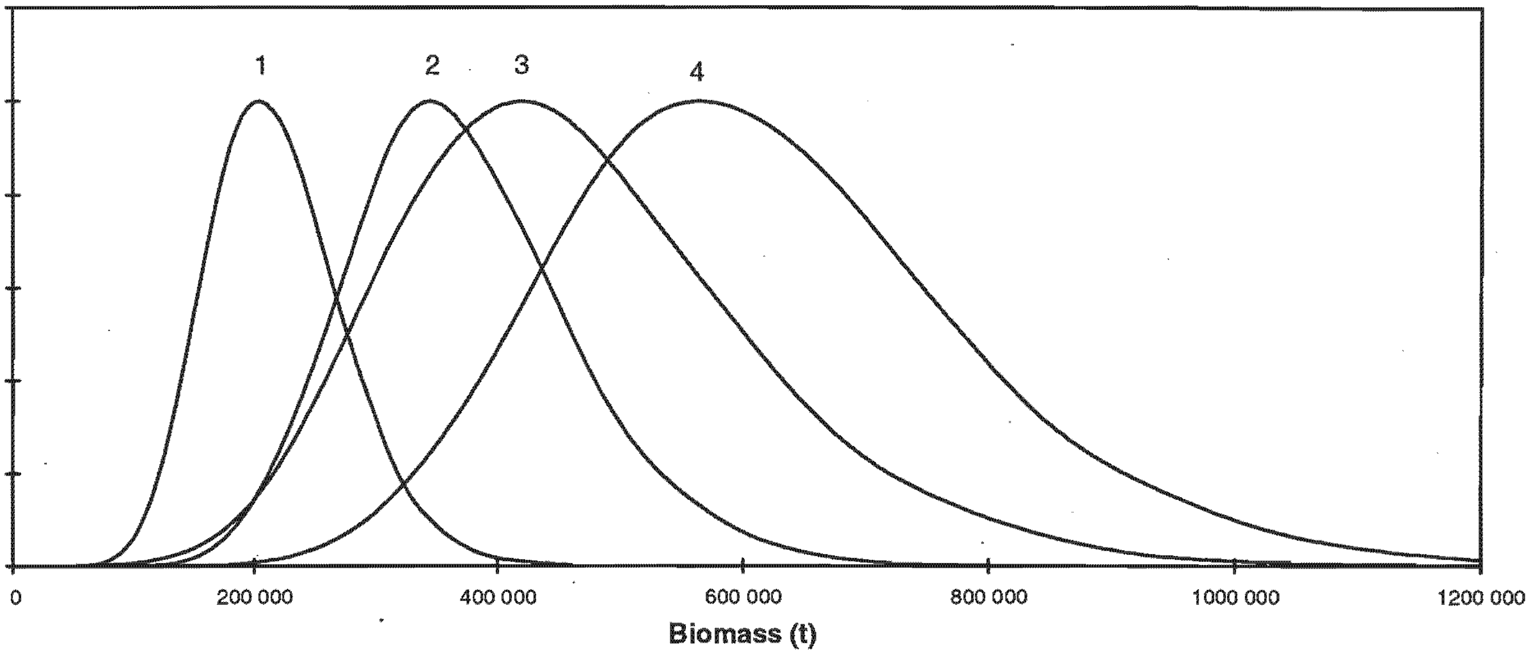

Figure 4.3a Preliminary total biomass estimates for orange roughy off Namibia. The smoothed curves are pdfs, but are scaled so that their modal heights are the same. See Section 3.5 for an explanation of the smoothing technique used. Four cases are presented:

(1) Known aggregations only; values for directed fishing (R_{out}) derived from the *Matsuyama Maru* survey.

(2) Known aggregations only; values for R_{out} not derived directly from the *Matsuyama Maru* survey.

(3) Including possible undiscovered aggregations; values for R_{out} derived from the *Matsuyama Maru* survey.

(4) Including possible undiscovered aggregations; values for R_{out} not derived directly from the *Matsuyama Maru* survey.

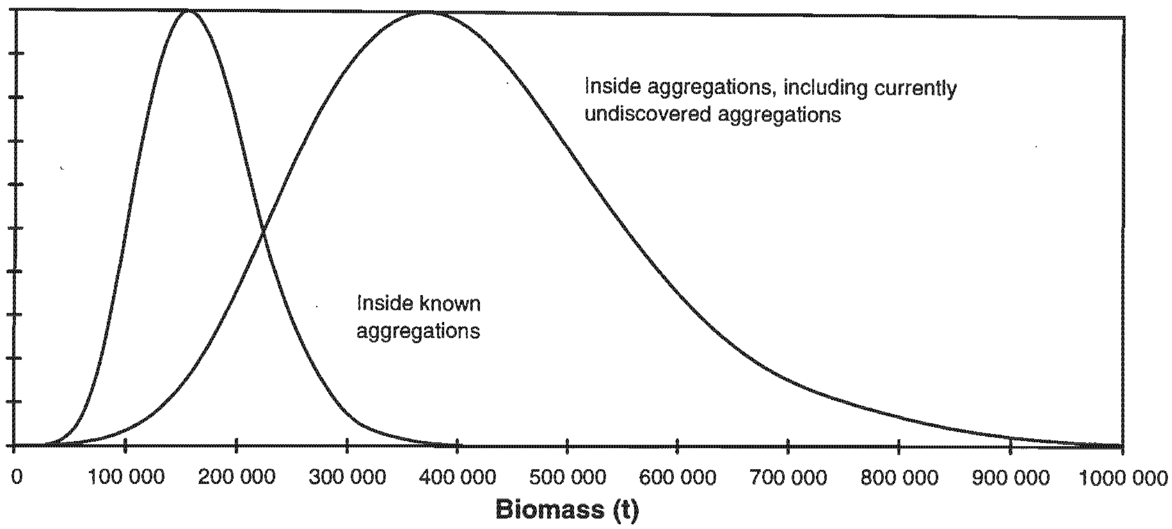

Figure 4.3b Preliminary biomass estimates for orange roughy *inside aggregations* off Namibia. One probability density function is based on known aggregations, whereas the other accounts for the possibility that additional, undiscovered aggregations may be found in the future, thus increasing the estimates. See text for an explanation of the smoothing technique used. The two probability density functions are scaled differently, in a manner that renders their modal heights the same.

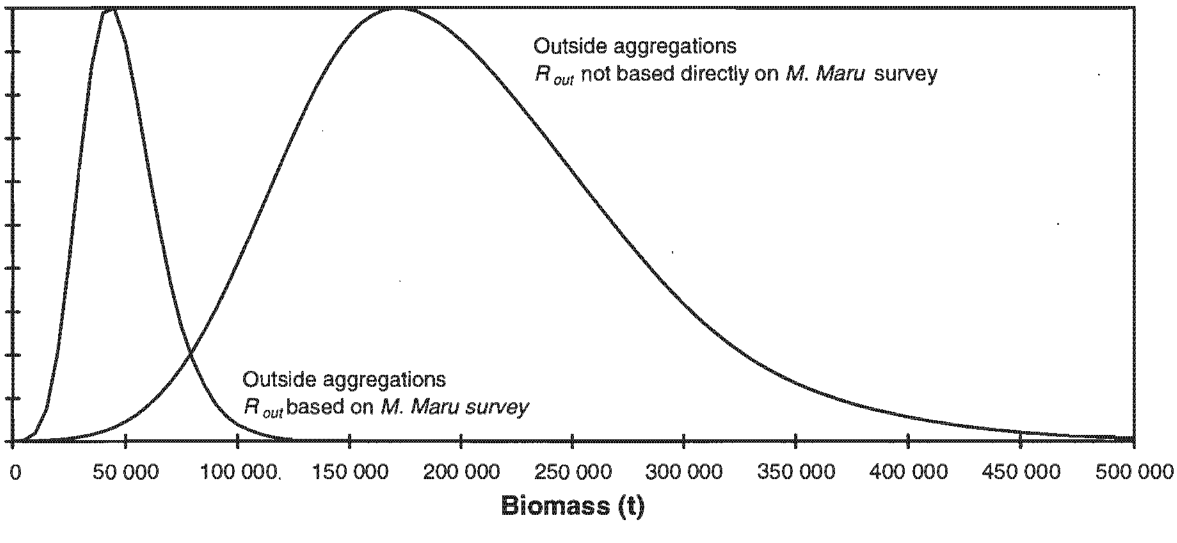

Figure 4.3c Preliminary biomass estimates for orange roughy *outside aggregations* off Namibia. Two cases are presented, one where the bias for directed fishing (R_{out}) is estimated from the *Matsuyama Maru* survey, and the other where R_{out} is not estimated from the *M. Maru* survey. The smoothed curves are pdfs, but are scaled so that their modal heights are the same. See text for an explanation of the smoothing technique used.

Appendix B for a fuller discussion). If values for R_{out} are argued effectively independently of the results from the *Matsuyama Maru* survey, the median biomass estimate for orange roughy outside aggregations increases considerably to 192 000 t (CV = 36%), with a 90% probability interval of 105 000–335 000 t (Figure 4.3c. The total biomass is then estimated to be 362 000 t (CV = 24%), with a 90% probability interval of 242 000–536 000 t. In this case, only 53% (median) of the biomass is estimated to be contained inside the aggregations.

It is probable that a number of undiscovered aggregations remain off Namibia. When this factor is taken into account, the estimated total biomass increases to 447 000 t (CV = 30%), with a 90% probability interval of 270 000–732 000 t (Figure 4.3a). The estimated biomass inside the aggregations increases to 397 000 t (CV = 30%), with a 90% probability interval of 221 000–677 000 t (Figure 4.3b). The percentage of the biomass inside the aggregations increases to 89% (median).

If the *Matsuyama Maru* survey is disregarded as above, and the undiscovered aggregations are taken into account, the median estimate for the total biomass increases to 600 000 t (CV = 26%), with a 90% probability interval of 386 000–917 000 t. The percentage of the biomass inside aggregations is then 66% (median).

Decisions reached at the January 14 meeting

A number of consensus decisions were reached between Namibian ministry officials and Gendor representatives at the January 14 meeting. These include directions for work to be completed before another joint meeting on 28–29 January 1997.

It was agreed by both Namibian ministry officials and Gendor representatives that the *Matsuyama Maru* survey should be disregarded as a basis for estimating the values of R_{out}. It was also deemed premature to base any management decisions on suppositions about as-yet undiscovered aggregations. Further estimates were therefore based on known aggregations only, and estimates of R_{out} that were not derived directly from the *Matsuyama Maru* survey.

The values to be used for R_{out} were a major concern. Gendor representatives noted that earlier exploratory tows outside the aggregations were independent of any knowledge about the resource distribution, while later tows were more directed. It was therefore agreed that an examination of changes in density estimates over time in a particular stratum might give an appropriate value for R_{out}.

The possibility was raised that "double-counting" was occurring due to migratory patterns. If fish migrated into the aggregations during the spawning season, this situation would arise if there was more effort outside the aggregations during the non-spawning season, and more effort inside the aggregations during the spawning season.

4.6 Final consensus on bias factors

Alternative sets of bias factors

The initial estimates for all the bias factors were thoroughly debated at the January 14 meeting, and the Namibian ministry representatives proposed an alternative set of bias factors, referred to as the "Revised Namibian" set of factors. The assessment results were sent to two independent international consultants: Malcolm Clark (NIWA, New Zealand) and Murdoch McAllister (MRAG, Imperial College, UK), who also proposed changes in the bias factors. The suggestions from these sources are summarised in Table 4.9. Major debate focused on the values assigned to the increase in known extent of the aggregations, and the values for catchability and directed fishing inside the aggregations. One option suggested by McAllister was to re-compute the estimates using a uniform distribution for the bias factors between the minimum and maximum values in the original specifications ("First McAllister"); a second option was to use a uniform distribution just for the C_{agg}, R_{agg} and H factors ("Second McAllister").

Table 4.9 Bias specifications suggested by different authorities. The original specifications are those presented at the January 14 meeting in 1997. Revised Namibian specifications are those suggested by the Namibian authorities in this meeting, with the major difference in the values for *E*. Malcolm Clark suggested widening the range for C_{agg}. The first suggestion by McAllister was to widen the most likely range to encompass the minimum and maximum values. The second McAllister suggestion involved changes in the specifications for $C_{agg,}$ R_{agg} and *H*.

Bias factor specification	Symbol	Set of specifications	Minimum	Most likely range	Maximum
Catchability inside the aggregations	C_{agg}	Original	0.27	0.40 – 0.50	0.73
		Revised (Namibian)	0.30	0.45 – 0.55	0.70
		Clark	0.20	0.30 – 0.60	0.80
		First McAllister	0.27	0.27 – 0.73	0.73
		Second McAllister	0.27	0.27 – 0.90	0.90
Catchability outside the aggregations	C_{out}	Original	0.50	0.58 – 0.68	0.76
		Revised (Namibian)	0.50	0.60 – 0.70	1.00
		Clark	0.50	0.58 – 0.68	0.76
		First McAllister	0.50	0.50 – 0.76	0.76
		Second McAllister	0.50	0.58 – 0.68	0.76
Directed fishing inside the aggregations	R_{agg}	Original	0.50	0.70 – 0.80	0.90
		Revised (Namibian)	0.40	0.55 – 0.65	0.80
		Clark	0.50	0.70 – 0.80	0.90
		First McAllister	0.50	0.50 – 0.90	0.90
		Second McAllister	0.10	0.10 – 0.90	0.90
Directed fishing outside the aggregations	R_{out}	Original	0.2	0.4 – 0.6	0.8
		Revised (Namibian)	0.2	0.4 – 0.6	0.8
		Clark	0.2	0.4 – 0.6	0.8
		First McAllister	0.2	0.2 – 0.8	0.8
		Second McAllister	0.2	0.4 – 0.6	0.8
Herding by the doors	H	Original	0.75	1.00 – 1.00	1.00
		Revised (Namibian)	0.75	1.00 – 1.00	1.00
		Clark	0.75	1.00 – 1.00	1.00
		First McAllister	0.75	1.00 – 1.00	1.00
		Second McAllister	0.60	1.00 – 1.00	1.00
Increase in known extent of aggregations	E	Original	1.4	3.0 – 4.0	5.0
		Revised (Namibian)	1.4	1.7 – 2.3	3.0
		Clark	1.4	3.0 – 4.0	5.0
		First McAllister	1.4	1.4 – 5.0	5.0
		Second McAllister	1.4	3.0 – 4.0	5.0
Loss of catch	L	Original	1.00	1.04 – 1.07	1.10
		Revised (Namibian)	1.00	1.04 – 1.07	1.10
		Clark	1.00	1.04 – 1.07	1.10
		First McAllister	1.00	1.00 – 1.10	1.10
		Second McAllister	1.00	1.04 – 1.07	1.10
Fish outside defined strata	O	Original	1.20	1.22 – 1.24	1.30
		Revised (Namibian)	1.20	1.24 – 1.26	1.30
		Clark	1.20	1.22 – 1.24	1.30
		First McAllister	1.20	1.20 – 1.30	1.30
		Second McAllister	1.20	1.22 – 1.24	1.30

Further estimation of the effects of directed fishing (R_{out})

Earlier tows in the exploratory phase of the orange roughy fishery may have been conducted at random, whereas later tows were more directed. A comparison of density estimates could be used to give an estimate of the effect of directed fishing outside the aggregations. Only one stratum, *South Namibia*, contained sufficient tows over a period of time to obtain estimates in this manner. Density estimates fluctuate between the years, with highest density estimates obtained using the 1995 and then the 1990 tows (Table 4.10a). However, differences between density estimates were almost solely due to the vessels used in those years (Table 4.10b), and the large standard errors prevented significant differences being detected among the years. This method of estimating R_{out} was therefore abandoned.

"Double counting" of fish inside and outside the aggregations

The possibility was raised in the January 14 meeting that fish were being "double counted" because of migration patterns. To address this possibility, the tows in the database were separated by month. The spawning season was assumed to be July and August combined—in reality, it encompasses a shorter period at the end of July and the start of August. Estimated densities inside the aggregations were higher during the spawning season (11.0 $t.km^{-2}$) than out of the spawning season (8.2 $t.km^{-2}$) (Table 4.11a). However, only 13% of the tows in aggregations were performed during the spawning season, mainly because the assessment was based on data up until July 1996. Catch rates outside the aggregations were lower during the spawning season (0.22 $t.km^{-2}$) than the non-spawning period (0.29 $t.km^{-2}$) (Table 4.11b). In all, 39% of the tows outside the aggregations were performed during the spawning season. The conclusion is therefore that more tows in the database were performed inside the aggregations when the density was *lower*; and more effort was concentrated outside the aggregations, also when the density there was lower. It was therefore concluded that "double counting" was not problematic, and in fact, the opposite problem may have occurred—"half counting".

Table 4.10a Density estimates of orange roughy in the *South Namibia* stratum, based on tows in different *years*. One big catch in 1995 has a disproportionate effect on the mean density: estimates including and excluding this tow are given.

Year	Mean ($t.km^{-2}$)	Tows (n)	SE
1988	4.9	54	3.3
1990	26.7	17	21.0
1994	13.3	84	3.3
1995 (incl.)	112.4	13	78.5
1995 (excl.)	36.5	12	21.7
1996	0.0	1	–

Table 4.10b Density estimates of orange roughy in the *South Namibia* stratum, based on tows made by different *vessels*. One big catch made by the *Southern Aquarius* had a disproportionate effect on the density estimate: estimates including and excluding this tow are given.

Vessel	Year	Mean ($t.km^{-2}$)	Tows (n)	SE
Sill	1988	0.0	21	0.0
H. Gardenia	1988	15.6	2	15.2
Ribadeo	1988	7.5	31	5.6
Verbena	1990	26.7	17	21.0
Toralla	1994	13.3	84	3.3
Aquarius (incl.)	1995	100.2	12	84.3
Aquarius (excl.)	1995	16.2	11	8.6
Whitby	1995	259.6	1	–

Table 4.11a Estimated density of orange roughy *inside* the defined aggregations during various months of the year. The spawning season is assumed to encompass July and August. The table is based on the tow information up to mid-July 1996 which was used for the swept-area estimate.

Month	Mean (t.km^{-2})	Tows (n)	SE
January	6.12	157	1.05
February	6.37	192	1.00
March	2.55	236	0.32
April	16.19	152	3.05
May	5.95	118	0.90
June	16.16	177	1.17
July	10.59	123	1.29
August	12.00	55	2.38
September	14.29	44	1.20
October	7.50	2	5.50
November	3.77	80	1.04
December	1.29	40	0.54
Inside spawning season	11.02	178	1.14
Outside spawning season	8.19	1 198	0.52

Table 4.11b Estimated density of orange roughy *outside* the defined aggregations during various months of the year. The spawning season is assumed to encompass July and August. The table is based on the tow information up to mid-July 1996 which was used for the swept-area estimate.

Month	Mean (t.km^{-2})	Tows (n)	SE
January	0.021	17	0.01
February	0.000	1	–
March	0.000	5	0.00
April	0.002	6	0.00
May	0.146	68	0.08
June	0.331	83	0.06
July	0.079	51	0.05
August	0.316	75	0.20
September	1.487	11	0.41
October	–	–	–
November	0.332	10	0.30
December	–	–	–
Inside spawning season	0.220	126	0.12
Outside spawning season	0.286	201	0.05

Final sets of bias factors

There was further discussion at the second meeting (28–29 January 1997), among Gendor representatives, Namibian ministry representatives and the two independent scientific consultants. This resulted in the presentation of two final sets of bias specifications, proposed by Gendor and the Namibian ministry, respectively (Table 4.12). Biomass estimates obtained from these two sets were in good agreement, although the Namibian ministry biases gave estimates which were slightly lower, and had wider confidence limits, than those proposed by Gendor.

The two final sets of bias factors differed from the original specifications in two important ways. First, the range of most likely values was increased considerably for most of the bias factors, better reflecting the uncertainty in these estimates. Secondly, the lower value of the most likely range for the increase in the extent of the aggregations was lowered, ranging from 2–4 instead of the original 3–4. Of the eight bias factors, Gendor and Ministry agreed on the values for five, differing only with respect to C_{agg}, C_{out}, and R_{agg}.

4.7 Final results

Using the Namibian ministry's set of bias factors, total biomass (giving 90% probability intervals) was estimated at 173 000–520 000 t (CV = 34%), with 56 000–272 000 t (CV = 53%) inside the aggregations (Table 4.13). The estimate of biomass using Gendor's set of bias factors was 197 000–510 000 t (CV = 29%), with 71 000–251 000 t (CV = 39%) inside the aggregations (Table 4.13). The aggregations were estimated to hold a median of 38% (Ministry) and 42% (Gendor) of the total biomass off Namibia.

4.8 Discussion

Influence of the final bias factors on the swept-area estimates

Final estimates of biomass increased from the baseline swept-area estimate of 243 000 t to a median of 306 000 t or 321 000 t under the two final sets of bias specifications. Estimates inside the aggregations increased from the swept-area estimate of 32 000 t to

Table 4.12 Suggested bias specifications at 28-29 January 1997. The original specifications are those presented at the January 14 meeting in 1997. Final ministry specifications are those suggested at the second January 1997 meeting by the Namibian ministry and the independent consultants: Clark and McAllister; these are contrasted with the final specifications from Gendor. Both sets of revised specifications have much wider "most likely" ranges for all the bias factors, in the spirit of McAllister's initial comments. The values for E and H are lower than the original suggestions. Differences in bias specifications between the ministry and Gendor still exist in the values for C_{agg} , C_{out} and $R_{agg.}$

Bias factor specification	Symbol	Set of specifications	Minimum	Most likely range	Maximum
Catchability inside the aggregations	C_{agg}	Original	0.27	0.40 – 0.50	0.73
		Ministry (final)	0.10	0.30 – 0.70	0.80
		Gendor (final)	0.27	0.34 – 0.61	0.73
Catchability outside the aggregations	C_{out}	Original	0.50	0.58 – 0.68	0.76
		Ministry (final)	0.40	0.50 – 0.80	0.90
		Gendor (final)	0.50	0.54 – 0.72	0.76
Directed fishing inside the aggregations	R_{agg}	Original	0.50	0.70 – 0.80	0.90
		Ministry (final)	0.40	0.45 – 0.75	0.90
		Gendor (final)	0.50	0.60 – 0.85	0.90
Directed fishing outside the aggregations	R_{out}	Original	0.2	0.4 – 0.6	0.8
		Ministry (final)	0.2	0.3 – 0.7	0.8
		Gendor (final)	0.2	0.3 – 0.7	0.8
Herding by the doors	H	Original	0.75	1.00 – 1.00	1.00
		Ministry (final)	0.60	1.00 – 1.00	1.00
		Gendor (final)	0.60	1.00 – 1.00	1.00
Increase in known extent of aggregations	E	Original	1.4	3.0 – 4.0	5.0
		Ministry (final)	1.4	2.0 – 4.0	5.0
		Gendor (final)	1.4	2.0 – 4.0	5.0
Loss of catch	L	Original	1.00	1.04 – 1.07	1.10
		Ministry (final)	1.00	1.02 – 1.08	1.10
		Gendor (final)	1.00	1.02 – 1.08	1.10
Fish outside defined strata	O	Original	1.20	1.22 – 1.24	1.30
		Ministry (final)	1.20	1.21 – 1.27	1.30
		Gendor (final)	1.20	1.21 – 1.27	1.30

Table 4.13 Biomass estimates (in tonnes) obtained when using either the revised Namibian ministry's bias factor specifications, or those proposed by Gendor representatives. The bias factors are those proposed on 28 29 January 1997, and used in the final analyses.

Ministry	Median	CV	Lower 90%	Upper 90%
Inside aggregations	117 000	53%	56 000	272 000
Outside aggregations	175 000	43%	83 000	340 000
Total	306 000	34%	173 000	520 000

Gendor	Median	CV	Lower 90%	Upper 90%
Inside aggregations	135 000	39%	71 000	251 000
Outside aggregations	179 000	40%	87 000	334 000
Total	321 000	29%	197 000	510 000

medians of 117 000 t and 135 000 t, while estimates of biomass outside the aggregations decreased from 211 000 t to medians of 175 000 and 179 000 t.

The estimates of biomass inside the aggregations increased substantially, mainly because of two factors: catchability (C_{agg}) and the increase in the extent of the aggregations (E). In the swept-area results, catchability was assumed to be 100% of the fish in the path of the net. In reality, fish would pass over and under the nets, and may even actively avoid the nets (Koslow *et al.* 1995b). The extent of the aggregations had been severely underestimated, as the catches taken during the spawning survey expanded the known area of three of the strata—*Hotspot*, *Rix*, and *Frankies*—considerably. This factor was assigned a most likely range of 2–4.

The slightly lower estimate for outside the aggregations is due to a combination of factors. First, the bias due to the directed nature of the exploratory fishing (R_{out}) decreased the estimates considerably (most likely range of 0.3–0.7). This decrease was not compensated by other bias factors: catchability outside the aggregations (C_{out}) was presumed to be higher than inside the aggregations, and the extent of the strata was not increased.

The percentage of biomass estimated to fall within the aggregations increased from 13% for the baseline estimate to 38% or 42% depending on the final set of bias factors. This estimate was averaged from tows performed throughout the year, with no apparent "double counting" bias in the data due to migratory patterns. However, there is circumstantial evidence off both Australia and New Zealand that fish migrate into the aggregations over the spawning season (Bell *et al.* 1992; Coburn & Doonan 1994). It is therefore likely that a greater proportion (than 38–42%) of the biomass is inside the aggregations during the spawning season, and a lower proportion outside the spawning season. The percentage of fish inside the aggregations is important, because only the aggregations contain orange roughy in sufficient density to support a fishery. If, for example, most of the biomass never moves into an aggregation, then replacement of fish caught on the aggregations will be slow, although a large reserve of biomass will remain outside the aggregations. Of course, not all persistent aggregations are spawning aggregation: some may be feeding aggregations.

Participation of interested parties in the biomass estimation process

Decisions made at the two meetings in Namibia formed an integral part of the biomass estimation process. All major decisions were thoroughly debated by representatives from the exploratory fishing company, Gendor; officials from the Namibian ministry of fisheries and marine resources and its research arm (NatMIRC); and two independent international consultants: Murdoch McAllister and Malcolm Clark. It was decided not to include results from a survey by the *Matsuyama Maru* and to exclude estimates based on as-yet undiscovered aggregations. In addition, the values for the bias factors were subject to extensive discussion, until all parties were satisfied with the final values. The spirit of the decision-making process throughout was one of co-operation rather than confrontation. Many parallels can be drawn between the developing protocol in Namibia and the Australian (and New Zealand) orange roughy fishery. In all three countries, industry, scientists and managers work together closely, with industry funding most of the research. Consequently, industry is involved in assessing research needs, evaluating assessment results, and developing long-term strategies for managing the stocks. In Australia, the good working relationship between industry, scientists and managers eased the transition from catches in excess of 50 000 t in 1990 to catches under 10 000 t in 1994 (Bax 1997; Ross & Smith 1997; Figure 1.1).

Limitations of this analysis

These results should be treated with caution. Although every attempt was made to assign reasonable ranges to the various bias factors, it is possible that erroneous assumptions were made in the process. Biomass estimation for orange roughy based on commercial trawl data is generally held to be problematic (A. Punt, pers. comm.), and both J.A. Koslow (pers. comm.) and M.R. Clark (pers. comm.) have expressed reservations about the methodology used here. However, in the absence of the scientific survey data available to orange roughy scientists in Australia and New Zealand, there has been no choice but to attempt an initial estimate of orange roughy biomass in Namibia based on commercial trawl data alone. At the very least, this has fulfilled the important objective of obtaining some idea of the plausible bounds for orange roughy biomass at the outset of the fishery in Namibia.

This analysis has a potential flaw in that all of the aggregations have been grouped together. Each defined aggregation has a different density, and was discovered at a different period in the development of the fishery off Namibia. Since operations have commenced in Namibia, the efficiency of the vessels has presumably increased to some extent, so that the aggregations that were discovered later may have associated density estimates that are more inflated (compared to a random trawl survey) than those for aggregations discovered earlier in the fishery. As an alternative to the grouping method used here, each aggregation could be assessed separately, with different ranges assigned to the R_{agg} and E bias factors.

The 90% probability intervals are as important as the median estimates of biomass, since they play a major role in determining the risk of over-fishing associated with different fishing policies. In Chapter 7, this risk is quantified by exploring the effects of different future catch trajectories on these estimates. In Chapter 8, this concept is taken a step further, with the investigation of adaptive management possibilities for the Namibian resource. In essence, this takes into account learning about changes in the biomass provided by future acoustic surveys, which would reduce the risks of over-fishing if catch levels were too high initially. The first in a proposed series of annual acoustic surveys was performed in July 1997 off Namibia.

5. Swept-area results for South African orange roughy

Catches from exploratory fishing for orange roughy off South Africa have been poor, with only 14 t being caught by mid-1997. Fishing effort has therefore been directed primarily at oreo dories, particularly warty oreo dory (*Allocyttus verrucosus*). Oreo dories do not command the high market prices of orange roughy; nevertheless, there was strong pressure from industry for deepwater fishing permits in addition to the two which had been issued (Tilney 1997). Assessments were therefore undertaken to estimate the biomass of both orange roughy (this chapter) and oreo dories (Chapter 6) off South Africa, to determine whether additional fishing effort was warranted. The swept-area methodology outlined in Chapter 3, and refined in an assessment of orange roughy biomass off Namibia (Chapter 4), was used for these assessments. The results were presented on 18 June 1997 at the Sea Fisheries Research Institute (SFRI) to representatives of the permit-holders and of the SFRI.

5.1 Data

In total, 355 tows were considered in the assessment, which included all known deepwater tows off South Africa until mid-February 1997. Tows from the *Iris* (192 tows) were not included because of a paucity of positional and catch information on orange roughy—only 280 kg of orange roughy was reported in those tows. Most of the tows came from the *Nicola* (267 tows) and the *Southern Aquarius* (69). Nearly all of the tows used in the analysis (94%) were made within the 500–1 000 m depth interval, and no orange roughy was caught in any of the 26 tows (4 deeper and 22 shallower) outside these depths.

5.2 Strata definition

There were no areas where high catches (indicating the discovery of aggregations) had been taken. However, consistent small catches of orange roughy were made from a natural feature, designated the *Cape Canyon*; and large catches of oreo dory were made from another region, referred to as the *Dory Patch*. These two strata were delimited as if they were aggregations (Section 3.2). Additional strata (*North-west SA*, *West SA* and *South SA*) were defined around the coast between the 500 m and 1 000 m depth contours (Figure 5.1).

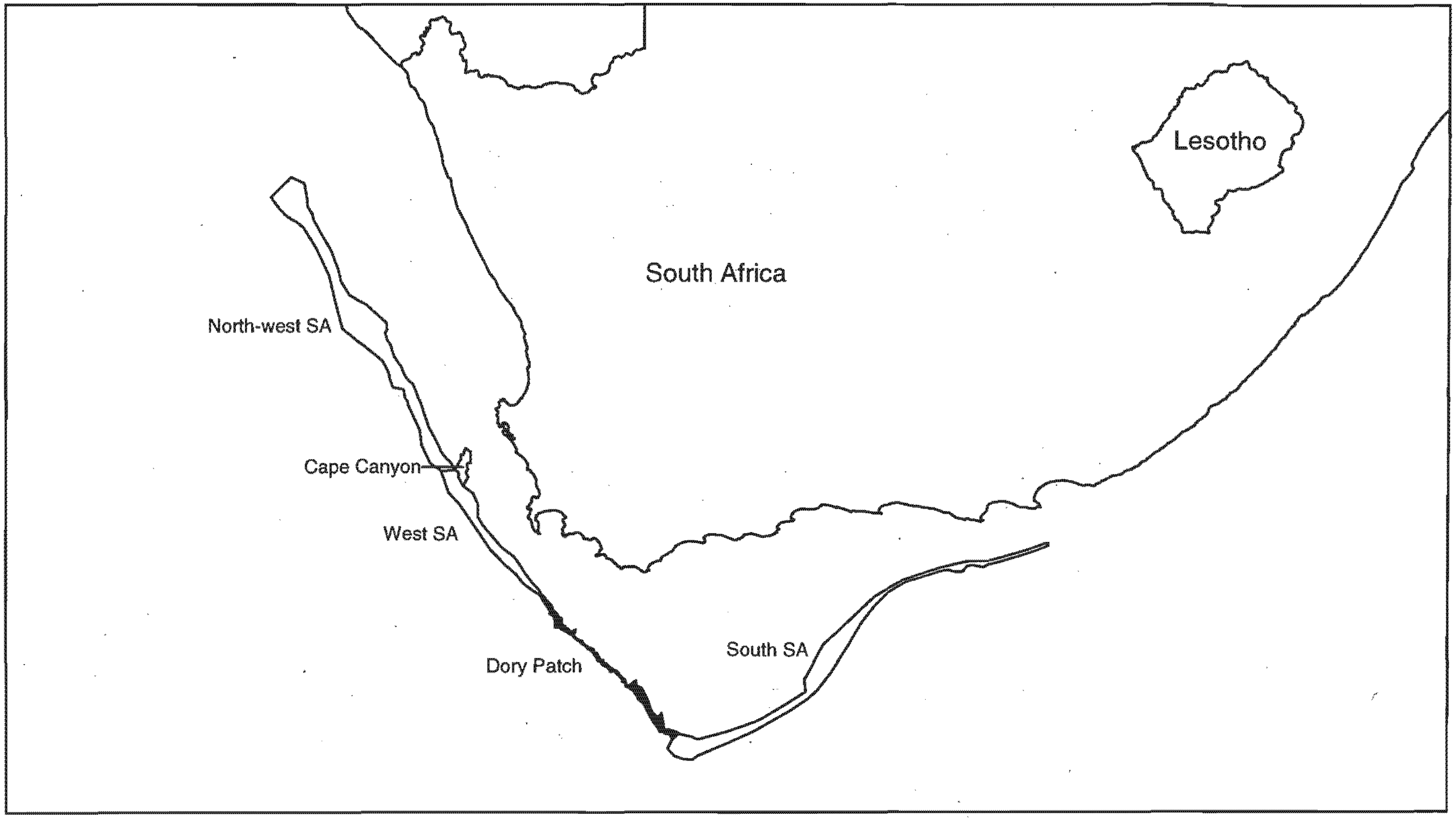

Figure 5.1 The strata used in the baseline swept-area assessment for orange roughy off South Africa.

This stratification is referred to as the "five strata" option. Depth-stratification by equal-area 100-m depth intervals (Section 3.2) resulted in each of these five strata being divided into five bands, the "twenty-five strata" option. The total area included in the strata was 23 600 km².

5.3 Swept-area results

The "five strata" option gives a baseline estimate of 8 853 t (CV = 50%), with a mean density estimate (weighted by stratum area) of 0.37 $t.km^{-2}$ (Table 5.1a). The "twenty-five strata" option estimates biomass at 9 016 t (CV = 19%) with a mean density estimate (weighted by stratum area) of 0.38 $t.km^{-2}$ (Table 5.1b). Both options estimated that 97% of this biomass was in the *North-west SA* stratum. The "five strata" and "twenty-five strata" options do not give markedly different estimates for the five strata. However, the "twenty-five strata" estimate had a lower CV (Table 5.1b) and is therefore emphasised.

5.4 Specifying values for the bias factors

Values for the bias factors were obtained from a variety of sources: a brief explanation is given below. In many cases, the specifications agreed upon for Namibian orange roughy (Section 4.4) were used as a basis. The specifications for the bias factors were accepted with little discussion by the Industry and the SFRI representatives. A summary of the values used for the pdfs for each bias factor, and the directional effect of each on the swept-area biomass estimates, is given in Table 5.2. The pdfs are presented in Figures 5.2a-e.

Catchability outside the aggregations (C_{out})

The initial arguments for different values of catchability are summarised in Section 4.4. After discussions between Gendor and the Namibian authorities, two (fairly similar) specifications were derived for C_{out} (Table 4.12). The averages of the minimum, most likely and maximum specifications of those two sets are used here (Figure 5.2a).

Table 5.1a Baseline biomass estimates for orange roughy in South African waters for the the "five strata" option. The area around the coastline was divided into five strata.

Stratum name	Stratum area (km²)	Tows (n)	Area trawled (km²)	Catches (kg)	Density (t.km⁻²)	Estimate (t)	CV
Cape Canyon	553.3	71	11.19	4 080	0.36	202	19%
Dory Patch	1 353.3	166	50.19		0.00		0%
North-west SA	10 996.1	81	12.79	9 960	0.78	8 564	52%
South SA	7 627.6	19	3.94		0.00		0%
West SA	3 072.1	18	3.16	90	0.03	87	135%
Grand Total	23 602.3	355	81.27	14 130	0.38	8 853	50%

Table 5.1b Baseline biomass estimates for orange roughy off South Africa for the "twenty-five strata" option. Each of the initial five strata were divided into depth ranges.

Stratum name	Depth (m)	Stratum area (km²)	Tows (n)	Area trawled (km²)	Catches (kg)	Density (t.km⁻²)	Estimate (t)	CV
Cape Canyon	< 500	–	0	0.00				–
	500–599	110.7	5	0.67				0%
	600–699	110.7	36	5.34	1 560	0.29	32	15%
	700–799	110.7	23	4.11	2 130	0.52	57	17%
	800–899	110.7	6	0.77	150	0.19	21	223%
	900–1000	110.7	1	0.29	240	0.82	91	–
	> 1000	–	0	0.00				–
Total		553.3	71	11.19	4 080	–	202	–
Dory Patch	< 500	–	5	1.15				–
	500–599	270.7	0	0.00				–
	600–699	270.7	5	1.38				0%
	700–799	270.7	33	9.14				0%
	800–899	270.7	87	28.57				0%
	900–1000	270.7	36	9.95				0%
	> 1000	–	0	0.00				–
Total		1 353.3	166	50.19		–		–
North-west SA	< 500	–	11	2.23				–
	500–599	2 199.2	17	1.74	2 070	1.19	2 610	43%
	600–699	2 199.2	22	3.05	7 560	2.48	5 443	24%
	700–799	2 199.2	19	3.91	90	0.02	51	27%
	800–899	2 199.2	6	1.04	30	0.03	63	67%
	900–1000	2 199.2	5	0.79	210	0.26	583	57%
	> 1000	–	1	0.02				–
Total		10 996.1	81	12.79	9 960	–	8 750	–
South SA	< 500	–	5	1.26				–
	500–599	1 525.5	2	0.24				0%
	600–699	1 525.5	1	0.09				–
	700–799	1 525.5	2	0.43				0%
	800–899	1 525.5	5	1.42				0%
	900–1000	1 525.5	3	0.47				0%
	> 1000	–	1	0.03			–	–
Total		7 627.6	19	3.94		–		–
West SA	< 500	–	1	0.27				–
	500–599	614.4	3	0.37				0%
	600–699	614.4	6	0.87	90	0.10	64	143%
	700–799	614.4	4	0.84				0%
	800–899	614.4	2	0.43				0%
	900–1000	614.4	1	0.32				–
	> 1000	–	1	0.06				–
Total		3 072.1	18	3.16	90	–	64	–
Overall total		23 602.3	355	81.27	14 130	0.38	9 016	19%

Table 5.2 Suggested (and final) specifications for the bias factors affecting the swept-area estimates of biomass for South African orange roughy. The specifications for R_{out}, C_{out}, H and O were derived at least partially from those presented in the Namibian assessment by the Namibian ministry and Gendor. Values for Z and CV are specific to South Africa. See text for a detailed discussion of how these values were obtained.

Bias	Symbol	Minimum	Most likely range	Maximum	Effect on estimate
Catchability outside aggregations	C_{out}	0.45	0.52 – 0.76	0.83	Increase
Directed fishing outside aggregations	R_{out}	0.2	0.3 – 1.9	2.0	Decrease/Increase
Herding by the doors	H	0.6	1.0 – 1.0	1.0	Decrease
Fish outside defined strata	O	1.10	1.15 – 1.25	1.30	Increase
Erroneous "zero" catches	Z	1.08	1.23 – 1.33	1.45	Increase
Negatively biased CVs	CV	0.21		0.50	Widens confidence interval

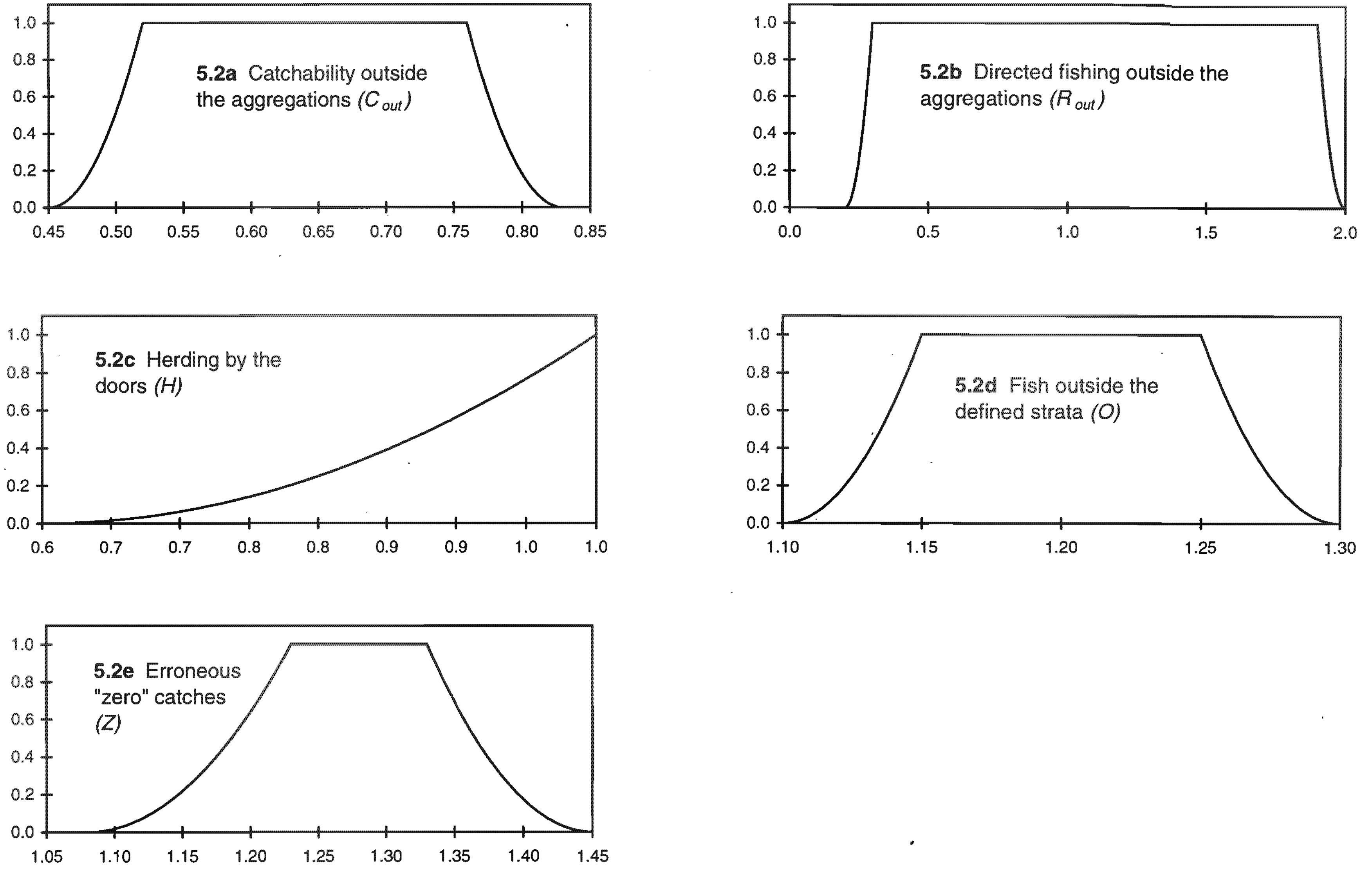

Figure 5.2a-e Pdfs for bias factórs affecting the South African orange roughy swept-area results. These pdfs were determined from a variety of sources–see text for a discussion. The maximum values have been re-scaled to 1, for ease of presentation.

Non-random positioning of trawls outside the aggregations (R_{out})

A survey performed by the *Matsuyama Maru* off Namibia yielded an estimate of 0.11 for this factor, but the comparability of the fishing methods and trawling gear used to that of the commercial vessels was questioned (Appendix B), and the results eventually disregarded. Final specifications for this factor agreed upon in Namibia were 0.2; 0.3–0.7; 0.8. In South Africa, however, oreo dories (and not orange roughy) are the target species in most trawls, so that the orange roughy estimate could in fact be negatively biased. Density estimates of orange roughy in South Africa are two orders of magnitude lower than those recorded outside aggregations in Namibia; this may be partially due to targeting on oreo dories. For this reason, the most likely range of this factor was extended at its higher end to cover 0.3–1.9 and the maximum value was increased to 2.0 (Figure 5.2b). No firm basis is offered for these revised upper values; the revision is merely intended to emphasise the greater uncertainty in this factor, when compared to Namibia. The lower end of the specifications used in Namibia were retained since the sparse estimated densities off South Africa could be a true reflection of the scarcity of orange roughy in South African waters.

Herding (H)

The value for H was taken to be the same as that used off Namibia, with a tapering tail from 1 down to 0.6 (Figure 5.2c).

Depth ranges chosen for the strata (O)

The strata were defined between 500 and 1 000 m (Branch 1997). However, orange roughy have been caught in both shallower and deeper waters elsewhere, and the strata do not extend around the east coast of South Africa. Off Namibia, an estimated 10% of the biomass is found in deeper waters (Section 4.4). This value was used as a lower limit. It is further assumed that a maximum of 20% of the biomass may be present on the east coast, bounding this factor above by 30% (Figure 5.2d).

Table 5.3 The effect of erroneous "zeros" recorded in the trawl sheets, on the swept-area estimate. Each tow where the catch of orange roughy was recorded as 0, was replaced by 5 kg, 15 kg, 22 kg and 30 kg, and the estimates recalculated. The *Nicola* recorded catches (effective greenweight) in 30 kg cases, and the *Southern Aquarius* in 44 kg cases. Tows that fell outside the 500 m to 1000 m depth range were excluded for the purposes of estimating this factor.

Stratum	Depth	Tows	"Zero" tows	Estimate	Revised estimate (t) replacing zeros with:			
Name	(m)	(n)	(n)	(t)	5 kg	15 kg	22 kg	30 kg
	500–599	5	5	0	4	12	18	25
	600–699	36	21	32	34	39	42	45
Cape Canyon	700–799	23	6	57	58	60	61	62
	800–899	6	5	21	25	32	37	43
	900–1000	1	0	91	91	91	91	91
Total		71	37	202	213	234	249	266
	500–599	0	0	0	0	0	0	0
	600–699	5	5	0	5	15	22	29
Dory Patch	700–799	33	33	0	5	15	21	29
	800–899	87	87	0	4	12	18	25
	900–1000	36	36	0	5	15	22	29
Total		161	161	0	19	56	83	113
	500–599	17	16	2 610	2 711	2 913	3 054	3 215
	600–699	22	19	5 443	5 511	5 648	5 744	5 853
North-west SA	700–799	19	17	51	98	194	261	338
	800–899	6	5	63	116	222	296	381
	900–1000	5	3	583	624	708	766	833
Total		69	60	8 750	9 062	9 685	10 121	10 620
	500–599	2	2	0	65	195	286	389
	600–699	1	1	0	81	244	358	489
South SA	700–799	2	2	0	36	107	157	214
	800–899	5	5	0	27	80	118	161
	900–1000	3	3	0	48	145	213	290
Total		13	13	0	257	771	1 131	1 543
	500–599	3	3	0	25	75	111	151
	600–699	6	5	64	81	117	141	169
West SA	700–799	4	4	0	15	44	64	88
	800–899	2	2	0	14	43	63	86
	900–1000	1	1	0	10	29	42	58
Total		16	15	64	145	308	422	552
Overall total		330	286	9 016	9 695	11 055	12 006	13 093
Percentage increase		–	–	0	8	23	33	45

However, in the absence of any known aggregations off South Africa, this factor was not included as a bias factor.

Biased CVs (*CV*)

The CVs of the baseline estimate are likely to be negatively biased because the directed trawls are neither random nor independent of one another. As a crude initial adjustment, an additional term with a 10% CV was added to the baseline variance. As a result, the CV was adjusted from 19% to 21%. However, McAllister & Kirkwood (1997) raised concern that the CVs for the baseline estimates off Namibia were too low, especially as systematic trawl surveys often result in estimates with CVs over 50%. Computations were therefore repeated with a CV of 50%.

5.5 Bias-corrected estimates of biomass

The median biomass was estimated at 20 600 t (CV = 53%), with a 90% probability interval of 6 400–43 400 t, if the baseline CV = 21%. This decreases to 18 200 t (CV = 73%), with a 90% probability interval of 4 900–52 500 t, if the baseline CV = 50% (Figure 5.3).

5.6 Discussion

Consideration of the bias factors highlights the uncertainty involved in these estimates. The baseline biomass estimate of 9 000 t increases to a median of 20 600 t (CV = 53%) or 18 200 t (CV = 73%), when the bias factors are considered. Three of the five bias factors (catchability, fish outside defined strata and erroneous zeros) cause an increase in the estimate; one (herding) decreases the overall estimate; and the fifth (effects of directed fishing) causes either an increase or a decrease in the estimate depending on the exact value chosen during the Monte Carlo procedure. The effects of directed fishing played an important role in the results, because this was taken to range over an order of magnitude (0.2–2.0). Greater precision in the specification of this factor is required if the bounds on biomass are to be narrowed.

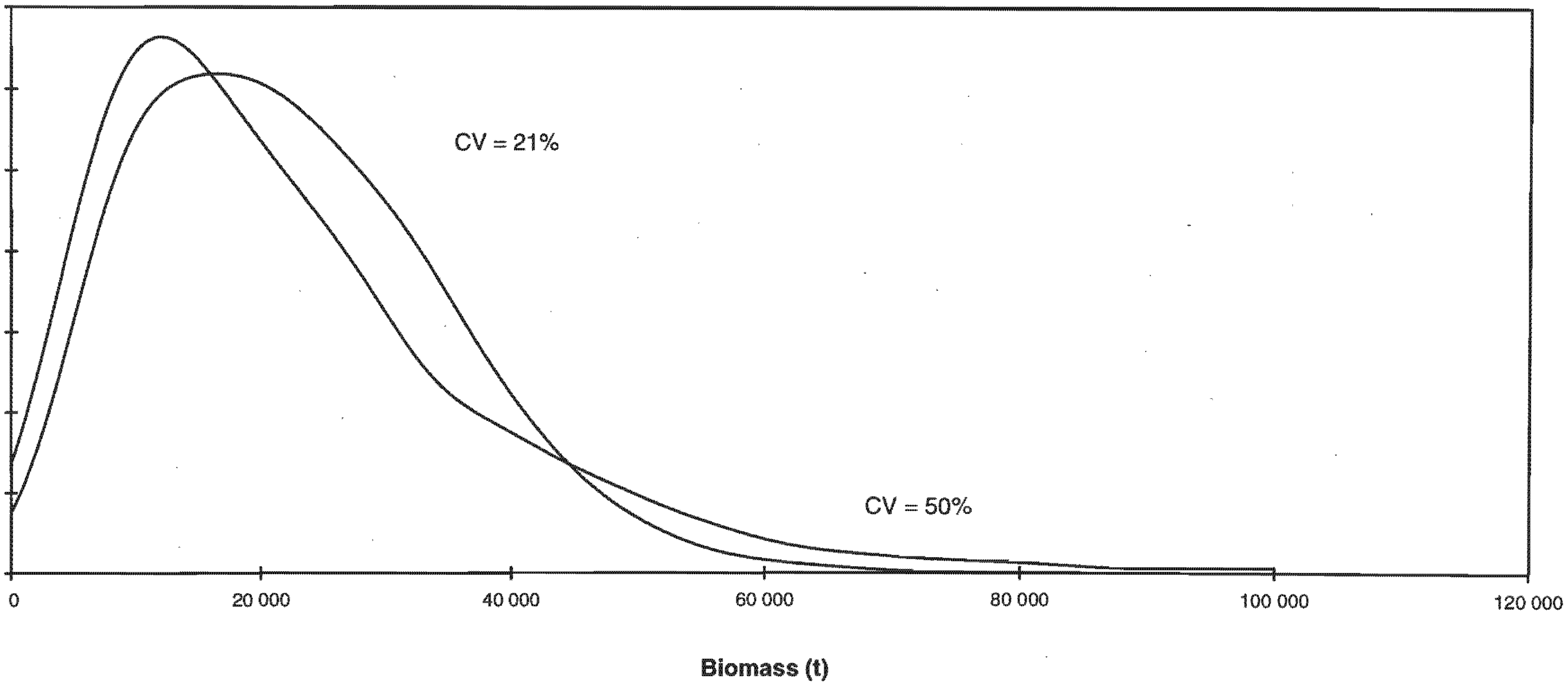

Figure 5.3 Smoothed biomass estimates for orange roughy off South Africa, when the baseline swept-area estimate is assumed to have had a CV of either 21% or 50%. In the former instance, the median biomass estimate is 20 600 t (CV = 53%); in the latter case, the median biomass estimate is 18 200 t (CV = 73%). The pdfs are obtained from the realisations produced after the bias factors are taken into account. See text for an explanation of the smoothing technique used. Note that the smallest realisation is non-zero in both instances, but the smoothing procedure increases the standard deviation of the curves by 3%, so that it appears (erroneously) as if some of the resultant realisations are zero.

The estimated densities of orange roughy off South Africa are two orders of magnitude lower than those estimated off Namibia *outside* aggregations (Table 4.2). The difference in estimated density could be due to South African vessels targeting oreo dories instead of orange roughy. If that is true, directed fishing on oreo dories may have introduced substantial negative bias in the South African orange roughy estimates.

The wide 90% probability intervals are cause for caution from a management point of view. They also convey some of the problems inherent in the use of a non-random, trawl-based information source. More accurate estimates would probably be obtained from random trawl surveys (e.g. Clark & Tracey 1993), from acoustic surveys (e.g. Kloser *et al.* 1996), or by using egg surveys (e.g. Koslow et al. 1995a; Cordue 1996a).

This analysis does not make allowance for possible undiscovered aggregations off South Africa. A commercial fishery for orange roughy is only viable when such aggregations are present on trawlable ground, since the densities of orange roughy outside aggregations are very low. Based on the Namibian experience, nearly all of the catch would come from the aggregations, if an orange roughy fishery becomes commercially viable.

5.7 Conclusions and recommendations

The long-term sustainable yield of orange roughy is thought to be about 1.5% of the virgin biomass (Annala & Sullivan 1997), which translates to a 90% probability interval of 60–790 t a year for the biomass estimate with a baseline CV of 50%. Catches would be higher than this during the fishing-down phase: 5% of virgin biomass was suggested for the Namibian orange roughy, which translates to 245–2 625 t per year. However, these catch limits would not be realistic until at least one aggregation is discovered off South Africa, since it is not economically viable to catch dispersed orange roughy outside aggregations.

A preliminary decision by the South African management authorities for the 1998 fishing year, based on the results presented in this chapter, is that there should be a "trigger" limit of 500 t to encourage further exploratory fishing for orange roughy (R. Tilney, pers.

comm.). Under this rule, if an aggregation is discovered, up to 500 t can be caught before notification is given by the permit-holder. At this point, the aggregation would be assessed and a formal TAC set.

6. Swept-area results for South African oreo dories

Exploratory deepwater trawling off South Africa started in 1994, initially searching for orange roughy. However, poor catches of orange roughy, and the discovery of commercial quantities of oreo dories, caused a switch in focus to oreo dories. The reported catch of oreos in South African waters was 1 668 t up to mid-February 1997. Most of this catch (80%) was warty oreo dory (*Allocyttus verrucosus*), although there was also a small proportion (20%) of smooth oreo dory (*Pseudocyttus maculatus*), and traces of spiky oreo dory (*Neocyttus rhomboidalis*). The South African finds represent the only known commercially viable quantities of warty oreo dory in the world.

There was strong pressure from industry to increase the number of permits from the existing two for deepwater species (Tilney 1997). However, it was uncertain whether the oreo finds were extensive enough to support more exploratory fishing. An assessment was therefore performed using the swept-area methodology outlined in Chapter 3. Results were presented on 18 June 1997 to representatives of the permit-holders and the SFRI.

6.1 Introduction

Oreo dories are not as valuable as orange roughy, fetching 3–5 times less on the market place (New Zealand Fishing Industry Board 1997a, b; R. Tilney, pers. comm.). The oreo dories (family Oreosomatidae), or oreos, are part of a complex of deepwater fish species with a world-wide distribution which are often found in association with orange roughy.

New Zealand and Australia have commercial fisheries which take oreos as bycatch to orange roughy. Reductions in the total allowable catches (TACs) for orange roughy in those countries have resulted in greater effort being expended on oreos. Annual catches of oreos in New Zealand over the past nine years were 18 000–24 000 t from 1987–88 to 1995–96, against TACs of 24 000–26 160 t over the same period (Annala & Sullivan 1997). Initially, more black oreo (*Allocyttus niger*) were caught, but as the fishery grew, catches of smooth oreo predominated, contributing 68% of the catch over the past nine years. In Australia, about 95% of the retained catch is smooth oreo; reported annual oreo catches were 1 000–3 000 t over the period 1990–94 (Ward *et al.* 1996). However, actual catches are likely higher due to non-reporting and discarding (Lyle *et al.* 1992). Smooth oreos are preferred to warty oreos because they are larger and their flesh is less tough (Lyle *et al.* 1992).

Survey methods

Oreo dories live in similar habitat to orange roughy, so that it might be thought that similar survey techniques could be used for them. In Australia and New Zealand, acoustic surveys, egg and larval surveys, trawl surveys and commercial CPUE data form the basis for management of orange roughy. Acoustic methods are not currently used for oreos, but would probably give reliable abundance indices (Cordue 1996a). Egg and larval surveys are not considered practical for oreos because spawning is widespread and the spawning season more lengthy than that of orange roughy (Clark 1995b). No assessment on oreos is performed in Australia (J.A. Koslow, pers. comm.). The main assessment for oreos in New Zealand is performed using a combination of research trawl surveys and commercial CPUE data (Doonan *et al.* 1995a; Doonan *et al.* 1996; Doonan *et al.* 1997). The indices obtained are used in stock reduction analyses to obtain likely levels of virgin biomass. Using these methods it is estimated that smooth oreo biomass is 14–40% of pristine biomass (B_0) for the OEO 4 area, and 10–23% of B_0 for the OEO 3A area off New Zealand (Doonan *et al.* 1997).

Rationale for using swept-area method

The approach used in New Zealand cannot be applied to South Africa because the oreo fishery is still in its infancy, and the requisite time series of indices is not yet available. The swept-area technique described in Chapter 3, which was applied to orange roughy off Namibia (Chapter 4) and South Africa (Chapter 5) was therefore used to assess oreo biomass off South Africa.

6.2 Biology and stock structure of oreos

Oreos are less well studied than orange roughy, probably because of their lower commercial value. Their low fecundity, extreme longevity and slow growth rate (similar to that of orange roughy) make oreos susceptible to fishing levels greater than surplus production. Warty and smooth oreo dory are widespread in the Southern Hemisphere at depths of 340–1 300 m (warty) and 400–1 500 m (smooth) (James *et al.* 1988; Annala & Sullivan 1997; Lyle & Smith 1997). There is also an isolated report of oreos being caught off Ireland (Kow & Chamberlain 1993). Warty oreo dory apparently prefer soft-bottom habitat off Australia, while smooth oreos are more common over rough bottom (Lyle & Smith 1997). Adult warty oreo dories are 10–40 cm total length; smooth oreo dories 16–60 cm (Mel'nikov 1982; James *et al.* 1988; Lyle *et al.* 1992; Stewart *et al.* 1995). Formal descriptions of these species are given in James *et al.* (1988).

Reproduction and egg development

Off Australia, warty oreo spawn in May–June, probably over a relatively short period (Lyle *et al.* 1992; Lyle & Smith 1997). Smooth oreo (and black oreo) spawn in late October to December off New Zealand (Pankhurst *et al.* 1987; Annala & Sullivan 1997). Fecundity recorded in New Zealand waters for smooth oreo is low: 6 000–84 000 eggs/female, as is relative fecundity: 10 800 eggs/kg body mass (Conroy & Pankhurst 1989). Their values for black oreo are similar, so that it is possible that this low fecundity is a characteristic of warty oreos too. This level of fecundity is even lower than in orange roughy, and a further order of magnitude lower than any other commercially exploited species off New Zealand (Conroy & Pankhurst 1989). The fertilised eggs of oreos are positively buoyant, and rise to the surface. Juveniles are pelagic (for 5–6 years in smooth oreos) and rarely caught (Lyle *et al.* 1992; Annala & Sullivan 1997). Juveniles of all oreo species are markedly different in appearance from adults of the same species—in some cases, juveniles and adults have even been classified as different species (James *et al.* 1988).

Ageing studies

Ageing studies have produced controversial results, having followed a similar pattern to those for orange roughy: initial studies gave young ages while later studies indicated extreme longevity. Mel'nikov (1982) aged whole otoliths and scales of warty oreos off South Africa, and found that the number of annuli on the scales and otoliths of a particular fish were identical. A maximum age of 14 years was recorded. Davies *et al.* (1988) concluded that it was not possible to age smooth oreo otoliths because of their complex structure and the variable widths in checks and microincrements. A study of smooth oreo scales gave maximum ages of 11–12 years if troughs in calcium and fluorine represent annual events (Gauldie *et al.* 1991).

Later studies relied on the sectioned otolith and radiometric methods developed for orange roughy. A maximum age of 130–170 years was assigned to warty oreo based on radiometric ageing, and 130 years based on sectioned otoliths (Stewart *et al.* 1995). Considerable difficulty was encountered in sectioning the otoliths, but these authors concluded that whole otoliths were inappropriate for ageing warty oreos. Maximum ages for smooth oreos were estimated at 86 years, with an age at maturity of 30 years (Doonan *et al.* 1995b).

Aggregating behaviour

Warty oreos form small aggregations during the summer months which are probably related to feeding (Lyle & Smith 1997). It is not known whether they form spawning aggregations. Sex ratios of warty oreo were significantly different from 50:50 in seven out of eight surveys conducted off Australia; females dominated off western Australia, while males dominated off the western Bass Strait (Lyle & Smith 1997).

Smooth oreos aggregate on rough ground near seamounts or canyons, and may form localised 'hot spots' of different species. Marks are frequently observed well off the bottom, but catches greater than 40–50 t per tow have been recorded when they settle (Lyle *et al.* 1992; Lyle & Smith 1997). In New Zealand, they tend to congregate around the tops of hills, while orange roughy are found further down the slopes (Cordue 1996a). During spawning, they form small aggregations which are spread over a wide area (Lyle *et al.* 1992). Large catches (> 10 t) of smooth oreos are also made over a wide area on flat ground on the South Chatham Rise off New Zealand (McMillan *et al.* 1996). Most of the commercial catch (62%) is made on this flat ground, and not on the hills in that area.

Diet and feeding

Adult warty oreos off South Africa feed mainly on shrimps, cephalopods and fish (Mel'nikov 1980). Feeding patterns do not alter markedly over the course of the year, and the percentage of empty stomachs recorded by Mel'nikov (1980) was never more than 15.3%. During the spawning season, warty oreos feed actively (Mel'nikov 1980), unlike orange roughy (Section 2.5). Warty oreos off Australia feed mainly on crustaceans, fish and cephalopods (Lyle & Smith 1997). Warty oreos have a gas-filled swim bladder, and consequently the stomachs of trawled animals are often (56%) everted (Lyle & Smith 1997). Adult smooth oreos feed mainly on salps, which comprises 90% of their diet off New Zealand (Clark *et al.* 1989).

Flesh characteristics

Warty oreo dory flesh is tough because of the accumulation of formaldehyde after death (Chamberlain & Kow 1994). This reduces the commercial value of warty oreo catches. The flesh of oreos examined by Bakes *et al.* (1995) demonstrated low levels of lipids: 0.5–3.0% of wet weight. Warty oreo lipids included medium levels of monounsaturated lipids (34%), with high levels of the essential fatty acids, EPA (5.9%) and DHA (14.8%). Smooth oreo lipids included higher levels of monounsaturated lipids (60.9%), and high levels of EPA (4.1%) and DHA (9.5%). These results contrast with the anomalous levels of monounsaturated lipids (> 82%), and the rarity of EPA and DHA (< 3% in total), recorded in orange roughy flesh (Section 2.6).

Genetics and stock structure

No differences were found between New Zealand and Australia smooth oreo samples using genetic (allozyme and mitochondrial DNA) and morphological approaches (Ward *et al.* 1996). It is possible that there is a single stock over this broad area, but more likely that the genetic methods used are not suitable for stock discrimination. The length-frequency distributions for smooth oreo are markedly different between New Zealand and southern Tasmania, with modes of 35 cm and 42 cm respectively (Lyle *et al.* 1992), which may indicate stock separation.

Warty oreos off southern Tasmania are different from those off Western Australia and New South Wales in a single allozyme locus, providing weak evidence of two stocks. Morphological counts suggest that the Lord Howe Rise might be a third stock (Ward *et al.* 1996).

Oreos off New Zealand are managed in four areas, but the TAC is set for the three species (black, smooth and spiky oreo) combined. Nevertheless, they recommend managing each species separately since the species have different depth preferences and geographical ranges, and differ in their productivity (Annala & Sullivan 1997).

6.3 Data for the assessment

In all, 741 deepwater tows were considered in the assessment. These tows are a superset of the tows used for the South African orange roughy assessment (Chapter 5). Two sets of data are added to that database: 204 tows performed by the *Aquarius* in 1994, and 192 tows performed by the *Iris* in 1996–97. Records for the *Iris* did not contain detailed positional information—only the SFRI positional code (20′×20′ squares) was recorded for each tow. Bottom distances for those tows were inferred from the duration of the tows. Data were included up to 22 January 1997 (*Iris*) and 18 February 1997 (*Nicola*).

6.4 Strata definition

The strata are similar to those used in the orange roughy assessment off South Africa (Figure 5.1), except that the *Dory Patch* has been widened to extend from 500 to 1 000 m and lengthened to include all large oreo catches (> 5 t) close to its boundaries depicted in Figure 5.1. The revised strata are shown in Figure 6.1. Most of the tows (74%) were in the *Dory Patch*, where the majority of the oreo catches (97%) were made. The total area included in the strata increased to 23 600 km². The assessment based on these five strata is referred to as the "five strata" option. Nearly all (97%) the tows were performed at depths between 500 and 1 000 m, and only 13.5 t (< 1%) of oreos was caught outside those depths. Depth-stratification by equal-area 100-m depth intervals (Section 3.2) resulted in each of these five strata being divided into five bands—the "twenty-five strata" option.

6.5 Rationale for grouping the oreo species

Identification of oreo species is erratic in the available data. Catches made by the *Aquarius*, *Harvest Gardenia*, *Salvia* and *Toralla* were recorded under the general label "oreo", as were a portion of the catches by the *Nicola* (31%) and *Iris* (< 1%) (Table 6.1). The greatest proportion of the oreo catches was recorded between 700 m and 1 000 m, with only relatively small proportions being caught at shallower depths (Table 6.1). Most of the identified catches were warty oreos (80%), with the remainder comprising smooth oreo (20%) and spiky oreo (< 1%) (Table 6.1). The *Iris* caught 188 t (90%) of the smooth oreo (Table 6.1), all under one SFRI positional code; warty oreo dory catches were widespread throughout the *Dory Patch*. Hake was landed as a bycatch (total of 174 t) to the deepwater fishing.

Although it was recognised that the warty and smooth oreo dory are more abundant in different areas in the *Dory Patch*, the lack of species identification for 37% of the catches hindered attempts to assess these species separately. The species were therefore combined in the assessment.

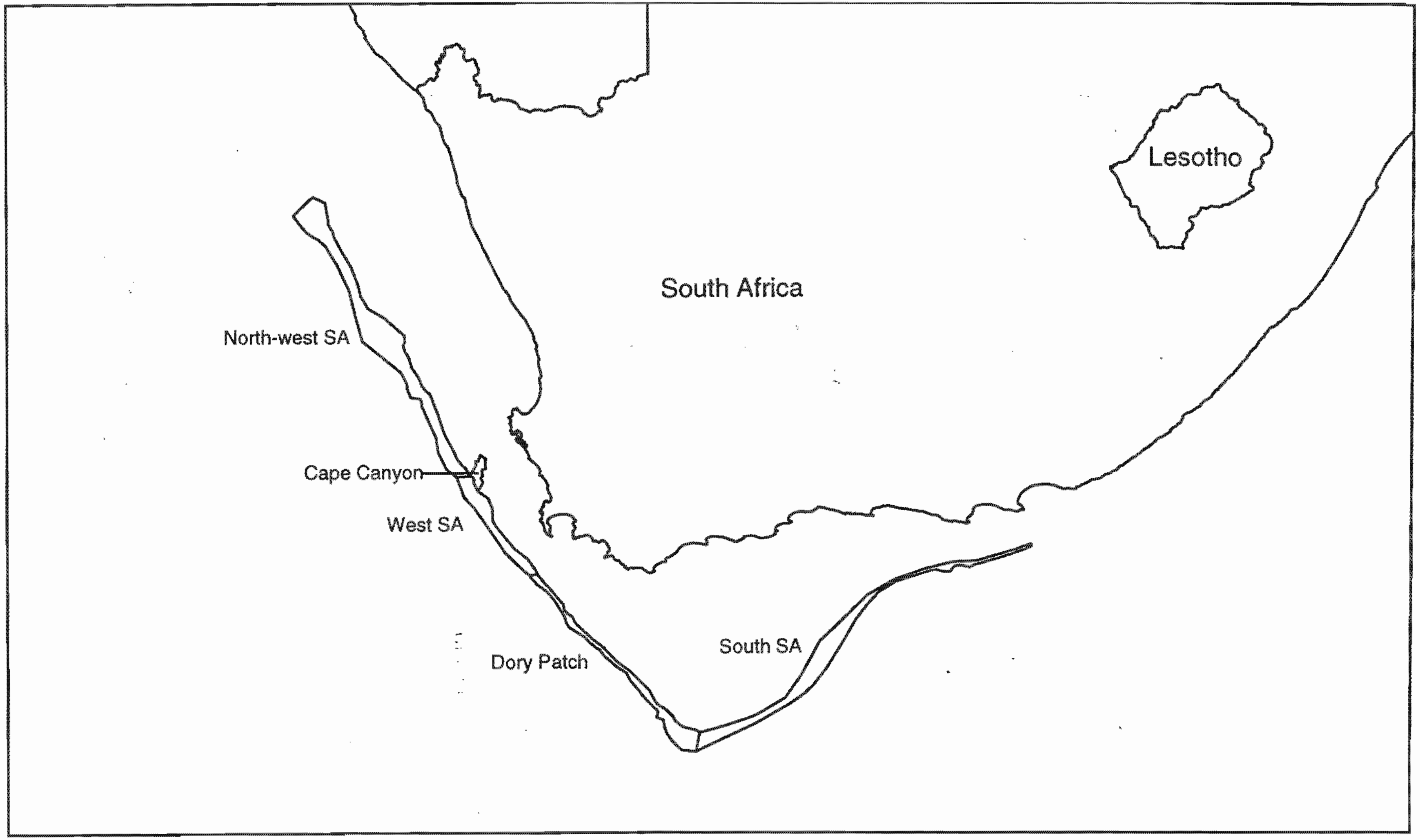

Figure 6.1 The strata used in the baseline swept-area assessment for oreo dories off South Africa. Note that the stratum *Dory Patch* is longer and wider than the *Dory Patch* stratum used for the South African orange roughy assessment (Chapter 5, Figure 5.1).

Table 6.1 Catches of oreos by vessel and depth range. The assessment lumped all species of oreos because of the high proportion (37%) of catches in which the species was not identified. Most of the identified oreo catches were warty oreo (80%), but there were also large catches of smooth oreos. Catches of oreos were primarily between 700 and 1 000 m.

				Oreo dory catches (greenweight tonnes)				
Vessel	Depth (m)	Tows (n)	Hake (t)	Warty	Smooth	Spiky	Unspecified	Total
Aquarius 1994–95	< 500	13	1.1	–	–	–	–	–
	500–599	17	3.3	–	–	–	2.0	2.0
	600–699	18	7.4	–	–	–	0.8	0.8
	700–799	19	7.4	–	–	–	8.5	8.5
	800–899	142	32.6	–	–	–	304.8	304.8
	900-1000	55	3.8	–	–	–	123.8	123.8
	> 1000	–	–	–	–	–	–	–
Total		264	55.7	0.0	0.0	0.0	439.9	439.9
Nicola 1996–97	< 500	4	0.5	–	–	–	–	–
	500–599	11	1.1	–	4.8	0.5	2.4	7.8
	600–699	52	5.0	2.4	13.9	1.8	1.0	19.1
	700–799	71	13.4	51.9	1.4	0.6	19.5	73.4
	800–899	94	11.2	163.7	0.2	–	63.5	227.3
	900-1000	34	1.7	44.8	–	0.4	41.1	86.3
	> 1000	–	–	–	–	–	–	–
Total		266	32.9	262.7	20.3	3.4	127.4	413.8
Iris 1996–97	< 500	1	0.1	0.3	–	–	–	0.3
	500–599	7	6.9	6.5	–	–	–	6.5
	600–699	–	–	–	–	–	–	–
	700–799	47	23.8	71.2	77.4	1.4	–	150.0
	800–899	115	51.2	417.9	68.6	0.6	2.6	489.7
	900-1000	19	2.2	80.1	42.9	–	0.1	123.1
	> 1000	3	0.1	1.9	–	–	–	1.9
Total		192	84.4	578.0	188.8	2.0	2.7	771.5
Other vessels 1988–89, 94	< 500	–	–	–	–	–	–	–
	500–599	–	–	–	–	–	–	–
	600–699	1	0.8	–	–	–	–	–
	700–799	1	–	–	–	–	1.5	1.5
	800–899	5	–	–	–	–	6.8	6.8
	900-1000	8	–	–	–	–	23.5	23.5
	> 1000	4	–	–	–	–	11.3	11.3
Total		19	0.8	0.0	0.0	0.0	43.1	43.1
Grand Total		741	173.6	840.6	209.2	5.5	613.0	1668.2

6.6 Swept-area results

The "five-strata" option gave an estimate of 86 000 t (CV = 23%), with a mean density (weighted by stratum area) of 3.5 $t.km^{-2}$ (Table 6.2a). The "twenty-five strata" option estimated biomass at 77 000 t (CV = 24%) with a mean density estimate (weighted by stratum area) of 3.1 $t.km^{-2}$ (Table 6.2b). Estimated densities for the individual strata under the "twenty-five strata" option were 0.8–8.6 $t.km^{-2}$ (Table 6.2b).

The "five strata" and "twenty-five strata" options gave different estimates of biomass for the five strata defined in the analysis. For example, the biomass in the *Dory Patch* was estimated at 37 800 t (CV = 8%) by the "five strata" option, but only 26 500 t (CV = 10%) by the "twenty-five strata" option. There were significant differences in density at different depths within the *Dory Patch* (Table 6.2b, ANOVA, F = 2.43, $P < 0.05$) under the "twenty-five strata" option, suggesting that variation of density with depth is to be expected in the other strata. However, the present sample size is insufficient to confirm these differences in the other strata. Since the increase from five to twenty-five strata hardly raised the CV on the total biomass estimate, the "twenty-five strata" option is preferred in this analysis.

6.7 Specifying values for the bias factors

Plausible specifications for the bias factors were obtained from a number of sources. Bias factors were represented by the pdfs in Figures 6.2a-d. For many of the factors, the specifications agreed upon for Namibian (Section 4.6) and South African (Section 5.4) orange roughy were used as a basis. The values suggested here were accepted with little discussion by representatives of the SFRI and industry at the meeting on 18 June 1997. A summary of the values used for each bias factor, and the directional effect of each on the biomass estimates, is given in Table 6.3.

Catchability and herding (C_{out})

The best available estimates are those based on long-term New Zealand trawl survey series. This method of estimating catchability incorporates the effects of herding, so that

Table 6.2a Swept-area biomass estimates for oreo off South Africa for the *"five strata"* option. Oreo species were combined for the analysis. The overall mean density is weighted according to the areas of the strata.

Stratum name	Area (km²)	Tows (n)	Swept area (km^2)	Catches (t)	Density (t.km^{-2})	Estimate (t)	CV
Cape Canyon	553	71	11.19	7.0	0.6	344	36%
Dory Patch	3 076	549	131.37	1 615.4	12.3	37 824	8%
North-west SA	10 996	84	13.36	26.3	2.0	21 630	76%
South SA	6 729	15	3.02	7.6	2.5	16 850	53%
West SA	3 290	22	4.23	12.0	2.8	9 325	70%
Total	24 644	741	163.17	1 668.3	3.5	85 974	23%

Table 6.2b Swept-area biomass estimates for oreos off South Africa for the *"25 strata"* option. Each of the five strata were divided into 100 m depth intervals between 500 and 1000 m, and the baseline biomass of oreos estimated (all species combined). Density estimates are weighted according to the areas of the

Stratum	Depth	Area (km²)	Tows (n)	Swept area (km^2)	Catches (t)	Density (t.km^{-2})	Estimate (t)	CV
Cape Canyon	500–599	111	5	0.67	0.0	0.0	0	0%
	600–699	111	36	5.34	3.3	0.6	68	45%
	700–799	111	23	4.11	2.3	0.6	61	34%
	800–899	111	6	0.77	1.0	1.3	142	188%
	900-1000	111	1	0.29	0.4	1.4	159	–
Total		553	71	11.19	7.0	0.8	430	63%
Dory Patch	< 500	–	1	0.23	0.3	1.2	–	–
	500–599	615	8	2.07	7.0	3.4	2 095	59%
	600–699	615	6	1.01	0.0	0.0	27	140%
	700–799	615	87	19.89	218.8	11.0	6 767	17%
	800–899	615	336	86.36	1020.0	11.8	7 266	10%
	900-1000	615	107	21.08	356.1	16.9	10 392	20%
	> 1000	–	4	0.74	13.2	17.8	–	–
Total		3 076	549	131.37	1615.4	8.6	26 547	10%
North-west SA	< 500	–	11	2.23	0.0	0.0	–	–
	500–599	2 199	17	1.74	3.9	2.3	4 956	118%
	600–699	2 199	22	3.05	11.6	3.8	8 382	154%
	700–799	2 199	21	4.21	9.7	2.3	5 061	31%
	800–899	2 199	6	1.04	0.8	0.8	1 776	70%
	900-1000	2 199	6	1.06	0.2	0.2	372	72%
	> 1000	–	1	0.02	0.0	0.0	–	–
Total		10 996	84	13.36	26.3	1.9	20 547	70%
South SA	< 500	–	5	1.26	0.0	0.0	–	–
	500–599	1 346	2	0.24	0.0	0.0	0	0%
	600–699	1 346	1	0.09	0.0	0.0	0	–
	700–799	1 346	2	0.43	1.6	3.6	4 897	53%
	800–899	1 346	3	0.81	6.0	7.5	10 027	68%
	900-1000	1 346	1	0.17	0.0	0.0	0	0%
	> 1000	–	1	0.03	0.0	0.0	–	0%
Total		6 729	15	3.02	7.6	2.2	14 924	49%
West SA	< 500	–	1	0.27	0.0	0.0	–	–
	500–599	658	3	0.37	5.4	14.6	9 633	79%
	600–699	658	6	0.87	4.9	5.6	3 676	114%
	700–799	658	5	0.95	1.1	1.2	792	36%
	800–899	658	5	1.39	0.6	0.5	297	81%
	900-1000	658	1	0.32	0.0	0.0	0	0%
	> 1000	–	1	0.06	0.0	0.0	–	–
Total	1668.198	3 290	22	4.23	12.0	4.4	14 399	61%
Grand Total		24 644	741	163.17	1 668.2	3.1	76 847	24%

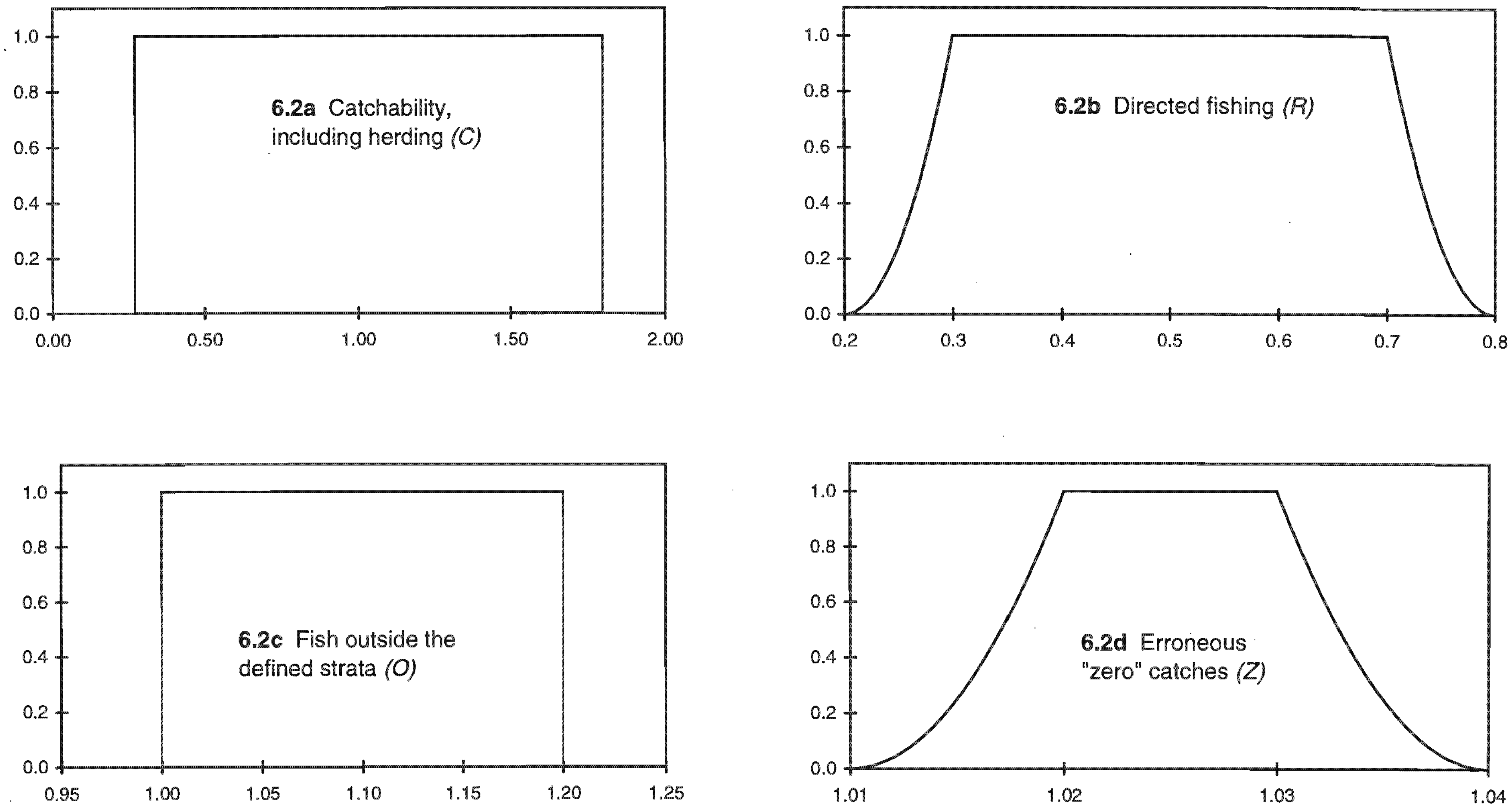

Figure 6.2a-d Pdfs for bias factors affecting the swept-area results for oreos off South Africa. These pdfs were determined from a variety of sources, see text for a discussion. The maximum values have been rescaled to one for ease of presentation.

Table 6.3 Suggested (and final) specifications for the bias factors affecting the swept-area estimates of biomass for South African oreos. The values for C_{out} are obtained from New Zealand stock assessments for smooth oreo (Annala & Sullivan 1997). The specification for R_{out} is that used for Namibian and South African orange roughy. Values for *O*, *Z* and *CV* were derived specifically for South African oreo dories.

Bias	Symbol	Minimum	Most likely range	Maximum	Effect on estimate
Catchability plus herding	C_{out}	0.27	0.27 – 1.80	1.80	Increase/Decrease
Directed fishing	R_{out}	0.2	0.3 – 0.7	0.8	Decrease
Fish outside defined strata	*O*	1.00	1.00 – 1.20	1.20	Increase
Erroneous "zero" catches	*Z*	1.01	1.02 – 1.03	1.04	Increase
Negatively biased CVs	*CV*	0.26		0.50	Widens confidence interval

the two factors were merged here. The New Zealand trawl surveys are used as a relative index, and the catch history is used to back-calculate the absolute biomass in each year by means of a production model (i.e. stock reduction analysis). The ratio of the relative index to the absolute biomass in each survey year gives an estimate of the catchability. Unfortunately, these estimates fluctuate wildly. In the 1997 assessment, the estimate was 3.4 (Annala & Sullivan 1997), in 1996 it was 4.0 (Doonan *et al.* 1996). Other estimates have been 0.03–0.3 (from the *Tangaroa* data) and 0.4–2.0 from surveys in 1986, 1987 and 1990 (Doonan *et al.* 1996). Catchabilities greater than three are not regarded as reliable or consistent with values estimated for other species like orange roughy (Doonan *et al.* 1996; Annala & Sullivan 1997; M. Clark, pers. comm.). In order to address these problems, a method described by Cordue (1996b) was used in New Zealand to assign bounds on catchability (Annala & Sullivan 1997). Values were assigned to three contributing factors:

(1) vertical availability, the proportion of fish available below the headline of the net (u_v), (0.8–1.0);

(2) areal availability: the proportion of fish in the survey area at the time of the survey (u_a) (0.5–0.9);

(3) vulnerability (v): the average proportion of fish available to the net that are caught (0.67–2.0). Values greater than one incorporate the influence of the herding of the doors. Values less than one assume that the net is not 100% efficient at catching those fish that are present.

The lower limits of the three factors are multiplied together to obtain 0.27, and the upper limits are multiplied together to obtain 1.8 (Annala & Sullivan 1997). No most likely range is specified for this factor; the minimum is taken to be 0.27, and the maximum 1.80 (Figure 6.2a).

Non-random positioning of trawls (R_{out})

Directed fishing may substantially inflate estimates, compared to random trawl surveys. Little basis exists for any particular values for this factor, so that the final values agreed upon for orange roughy (Table 4.12) in Namibia are applied here: minimum 0.2, maximum 0.8 and most likely range 0.3–0.7 (Figure 6.2b).

Fish outside the defined strata (*O*)

The New Zealand estimates for catchability include a factor for fish that are not present inside their survey area. In this assessment, the strata did not extend completely around the east coast of South Africa, because no deepwater tows had been performed there. It is assumed that up to 20% of the oreo biomass could lie in this region, and this factor is assigned a uniform probability density from 1.0 to 1.2 (Figure 6.2c).

Erroneous zeros (*Z*)

Many "zeros" recorded in the database were catches of less than one case of oreo. The procedure used for determining this factor in South African orange roughy (Section 5.4) is used here. There were 142 "zero" tows, 20% of the tows inside the depth range chosen. Modification of the "zeros" increased the biomass estimate by 1%, 2%, 3% and 4% respectively (Table 6.4). This factor therefore has only a negligible impact on the estimates. The four values obtained from the re-calculation were used as minimum (1.01), most likely range (1.02–1.03), and maximum values (1.04) (Figure 6.2d).

Lost catch

Catch is primarily lost through windows in the side of the net when catches exceed a certain limit, usually 20 t. For two reasons, the influence of this factor is thought to be negligible in this case. First, only six tows had recorded oreo catches of over 20 t. Secondly, most of the vessels did not use windows (A. Rees, pers. comm.). This factor was therefore ignored.

Migratory behaviour

The migratory behaviour of oreos is poorly known, and it is premature to speculate on the influence this factor may have. Both double counting and under counting are possible consequences. In Namibia, this factor was investigated for orange roughy, which form dense aggregations, and it was found to be unimportant. It is not taken into consideration in this chapter.

Table 6.4 The effect of erroneous "zeros" recorded in the trawl sheets (*Z*) on the swept-area estimate of oreo. Each tow where the oreo catch was recorded as 0 was replaced by 5 kg, 10 kg, 22 kg or 30 kg, and the estimates recalculated. The *Nicola* recorded catches (effective greenweight) in 30 kg cases, and the Aquarius in 44 kg cases. Tows that fell outside the 500-1000 m depth range were excluded in estimating this factor.

					Revised estimate (t) replacing zeros with:			
Stratum	Depth (m)	Tows (n)	Zero tows	Estimate (t)	5 kg	15 kg	22 kg	30 kg
Cape Canyon	500–599	5	5	0	4	12	18	25
	600–699	36	15	68	69	72	75	77
	700–799	23	1	61	62	62	62	62
	800–899	6	2	142	143	146	148	150
	900-1000	1		159	159	159	159	159
Total		71	23	430	437	452	462	474
Dory Patch	500–599	8	2	2 095	2 098	2 104	2 108	2 113
	600–699	6	5	27	42	73	94	119
	700–799	87	9	6 767	6 769	6 771	6 773	6 776
	800–899	336	19	7 266	7 267	7 268	7 269	7 270
	900-1000	107	5	10 392	10 393	10 394	10 395	10 396
Total		549	41	26 547	26 568	26 611	26 640	26 674
North-west SA	500–599	17	14	4 956	5 044	5 220	5 344	5 485
	600–699	22	14	8 382	8 432	8 533	8 604	8 684
	700–799	21	6	5 061	5 077	5 108	5 130	5 155
	800–899	6	5	1 776	1 829	1 935	2 009	2 093
	900-1000	6	4	372	414	496	554	621
Total		84	55	20 547	20 796	21 293	21 641	22 039
South SA	500–599	2	2	0	57	172	252	344
	600–699	1	1	0	72	215	316	431
	700–799	2		4 897	4 897	4 897	4 897	4 897
	800–899	3	2	10 027	10 043	10 077	10 100	10 127
	900-1000	1	1	0	39	118	173	236
Total		15	12	14 924	15 109	15 479	15 738	16 034
West SA	500–599	3		9 633	9 633	9 633	9 633	9 633
	600–699	6	4	3 676	3 691	3 721	3 742	3 767
	700–799	5	1	792	796	803	808	813
	800–899	5	3	297	304	318	328	340
	900-1000	1	1	0	10	31	46	62
Total		22	11	14 399	14 435	14 507	14 557	14 615
Grand Total		741	142	76 847	77 345	78 341	79 039	79 835
Increase				–	1%	2%	3%	4%

Grouped species

All species of oreos caught were lumped in this analysis. It would be preferable to assess and manage each species separately, particularly warty and smooth oreos which constitute the majority of the catches. However, this factor is not thought to bias the estimates, and separation of the species is in any case impractical for the available data.

Biased CVs (*CV*)

The CVs of the baseline estimate are likely to be negatively biased because the trawls are neither random nor independent of one another. As a crude initial adjustment, an additional term with a 10% CV was added to the baseline variance. As a result, the CV was increased from 24% to 26%. McAllister & Kirkwood (1997) raised concerns that the CV of 19% for the swept-area estimates of orange roughy off Namibia was too low, especially as systematic trawl surveys often result in estimates with CVs over 50%. An additional analysis was therefore performed, where the swept-area CV was set to 50%. Typical trawl surveys for oreos off New Zealand had CVs of 23–39% in area OEO 4, where the number of stations was 110–149, and 19–93% in area OEO 3A where only 23–44 stations were sampled (Doonan *et al.* 1996; Annala & Sullivan 1997).

6.8 Bias-corrected estimates of biomass

The median biomass was estimated at 41 100 t (CV = 74%), with a 90% probability interval of 16 400–132 300 t, if the baseline CV = 26%. This decreased to 39 200 t (CV = 90%), with a 90% probability interval of 12 300–145 200 t, if the baseline CV = 50% (Figure 6.3).

6.9 Discussion

The bias-corrected results for oreos have very wide probability intervals and high CVs. Baseline swept-area estimates decreased from 77 000 t to 41 100 t (CV = 74%) or 39 200 t (CV = 90%) when the bias factors were incorporated. The bias factors for fish outside defined strata, and erroneous zeros, caused a slight increase in the estimates; the major

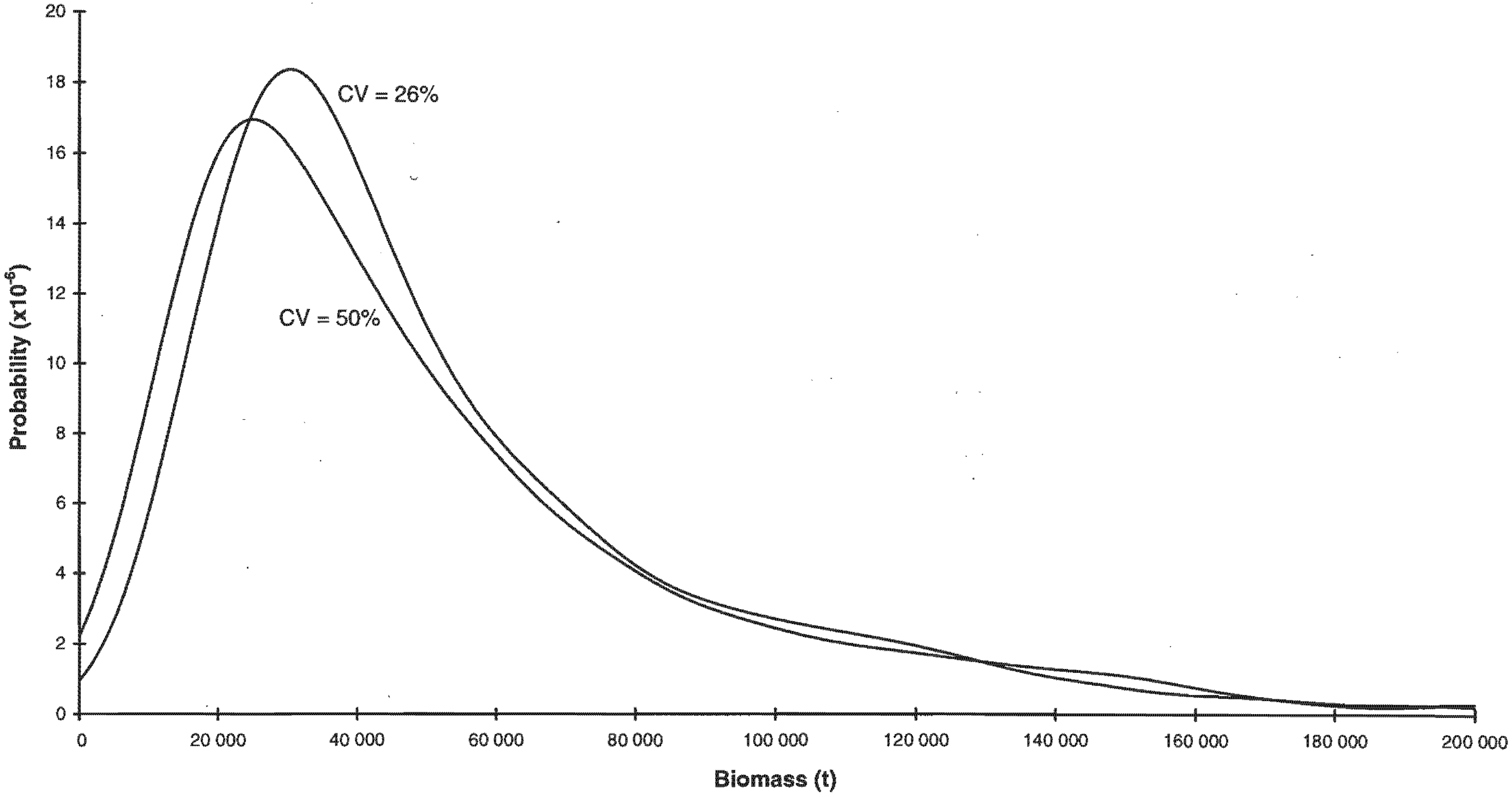

Figure 6.3 Smoothed biomass estimates for oreo off South Africa. The baseline biomass estimate (77 000 t) was assumed to have a CV of either 26% or 50%. See text for an explanation of the smoothing technique used. The non-zero values of the pdfs at zero biomass are an artefact of the smoothing procedure described in Chapter 3.5, which increases the standard deviation by 2%.

factors were catchability and the effects of directed fishing. The catchability factor did not cause any dramatic net increase or decrease, but was an important determinant of the extremely high CVs. The directed fishing factor accounted for most of the decrease in estimated biomass. The specifications for these latter two bias factors need to be more precise if the bounds on the biomass estimate are to be narrowed.

Estimated swept-area densities of oreos (0.8–8.6 $t.km^{-2}$) were an order of magnitude higher than for orange roughy off South Africa (0.0–0.8 $t.km^{-2}$), but lower than the densities of 0.6–39.0 $t.km^{-2}$ for orange roughy recorded outside aggregations off Namibia. The estimated density of oreos inside the *Dory Patch* (8.6 $t.km^{-2}$) is still one to two orders of magnitude lower than the densities of orange roughy inside aggregations off Namibia (89–641 $t.km^{-2}$). This is an indication that the oreos do not form the dense localised aggregations that are characteristic of orange roughy.

The very wide 90% probability intervals are cause for caution from a management point of view. More useful estimates of biomass could be obtained from a long-term series of random trawl surveys (McMillan *et al.* 1996), or from acoustic surveys (Cordue 1996a; Kloser *et al.* 1996). In New Zealand, the favoured survey type (in principle) is acoustic (Cordue 1996a, M. Clark, pers. comm.), because of the problems with determining the catchability associated with trawl surveys of oreos.

Limitations of this analysis

The lack of critical review (compared to that for Namibian orange roughy) over the specifications for the bias factors means that results should be treated with caution. It is quite possible that erroneous assumptions have been made when specifying pdfs for the different factors, especially since some of the factors were developed for assessments of orange roughy.

All species of oreos have been lumped for this analysis, which could be problematic. It would be more appropriate to split assessments and TACs for the different oreo species, since they have different biological parameters (Annala & Sullivan 1997). Separate catch limits for each species would decrease the risk of over- or under-fishing a particular species.

6.10 Conclusions and recommendations

The maximum constant yield for smooth oreo off New Zealand is estimated to be 1.6% of pristine biomass (B_0) per annum, which results in a mean final biomass at 44% of B_0 (Annala & Sullivan 1997). During the fishing-down phase, a higher level of catches can be taken. A level of 5% is suggested for Namibian orange roughy (Butterworth & Branch 1996), which has similar population parameters to those of the oreos. These ballpark figures can be applied to the results from the scenario with an initial CV of 50%. The long-term yield under these guidelines is 180–2 200 t (median 600 t) per year; during the fishing-down phase this increases to 600–7 300 t (median 2 000 t) per year.

The two vessels using deepwater permits at present are the *Nicola* and *Iris*. They fished a combined total of ten months in 1996, catching 940 t of oreos; and two months in 1997, catching 244 t of oreos. The potential therefore exists for oreo catches of 2 300–2 900 t from these two vessels alone in a full year of fishing (provided, of course, that catch rates do not decline).

A preliminary decision has been made for oreos off South Africa in the 1998 fishing year (R. Tilney, pers. comm.). The number of permits will remain at two, but might be combined for use on one vessel only. There will be a trigger level of 1 000 t inside the *Dory Patch*, and 500 t outside the *Dory Patch*, after which the fishery will be re-assessed and a formal TAC set. These limits are intended to serve as incentive for further exploratory fishing, while recognising that the oreo resource is limited.

7. Modelling the effects of alternative catch levels on Namibian orange roughy

7.1 Introduction

The biomass assessment for orange roughy off Namibia (Chapter 4) indicated that there was potential for a sizeable fishery for this species. However, the biomass information alone does not provide a sufficient basis for TAC decisions. The dynamics of the population need to be taken into account. Orange roughy is thought to be extremely long-lived and hence to have poor productivity (e.g. Annala & Sullivan 1997; Bax 1997). The utilisation of this resource will therefore involve an initial "fishing down" phase as the resource is reduced to the level at which MSY can be taken (the MSYL), followed by sustainable annual takes close to the MSY. The fishing-down phase will involve catches in excess of the sustainable yields, and needs to be carefully managed. Responsible management will ensure that the fishing-down phase is spread out over a number of years, and that the reduction in catch and effort levels to the MSYL is gradual. Long-term planning is therefore crucial in the exploitation of orange roughy, to limit overcapitalisation in the initial stages and subsequent sudden changes in employment levels.

This chapter outlines a simple age-structured model which was used to provide information about the risks of different management options during the fishing-down phase. An interactive process was followed in presenting the results at two meetings in January 1997 (the first meeting was on January 14 and the second during 28–29 January). Results were presented concurrently with the biomass estimates outlined in Chapter 4 so that when changes in the bias specifications were made, these were reflected in changed estimates of the risks of different catch levels.

7.2 Age-structured model used

The biomass estimated by the swept-area methodology was assumed to be near to the pristine level. When further catches are taken, the drop in biomass will be compensated by the surplus production of the population (or compensatory growth). A model of the population dynamics is needed to calculate the extent to which alternative TAC levels will reduce the present biomass.

A lumped surplus production model based on biomass had an initial appeal. But some parameters could only be argued by analogy with other orange roughy stocks, and there may, for example, be different ages at recruitment in Namibia when compared to New Zealand. In addition, orange roughy have a high age at maturity and recruitment, so that responses to exploitation should be delayed. A lumped surplus production model is unable to model those response delays, hence the use of an age-structured production model, with its increased complexity.

The age-structured model (Appendix C) is a simplified form of that used for the orange roughy resource off the Chatham Rise, New Zealand (Francis *et al.* 1995). One advantage of this approach is that the biological parameters which have not been estimated for orange roughy off Namibia can be taken from Francis *et al.* Key simplifications are that the sexes are lumped instead of being considered separately; the ages at recruitment and maturity are assumed to be knife-edge instead of logistic; and recruitment is deterministic and not stochastic. Subsequent calculations by McAllister & Kirkwood (1997) demonstrated that when stochastic recruitment is incorporated into this model, risks to the resource actually diminish. The final assumption is therefore conservative.

To verify that no programming errors had been introduced in the coding of the age-structured model (implemented in the programming language C), the program was independently duplicated by H. Geromont in FORTRAN. Results were identical for the two programs.

Growth, natural mortality and steepness parameters have not been estimated for orange roughy off Namibia; they are taken to be the values for the New Zealand resource (Francis *et al.* 1995), averaged over the sexes (Table 7.1). The major point of departure from Francis *et al.* (1995) in the parameter values used for the preliminary analysis was for age

Table 7.1 Full set of population parameter values used in the age-structured model to obtain the preliminary results presented at the first meeting in January 1997. These are referred to as the "Original specifications" in the text. The values were taken primarily from those used in an assessment of the New Zealand Chatham Rise fishery for orange roughy (Francis *et al*. 1995), with an adjustment made to the age at maturity and recruitment. The value of ℓ_∞ was erroneously printed as 37.6 cm in Butterworth & Branch (1996). The von Bertalanffy, length-mass and Beverton-Holt equations are given in Appendix C, equations (C5), (C6) and (C10–12).

Population parameter	Preliminary value	Application
M	0.045 yr^{-1}	natural mortality
κ	0.0655 yr^{-1}	von Bertalanffy
ℓ_∞	37.2 cm	von Bertalanffy
t_0	-0.5 yr	von Bertalanffy
c	0.0921 $\text{gm/cm}^{2.71}$	length-mass parameter
d	2.71	length-mass parameter
h	0.75	steepness of Beverton-Holt recruitment curve
a_m	14 yr	age at maturity
a_r	14 yr	age at recruitment

at recruitment (a_r) and maturity (a_m). In Francis *et al.* (1995), these are both taken to be 33 years for males and 34 years for females. However, the orange roughy taken off Namibia show a much greater spatial variation in length than those on the Chatham Rise. The length-frequency distributions on Rix, Frankies and Johnies were similar, but markedly different from that for Hotspot. On Johnies, the peak of the distribution occurs at 29 cm standard length, which corresponds to 23-year-old fish using the von Bertalanffy parameters for the Chatham Rise resource (Figure 7.1, unpublished data, A. Rees). This could mean that recruitment to the fishery is at a much younger age off Namibia. The mid-way point of the ascending limb of the length-frequency distribution on Johnies is at 23 cm, which corresponds to an $a_r = 14$ years. Female orange roughy have been observed spawning at these lengths (A. Rees, pers. comm.), so that the age at maturity a_m was also set to 14 years. These values of a_r and a_m were intended to be minimum values, and were open to discussion at the subsequent meetings.

The impact of catches on the stock is measured by the extent to which the spawning biomass is reduced over the fishing-down period, i.e. the ratio $B^{sp}_{final} / B^{sp}_0$. Preliminary results were obtained by choosing 2 000 realisations of B_0 from the pdfs for biomass presented in Section 4.5. For a given TAC time series, each instance of B_0 was projected forward to yield a value of B^{sp}_{final}, from which the $B^{sp}_{final} / B^{sp}_0$ ratio could be obtained. Distribution medians and 90% probability intervals of the resulting pdfs were calculated, and the pdfs were smoothed for presentation using the normal kernel process described in Section 3.5.

The preliminary values for the parameters correspond to an MSY of 1.6% of the bias-corrected swept-area estimates, which is obtained at an MSYL of about 32% of B_0. The fishing-down phase should therefore not allow more than a 2/3rd reduction of the current size of the resource.

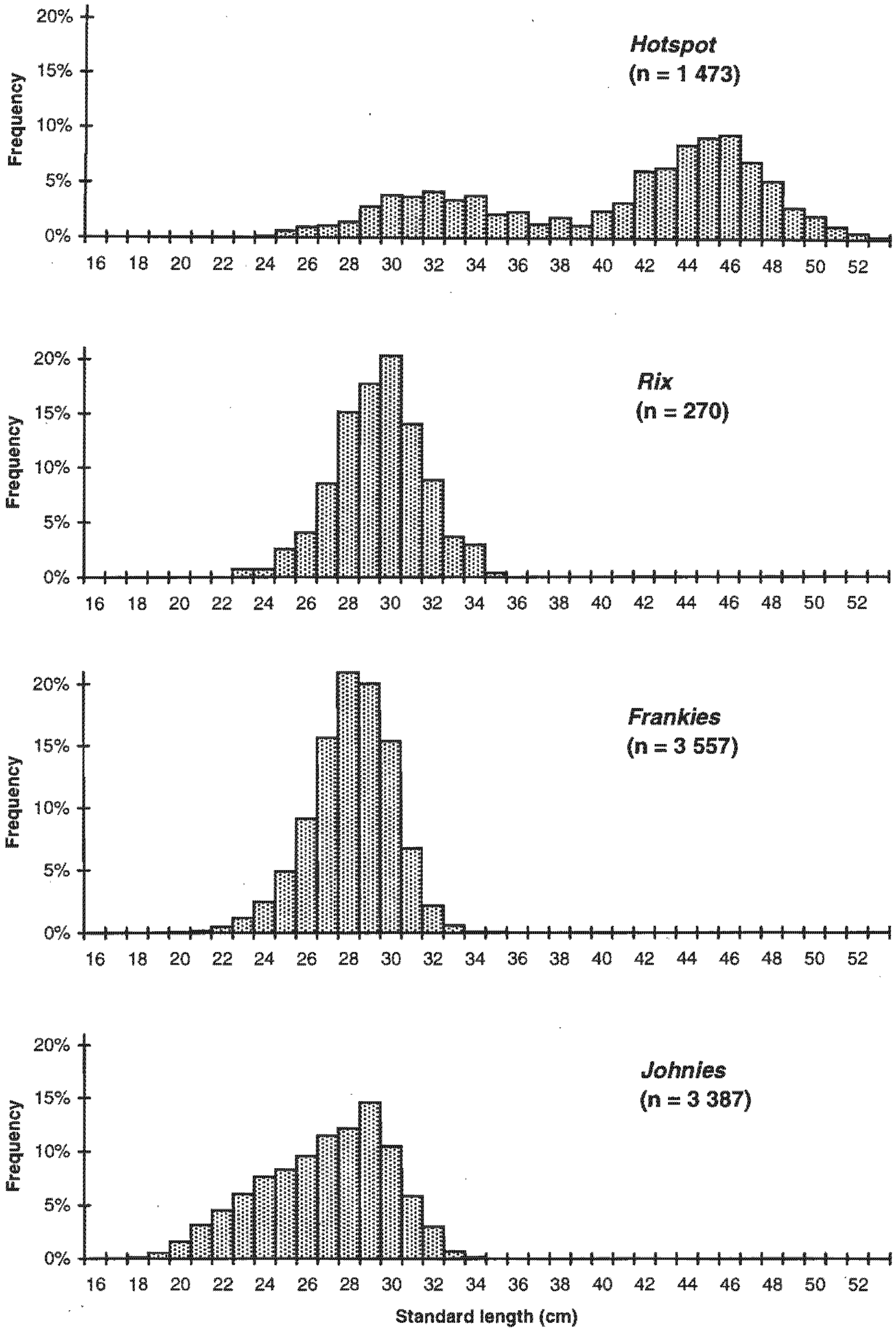

Figure 7.1 Disparity in the length-frequency distributions of orange roughy taken from the four known aggregations off Namibia: *Hotspot*, *Rix*, *Frankies* and *Johnies*. Samples were taken during July 1995 for *Hotspot* and June–July 1996 for the other three aggregations. The distributions do not take account of weighting by total catches in the source tows. The bimodal distribution for *Hotspot* was consistently recorded in a number of tows. (Source: A. Rees, unpubl. data).

7.3 Preliminary results presented at the first meeting (14 January 1997)

Preliminary results were presented at the first meeting for four scenarios of the initial biomass pdfs: whether or not an attempt is made to take account of additional aggregations being discovered in the future; and whether or not data from the *Matsuyama Maru* survey are used directly for estimation of the directed fishing bias factor (R_{out}). There was agreement at that meeting that undiscovered aggregations should not be taken into account, and that the values for R_{out} should be derived effectively independently of the *Matsuyama Maru* survey. Consequently, in the interests of brevity, preliminary results for those scenarios are not repeated here, and the analysis is reduced to a single scenario (Figure 7.2).

Preliminary calculations were performed for four annual TAC levels (5 000 t, 10 000 t, 15 000 t and 20 000 t). TAC levels were fixed for a period of 20 years for the initial calculations. This time period satisfies two tenets of Namibian governmental policy: first, the commitment of their Constitution to utilise natural resources on a "sustainable basis, for the benefit of Namibians, both past and present"; and secondly, because fishing rights are granted for periods of ten, seven and four years (Manning 1997) so that the 20-year period would be double the longest period granted for fishing rights.

Resultant biomass levels after 20 years under these catch levels are summarised in Table 7.2, and the associated pdfs illustrated in Figure 7.2. The MSY is estimated to be 5 700 t, with a probability interval of 3 800–8 400 t. The probability of "collapse[15]" was zero for TACs of 5 000 t and 10 000 t, but rose to 5% for 15 000 t and to 32% for 20 000 t per annum. Under an annual TAC of 15 000 t, the median biomass (35% of B_0) is close to the MSYL (32%), but the 90% probability interval is 2–57% of B_0. Under an annual TAC of 10 000 t, the median biomass is well above MSYL, and the 90% probability interval also falls above the MSYL (36–71% of B_0).

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[15] "Collapse" is defined as occurring if the TAC set in a particular year exceeds the spawning biomass remaining in that year. There would still be many years of recruits to replenish the lost biomass, but a commercial fishery would not be able to continue after this point had been reached. A perceived collapse could occur before this point if some of the spawning biomass was unavailable to the fishery.

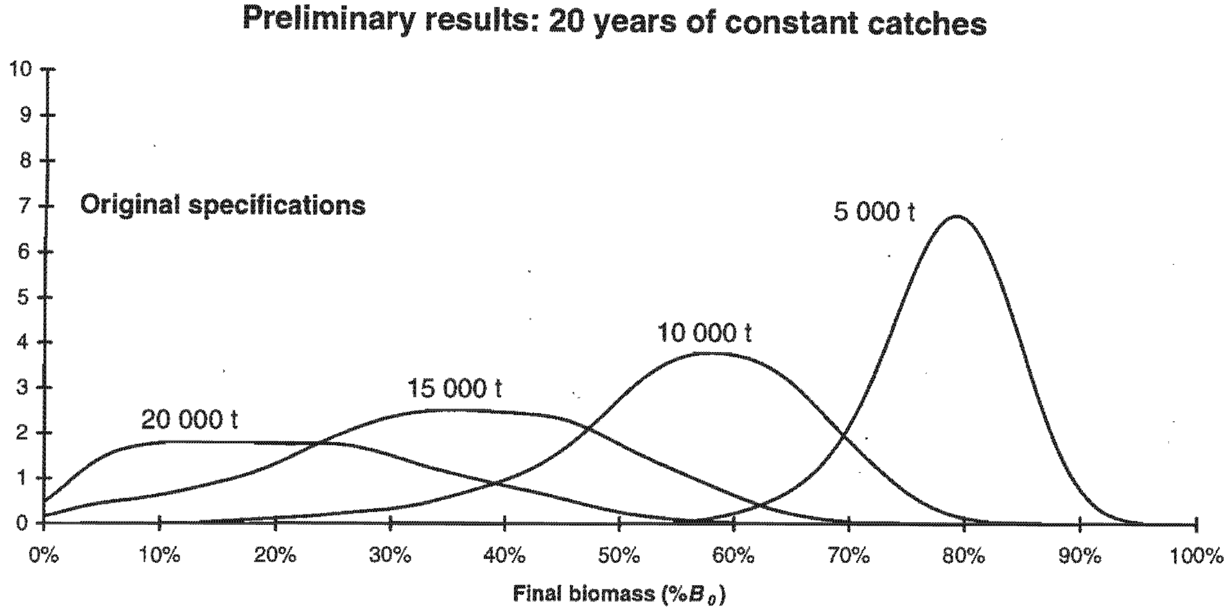

Figure 7.2 "Preliminary" results presented at the first meeting on January 14 1997, simulating the effects of 20 years of fixed catches on the estimated biomass. Biomass estimates were obtained using the original specifications. Realisations where the stock "collapsed" were excluded in the smoothing process: this occurred when the TAC was 15 000 t (5%) and 20 000 t (32%).

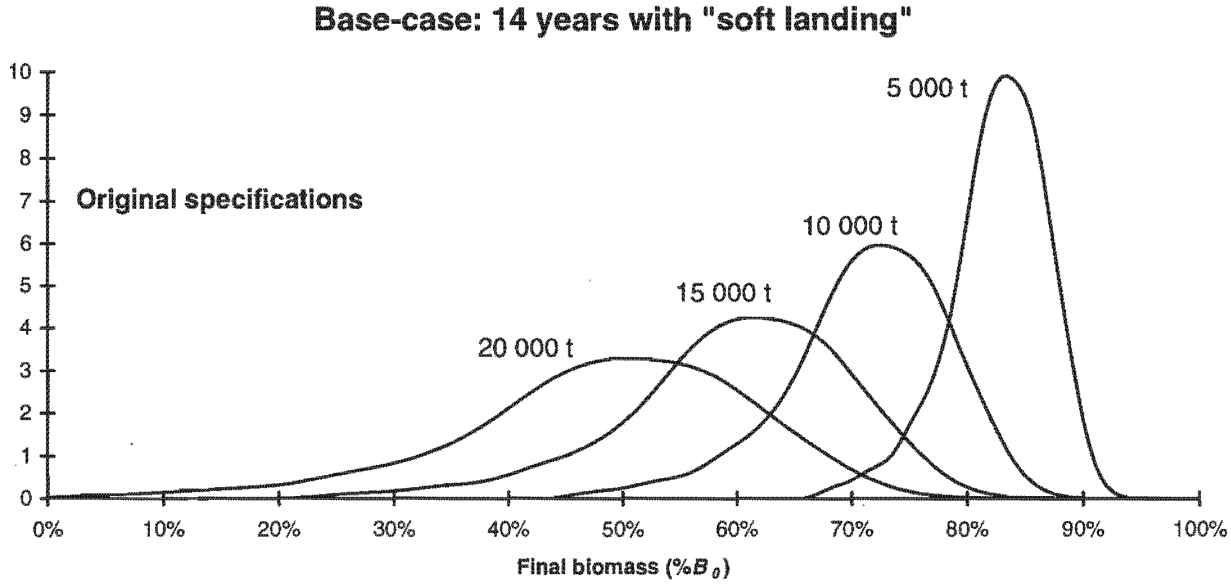

Figure 7.3 "Base case" results presented at the start of the second meeting on January 27 1997. A 14-year fishing-down period was simulated, with constant catches (as indicated) for the first seven years, followed by a linear decrease in TAC over a further seven years to 5 700 t. Biomass estimates were obtained using the original specifications. Stock collapse did not occur under any of these fishing-down policies. The smoothing process adds 3% to the standard deviation of the distributions.

Table 7.2 "Preliminary" results (presented at the first meeting) and "base case" results (presented at the start of the second meeting). In the "preliminary" case, the catches are fixed for a period of 20 years, while in the "base" case the fishing-down period is seven years of constant catches (initial TAC) followed by a linear decrease to 5 700 t over a further seven years.

Results	Fishing-down period	Initial TAC	Median (%B_0)	Collapse	$< 0.2B_0$	< MSYL	$< 0.5B_0$
Preliminary (Jan 14 1997)	20 years Constant catches	5 000 t	79%	0%	0%	0%	0%
		10 000 t	57%	0%	1%	3%	25%
		15 000 t	35%	5%	18%	43%	86%
		20 000 t	12%	32%	65%	85%	99%
Base case (Jan 27 1997)	14 years "Soft landing"	5 000 t	83%	0%	0%	0%	0%
		10 000 t	72%	0%	0%	0%	1%
		15 000 t	61%	0%	0%	1%	14%
		20 000 t	50%	0%	3%	10%	51%

7.4 Decisions reached at the first meeting

The preliminary results indicated that a TAC of 10 000–15 000 t would be appropriate for a 20-year fishing-down phase. The smaller TAC would be best if the objective was to be 95% confident that the final biomass would be above MSYL; the larger value would be chosen if the objective was a final biomass equally likely to be above or below MSYL.

Exclude undiscovered aggregations and the *Matsuyama Maru* survey

The decision was made to focus on results where the implications of additional discoveries of aggregations were ignored, and where the bias factors for directed fishing outside aggregations were not based directly on the *Matsuyama Maru* survey data.

"Soft landing" phase

There was general concern that a sudden drop from a fixed TAC over 20 years to a sustainable TAC would be economically unwise. It was decided to implement a "soft landing" phase to smooth the transition between TACs during the fishing-down phase and long-term sustainable TACs. Under this alternative, TACs would be constant for the first half of the fishing-down period, and would then decrease linearly to the MSY over the second half of the fishing-down period. The "MSY" was taken to be 5 700 t, which is the median MSY under the original bias factor specifications. This value was not re-calculated for later changes to the bias factor specifications, nor for alterations to the natural mortality and age at maturity. The main advantage of this approach is that the same catch trajectory is followed regardless of the scenario being considered, facilitating comparability.

Fishing-down period of 14 years instead of 20 years

The fishing-down period of 20 years was deemed over-lengthy. Major orange roughy fisheries elsewhere have had a fishing-down period (albeit inadvertently) of less than 10 years (notably the Chatham Rise & Challenger Plateau off New Zealand, and the South-east fishery off Tasmania) (inferred from Annala & Sullivan 1997 and Bax 1997). There were also socio-political considerations involved. In April 1997, the Namibian authorities intended to increase the participation in the fishery to more than the single exploratory company involved at that time. A shorter fishing-down period would allow greater immediate TACs which would then be sufficiently large to render increased participation viable. A decision was therefore made to decrease the simulated fishing-down period to 14 years. An additional advantage of this choice is that fishing rights are granted in Namibia for periods of seven years (as an alternative to granting rights for ten years) (Manning 1997), so that the fishing-down phase could proceed with constant catches over the first seven-year period of fishing rights, and a soft landing over the second seven-year period.

Final TAC set to 90% of MSY instead of MSY

An additional precautionary measure for the fishing-down phase was also agreed upon: instead of reducing TACs to a final level of 5 700 t (the MSY), catches would be reduced to 5 130 t (90% of the MSY), in recognition of the uncertainty associated with the estimate of the MSY. This approach is analogous to that taken by the International Whaling Commission in the development of its "New Management Procedure" in the late 1970s (Young & Smith 1993).

7.5 Base case results presented at the start of the second meeting

The original specifications were used for the bias factors described in Chapter 4 (Table 4.4) to produce realisations that served as a set of B_0 values for the population dynamics model. Results were presented at the second meeting on 28–29 January 1997. Shortly before presentation, an error was discovered in the computer model: instead of reducing the TAC to 5 700 t by the end the fishing-down period, the TAC was reduced to 3 400 t. It was too late to re-run the analyses, so that the (slightly) incorrect results were presented at the meeting together with a sensitivity test to determine the effect of this error on the results. The error introduced a negative bias of 2–4% in the median final biomass. The results presented below are corrected for this error.

Soft landing over a 14-year fishing-down period

Both changing the fishing-down period to 14 years and incorporating a soft landing, reduced the risk of over-fishing considerably (Table 7.2; Figure 7.3).

Final TAC reduced to 90% of the MSY

The impact of altering this target had a negligible impact on the final biomass levels. The median biomass (B_{14}^{sp} / B_0^{sp}) increased by at most 1%. Consequently, further results were presented only for the option where the TAC is reduced linearly to the MSY level (5 700 t) by the end of the fishing-down period.

7.6 Further decisions reached

The second meeting in January took place over two days. On the first day, the base case results were presented to a full complement of representatives from Gendor, independent consultants and members of the Namibian ministry of fisheries. That night, suggested variants of the model were re-run, and the results were presented to the forum on the second day of the meeting.

Error correction

One of the independent consultants, M. McAllister, later replicated the work presented at the second meeting (McAllister & Kirkwood 1997), and discovered a discrepancy between their results and those presented on the final day of that meeting. The simulated catches in the model were erroneously high during the fishing-down phase. This resulted in median biomasses in the scenarios for the final results being 1–5% lower than the correct values, and risks being accordingly greater in the presented results. This error is corrected in the results presented below.

Omit results for an TAC of 5 000 t

The base case computations had shown that an initial TAC of 5 000 t (smaller than the median MSY of 5 700 t) would hardly reduce the biomass over a 14-year period, consequently wasting the resource. Final results were therefore computed for initial TACs of 10 000 t, 15 000 t and 20 000 t only.

Natural mortality scenarios: "high *M*" and "low *M*"

The age-structured model had assumed a lower age at maturity and recruitment to the fishery (14 years) than that used in the New Zealand model (33 years), because the recruited fish off Namibia were of a much smaller size than those off New Zealand. An alternative explanation is that the Namibian fish are equally long-lived, but have slower growth rates. If the initial explanation is correct, then the orange roughy off Namibia should grow more rapidly and probably have higher natural mortality rates than the 0.045 used in the New Zealand model. A value of 0.1 was chosen because it represented an upper limit for natural mortality. This scenario is referred to as the "high *M*" scenario. If the second alternative explanation is correct, then the age at recruitment and maturity should be 33 years, but the maximum length (ℓ_∞) must be shorter than 37.2 cm and the growth parameter (κ) should be smaller. This scenario was referred to as the "low *M*" scenario. The parameter values suggested for these two scenarios are presented in Table 7.3 where they are contrasted with those used for the preliminary results, the New Zealand Chatham Rise parameters (Francis *et al.* 1995), and the parameters used in assessing Australia orange roughy (Bax 1997).

Final biomass specifications

On January 28, the participants decided on two final sets of specifications for the bias factors as described in Chapter 4 (Table 4.12). The simulations were re-run to determine the effect of these changes.

7.7 Final results

Different scenarios for natural mortality and the age at maturity

Somewhat counter-intuitively, both alternative scenarios gave more optimistic results than the base case. In the "high *M*" scenario, this was because of the increase in natural mortality from 0.045 to 0.1 led to a more productive resource. For an initial TAC of 15 000 t, median final biomass (B_{14}^{sp} / B_0^{sp}) was 61% under the original specifications, but this increased to 71% under the "high *M*" scenario (Table 7.4). The risk of over-

Table 7.3 Suggested alterations in some of the population parameters used in the age-structured model. The "Original" parameter values were based on those used in the New Zealand Chatham Rise fishery for orange roughy (Francis *et al.* 1995), with a reduction in the age at maturity and recruitment. The parameters for the "low *M*" and "high *M*" scenarios were suggested at the second meeting (27 January 1997). For comparison, the parameter values used in the Australian orange roughy assessments are included (Bax 1997); these were unavailable at the time of the Namibian meeting in question.

Population parameters	New Zealand	Original	"low *M*"	"high *M*"	Australia
M	0.045	0.045	0.045	0.1	0.048–0.064
κ	0.0655	0.0655	0.03	0.0655	0.06
ℓ_∞	37.2	37.2	32	37.2	39.1
$a_m = a_r$	33–34	14	33	14	31–40

exploitation was also considerably decreased. The "low *M*" option also gave slightly more optimistic results than the original parameter values, but the increase in median final biomass levels was small: 1–2% (Table 7.4).

Results for updated biomass estimates

The two final sets of specifications gave similar results. Median final biomass levels were 2–3% higher under the Gendor specifications than under the Ministry specifications (Table 7.5). The risk of dropping below MSYL was also up to 8% lower under the Gendor specifications. When the pdfs for final biomass are plotted, it can be seen that the modal final biomass is slightly lower for the Ministry specifications, and that the Ministry specifications result in a broader spread of final biomass values (Figure 7.4a-d). Nevertheless, the difference between the two sets of specifications is fairly minor compared to the disparity in the results under the "low *M*" and "high *M*" scenarios.

Under the "high *M*" scenario with an initial catch of 15 000 t, median final biomass is 66–68% of B_0, and the probability of dropping below the MSYL is only 1–2%. Even with an initial catch of 20 000 t, this risk is still only 5–11% (Table 7.5). Results are less encouraging under the "low *M*" scenario, with median final biomass of 55–58% of B_0 when the initial catch is 15 000 t. The risk of dropping below the MSYL increases to 5–12% under this scenario and initial catch level. If the initial TAC is 20 000 t, the stock collapses in 3–7% of the simulations.

7.8 Discussion

The assessment process described here allowed broad participation by all of the interested parties. By proceeding in several steps, with input at each step, the process allowed members to "buy into" the assessment and to become more involved in the decision-making process. The presence of independent consultants undoubtedly helped in eliminating the antagonism that can occur between industry representatives and governmental fisheries managers. The results were re-calculated by McAllister & Kirkwood (1997) which enhanced the assessment performed, especially since an error was

Table 7.4 The consequences of different scenarios used to explain the shorter length-at-maturity of orange roughy off Namibia, when compared to that off New Zealand. The "original" model parameters are based on those used for New Zealand orange roughy, except that the ages at maturity and recruitment are altered to 14 years instead of 33 years. This scenario is unrealistic since a faster-maturing fish would be expected to have a higher natural mortality. Therefore, in the "high *M*" scenario, the natural mortality rate is altered to 0.1 instead of 0.045. In the other scenario considered ("low *M*"), the natural mortality rate is 0.045, and the age at maturity and recruitment is 33 years, but the von Bertalanffy parameter ℓ_∞ is reduced from 37.2 to 32 cm and κ is decreased from 0.0655 to 0.03. In all cases, the fishing-down period is 14 years with a "soft landing" to 5 700 t, and the estimates of biomass are based on the results using the "original" bias factor specifications (Table 4.12).

Model parameters	Initial TAC	Median (%B_0)	Collapse	< 0.2B_0	< MSYL	< 0.5B_0
Original	5 000 t	83%	0%	0%	0%	0%
	10 000 t	72%	0%	0%	0%	1%
	15 000 t	61%	0%	0%	1%	14%
	20 000 t	50%	0%	3%	10%	51%
High *M* option	5 000 t	87%	0%	0%	0%	0%
	10 000 t	79%	0%	0%	0%	0%
	15 000 t	71%	0%	0%	0%	1%
	20 000 t	63%	0%	0%	1%	10%
Low *M* option	5 000 t	84%	0%	0%	0%	0%
	10 000 t	73%	0%	0%	0%	0%
	15 000 t	62%	0%	0%	1%	11%
	20 000 t	52%	0%	2%	8%	44%

Table 7.5 Final results of the impact on the orange roughy stock by different fishing-down strategies. These results were presented on 29 January 1997 in Namibia. An error in the program later detected by M. McAllister is corrected here. The fishing-down phase consisted of seven years of constant catches (Initial TAC) followed by a linear decrease to 5 700 t over a further seven-year period (a "soft landing"). Two sets of consistent population parameters are used: the "high *M*" and the "low *M*" options. The results are based on biomass estimates produced using the final Ministry specifications and Gendor specifications (Table 4.12).

Model parameters	Bias factors	Initial TAC	Median (%B_0)	Collapse	< $0.2B_0$	< MSYL	< $0.5B_0$
High *M* option $M = 0.1$ yr^{-1} $K = 0.1$ yr^{-1} $\ell_\infty = 37.2$ cm $A_m = A_r = 14$ yr^{-1}	Ministry	10 000 t	75%	0%	0%	0%	2%
		15 000 t	66%	0%	1%	2%	14%
		20 000 t	56%	2%	5%	11%	35%
	Gendor	10 000 t	77%	0%	0%	0%	1%
		15 000 t	68%	0%	0%	1%	8%
		20 000 t	59%	1%	2%	5%	27%
Low *M* option $M = 0.045$ yr^{-1} $K = 0.045$ yr^{-1} $\ell_\infty = 32.0$ cm $A_m = A_r = 33$ yr^{-1}	Ministry	10 000 t	68%	0%	0%	1%	10%
		15 000 t	55%	1%	5%	12%	37%
		20 000 t	43%	7%	17%	31%	65%
	Gendor	10 000 t	70%	0%	0%	1%	5%
		15 000 t	58%	0%	2%	5%	29%
		20 000 t	46%	3%	10%	23%	60%

"High *M*" option for population parameter values

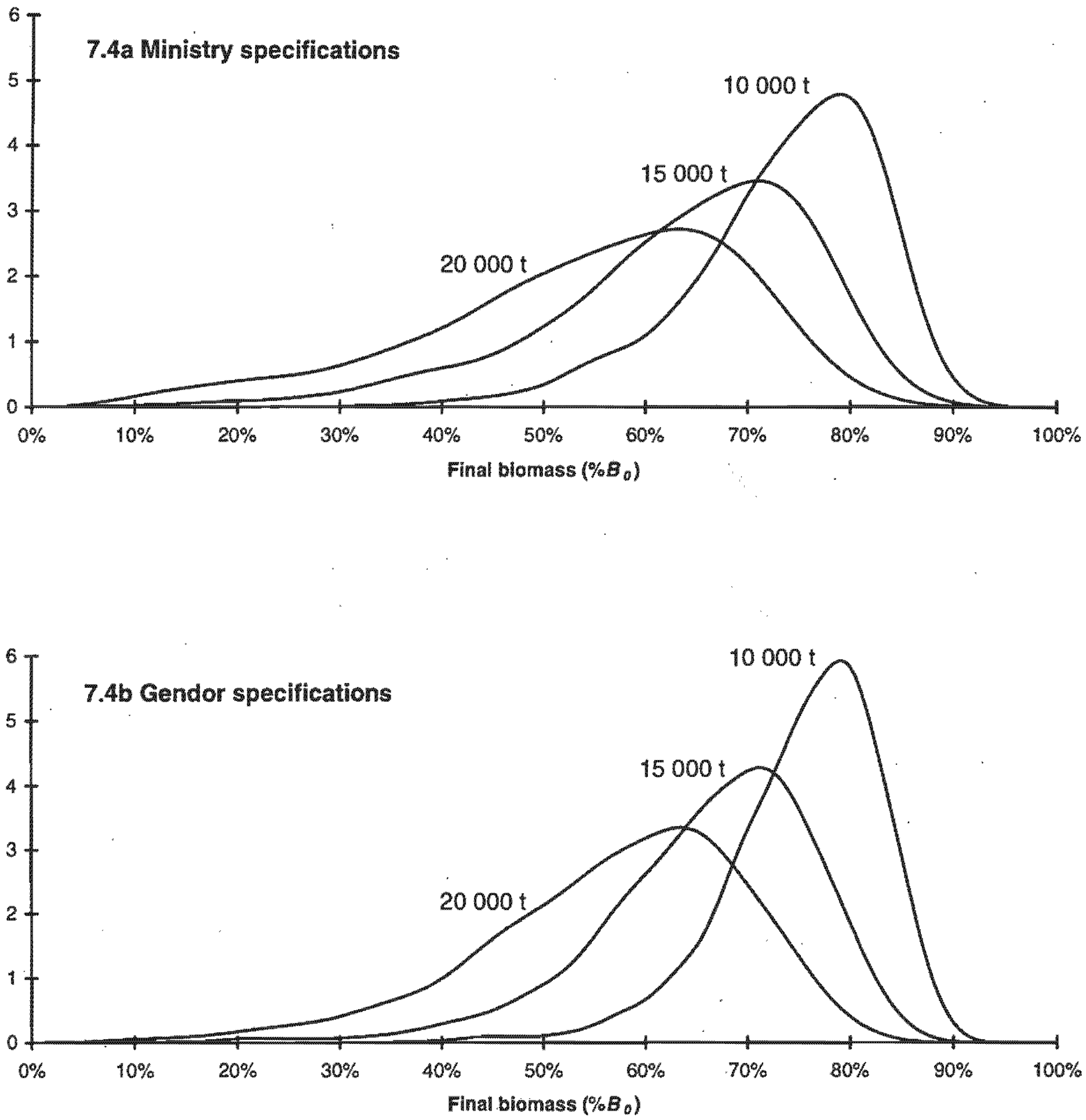

Figure 7.4a-b Final results showing the projected impact of various fishing-down strategies on the Namibian orange roughy stock. The results are shown under the "high *M*" option for population parameter values in the age-structured model. The fishing-down strategies consisted of seven years of constant TACs (the values indicated) followed by a linear decrease in TAC for seven years to a final TAC of 5 700 t. The Ministry and Gendor specifications are the final values (Table 4.12) for the bias factors affecting the swept-area biomass estimates.

Gendor specifications are the final values (Table 4.12) for the bias factors affecting the swept-area biomass estimates.

The actual TAC set by the Namibian government for the year April 1997–March 1998 was 12 000 t. Minimum and maximum TACs were imposed on four Quota Management Areas (the four aggregations): 600–1 800 t for Hotspot, 1 000–1 200 t for Rix, 3 500–6 000 t for Frankies and 2 500–5 000 t for Johnies. The total TAC might seem quite precautionary given the results in this chapter. However, with the benefit of hindsight, it seems partially justified. An acoustic survey performed in July 1997 estimated biomass on Rix, Frankies and Johnies to be 50 000–100 000 t, although the authors (and Clark 1997) warned that these results should be treated only as a relative index of abundance (Huse *et al.* 1997).

However, the acoustic results are not directly comparable to the swept-area results (90% probability interval of 173 000–520 000 t, median 306 000 t; Table 4.13) for a variety of reasons. First, a number of bias factors are not incorporated into those estimates (e.g. fish in the shadow zone, fish outside schools, uncertainty about the target strength of orange roughy and the effect of sound absorption coefficients). Secondly, the survey covered only those portions of the Namibian coastline that corresponded to broad strata around *Rix*, *Frankies* and *Johnies* as defined in Section 4.2. A later analysis estimated that 33% of the biomass lies outside the strata used in the acoustic survey (Branch & Roberts 1998a). Thirdly, the swept-area results correspond to a biomass estimate at approximately the start of 1996, while the acoustic estimates are for July 1997. In the interim period, some 20 000 t of orange roughy were landed. In the most recent assessment meeting (25–30 January 1998), the biases mentioned in the first two points above were incorporated in the acoustic estimates to obtain 90% probability intervals of 54 000–225 000 (Deep Water Fisheries Working Group 1998a). If the third point is taken into account (crudely) by adding 20 000 t to the estimated biomass, the acoustic estimate corresponds to a January 1996 biomass of 74 000–245 000 t (median 167 000 t), still considerably lower than the swept-area results, but certainly in closer agreement than the initial acoustic results of 50 000–100 000 t.

8. Adaptive management of orange roughy off Namibia

8.1 Introduction

What do fisheries managers do? They try to answer one primary question: How many fish can be caught safely each year? Usually they need to answer another question first: How many fish are out there? These two questions are vexing enough to provide hundreds of people with jobs every year. Surveys and data analyses are undertaken to "count" the fish, while information about the population dynamics of the exploited stock is required to determine the "optimum biomass level" and the sustainable yield.

Active adaptive management has been proposed as a solution to both of these questions. "Adaptive management" describes fisheries in which learning occurs as management proceeds. Management strategies can be divided into three categories: nonadaptive, passively adaptive and actively adaptive (Walters & Hilborn 1978; Smith & Walters 1981; Walters 1986). The first category includes those strategies in which no learning occurs after a certain period; the second involves only accidental learning; and the third involves deliberate attempts to improve knowledge about the system. Actively adaptive policies (AAPs) introduce an experimental approach to fisheries management, which may include deliberately increasing or decreasing catches to improve the current information. For example, a "probing" increase in catches may be used to test whether the population is near to its MSY level. Theoretically, AAPs should improve knowledge about the underlying dynamics or stock structure of the system, which would lead to better management. Despite this promise, there are still relatively few examples of their use in fisheries because it is difficult to persuade authorities and fishers to agree on long-term policies.

One AAP that tried to improve knowledge of population dynamics is the Rivers Inlet sockeye salmon fishery (Walters *et al.* 1993). Two alternative hypotheses were considered: first, that the stock was at its "optimum" level, and second, that it was well below this level. As an experiment, fishing was cut drastically in 1979–1984 to improve escapement. The promised benefits did not materialise, indicating that the original stock size had been near optimal. The loss of catches over the experimental period led to fishers expressing a strong distrust in the experimental policy, and it was viewed as a failure (hindsight as always providing 20–20 vision!) (Walters *et al.* 1993; McLain & Lee 1996).

Spatially replicated systems provide a unique opportunity for experimental manipulation of catches. The availability of control populations makes this concept attractive: in a single stock system, one can never be certain whether the stock is responding to changes in catch level, or to some environmental change (Collie & Walters 1991). An analysis in their paper indicates that adaptive management of replicated populations of the yellowtail flounder (*Limanda ferruginea*) would allow greater long-term yield because of improved understanding of the optimal levels of harvest.

Adaptive management can also be used to test different stock hypotheses. In the New Zealand orange roughy fishery, there was debate as to whether trawl surveys in the "Spawning Box" were an accurate index of abundance on the whole Chatham Rise. An adaptive management plan suggested relocating catches to outside the "Spawning Box" to try and answer this question (Punt 1994). Preliminary results of this experiment indicated that the "Spawning Box" indeed indexed only a portion of the resource on the Chatham Rise. Consequently, the latest assessment now provides a more optimistic view of Chatham Rise resource than earlier assessments (Annala & Sullivan 1997).

AAPs were originally developed for fisheries in equilibrium (Walters & Hilborn 1976), but the philosophy has been extended to developing fisheries. In fact, they are more suited to such systems since there is less risk of long-term harm at the outset of the fishery. A major problem in developing new fisheries is the reduction in effort that is required when the target biomass is reached (Hilborn & Sibert 1988). AAPs can be used to infer accurate values for pristine biomass during the fishing-down phase, thereby providing more reliable predictions of when effort reduction will be necessary.

Adaptive management of a developing orange roughy fishery is being implemented for the Bay of Plenty fishery off New Zealand (Starr *et al.* 1996; Francis 1997), although it is still too early to verify its success. A decision rule is applied to the results of trawl surveys, to provide further information about the stock size in this area. For example, if the first two surveys indicate that the population is still under-exploited, catches are increased by a specified amount. Simulation modelling is then used to see how well the stock size can be estimated if this decision rule is implemented. An important facet is that the survey estimates must have sufficient precision to provide early warning if the stock is being over-exploited. The value of this decision rule is that it specifies in advance what data need to be collected and what steps are to be taken as the fishery progresses (Starr *et al.* 1996), thus forestalling the inevitable haggling over TACs as the fishery progresses. Co-operation between industry representatives and fisheries scientists and managers is crucial for the success of this plan. Francis (1997) highlights the importance of defining trade-offs between the different performance statistics. In particular, how large can catches be before they lead to an unacceptable risk of over-fishing?

The Bay of Plenty decision rule is too specific to be applied to other orange roughy fisheries, but Smith (1993) provides a framework for an AAP of a developing orange roughy fishery. In his analysis, the main source of uncertainty is the size of the resource, and the only information available is the catch history and relative indices of stock size. The framework for his model is depicted in Figure 8.1, and is adopted in this chapter for the Namibian orange roughy fishery. The performance of a particular decision rule can be measured by keeping track of the "true biomass" by means of an "operating model" of the population dynamics, and generating indices (with observational error included, simulating the sampling variability from survey estimates) every year from this true biomass. The "manager" can only "see" the indices and the catch history, being unaware of the "true biomass". Smith (1993) provides a method for estimating B_0 (the pristine biomass) directly from this information. In turn, this estimate is used by the "manager" to set a catch for the following year. The "true biomass" is then adjusted for natural growth and the catch made,

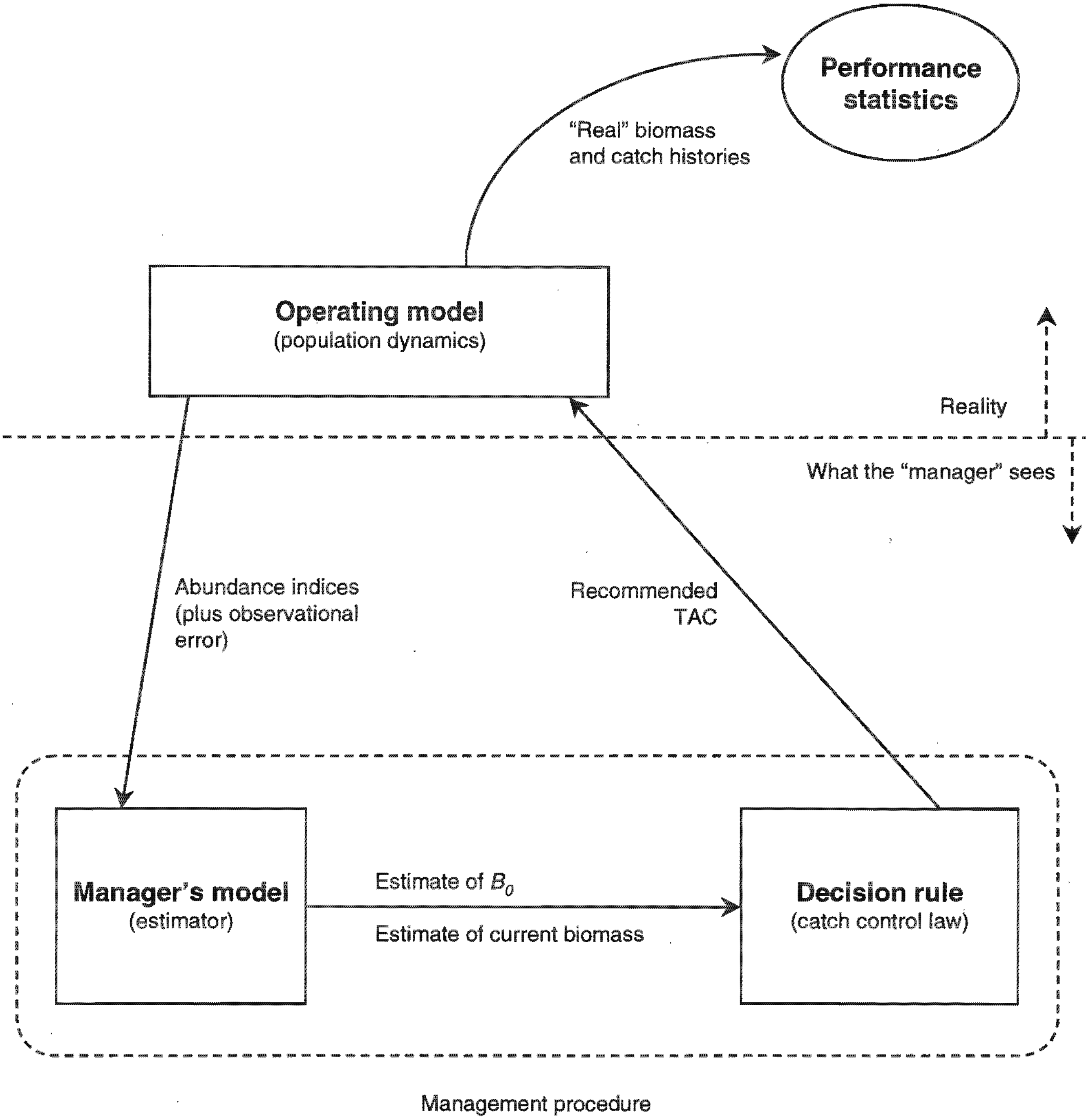

Figure 8.1 Relationships among the three sections of the adaptive management procedure: the operating model, the manager's model and the decision rule. The operating model keeps track of "reality" using an age-structured population model. An index of abundance is then passed to the manager's model, based on the true biomass but incorporating the effects of observational error and the catchability coefficient. The manager's model in Smith (1993), and in this chapter, is an estimator for virgin biomass (B_0) and current biomass. The decision rule uses that information to set a TAC for the following year. The true biomass is then updated and another biomass index is generated. At the end of the simulation period (say, 14 years), the performance of the decision rule is evaluated using the operating model to determine the true status of the resource.

and the process repeated for a number of years. At the end of this period, the manager's performance can be assessed by checking what has happened to the true biomass.

One of the major trade-offs examined by Smith (1993) was between the economic risk of under-fishing, and the biological risk of over-fishing. Sometimes, when the initial estimate of B_0 was low compared to the true value, initial catches proved too low to generate enough contrast in the indices to override the observational error. The management strategy could then become locked into a cycle of low B_0 estimates and low catches. Conversely, if initial catches were too high compared to the "true biomass", there was a large risk of biological over-exploitation.

In this chapter, the methodology of Smith (1993) is applied to the developing Namibian orange roughy fishery. However, a number of modifications are made to his approach:

1) Smith's underlying simple "true model" of biomass dynamics is replaced by the age-structured model described in Section 7.2 (Appendix C).
2) Emphasis is placed on reducing inter-annual variability in catches.
3) The performance of a range of different decision rules is tested.
4) The target biomass considered is 40% of B_0, which is more conservative than the 30% chosen by Smith (1993).
5) Robustness tests are implemented to test the performance of the chosen decision rules, when fundamental assumptions about the underlying model of the actual dynamics are incorrect.
6) Meta-rules are developed and applied to all candidate decision rules. For example, catch changes from year to year were limited to a certain percentage unless the decision rule specified a zero catch in that year. Sensitivity tests are used to determine the impact of these meta-rules.

8.2 Methods

The overall process consists of three components: the "operating model", the "manager's model" and the "decision rules" (as depicted in Figure 8.1). The operating model tracks the actual changes in abundance that follow from the catches made in each year, representing "reality". The manager's model is provided with an estimate of initial biomass, and a series of relative abundance indices generated from the true biomass in each year (with some observational error added). In the manager's model, which is really an estimator, estimates of B_0 and hence the biomass in the current year, are calculated directly from the indices and the catch history. This is the information usually available to a real-life fisheries manager, hence the term used for this component. Based on the information obtained from the manager's model, a decision rule (or "catch control law") sets the catch for the next year. This catch is passed to the operating model, the true biomass is updated, and an index is generated for the following year and passed to the manager's model. This process is simulated for 14 years, at the end of which the performance of that decision rule (and the manager's model) is evaluated. Together, the decision rule and manager's model are often termed a "management procedure".

8.2.1 The operating model

The age-structured model is the same as the one described in Section 7.2 and in Appendix C, except that some population parameters are altered to include data not available at that time. The parameters presented in this section are referred to as the "base case" parameters for the operating model (Table 8.1).

1) The age at recruitment and age at maturity were both reduced from 33 years to 30 years in accordance with an update presented in Annala & Sullivan (1997).
2) Parameters in the von Bertalanffy equation (Appendix C, Equation C5) were altered to better characterise Namibian orange roughy: ℓ_∞ was reduced from 37.2 cm to 33 cm; and κ was reduced from 0.0655 yr^{-1} to 0.046 yr^{-1}.

Table 8.1 Values used for the population parameters in the operating model. These values were adapted from those in Francis *et al*. (1995) and Annala & Sullivan (1997) for the New Zealand ORH3B area, which includes the Chatham Rise. Their values were averaged over the sexes. Alterations were made to κ and to ℓ_∞ to take into account the smaller fish obtained off Namibia reported by Huse *et al*. (1997) and A. Rees (unpubl. data). These changes are discussed in Section 8.2.1.

Population parameter	Base case value	High M scenario	Application
M	0.045 yr^{-1}	0.1 yr^{-1}	natural mortality
κ	0.046 yr^{-1}	0.102 yr^{-1}	von Bertalanffy
ℓ_∞	33 cm	33 cm	von Bertalanffy
t_0	-0.5 yr	-0.5 yr	von Bertalanffy
c	0.0921 $\text{gm/cm}^{2.71}$	0.0921 $\text{gm/cm}^{2.71}$	length-weight parameter
d	2.71	2.71	length-weight parameter
h	0.75	0.75	steepness of Beverton-Holt recruitment curve
a_m	30 yr	13 yr	age at maturity
a_r	30 yr	13 yr	age at recruitment

The second change is substantive, and requires further explanation. The survey performed by Huse *et al.* (1997) provided more information about the orange roughy resource than was available for the analyses presented in Chapter 7. The maximum standard length (ℓ_∞) found by Huse *et al.* was about 33 cm. Fishing on Hotspot, where larger fish are caught, is limited under present regulations. The standard length at 50% maturity (ℓ_m) is given as 25 cm (Huse *et al.* 1997). Both measurements are close to those in Chapter 7 ($\ell_\infty = 32$ cm, $\ell_m = 24$ cm). The revised value of κ (0.046 yr^{-1}) was then chosen so that fish of length 25 cm would be 30 years old.

8.2.2 The manager's model

The model is derived almost exclusively from Smith (1993); deviations from Smith (1993) are noted where they occur. The simple structure of the model enables direct estimation of B_0 (Appendix D) without resorting to minimisation procedures which are computationally intensive. The coded implementation was verified using two minimisation techniques: "amoeba" in Press *et al.* (1990), and "Solver" in Microsoft Excel 7.0, which gave identical results.

Population dynamics in the manager's model

Changes in biomass are modelled by:

$$B_{t+1} = SB_t - C_t + R_t \tag{8.1}$$

where t is the year, B is biomass, C is annual catch, R is annual recruitment and S is annual survival (actually "biomass survival", a combination of natural mortality and growth). The time frame for evaluation is 14 years (for reasons discussed in Section 7.4), which is well within the 30 years assumed for a_r. Virgin levels of recruitment are therefore given by:

$$R_0 = (1 - S)B_0 \tag{8.2}$$

In the age-structured model, natural mortality is assumed to be 0.045 yr^{-1}. Growth after recruitment is slow in orange roughy, so that its effect on S is assumed to be negligible. Smith (1993) assigned a value of 0.95 to S, which was shared by his identical operating and manager's models (Equation 8.1). In this chapter, the more complex age-structured operating model differs from the manager's model. To obtain a value of S in the manager's model which is representative of the $M = 0.045$ used for the base case operating model, a population of 1 000 t was modelled with fixed catches of 40, 50, 60, 70 and 80 t per year. The best fit for final biomass after 14 years was obtained for $S = 0.968$ yr^{-1}, which is accordingly used in implementing the manager's model.

Abundance indices

A series of annual indices of abundance will become available for Namibia, based on acoustic surveys performed each year. Although an acoustic survey nominally provides an absolute index of abundance, problems with target strength, identification of species and the acoustic dead-zone render these survey results more reliable as a relative index than as an absolute estimate of biomass. Each index is subject to observational error because of the sampling process during the survey, so that the index is related to the true biomass by:

$$Y_t = qB_t + \varepsilon_t \tag{8.3}$$

where Y_t is the index at time t, q is the constant of proportionality, and $\varepsilon_t \sim N(0,\sigma_t^2)$ is the error term. The value for σ_t^2 is set so that the CVs are 20% for all indices. The catch C_t is assumed to be observable without error.

Estimation of B_0 from the indices

Estimates of B_0 are obtained directly from a time series of indices and catches, using the maximum likelihood estimator described by Smith (1993). This estimator is reproduced in Appendix D. The estimation process requires at least three indices and a complete catch history. Consequently it is not possible to estimate B_0 until at least the third year of the surveys. In the intervening period, another source is needed for $\hat{B}_0$ (the estimate of B_0).

Smith (1993) drew a set of initial $\hat{B}_0$ values from a distribution around the "true" B_0 with a CV of 50%. However, for Namibia (and probably in other cases), an estimate with an associated CV has been produced, in which case the initial estimate $\hat{B}_0$ is known, while the true B_0 lies within the distribution around $\hat{B}_0$. In the case of the Namibian orange roughy fishery, a median biomass estimate of 306 000 t (CV = 34%) was obtained under the "Ministry (latest)" set of bias specifications (Table 4.13). However, this is not $\hat{B}_0$ since the swept-area estimate is for the average biomass over the period of commercial catches used in the analysis. To obtain $\hat{B}_0$, half of those catches (half of 11 528 t, or 5 764 t) is added to the swept-area estimate. This is a reasonable assumption since any compensatory increase in biomass would be negligible when the biomass is near to B_0. The true B_0 for each of 1 000 realisations was drawn from the distribution surrounding the corrected median value. The true q in the operating model was set to 0.65, in accordance with estimates of q in the Chatham Rise orange roughy fishery in New Zealand (Doonan *et al.* 1997). Of course, the actual value chosen here is irrelevant since the acoustic surveys are analysed as relative indices of abundance.

The catch history was incorporated in the swept-area estimates to obtain the estimated biomass at the start of the 1997–98 fishing season, using the age-structured population model. Catches were obtained from the Gendor database (with each season starting on April 1): 1994–95 (2 279 t), 1995–96 (6 669 t) and 1996–97 (15 699 t, including an estimated 2 131 t for tows missing from the database). The acoustic survey occurred in June 1997. In total, 1 679 t of orange roughy had been caught between 1 April and 23 June 1997 (the middle of the acoustic survey), so that this catch was added to the acoustic survey to obtain an equivalent biomass estimate at the start of the 1997–98 fishing season. Estimates of B_0 from the acoustic survey were obtained by back-calculating to 1994–95, as done for the swept-area estimates. The adaptive management simulations were run over a 14-year period starting in 1997–98, with the catches in 1997–98 assumed to be 12 000 t (the TAC for that fishing season).

8.2.3 Decision rules

Eight decision rules are contrasted in terms of their performance in the simulations. These fell into "experimental" and "control" groups. The experimental decision rules are *Parabola, Jagged, Walters, Strict, Smooth* and *Modified Smith*; the controls were *Smith* and *Myopic* (Figure 8.2). The latter two are designated "controls" because they represent decision rules that have previously been applied to orange roughy fisheries: *Smith* in Australia (Smith 1993, 1997), and *Myopic* in Namibia (Chapter 7); and thus provide a useful basis for comparison with the "experimental" rules. Detailed descriptions of these rules are given in Appendix E.

The decision rule *Smith* is that used in Smith (1993). *Modified Smith* is the same as *Smith* except that it is subject to the "meta-rules" described below. The *Myopic* decision rule is based on the "soft landing" variant used in Chapter 7. It ignores all information provided by subsequent surveys, and may be technically described as a "myopic Bayes" strategy (*sensu* Ludwig & Walters 1982). The *Walters* strategy was obtained from strategy C in Walters *et al.* (1993), the preferred strategy in that paper. Two of the decision rules, *Strict* and *Smooth*, were "probing", in that they tried to set high initial catches to learn rapidly about the stock size. *Smooth* allows some catches even when the estimated biomass is well below 20% of B_0, whilst *Strict* calls for zero catches when the estimated biomass is below 20% of B_0. The final two strategies, *Parabola* and *Jagged*, attempt to start off with lower catches, then increase catches while the biomass is still at a safe level, before reducing catches to the MSY. *Jagged* allows small catches to be taken at very low biomass levels, while *Parabola* sets catches to zero if the estimated biomass drops below 25% of B_0.

8.2.4 Meta-rules

The recommended catches for the six experimental decision rules, but not the control decision rules, were all subject to a number of constraints, or "meta-rules":

1. The catch in any year may not increase or decrease by more than 20% from that of the previous year.

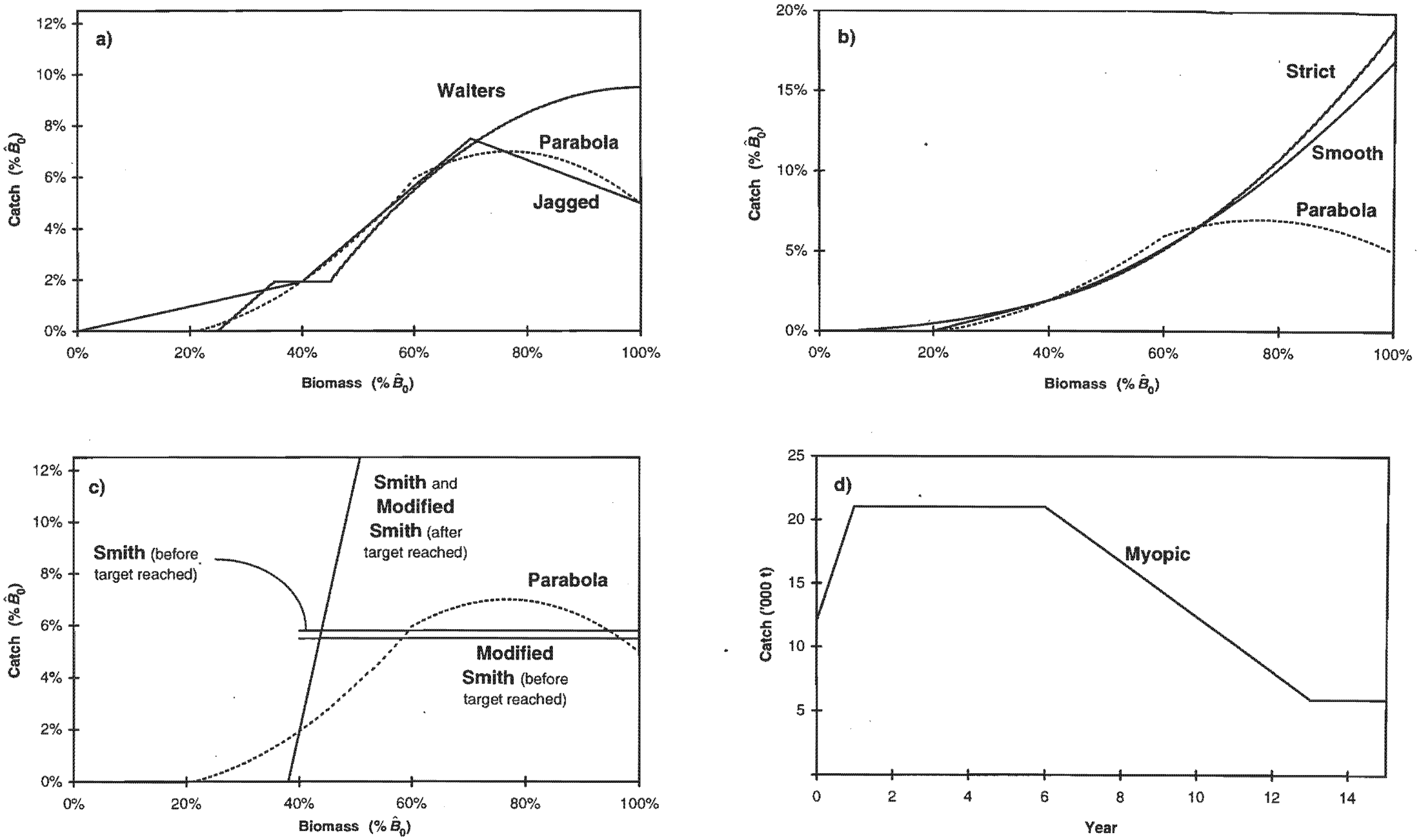

Figure 8.2a-d The different decision rules. The rules (except for *Myopic*) use curves to relate the current estimated biomass level to a particular TAC. *Parabola* is shown for comparative purposes on a), b) and c). Note that *Myopic* does not use a rule based on the current biomass level, but has a fixed catch trajectory which is computed at the start of the management period. Note also that the axes for *Myopic*(d) reflect the fixed catch levels in a particular year, causing the anomalous-looking shape of its catch curve, which is a time trajectory unlike the other plots.

2. If the estimation process for B_0 "fails" in the current year (because the trend in indices is increasing due to observational error, which results in a negative $\hat{B}_0$), then the catch is increased by 10% over the previous year.
3. If the decision rule recommends a zero catch, then the actual catch is 40% less than the previous year's catch. (This meta-rule takes precedence over meta-rule 1 above.)

8.2.5 Standardisation

Some form of standardisation was needed in order to compare the performance of the different decision rules. If management is successful, the stocks should be at the pre-defined target level at the end of the management period. Standardisation therefore consisted of tuning the decision rules so that the median *true* biomass at the end of the 14-year period (the final biomass) was equal to the target biomass—in this case, 40% of the pristine biomass (as illustrated in Figure 8.3b). Tuning consisted of adjusting the control parameters H, I, L and/or Z, as appropriate (i.e. changing the shape of the decision rules in Figure 8.2). The particular control parameters used for the decision rules and meta-rules will be referred to as the "baseline" parameters, to distinguish them from the "base case" parameters for the operating model.

8.2.6 Robustness tests

There is a danger that tuning the decision rules to the operating model gives a greater degree of security in the results than is actually the case. "Robustness tests" are used to check that the decision rules were robust when fundamental assumptions in the operating model were altered. The manager's model and the decision rules were kept tuned to the base case parameters for the operating model throughout the robustness tests.

1. The small size at maturity of the Namibian orange roughy may indicate one of two possibilities. Either they are very slow-growing compared to the New Zealand orange roughy, but live to the same age and have a similar natural mortality ("low M"); or they mature at a younger age and have a higher natural mortality than the New Zealand orange roughy ("high M"). The operating model explicitly assumes the "low M"

scenario ($M = 0.045$). The possibility of a "high M" scenario ($M = 0.1$), akin to the "high M" scenario in Section 7.6, was therefore tested. A list of the parameter values for this scenario, is included in Table 8.1. To maintain the same M/κ ratio of 0.98 as the base case operating model, which is suggested as an "invariant ratio" by Jensen (1996), κ was therefore increased from 0.046 to 0.102. For these parameter values, fish of 25 cm, the length at 50% maturity in Huse *et al.* (1997), would be 13 years old. Therefore, $a_m = a_r = 13$ yr was chosen as the age of maturity and recruitment to the fishery. The values for a_m and a_r are assumed to be identical, following the convention adopted by Annala & Sullivan (1997) and Bax (1997). Note that the M/κ ratio of 0.98 is higher than the 0.69 in Annala & Sullivan (1997) for New Zealand orange roughy, but within the range of 0.80–1.07 reported for Australian orange roughy (Bax 1997), and lower than that of 85% of the fish stocks reported in Pauly (1980).

2. The swept-area estimates of biomass in Chapter 4 presume that fish caught during commercial operations will be replaced by fish migrating in from low-density surrounding areas. If this assumption is incorrect, only the fish on the aggregations will be available to the fishery. Accordingly, the true values of B_0 were drawn from a distribution for the biomass inside the aggregations obtained by the swept-area method for the final Ministry specifications for the bias factors (Table 4.13); this has a median of 117 000 t (CV = 53%).

3. A preliminary estimate of biomass has been obtained for Rix, Frankies and Johnies, based upon an acoustic survey performed in July 1997 (Huse *et al.* 1997). This estimate is 50 000–100 000 t, although various possible bias factors remain to be taken into account. The adaptive management decision rules were tested under the assumption that the true total biomass off Namibia was between 50 000 and 100 000 t. True B_0 values were chosen randomly over this range. This represents a precautionary range for the acoustic estimate, as discussed in detail in Section 8.4.2.

4. The CVs on the relative indices were altered from 20% to 10% and then to 40% to test the effectiveness of the decision rules in the face of decreased and increased amounts of observational error in the survey results.

8.2.7 Sensitivity tests

The performance of the decision rules was tested to changes in their control parameters, particularly with respect to the meta-rules, which affected all of the experimental decision rules. These changes are referred to as sensitivity tests because it is within the power of the fisheries manager to alter any of these parameters (for example, the CV on the acoustic estimates can be decreased by increasing the number of transects during the survey).

1. The decision rules were tuned to achieve a precautionary target level of 40% of B_0 after 14 years for the base case operating model. However, 30% of B_0 is considered to be the level of biomass at which MSY is obtained (Annala & Sullivan 1997; Bax 1997). In Chapter 7, Table 7.5, it can be seen that the *Myopic*-type decision rule used there under the "low *M*" scenario and the Ministry bias factors, gave a risk of 1% of collapse when the median final biomass was 55% of B_0, and the risk as 7% when this biomass was 43%. A "safe" final level for the *Myopic* decision rule therefore probably lies around 50% of B_0. This target level has also been suggested for Namibian orange roughy by Clark (1997). Decision rules were accordingly tuned to target levels of 30% and 50% of B_0, in addition to the baseline choice of 40%, to examine the resulting trade-offs.
2. The maximum percentage change in catch allowed from one year to the next was varied over the range 10–30% (baseline = 20%).
3. The increase in catches when estimation of B_0 fails was varied over the range 0–40% (baseline = 10%).
4. The decrease in catch when the recommended catch is zero was varied over the range 20–60% (baseline = 40%). This meta-rule is called into play, for example, when the estimated biomass falls below 25% of $\hat{B}_0$ under the *Parabola* decision rule, and when it falls below 38% under *Modified Smith*.

8.2.8 Performance statistics

Four performance statistics were recorded: total catch (t), inter-annual catch variation (mean % per year), final biomass (%B_0) and lowest biomass (%B_0). These performance statistics were obtained over a management period of 14 years. This period was agreed upon for the simulations presented in Chapter 7 (the reasons for this choice are outlined in Section 7.4).

- **Total catch** is presented with the median and 95% probability intervals indicated. When compared with calculations of the present value of the catch (with the discount rate at 3%), the relative performance of the different decision rules did not alter. The more easily understood of the two measures, total catch, was therefore used. Total catch, and not the present value of the catch, was also used by Smith (1993) and Francis (1997) in evaluating their adaptive management policies for orange roughy. When total catch presented as a percentage of B_0, it was not immediately obvious whether one decision rule gave better catches than another because the value of B_0 changes from realisation to realisation, so that results are presented in tonnes.
- **Average annual variation** (AAV) was calculated using the formula in Butterworth (1992):

  $$AAV = \frac{1}{n-1}\sum_{t=1}^{n-1}\frac{\left|C_{t+1}-C_t\right|}{\overline{C}} \qquad (8.4)$$

  where n is the number of years and C_t is the catch in year t. Fluctuations are thus measured as the mean percentage change in catch per year.
- The **final biomass** at the start of the fifteenth year was recorded, with the median and 95% probability intervals indicated.
- The **lowest biomass** during the management period was recorded: median and 95% probability intervals are indicated. This measure is included because the possibility exists that the biomass can be fished well below the target biomass level, but then recovers by the end of the management period. Although the model allows this recovery to happen, provided the catches are reduced, in reality the stock-recruitment

relationship in orange roughy is poorly known, and there is therefore a danger that the predicted recovery may not materialise.

8.3 Results

8.3.1 Comparison of decision rules

Each of the decision rules was compared under the base case operating model (Figure 8.3). There were obvious trade-offs in performance evident from the different performance statistics. For example, *Myopic* had the lowest level of catch fluctuation but the lower 5%-tile for final biomass was much lower (an indication of higher risk of collapse) than for the other decision rules. The two "control" decision rules, *Smith* and *Myopic*, both showed unacceptably poor performance for at least one of the performance statistics. The risk of collapse under *Myopic* was higher than for any other decision rule; and the large catch fluctuations under *Smith* would prove unpopular with any fishing industry. The experimental decision rules were therefore contrasted to try and choose the "best" one. In an attempt to avoid verbosity in describing the results, the following terms will be used:

AAV = is used to describe the average annual variation in catches. A large AAV is an indication of major "catch fluctuations" from one year to the next.

Minimum = refers to the lower 95%-ile of one of the performance statistics. For example, the minimum lowest biomass refers to the lower 95%-ile of the lowest biomass recorded over the management period.

Maximum = refers to the upper 95%-ile of one of the performance statistics.

Risk of over-fishing: refers to the lower 95%-ile of the final biomass (or lowest biomass)—a dangerous risk to the spawning biomass is characterised by a small lower 95%-ile.

Risk of under-exploitation = refers to the upper 95%-ile of the final biomass (or lowest biomass): an economically inefficient decision rule is characterised by a high upper 95%-ile, indicating that the biomass was not reasonably utilised on many occasions.

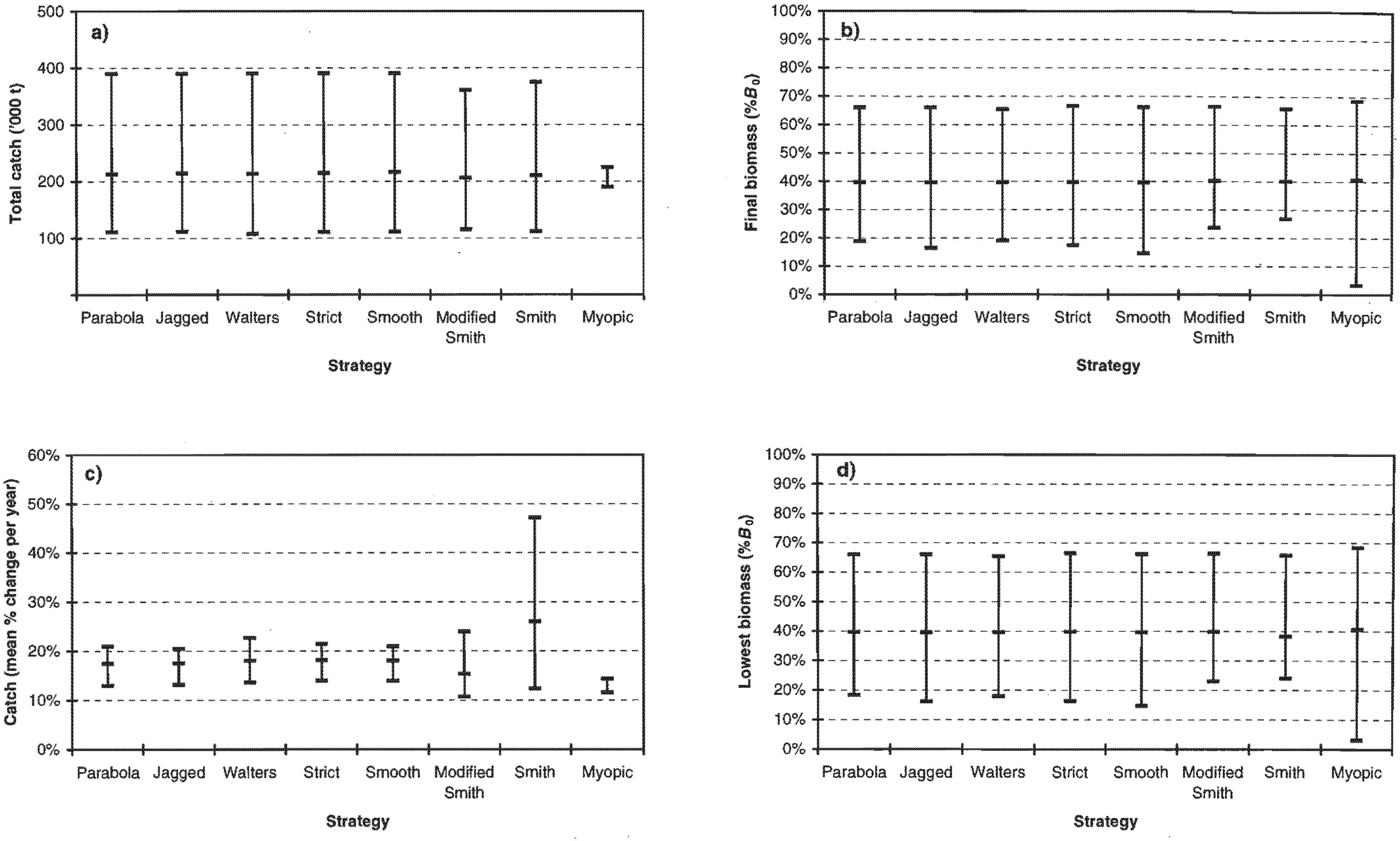

Figure 8.3a-d Performance statistics of the eight decision rules for the base case operating model. The experimental decision rules are *Parabola*, *Jagged*, *Walters*, *Strict*, *Smooth* and *Modified Smith*. *Smith* and *Myopic* are the control decision rules. Distribution medians and 95% probability intervals are presented.

(These definitions of "minimum" and "maximum" are not strictly correct, since 5% of the realisations must fall outside the 95%-iles. They are used for practical purposes only.)

The six rules can be placed in three groups based on the performance statistics. The first group, containing just *Modified Smith*, had lower maximum and median catches, the lowest risk of over-fishing, and the lowest probability of under-exploitation. Median AAV was lowest for *Modified Smith*, but AAV had the greatest range (11–24%). *Parabola*, *Walters*, and *Strict* fall into the second group. These decision rules had a greater risk of over-fishing than *Modified Smith*, but their median AAVs were higher and their AAVs encompassed a narrower range. Median total catch was greater than *Modified Smith*. The third group of decision rules encompassed *Jagged* and *Smooth* which had the narrowest AAV range, but the greatest risk of over-fishing: minimum lowest biomass dropping to 15% of B_0 in *Smooth* and 16% of B_0 in *Jagged.*

The risk of over-fishing was considered to be too great (by the author) in the third group of decision rules; the *Jagged* and *Smooth* decision rules were consequently eliminated from contention. In the second group, change in catches was similar for all three decision rules, as was the median (and minimum) total catch. The *Parabola* and *Walters* decision rules had a slightly smaller risk of over-fishing than the *Strict* decision rule, but were almost identical in performance to each other. However, the range of lowest biomasses was slightly narrower for the *Parabola* method, and this was therefore considered to be the best decision rule in group two. Nonetheless, *Modified Smith* seemed to give the best overall performance: the smallest risk of over-fishing and of under-exploitation, and also the lowest median AAV. On the negative side, *Modified Smith* had the greatest maximum AAV of the experimental decision rules.

When catch trajectories for different true B_0 values are examined, the *Parabola*, *Jagged*, *Walters*, *Strict* and *Smooth* decision rules differ little (Figure 8.4). In each of the sample cases, when the real B_0 is larger than the initial $\hat{B}_0$, exactly the same catch trajectory is followed. This occurs because (for this particular set of observation errors) the estimation

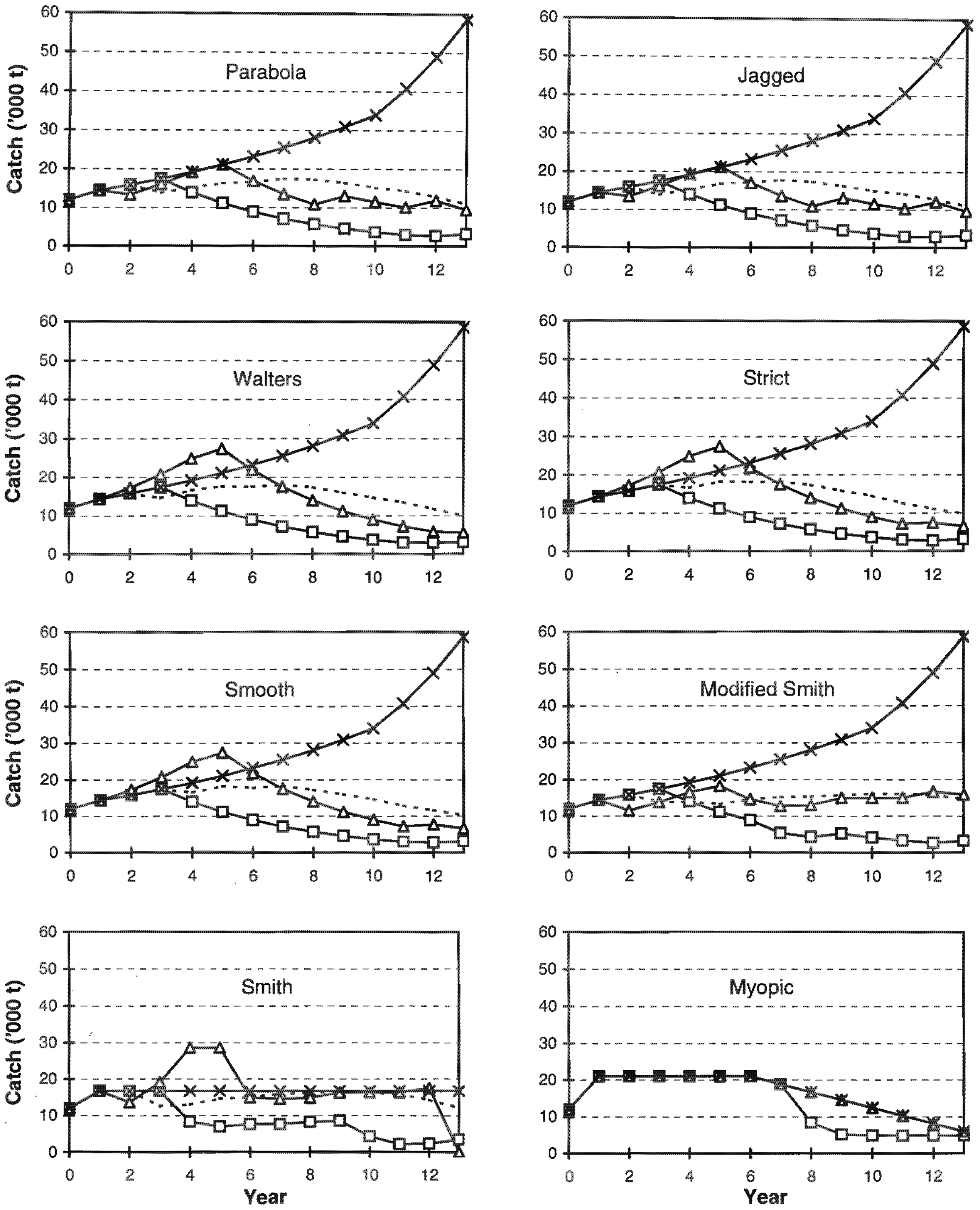

Figure 8.4 Sample catch trajectories under the base case scenario for the different decision rules. The dotted lines represent the median catches over the 14-year period, where this median is over the 1000 realisations produced by different B_0 values. The trajectories represent the case when the true biomass is equal to the upper 95%-ile of the pdf for the true biomass (crosses), when the true biomass is equal to the median of the pdf (triangles) and when the true biomass is equal to the lower 95%-ile of the pdf (squares).

process fails to year 11, a result of the series of indices increasing until this point. When the real biomass is much smaller than the swept-area estimate, catches drop from year 4 onwards in each case. When the real biomass is similar to the median estimate, catches increase until year 5 and then gradually decrease. Unlike the other five experimental decision rules, the *Modified Smith* decision rule follows a fairly constant catch trajectory when the true biomass is close to the initial estimate. This is the primary reason why *Modified Smith* has a low median AAV. The control decision rule *Smith* requires a large AAV, in order to ensure that TACs are small for depleted populations while healthy populations are maximally exploited (Figure 8.4). When the true B_0 is close to the initial estimate of B_0, TACs drop from 28 600 t to 14 900 t in year 6, and from 17 500 t to 0 t in the final year. Far greater changes than these occur in some of the other realisations (which have a different series of observational errors). The catch trajectory of the *Myopic* decision rule is unchanged, except when the biomass is too small to sustain the planned catches (Figure 8.4).

Biomass "trajectories" in Figure 8.5 demonstrate that *Modified Smith*, followed by *Parabola* have the narrowest envelopes of the experimental decision rules at the end of 14 years, and the highest minimum values. *Smith* is better than all the experimental rules, but *Myopic* is the worst by far, demonstrating both over-fishing and under-exploitation of the resource.

The best overall performance after 14 years, based on the discussion above, seems to be by *Modified Smith*, followed by *Parabola*. The most important factors in making this selection are that these decision rules give the smallest risks of both over-fishing and under-exploitation. Their median AAVs are lower than those of the other experimental decision rules although *Modified Smith* has the highest maximum AAV. Total catch is similar for all the decision rules except *Modified Smith*, which has a slightly lower maximum and median total catch than the other rules.

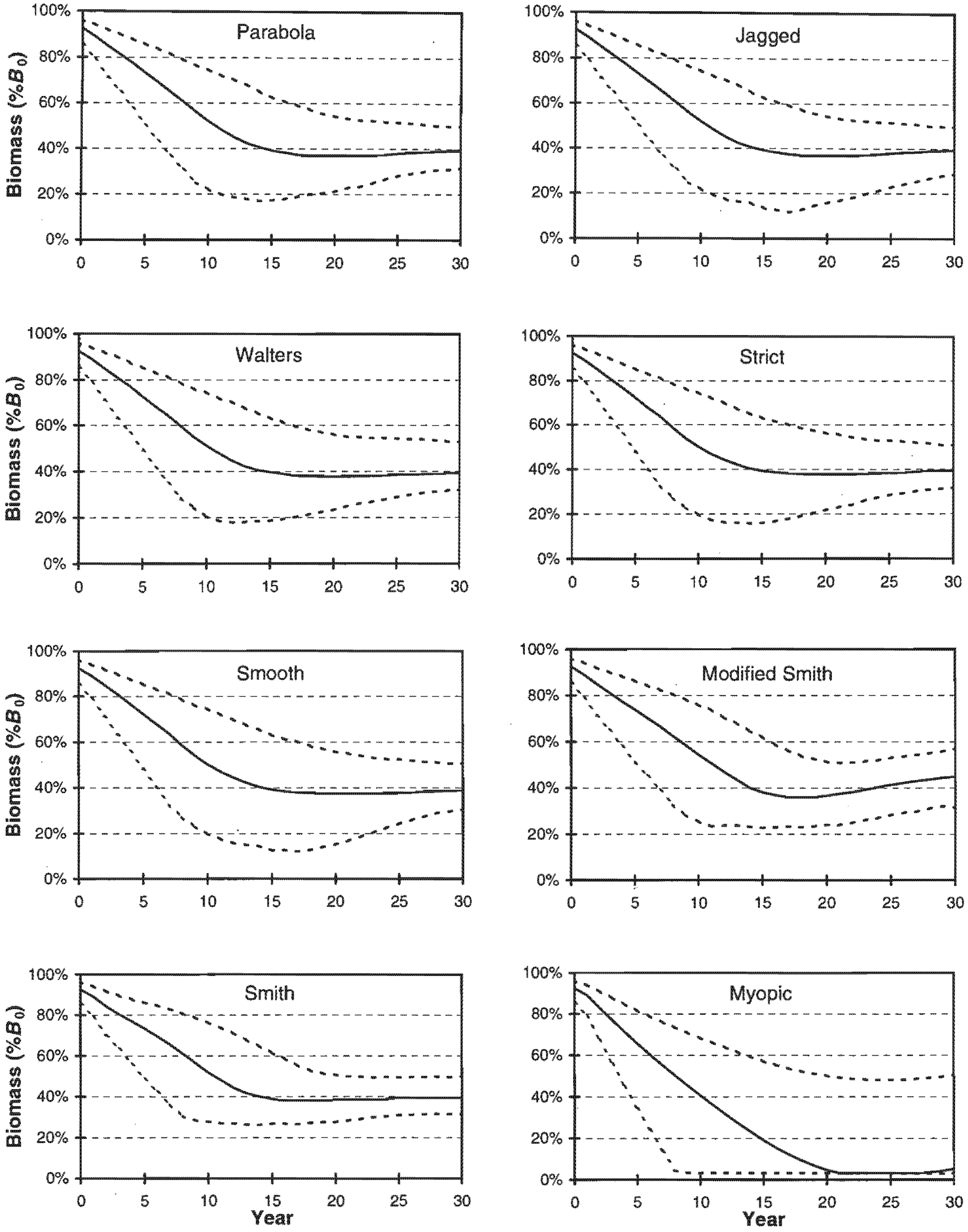

Figure 8.5 Biomass trajectories over 30 years under the base case operating model for all of the decision rules. Distribution medians and 95% probability intervals are indicated. The lines join the medians and the 5 or 95%-iles for each year.

However, when the projections are extended from 14 to 30 years (Figure 8.5), *Modified Smith* begins to give erratic results. In particular, the median biomass at the end of the period rose from the target of 40% to 45% of B_0, and the range of possible final biomass values was the largest amongst the experimental rules: 31–57% of B_0. This poor performance occurs because the *Modified Smith* decision rule recommends a catch of zero when the biomass fails below about 38% of B_0, and catches are reduced by 40% per year until it recovers above this level. When biomass is well above 40% though, catches can only be increased by 20% per year (the maximum change limitation), so that it takes longer to return to the target biomass level. In contrast to the *Modified Smith*, final biomass for *Parabola* after 30 years was 39% of B_0, with the narrowest envelope of final biomass of the experimental decision rules: 31–50%, almost outperforming *Smith* in this respect. *Modified Smith* may therefore perform well over 14 years, but over longer time spans, *Parabola* returns better results.

8.3.2 Robustness tests

"Robustness tests" are tests of the decision rules when underlying assumptions of the manager's model are incorrect. Robustness tests were performed on all the decision rules, with very similar patterns to the baseline case. In all cases, *Modified Smith* and *Parabola* were "better" than the other experimental decision rules. In the interests of both brevity and clarity, results are therefore shown only for those two decision rules.

High mortality option

Under the "high *M*" scenario, catches increased dramatically—by 15–17% (Figure 8.6a). At the same time, median final biomass increased from 40% to 47% under both decision rules (Figure 8.6b). The lowest biomass showed a similar pattern to the final biomass (Figure 8.6d). There was also a very small decrease in the AAV (Figure 8.6c).

Under the "high *M*" option, the *Modified Smith* decision rule provided lower median catches than *Parabola* (Figure 8.6a), but a minimum final biomass that was closer to the

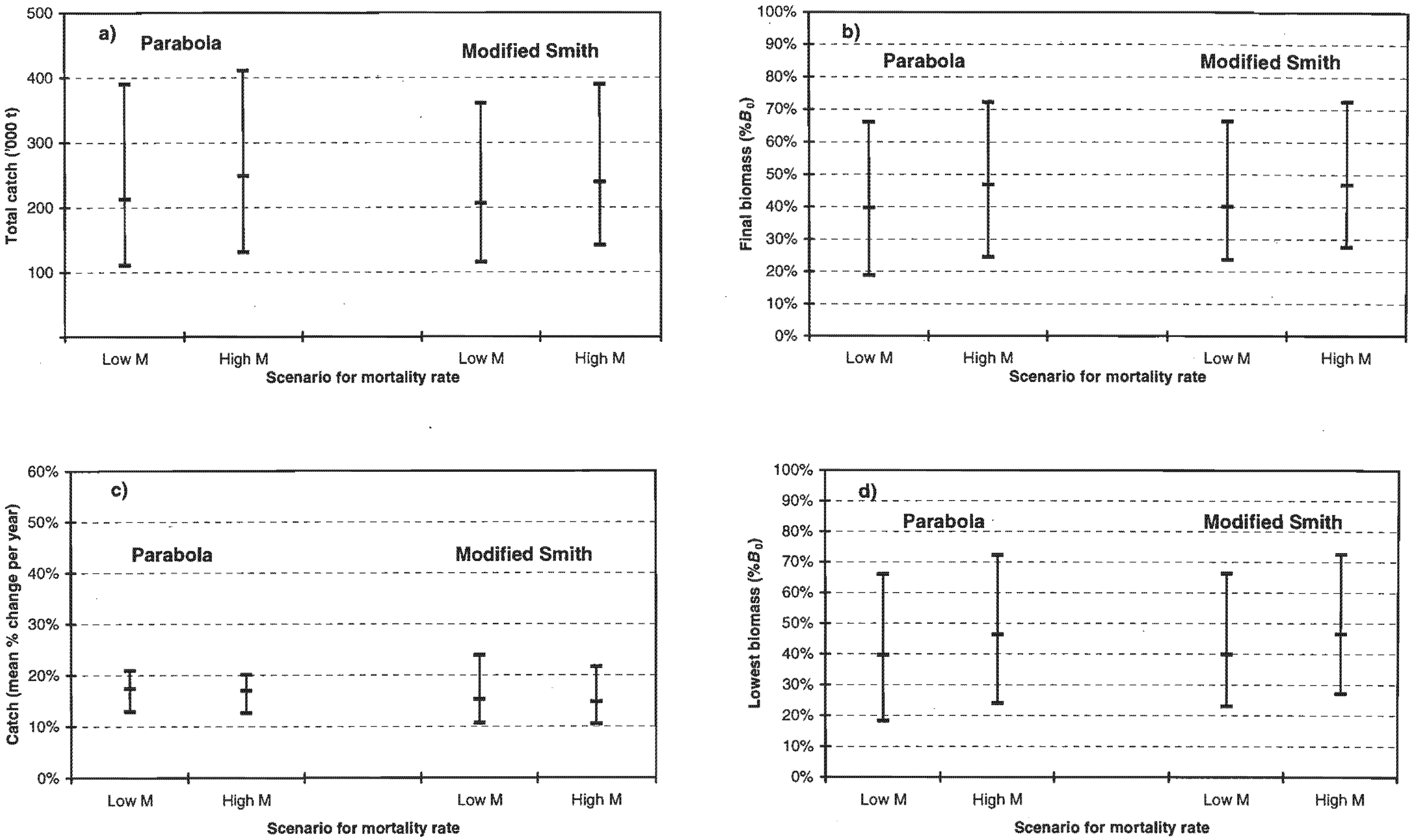

Figure 8.6a-d Performance of the *Parabola* and *Modified Smith* decision rules under the base case operating model (low natural mortality), and under the high natural mortality scenario. Distribution medians and 95% probability intervals are presented for each case.

target level (Figure 8.6b). The AAV was more variable under *Modified Smith*, but the median AAV was lower (Figure 8.6c).

Acoustic survey assumed to be an accurate absolute estimate of biomass

Under this scenario, the biomass was rapidly fished down to a median of 17% (*Parabola*), or 23%, of B_0 (*Modified Smith*) (Figure 8.7d). Recovery towards the target biomass was slow, and by the end of the period, not complete (Figure 8.7b). AAV was much higher than in the base case (Figure 8.7c), and total catches were much lower (Figure 8.7a).

The *Modified Smith* decision rule provides a far better recovery towards the target biomass than *Parabola*. The median biomass was 33% after 14 years, while under *Parabola* it is just 25% of B_0 (Figure 8.7b). However, catches are slightly higher, and AAV much lower, under *Parabola* (Figures 8.7a,c).

No migration into aggregations

Again, biomass was reduced to well below the target level (Figure 8.7d), and had not recovered to the target level at the end of the 14-year management period (Figure 8.7b). The AAV range was extremely large (Figure 8.7c), with a maximum of over 40% under both decision rules.

The *Modified Smith* decision rule again outperformed *Parabola* in recovering back towards the target biomass, its median final biomass being 32%, but only 28% under *Parabola* (Figure 8.7b). Median and maximum catches were greater under *Parabola* (Figure 8.7a). Median AAV was larger under the *Modified Smith* decision rule, but the minimum AAV was smaller (Figure 8.7c).

CV on the acoustic indices

Increasing the CV on the acoustic indices reduced median total catches (Figure 8.8a), increased median AAV (Figure 8.8c) and dramatically increased the range of final biomass

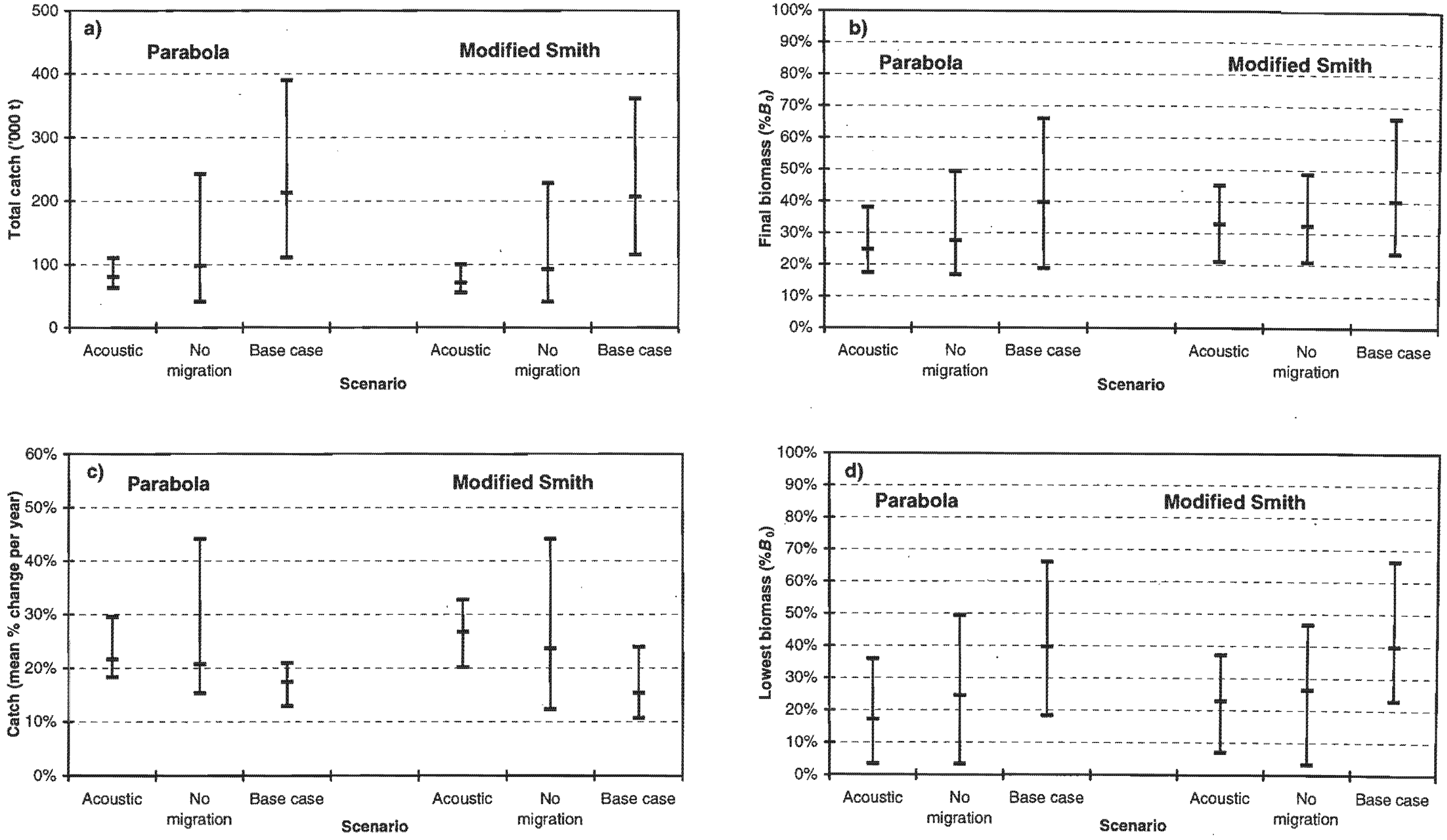

Figure 8.7a-d Performance of the *Parabola* and *Modified Smith* decision rules under two alternative low biomass scenarios. First, that the acoustic estimate (and not the swept-area estimate used in the base case operating model) provides the best estimate of biomass; and second, that there is no migration into aggregations to replace fish caught, so that only the fish inside the aggregations are available to the fishery. Distribution medians and 95% probability intervals are presented for each performance statistic.

levels (Figure 8.8b). The lowest biomass attained was almost identical to the final biomass levels (Figure 8.8d).

When the CV is low (10%), *Modified Smith* has a lower median AAV than *Parabola*. When the survey CV is high (40%), *Parabola* achieves a lower maximum AAV (Figure 8.8c), and a median final biomass closer to the target biomass (Figure 8.8b), at the expense of a greater risk of over-fishing (Figures 8.8b,d).

8.3.3 Sensitivity tests

Sensitivity tests attempt to "tweak" certain control law parameters to improve the performance of the decision rules. In this case, only aspects which apply to all of the decision rules are tweaked. (The catch-biomass curves in Figure 8.2 could also have been altered by changing the parameters in Appendix E.)

Different target levels

At target levels of 30% and 50%, the I (initial catch) values for *Modified Smith* were 0.069 and 0.045 respectively. For *Parabola*, I was set to 0.05, and M was tuned to 0.11 and 0.051 respectively.

As expected, catch levels were greater for lower target levels (Figure 8.9a), and final biomasses smaller (Figure 8.9b). The lowest biomass (Figure 8.9d) was very similar to the final biomass in all cases. AAV increased slightly with an increase in the target level (Figure 8.9c).

Parabola gave greater maximum catches than *Modified Smith* (Figure 8.9a), but these are attained by increasing the risk of over-fishing the resource (Figure 8.9b). AAV had lower median and minimum values under the M*odified Smith* decision rule, but higher maximum values.

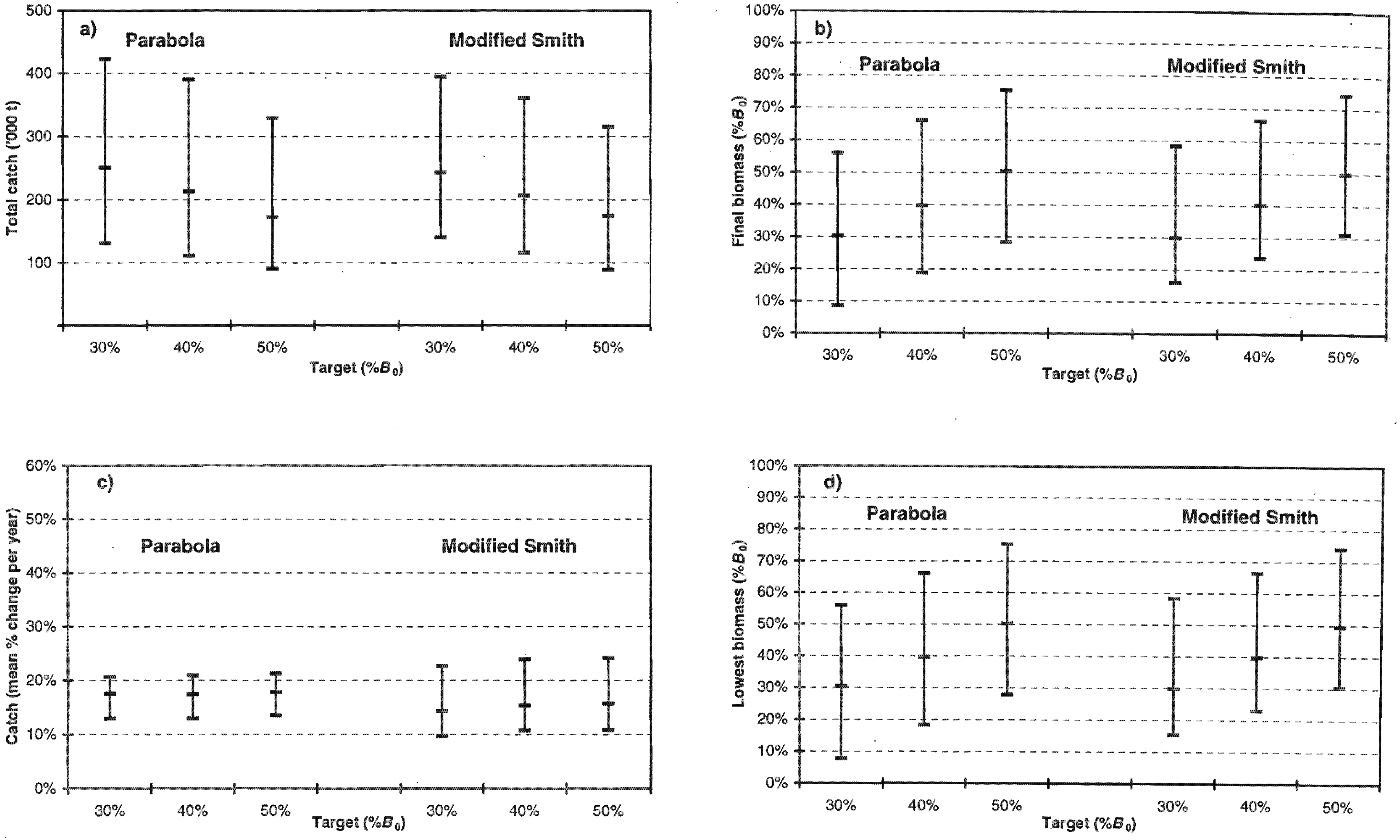

Figure 8.9a-d Performance of the *Parabola* and *Modified Smith* decision rules when they are tuned to different target biomasses at the end of the fourteenth year. The baseline target is 40% of B_0. Distribution medians and 95% probability intervals are indicated.

Maximum change in catches

Altering this parameter between 10% and 30% had little effect on the median total catch attained (Figure 8.10a), the final biomass level (Figure 8.10b), or on the lowest biomass level (Figure 8.10d). However, the maximum total catch increased substantially with increasing values of this parameter (Figure 8.10a). As would be expected, greater maximum changes resulted in increased AAV (Figure 8.10c).

Modified Smith had a smaller median (and minimum) AAV than *Parabola* in each case, but a larger maximum AAV(Figure 8.10c).

However, a maximum change of less than 20% results in poor performance under two of the robustness tests. First, if projections are continued for 30 years instead of 14 years, the lowest biomass recorded is markedly smaller than if a maximum change of 20% or greater is allowed. Second, if the true biomass is much smaller than the swept-area results indicate (acoustic estimate correct, or "no migration" scenario correct), then the lowest biomass becomes chronically small. In both these instances, the recovery to the target level is also much slower if the maximum change allowed is less than 20%.

Percentage increase when the process of estimating B_0 fails

The maximum total catch increased with increasing values of this parameter (Figure 8.11a), but the median and minimum total catch remained fairly constant. The risk of under-exploitation (indicated by the upper limits to the final biomass) decreased when this parameter was increased from 0% to 10% (the baseline value), but not much more when it is further increased to 20% or 40%. The risk of over-exploitation increased as this parameter increased (Figure 8.11b). AAVs increased substantially with increasing values of this parameter (Figure 8.11c). *Modified Smith* generally outperformed *Parabola* in all criteria, regardless of the values assigned to this parameter.

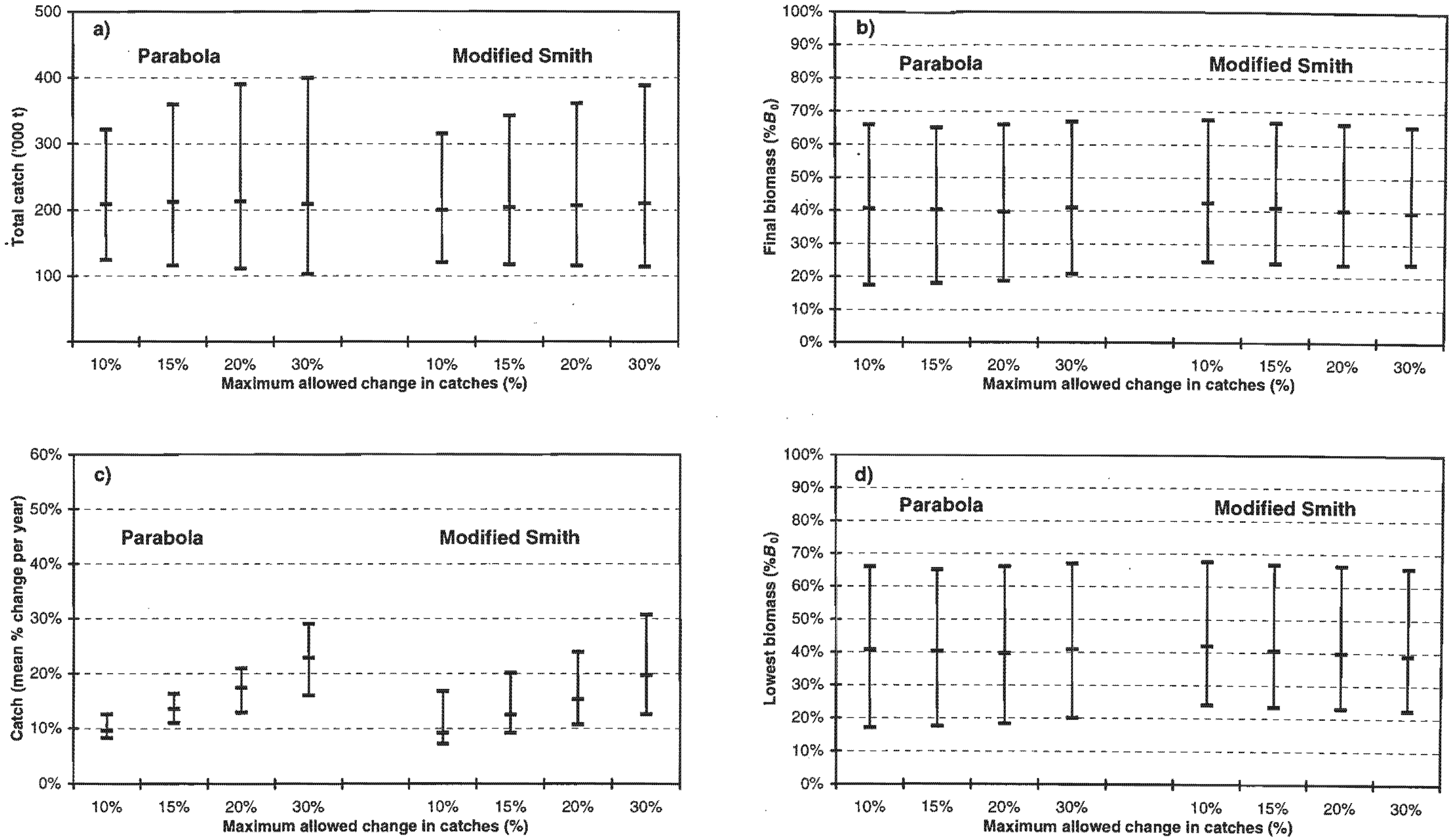

Figure 8.10a-d Performance statistics of the *Parabola* and *Modified Smith* decision rules when the "meta-rule" governing the maximum allowed change in catches, is altered. The baseline value is 20%. Distribution medians and 95% probability intervals are indicated.

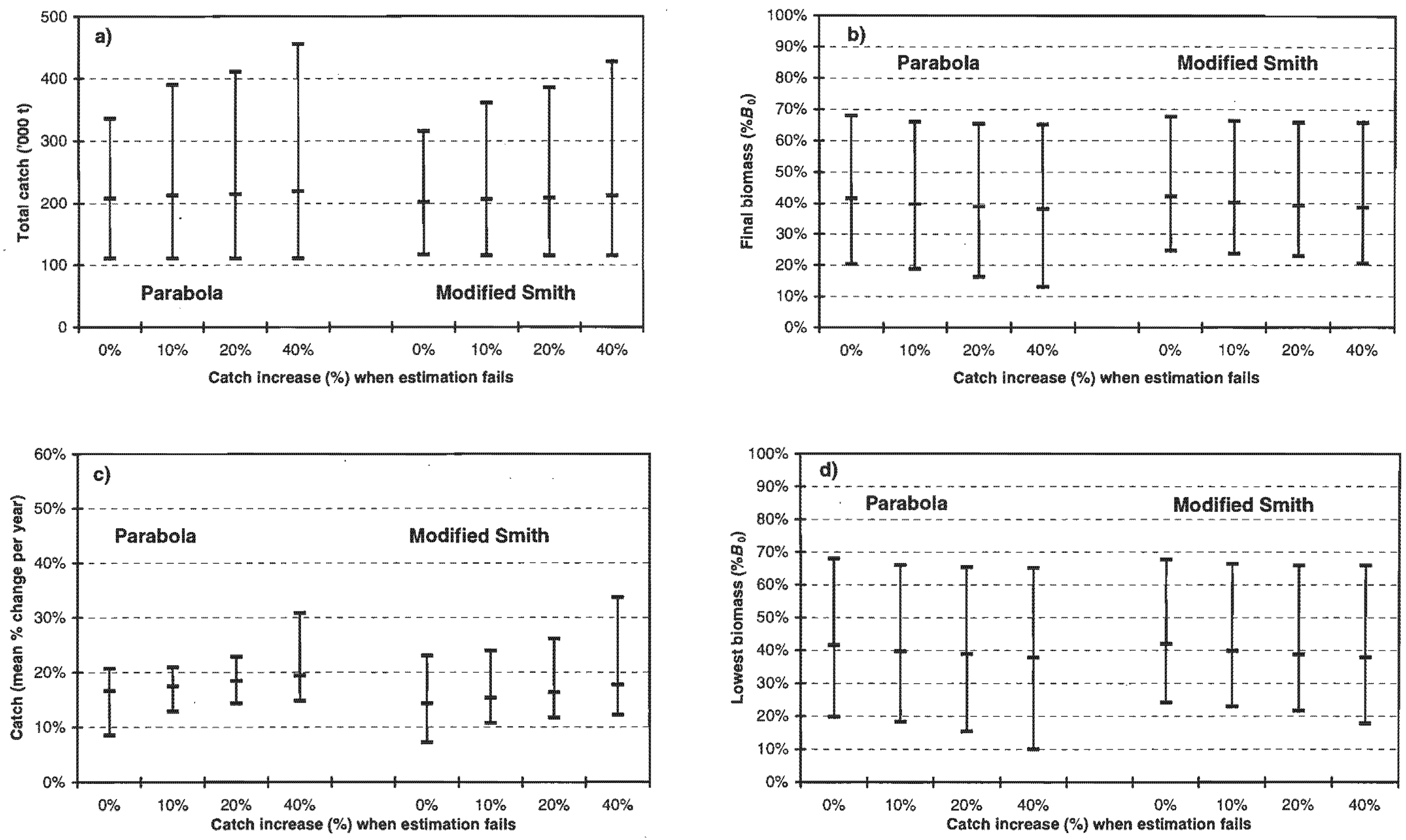

Figure 8.11a-d Performance statistics of the *Parabola* and *Modified Smith* decision rules when the "meta-rule" which governs the percentage increase in catch when the estimation process fails, is altered. The baseline value for this parameter is 10%. Distribution medians and 95% probability intervals are indicated.

Decrease in catch when recommended catches are zero ("zero-decrease")

Total catches were almost identical for all values of zero-decrease (Figure 8.12a). Final biomass (lowest biomass gave very similar results) had near-identical maximum and median levels, but the minimum level was smaller when the zero-decrease was 20% than when it was 40% or 60% (Figure 8.12b). AAV had similar minimum and median values, regardless of the values of zero-decrease. However, maximum fluctuations under *Modified Smith* rose sharply with increasing values of zero-decrease (Figure 8.12c).

Modified Smith offered slightly lower total catches, slightly reduced risk of over-fishing, and smaller (but more variable) AAV, than the *Parabola* decision rule. This was true for all values of the zero-decrease parameter.

8.4 Discussion

An investigation into different adaptive management programs invariably highlights trade-offs under different types of management strategies, or decision rules. For example, it is not possible to maximise catch while minimising the risk of over-exploitation at the same time. It is therefore important (for the DWFWG, in this instance) to define which trade-offs are acceptable before a final decision can be made in choosing a decision rule (Francis 1997). Acceptable trade-offs may take the form of biological reference points such as those used to decide on TACs for Australian orange roughy (Smith 1997).

Two decision rules were suggested above as the "best" decision rules amongst those considered: *Parabola* and *Modified Smith.* However, if more emphasis is placed on reducing catch variability than on the risk of over-exploitation, the *Jagged* and *Smooth* decision rules might be considered to be more appropriate (Figure 8.3). The two control decision rules, *Smith* and *Myopic*, performed considerably worse than the experimental decision rules in at least one aspect. *Smith*, based on Smith (1993), placed emphasis on narrowing the range of final biomass, but this resulted in enormous variability in catches. *Myopic*, based on Butterworth & Branch (1996), reduced catch variability, but the risk of biological over-exploitation increased dramatically. The two "best" decision rules

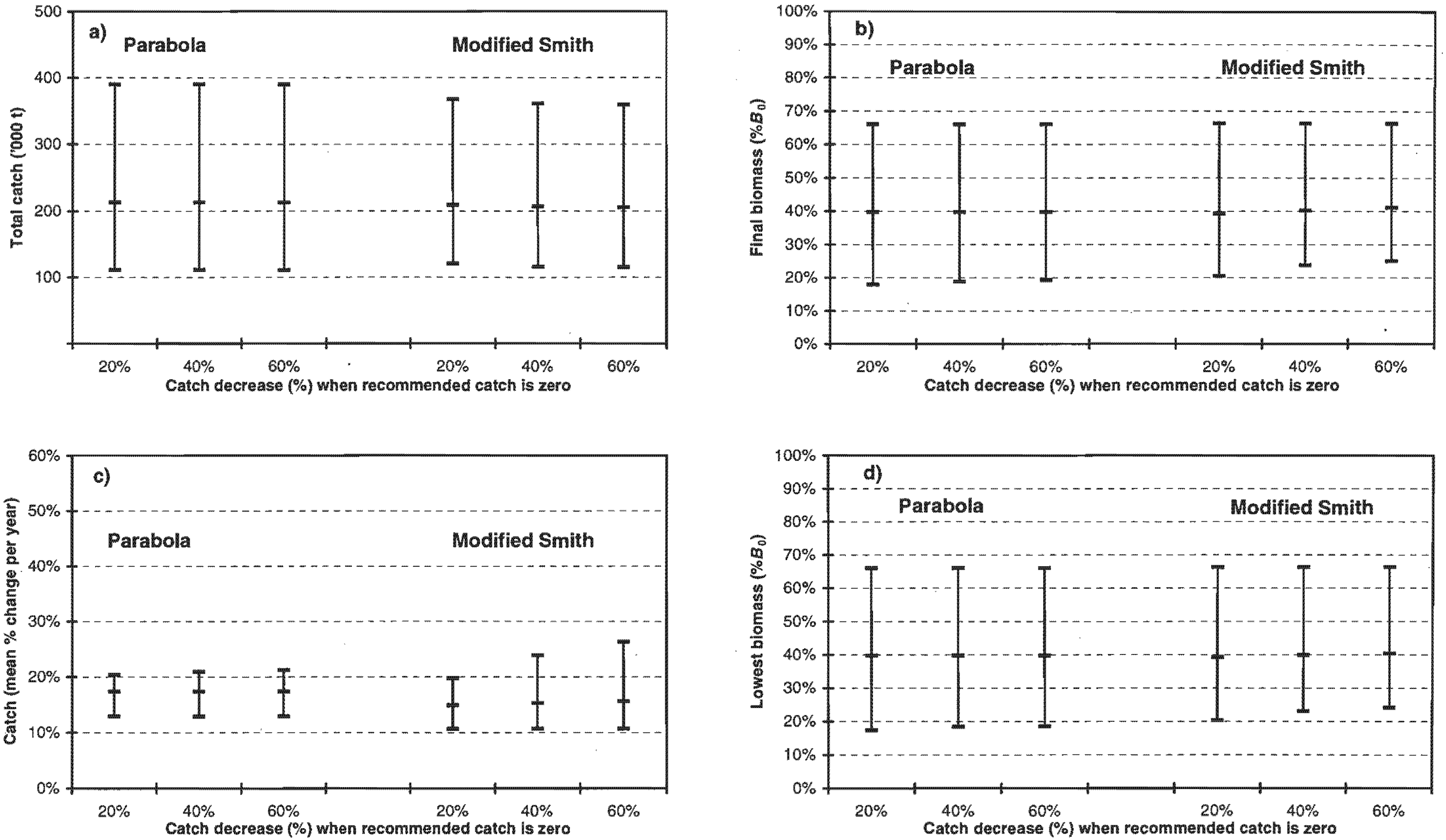

Figure 8.12a-d Performance of the *Parabola* and *Modified Smith* decision rules when the "meta-rule" which governs the decrease in catches when the decision rule recommends a zero catch, is altered. The baseline value for this parameter is 40%. Distribution medians and 95% probability intervals are indicated.

achieved a low risk of over-exploitation at the expense of a maximum level of catch variation which is higher than the other decision rules.

8.4.1 Catch variability

One trade-off that is explicitly examined in this analysis, is that between variation in catches and the risk of over-exploitation. Smith & Walters (1981) suggest that a penalty be placed on large variability in catches, but neither they nor Smith (1993) apply this guideline to their adaptive management procedures. As a result, under the 10% strategy favoured by Smith (1993) (the *Smith* decision rule with initial catches set to 10% of B_0), dramatic changes in catches sometimes occur—catches may be reduced from 10% of B_0 to zero in the space of a single year (Figure 2a in Smith 1993). Such changes would be economically disastrous in most fisheries.

The measure of catch variation used by the International Whaling Commission (1992) for their adaptive management models for baleen whales (Butterworth 1992), is adopted here. This statistic is used to measure the performance of the different decision rules in terms of average annual variation in catches (catch fluctuation). A simple set of "meta-rules" (rules superseding the decision rules) is applied to all of the experimental decision rules to attempt to reduce catch variation. In the baseline scenario, application of these meta-rules reduced the 95% probability intervals for the catch fluctuations from 12–47% per annum for the Smith (1993) model (*Smith* decision rule) to a more acceptable 11–24% per annum (*Modified Smith* decision rule). However, the range (95% probability interval) of final biomasses increased from 27–66% of B_0 for the Smith (1993) model, to 23–66% of B_0 under *Modified Smith* (Figures 8.3b,c), demonstrating the trade-off resulting from decreased catch fluctuations. How do these catch fluctuation values compare with those that have occurred in established orange roughy fisheries? Mean AAV is 16% for the New Zealand catch history and 70% for Australia (from Figure 2.1; after Annala & Sullivan 1997 and Bax 1997). The enormous value for Australia reflects the boom-and-bust nature of the orange roughy fishery there: it should not be regarded as a model for economic stability.

The most important determinant of fluctuation in catches is the meta-rule placing a limit on the maximum change in catches from one year to the next. In the baseline scenario, changes are limited to 20% (unless recommended catches are zero), resulting in catch fluctuations for *Modified Smith* of 11–24%. Altering this parameter to 10% reduces catch variation to 7–16%, with little increased risk to the fishery for the base case operating model. However, if the acoustic survey is treated as an absolute biomass estimate (although note the warnings from Huse *et al.* (1997) that it should be regarded only as a relative index), the decision rules, especially *Parabola*, fare poorly.

8.4.2 Robustness tests

Natural mortality

One of the most important factors in altering the performance of the decision rules, was the value accorded to natural mortality (M) in the base case operating model (Figure 8.6). Under the "high M" scenario, there were substantial increases in catches, marked increases in the final biomass levels, and even a reduction in catch variability. It was encouraging that the decision rules were able to adapt to the increased productivity even though the estimation procedure in the manager's model was not altered (the survival value S remained 0.968, implicitly assuming that the resource has low productivity). In other words, despite assuming a model of productivity in the estimation process that was different to that in the operating model, performance was still good. Nevertheless, the exact values for M remain crucial in assessing the productivity of orange roughy. For example, even despite the good adaptive behaviour of the rules considered here, even better performance could be achieved if M was accurately known, and the manager's model adjusted accordingly. Orange roughy off Namibia are considerably smaller than those on the Chatham Rise, New Zealand, but no ageing work has yet been completed on this stock. Any changes to the value of $M = 0.045\ \text{yr}^{-1}$ used in New Zealand must therefore be regarded as premature until hard evidence is obtained. Nonetheless, the smaller sizes of orange roughy off Namibia indicate possible higher values for M there, so that the retention of the "low M" scenario is a precautionary approach (FAO 1997).

Acoustic survey assumed to be an absolute estimate of biomass

The acoustic survey performed off Namibia in July 1997 reported a lower biomass estimate (50 000–100 000 t, Huse *et al.* 1997) than that obtained using a swept-area technique on commercial data (90% probability interval of 173 000–520 000 t; Table 4.13, Ministry bias factors). If the true biomass is drawn from the range suggested by the acoustic survey, then the decision rules perform poorly (Figure 8.7), with the biomass decreasing to a median low point of 17% under *Parabola* and 23% under *Modified Smith*. Catch fluctuation is also extremely large—nearly always over 20%—under this scenario. It is therefore worthwhile to examine the reliability of these two methods of biomass estimation critically.

Acoustic surveys have been used as a central basis for the St Helens fishery off Australia (e.g. Kloser *et al.* 1996), and the technique is quite well established. The low CV obtained makes acoustic indices ideal for tracking changes in abundance from year to year. However, problems in determining the target strength of orange roughy (e.g. Kloser *et al.* 1997), reducing the shadow zone (e.g. Kloser 1996), and confirming species identity (e.g. Cordue 1996a), make the conversion from relative indices into absolute biomass estimates problematic. Huse *et al.* (1997) outline a number of biases that could change the biomass estimate, and emphasise that the value of their Namibian acoustic survey of orange roughy is to provide a relative rather than an absolute estimate of abundance[16].

The acoustic survey is intended to survey the total biomass off Namibia, with the underlying premise that all the biomass is concentrated into the aggregations at the time of the survey. In New Zealand, there have been ongoing discussions as to whether the "Spawning Box" on the Chatham Rise indexes all, or only part, of the biomass on the Chatham Rise (Punt 1994; Annala & Sullivan 1997). It is likely that only part of the orange roughy biomass off Namibia was present in the aggregations at the time of the

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[16] The bias factors, and the percentage of biomass outside the survey area, were taken into account during the January 1998 assessment, to obtain a bias-corrected absolute estimate of 86 000–237 000 t (CV = 37%), as described in the Postscript (Section 10.2).

surveys, since commercial catches at that time of the year do indicate orange roughy outside aggregations. In contrast to the acoustic results, the swept-area method obtained biomass estimates both inside and outside the aggregations, spread throughout the year.

The acoustic survey also measures biomass some 13 months after the estimate made by the swept-area analysis. In the intervening period, 20 000 t of orange roughy was caught (reported catches in Gendor database)[17]. In addition, the swept-area estimate includes Hotspot, whereas the acoustic survey never assessed the Hotspot aggregation. In total, 1 900 t of orange roughy was caught on that aggregation before June 1996, although this aggregation is thought to have a relatively small remaining biomass (M.R. Clark, pers. comm.).

Despite these reservations, the acoustic survey remains an established technique for assessing orange roughy, unlike the swept-area technique attempted in Chapters 3–4. Reservations have been expressed about the validity of the swept-area analysis, especially by M.R. Clark (pers. comm.) and J.A. Koslow (pers. comm.). Nonetheless, at the time it was applied, it was the only way in which an urgently needed estimate of biomass could be obtained. A series of acoustic indices treated as relative indices of abundance would probably be a more reliable guide for future management, but several more years would need to elapse before a meaningful trend in these estimates could be obtained.

No migration into the aggregations

There might not be a rapid migration of orange roughy into the aggregations to replace fish lost through catches. In an extreme case, only the fish currently on the aggregations would ever be catchable, while those outside aggregations would remain there at low densities and be unavailable commercially. Under this assumption, the risk of over-fishing was again large, with the 95% probability intervals for the lowest biomass reaching close to

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[17] This factor can be taken into account very crudely by adding 20 000 t to the bias-corrected acoustic estimate (Section 10.2), resulting in a 90% probability interval of 106 000–257 000 t, not significantly different from the 173 000–520 000 t obtained using the swept-area method. The range used in this chapter for the acoustic estimate was therefore overly precautionary, but this could not have been predicted at the time of the work.

zero (Figure 8.7). However, the median lowest biomass was still higher than that if the acoustic estimate was true. The spread of values was much greater under this scenario, because of the high CV associated with swept-area estimates of biomass inside the aggregations (CV = 53%).

CV on the acoustic estimates

Smaller CVs on the acoustic surveys played an important role in attaining the target biomass more closely (Figure 8.8). With a low CV (10%) under the *Modified Smith* decision rule, the final biomass covered a range of only 27% of the B_0 value, but when the CV was 40%, it covered 66% of the possible range. Both the risk of biological over-exploitation and economic under-exploitation increased dramatically with increasing CVs. It is therefore imperative that the acoustic survey provides estimates with low sampling CVs.

The base case value[18] for the acoustic CV was 20%. Acoustic surveys can obtain very precise estimates—on St Helens off Australia, acoustic estimates over three years had CVs of 7–15% (Kloser *et al.* 1996). Indices from trawl surveys generally have larger CVs—the Chatham Rise trawl survey series had a mean CV of 18% for the first seven years (Annala & Sullivan 1997), but when the biomass declined further, CVs increased to 34% and 67% before the survey series was discontinued (Clark 1996b). Egg surveys are not appropriate for a time series of indices, since the CVs obtained are very high, typically 41–50% (Koslow et al. 1995a; Zeldis *et al.* 1997). In light of the magnitude of CVs obtained from the different survey types, it would seem that acoustic surveys are far better suited to forming the basis for a series of abundance indices than the other two survey methods.

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[18] This value compares well to the subsequently estimated CVs of 15–25% for *Johnies*, *Frankies* and *Rix* and overall CV of 13% in the 1997 acoustic survey of orange roughy off Namibia (re-calculated values from the DWFWG in January 1998, correcting erroneous values in Huse *et al.* 1997).

8.4.3 Sensitivity tests

Altering the target biomass

The target biomass choice for the Namibian orange roughy fishery is critical. There is a marked trade-off between increased catch levels at a lower target biomass, and increasing risk of over-exploitation (Figure 8.9). Decisions about what target levels should be set will probably depend on what level of risk is acceptable to the managers. If it is decided that the biomass should not fall below 20% of B_0, then a target of 30% is clearly unrealistic under the base-case operating model. However, if the acoustic indices can be obtained with CVs close to 10%, this target level may be feasible. A target level below 50% is not feasible under the *Myopic* decision rule, which ignores all feedback information about the resource (a similar rule was used in Chapter 7). However, the adaptive management decision rules in this analysis perform considerably better than *Myopic* in this sense. The target biomass, or assumed level at which MSY is obtained, is 30% in both New Zealand (Annala & Sullivan 1997) and Australia (Lyle 1994), so that any target above this value could be considered to reflect a conservative decision rule.

Maximum allowed annual change in catches

Reducing the maximum year-to-year change in catches to 15% or even 10%, did not have a marked influence on the biomass levels attained after 14 years. The only real impact this parameter has is in reducing the fluctuation in catches between years, an encouraging sign. A case could certainly be made for reducing the maximum change to 10%, with the proviso that the other meta-rule is retained: when recommended catches are zero, catches are decreased by 40%. This latter meta-rule plays a major role in reducing the risk of over-fishing, which overrides the impact of the maximum change parameter. However, it should be noted that the maximum change parameter has an important impact on the pattern of recovery of the fishery. When stocks are hit hard (e.g. under the acoustic scenario with decision rules initially based on the swept-area estimates), there may be a lengthy period of 40% reductions in catches until the biomass rebuilds to the target level. But subsequent increases in catches will be limited by the maximum change parameter, so that it may be a long time before catches are again large enough to reduce the biomass to the target biomass.

Decrease in catch when the recommended catch is zero

The baseline value chosen for this parameter (40%) appeared to be appropriate (Figure 8.12), with a markedly greater risk of over-exploitation if it was decreased to 20%, but little difference when it was increased to 60%. The upper limit of fluctuation in catches increased as this parameter was increased, but median fluctuations remained similar.

Percentage increase when the process of estimating B_0 fails

Smith (1993) pointed out that his model could become locked into a cycle of setting catches which are too low to produce contrasts in the indices, which in turn leads to recommending catches which are still too low. The same problem was encountered initially by the decision rules in this Chapter. To counter this problem, a parameter was introduced which increases the TAC whenever the estimation process fails. The introduction of this parameter did not seem to have a major influence on reducing the risk of economic under-exploitation; it would be expected that the upper interval of final biomass would decrease with increasing values, but this effect was scarcely detectable (Figure 8.11b). However, the maximum total catches attainable were much larger when this parameter was high. It may be argued that a value of zero for this parameter is optimal since this reduces catch fluctuations quite markedly. This avenue did not appear to be an easy way to counter the problem outlined by Smith (1993).

One solution to the negative cycle of small catches would be to introduce a 'probing catch' (i.e., a catch well in excess of the recommended catch) when the estimation process concludes that biomass has been at the target level for a few years. It is possible that the estimated biomass is much smaller than the true biomass (Walters & Hilborn 1976). If this is the case, a large probing catch would produce only a small decrease in the following index. However, the possibility of increased economic benefits would need to be weighed against the biological risk of such a strategy if the biomass is actually at or below the true biomass. This ‘probing’ policy is itself an adaptive management program that has been explored by Walters & Hilborn (1978) and Smith & Walters (1981). Learning is increased most by large perturbations, but these in turn result in higher risk to the fishery (Walters & Hilborn 1978).

8.5 Conclusions and recommendations

The simple fixed catch policies (myopic policies) presented in Chapter 7 give substantially worse performance than adaptive decision rules. Their only advantage is greater economic stability—companies can plan ahead since TACs remain unchanged for many years. In reality, responsible fisheries managers would never adhere blindly to a fixed TAC trajectory. As they gain more knowledge about the size of the resource, they would alter TACs accordingly, either following a decision rule like *Modified Smith* or *Parabola*, or making appropriate *ad hoc* adjustments. In either case, the biological risks would be less, and the economic rewards greater, than under a fixed TAC trajectory. The analyses in Chapter 7 should therefore be replaced by adaptive rules in future assessment of Namibian orange roughy.

The weighting assigned to different performance criteria is important in choosing the “best” decision rule. This rule will attempt to maximise total catch, minimise the risk to the resource, and keep inter-annual changes in TACs as low as possible. *Modified Smith* and *Parabola* seemed to fulfil these aims better than the other candidate decision rules.

Careful consideration needs to be given to the maximum allowable change in TAC from one year to the next. The value assigned to this “meta-rule” plays a central role in determining the year-to-year stability of the fishing industry. Other meta-rules do not have a great influence on the performance of the decision rules.

The adaptive rules were able to self-correct when the underlying reality was different from that assumed in the manager’s model. If the stock was much more productive (high natural mortality), the performance of the decision rules improved under all criteria, even though biomass estimation still assumed low natural mortality. Conversely, if the stock was much smaller than initially assumed, the adaptive rules allowed the stock to recover almost back to the target level by the end of the 14-year management period.

Survey CVs are crucially important in determining the performance of the adaptive management policies. If CVs are relatively low, say 10%, good estimates of pristine biomass can be made. As a result, economic performance is improved and the risks to the resource can be reduced substantially. Conversely, if CVs are high (e.g. 40%), poor estimates of pristine biomass are obtained, economic performance is consequently poor and biological risks are great. High sampling intensity (resulting in low CVs) is therefore recommended for the planned acoustic surveys.

The adaptive management possibilities outlined in this chapter evaluate the trade-offs resulting from different policies. These analyses could be used easily to decide on a management rule for Namibian orange roughy, similar to that implemented in New Zealand (in the Bay of Plenty fishery, Francis 1997) and in Australia (Smith 1997).

9. Overall conclusions

The swept-area methodology developed for orange roughy off Namibia (Chapter 3, 4) can be applied to other fisheries deceptively easily, as shown by the assessments for South African orange roughy (Chapter 5) and oreo dories (Chapter 6). The underlying basis is quite straightforward, but the major problem with this technique lies in obtaining plausible values for the bias factors. For the Namibian orange roughy fishery, a number of sources were consulted and a range of different scientists discussed the values to be used for these bias factors, so that there was some confidence in their validity. However, for the South African assessments, there was little discussion about these values, and accordingly less faith should be placed in the resulting biomass estimates.

The swept-area methodology used for commercial catch data is not a widely applied technique. It would have been preferable to base results on acoustic surveys, trawl surveys or egg surveys, which have been used elsewhere with some success. In their absence though, the swept-area technique was used, as it was the only technique that could be applied. The estimates of biomass obtained from it are higher than those obtained from the subsequent first acoustic survey performed off Namibia, but more surveys are needed before it will be possible to determine which of the two methods gives a more reliable estimate.

The simple fishing-down model used initially to formulate management advice for the Namibian orange roughy fishery (Chapter 7) proved useful in its context. It was easily understandable and accordingly gained acceptance by the delegates at the meetings in Namibia in January 1997. However, it gives a pessimistic view of the risks to the fishery because it ignores the learning that occurs during the course of the fishery—it is "myopic". The adaptive management procedure (Chapter 8) takes into account future learning about the resource, based on a series of acoustic survey estimates each year. It demonstrates that the risk of over-fishing caused by the "myopic" fishing-down strategy is much greater than that of a policy which incorporates more information about the fishery as the fishery develops. However, it is considerably more complex and hence likely to be more difficult to "sell" to fisheries managers.

As is the case for any project with a modelling component, there are numerous improvements and extensions which could be made to the work presented in this thesis (e.g. modelling recruitment as a stochastic function). However, the two most important improvements needed are:

(1) For the Namibian orange roughy fishery, the management procedures and final biomass estimates need to be separated for each of the four major aggregations. This would provide more useful advice to the managers of the resource.

(2) Separate assessments are needed for each species of oreo dory off South Africa, to avoid the New Zealand experience where the TAC is lumped for all the oreo species.

The methods used here show considerable promise but further cross-checking (probably against future acoustic surveys) is needed before more confidence can be placed in the results they produce. Nevertheless, they have been extremely successful in involving scientists, managers and industry in the assessment process. The management decisions reached by these disparate parties in both Namibia and South Africa were achieved by mutual agreement, and without animosity—a rare event indeed in fisheries management in the region. While the swept-area approach may be displaced by acoustic methods once a sufficiently lengthy time series is available, in the absence of data showing trends in the resource over time, the swept-area technique has proved extremely valuable.

10. Postscript: recent developments in Namibia and South Africa

Fisheries assessments are superseded rapidly by new (and hopefully more accurate) information. The work presented in this thesis is no exception. This postscript is an update on the most recent events in Namibia and South Africa after November 1997. Although some of the results presented for Namibia in this thesis have now been revised, the underlying methodology has played an important role in many facets of the subsequent assessments.

10.1 South African oreo dories

Little deepwater fishing (just 40 days) has been conducted in South Africa since the assessments presented in Chapters 5–6. Landed catches from June 1997 to January 1998 included 111 t of warty oreo dory, 19 t of smooth oreo dory and 0.8 t of orange roughy (R. Tilney, pers. comm.). In order to encourage exploration, two additional permits were issued in January 1998 to Viking Fishing and Marpro Trawling. The additional permit-holders are restricted to 50 t of oreo dory bycatch inside the Dory Patch, but are allowed to catch up to 500 t of orange roughy and 500 t of oreo dory outside this area (R. Tilney, pers. comm.).

10.2 Namibian orange roughy

The Namibian Deep Water Fisheries Working Group (DWFWG) met in Swakopmund (26–30 January 1998), focusing on orange roughy. The DWFWG comprises representatives of the three quota-holding companies, independent scientists, and Namibian scientists and managers. The terms of reference for this working group were discussed. Some felt that the DWFWG should provide advice directly to the Minister, whereas others felt that this level of responsibility was premature (Japp 1998). The working group is currently an advisory body which provides advice (in the form of a consensus document) on the research and management of the Namibian deepwater fishery. This advice is considered by the Fisheries Management Committee before being submitted directly to the Ministry of Fisheries and Marine Resources.

CPUE analysis for orange roughy

Unstandardised monthly catch rates (in tonnes/tow) were calculated for each aggregation (Branch & Roberts 1998b). Marked declines were evident, but were due in part to new vessels entering the fishery and to increased targeting on alfonsino. After allowance had been made for these factors, a downward trend still remained for Hotspot, Frankies and Johnies, raising some concerns. However, interpretation of this trend is further confounded by two more factors: first, in New Zealand and Australia, CPUE tends to overestimate the extent of resource decline (Annala & Sullivan 1997; Koslow *et al.* 1997); secondly, Namibian management rules forcing exploratory fishing outside the known aggregations may have depressed catch rates.

Updated swept-area estimate for orange roughy

The analysis in Chapter 4 was repeated using catch data from July 1996 to mid-December 1997. Some bias factors were updated, notably the increase in extent (E) factor for aggregations (the known extent of *Rix* and *Frankies* had increased substantially). Median (bias-corrected) biomass was estimated at 224 000 t (CV = 44%) with a 90% probability interval of 122 000–438 000 t (Branch & Roberts 1998a). This was rather lower than the January 1997 median estimates of 306 000 t and 321 000 t. However, since the swept-area estimate is based on commercial catch data, this drop essentially reflects the decline in CPUE discussed above. The implication of this change in CPUE is that (if the first swept-area estimate was correct) the updated estimate will be negatively biased. For this reason, the updated estimate did not play a major role in the assessment process.

Bias-corrected acoustic estimates

The targeted acoustic estimate for Rix, Frankies and Johnies in Huse *et al.* (1997) were revised to 63 300 t (CV = 13%) as a result of making corrections to some of the underlying factors. Possible biases were then incorporated using the methodology described in Chapter 3. The most important of these biases were target strength uncertainties and the percentage of orange roughy outside the acoustic strata. The bias-corrected estimate (for the whole of Namibia) was 147 000 t (CV = 37%) with a 90% probability interval of 86 000–237 000 t.

Updated biological parameters for Namibian orange roughy

Sectioned otoliths were aged by NIWA, New Zealand, resulting in total age estimates of 20–72 years (Clark 1997). Other parameters estimated were a_m (24 yr), ℓ_∞ (30 cm) and κ (0.08 yr^{-1}), when t_0 is constrained to -1.0 yr. Since these age estimates were lower than those for New Zealand orange roughy, natural mortality (M) is probably 0.06–0.07 yr^{-1}. The Namibian resource is therefore thought to be more productive (higher M) than that in New Zealand (where $M = 0.045\ \text{yr}^{-1}$).

Population modelling

The modelling in Chapter 7 was repeated by M.K. McAllister for the bias-corrected acoustic and swept-area (January 1997) estimates. The updated biological parameters of Clark (1997) were incorporated. Three 14-year catch trajectories, starting in 1997–98 (assuming the 12 000 t TAC for that season), were examined: 15 000 t decreasing to 6 000 t, 12 000 t decreasing to 5 000 t, and 10 000 t decreasing to 4 000 t. For all three options, no serious risks to the resource were predicted for seven years, but if the acoustic estimates are correct, there could be some risk at the end of the 14-year period.

Adaptive management

A short presentation was made of the results in Chapter 8 of this thesis, demonstrating that the risks to the fishery are considerably less than indicated by the simple fixed catch trajectories in the population modelling exercise above. Despite initial misgivings about being able to "sell" adaptive management to fisheries managers (voiced in the Overall Conclusions), the brief presentation was sufficient to convince the DWFWG that adaptive management strategies should be pursued in the future.

Management recommendations for orange roughy

The recommendation was made that the TAC should remain at 12 000 t since there should not be any short-term risk to the fishery and this would maintain economic stability. However, the difference between the acoustic and swept-area estimates was highlighted as a major concern. It was noted that the biomass could be considerably less than previously thought, and that the TAC might need to be reduced before the end of the first seven-year period. Further risk estimation should use adaptive management strategies (as contained in Chapter 8) and not fixed catch levels.

10.3 Namibian alfonsino

A subsidiary concern of the DWFWG was the Namibian population of alfonsino (*Beryx splendens*), a deepwater species found in slightly shallower waters (300–500 m) than orange roughy. The TAC of 10 000 t for the 1997–98 season was severely undercaught (< 1 000 t by December 1997), leading to management concerns. The swept-area method was consequently applied to alfonsino off Namibia to obtain a median bias-corrected estimate of 13 100 t (CV = 100%), with a probability interval of 2 900–57 000 t (Roberts & Branch 1998). However, there were two main problems with this assessment: first, the mid-water aggregations of this species (Galaktinov 1984; Horn & Massey 1989) require specialised mid-water fishing gear which is not being used at present, so that catchability may be extremely low; secondly, they are caught only on Hotspot, Rix and Frankies and at depths overlapping with those characterised by orange roughy, so that most tows used in the analysis were probably targeting orange roughy. For these reasons, it was probably premature to apply the swept-area technique to alfonsino. Nevertheless, the estimate (together with the failure to catch the TAC) provided sufficient warning for the 10 000 t TAC to be considered inappropriate. In the 1998–99 season it will therefore be replaced by a "trigger level" of 2 000 t. If this level is attained, the management and research priorities for alfonsino would be reviewed by the DWFWG (Deep Water Fisheries Working Group 1998b).

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Appendix A

CV calculations for the swept-area analysis

Estimates of the density (D) in each stratum were weighted according to the effort (swept-area) expended on each tow. The resultant formula for D is:

$$D = \frac{\sum_{i=1}^{n} C_i}{\sum_{i=1}^{n} E_i} \qquad \text{(A1)}$$

Where C_i = catch in tow i, E_i = effort expended in tow i (the swept area, the product of wingspread and bottom distance) and n = number of tows in a stratum. The proportion of total effort in a stratum expended by a single tow i is given by w_i:

$$w_i = \frac{E_i}{\sum_{j=1}^{n} E_j} \qquad \text{(A2)}$$

The standard error of the density estimate in a particular stratum is then:

$$SE = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} w_i \left(\frac{C_i}{E_i} - D\right)^2} \qquad \text{(A3)}$$

The CV of the density estimate for that stratum is:

$$CV = \frac{SE}{D} \qquad \text{(A4)}$$

The CVs calculated in (A4) are applied to the biomass estimates B_k for each stratum k, where the number of strata is r. The associated CV for each stratum is CV_k. When the overall estimates of biomass are obtained, the overall CV for several strata is calculated by the following procedure:

$$CV = \frac{\sqrt{\sum_{k=1}^{r} (CV_k \times B_k)^2}}{B_{total}} \qquad \text{(A5)}$$

where:

$$B_{total} = \sum_{k=1}^{r} B_k \qquad \text{(A6)}$$

Appendix B

Reproduced from Appendix A in Branch & Butterworth (1996).

Some concerns about the reliability of data collected on the *R. V. Matsuyama Maru* survey to provide unbiased estimates of orange roughy density outside aggregations

A. Rees and A. James, Gendor Fishing Company

The *R.V. Matsuyama Maru* was deployed by the Namibian Ministry of Fisheries and Marine Resources to conduct a random stratified trawl survey for orange roughy during 1995. The results are published in a cruise report by Lesch (1995). A number of aspects concerning the nature of these data and the circumstances surrounding their collection strongly suggest that swept-area estimates of orange roughy density derived therefrom will be strongly biased downwards.

- The gear that was utilised by the vessel (a hake net) is not designed for deep water fishing.
- The vessel is not designed to conduct deep water fishing.
- The lack of deep water fishing experience aboard brings the fishing efficiency and deployment of the gear at depth into question.
- The report of the survey states that despite fishing in the same area as the exploratory vessels, the catch rates achieved by the *Matsuyama Maru* were generally lower than those by the exploratory vessels.The vessel was sighted by the *Southern Aquarius* to be fishing on the aggregation known as *Johnies*. Whilst the *Southern Aquarius* landed a 20 GWT catch of clean orange roughy for 3-5 minutes bottom time, the *Matsuyama Maru* recorded a very low catch - less than one tonne - from the same tow line. This was despite fishing information being exchanged between the observers aboard the *Southern Aquarius* and the cruise leader aboard the *Matsuyama Maru.* This provides a specific example of the consequences of the lesser efficiency of the *Matsuyama Maru* alluded to above.

We therefore consider that operations by the *Matsuyama Maru* and the Gendor exploratory fishing vessels are not comparable, and that a random stratified trawl survey conducted by the latter would yield much higher catch rates and hence swept-area estimates of orange roughy density than follow from analysis of data from the *Matsuyama Maru.*

Appendix C

Age-structured population model

This model is based on the age-structured model presented in Francis *et al.* (1995), which is used to model the population dynamics of orange roughy on the Chatham Rise, New Zealand.

Population dynamics

$$N_{y+1,0} = R(B^{sp}_{y+1}) \qquad \text{(C1)}$$

$$N_{y+1,a+1} = (N_{y,a} - C_{y,a})\, e^{-M} \qquad 0 \le a \le m\text{-}2 \qquad \text{(C2)}$$

$$N_{y+1,m} = (N_{y,m} - C_{y,m})\, e^{-M} + (N_{y,m-1} - C_{y,m-1})\, e^{-M} \qquad \text{(C3)}$$

where:

$N_{y,a}$ = number of orange roughy of age *a* at the start of year *y*
$C_{y,a}$ = number of orange roughy of age *a* taken by the fishery in year *y*
$R(B^{sp})$ = the Beverton-Holt stock-recruitment relationship described by (C10)
B^{sp} = spawning biomass
M = natural mortality (assumed to be independent of age)
m = largest age considered (i.e. the "plus group").

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

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

$$C_y = \sum_{a=a_r}^{m} w_a\, C_{y,a} \qquad \text{(C4)}$$

where:

w_a = mass of a fish at age *a*
a_r = age at recruitment to the fishery.

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.

$$\ell(a) = \ell_\infty[1 - e^{-\kappa(a-t_0)}] \qquad \text{(C5)}$$

$$w_a = c\ell(a)^d \qquad \text{(C6)}$$

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

$$C_y = \sum_{a=a_r}^{m} w_a F_y N_{y,a} \tag{C7}$$

which can be re-written as:

$$F_y = \frac{C_y}{\sum_{a=a_r}^{m} w_a N_{y,a}} \tag{C8}$$

where:

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

Stock-recruitment relationship

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

$$B_y^{sp} = \sum_{a=a_m}^{m} w_a N_{y,a} \tag{C9}$$

where

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

The Beverton-Holt form is assumed for the stock-recruitment relationship:

$$R(B^{sp}) = \frac{\alpha B^{sp}}{\beta + B^{sp}} \tag{C10}$$

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 (C11)–(C15). 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.:

$$hR_0 = R(0.2B_0^{sp}) \tag{C11}$$

from which it can be shown that:

$$h = \frac{0.2(\beta + B_0^{sp})}{\beta + 0.2B_0^{sp}} \tag{C12}$$

Rearranging gives:

$$\beta = \frac{0.2 B_0^{sp}(1-h)}{h-0.2} \tag{C13}$$

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:

$$\gamma\, B_0^{sp} = R_0 = \frac{\alpha B_0^{sp}}{\beta + B_0^{sp}} \tag{C14}$$

where:

$$\gamma = \left\{ e^{-Ma_m} \left(\sum_{a=a_m}^{m-1} w_a e^{-M(a-a_m)} + \frac{w_m e^{-M(m-a_m)}}{1-e^{-M}} \right) \right\}^{-1} \tag{C15}$$

Projections

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

$$B_0^{rec} = R_0 e^{-Ma_r} \left(\sum_{a=a_r}^{m-1} w_a e^{-M(a-a_r)} + \frac{w_m e^{-M(m-a_r)}}{1-e^{-M}} \right) \tag{C16}$$

which can be solved for R_0. In this manner, B_0^{sp} can be obtained from (C14) and (C15). The initial numbers at each age a are therefore given by:

$$N_{0,a} = \begin{cases} R_0 e^{-Ma} & 0 \le a \le m-1 \\ \dfrac{R_0 e^{-Ma}}{1-e^{-M}} & a = m \end{cases} \tag{C17}$$

Numbers-at-age for future years are then computed by means of (C1)–(C4) and (C7)–(C10) under the series of annual catches given. In cases where (C8) 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 recorded will be less than the proposed catch.

Appendix D

Estimation procedure used

Reproduced with permission from the Appendix in Smith (1993).

Given Equations 8.1–8.3 in the main text, describing the operational model and the observational process (Section 8.2.2), the problem is how to estimate B_0 at any time $T \geq 3$, given the complete catch history $\{C_t\}$ $(t = 0,\ldots,T)$, and given a set of abundance indices $\{Y_i\}$ $(i = 1,\ldots j)$ where j is the number of observed indices $(j \leq T)$. From the dynamic model (Equations 8.1, 8.2) , we can derive the target biomass B_{target} (40% of B_0) as a function of true biomass (B_0), biomass survival (S) and the catch history $\{C_t\}$:

$$B_{\text{target}} = B_0 - \sum_{j=0}^{t-1} S^j C_{t-1-j} \qquad \text{(D1)}$$

and rewrite it as

$$B_{t_i} = B_0 - f_i \qquad \text{(D2)}$$

where

$$f_i = \sum_{j=0}^{t_i-1} S^j C_{t_i-1-j} \qquad \text{(D3)}$$

Since Y_i is distributed as a normal distribution with mean qB_{t_i} and variance σ_i^2, we can write the likelihood function for the $\{Y_i\}$ as

$$L = \prod_{i=1}^{j} \left\{ \frac{1}{\sigma_i \sqrt{2\pi}} \exp\left[-0.5 \frac{(Y_i - qB_{t_i})^2}{\sigma_i^2} \right] \right\} \qquad \text{(D4)}$$

and the log likelihood (ignoring terms which are independent of B_0 and q) is:

$$\lambda = -0.5 \sum_{i=1}^{j} \frac{(Y_i - qB_{t_i})^2}{\sigma_i^2} \qquad \text{(D5)}$$

Expanding (D5) and substituting for B_{t_i} from (D2) gives:

$$\lambda = -0.5\,[P_6 - 2qB_0P_4 + 2qP_5 + q^2B_0^2P_1 - 2q^2B_0P_2 + q^2P_3] \qquad \text{(D6)}$$

where:

$$P_1 = \sum\frac{1}{\sigma_i^2} \qquad P_2 = \sum\frac{f_i}{\sigma_i^2} \qquad P_3 = \sum\frac{f_i^2}{\sigma_i^2}$$

(D7–

D9)

$$P_4 = \sum\frac{Y_i}{\sigma_i^2} \qquad P_5 = \sum\frac{f_iY_i}{\sigma_i^2} \qquad P_6 = \sum\frac{Y_i^2}{\sigma_i^2}$$

(D10–

D12)

and all sums are over $i = 1,\ldots,j$.

Taking derivatives of λ with respect to B_0 and q

$$\frac{\partial\lambda}{\partial B_0} = qP_4 - q^2B_0P_1 + q^2P_2 \tag{D13}$$

$$\frac{\partial\lambda}{\partial q} = B_0P_4 - P_5 - qB_0^2P_1 + 2qB_0P_2 - qP_3 \tag{D14}$$

Equating (D13) and (D14) to zero and solving for B_0 and q gives

$$B_0 = \frac{(P_3P_4 - P_2P_5)}{(P_2P_4 - P_1P_5)} \tag{D15}$$

$$q = \frac{(P_2P_4 - P_1P_5)}{(P_1P_4 - P_2P_2)} \tag{D16}$$

which are the maximum likelihood estimates for B_0 and q.

To estimate the uncertainty in the maximum likelihood estimates, let A be a 2×2 matrix where

$$A = -E\begin{bmatrix} \dfrac{\partial^2\lambda}{\partial B_0^2} & \dfrac{\partial^2\lambda}{\partial B_0\partial q} \\ \dfrac{\partial^2\lambda}{\partial B_0\partial q} & \dfrac{\partial^2\lambda}{\partial q^2} \end{bmatrix} \tag{D17}$$

The equations for the individual elements are found by differentiating (D13) and (D14) with respect to B_0 and q, while the expectation is taken by calculating the elements of the matrix at the maximum likelihood estimates given in (D15) and (D16). Bard (1974) shows that the covariance matrix V of the vector of parameter estimates $[B_0, q]$ is approximated by

$$V = A^{-1} \tag{D18}$$

The first element of the matrix V is an estimate of the variance in the estimate of B_0, from which the CV in $\hat{B}_0$ is directly obtained.

Appendix E

Equations used for the different decision rules

Eight decision rules were tested. The first six (*Parabola*, *Jagged*, *Walters*, *Strict*, *Smooth* and *Modified Smith*) can be termed experimental decision rules, while the *Smith* and *Myopic* decision rules served as controls against which the performances of the experimental decision rules could be judged. All of the decision rules (except *Myopic*) set catches based on some curve relating the current biomass level (as a proportion of the estimated virgin biomass) to a suggested catch (also as a proportion of the estimated virgin biomass). The six experimental decision rules were subjected to additional meta-rules, described in Section 9.2.3. For standardisation under the baseline evaluation, the biomass at the end of the 14-year management period had to be 40% of the simulated true virgin biomass.

Constants used in fitting the catch curves

All values assigned to these constants are proportions of the estimated pristine biomass.

T = Target biomass—equal to 0.4 in the baseline evaluation.
M = Sustainable yield at the target biomass. According to the simplified model (Equations 8.1, 8.2 in Section 8.2.2), this is 0.0192 when $T = 0.4$. This is the reason that the curves (Figure 8.2) representing the decision rules all intersect at (0.4; 0.0192).
L = Maximum catch level.
I = Initial catch.
H = The form of the catch-biomass curve is changed at this biomass level.
Z = Below this biomass level, recommended catches are zero.

Variables used

C = Catch (proportion of estimated B_0).
B = Current biomass (proportion of estimated B_0).

Parabola

Two parabolas were fitted. For $B \geq H$, the first parabola is used; while for $B < H$, the second parabola is used. The two parabolas intersect at $B = H$. The first parabola passes through (1; I) and (T; M), and has a turning point at $C = L$. The equation may be written as:

$$C(B) = L - \frac{L-I}{(1-p)^2}(B-p)^2 \qquad \text{where} \quad p = \frac{\sqrt{\frac{L-M}{L-I}} + T}{\sqrt{\frac{L-M}{L-I}} + 1} \qquad \text{(E1)}$$

The second parabola passes through the (0; 0), (T; M), and (H; C_H). The value for C_H is obtained by substituting $B = H$ into (E1). Solving for these conditions gives:

$$C(B) = \frac{B\left(\left[TC_H - HM\right]B - H^2 M + T^2 C_H\right)}{HT(H-T)} \tag{E2}$$

The parameters *H* and *I* were chosen to be 0.6 and 0.05 respectively, with *L* tuned to 0.07 to achieve the standardisation criterion. Given these values, the second parabola is negative when $B < 0.28 \times B_0$ so that the catches are implicitly set to zero below this biomass level.

Jagged

This decision rule comprises three straight line segments. The first segment joins the origin and (*T*; *M*). The second segment joins (*T*; *M*) and $(\frac{T+1}{2}; L)$. The third segment joins $(\frac{T+1}{2}; L)$ and (1; *I*).

Solving for these conditions gives the following equations:

$$C(B) = \begin{cases} \dfrac{M}{T}B & B < T \\ 2\left[\dfrac{(L-M)(B-T)}{1-T}\right] + M & T \le B < \dfrac{T+1}{2} \\ 2\left[\dfrac{(L-I)(1-B)}{1-T}\right] + I & \dfrac{T+1}{2} \le B \le 1 \end{cases} \tag{E3}$$

Parameter *I* was fixed at 0.06, and *L* tuned to 0.075 for standardisation.

Walters

This decision rule was inspired by curve C on page 260 of Walters *et al.* (1993). It consists of four parts. When the biomass is below *Z*, the catches are set to zero. If the biomass is between *Z* and $T - 0.05$, a straight line connects (*Z*; 0) and ($T - 0.05$; *M*). When the biomass is between $T - 0.05$ and $T + 0.05$, the catches are set to *M*. Finally, for a biomass greater than $T + 0.05$, a parabola is drawn, with a turning point at (1; I), which passes through ($T + 0.05$; M). Solving for these conditions gives:

$$C(B) = \begin{cases} 0 & B < Z \\ \dfrac{M}{0.1}(B + 0.15 - T) & Z \le B < T - 0.05 \\ M & T - 0.05 \le B < T + 0.05 \\ I - \dfrac{I - M}{(0.95 - T)^2}(1 - B)^2 & T + 0.05 \le B \le 1 \end{cases} \tag{E4}$$

For standardisation, *Z* was set to 0.25, and *I* tuned to 0.095.

Strict

Recommended catches are zero when the biomass falls below *Z*. When the biomass is between *Z* and *T*, the rule is characterised by straight line connecting (*Z*; 0) and (*T*; *M*). When the biomass is above *T*, the decision rule becomes a parabola rising up from (*T*;

M) to (1; I). In addition, the gradient of the catch-biomass curve is required to be continuous at $B = T$. Solving gives:

$$C(B) = \begin{cases} \dfrac{M(B-Z)}{T-Z} & B < T \\ \dfrac{M(B-Z)}{T-Z} + \dfrac{I(T-Z) - M(1-Z)}{(T-Z)(1-T)^2}(B-T)^2 & B \geq T \end{cases} \tag{E5}$$

For standardisation, Z was fixed at 0.2 and I tuned to 0.19.

Smooth

This decision rule comprises a parabola from the origin to (T; M), together with another parabola from (T; M) which passes through (1; I), and has a turning point at $C = L$. The gradient at $B = T$ is required to be continuous. Solving for these conditions gives:

$$C(B) = \begin{cases} \dfrac{M}{T^2}B^2 & B < T \\ L - \dfrac{\left[M(B-T) - 2T^2(L-M)\right]^2}{4T^4(L-M)} & B \geq T \end{cases} \tag{E6}$$

where L can be expressed in terms of I since at $C = I$, $B = 1$:

$$L = M - \frac{M^2(1-T)^2}{4T^2\left(IT^2 - M + MT - MT^2\right)} \tag{E7}$$

The single parameter I was tuned to 0.17 for standardisation.

Modified Smith

This decision rule is based on a slightly different rationale: catches are set to a constant proportion of B_0 until the target biomass is reached. If the target biomass is reached at some point in the catch history ($B_{lowest} \leq T$), then the catches are set on a straight line passing through (T; M). The equation for this straight line is chosen so that the biomass in the following year is equal to the target biomass. When catches predicted by this line are negative, the recommended catches are set to zero. This decision rule is the same as *Smith* (outlined in Smith 1993), except that the meta-rules are applied to its recommended catches. The original formulation in Smith (1993) can be written as:

$$C(B) = \begin{cases} I & B_{lowest} > T \\ SB - T + (1-S) & B_{lowest} \leq T \end{cases} \tag{E8}$$

where S is survival.

In turn, S can be written in terms of M and T by substituting the point (T; M) into (E8):

$$S = 1 - \frac{M}{1-T} \tag{E9}$$

Substituting for S and simplifying gives:

$$C(B)=\begin{cases} I & B_{lowest}>T \\ \dfrac{M(1-B)}{1-T}-(T-B) & B_{lowest}\leq T \end{cases} \qquad \text{(E10)}$$

Standardisation was obtained by tuning I to 0.055.

Smith

This is the method used in Smith (1993) to set catches in his adaptive model. The meta-rules that apply to the first six decision rules do not apply here, so that this rule provides a useful benchmark to analyse the influence of the meta-rules. The formula used is the same as described in the *Modified Smith* decision rule:

$$C(B)=\begin{cases} I & B_{lowest}>T \\ \dfrac{M(1-B)}{1-T}-(T-B) & B_{lowest}\leq T \end{cases} \qquad \text{(E11)}$$

Instead of limiting changes in catches from one year to the next to a maximum of 20% (required by one of the meta-rules used here), *Smith* allows a catch of up to 1.5 times greater than the previous maximum catch, and down to 0.5 times the previous minimum catch. This restriction is lifted altogether if the CV on the estimate of B_0 is less than 0.1. If the decision rule generates a recommended catch below zero, the catch is set to zero. Finally, if the estimation process fails (in the case of an increasing series of biomass indices), the catch is set to the same level as that in the previous year. Standardising gave $I = 0.058$.

Myopic

This is the catch rule used thus far to provide management advice for the Namibian orange roughy fishery. It ignores all future survey results, setting a constant catch for seven years, followed by a linear decrease in catches over a further seven years to the presumed MSY. Because it does not take future learning into account, it is a "myopic Bayes" strategy (sensu Ludwig & Walters 1982). The *Myopic* decision rule is a control, against which the performance of the adaptive strategies can be evaluated.

$$C(t)=\begin{cases} I & t<\dfrac{t_{\max}}{2} \\ I-2\left(t-\dfrac{t_{\max}}{2}+1\right)\left(\dfrac{I-M}{t_{\max}}\right) & t\geq\dfrac{t_{\max}}{2} \end{cases} \qquad \text{(E12)}$$

Where t is the year and $t_{max} = 14$ is the number of years in the fishing-down period. To fulfil the standardisation criterion, $I = 0.072$, corresponding to a catch of 21 000 t. Note that this is greater than the recommended TAC of 15 000 t in January 1997 because the target biomass there was higher than $0.4\times B_0$.