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THE DEVELOPMENT AND IMPLEMENTATION OF A JOINT MANAGEMENT PROCEDURE FOR THE SOUTH AFRICAN PILCHARD AND ANCHOVY RESOURCES

by

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To my wife Vetta and son Jonathan

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ABSTRACT

Pilchard and anchovy are the main targets of the pelagic fishery, South Africa's second most valuable fishery in monetary terms, but producing the highest annual yield in terms of landed mass. It is the most dynamic of South Africa's major commercial fisheries, because the species it targets are relatively short-lived, often occur in mixed shoals and experience large fluctuations in abundance. Mixed shoaling causes operational problems for the pelagic fishery because of the inevitability of juvenile pilchard bycatch (more valued as adults for canning) in the anchovy directed fishery. The operational interactions imply a trade-off between these species, and necessitate that they are managed together. The thesis describes the development of a joint management procedure, which provides a framework for quantifying this trade-off such that acceptable levels of *risk* of resource "collapse" are not exceeded for either resource.

A management procedure in this context is essentially a computer-simulation tested set of formulae used to recommend catch levels based upon the results of two research surveys of resource abundance, one based on adult fish, and the other on recruitment (juveniles). Parameter estimates for the underlying models used in these simulation tests are derived from assessments of each resource, which fit models to the observations from research surveys and commercial catches using maximum likelihood estimation. Assessment results indicate adult and juvenile natural mortality values of 0.4 and 1.0.year^{-1} for pilchard, and 0.9.year^{-1} each for anchovy. They also suggest that recruitment surveys for pilchard are much less precise than sampling CVs alone indicate, but this may be an artefact of problems in the age data, which require further investigation. A range of alternative assessments for pilchard and anchovy is selected for the purpose of performing management procedure robustness trials as part of the simulation tests.

The thesis presents two methods for incorporating a trade-off decision between pilchard and anchovy into management procedures. The first develops the trade-off decision as "external" (the external trade-off decision, or ETD method), where the responsible Minister makes a trade-off decision for the industry as a whole. This method is problematic because it requires a compromise between those rights holders that prefer pilchard (for canning), and those that prefer anchovy (for reduction). The trade-off decision is then developed as "internal" (the internal trade-off decision or ITD method), where rights holders make their own trade-off decision based on their particular preferences. The ETD method specifies a pilchard-anchovy ratio for the whole industry, calculates TACs (total allowable catches) on the basis of this selection, and then allocates quotas to each rights holder on the basis of a percentage right for each fishery (pilchard and anchovy). In contrast, the ITD method collapses separate rights for pilchard and anchovy into a single right for the pelagic fishery, and allocates quotas on the basis of trade-off decisions made by individual rights holders, thus avoiding an overall compromise choice. The introduction of non-linear adjustment factors ensures that (over time) allocations to individual rights holders would be near-identical, whichever of the two methods is used. The ITD method is currently (2002) being used by Marine and Coastal Management as the basis to set pilchard and anchovy TACs and to allocate individual quotas.

The thesis analyses two further aspects of management procedures. The first looks at whether the performance of management procedures can be improved if they incorporate information about regime shifts, modified as sinusoidal cycles. Results indicate that improvement is possible, but that, surprisingly, one would do better using a running mean of research survey estimates of abundance to track a regime cycle, than direct measurements of the actual position in the cycle. The second investigates the benefits of using environmental indices in management procedures, where these indices are used as short-term predictors of recruitment and replace the assumption (made because of lack of information) that forthcoming recruitment will be average. Results indicate that, given the uncertainties related to using such indices, they would need to explain at least 50% of the variation in recruitment before management procedures start showing appreciably improved performance.

Priorities for future work include: investigating the implications of a possible changed perception of the bias associated with pilchard adult surveys than that adopted to test the present management procedure; developing the daily egg production method to provide unbiased estimates of pilchard abundance; and performing a thorough investigation of pilchard age data to isolate any problems.

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PREFACE

The management procedures presented in the thesis were developed in close consultation with the Pelagic Working Group of Marine and Coastal Management, for which I was convenor over the period 1996-2000. The Working Group met on a regular basis to advise on pelagic total allowable catches (TACs), oversee the development of management procedures to set these TACs, and review pelagic research. The Working Group also provided a forum to interact with the pelagic industry, and thus provide industry input into key features of the management procedures.

The summaries to Chapters 2, 3 and 5 were drawn from the Report of the BENEFIT Stock Assessment Workshop (Anon. 2001b), in which they were included (drafted by myself) to summarise the papers I had contributed to that meeting. Similarly, sections of Chapter 4 related to the description of management procedures were drawn from De Oliveira *et al.* (1998a), which I drafted as first author. My supervisor, Professor Butterworth, drafted the text for Appendix 5.4 for a presentation to the industry, but all computations and plots were provided by myself. The Fishery Resources Division, FAO, provided financial support for the work presented in Chapter 7. Participation in the SPACC/IOC Study Group on the "Use of Environmental Indices in the Management of Pelagic Fish Populations" provided a forum for presentation and discussion of the results of Chapter 8. Some of the recommendations for future work in Chapter 9 were developed in discussions with Professor Butterworth. Most computations were carried out using Fortran PowerStation 4.0 in Microsoft Developer Studio (Copyright © 1994-95 Microsoft Corporation), with some of the numerical routines taken from Press *et al.* (1989). Microsoft Excel® and Access® were used for some data analyses, Excel® and PowerPoint® to construct most Figures, and Word® to type the thesis.

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CHAPTER 1

Background

Pilchard and anchovy are the most important components of the South African pelagic fishery, and are sustained by the highly productive waters of the Benguela current system. The pelagic fishery is South Africa's second most valuable fishery in monetary terms, but provides the highest yields in terms of landed mass. It is also the most dynamic fishery, because the species it targets are relatively short-lived, often occur in mixed shoals and experience large fluctuations in abundance. A detailed account is provided of the historical development of the fishery and associated management and biological research, from its beginnings in the 1940s, through its rapid expansion in the 1950s, the shift from pilchard to anchovy following the collapse of pilchard in the 1960s, the introduction of a global TAC and company-specific quota allocations in the 1970s, the introduction of acoustic surveys and species-specific TACs in the 1980s, and finally the transformation of the fishery (from the point of view of previously disadvantaged groups) in the 1990s. Particularly important was the introduction of acoustic surveys, which provided fishery-independent estimates of abundance with associated estimates of precision. This allowed the dynamics of the pilchard and anchovy to be modelled with far greater reliability than previously possible, and formed the basis of the assessments presented in later Chapters. A description is provided of the pelagic fishery entering the 21st century.

1.1 Introduction

More clupeoid fishes are exploited than any other single systematic group of fish (Whitehead 1985). This is borne out in FAO fisheries statistics[1], which indicate that over the period 1970-2000, clupeoids (categorised by FAO as "herrings, sardines[2] and anchovies") accounted for between 18 and 41% (31% on average) of the total world catch of fish, crustaceans, molluscs, etc[3]. The only exception during this period was in 1973, when catches of "cods, hakes and haddocks" exceeded those of clupeoids in terms of tonnage landed.

There are more than 300 species of clupeoids categorised into four families and 80 genera (Whitehead 1985, Whitehead *et al.* 1988). Over the period 1950-2000, five species, namely *Engraulis ringens*, *Engraulis japonicus*, *Sardinops sagax*, *Sardina pilchardus* and *Clupea harengus* constituted, on average, 70% of the total annual landings of clupeoids (Figure 1.1a). The genus *Engraulis* makes the largest contribution to the annual clupeoid catch (33% on average – Figure 1.1b) and, excepting in the western Atlantic, occurs with species of *Sardinops* or *Sardina*. The genera *Sardinops* and *Sardina* together constitute 24% of the annual clupeoid catch on average.

[1] Software developed through FAO, namely FISHSTAT Plus, version 2.3 © 1997-2000, was used to analyse the database "Capture Production 1970-2000" obtained from the FAO website www.fao.org/fi (Anon. 2000).

[2] With reference to the South African sardine resource, it is more popularly known as pilchard locally, and this is the name used for the resource throughout.

[3] This excludes marine mammals, corals, sponges and aquatic plants, as well as the harvest from mariculture, aquaculture and other kinds of fish farming.

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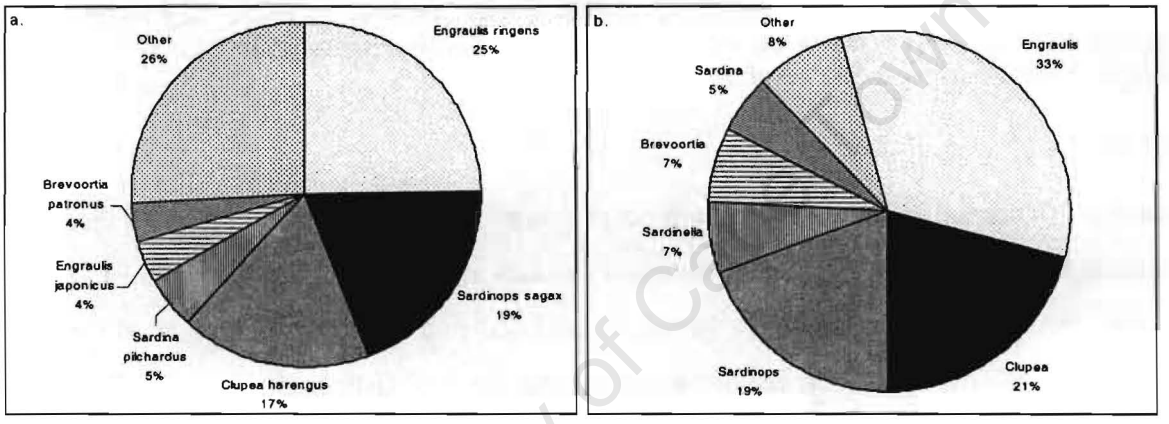
Although Whitehead (1985) recognises five species of *Sardinops*, Parrish *et al.* (1989) argue that this division into different species is based purely on geographical separation, and that there are no appreciable differences at anatomical, morphometric, meristic or biochemical levels. They have therefore classed *Sardinops* as a monotypic genus (likewise *Sardina*), with the five "species" of *Sardinops* (*S. sagax*, *S. melanostictus*, *S. ocellatus*, *S. caeruleus*, *S. neopilchardus*) comprising a single species, *Sardinops sagax*. Whitehead *et al.* (1988) also indicated that a similar regrouping of certain of the eight *Engraulis* species is likely to occur in future, based on further taxonomical work.

Figure 1.1: Average composition (expressed as a percentage) of the total world catch of clupeoids according to a) species and b) genus for the period 1950-2000[4].



Whitehead (1985) argues that there are two reasons why some of the largest fisheries in the world are based on clupeoids. The first is that the majority of clupeoids feed close to the base of the food chain, thus benefiting more directly from nutrient-rich areas that experience seasonal or continuous blooms of plankton. The second is that clupeoids are generally schooling fish, and are therefore extremely vulnerable to nets, particularly purse-seine nets, which are able to capture a large mass of fish within a short space of time. Areas richest in plankton and nutrient levels are found in the cooler high latitude seas where coastal upwelling is prominent, and it is in these highly productive areas where the major clupeoid fisheries exist (Whitehead 1985, Crawford *et al.* 1987, Lluch-Belda *et al.* 1989).

The Benguela system in the southeast Atlantic Ocean, one of four major eastern boundary current systems, is one such highly productive area, and has supported large fisheries for

[4] As before, FISHSTAT Plus was used, but this time to analyse the FAO database "Total Production 1950-2000" (Anon. 2000). Although this database includes the harvest from the different kinds of fish farming, this does not affect catch figures for clupeoids.

pilchard (*Sardinops sagax*) and anchovy (*Engraulis capensis*) over the last century off the South African and Namibian coasts (Crawford *et al.* 1987). The other eastern boundary current systems also support large fisheries for pilchard and anchovy: the Humboldt system in the southeast Pacific (*S. sagax*, *E. ringens*), the California Current in the northeast Pacific (*S. sagax*, *E. mordax*) and the Canary Current in the northeast Atlantic (*Sardina pilchardus*, *E. encrasicolus*; Figure 1.2; Lluch-Belda *et al.* 1989, Jacobson *et al.* 2001). Although not an eastern boundary system, the Japanese system is also highly productive and supports large fisheries for pilchard and anchovy (*Sardinops sagax*, *E. japonica*; Lluch-Belda *et al.* 1989, Jacobson *et al.* 2001). Furthermore, pilchard and anchovy co-occur off Australia (*S. sagax*, *E. australis*), but the fishery for pilchard is small relative to the other regions, and there is no consistent fishery for anchovy (Table 1, Schwartzlose *et al.* 1999).

Figure 1.2: Regions where pilchard (*Sardinops/Sardina*) and anchovy (*Engraulis*) species co-occur.

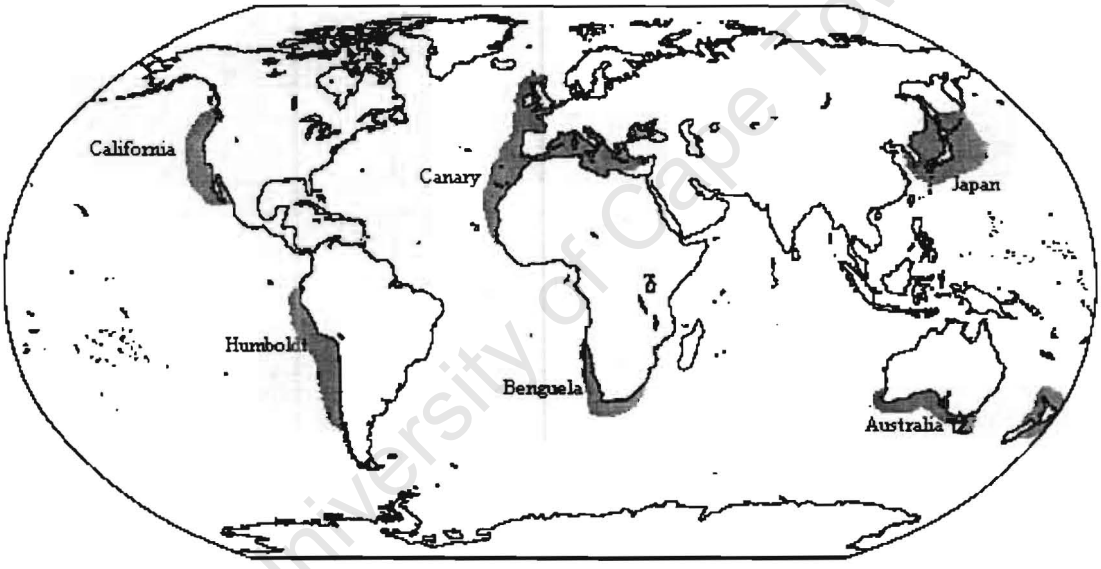


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Table 1 compares peak catches and periods of sustained high catches for the different regions where pilchard and anchovy co-occur. The Humboldt and Japanese systems are by far the most productive in terms of both pilchard and anchovy, followed by the Benguela, Canary and California systems. In each of the different regions, several stocks of each species can be found (Schwartzlose *et al.* 1999), with the Benguela system supporting stocks of pilchard and anchovy both north and south of an area of intense perennial upwelling near Lüderitz (just north of the Orange river) off the Namibian coast (see insert, Figure 1.4). This is the principal upwelling centre of the Benguela system, where the cool, highly turbulent and weakly stratified water is believed to form an environmental barrier that effectively divides the system (Shannon 1985, Crawford *et al.* 1987). Stocks of pilchard and anchovy to the north and south of this upwelling

cell are therefore believed to be relatively discreet. This is supported by tagging studies over a period of nine years (1957-1965) on the northern and southern stocks of pilchard that indicated little north-to-south movement and no movement in the opposite direction (Newman 1970, Crawford *et al.* 1987). Therefore, even though Grant (1985a, 1985b), using biochemical genetic markers, found no genetic differences between South African and Namibian stocks of pilchard or anchovy, the South African stocks are managed independently of their Namibian counterparts.

Table 1.1: Comparison of peak catches and periods of sustained high catches for the different systems where pilchard (*Sardinops/Sardina*) and anchovy (*Engraulis*) species co-occur. Data up to 1949 are from Schwartzlose *et al.* (1999) for the Humboldt, Japanese and California systems, and from ICES (2001) and Kifani (1998) for the Canary system[5]. Data for the period 1950-2000 are from FAO[6] for all systems except Australia, where FAO catch data were well below those reported in Schwartzlose *et al.* (1999), and therefore discarded in favour of the latter.

	Period considered	Number of years	Peak catch ('000t)	Year of peak catch	Number of years catch ≥ ½×peak	Sustained periods* of high catch
Pilchard						
Humboldt	1961-2000	40	6509	1985	11	1
Japan	1894-2000	107	5429	1988	13	2
Benguela	1950-2000	51	1516	1968	9	1
Canary	1940-2000	61	1539	1989	28	1
California	1916-2000	85	718	1936	25	3
Australia	1975-1996	22	16	1996	9	1
Anchovy						
Humboldt	1950-2000	51	13060	1970	17	2
Japan	1905-2000	96	2094	1998	5	1
Benguela	1963-2000	38	969	1987	8	3
Canary	1950-2000	51	859	1988	24	2
California	1916-2000	85	424	1981	5	1

* periods of two or more consecutive years where catch ≥ ½×peak, that are not interrupted by more than 1 year where catch < ½×peak

Apart from pilchard and anchovy, there are four other small pelagic species that occur in purse-seine catches in South African waters, namely round herring[7] (*Etrumeus whiteheadi*), horse mackerel[8] (*Trachurus trachurus capensis*), chub mackerel (*Scomber japonicus*) and lanternfish (*Lampanyctodes hectoris*). Table 1.2 provides a time-series of catches of small pelagic fish off South African waters for the period 1950-2000.

[5] Schwartzlose *et al.* (1999) did not include the Canary system in their paper, and therefore alternative sources were sought.

[6] As before FISHSTAT Plus is used to analyse the database "Total Production 1950-2000" (Anon. 2000).

[7] Also called redeye locally.

[8] Also called maasbanker locally.

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Table 1.2: Annual landings (thousand tons[9]) in the South African pelagic fishery for the period 1950-2000.

Year	Pilchard	Anchovy	Horse mackerel	Chub mackerel	Round herring	Lantern fish	Other	TOTAL
1950	85.3	0.0	49.9	0.0	0.0	0.0	0.0	135.2
1951	101.9	0.0	98.9	0.0	0.0	0.0	0.0	200.4
1952	170.0	0.0	102.6	0.0	0.0	0.0	0.0	272.6
1953	132.5	0.0	85.2	0.0	0.0	0.0	0.0	217.7
1954	88.3	0.0	118.1	4.0	0.0	0.0	0.0	210.5
1955	121.9	0.0	78.8	20.2	0.0	0.0	0.0	221.0
1956	76.6	0.0	45.8	32.6	0.0	0.0	0.0	154.9
1957	109.5	0.0	84.6	7.4	0.0	0.0	0.0	201.5
1958	194.4	0.2	56.4	21.6	0.8	0.0	0.0	273.4
1959	260.2	1.4	17.7	33.1	2.6	0.0	0.0	314.9
1960	318.0	0.0	62.9	31.0	0.1	0.0	0.0	412.0
1961	402.2	0.0	38.9	49.7	0.1	0.0	0.0	490.0
1962	410.2	0.0	66.7	20.4	0.1	0.0	0.0	497.3
1963	390.1	0.3	23.3	13.2	0.2	0.0	0.0	427.0
1964	256.1	92.4	24.4	50.0	2.7	0.0	0.0	425.6
1965	204.5	171.0	55.0	41.4	8.2	0.0	0.0	480.1
1966	118.0	143.9	26.3	53.4	15.4	0.0	0.0	357.1
1967	69.7	270.6	8.8	128.2	32.0	0.0	0.0	509.3
1968	107.8	138.1	1.4	91.0	30.3	0.1	0.0	368.6
1969	56.1	149.2	26.8	91.7	23.3	4.9	0.0	352.0
1970	61.8	169.3	7.9	77.9	23.7	18.2	0.0	358.0
1971	87.6	157.3	2.2	54.2	21.6	2.0	0.0	324.9
1972	104.2	235.6	1.3	56.7	20.6	15.2	0.0	433.6
1973	69.0	250.9	1.6	58.8	28.7	42.4	0.0	451.4
1974	16.0	349.8	2.5	30.7	1.3	0.3	0.0	400.5
1975	89.2	223.6	1.6	69.3	23.6	0.1	0.0	407.4
1976	176.4	218.3	0.4	0.5	11.7	0.1	0.0	407.5
1977	57.8	235.5	1.9	21.3	35.0	5.6	0.0	357.2
1978	97.0	209.5	3.6	2.4	67.0	1.0	0.0	380.4
1979	52.9	291.4	4.3	2.7	21.0	8.7	0.0	380.9
1980	50.4	315.5	0.4	0.2	14.1	0.1	0.0	380.5
1981	46.2	292.0	6.1	0.3	24.3	10.3	0.0	379.2
1982	35.2	306.1	1.1	2.7	31.2	0.7	0.0	377.0
1983	65.4	235.0	2.1	4.2	68.5	1.4	1.0	377.6
1984	29.5	268.9	2.8	1.2	27.0	18.1	1.2	348.7
1985	29.6	277.0	0.7	0.1	37.7	32.2	4.9	382.2
1986	35.4	303.8	0.5	0.1	52.3	0.6	0.5	393.2
1987	34.3	595.9	2.8	0.8	33.3	0.0	1.9	671.9
1988	36.2	570.0	6.3	0.3	62.6	0.1	1.0	676.5
1989	34.7	294.0	25.5	0.3	44.6	4.7	2.3	406.1
1990	56.9	150.0	7.2	0.0	44.7	0.6	0.4	259.8
1991	51.4	150.7	0.5	9.8	33.4	0.6	2.0	248.3
1992	53.4	347.4	1.9	0.3	47.4	0.6	0.7	451.7
1993	50.6	235.8	11.6	0.4	56.3	1.2	1.0	357.0
1994	93.4	155.6	8.2	2.0	54.1	0.9	0.9	314.8
1995	115.1	170.3	2.0	2.7	76.7	0.9	0.4	368.0
1996	105.2	40.7	19.0	1.1	47.1	0.0	0.1	213.7
1997	117.0	60.1	12.7	3.7	92.2	0.2	0.4	286.3
1998	128.2	107.6	26.7	0.1	52.5	6.6	0.3	321.9
1999	132.3	180.5	2.1	0.4	58.9	0.2	1.1	375.4
2000	136.1	268.1	4.6	0.3	37.8	0.3	0.4	447.4

[9] All tonnages reported are in metric tons (rather than short tons).

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1.2 Background to the South African pelagic fishery

Although public attention was drawn to the presence of large shoals of pilchard and horse mackerel on the South African west coast in the early 1930s, and pilchard was canned as early as 1935, commercial fishing operations commenced only in 1943 in response to a demand for canned products during World War II (Du Plessis 1959, Crawford *et al.* 1987). Lees (1969), whose book provides a detailed account of the early history of the South African fishing industry, quotes Gilchrist as having commented on the relatively late development of the pelagic fishery as follows: "The initial outlay in testing the practicability of success, and the financial risk involved, prevent any serious enterprises by private firms". Other factors that initially impeded the development of the fishery included uncertainty about the occurrence of pilchard, which tended to keep well offshore except at certain times, and the lack of a ready market in South Africa for horse mackerel and chub mackerel (Lees 1969).

Until the end of 1949, there was no legal restriction on the expansion of the fishery, and as a result catches increased rapidly from 4 000 tons processed through two factories in 1943, to 68 000 tons processed through 13 factories in 1949 (Davies 1957a, Du Plessis 1959, Crawford 1981b)[10]. Because no official catch statistics were kept prior to 1950, these catch figures were estimated from the quantities of fishmeal and canned fish produced.

By 1950, the rapid growth of the pelagic fishery, which initially targeted pilchard and horse mackerel and was still largely confined to St Helena Bay and its immediate vicinity on the west coast (Figure 1.3), was starting to cause the management authority[11] some concern. A decision was therefore taken to start regulating the development of the fishery through a series of control measures in order to protect the resources and guard against an unstable economy within the fishery (Du Plessis 1959). These control measures were implemented from 1950 onwards, after consultation with processors and fishermen, and included the following (Du Plessis 1959, Crawford 1981a):

- *Minimum mesh size of net* – Although the restriction was 38mm, cotton nets rapidly shrank to 32mm after successive preservative treatments, so that when synthetic nets were introduced, the restriction was modified to 32mm because these synthetic nets did not shrink.

[10] Each factory consisted of a processing plant for fishmeal and oil, and a cannery (Davies 1957a).

[11] The Division of Fisheries, Department of Commerce and Industries, was the state organ responsible for the control of fisheries at the time.

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- *Closed fishing season* – This measure (applied within the period August-December) was initially used for pilchard from 1951, but included horse mackerel from 1952 (these two species were managed as a unit to give the fishery the flexibility it needed to counteract the economic effects of year-to-year fluctuations in the two species). The main reason for this restriction was that research had indicated that pilchard were spawning and in poor condition for industrial processing during spring. However, the closed season was abandoned from 1955 to 1957, but then re-introduced and extended to other species from 1958.
- *Limitation on the number and capacity of processing plants* – Initially this restriction applied only to reduction plants, which processed fishmeal, oil and fertiliser, but was later extended to pilchard canneries.
- *Limitation on the number of vessels and total hold capacity* – This limitation applied only to vessels targeting pilchard.
- *Maximum annual catch restriction* – This restriction (termed Total Allowable Catch, or TAC) (226 900 tons) was applied to both pilchard and horse mackerel catches from 1953, but was abandoned from 1961 when it became clear that it was unenforceable.

In the context of their ability to limit exploitation in the early years, these control measures were not effective. For example, the maximum annual catch restriction was not applied rigorously, because vessels were allowed to continue fishing if the TAC was reached before the end of the season. Furthermore, the closed season was implemented over a period (August-December) when catches were usually low relative to the rest of the year, and occasions on which factories received raw material in excess of what they could handle were rare (Stander and Roux 1968).

At the time (1950s and 1960s), limiting the total hold capacity of the pelagic fleet was regarded as the most important measure of all those mentioned above, in the context of controlling fishing effort (Stander and Roux 1968). Table 1.3 provides a time-series of total fleet hold capacity and number of vessels in the pelagic fishing fleet, together with the average hold capacity. On the face of it, the limitations on fleet hold capacity and number of vessels appeared to have had some success when they were first implemented (Tables 1.2 and 1.3). Whereas before, the fleet hold capacity, number of vessels and catches increased rapidly (1950-1952), this was followed by a period of relative stability (1953-1957) after the limitations came into effect in 1953. Even though this "stability" did not last, there was the belief that the limitation on fleet hold capacity helped to prevent gross over-investment, and enabled the fishery to cope financially with both

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fluctuating fishmeal prices and the wide fluctuations in resource abundance and availability typical of pelagic stocks (Gertenbach 1973, Newman *et al.* 1979).

Table 1.3: Changes in characteristics of the pelagic fishing fleet, 1950-1976 (data are from Crawford 1981a).

	Total fleet hold capacity (tons)	Number of vessels	Average hold capacity (tons per vessel)	Percentage of vessels equipped with:			
				echo sounder	power block	sonar	fish pump
1950	4399	150	29.32	0	0	0	0
1951	5806	183	31.73	0	0	0	0
1952	6586	197	33.43	0	0	0	0
1953	7547	229	32.96	0	0	0	0
1954	7683	225	34.15	0	0	0	0
1955	7529	228	33.02	0-100	0	0	0
1956	7448	222	33.55	0-100	0	0	0
1957	7448	210	33.47	0-100	0	0	0
1958	7693	210	36.63	0-100	0	0	0
1959	7856	165	47.61	0-100	0	0	0
1960	7538	143	52.71	100	0	0	0
1961	8445	131	64.47	100	0	0	0
1962	8926	122	73.16	100	0	0	0
1963	9906	127	78.00	100	39	0	0
1964	10296	126	81.71	100	77	0	0
1965	10641	125	85.13	100	100	6	0
1966	10656	125	85.25	100	100	6	50
1967	11665	135	86.41	100	100	6	75
1968	12783	130	98.33	100	100	25	100
1969	12609	127	99.28	100	100	33	100
1970	12157	118	103.03	100	100	33	100
1971	12983	121	107.30	100	100	45	100
1972	12250	120	102.08	100	100	48	100
1973	13176	119	110.72	100	100	73	100
1974	13058	117	111.61	100	100	81	100
1975	12271	109	112.58	100	100	83	100
1976	11055	99	111.67	100	100	86	100

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There were, however, some fundamental characteristics of the fishing fleet and the way it operated that were changing over time, and hence tended to further undermine the efficacy of any measure aimed at limiting exploitation. The fishery started with vessels as small as 10-11m long, but towards the end of the 1950s most of these were replaced with vessels 15-18 metres long (Davies 1957a). However, the restriction on total hold capacity meant that, initially at least, two small vessels were replaced by a single large vessel with a hold capacity equivalent to that of the two smaller ones. This process of moving from smaller to larger vessels continued well into the 1960s and beyond, as indicated by the increase in average hold capacity in Table 1.3.

The switch from cotton to synthetic fibres, making nets lighter and giving them better handling qualities, coupled with the conversion to larger vessels, eventually led to the use of longer and deeper nets, thus increasing the overall efficiency of the gear (Stander and Roux 1968). Vessels were also gradually equipped with fishing aids such as more efficient winching systems, echo-

sounders, power blocks, sonar and fish pumps. From the late 1960s, aircraft were used to guide vessels to areas where fish were most abundant (Newman *et al.* 1979). Table 1.3 lists the percentage of vessels equipped with various fishing aids over time. In addition to the technological improvement of vessels, processing plants underwent continual modernisation to cope with those occasions when catches were at a peak and demanded increased processing rates (Du Plessis 1959).

The effect of these technological improvements was to cause the fishing effort exerted in the pelagic fishery to increase much faster than any increase in the fleet hold capacity alone. For example, Newman *et al.* (1979) and Crawford (1981a) analysed the effect of changes in vessel characteristics and acquisition of fishing aids on fishing power, using different measures of fishing effort. Over the period 1964-1972, although fleet hold capacity increased by only 20%, the increase in fishing effort was 145-150%. Furthermore, Newman *et al.* (1979) noted that this increase in effort excluded the effect of aerial spotting of fish shoals, and the skill of a vessel's skipper. These analyses highlighted the inadequacy of fleet hold limitations to curb fishing pressure on pelagic resources in the face of improvements in fishing efficiency.

Another factor, first noted by Stander and Roux (1968), that contributed towards the difficulty of limiting exploitation, was the gradual expansion of the fishing area once the St Helena Bay region experienced a series of poor fishing seasons in the mid- to late-1950s. This expansion was made possible by the phasing into the fishery of larger vessels that were generally more powerful and able to venture farther afield. These vessels moved farther south, which eventually led to the erection of fish reduction plants close to the new fishing grounds, making it possible for the fishery to exploit the southern areas more efficiently. The move south also made available to the fleet age groups of fish that had previously not been fished to any great extent, so contributing towards a more extensive exploitation of the fish stocks (Crawford *et al.* 1980, Crawford 1981a). Figure 1.3 depicts the growth of the fishing area at various stages of the development of the pelagic fishery.

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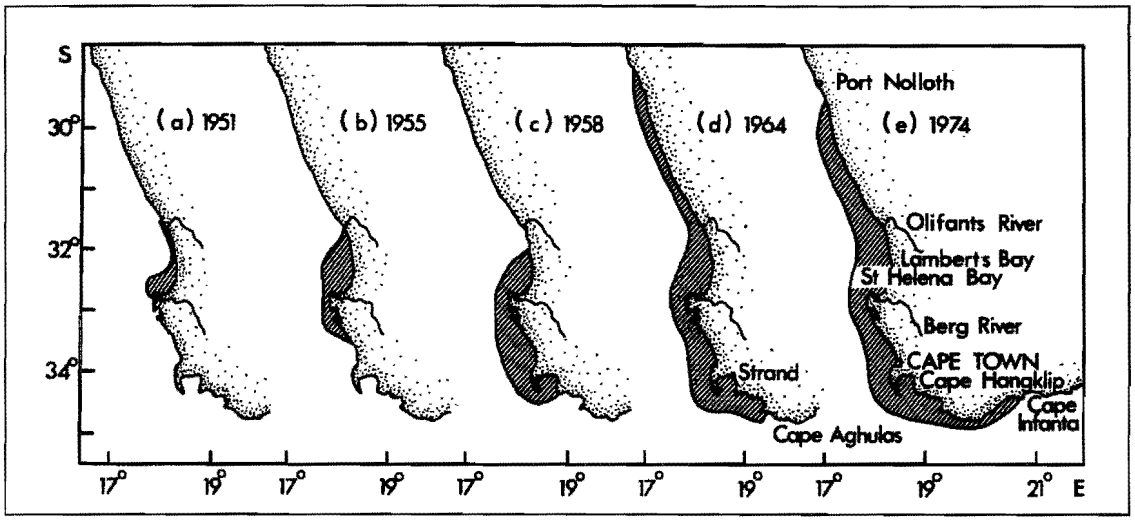
Figure 1.3: Areas of purse-seine fishing off South Africa's Western Cape at various stages in the development of the fishery (taken from Crawford *et al.* 1987).



Despite restrictions aimed at limiting exploitation, and fuelled by technological improvements, catches of pilchard rose dramatically during the late 1950s and early 1960s, peaking at 410 000 tons in 1962 (Table 1.2). Thereafter, a steady decline set in, followed by catches an order of magnitude lower that would persist for the next 25 years. In order to counter this decline in pilchard catches, fishing was extended to anchovy and other resources through the introduction of nets of smaller mesh size (12.7mm as opposed to 32mm) between 1963 and 1965 (Crawford *et al.* 1980). Although these nets were initially restricted to anchovy only, they were later allowed for targeting all pelagic species because anchovy were often encountered in mixed shoals with other species, making it impractical to enforce the use of nets of different mesh size for different species (Crawford 1981b). The introduction of the smaller mesh size led to profound changes in the pelagic fishery.

- It increased the size and species range available to the fishing fleet, so further increasing the harvesting efficiency of the fleet (Newman and Crawford 1980)
- It brought about a pronounced change in the age composition of the pilchard catch:
  - the incidence of 0-year-old fish increased from <1% to average some 60% of the annual total catch by number (catch-at-age Table in Shelton 1982, Armstrong *et al.* 1983);
  - the older pilchard age classes disappeared from catches taken in the northern areas, and as a result pilchard spawning in these areas virtually stopped (Crawford *et al.* 1980).
- It permitted intensive exploitation of pelagic fish prior to first maturity (Armstrong 1984).
- Anchovy catches dominated pelagic landings for the next 30 years (1966-1995, Table 1.2).

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- Because anchovy and pilchard shoal together during their first few months of life when they are of a similar size (Crawford *et al.* 1980, Crawford 1981b), directed fishing for anchovy was inevitably accompanied by a bycatch of juvenile pilchard. Newman and Crawford (1980) noted that, after 1964, 60% of the landed weight of juvenile anchovy occurred in mixed shoals with juvenile pilchard. This is probably the main reason for the increased incidence of 0-year-old pilchard in the catch, mentioned above, because pilchard are more valued as larger fish for canning, and juvenile pilchard were therefore not targeted.

After the abolition, from 1961, of the rather flexibly applied catch restriction on pilchard and horse mackerel, the catch was primarily controlled by restricting the duration of the fishing season (Crawford 1981a). However, effort continued to escalate, and it became necessary to revert to a TAC system in 1971. This time, a global TAC (all species combined) was introduced, based on the belief that a multi-species fishery would provide some insurance against adverse fluctuations in the stock of a particular species, rather than on any evidence of a combined species carrying capacity (Butterworth 1983). The global TAC management approach was therefore intuitive rather than scientific, and it was recognised that this approach was unable to take full advantage of good year classes, and equally unable to protect species experiencing poor recruitment (Newman and Crawford 1980, Butterworth 1983). Nevertheless, it remained the most effective and important means of limiting exploitation in the pelagic fishery (Crawford 1981a, Davies *et al.* 1981).

The global TAC management approach has undergone some fundamental changes since it was reintroduced in 1971. First, there was the decision to allocate a small proportion of the 1974 TAC (35 000 tons), and all subsequent TACs, to individual processors (Crawford 1981a). Whereas before, factories would compete for as large a share as possible of the global TAC, this decision encouraged processors, secure in the knowledge that their share of the TAC was safe, to schedule fishing activities and to wait for fish to become available locally. This in turn led to savings in fuel costs and better yields from equivalent amounts of raw material, and eventually allowed processors to rationalise their fleets, so optimising effort according to their own criteria (Newman *et al.* 1979, Crawford 1981a).

The second fundamental change came in 1983 with the decision to change from a global TAC (covering all species) to a TAC for pilchard and anchovy only. The other pelagic species were designated "non-quota" species and therefore avoided catch restrictions. This change was introduced because, even though the global TAC "curtailed gross abuse" of pelagic stocks, and

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appeared to have "stabilised" the total yield from the pelagic fishery, this "stability" masked a highly unstable species composition (Newman and Crawford 1980). Shelton (1982) noted that, following the peak pilchard catch of 1962, during which pilchard up to six years old were common, the pelagic fishery changed from one based on five or six age classes of pilchard to one based on only two age classes of anchovy. The fishery had thus followed the classic pattern of moving from more- to less-valuable species, and the multi-species "safety net" was no longer available (Butterworth 1983). The move to a combined pilchard-anchovy TAC was seen as a way to encourage diversification of the fishery, given its heavy reliance on these two species. This approach was taken a step further the following year (1984) when species-specific TACs were introduced for pilchard and anchovy, in order to assume more control over the depleted pilchard resource and to prevent over-exploitation of anchovy (Armstrong 1984).

The introduction of single-species TACs for pilchard and anchovy initiated a new phase in the development of management approaches for South African pelagic stocks. This would see the use of direct surveys for setting TACs for both pilchard and anchovy and the implementation of International Whaling Commission (IWC)-type management procedures (Kirkwood 1992) for the joint management of pilchard and anchovy. A fundamental feature of these joint management procedures (described in detail in later Chapters) is to incorporate the negative effect of catches of juvenile pilchard on future yields of adult pilchard. This negative effect was used by Newman and Crawford (1980) to discount the hypothesis that more intensive fishing of anchovy would alleviate pilchard-anchovy competition, and so promote the recovery of pilchard. Instead they suggested that, because of the mixed-shoal problems, more intense fishing on anchovy could have the opposite effect. Furthermore, Crawford *et al.* (1980) suggested that the good directed catch of pilchard in 1976 (more than twice the average pilchard catch for that decade, Table 1.2) was a result of the lack of fishing on juveniles two years earlier. Essentially, there was a large concentration of anchovy in the St Helena Bay and southern fishing grounds early in the 1974 season (Figure 1.3e), which resulted in the bulk of the TAC that year (400 000 tons) being filled by mid-April. Consequently, juvenile pilchard and anchovy, which only recruit to the fishery from March/April onwards, were lightly exploited in 1974, resulting in the large catch of adult pilchard two years later.

The problem of the bycatch of juvenile pilchard in the anchovy fishery was to remain a feature of the pelagic fishery, and was to intensify as the pilchard stock recovered towards the end of the 1990s.

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1.3 Biological background

Research on pelagic fish initially concentrated on pilchard with the launch of the "Pilchard Research Programme" in 1950, later extended to include horse mackerel. Topics covered by this programme included development, occurrence and distribution of eggs and larvae (Davies 1954), sexual maturity and reproduction (Davies 1956a), migration (Davies 1956b), size and age composition of commercial catches (Davies 1957a, Davies 1958), young fish surveys (Davies 1957b), feeding (Davies 1957c), trends in the fishery (Du Plessis 1959), and various other topics covering predators, and the food and physical environment. Generally, eggs and larvae were sampled by oblique and surface tow nets, and juvenile fish by using a blanket-net technique. The adult stock was studied by taking random samples from commercial fishing vessels (Stander and Roux 1968). These studies were later updated and are therefore not discussed further here.

A wealth of information was obtained on spawning behaviour and the distribution, availability and movements of pelagic fish (Crawford 1979, 1980, Crawford *et al.* 1980, Shelton 1986):

- by analysing information from surface plankton tows conducted on a regular basis during the 1950s and 1960s;
- from the Cape Egg and Larva Programme (CELP) in the late 1970s; and
- by examining spatially disaggregated catch-at-age data and the length mode progressions evident in these data for the period 1964-1976.

For the last of these analyses, the specified period was chosen because catch information was reasonably comprehensive in terms of species composition only from 1964 onwards (Crawford *et al.* 1978).

Analysis of data from surface plankton tows and commercial catches revealed close similarities between the spawning behaviour and movement of pilchard and anchovy, which Crawford *et al.* (1980) attributed to their response to the environment. For example, spawning by both pilchard and anchovy appears to be almost entirely confined to spring and summer (pilchard having a protracted spawning period peaking in September/October and February/March, and anchovy spawning between October and February – Shelton 1986, Hutchings *et al.* 1998). This is the main upwelling season, which would ensure an abundant supply of food for the developing larvae and juveniles when they reach the nursery areas on the west coast (Figure 1.4). Spawning by both species appears to be heaviest east off Cape Point on the western Agulhas Bank (Figure 1.4), where there appears to be greater thermal stability and a more consistent food environment than in surrounding areas, and where the Agulhas Current is responsible for the well-mixed and warm upper layers of the water column, (Crawford *et al.* 1980, Richardson *et al.*

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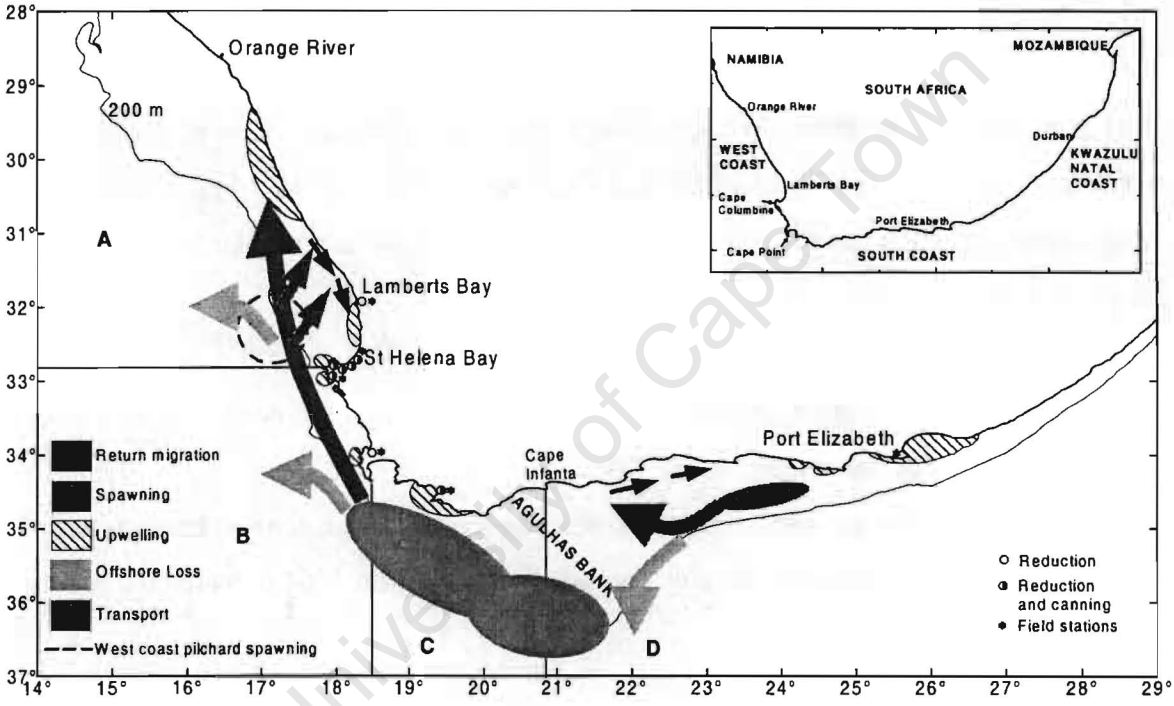
1998). These relatively warm waters probably enhance the survival of early ichthyoplankton stages, because the initial rate of development increases exponentially with temperature – pilchard and anchovy larvae are vulnerable to abnormal development and mortality at temperatures below 13 and 14°C respectively (King 1977, King *et al.* 1978). Spawning products of both species are subsequently transported from the spawning grounds in the south to the food-rich nursery areas along the west coast by a strong shelf-edge frontal jet, which entrains large volumes of water from the spawning areas to the west coast at rapid speed (Figure 1.4; Crawford *et al.* 1980, Shelton and Hutchings 1982, Fowler and Boyd 1998).

Figure 1.4: Conceptual map of the distribution and movement of pilchard and anchovy (after Coetzee 2001), and the location of processing facilities and field stations used to sample landings.



Recruitment of pilchard and anchovy juveniles to the fishery first occurs in the northern areas of the west coast in March/April, where the highest concentrations of plankton are found (Crawford *et al.* 1980). These juveniles often live together in mixed shoals, and their availability to the pelagic fleet may result from a series of factors (Crawford *et al.*, 1980, Crawford 1981b), namely:

- a preference for near-shore areas of rich food supply; and
- these fish initiating shoaling behaviour and reaching a size at which they are fully susceptible to the fishing gear.

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As the season progresses, there is a general southward movement, aided by inshore countercurrents, into newly productive areas, and eventually back to the spawning areas. Both species tend to move off the fishing grounds in an eastward direction once spawning is complete, with anchovy shoals positioned slightly to the west of pilchard shoals (Crawford 1980, Crawford 1981c).

There are certain differences, however, in the behaviour of pilchard and anchovy that can be attributed to the younger age-at-maturity and shorter lifespan of anchovy (Crawford 1981b, 1981c). At the end of their southward migration, anchovy have returned to the southern spawning grounds and are nearing maturity in preparation for the forthcoming spawning season, thereby completing an annual cycle of migration. Pilchard, on the other hand, only mature in their second year[12], and because many of these fish do not yet need to spawn, substantial numbers remain on the west coast to take advantage of the food from highly productive upwelling areas. Furthermore, pilchard aged 5 and 6 years were traditionally encountered in the St Helena Bay region (Figure 1.4) in the first few months of the year, and it was thought that these fish were responsible for summer spawning in the area, aided by warm water of oceanic origin. However, these fish disappeared from landings when the 12.7mm net was introduced in the mid-1960s, and was followed by a severe decline in egg production in the St Helen Bay vicinity (Crawford 1981b).

A phenomenon unique to pilchard is what has come to be known as the KwaZulu-Natal "sardine run" (Davies 1956b, Baird 1971, Armstrong *et al.* 1991). Essentially, there is a regular appearance of pilchard shoals off KwaZulu-Natal during winter (June) each year. These shoals move northwards, commencing around Port Elizabeth and disappearing north of Durban (Figure 1.4), and are preyed upon by numerous sharks and other predatory fish, dolphins and gannets on their journey north (Baird 1971). During the "sardine run", pilchard frequently strand on the beaches, and are caught by local fishermen using conventional beach seines, regulated by limited entry. Catches, however, are very small compared to those on the south and west coasts (typically <1000 tons), and are not included in the catch statistics for the pilchard stock. Armstrong *et al.* (1991) proposed that the "sardine run" arises from an expansion of the environment suitable for pilchard during the cooler water conditions of winter. This expansion, combined with the effects of current reversals, upwelling of cool water onto the narrow shelf,

[12] Armstrong *et al.* (1989) later showed that age at 50% maturity declined from two years old during the period 1965-1975 to only one year old for the period 1976-1987.

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and even their pursuit by predators, leads to a leakage of shoals of pilchard on to the KwaZulu-Natal coast.

1.4 Acoustic Surveys

Although the analyses of commercial catch data have provided invaluable information on the distribution and movement of pelagic fish stocks, this information has serious limitations because of its dependence on the availability of fish stocks to the fishing fleet, and the limitation imposed by the specific deployment of vessels in time and space. In order to overcome these limitations and to provide catch-independent information on the abundance of pelagic fish stocks, a direct survey programme was introduced in 1983 using the acoustic and midwater trawling facilities on board the research vessel F.R.S. *Africana* (Hampton *et al.* 1985, Hampton 1987). Surveys initially used systematic grids of parallel transects running normal to the coast, but this was later changed to a random stratified design, consisting of a series of pre-stratified, randomly spaced, parallel transects, to allow sampling variance to be estimated rigorously (Hampton 1992, Barange *et al.* 1999). The survey programme focused on obtaining reliable abundance estimates for anchovy, both in November during the peak of the anchovy spawning season (providing estimates of anchovy spawner biomass) and between May and July at the height of the anchovy recruit fishery (providing estimates of anchovy recruitment). Initially, surveys were extensive in order to establish the limits of the anchovy distribution, but later, November surveys focused mainly on the south coast, and recruit surveys on the west coast (Hampton 1987)[13]. The first reliable estimates of anchovy spawner biomass and recruitment come from the 1984 November survey and the 1985 recruit survey respectively.

From the outset, the November surveys provided both acoustic and daily egg production method estimates (called "egg" estimates hereafter) of anchovy spawner biomass (Hampton *et al.* 1985, Armstrong *et al.* 1988, Hampton *et al.* 1990, Shelton *et al.* 1993). Both methods required frequent sampling of fish: the acoustic method to identify targets, and the egg production method to sample spawning fish for estimating parameters such as the number of eggs produced per female, the percentage of fish spawning and the average weight of the fish in the spawning area. These methods were therefore complementary and could be integrated into a single survey, with the acoustic method providing estimates with relatively high precision but potentially low accuracy, and the egg production method (considered to be unbiased) providing relatively

[13] For the purposes of calculating comparable abundance indices and their associated coefficients of variation (CVs), the core area for the November surveys is Hondeklip Bay to Port Alfred, and for the recruit surveys, Orange River to Cape Infanta (Figures 1.6 and 1.7; Barange *et al.* 1999).

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imprecise estimates (Armstrong *et al.* 1988). Hampton *et al.* (1990) put forward a means of combining the estimates from the two methods to produce a single estimate each year that is less susceptible to bias than either method alone (although also less precise than the acoustic method), but this approach was never implemented. An advantage of providing two estimates was that the "unbiased" egg survey estimates could be used to verify and scale the acoustic estimates.

Egg survey estimates of anchovy spawner biomass have been discontinued since the mid-1990s. This was mainly because the method was labour-intensive and imprecise, with limited potential for improvement without a substantial increase in survey effort (Armstrong *et al.* 1988, Hampton 1996). Furthermore, the primary value of the time-series of egg survey estimates was its ability to scale the acoustic estimates, and the additional value of further egg survey estimates to the time-series would therefore have been small (and would have diminished further, the longer the time-series). This was because there were already enough data points in the time-series to fulfil the "scaling" function. However, renewed efforts are currently underway to apply the daily egg production method to pilchard (van der Lingen 1998).

The timing of the recruit survey required careful consideration (Hampton 1987). These surveys had to take place sufficiently late to ensure that most of the recruits were acoustically detectable (which was possible for caudal lengths as small as 5cm). However, if they were scheduled too late, their results would not be available in time to be used to regulate fishing on the incoming recruits, whose availability to the fishery did not extend much beyond August. There was therefore only a short time window of about two months (May-June) within which to conduct the survey.

Although spawner biomass and recruit estimates for pilchard are available from 1984 and 1985 respectively, the estimates were initially seen as a by-product of "anchovy" surveys. It was only in 1986 that trawls on the November surveys started targeting pilchard and round herring in addition to anchovy. Spawner biomass estimates for pilchard were initially poor, but precision later improved, largely because of the increasing stock size (Hampton 1992). Furthermore, it was only in 1991 that sufficient coverage was achieved to allow reliable estimation of pilchard recruitment, and 1991 was also the first year that trawls targeted pilchard recruits in addition to anchovy recruits (Hampton 1992). This meant that prior to 1991, CVs were not computed for pilchard recruit survey estimates. Nevertheless, the whole time-series of pilchard recruitment estimates has been used in assessments, with high CVs allocated to years prior to 1991.

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Results from the November and recruit surveys confirmed the general patterns inferred from catch statistics of adults on the south coast and recruits on the west coast, as well as longshore and offshore trends in length[14], with pilchard showing a greater preference for inshore, warm waters than anchovy (Hampton 1987, 1992, Barange *et al.* 1999). Nevertheless, the acoustic survey programme substantially altered previous perceptions of the abundance and overall distribution of pelagic fish, and added to existing knowledge of migration patterns by providing information from areas well beyond the range of the fishery. For example, anchovy were more abundant and much more widely distributed on the south coast during summer than previously believed, and the pelagic fishery was shown to have heavily undersampled older anchovy, which invalidated the assumptions of previous VPA assessments used for this species (Hampton 1992). Geostatistical analysis of acoustic data also showed that pilchard are more patchily distributed than anchovy, and remain in relatively high-density schools throughout the day and night, unlike anchovy, which form high-density schools during the day, breaking up into larger, low-density aggregations at night (Barange and Hampton 1997). Most importantly, acoustic surveys provided a means of direct estimation of abundance with associated estimates of precision, which allowed the dynamics of pelagic stocks to be modelled with far greater reliability than previously possible (Hampton 1992).

The major problems associated with acoustic surveys have been highlighted as the lack of a target-strength expression derived *in situ* (the expression used being one derived for north Atlantic herring, *Clupea harengus*)[15], and calibration errors (Hampton 1987, 1992). Recent work (Hampton *et al.* 2001) highlighted other important sources of error, such as absorption, species identification calibration error, aeration, vessel avoidance and the unavailability of part of the stock to the survey (mostly fish inshore of the survey grid). The most serious of these, not fully appreciated in the past and with the potential of far outweighing the other sources of error, was the effect of absorption attributable to dense shoals (a negative bias). This changed the perception somewhat of the effective acoustic bias for the November pilchard estimates where, unlike anchovy, "unbiased" egg survey estimates were not available to scale these November estimates, and therefore an assumption about the bias in these estimates was needed. Whereas previously, target strength (likely a positive bias) was thought to dominate and November acoustic estimates for pilchard were assumed to have a 50% positive bias (De Oliveira *et al.*

[14] i.e. the southward movement of juveniles on the west coast, and eastward and offshore movement with age of adults on the south coast.

[15] More realistic *in situ* target strength expressions have now been obtained for both pilchard and anchovy (Barange *et al.* 1996), but the old expression is still used to maintain the continuity of the acoustic time-series.

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1998a), the negative bias caused by absorption is now thought largely to cancel this positive bias. Therefore, the base case assessment presented in Chapter 2 assumes a zero bias for November acoustic estimates of pilchard abundance.

A further problem is that, whereas the current acoustic survey design is well suited to the spatial distribution of anchovy, this is not the case for pilchard. This is because, when the acoustic survey programme first commenced, the design and timing of surveys focused on anchovy, whose key distribution characteristics differ from pilchard, with consequent implications for survey design (Barange and Hampton 1997). For example, pilchard have a distribution that is patchier but also more widespread, lack a single peak during their spawning season, and show greater preference for inshore and warmer water than anchovy. Barange and Hampton (1997) suggest that a possible way to improve pilchard estimates would be to use adaptive sampling designs (linked to analyses methods which ensure that estimators of mean and sampling variance remain unbiased) for future surveys, whereby initial sampling effort is increased immediately after encountering high-density areas. They add, however, that such an approach would need to ensure that there is no deterioration in the anchovy estimates, irrespective of the stock distribution.

Since the inception of acoustic surveys, improved echo-sounder technology has been implemented at various times. The first surveys were performed using the Simrad EKS-38 echo-sounder, but this was upgraded to a Simrad EK400 echo-sounder for the November 1990 and subsequent surveys (Hampton 1992). A further upgrade took place for the recruit survey in June 1997 and all subsequent acoustic surveys, when the Simrad EK400 was replaced by a Simrad EK500 (Barange *et al.* 1999). An inter-calibration study to compare performance of the EK400 and EK500 sounders showed that results were similar except when signals were very strong, for which the EK400 did not respond linearly, resulting in saturation (Barange 1998, Coetzee 2001). This meant that the EK400 underestimated back-scattering strength when fish density was great, this problem being avoided by the EK500 because of its wider dynamic range. Saturation was more frequent for pilchard than for anchovy, and for adults than for juveniles, because pilchard tend to form denser shoals than anchovy, and juveniles less dense shoals than adults (Coetzee 2001).

Because the saturation problem was complex and non-linear and depended on factors such as the species concerned, whether the fish were adults or juveniles, and the size of the stock being assessed, the calculation of a single calibration factor between the EK400 and EK500 sounders

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was not possible (Barange 1998, 1999, Coetzee 2001). Therefore, in order to maintain a consistent time-series of acoustic estimates, the effect of EK400 saturation was simulated on data collected by the EK500 by capping the acoustic signal to a maximum back-scattering strength of -29.9 dB, the value at which saturation in the EK400 occurred (Barange 1998). This resulted in both a "capped" and an "uncapped" series of abundance estimates being kept for each species and survey since the introduction of the EK500 sounder in 1997, and allowed for the continued use of the pre-1997 estimates in conjunction with the "capped" estimates obtained since 1997. The double time-series of estimates also allowed for the possibility of developing empirical regressions once there were enough data points, so eventually the old estimates could be corrected for saturation and the new estimates used without having to be "capped" (Barange 1999). Work on this is currently underway using GLM and multiple linear regression techniques, but it has not yet been completed (Coetzee 2001). Therefore, even though the EK500 technology is far superior to the older equipment, providing more accurate estimates, "capped" estimates are used for the assessments presented here (Chapters 2 and 3).

Figure 1.5 shows trajectories of the "capped" November spawner biomass estimates for pilchard and anchovy for the period 1984-2000. A bar graph depicting estimates of the pilchard bycatch that occurs when anchovy are targeted is superimposed on these trajectories to illustrate the problem (highlighted previously) of pilchard bycatch when anchovy are targeted. Particularly noticeable is the increase of the pilchard bycatch as a proportion of the anchovy catch as the abundances of the two species reached similar levels.

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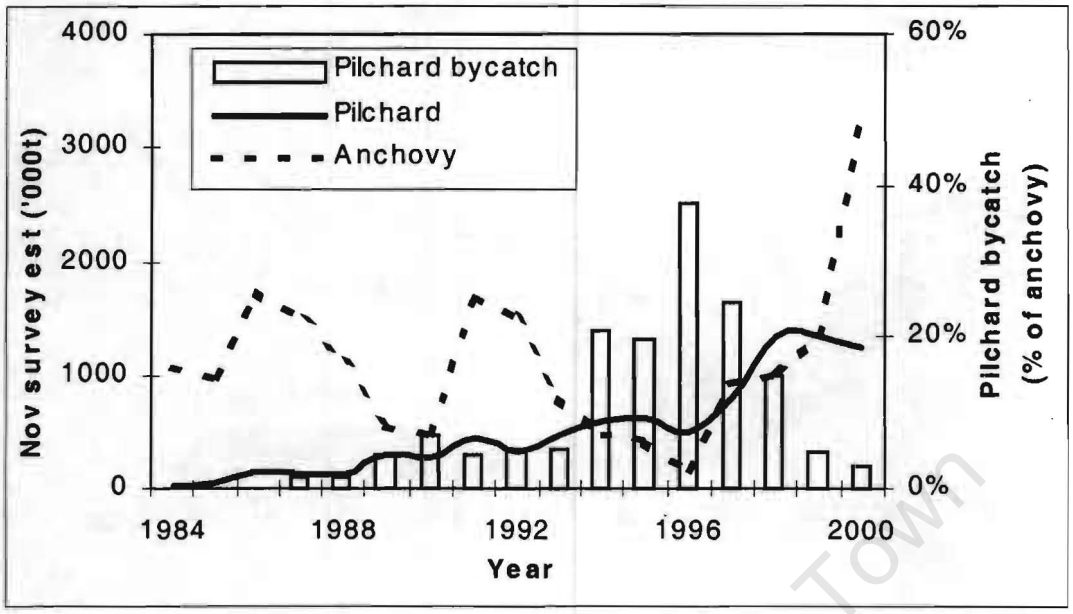
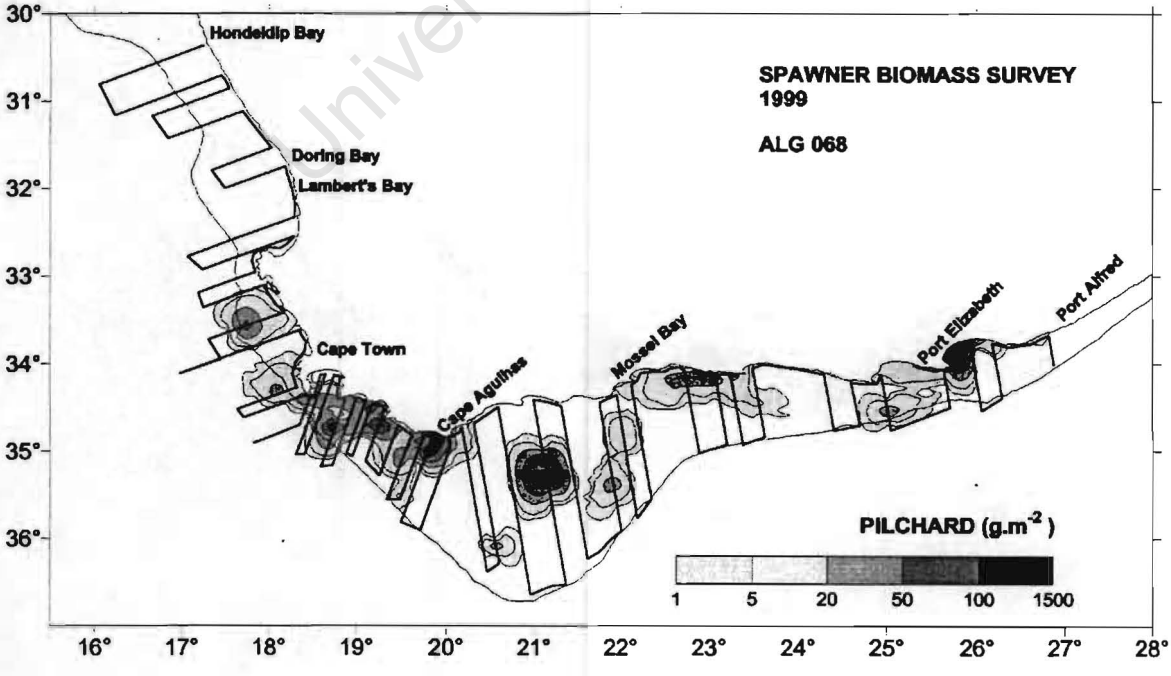
Figure 1.5: November acoustic survey estimates ("capped") of spawner biomass ('000 tons) for pilchard and anchovy, together with values of the pilchard bycatch when anchovy are targeted, expressed as a percentage of the corresponding anchovy catch. [Note that although this figure reflects survey results in the year that they took place, the convention adopted for the remaining Chapters is that estimates from the November survey of year *y* are reflected as estimates for the beginning of year *y*+1.]



Figures 1.6 and 1.7 show typical distribution and abundance maps for the November and recruit surveys, with the survey track superimposed.

Figure 1.6: Distribution and abundance maps for (a) pilchard and (b) anchovy for the November 1999 survey, with the survey track superimposed (from Coetzee *et al.* 2000).

a.



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b.

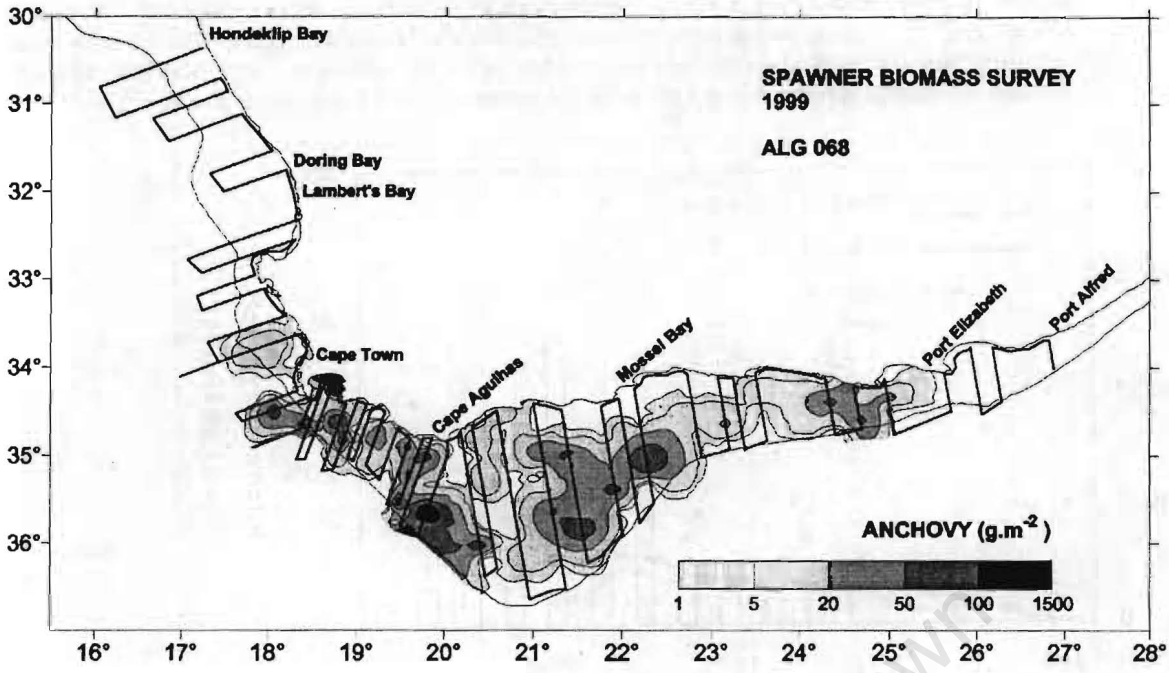
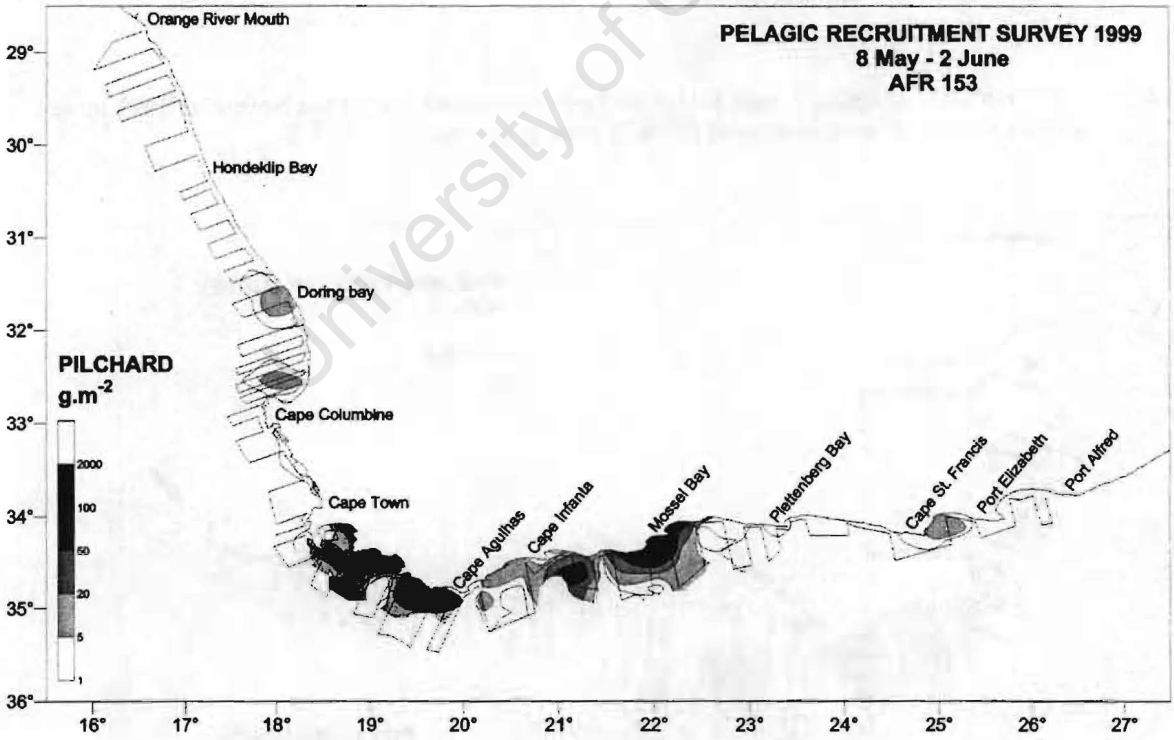


Figure 1.7: Distribution and abundance maps for (a) pilchard and (b) anchovy for the 1999 recruit survey, with the survey track superimposed (from Barange and Coetzee 1999).

a.



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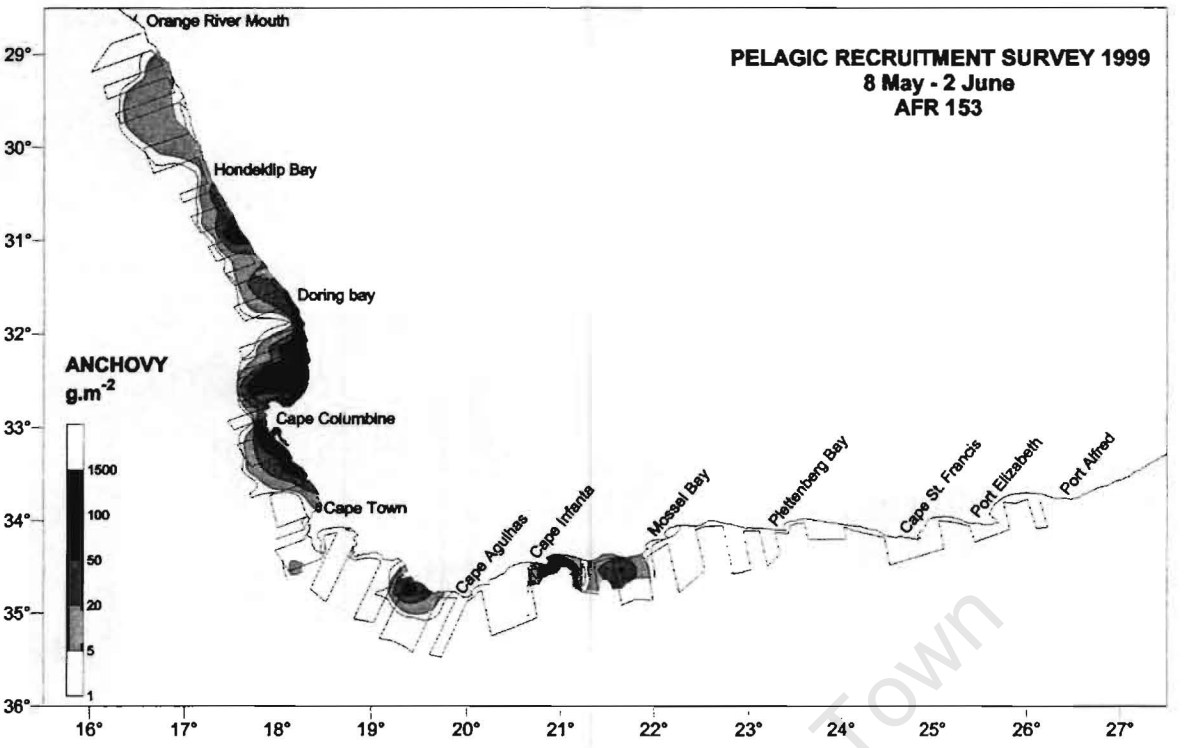
b.



1.5 The pelagic fishery entering the 21st century

South Africa is not regarded as one of the world's top fishing nations, accounting for only 0.6% of total world catch from 1990-2000, with its fisheries having a combined economic value of <1% of the country's GDP. Fishing is nevertheless an important economic activity along the coast, employing some 25 000 people (Cochrane *et al.* 1997, Cochrane and Payne 1998, Anon. 2000). By mass, the pelagic sector makes the largest contribution to the total landings in South Africa, but ranks second to the demersal sector in terms of wholesale processed value, approaching R500 million in 1998 (Figure 1.8; Anon. 2001a). Within the pelagic sector, canned products (mainly pilchard) are the most valuable, followed by fishmeal, bait and fish oil.

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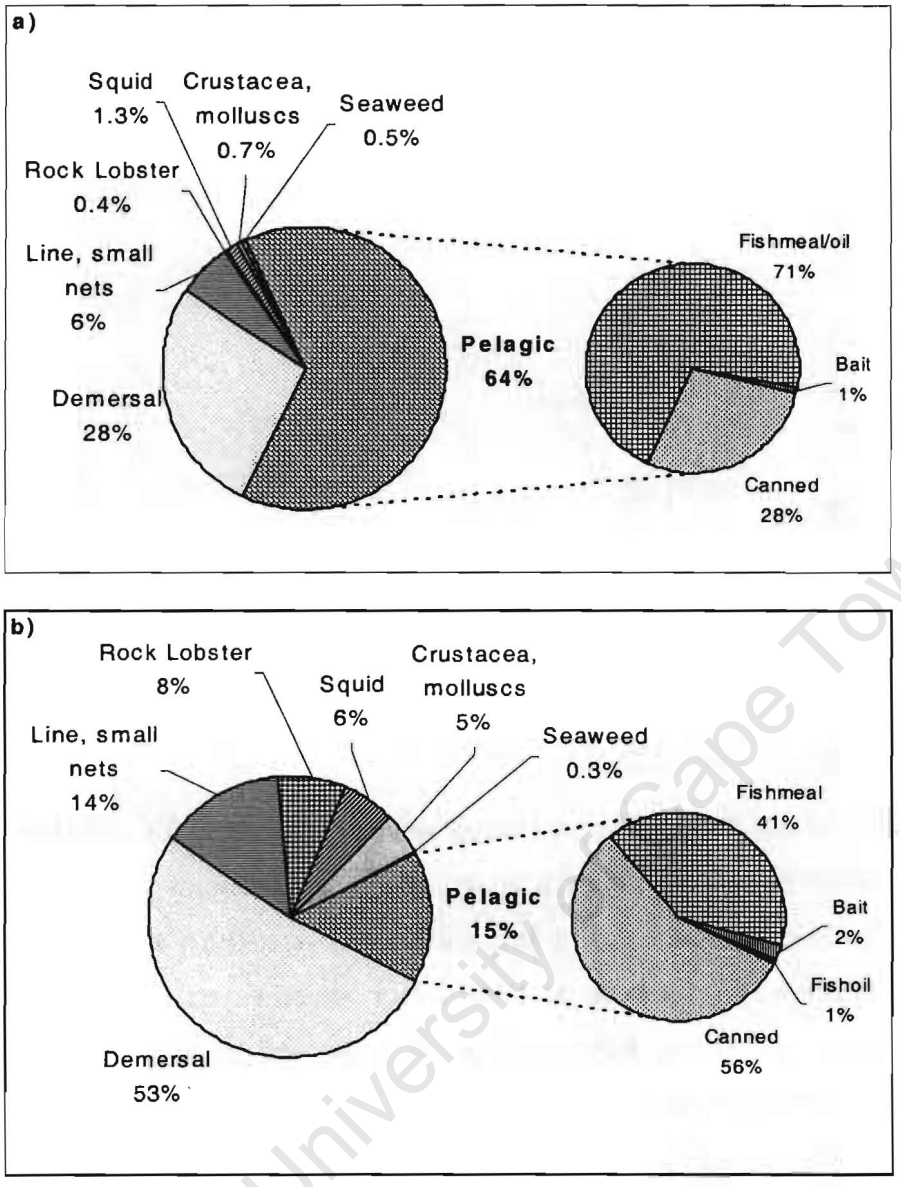
Figure 1.8: Relative values of South African fisheries in 1998, by fishing sector (large pie graph) and within the pelagic fishery (small pie graph), in terms of a) landed mass and b) wholesale processed value (Anon. 2001a).



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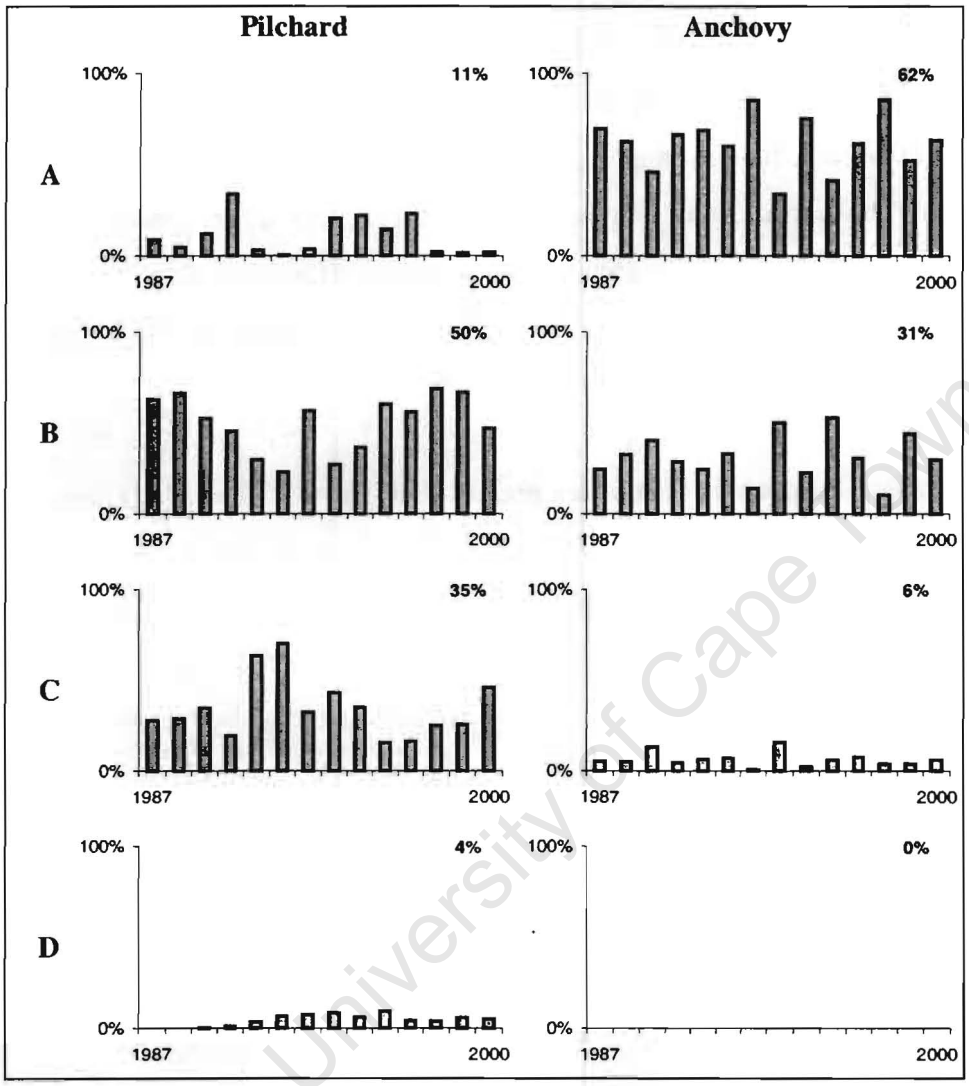
The pelagic fishery operates in environs that have not changed much since the mid-1970s (Figure 1.3e), with the exception of the 1990s when a canning plant was erected in Port Elizabeth and pilchard catches from that area rose from <1 000 tons in 1990 to >7 000 tons in 1996. Figure 1.9 shows the annual contribution of catches from each of four different areas (areas A-D in Figure 1.4), to the total annual catch, expressed as percentages, for pilchard and anchovy. These plots show that, since 1987, the largest catches of anchovy have been on the west coast north of Cape Columbine (including St Helena Bay), whereas most catches of pilchard have come from the area between Cape Columbine and Cape Point. The contribution from the area east of Cape Infanta, which includes the area around Port Elizabeth, is small, averaging only 4% over the period 1987-2000.

Figure 1.9: Annual contribution of pilchard (left column) and anchovy (right column) catches from four different areas, expressed as percentages of the total annual catch for each species. The areas are labelled A to D (top to bottom), and are the areas shown in Figure 1.4 (from north to south: A = north of Cape Columbine; B = Cape Columbine to Cape Point; C = Cape Point to Cape Infanta; D = east of Cape Infanta). The average contribution from each area for the period 1987-2000 is shown in the top right hand corner of each plot.



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The pelagic industry employs some 700 fishermen, 4 500 full-time personnel and 2 500 seasonal workers, and provides a further 2 400 jobs indirectly through services associated with the industry (Sauer *et al.* 2002). The nature of the industry (fish resources based offshore, industry based on high volume, etc.) is such that it is highly capital intensive, with an infrastructure valued at approximately R1.2 billion[16] (S.J. Malherbe, South African Pelagic Fishing Industry Association, Cape Town, South Africa, pers. comm.). The industry operates eight reduction plants and six canning plants around the west and southeast coasts, from Lambert's Bay to Port Elizabeth (Figure 1.4). There are also more than 40 smaller plants for freezing and packing

[16] Billion = 10^9 throughout.

pilchard (Sauer *et al.* 2002). The industry supplies mainly the domestic market, with roughly 5% of the TAC exported, but this figure could rise to 40% under certain market conditions (S.J. Malherbe, pers. comm.).

Pilchard and anchovy are currently the main targets of the pelagic industry and, together with round herring, have accounted for >90% of the total purse-seine landings each year since the mid-1970s (Table 1.2). The anchovy fishery is predominantly a recruitment fishery, with more than 80% (by mass and number) of the fish caught each year being juveniles. Anchovy catches are processed for fishmeal (on occasion, small amounts have been processed for human consumption). The bulk of the anchovy catch each year is taken from March/April to August/September, when juvenile anchovy migrate through the fishing grounds on their way to the Agulhas Bank from their nursery grounds on the west coast (Figure 1.4).

In contrast, the directed fishery for pilchard comprises mainly adult fish used for canning/bait[17], with fishing spread fairly evenly throughout the year. Although juvenile pilchard are not targeted, they occur as a bycatch in the anchovy fishery, because juvenile pilchard and anchovy initially tend to shoal together while of a similar size, a process that terminates in about August when anchovy growth slows. A bycatch of pilchard also occurs in the round herring fishery, but those pilchard are mainly adult fish.

Despite the abundance of round herring off South African waters (as observed during acoustic surveys), the resource is lightly exploited, with catches rarely exceeding 70 000 tons in any year (Table 1.2). This is because the resource is relatively inaccessible to the majority of purse-seine vessels, being frequently distributed far offshore and forming shoals deeper than those of pilchard and anchovy.

Currently, pilchard and anchovy are the only pelagic species subject to a TAC, the remaining species being designated as "non-quota" species. However, there are certain restrictions on these "non-quota" species; for example, they may only be targeted if one has a right to catch either anchovy or pilchard, or both. Furthermore, catches of horse mackerel have been restricted to a maximum of 5 000 tons, following a study that highlighted the negative impact of large catches of horse mackerel taken in the pelagic fishery (mainly juveniles) on subsequent catches of horse mackerel in the demersal fishery (mainly adults) (Horsten 1999a, 1999b).

[17] About 10% of the pilchard catch is packed whole for the bait market or as cutlets for human consumption.

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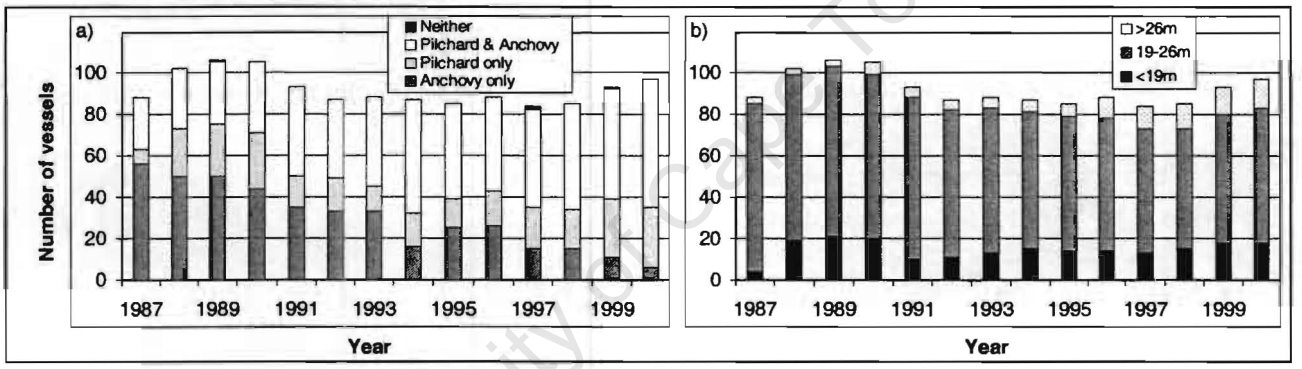
Once a right has been allocated for either anchovy or pilchard (or both), the rights holder may apply for vessel permits in order to target the relevant "quota" species and other "non-quota" species. Figure 1.10 shows how the number of vessels registered in the pelagic fishery has varied over the period 1987-2000, with (a) indicating the number of vessels that targeted either pilchard or anchovy or both. The "neither" category refers to vessels used only for "non-quota" species (a rights holder may apply for more than one vessel permit, so that the situation where a vessel registered in the pelagic fishery targets only "non-quota" species is possible). Figure 1.10(b) categorises the number of vessels operating each year into length groups. For 2000, 97 vessels were registered in the pelagic fishery. [Appendix 7.2 in Chapter 7 provides information related to economic features of the fishery.]

Figure 1.10: Time series of the number of vessels registered in the pelagic fishery, categorised by (a) species targeted and (b) vessel length.



In the pelagic fishery, where fish are targeted for canning or packing as bait, these fish are kept cool using either ice or refrigeration facilities. Fish targeted for the reduction plants (to produce fishmeal or oil) are not cooled.

Smaller vessels (13-18m) are generally used for bait, and do not usually target fish for the reduction plants (Figure 1.11). Of the larger vessels (>19m), some do not have cooling facilities and are therefore used exclusively to target fish for reduction plants. However, the majority of vessels >19m can now switch between targeting fish for canning/bait and targeting fish for fishmeal/oil. The largest vessels in the pelagic fishery (27-37m) have steel hulls with a maximum hold capacity of about 300 tons (Figure 1.12). The trends evident in Figure 1.11 (particularly the bottom panel) are mainly attributable to the introduction of these large vessels in recent years (see Figure 1.10).

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Figure 1.11: Time-series of the number of vessels used to target fish for (a) canning/bait and (b) fishmeal, by length category of vessel. The bottom row shows corresponding plots for proportion of landings by vessel length category. [Note, data for 2000, categorised in the manner shown, were not available.]

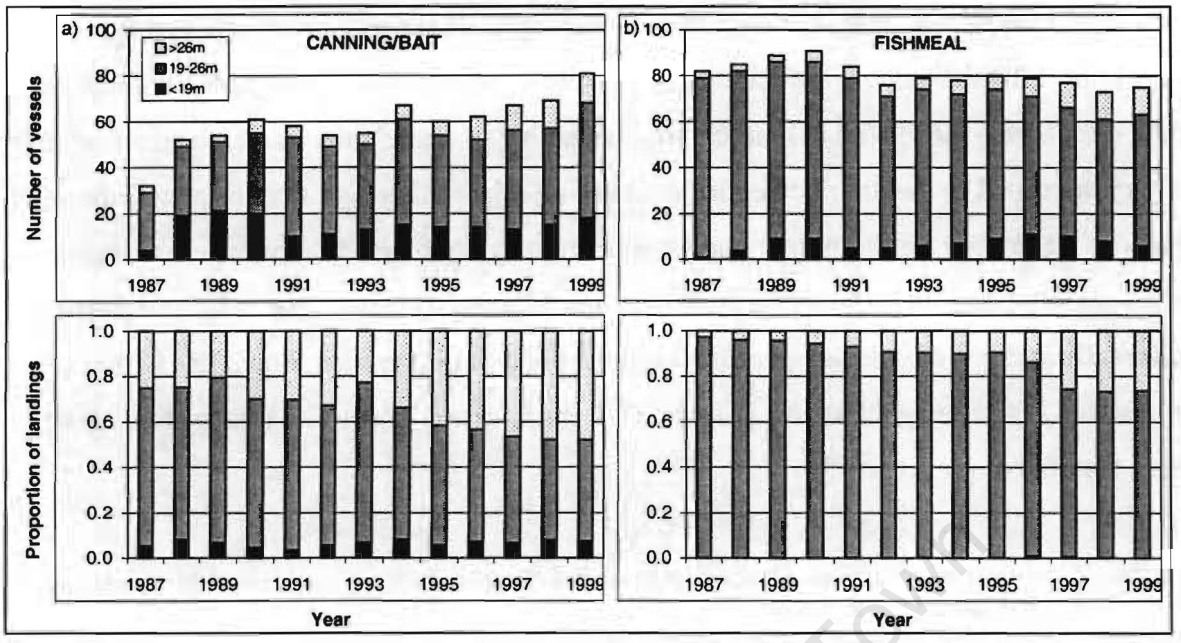
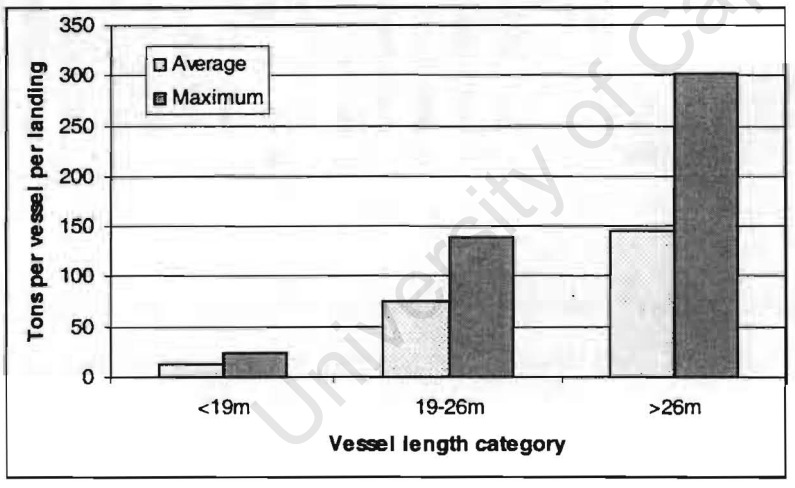


Figure 1.12: The average and maximum tonnage landed per vessel in 2000, divided into three different length categories



Since the early 1990s, South Africa has embarked on a new political course signalling the end of white minority rule, with the redistribution of wealth and opportunity being the focal point of many spheres of public life (Hersoug and Holm 2000, Mayekiso *et al.* 2001, van Sittert 2002). South African fisheries have followed the same course and have undergone a process of "transformation", whereby fishing rights traditionally held by "white-owned" companies or individuals have been re-distributed to "Previously Disadvantaged Groups" (PDGs). These reforms were aimed at granting PDGs access to marine resources without destabilising the established industry (van Sittert 2002).

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The pelagic industry has therefore undergone some profound changes since the early 1990s (Sauer *et al.* 2002). In 1990 there were only 10 pilchard and 12 anchovy "traditional" rights holders, who between them held 90 and 100% of the pilchard and anchovy TACs respectively (the remainder of the pilchard TAC was allocated to 25 bait rights holders). The traditional rights holders were typically large companies having both pilchard and anchovy rights, with several purpose-built vessels to ensure effective operation and full usage of allocated quotas. They also owned all the canning and fishmeal plants. By 2000 there were 107 pilchard and 51 anchovy rights holders, with the majority of the "new entrants" opting to sell their allocated quota to one of the major canning or fishmeal plants at a negotiated price, and the remainder following higher-risk options such as entering into joint ventures with established companies, establishing small to medium enterprises, or forming empowerment companies and acquiring substantial share holdings in some of the larger traditional companies (Sauer *et al.* 2002). The apportionment of the pilchard and anchovy TACs to the traditional rights holders has decreased to 46% and 55% respectively. Transformation has also taken place within the traditional companies, with the restructuring of ownership.

A re-allocation of rights across all South African fisheries sectors took place towards the end of 2001 (Chapter 6), with the level of transformation for each applicant playing an important role in the decisions made.

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CHAPTER 2

Pilchard Assessment

Maximum likelihood estimation is used for the assessment of South African pilchard, which incorporates catch-at-age data (20 years), estimates of the abundance of adult and juvenile fish (16 and 14 years) from the November and recruit surveys respectively, and information on the age structure (proportions-at-age – 12 years for 5 age-classes) of the adult stock from the November surveys. The abundance and proportion-at-age data are included in a likelihood function (assuming log-normal error structure), with juvenile and adult natural mortality and the bias of the November surveys treated as input parameters. Estimable parameters include a 20-year time series of begin-year recruitment estimates, with closed-form estimators available for the "additional variances" associated with the surveys and the relative bias associated with the recruitment surveys. The likelihood indicates that the best fits are achieved for an adult natural mortality value of 0.4.year^{-1}, but provides little discrimination across values for juvenile natural mortality. A central value for the adults survey multiplicative bias of 1 (reflecting an assumption that the November surveys are unbiased) was selected on the basis of advice from scientists responsible for acoustic survey, and pending further evaluation of survey errors. These scientists advised upper and lower bounds for the ratio of recruit:adult survey bias – a juvenile natural mortality of 0.8.year^{-1} was consistent with the bounds set for this ratio. A range of alternative assessments was selected for the purpose of performing management procedure robustness tests.

2.1 Introduction

The first attempt to carry out a quantitative assessment of sustainable yield for the South African pelagic fishery was a simple regression of CPUE[18] against effort for the period 1964-1972, which yielded a combined species MSY estimate of 360 thousand tons (Newman *et al.* 1974). It was based on the assumption that production was independent of species composition, and was used for management of the pelagic fishery until the late 1970s. However, CPUE indices were problematic as measures of abundance for the pelagic fishery, because of the effects of improved technology, and problems of defining and allocating effort in a mixed-species fishery, where species-directed fishing occurs (Butterworth 1983). Furthermore, Newman and Crawford (1980) argued that fishing strategy and shoaling behaviour could result in the maintenance of catch rates in purse-seine fisheries in the face of declining stocks, and that catch rates could be more sensitive to the location of shoals in relation to land-based factories, than to actual fish abundance.

By the end of the 1970s, VPA assessments of biomass and year-class strength were available for the most important species (Centurier-Harris 1977, Newman and Crawford 1980, Crawford *et al.* 1987). These VPA assessments used effort and catch-at-age data, for which combined age-length

[18] The CPUE was adjusted to take into account the effects of fishing aids, although not all factors could be taken into account, for example aerial spotting of shoals and the skill of skippers (Newman *et al.* 1979).

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keys (ALKs) from later years were applied to earlier years for which ALKs were not available[19]. This resulted in VPAs producing smoothed biomass and recruitment trends, and probably doing no more than duplicating (while slightly preceding) the catch history (Newman and Crawford 1980, Butterworth 1983).

Applying inappropriate ALKs would be particularly problematic for pilchard if density-dependent changes in growth occurred around the time of the collapse of the pilchard fishery in the early to mid-1960s[20]. Under these circumstances, it is possible that ALKs from a period of fast growth following the pilchard collapse were applied to a period of plausibly slower growth prior to the collapse, so that age in the earlier years was underestimated. This would result in the VPAs producing lower biomass levels and a steeper biomass rise prior to the collapse than might have been the case in reality (Butterworth 1983). The collapse may therefore have been a classic case of catches rising beyond sustainable yields which, coupled with poor recruitment, led to a rapid decline in the stock, rather than the traditional view (Newman and Crawford 1980, Armstrong *et al.* 1985) that the fishery developed purely on the back of a few years of very good recruitment and then, when recruitment returned to more usual levels, was unable to cut back on effort with sufficient speed because of over-capitalisation. A further counter to this traditional view follows from the results from a separable VPA carried out by Bergh (1986) using a guano-linked recruitment index, which suggests a steady decline of the pilchard resource under fishing since the early 1950s, with a relatively minor perturbation to this trend at the end of that decade.

A further problem with using VPA based on effort and catch-at-age data only, particularly for management, was the poor confidence in estimates for the most recent years, which meant that biomass fluctuations were unlikely to be detected in time to take appropriate management action (Armstrong *et al.* 1983). Butterworth (1987) emphasised that catch and age-structure data alone were insufficient to determine biomass trends with any reasonable precision, and that VPAs must also incorporate some time-series of an index of relative abundance to obviate this problem. Acoustic surveys offered the solution (Butterworth 1983, Armstrong 1984, Hampton 1987), particularly as they produced a direct measurement of fish abundance, which Butterworth (1983) argued was preferable to indirect measurements. This is because trends in the latter may be

[19] Due to the lack of ALKs prior to 1965 for pilchard, a combined ALK for the period 1965-1967 was applied to the period 1950-1971, with the years after 1971 assigned their "own" ALKs. For anchovy, age determination was difficult and material for ageing was sparse, so that only a combined ALK for the period 1965-1967 was available (Crawford *et al.* 1978, Newman and Crawford 1980).

[20] Changes in length at maturity for pilchard before and after the collapse (Armstrong *et al.* 1989) may reflect such compensatory growth rate changes.

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confounded by a changing relationship between the fish and index being measured. However, acoustic surveys were not used as a basis for setting pilchard TACs until 1987, because the trawl component of these surveys only started focussing on pilchard from the end of 1986, and the pilchard acoustic estimates prior to this were considered too imprecise to be used, a result of the resource initially showing a low abundance and very patchy distribution (Anon. 1988, Hampton 1992).

A Maximum Likelihood VPA (MLVPA) assessment approach, similar to ADAPT (Gavaris 1988), was first used to set pilchard TACs from 1990 (Punt 1989), and later formed the basis of the management procedure used to set pilchard TACs from 1994 to 1996 (De Oliveira *et al.* 1998b). The MLVPA took into account all available information on independent indices of abundance (e.g. acoustic estimates) and their associated standard errors, in addition to catch-at-age data, but did not utilise effort information (De Oliveira *et al.* 1998b). The approach was new in that it treated the fishing mortalities at age of the last year for which data were available as estimable parameters, so as to provide trends in biomass and recruitment that matched the trends inferred from the independent indices as closely as possible (Anon. 1989, Punt 1989). This was a notable advance over earlier VPAs, which had not taken appropriate account of the variances and possible biases associated with acoustic estimates of abundance (Anon. 1989). Nevertheless, this approach was regarded as too rigid because it assumed a constant exploitation pattern over time. It was therefore replaced by the assessment method presented below[21], as a basis for the management procedures presented in subsequent Chapters.

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2.2 Current assessment approach

Stock assessment methods available today are numerous and wide-ranging, from age-aggregated production models, which are parameterised in terms of intrinsic growth rate and carrying capacity, to more complex statistical catch-at-age or spatially disaggregated age-structured models that introduce auxiliary information within a Bayesian framework (e.g. Megrey 1989, Hilborn and Walters 1992, Quinn and Deriso 1999). The choice of assessment method depends on the type and quality of data available, and on the hypotheses being investigated or questions being asked. The availability of age structure information from both commercial catch data and fishery-independent surveys, and the importance of differentiating between juvenile and adult

[21] Initial developments of the assessment approach presented in this Chapter formed the basis of the pilchard-only management procedure presented by De Oliveira *et al.* (1998a), and the pilchard-anchovy procedure presented by Geromont *et al.* (1999).

pilchard because of the conflicting interests between the pilchard and anchovy fisheries (where pilchard bycatch is taken in the latter – see Chapter 1), imply that an age-structured assessment method is appropriated for pilchard. Estimation has been developed on a maximum likelihood estimation basis as far as is possible, to achieve statistically appropriate relative weightings of different data sources in accordance with their levels of variability, and to admit the possibility of inference of statistical precision of parameter values estimated.

Appendix 2.1 provides details of the assessment method used here, including the basic equations of the age-structured model, the assumptions of the model and the available data. Three time-series of observations[22] are used in the likelihood (equation A2.1.6), namely the November survey adult biomass estimates (and their associated CVs), estimates of juvenile abundance from the mid-year recruit survey (and their associated CVs), and the age composition of the stock (in the form of proportions-at-age), as derived from samples taken from trawls on the November survey. These observations are all assumed to be log-normally distributed about their expected values, and a sample-size weighting term ($n_y p^P_{y,a,Nov}$ - see equation A2.1.6) is introduced in the proportions-at-age component of the likelihood in order to avoid giving undue importance to observations based on only a few samples (Geromont and Butterworth, 1999). Likelihood weights (W^P_N, W^P_r and W^P_p in equation A2.1.6) govern whether each data series is used in the likelihood (e.g. $W^P_p = 0$ implies that the proportions-at-age time series is not used).

The method relies on values for adult and juvenile natural mortality (M^P_{ad} and M^P_{ju}) and the November survey bias (k^P_N) being input, as there is insufficient information (see below) in the data to allow them to be estimated satisfactorily in the likelihood maximisation process. Additional variances (over and above survey sampling CVs) for the November and recruit survey estimates ($(\lambda^P_N)^2$ and $(\lambda^P_r)^2$ respectively) are incorporated, and the overall variance of the log-transformed proportions-at-age observations ($(\sigma^P_p)^2$) is estimated. The unknown bias associated with the recruit survey (k^P_r) is also estimated. Apart from these parameters (which are either input or follow immediately from closed-form solutions obtained by setting the partial derivative of the likelihood with respect to that parameter to zero), the estimable parameters of the model (obtained by multi-dimensional search over the log-likelihood surface) are the 20

[22] "Observations" are taken throughout to mean either data or estimates derived directly from data (e.g. abundance indices from acoustic surveys).

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values for annual pilchard recruitment, corresponding to the number of 0-year-old fish at the beginning of each year ($N^P_{1980,0},\ldots,N^P_{1999,0}$).

Results were obtained across a range of M^P_{ad} and M^P_{ju} values (M^P_{ad} = 0.1, 0.2,..., 0.6 year^{-1}; M^P_{ju} = 0.4, 0.6,..., 1.4 year^{-1})[23]. In addition to the corresponding minimum values of -lnL_{tot} (the total negative log-likelihood value -ln$L$ in equation A2.1.6), values are also reported below for -lnL_{Nov} (the November survey component of -ln$L$), -lnL_{rec} (the recruit survey component of -ln$L$), -lnL_{prop} (the proportions-at-age component of -ln$L$), k^P_r / k^P_N, λ^P_N, λ^P_r, σ^P_p and $N^P_{0,med}$ (the median of $N^P_{1980,0},\ldots,N^P_{1999,0}$, which "scales" the model in the optimisation routine – see Appendix 2.1). Different sets of results were obtained by varying only four input parameters (other than M^P_{ad} and M^P_{ju}), namely W^P_p, k^P_N, λ^P_N and λ^P_r (the latter two were either estimated or treated as input parameters with a fixed value, while $W^P_N = W^P_r = 1$ for all results).

The value of ratio k^P_r / k^P_N was regarded as an important diagnostic for selecting realistic model fits. Since the November survey is considered to cover the full distributional range of the resource, this ratio reflects the average proportion of pilchard recruits in the recruit survey area at the time that survey takes place (note that because of the extended spawning season for pilchard, some pilchard have yet to recruit by that time, while others are already on the Agulhas Bank and outside the area covered by the recruit survey). Upper and lower bounds for this ratio were selected on the basis of advice provided by the scientists responsible for the acoustic surveys of South African pelagic stocks, who indicated that values far outside the range [0.5; 1] for this ratio should be regarded as unlikely to reflect reality.

Selecting a central value for the range of k^P_N values to be considered proved more difficult. Prior to the Survey Errors Workshop held in December 2000 (Hampton *et al.* 2001), a central value of 1.5 was used (implying acoustic surveys overestimate biomass by 50%), which accounted only for the bias introduced by assuming the acoustic target strength relationship for north Atlantic herring to apply to pilchard. The aim of the Survey Errors Workshop was to assess the nature and likely magnitude of errors in acoustic surveys in South Africa and Namibia (Hampton *et al.* 2001). Apart from the target strength bias, the workshop identified another major source of error,

[23] For convenience, the units of M values are omitted hereafter.

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namely the negative bias resulting from absorption of sound in dense, vertically extensive schools of pilchard, commonly found during daytime in both South Africa and Namibia.

The combined effect of target strength, absorption and other smaller errors was investigated through Monte Carlo simulations, which found that acoustic estimates are probably negatively biased, with CVs incorporating all sources of error substantially higher than those usually quoted (which reflected sampling variance alone, Anon. 2001b). These results indicate that a range for k_N^P centred on 1.5 is inappropriate, and a central value closer to 1 (or less) should be considered instead.

Further support for a central value for k_N^P of less than 1 comes from a source of error that was not previously considered by the Survey Errors Workshop, namely the effect of saturation of the echo-sounder (Anon. 2001b, Coetzee 2001). This problem was known to have occurred prior to 1997 when an older model (Simrad EK400) echo sounder than that used currently (Simrad EK500) was in operation. The EK400 had a limited dynamic range and became saturated when dense schools were encountered, causing an appreciable negative bias in both pilchard and anchovy estimates of abundance. The EK500 has a much larger dynamic range, and estimates derived by the EK500 are currently scaled down by a "capping" process to simulate the effect of the saturation in the older echo sounder, in order to provide a consistent time series of abundance estimates (Chapter 1).

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Because of the preliminary nature of the work on survey errors (from the Survey Errors Workshop, and subsequent work on echo sounder saturation – further work is currently underway), it was considered by Marine and Coastal Management's Pelagic Working Group (see Chapter 4) that moving from $k_N^P = 1.5$ to a value less than 1 (0.5 say) as a central value for the range of k_N^P values considered plausible would be too extreme. However, maintaining the value at 1.5 could no longer be justified given the recent work, and therefore the analyses presented here use $k_N^P = 1$ as a central value from the range [0.5; 1.5].

2.3 Results

Table 2.1 shows results for the case $k_N^P = 1.0$ and $W_p^P = \lambda_N^P = \lambda_r^P = 0$. Using the likelihood ratio criterion, a decrease in $-\ln L_{tot}$ of 1.92 or more as the value of one parameter is changed indicates

a statistically significant improvement in the model fit at the 5% significance level[24]. There appears to be no appreciable change in -lnL_{tot} if M_{ad}^{P} values are increased from 0.1 to 0.6 for all M_{ju}^{P} values considered, except for $M_{ad}^{P} = 0.6$. The ratio k_r^P / k_N^P is outside the [0.5; 1] range except for the higher M_{ad}^{P} and M_{ju}^{P} values, indicating a conflict between better model fits in terms of -lnL_{tot} for lower M_{ad}^{P} values, and more realistic k_r^P / k_N^P ratios for higher M values. As expected, $N_{0,med}^{P}$ increases for higher M values. Although $W_p^P = 0$ in this case, it is important to take note of the values for -lnL_{prop} and the associated σ_p^P, for later comparison with model fits with $W_p^P = 1$ that take account of the proportions-at-age observations.

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[24] The term "significant" is used in this sense hereafter.

Table 2.1: Results for the model fits with $W_p^P = 0$; $\lambda_N^P = 0$; $\lambda_r^P = 0$; $k_N^P = 1.0$.

M_{ju}^P	0.4	0.6	0.8	1.0	1.2	1.4	0.4	0.6	0.8	1.0	1.2	1.4
	$-\ln L_{tot}$						$N_{0,med}^P$					
0.1	2.78	2.69	2.61	2.54	2.49	2.46	3.26	3.81	4.49	5.34	6.30	7.55
0.2	2.15	2.10	2.05	2.02	2.00	1.99	3.68	4.29	5.04	5.94	7.15	8.48
0.3	2.11	2.09	2.08	2.08	2.10	2.13	4.04	4.79	5.59	6.66	7.99	9.40
0.4	2.56	2.57	2.60	2.65	2.70	2.76	4.46	5.25	6.24	7.45	8.83	10.57
0.5	3.41	3.47	3.54	3.62	3.71	3.83	4.86	5.77	6.88	8.22	9.77	11.81
0.6	4.66	4.76	4.87	5.00	5.17	5.45	5.33	6.33	7.57	9.03	11.03	13.64
	$-\ln L_{Nov}$						σ_p^P					
0.1	1.03	1.08	1.18	1.27	1.30	1.42	13.14	12.92	12.90	12.74	13.05	13.10
0.2	1.14	1.27	1.29	1.31	1.44	1.45	12.67	12.07	12.44	12.33	12.61	12.16
0.3	1.34	1.41	1.38	1.50	1.62	1.63	11.27	11.34	11.11	11.59	11.83	11.98
0.4	1.55	1.57	1.68	1.74	1.74	1.85	11.17	11.39	11.23	11.35	11.46	11.82
0.5	1.69	1.74	1.85	1.94	2.00	2.18	10.98	11.61	11.22	11.57	12.16	11.91
0.6	2.07	2.08	2.18	2.29	2.48	2.81	11.42	11.78	13.06	14.50	13.07	13.76
	$-\ln L_{rec}$						k_r^P / k_N^P					
0.1	1.75	1.61	1.42	1.26	1.18	1.04	2.128	1.990	1.853	1.719	1.604	1.486
0.2	1.01	0.83	0.76	0.71	0.56	0.54	1.876	1.736	1.621	1.508	1.399	1.296
0.3	0.77	0.68	0.70	0.58	0.48	0.51	1.647	1.528	1.423	1.315	1.214	1.127
0.4	1.01	1.00	0.92	0.91	0.95	0.91	1.445	1.340	1.242	1.146	1.062	0.980
0.5	1.73	1.73	1.70	1.67	1.71	1.64	1.271	1.176	1.084	1.003	0.927	0.853
0.6	2.58	2.67	2.69	2.71	2.70	2.65	1.120	1.036	0.956	0.883	0.811	0.741
	$-\ln L_{prop}^*$											
0.1	126.5	125.5	125.4	124.7	126.1	126.3						
0.2	124.4	121.4	123.3	122.7	124.1	121.9						
0.3	117.3	117.7	116.5	119.0	120.2	121.0						
0.4	116.8	118.0	117.1	117.8	118.3	120.2						
0.5	115.8	119.1	117.1	118.9	121.9	120.7						
0.6	118.1	120.0	126.2	132.5	126.2	129.3						

M_{ad}^P

* These values do not contribute to $-\ln L_{tot}$ in this case for which $W_p^P = 0$ is specified.

Figure 2.1 shows model fits (associated with the results in Table 2.1) for a selected natural mortality- (M-) combination ($M_{ad}^P = 0.4$, $M_{ju}^P = 1.0$), with normalised residual plots for different M-combinations. There is slight suggestion of a systematic downward trend in the November survey residuals, this trend becoming more prominent as M_{ad}^P increases, indicating possible model mis-specification. The recruit survey residual plots show a poor fit to the 1994 recruit survey estimate relative to the other years, because the model deviates from that year's observations to a greater extent than would be expected given the relatively (perhaps mis-representatively) low sampling CV of 0.15 with which it is associated (Table A2.2.5).

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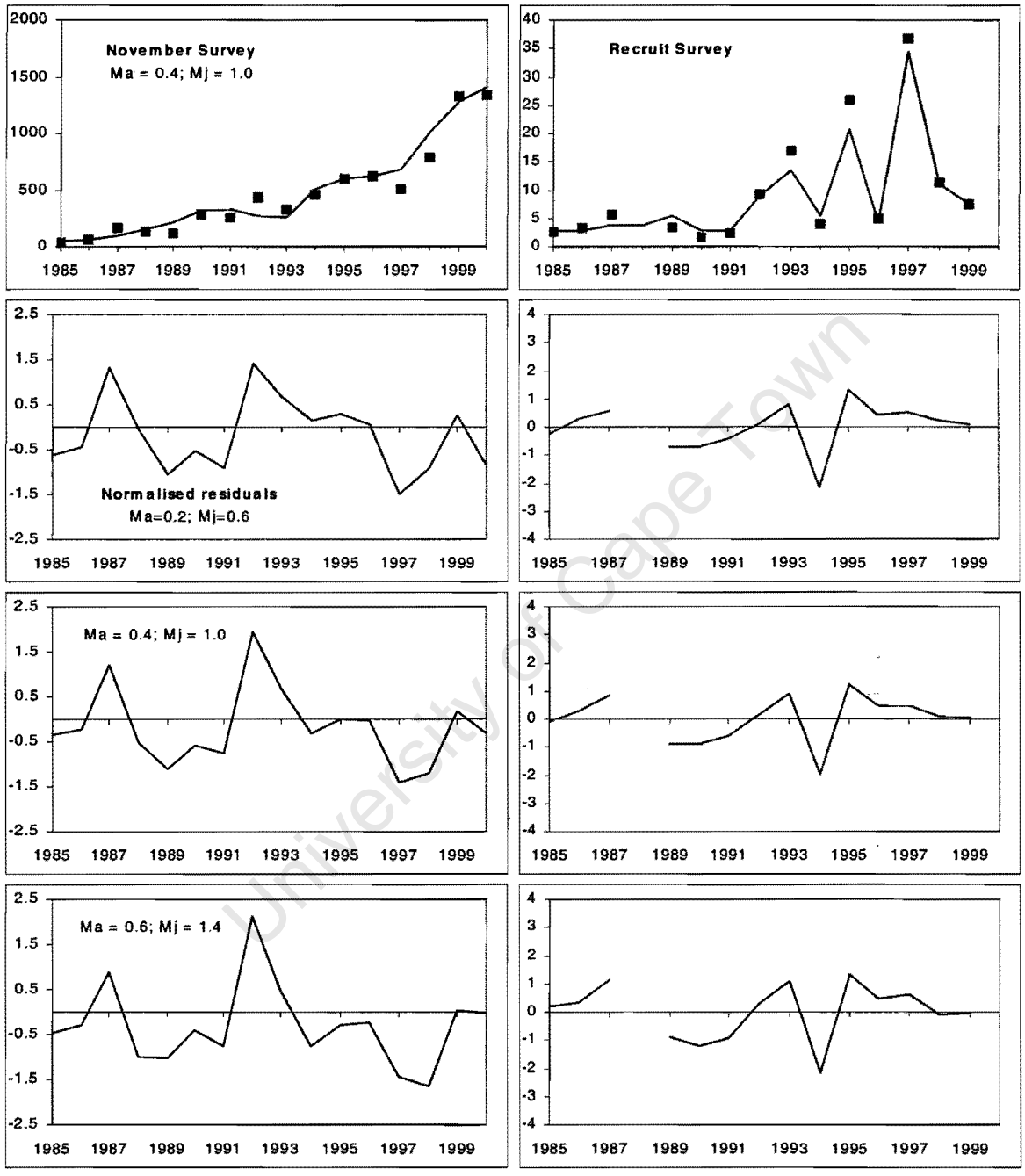
Figure 2.1: Plots, associated with Table 2.1 results, of the model fits to the November and recruit survey estimates for $M_{ad}^{P} = 0.4$ and $M_{ju}^{P} = 1.0$ (top pair of panels), with normalised residual plots for this and other M-combinations (bottom three pairs of panels). Squares indicate observations, while model estimates are shown joined by straight lines. November estimates are in thousand tons, and recruit estimates in billions of fish. The normalised residuals are calculated as $(\ln X_y - \ln \hat{X}_y)/\hat{\sigma}$, where the "hats" indicate model estimates, and the $\hat{\sigma}$ includes both additional and sampling variance (see equation A2.1.6).



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When estimating λ_N^P and λ_r^P (but keeping $W_p^P = 0$), Table 2.2 shows a small improvement in $-\ln L_{tot}$ for all M-combinations compared to Table 2.1, with trends in $-\ln L$ values and k_r^P / k_N^P as M values are varied remaining largely the same. The estimated value for λ_N^P is zero for all M-options, suggesting that provided the proportions-at-age observations are not taken into account, sampling CVs for the November survey estimates do not overestimate the overall precision of

these estimates in relation to the true abundance. However, λ_r^P values are estimated to be in the range 0.06-0.13 across all M-options, suggesting that the sampling CVs for the recruit surveys overestimate the overall precision of these surveys.

Table 2.2: Results for the model fits with $W_p^P = 0$; λ_N^P est; λ_r^P est; $k_N^P = 1.0$.

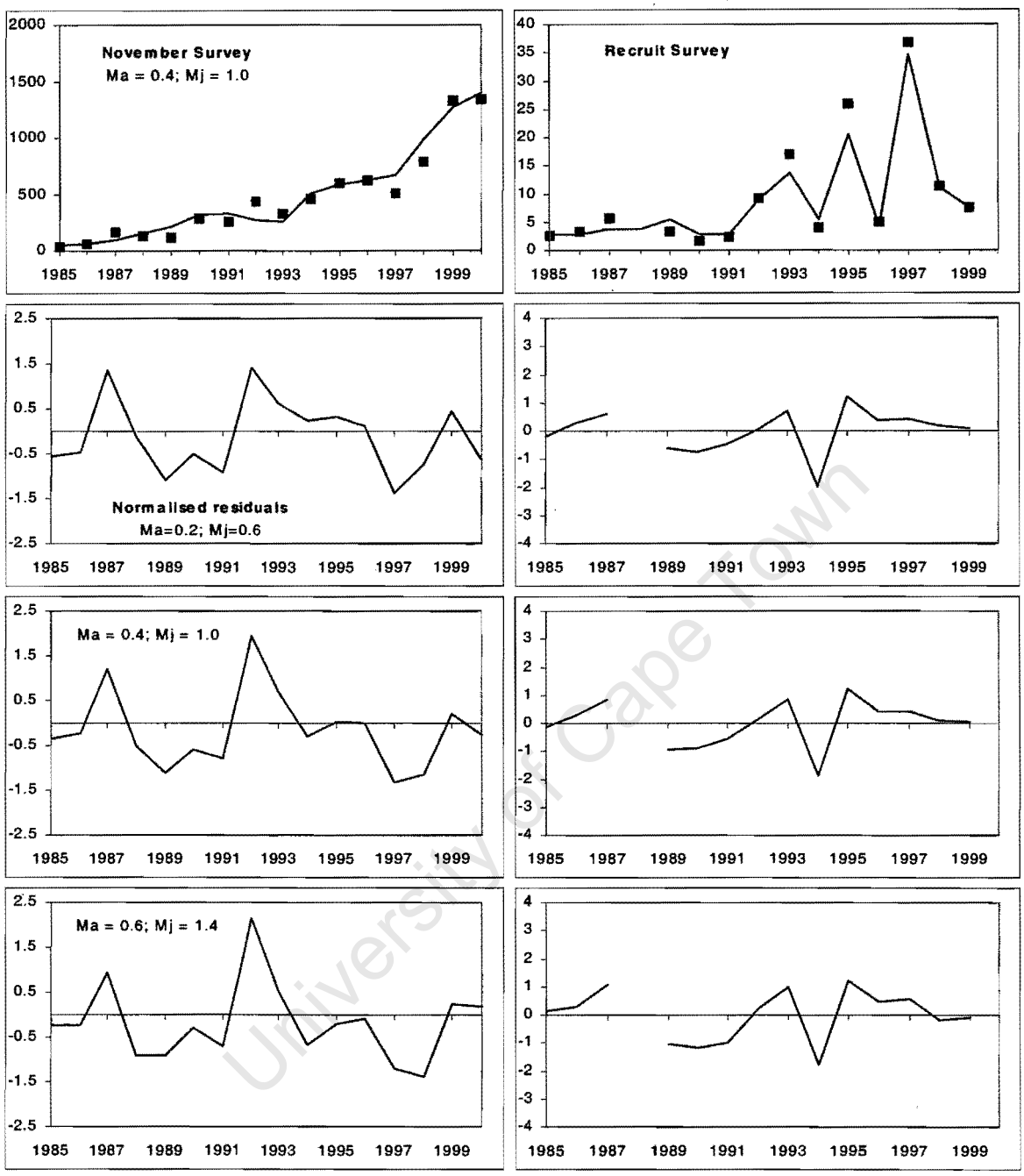
M_{ju}^P	0.4	0.6	0.8	1.0	1.2	1.4	0.4	0.6	0.8	1.0	1.2	1.4
	$-\ln L_{tot}$						$N_{0,med}^P$					
0.1	2.37	2.35	2.30	2.27	2.25	2.25	3.21	3.75	4.53	5.32	6.25	7.37
0.2	1.98	1.96	1.94	1.93	1.92	1.93	3.67	4.32	5.07	5.96	7.12	8.44
0.3	2.04	2.03	2.03	2.05	2.07	2.10	4.05	4.76	5.62	6.66	7.90	9.38
0.4	2.49	2.53	2.56	2.61	2.67	2.74	4.42	5.22	6.22	7.39	8.79	10.47
0.5	3.29	3.36	3.44	3.53	3.62	3.73	4.85	5.75	6.88	8.17	9.79	11.62
0.6	4.35	4.45	4.56	4.69	4.82	4.97	5.35	6.30	7.52	9.08	10.80	13.08
	$-\ln L_{Nov}$						σ_p^P					
0.1	0.50	0.59	0.74	0.80	0.90	0.94	12.62	13.00	13.52	13.11	13.00	12.56
0.2	0.76	0.86	1.00	1.08	1.20	1.23	12.28	13.34	12.52	14.73	12.16	12.39
0.3	1.07	1.18	1.27	1.34	1.39	1.43	11.19	11.13	11.43	11.58	11.51	11.56
0.4	1.23	1.29	1.45	1.54	1.57	1.64	11.13	11.16	11.86	11.46	11.61	12.33
0.5	1.31	1.34	1.47	1.57	1.67	1.62	11.72	12.37	11.20	11.47	13.20	14.18
0.6	1.35	1.33	1.41	1.56	1.57	1.78	10.91	11.66	11.20	11.58	13.20	11.89
	$-\ln L_{rec}$						k_r^P / k_N^P					
0.1	1.87	1.76	1.56	1.47	1.35	1.31	2.189	2.048	1.889	1.756	1.639	1.524
0.2	1.22	1.10	0.94	0.85	0.72	0.70	1.911	1.778	1.646	1.526	1.411	1.308
0.3	0.97	0.85	0.76	0.70	0.68	0.67	1.667	1.547	1.432	1.324	1.228	1.140
0.4	1.26	1.24	1.11	1.08	1.10	1.11	1.460	1.353	1.251	1.156	1.074	0.992
0.5	1.98	2.02	1.97	1.96	1.95	2.10	1.287	1.193	1.099	1.017	0.937	0.867
0.6	3.00	3.12	3.15	3.14	3.25	3.20	1.144	1.059	0.978	0.899	0.830	0.763
	$-\ln L_{prop}$ *						λ_r^P					
0.1	124.1	125.9	128.3	126.4	125.9	123.8	0.126	0.123	0.116	0.112	0.109	0.106
0.2	122.5	127.4	123.6	133.4	121.9	123.0	0.101	0.096	0.089	0.085	0.078	0.075
0.3	116.9	116.6	118.1	119.0	118.6	118.8	0.080	0.075	0.069	0.064	0.062	0.062
0.4	116.6	116.7	120.4	118.3	119.1	122.7	0.076	0.073	0.068	0.063	0.065	0.064
0.5	119.7	122.9	116.9	118.4	126.8	131.1	0.092	0.092	0.089	0.089	0.087	0.090
0.6	115.4	119.4	117.0	118.9	126.8	120.5	0.124	0.126	0.127	0.126	0.128	0.126
	λ_N^P											
0.1	0.000	0.000	0.000	0.000	0.000	0.000						
0.2	0.000	0.000	0.000	0.000	0.000	0.000						
0.3	0.000	0.000	0.000	0.000	0.000	0.000						
0.4	0.000	0.000	0.000	0.000	0.000	0.000						
0.5	0.000	0.000	0.000	0.000	0.000	0.000						
0.6	0.000	0.000	0.000	0.000	0.000	0.000						

M_{ad}^P

* These values do not contribute to $-\ln L_{tot}$ in this case for which $W_p^P = 0$ is specified.

The similarity of the results in Tables 2.1 and 2.2 is reflected in near identical plots shown in Figure 2.2 compared to Figure 2.1.

Figure 2.2: Plots associated with Table 2.2 results (see caption to Figure 2.1 for corresponding details).



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Including proportions-at-age observations provides a greater contrast in $-\ln L_{tot}$ values for different M_{ad}^{P} values (Tables 2.3 and 2.4). This indicates that the proportions-at-age estimates contain valuable information on M_{ad}^{P} and should therefore be included in the likelihood. Table 2.3 considers the case $W_p^P = 1$ and $\lambda_N^P = \lambda_r^P = 0$, and is therefore to be compared to Table 2.1.

Table 2.3: Results for the model fits with $W_p^P = 1$; $\lambda_N^P = 0$; $\lambda_r^P = 0$; $k_N^P = 1.0$.

M_{ju}^P	0.4	0.6	0.8	1.0	1.2	1.4	0.4	0.6	0.8	1.0	1.2	1.4
	$-\ln L_{tot}$						$N_{0,med}^P$					
M_{ad}^P 0.1	99.4	99.5	99.6	99.7	99.8	100.0	3.45	4.06	4.79	5.69	6.77	8.00
0.2	93.0	93.1	93.3	93.4	93.6	93.8	3.85	4.54	5.41	6.43	7.62	9.02
0.3	88.0	88.2	88.4	88.6	88.8	89.0	4.33	5.09	6.07	7.22	8.57	10.22
0.4	85.4	85.6	85.8	86.1	86.3	86.6	4.78	5.67	6.73	8.06	9.62	11.47
0.5	86.1	86.3	86.5	86.8	87.1	87.3	5.26	6.27	7.48	8.96	10.70	12.80
0.6	90.2	90.4	90.7	91.0	91.3	91.5	5.81	6.93	8.29	10.00	11.96	14.33
	$-\ln L_{Nov}$						σ_p^P					
M_{ad}^P 0.1	0.76	0.82	0.83	0.81	0.82	0.80	6.58	6.61	6.61	6.60	6.68	6.72
0.2	0.52	0.56	0.44	0.48	0.50	0.40	5.78	5.79	5.82	5.85	5.87	5.91
0.3	0.12	0.12	0.01	0.06	0.05	0.07	5.22	5.21	5.26	5.27	5.27	5.33
0.4	-0.24	-0.30	-0.27	-0.21	-0.22	-0.18	4.93	4.95	4.98	4.96	4.98	4.99
0.5	-0.51	-0.35	-0.38	-0.28	-0.28	-0.28	5.03	5.04	5.04	5.04	5.06	5.07
0.6	-0.06	-0.06	-0.05	0.18	0.18	0.24	5.46	5.47	5.47	5.47	5.47	5.49
	$-\ln L_{rec}$						k_r^P / k_N^P					
M_{ad}^P 0.1	13.66	13.39	13.42	13.68	13.08	12.84	1.987	1.851	1.722	1.597	1.483	1.380
0.2	15.18	15.19	15.10	14.98	14.92	14.78	1.738	1.620	1.502	1.393	1.291	1.204
0.3	16.70	17.05	16.77	16.76	16.95	16.47	1.523	1.417	1.317	1.218	1.130	1.043
0.4	17.92	17.98	17.81	18.13	18.22	18.29	1.351	1.253	1.159	1.070	0.988	0.913
0.5	17.70	17.64	17.86	18.01	18.08	18.21	1.207	1.110	1.029	0.947	0.876	0.807
0.6	16.44	16.53	16.73	16.81	17.11	17.15	1.074	0.994	0.918	0.842	0.777	0.715
	$-\ln L_{prop}$											
M_{ad}^P 0.1	85.0	85.3	85.4	85.2	85.9	86.3						
0.2	77.3	77.4	77.7	78.0	78.2	78.6						
0.3	71.2	71.0	71.6	71.7	71.8	72.5						
0.4	67.7	67.9	68.3	68.1	68.3	68.4						
0.5	68.9	69.0	69.1	69.1	69.3	69.4						
0.6	73.8	74.0	74.0	74.0	74.0	74.2						

Results in Table 2.3 show that the maximum likelihood fits are significantly better for M_{ad}^P values in the range 0.3-0.5 compared to other M_{ad}^P values. Furthermore, given a particular M_{ad}^P value, $-\ln L_{tot}$ remains relatively insensitive to M_{ju}^P. Although the likelihood values of Tables 2.1 and 2.3 are not strictly comparable because they apply to different sets of observations, an indication of the "improvement" in the likelihood fit achieved by inclusion of the proportions-at-age observations is possible if the sum $(-\ln L_{tot})+(-\ln L_{prop})$ from Table 2.1 is compared to $-\ln L_{tot}$ in Table 2.3. Indeed, the latter shows an improvement of between 28 and 47 in the log-likelihood value compared to the "pseudo" likelihood value of the former. Figures 2.3a and b show the model fits associated with the results in Table 2.3.

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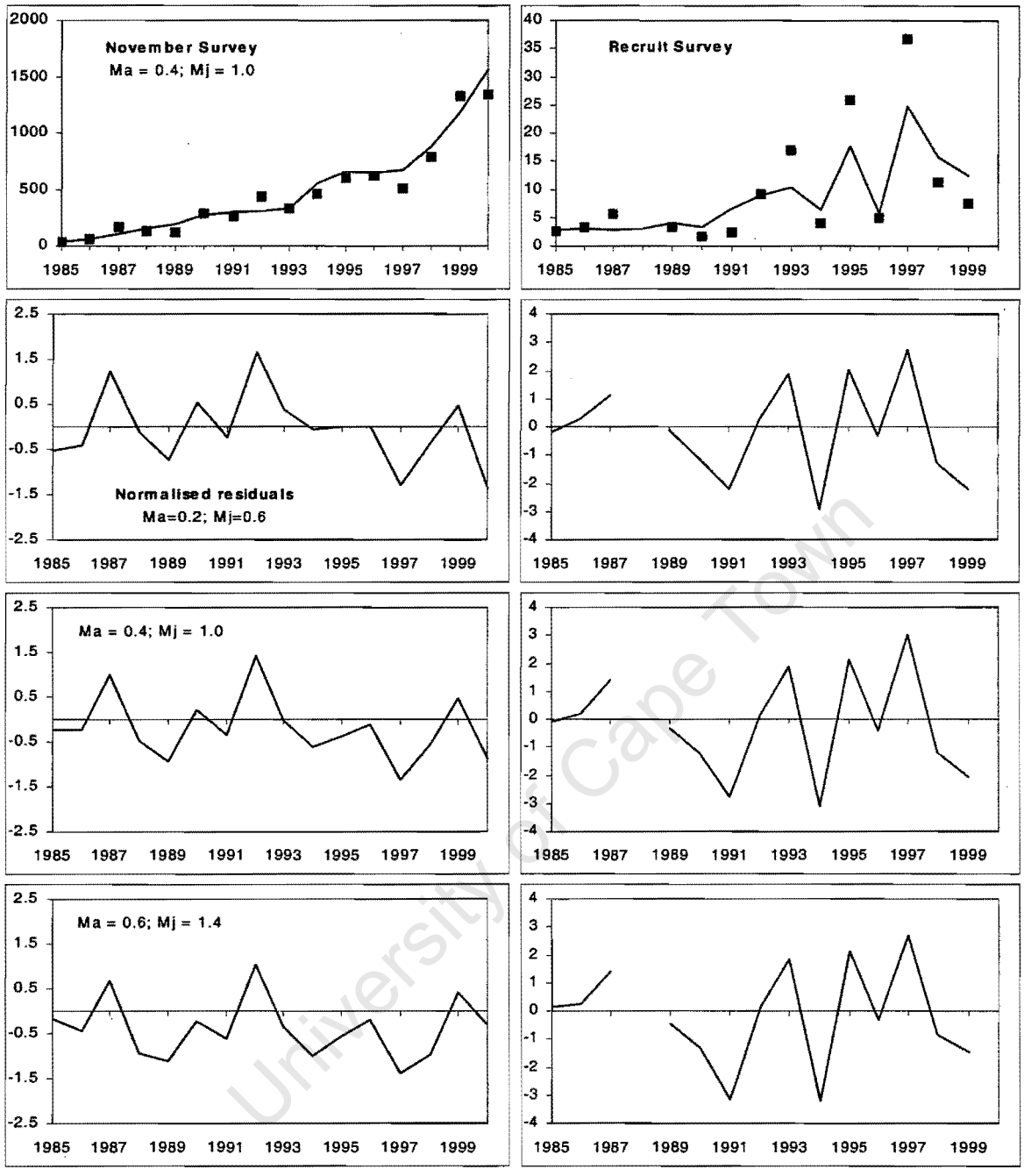
Figure 2.3a: Plots associated with Table 2.3 results (see caption to Figure 2.1 for corresponding details).



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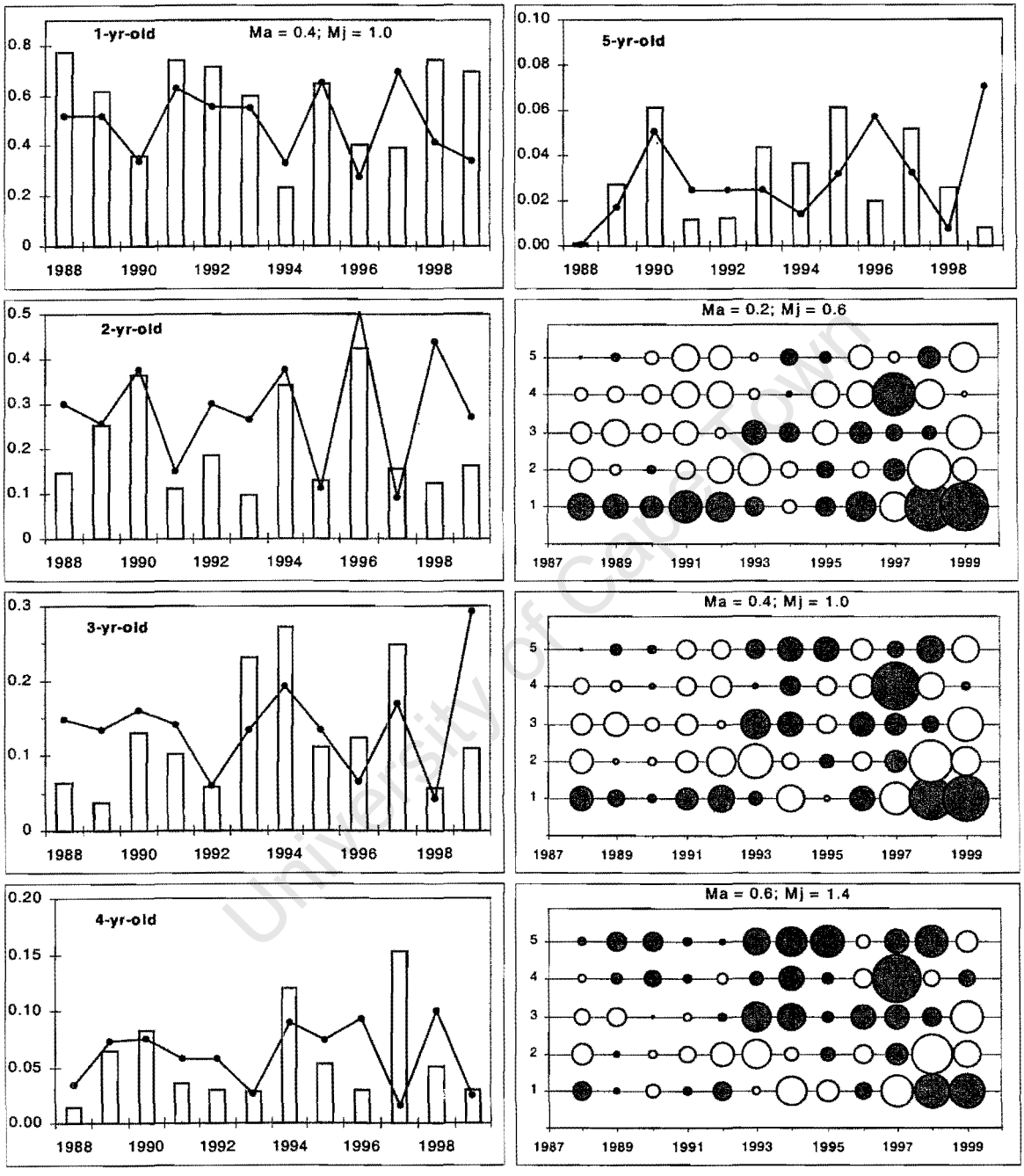
Model mis-specification is still apparent in the November survey plots of Figure 2.3a, both in terms of residual trends and bias (used here in the sense of a non-zero average residual) for the lower and higher M values respectively. Recruit survey residuals show a poorer fit to the observations compared to Figure 2.1, indicating some conflict between the recruit survey and proportions-at-age observations ($-\ln L_{\text{rec}}$ and $-\ln L_{\text{prop}}$ show opposite trends as M_{ad}^{P} increases in Table 2.3).

Figure 2.3b: Further plots, associated with Table 2.3 results, showing model fits to the proportions-at-age observations for $M_{ad}^{P} = 0.4$ and $M_{ju}^{P} = 1.0$ (bar-graphs) with normalised residual plots (bubble plots) for this and other M-combinations (bottom three pairs of panels). The bar-graphs show observations as bars with model estimates as solid dots linked by lines. Normalised residuals are calculated as $n_y p_{y,a}(\ln p_{y,a} - \ln \hat{p}_{y,a})/\hat{\sigma}$, where the "^" indicate model estimates (see equation A2.1.6), and are shown in the form of bubble plots, with shaded bubbles indicating positive residuals, white bubbles negative, and the area of each bubble indicating the magnitude of the corresponding residual.



The residual plots associated with the proportion-at-age observations are shown in Figure 2.3b, and indicate that for lower M-combinations, residuals for the younger ages are largely positive, becoming largely negative with increasing age, while the opposite trend is true for higher M-combinations. However, residuals for proportions of two year olds remain largely negative throughout. These results are not surprising, because lower M values mean more of the older fish

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survive, leading to higher model estimates for the proportions of older fish, and therefore lower estimates for the proportions of younger fish. This is reflected as largely negative residuals for older fish and largely positive residuals for younger fish if the M values used are too low. The converse applies (i.e. largely positive residuals for older and negative for younger fish) if M values are too high. The proportions-at-age observations therefore provide a basis for selecting an M-combination that leads to a balance between positive and negative residuals across all ages. Of the values considered, $M_{ad}^{P} = 0.4$ (regardless of the M_{ju}^{P} value) best achieves this in this case (see also -lnL_{tot} and -lnL_{prop} in Table 2.3).

Results for the case $W_p^P = 1$ where the additional variances $(\lambda_N^P)^2$ and $(\lambda_r^P)^2$ are estimated, are shown in Table 2.4. Estimating these additional variances significantly improves the maximum likelihood fits, by 20-30 log-likelihood points compared to Table 2.3, for all M-combinations. -lnL_{tot} also shows a slightly deeper trough across M_{ad}^{P} values for Table 2.4, with an improvement in the likelihood of 19.0 from highest to lowest likelihood value for $M_{ju}^{P} = 1.0$ (compared with 13.7 for Table 2.3). Higher values of λ_N^P and λ_r^P are estimated than was the case in Table 2.2, indicating that the acoustic surveys are not as precise as their sampling CVs would suggest, the effect being much worse for the recruit surveys than for the November surveys (overall CVs, which incorporate survey sampling CVs, exceed the sampling CVs by a multiplicative factor of 69-580% for the recruit surveys, and 0.4-167% for the November surveys across all M-combinations – see Tables A2.2.3 and A2.2.5). The model fits the proportions-at-age observations better than in Table 2.3, as shown by the improvement in -lnL_{prop} and smaller values for σ_p^P in Table 2.4. The size of the "realistic" region for k_r^P / k_N^P is greater than before, allowing more scope for selecting an appropriate (M_{ad}^{P}, M_{ju}^{P}) combination for a base-case assessment.

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Table 2.4: Results for the model fits with $W_p^P = 1$; λ_N^P est; λ_r^P est; $k_N^P = 1.0$.

M_{ju}^P	0.4	0.6	0.8	1.0	1.2	1.4	0.4	0.6	0.8	1.0	1.2	1.4
	$-\ln L_{tot}$						$N_{0,med}^P$					
0.1	76.0	76.2	76.3	76.4	76.6	76.7	3.56	4.16	4.93	5.83	6.89	8.18
0.2	68.0	68.1	68.2	68.3	68.5	68.6	3.92	4.62	5.50	6.52	7.74	9.19
0.3	60.8	60.9	61.0	61.1	61.2	61.3	4.35	5.16	6.11	7.31	8.69	10.40
0.4	57.1	57.2	57.3	57.4	57.5	57.6	4.85	5.80	6.90	8.23	9.84	11.77
0.5	58.8	58.9	59.0	59.1	59.2	59.3	5.41	6.48	7.71	9.25	11.08	13.31
0.6	66.1	66.2	66.2	66.3	66.4	66.5	6.10	7.32	8.72	10.46	12.66	15.07
	$-\ln L_{Nov}$						σ_p^P					
0.1	13.24	13.10	13.29	13.14	13.10	13.17	3.35	3.37	3.35	3.36	3.37	3.36
0.2	6.90	6.77	6.78	6.43	6.62	6.62	3.34	3.35	3.35	3.37	3.36	3.36
0.3	3.52	3.50	3.48	3.44	3.47	3.40	3.17	3.18	3.18	3.18	3.18	3.18
0.4	2.51	2.52	2.49	2.51	2.53	2.53	3.05	3.05	3.05	3.05	3.05	3.05
0.5	3.16	3.21	3.07	3.15	3.14	3.21	3.11	3.11	3.12	3.11	3.11	3.11
0.6	5.35	5.54	5.52	5.47	5.98	5.49	3.39	3.37	3.37	3.38	3.35	3.38
	$-\ln L_{rec}$						k_r^P / k_N^P					
0.1	18.20	18.19	18.40	18.51	18.61	18.79	1.715	1.619	1.498	1.394	1.302	1.210
0.2	16.70	16.71	16.92	16.93	17.12	17.16	1.541	1.438	1.324	1.235	1.147	1.069
0.3	15.95	16.06	16.15	16.23	16.38	16.47	1.365	1.267	1.181	1.089	1.011	0.934
0.4	15.67	15.75	15.86	15.96	16.09	16.18	1.206	1.113	1.031	0.954	0.884	0.818
0.5	15.56	15.64	15.72	15.86	15.94	16.06	1.065	0.982	0.910	0.839	0.775	0.715
0.6	15.53	15.64	15.76	15.87	16.00	16.04	0.938	0.865	0.802	0.740	0.678	0.631
	$-\ln L_{prop}$						λ_r^P					
0.1	44.6	44.9	44.6	44.8	44.8	44.7	0.837	0.836	0.849	0.857	0.863	0.875
0.2	44.4	44.6	44.5	45.0	44.7	44.8	0.744	0.744	0.756	0.756	0.768	0.769
0.3	41.3	41.3	41.4	41.4	41.4	41.5	0.701	0.707	0.711	0.716	0.724	0.728
0.4	38.9	38.9	39.0	38.9	38.9	38.9	0.686	0.690	0.695	0.701	0.707	0.712
0.5	40.1	40.1	40.2	40.1	40.1	40.0	0.680	0.684	0.688	0.695	0.699	0.705
0.6	45.2	45.0	45.0	45.0	44.5	45.0	0.678	0.684	0.690	0.695	0.703	0.704
	λ_N^P											
0.1	0.469	0.463	0.471	0.465	0.463	0.466						
0.2	0.250	0.245	0.247	0.235	0.242	0.240						
0.3	0.136	0.135	0.133	0.132	0.133	0.130						
0.4	0.078	0.078	0.076	0.076	0.073	0.078						
0.5	0.080	0.083	0.077	0.081	0.080	0.083						
0.6	0.154	0.161	0.162	0.160	0.177	0.161						

Figures 2.4a and b show model fits associated with the results in Table 2.4. There is less evidence of residual trends and bias for $M_{ad}^P = 0.4$ in the November survey plots of Figure 2.4a compared to Figure 2.3a. A non-zero λ_r^P value has dampened the fluctuations in the recruit residuals somewhat, the residual plots remaining relatively unchanged for the options shown.

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Trends in the residual plots shown in Figure 2.4b are similar to those in Figure 2.3b, although the magnitude of the residuals in the former is larger due to the smaller σ_p^P values (Table 2.4).

Figure 2.4a: Plots associated with Table 2.4 results (see caption to Figure 2.1 for corresponding details).

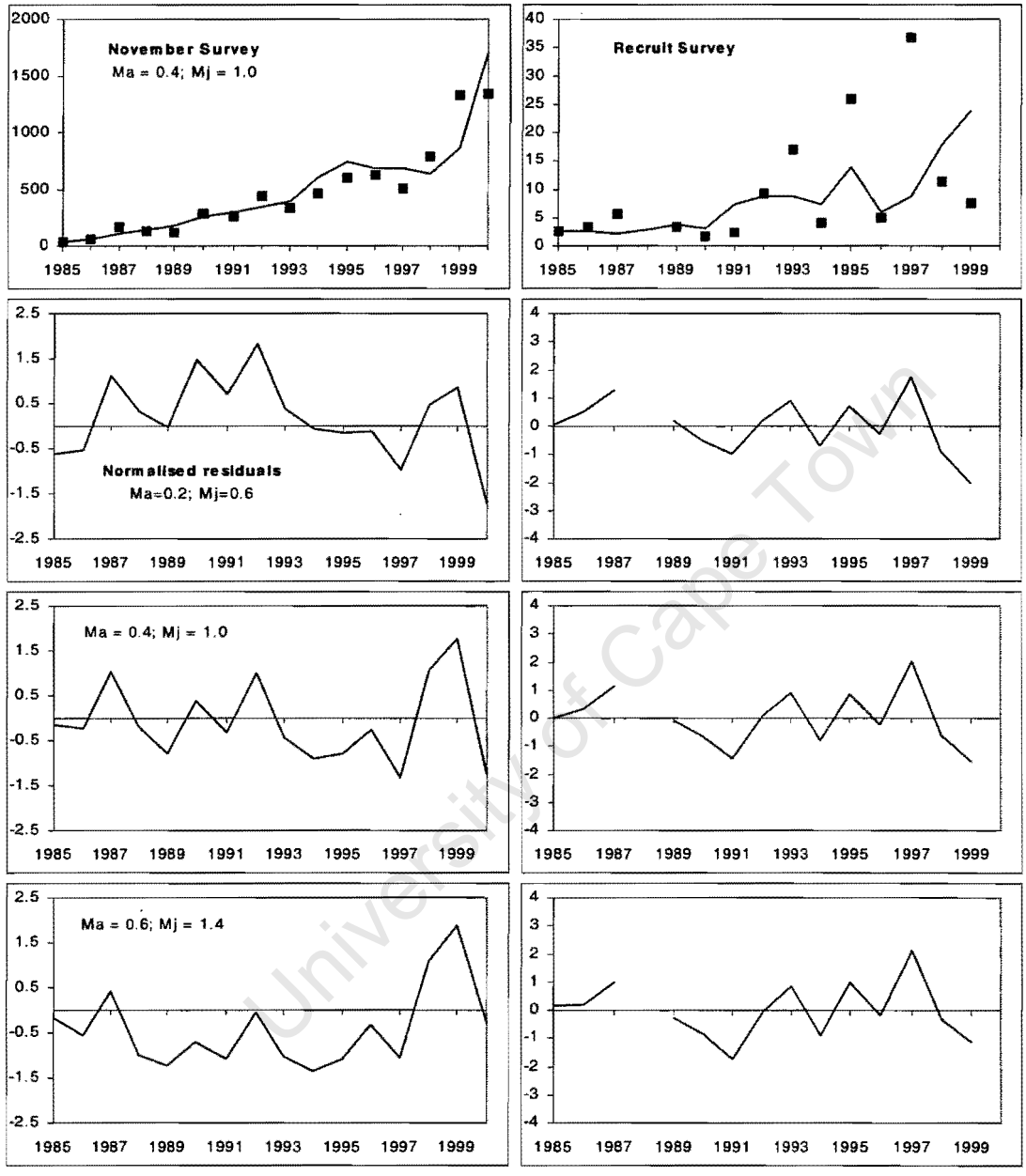

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Figure 2.4b: Further plots, associated with Table 2.4 (see caption to Figure 2.3b for corresponding details).

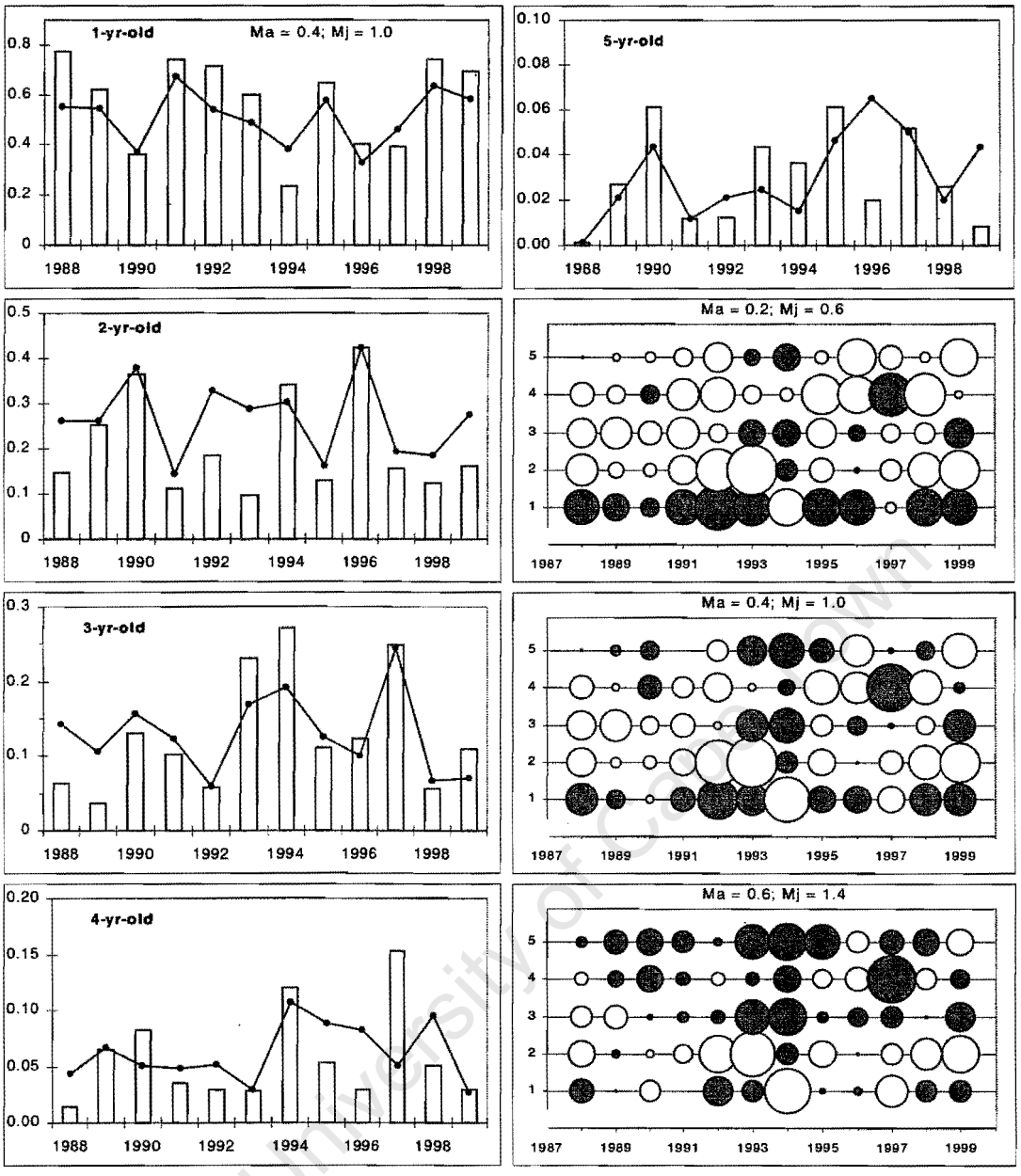

Table 2.5 shows a subset of results for keeping either λ_N^P or λ_r^P fixed while estimating the other. For the option of estimating λ_N^P while fixing λ_r^P, there are two reasons why λ_r^P was fixed at 0.38 rather than zero:

- 0.38 is the corresponding λ_r value for anchovy (Chapter 3), and because of the greater uncertainty surrounding acoustic estimates of pilchard recruitment compared to anchovy (Hampton 1992), it was felt that the additional variance associated with pilchard recruitment should be at least as large as that associated with anchovy recruitment; and

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- there is more uncertainty associated with recruit surveys than with November surveys for pilchard (Hampton 1992), hence it is unlikely that $\lambda_N^P > \lambda_r^P$ (which would be the case if λ_r^P is fixed at zero while λ_N^P is estimated).

Table 2.5: Results for the model fits for the two options shown in the first row.

		$W_p^P=1$; λ_N^P est; $\lambda_r^P=0.38$; $k_N^P=1.0$						$W_p^P=1$; $\lambda_N^P=0$; λ_r^P est; $k_N^P=1.0$					
M_{ju}^P		**0.4**	**0.6**	**0.8**	**1.0**	**1.2**	**1.4**	**0.4**	**0.6**	**0.8**	**1.0**	**1.2**	**1.4**
		-lnL_{tot}						-lnL_{tot}					
M_{ad}^P	**0.1**	81.7	81.9	82.1	82.3	82.5	82.8	78.7	78.9	79.0	79.1	79.2	79.3
	0.2	72.3	72.5	72.8	73.0	73.2	73.5	68.9	69.0	69.2	69.3	69.4	69.5
	0.3	64.7	64.9	65.1	65.4	65.6	65.8	61.0	61.1	61.2	61.3	61.4	61.6
	0.4	60.8	61.0	61.2	61.4	61.6	61.8	57.1	57.2	57.3	57.4	57.5	57.6
	0.5	62.4	62.6	62.8	63.0	63.1	63.4	58.8	58.9	59.0	59.1	59.3	59.3
	0.6	69.4	69.6	69.8	70.0	70.2	70.3	66.3	66.4	66.5	66.6	66.7	66.8
		λ_N^P						λ_r^P					
M_{ad}^P	**0.1**	0.186	0.168	0.176	0.156	0.142	0.144	0.682	0.690	0.697	0.697	0.707	0.712
	0.2	0.146	0.136	0.129	0.118	0.119	0.114	0.688	0.696	0.698	0.705	0.712	0.716
	0.3	0.074	0.072	0.070	0.066	0.064	0.060	0.688	0.693	0.696	0.705	0.709	0.715
	0.4	0.000	0.000	0.000	0.000	0.000	0.000	0.684	0.685	0.694	0.699	0.703	0.709
	0.5	0.000	0.000	0.000	0.000	0.000	0.000	0.675	0.681	0.684	0.692	0.695	0.702
	0.6	0.000	0.000	0.000	0.000	0.000	0.000	0.662	0.670	0.673	0.678	0.684	0.690

The two sets of results shown in Table 2.5 are intermediate to the set shown in Table 2.3 on the one hand, and that in Table 2.4 on the other. Results on the right-hand-side of Table 2.5 (λ_r^P estimated while $\lambda_N^P=0$) are much closer to Table 2.4 than those on the left. In fact, in all cases except those where $M_{ad}^P=0.1$, freeing both λ_N^P and λ_r^P (Table 2.4) does not lead to significantly better likelihood values compared to allowing only λ_r^P to be free (right-hand side of Table 2.5), indicating that λ_N^P could be set to zero. However there is still scope for improvement in the likelihood value for all *M*-combinations when fixing λ_r^P (compare left-hand-side of Table 2.5 to Table 2.4).

Results for varying k_N^P are shown in Table 2.6. Best fits occur for $M_{ad}^P=0.5$ when $k_N^P=0.5$ (left-hand-side set of results) and for $M_{ad}^P=0.4$ when $k_N^P=1.5$ (right-hand-side), although there is no significant improvement over $M_{ad}^P=0.3$ for the latter.

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Table 2.6: Results for the model fits for the two options shown in the first row.

		$W_p^P = 1$; λ_N^P est; λ_r^P est; $k_N^P = 0.5$						$W_p^P = 1$; λ_N^P est; λ_r^P est; $k_N^P = 1.5$					
	M_{ju}^P	**0.4**	**0.6**	**0.8**	**1.0**	**1.2**	**1.4**	**0.4**	**0.6**	**0.8**	**1.0**	**1.2**	**1.4**
		$-\ln L_{tot}$						$-\ln L_{tot}$					
M_{ad}^P	**0.1**	80.5	80.7	80.8	80.9	81.1	81.2	72.3	72.4	72.5	72.6	72.7	72.9
	0.2	72.9	73.0	73.1	73.3	73.4	73.5	65.3	65.4	65.5	65.6	65.7	65.8
	0.3	63.5	63.6	63.7	63.8	63.9	64.1	60.7	60.8	60.9	61.0	61.1	61.2
	0.4	56.4	56.5	56.6	56.7	56.8	56.9	60.6	60.7	60.8	60.9	61.0	61.1
	0.5	53.9	54.1	54.2	54.3	54.4	54.5	65.9	66.0	66.1	66.2	66.2	66.4
	0.6	57.6	57.7	57.8	57.9	58.0	58.1	74.3	74.4	74.4	74.5	74.6	74.7
		k_r^P / k_N^P						k_r^P / k_N^P					
M_{ad}^P	**0.1**	2.018	1.898	1.696	1.629	1.520	1.442	1.465	1.372	1.288	1.175	1.114	1.048
	0.2	1.853	1.709	1.589	1.467	1.364	1.274	1.312	1.227	1.138	1.063	0.983	0.914
	0.3	1.639	1.513	1.392	1.285	1.188	1.100	1.165	1.081	1.008	0.935	0.867	0.804
	0.4	1.431	1.324	1.220	1.127	1.039	0.955	1.030	0.956	0.886	0.823	0.763	0.708
	0.5	1.264	1.162	1.071	0.989	0.908	0.838	0.886	0.827	0.771	0.716	0.660	0.615
	0.6	1.121	1.031	0.952	0.871	0.803	0.740	0.723	0.677	0.622	0.568	0.527	0.490

2.4 Discussion

Selection of a base-case assessment

A base-case assessment is selected on the basis of being the "most likely" or "best" fit of the model to the available observations. It is important to select such an assessment because it is useful to provide the core of a basis for developing and testing management procedures (Chapters 4 and 5).

Model fits for the additional variances set to zero ($(\lambda_N^P)^2 = (\lambda_r^P)^2 = 0$) show residual trends and bias across all M-combinations, whether proportions-at-age observations are taken into account or not (Figures 2.1 and 2.3), indicating model mis-specification and the need to possibly estimate these additional variances. Model fits improve somewhat when these variances are estimated (Tables 2.2 and 2.4, Figures 2.2 and 2.4). This is particularly the case if λ_r^P is estimated (Table 2.5). Although there is no significant improvement for $M_{ad}^P > 0.1$ if λ_N^P is estimated instead of being set to zero (Tables 2.4 and 2.5), an estimated λ_N^P is considered to be more appropriate for a base-case assessment because the sampling CV alone is unlikely to reflect the overall precision of a survey.

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Introduction of the proportions-at-age observations provides the key to estimating M_{ad}^{P} by generating greater contrast in -lnL_{tot} for different M_{ad}^{P} values, and thus narrowing the range of M_{ad}^{P} values that lead to significantly better fits (Tables 2.3 and 2.4). Given this and the above concerns about estimating the additional variances, Table 2.4 seems to provide the most appropriate framework from which to select a base-case assessment.

The best fits in Table 2.4 are achieved when $M_{ad}^{P} = 0.4$, but a choice for M_{ju}^{P} is more difficult given the relative insensitivity of -lnL_{tot} to this value. This is because estimates of begin-year 0-year-old fish ($N_{y,0}^{P}$) can be equally well explained by a range of combinations of M_{ju}^{P} and k_r^P, i.e. these two parameters are confounded. The ratio k_r^P / k_N^P, which should be in the range [0.5; 1] according to acoustic survey scientists, therefore provides the only basis for selecting M_{ju}^{P}. Using this criterion, together with minimum -lnL_{tot} considerations, $M_{ju}^{P} = 1.0$ was selected. The base-case assessment specifications chosen were therefore: $M_{ad}^{P} = 0.4$ and $M_{ju}^{P} = 1.0$ for $W_p^P = 1$, λ_N^P estimated, λ_r^P estimated and $k_N^P = 1.0$.

Selection of alternative plausible scenarios

Although the base-case assessment is used in the sense of being "the best fit" to the available observations, there are other fits to the observations that are near equally plausible, and these need to be taken into account when developing management procedures, so that the management procedure eventually chosen shows adequately robust performance across a range of alternative, plausible assessments of the resource.

Table 2.7 summarises results taken from Tables 2.2-2.6 for the base-case assessment, P_0, and a range of alternatives P_1-P_{10}, which are forthwith treated as "best" estimates with associated bootstrap estimates of precision (given as CVs in the form of percentages; Appendix 2.1). These alternatives were selected on the basis of defining the "limits" of plausible assessments. Thus, M_{ad}^{P} values of 0.3 and 0.5 for $M_{ju}^{P} = 1.0$, and M_{ju}^{P} values of 0.6 and 1.4 for $M_{ad}^{P} = 0.4$ (P_1, P_2, P_3 and P_4) were selected from Table 2.4 because their associated -lnL_{tot} values are not greatly

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different to that for $M_{ad}^{P}=0.4$ and $M_{ju}^{P}=1.0$, and their ratios k_r^P / k_N^P are largely in the range [0.5; 1][25].

Similarly, $k_N^P=1.5$ and $k_N^P=0.5$ (P_5 and P_6) are chosen to reflect realistic upper and lower bounds for this parameter, with the associated M_{ad}^{P} values selected on the basis that they reflect better fits than other M_{ad}^{P} values, and that the ratio k_r^P / k_N^P is similar to that for the base-case assessment P_0 (Table 2.6). The options of ignoring the proportions-at-age observations (P_7), and alternately setting λ_N^P and λ_r^P (or both) to a fixed value (P_8, P_9 and P_{10}) are also considered.

Table 2.7: Summary of results for assessments P_0-P_{10} selected from Tables 2.2-2.6. Options for M_{ad}^{P}, M_{ju}^{P}, k_N^P, W_p^P, λ_N^P and λ_r^P are shown on the left, with empty cells taking on the corresponding option shown for P_0. Values in italics for $-\ln L_{prop}$, λ_N^P and λ_r^P indicate that they have been fixed rather than estimated. CVs associated with the "best estimates" shown are expressed as percentages in smaller print.

	M_{ad}^{P}	M_{ju}^{P}	k_N^P	W_p^P	λ_N^P	λ_r^P	$-\ln L_{tot}$	$\ln L_{Nov}$	$-\ln L_{rec}$	$-\ln L_{prop}$	λ_N^P	λ_r^P	k_r^P / k_N^P	σ_p^{P}*	$N_{0,med}^{P}$
P_0	0.4	1.0	1	1	est	est	57.4	2.51	16.0	38.9	0.076 160%	0.701 29%	0.954 20%	3.05 20%	8.23 6%
P_1	0.3						61.1	3.44	16.2	41.4	0.132 145%	0.716 30%	1.089 21%	3.18 20%	7.31 7%
P_2	0.5						59.1	3.15	15.9	40.1	0.081 147%	0.695 34%	0.839 23%	3.11 21%	9.25 12%
P_3		0.6					57.2	2.52	15.7	38.9	0.078 181%	0.690 32%	1.113 20%	3.05 24%	5.80 22%
P_4		1.4					57.6	2.51	16.2	38.9	0.077 153%	0.712 28%	0.814 23%	3.05 25%	11.81 12%
P_5		0.6	1.5				60.7	3.47	15.5	41.8	0.101 133%	0.677 27%	0.956 24%	3.20 21%	4.84 11%
P_6	0.5		0.5				54.3	2.10	16.3	35.9	0.044 188%	0.715 30%	0.989 22%	2.90 22%	13.95 10%
P_7				0			2.6	1.54	1.1	*0.0*	0.000 279%	0.063 580%	1.156 9%	11.46 20%	7.39 4%
P_8					0		57.4	2.49	15.9	39.0	*0.000*	0.699 37%	0.956 22%	3.05 28%	8.22 5%
P_9						0.38	61.4	1.73	18.4	41.3	0.000 270%	*0.380*	0.982 16%	3.17 23%	8.19 9%
P_{10}					0	0	86.1	-0.21	18.1	68.1	*0.000*	*0.000*	1.070 8%	4.96 25%	8.06 5%

*The proportions-at-age observations are not fitted for P_7, so that the σ_p^P value for P_7 is not a maximum likelihood estimate, but merely a reflection of the discrepancies between these observations and the model predictions.

Other parameter estimates for the operating model

In addition to M_{ad}^{P}, M_{ju}^{P}, λ_N^P, λ_r^P, k_N^P, k_r^P and $N_{0,med}^{P}$ (Table 2.7), other parameters required for the operating model used to test management procedures are the begin-year numbers-at-age for

[25] These criteria for selecting alternative assessments have been applied somewhat loosely; thus, P_1 is, strictly speaking, significantly different from P_0, and k_r^P / k_N^P is just greater than 1 for both P_1 and P_3 in Table 2.7.

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the first year of the projection period ($N^P_{2000,1}$,..., $N^P_{2000,5}$), fishing selectivity for 1-4-year-old pilchard (S^P_1,..., S^P_4), and parameters related to the stock-recruit curves, namely carrying capacity K^P, recruitment variability $(\sigma^P_r)^2$, recruitment serial correlation s^P_{cor}, the 1999 recruitment residual value η^P_{1999}, and the actual parameters of the stock-recruit curves a^P, b^P and m^P (equations A2.1.10-19). The estimates of begin-year numbers- and fishing selectivities-at-age for the base-case and the alternative assessments are shown in Table 2.8, while estimates of the parameters related to the stock-recruit curves are shown in Table 2.9, in both cases with bootstrap estimates of precision.

Table 2.8: Estimates of begin-year numbers-at-age for the first year of the management procedure projection period, $N^P_{2000,1}$,..., $N^P_{2000,5}$, and estimates of selectivities-at-age, S^P_1,..., S^P_4 for assessments P_0-P_{10} with associated CVs (expressed as percentages in small print).

	$N^P_{2000,1}$	$N^P_{2000,2}$	$N^P_{2000,3}$	$N^P_{2000,4}$	$N^P_{2000,5}$	S^P_1	S^P_2	S^P_3	S^P_4
P_0	14.919 29%	7.134 18%	1.810 22%	0.681 29%	1.124 29%	0.537 4%	1.000 0%	0.852 7%	0.445 12%
P_1	16.052 39%	7.747 25%	2.074 27%	0.814 31%	1.495 32%	0.576 4%	1.000 0%	0.798 8%	0.39 13%
P_2	14.593 41%	6.630 29%	1.636 32%	0.557 35%	0.826 31%	0.498 5%	1.000 0%	0.923 7%	0.52 15%
P_3	15.130 47%	7.106 43%	1.835 41%	0.679 37%	1.118 30%	0.537 4%	1.000 0%	0.855 8%	0.446 14%
P_4	15.082 37%	7.134 28%	1.823 32%	0.681 38%	1.119 28%	0.537 4%	1.000 0%	0.854 6%	0.446 12%
P_5	9.883 43%	4.613 30%	1.165 36%	0.371 47%	0.664 37%	0.520 5%	1.000 0%	0.910 7%	0.502 16%
P_6	29.997 34%	13.585 24%	3.454 25%	1.310 29%	1.858 28%	0.518 4%	1.000 0%	0.860 7%	0.452 12%
P_7	3.496 32%	3.238 32%	7.691 13%	0.169 112%	1.572 21%	0.331 17%	0.573 16%	0.722 16%	1.000 15%
P_8	14.808 32%	7.098 19%	1.811 23%	0.678 30%	1.120 26%	0.537 4%	1.000 0%	0.854 6%	0.446 12%
P_9	12.972 29%	6.771 18%	2.193 20%	0.655 33%	1.153 26%	0.542 4%	1.000 0%	0.883 6%	0.468 12%
P_{10}	6.714 30%	5.375 26%	5.796 13%	0.485 62%	1.394 28%	0.531 9%	0.950 5%	1.000 1%	0.588 15%

In Table 2.9, assessments P_0-P_{10} use the "SS" curve[26], while the combination of P_0 and the "BH" curve is renamed P_{11}, and P_0 and the "DS" curve P_{12}. When fitting these curves, constraints were used to ensure that feasible stock-recruit parameter estimates were obtained (these constraints are listed in Appendix 2.1). In the case of the "BH" curve (P_{11}), the constraint on K^P (<10 million tons) was rarely encountered, with only 9% of the bootstrap runs coming within 10% of this limit (in the case of the "SS" and "DS" curves - P_0 and P_{12} respectively - this constraint was never encountered). This constraint is justified on the basis that, although historical catches indicate

[26] "SS" = "Single-Sloped", "BH" = "Beverton-Holt" and "DS" = "Double-Sloped" – see equations A2.1.10-12 for details. [Note: The "SS" curve has traditionally been used for South African pelagic stocks. Because there is no clear reason to prefer any of the curves in Figure 2.5, it has continued to be used for most of the assessments presented.]

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that the pilchard biomass may have been in the millions of tons, it is unlikely that it exceeded ten million tons.

Although not immediately clear from Table 2.9, the constraint on b^P (i.e. that b^P should not exceed the largest $B^P_{y,N}$ values used in the fit) for the "SS" and "DS" curves (P_0 and P_{12} respectively) also played a role. In the both cases, b^P encountered this constraint in 13% of the bootstrap runs. The justification for this constraint is that, with no "data" beyond the largest $B^P_{y,N}$ value, the fitting procedure has no information on which to fix a "kink" in these two curves at some higher abundance. Figure 2.5 plots the three stock-recruit curves for the stock-recruit "best" estimates for assessment P_0, with 95% bootstrap confidence intervals also shown for these "best" estimates.

Table 2.9: Estimates of parameters related to the "SS" ("Single-Sloped") stock-recruit curves for assessments P_0-P_{10}, namely carrying capacity K^P, recruitment variability σ_r^P, recruitment serial correlation s_{cor}^P, the 1999 recruitment residual value η_{1999}^P, and the actual parameters of the stock-recruit curves a^P and b^P. P_{11} and P_{12} represent assessments identical to P_0, except that the "BH" ("Beverton-Holt") and "DS" ("Double Sloped") curves are used respectively, instead of the "SS" curve (see equations A2.1.10-12 for details). The "DS" curve requires an additional parameter, m^P. Bootstrap CVs are expressed as percentages in small print.

	K^P	σ_r^P	s_{cor}^P	η_{1999}^P	a^P	b^P	m^P
	"SS" curve						
P_0	1552 25%	0.499 18%	0.374 75%	1.336 37%	21.64 24%	413.7 47%	-
P_1	1725 36%	0.474 21%	0.303 67%	1.698 55%	20.24 36%	435.3 43%	-
P_2	1324 23%	0.498 18%	0.386 80%	1.277 59%	21.85 22%	369.3 60%	-
P_3	1598 27%	0.505 20%	0.391 88%	1.312 55%	14.89 25%	412.6 48%	-
P_4	1533 28%	0.497 18%	0.358 76%	1.373 45%	31.93 27%	429.8 49%	-
P_5	1150 20%	0.477 18%	0.442 63%	1.208 71%	10.86 19%	262.6 49%	-
P_6	2474 27%	0.506 23%	0.263 119%	1.413 47%	40.69 26%	847.3 51%	-
P_7	939 22%	0.655 9%	0.057 206%	-0.112 94%	11.97 20%	131.0 46%	-
P_8	1546 21%	0.501 19%	0.376 98%	1.326 43%	21.54 21%	412.8 37%	-
P_9	1532 24%	0.489 19%	0.369 88%	1.105 48%	21.47 24%	416.2 40%	-
P_{10}	1485 18%	0.523 18%	0.123 499%	-0.056 264%	20.46 20%	402.5 37%	-
	"BH" curve						
P_{11}	1727 96%	0.426 16%	0.261 80%	1.611 30%	30.05 125%	356.3 189%	-
	"DS" curve						
P_{12}	2009 22%	0.497 18%	0.384 72%	1.183 39%	21.64 24%	413.7 47%	0.0040 18%

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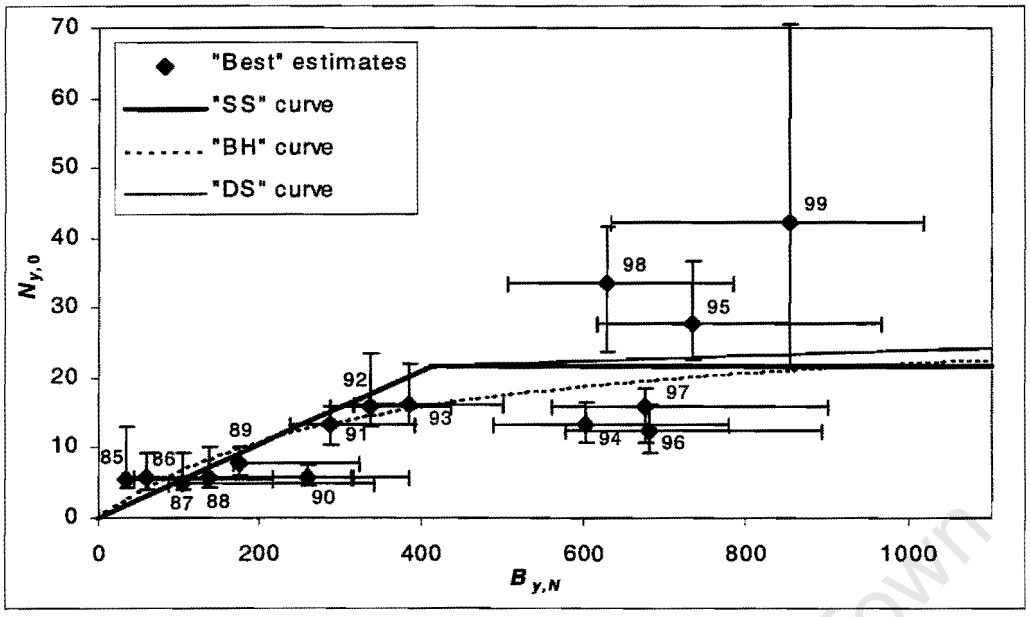
Figure 2.5: Three stock-recruit curves fitted to the stock-recruit "best" estimates for assessment P_0 (see Table 2.9 caption and Appendix 2.1 for details), with bootstrap-based 95% confidence intervals shown for these "best" estimates, together with corresponding years.



In order to obtain the bootstrap estimates of precision shown in Tables 2.7-2.9 and in Figure 2.5, pseudo-data sets based on fits to the actual data were generated. However, as the fits to the proportions-at-age observations were biased (e.g. Figure 2.4), these biases needed to be taken into account when generating the pseudo-data sets (Appendix 2.1). Table 2.10 shows these estimates of bias, $k_{p,a}^{P'}$, together with $\sigma_p^{P'}$, which is the σ_p^P value as adjusted to take these biases into account. The original σ_p^P "best" estimates are included in the Table for comparison with $\sigma_p^{P'}$.

Table 2.10: Estimates of bias, $k_{p,a}^{P'}$, for the model fits to the proportions-at-age observations for all assessments except P_7, together with the original and adjusted variance associated with these fits (given by $(\sigma_p^P)^2$ and $(\sigma_p^{P'})^2$ respectively).

	$k_{p,1}^{P'}$	$k_{p,2}^{P'}$	$k_{p,3}^{P'}$	$k_{p,4}^{P'}$	$k_{p,5}^{P'}$	$\sigma_p^{P'}$	σ_p^P
P_0	1.135	0.788	1.113	1.004	1.250	2.77	3.05
P_1	1.193	0.788	1.042	0.876	1.001	2.79	3.18
P_2	1.078	0.794	1.206	1.184	1.629	2.77	3.11
P_3	1.135	0.789	1.112	1.005	1.248	2.77	3.05
P_4	1.134	0.789	1.113	1.005	1.250	2.77	3.05
P_5	1.113	0.777	1.164	1.115	1.512	2.86	3.20
P_6	1.101	0.805	1.145	1.052	1.321	2.67	2.90
P_8	1.135	0.788	1.113	1.005	1.250	2.77	3.05
P_9	1.146	0.777	1.103	1.024	1.279	2.86	3.17
P_{10}	1.261	0.750	1.100	1.249	1.551	4.55	4.96

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APPENDIX 2.1

Pilchard assessment model

Model Assumptions

1. All fish have a theoretical birthdate of 1 November, but become available to the fishery only from 1 January.
2. Pilchard spawn for the first time (and are called adult pilchard) when they turn one year old.
3. Pilchard die once they reach five years of age and have spawned a final time.
4. Two surveys are held each year: the first takes place in November (known as the November survey) and surveys the adult stock; the second is in May/June (known as the recruit survey) and surveys juvenile pilchard (also called recruits or 0-year-old pilchard).
5. The November survey provides a relative index of abundance of known bias.
6. The recruit survey provides a relative index of abundance of unknown bias.
7. The survey strategy is such that it results in surveys of invariant bias over time.
8. Pulse fishing occurs 6 months after the birthdate.
9. Catches are measured without error.
10. Natural mortality is year-invariant for juvenile and adult fish, and age-invariant for adult fish.

[Assumption 9 is reasonable for the South African pelagic fishery because the sampling procedures and the overall coverage of landings are such that actual landings are fairly accurately represented. However, unknown and variable levels of dumping (for example when pilchard bycatch allocations in the anchovy fishery are in danger of being exceeded, when fish in directed catches of pilchard are too small to can, and when operational targets set by the canning factories are exceeded) are known to exist, but are ignored in the assessments. The recent introduction of wide observer coverage may in due course give some idea of the magnitude of this problem. Given such insight into possible dumping levels, subsequent analyses should consider the implications of dumping.]

Basic Dynamics

The basic dynamic equations are as follows.

Numbers-at-age at the beginning of the year:

$$N^{P}_{y+1,1} = (N^{P}_{y,0} e^{-M^{P}_{ju}/2} - C^{P}_{y,0} / w^{P}_{y,0c}) e^{-M^{P}_{ju}/2} \qquad \text{for } y = 1980,\ldots,1999 \qquad \text{A2.1.1}$$

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$$N^P_{y+1,a+1} = (N^P_{y,a} e^{-M^P_{ad}/2} - C^P_{y,a} / w^P_{y,ac}) e^{-M^P_{ad}/2} \quad \text{for the following combinations of } y \text{ and } a: \quad \text{A2.1.2}$$

y = 1981, a = 1;
y = 1982, a = 1,2;
y = 1983, a = 1,2,3; and
y = 1984,...,1999, a = 1,...,4

where:

$N^P_{y,a}$ is the number (in billions) of pilchard of age a at the beginning of year y;

$C^P_{y,a}$ is the mass (in thousand tons) of pilchard of age a caught in year y;

$w^P_{y,ac}$ is the mean mass (in grams) of pilchard associated with the catch $C^P_{y,a}$;

M^P_{ju} is the natural mortality (in year^{-1}) of juvenile pilchard (i.e. fish of age 0); and

M^P_{ad} is the natural mortality (in year^{-1}) of adult pilchard (i.e. fish of age 1+).

Biomass associated with the November survey:

$$B^P_{y,N} = \sum_{a=1}^{5} N^P_{y,a} w^P_{y,a} \quad \text{for } y = 1985,...,2000 \quad \text{A2.1.3}$$

where:

$B^P_{y,N}$ is the biomass (in thousand tons) of adult pilchard at the beginning of year y, associated with the November survey in year y-1; and

$w^P_{y,a}$ is the mean mass (in grams) of pilchard of age a sampled during the November survey of year y-1 (note that this differs from the mass of pilchard of the same age in the commercial catch $w^P_{y,ac}$).

Number of recruits at the time of the recruit survey:

The following equation assumes pulse fishing of juveniles half way between 1 November and the start of the recruit survey as an approximation to the actual catch of juveniles before the recruit survey, and is structured to reflect the variable nature of the timing of the recruit survey.

$$N^P_{y,r} = (N^P_{y,0} e^{-0.5(6+t^P_y)M^P_{ju}/12} - C^P_{y,0bs} / w^P_{y,0cbs}) e^{-0.5(6+t^P_y)M^P_{ju}/12} \quad \text{A2.1.4}$$

for y = 1985,...,1999

where:

$N^P_{y,r}$ is the number (in billions) of juvenile pilchard at the time of the recruit survey in year y;

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$C^P_{y,0bs}$ is the mass (in thousand tons) of juvenile pilchard caught between 1 January in year y and the day before the start of the recruit survey;

$w^P_{y,0cbs}$ is the mean mass (in grams) of juvenile pilchard associated with the catch $C^P_{y,0bs}$; and

t^P_y is the time lapsed (in months) between 1 May and the start of the recruit survey in year y.

Age composition associated with November survey:

$$p^P_{y,a} = \frac{N^P_{y,a}}{\sum_{a=1}^{5} N^P_{y,a}} \qquad \text{for } y = 1985,\ldots,2000 \qquad \text{A2.1.5}$$

where:

$p^P_{y,a}$ is the proportion of pilchard of age a at the beginning of year y, associated with the November survey in year y-1.

Fitting Criterion

Maximum likelihood estimation is used, assuming survey observations are log-normally distributed, to obtain parameter estimates. The standard errors of the log-distributions for the survey observations of adult biomass and recruitment numbers are approximated by the CVs of the untransformed distributions. The following negative log-likelihood function is minimised:

$$\begin{aligned} -\ln L = {} & \tfrac{1}{2} W^P_N \sum_{y \in Y_1} \left\{ \frac{\left(\ln B^P_{y,Nov} - \ln(k^P_N B^P_{y,N})\right)^2}{(\sigma^P_{y,Nov})^2 + (\lambda^P_N)^2} + \ln\left[2\pi\left((\sigma^P_{y,Nov})^2 + (\lambda^P_N)^2\right)\right] \right\} \\ & + \tfrac{1}{2} W^P_r \sum_{y \in Y_2} \left\{ \frac{\left(\ln N^P_{y,rec} - \ln(k^P_r N^P_{y,r})\right)^2}{(\sigma^P_{y,rec})^2 + (\lambda^P_r)^2} + \ln\left[2\pi\left((\sigma^P_{y,rec})^2 + (\lambda^P_r)^2\right)\right] \right\} \qquad \text{A2.1.6} \\ & + \tfrac{1}{2} W^P_p \sum_{y \in Y_3} \sum_{a=1}^{5} \left\{ \frac{n_y p^P_{y,a,Nov} \left(\ln p^P_{y,a,Nov} - \ln p^P_{y,a}\right)^2}{(\sigma^P_p)^2} + \ln\left[2\pi(\sigma^P_p)^2 / (n_y p^P_{y,a,Nov})\right] \right\} \end{aligned}$$

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where:

$B^P_{y,Nov}$ is the capped acoustic survey estimate (in thousand tons) of adult pilchard biomass from the November survey in year *y*-1, with associated CV $\sigma^P_{y,Nov}$ and constant of proportionality (multiplicative bias) k^P_N;

$N^P_{y,rec}$ is the capped acoustic survey estimate (in billions) of pilchard recruitment numbers from the recruit survey in year *y*, with associated CV $\sigma^P_{y,rec}$ and constant of proportionality k^P_r;

$p^P_{y,a,Nov}$ is an estimate of the proportion (by number) of pilchard of age *a* in the November survey of year *y*-1;

n_y is the number of fish from the November survey trawls in year *y*-1 used to compile the age-length key for calculating $p^P_{y,a,Nov}$;

$(\lambda^P_{N/r})^2$ is the additional variance (over and above the survey sampling CV $\sigma^P_{y,Nov/rec}$ that reflects survey inter-transect variance) associated with the November/recruit surveys;

$(\sigma^P_p)^2$ is the overall variance-related parameter for the log-transformed proportions-at-age observations, $p^P_{y,a,Nov}$ [note variance = $(\sigma^P_p)^2/(n_y p^P_{y,a,Nov})$];

Y_1 is the set of years for which there are observations for the November surveys, namely 1985-2000 (i.e. Nov 1984 - Nov 1999);

Y_2 is the set of years for which there are observations for the recruit surveys, namely 1985-1987 and 1989-1999 (although there was a recruit survey in 1988, it did not yield a satisfactory estimate of pilchard recruitment);

Y_3 is the set of years for which there are proportions-at-age observations for the November surveys, namely 1989-2000 (i.e. Nov 1988 - Nov 1999); and

$W^P_{N/r/p}$ is the likelihood weight that governs to what extent the associated observations are used in the likelihood (W=0 implies they are not used).

The third term in equation A2.1.6 (proportions-at-age) is structured so that undue importance is not given to observations that are based on only a few samples (Geromont and Butterworth 1999,

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following a suggestion originally offered by A. E. Punt). This form has its basis in the mean-variance relationship for multinomial sampling. [Note that for all equations above and to follow, subscripts *Nov/rec* refer to observations from the November/recruit surveys, while subscripts *N/r* indicate the corresponding model estimates.]

Estimable and input parameters

The estimable parameters of the likelihood L are: M_{ju}^{P}, M_{ad}^{P}, $N_{1980,0}^{P},\ldots,N_{1999,0}^{P}$, k_N^P, k_r^P, λ_N^P, λ_r^P and σ_p^P. However, in these applications M_{ju}^{P}, M_{ad}^{P} and k_N^P are treated as input parameters (i.e. they are fixed externally). Given values for these 3 parameters, partial differentiation of $-\ln L$ leads to closed form solutions for k_r^P, λ_N^P, λ_r^P and σ_p^P. [Note: in some of the results presented, λ_N^P and λ_r^P are treated as input parameters.] The numerical optimisation routine therefore requires initial values for $N_{1980,0}^{P},\ldots,N_{1999,0}^{P}$ and searches over a parameter space of 20 dimensions. The closed form solutions for k_r^P, λ_N^P, λ_r^P and σ_p^P are given below.

The parameterisation for the multi-dimensional search is structured in such a way that the search is actually performed over $N_{0,med}^{P}$, $N_{1980,0}^{P},\ldots,N_{1998,0}^{P}$, with $N_{1999,0}^{P}$ calculated as follows:

$$N_{1999,0}^{P}=\frac{(N_{0,med}^{P})^{20}}{\prod_{y=1980}^{1998}N_{y,0}^{P}}$$

This leads to a more orthogonal parameterisation, whereby the "scale" of the model is encapsulated in the single parameter, $N_{0,med}^{P}$, and recruitment variation estimated through $N_{1980,0}^{P},\ldots,N_{1998,0}^{P}$. This avoids the optimisation routine having to estimate both the scale of the model and recruitment variation through all 20 $N_{y,0}^{P}$ values simultaneously.

Parameters k_r^P and λ_r^P are calculated simultaneously (see paragraph following equation A2.1.8), with k_r^P calculated as follows:

$$k_r^P=\exp\left[\frac{\sum_{y\in Y_2}\left(\ln N_{y,rec}^{P}-\ln N_{y,r}^{P}\right)/\left((\sigma_{y,rec}^{P})^2+(\lambda_r^P)^2\right)}{\sum_{y\in Y_2}1/\left((\sigma_{y,rec}^{P})^2+(\lambda_r^P)^2\right)}\right] \qquad \text{A2.1.7}$$

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Solutions for λ_N^P and λ_r^P are found by using the following general equation:

$$f = \sum_{y \in Y} \frac{\sigma_y^2 + \lambda^2 - (\ln X_y - \ln k\, \hat{X}_y)^2}{(\sigma_y^2 + \lambda^2)^2} \qquad \text{A2.1.8}$$

[replace σ_y, λ, k, X_y, $\hat{X}_y$, Y with $\sigma_{y,Nov}^P$, λ_N^P, k_N^P, $B_{y,Nov}^P$, $B_{y,N}^P$, Y_1 for λ_N^P, and with $\sigma_{y,rec}^P$, λ_r^P, k_r^P, $N_{y,rec}^P$, $N_{y,r}^P$, Y_2 for λ_r^P]. An algorithm is used that fixes λ^2 (initially at zero), calculates k and f (using equations A2.1.7 and A2.1.8 – in the case of λ_N^P, $k = k_N^P$ is fixed), and iterates with increasing values for λ^2 until $f = 0$. If $f > 0$ when $\lambda^2 = 0$, then there is no solution for $f = 0$ for $\lambda^2 > 0$, and the algorithm sets $\lambda^2 = 0$.

Parameter σ_p^P is calculated as follows:

$$(\sigma_p^P)^2 = \sum_{y \in Y_3} \sum_{a=1}^{5} n_y p_{y,a,Nov}^P (\ln p_{y,a,Nov}^P - \ln p_{y,a}^P)^2 \Big/ \sum_{y \in Y_3} \sum_{a=1}^{5} 1 \qquad \text{A2.1.9}$$

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Stock-Recruit Curves

A recruitment generating function forms the basis of management procedure simulations, which require extrapolation of the population dynamics of a given fish stock into the future. Such a function is derived from model estimates of recruitment and spawner biomass once satisfactory fits of the assessment model to observations are achieved. The appropriate values for recruitment and spawner biomass in this assessment are $N_{y,0}^P$ and $B_{y,N}^P$ respectively for $y = 1985,\ldots,1999$ (see equations A2.1.1 and A2.1.3). Stock-recruit curves can be fitted to these "data" points by using maximum likelihood estimation as before (a log-normal assumption is also used here – see equation A2.1.13 below). Once the parameters of the stock-recruit curve are estimated, these can be used to generate the future recruitment values required for management procedure simulations.

Three types of stock-recruit curves are considered, namely the "SS" ("Single-Sloped") curve, the "BH" ("Beverton-Holt") curve, and the "DS" ("Double-Sloped") curve defined as follows:

"SS":
$$N_{y,0,sr}^P = \begin{cases} a^P & , \text{ if } B_{y,N}^P \geq b^P \\ \dfrac{a^P B_{y,N}^P}{b^P} & , \text{ if } B_{y,N}^P < b^P \end{cases} \qquad \text{A2.1.10}$$

"BH": $$N^P_{y,0,sr} = \frac{a^P B^P_{y,N}}{b^P + B^P_{y,N}} \qquad \text{A2.1.11}$$

"DS": $$N^P_{y,0,sr} = \begin{cases} m^P (B^P_{y,N} - b^P) + a^P & \text{, if } B^P_{y,N} \geq b^P \\ \dfrac{a^P B^P_{y,N}}{b^P} & \text{, if } B^P_{y,N} < b^P \end{cases} \qquad \text{A2.1.12}$$

The motivation for using the "DS" curve is to cover the possibility that the current positive temporal trend in pilchard abundance evident in Figure 2.5 will continue for some time in future. The negative log-likelihood function ($-\ln L_{sr}$) for the stock-recruit curves is as follows:

$$-\ln L_{sr} = \tfrac{1}{2} \sum_{y=1985}^{1999} \left\{ \frac{(\ln N^P_{y,0} - \ln N^P_{y,0,sr})^2}{(\sigma^P_r)^2} + \ln\left(2\pi(\sigma^P_r)^2\right) \right\} \qquad \text{A2.1.13}$$

[The range of years used is limited by the $B^P_{y,N}$ and $N^P_{y,0}$ estimates available.] The estimable parameters are a^P, b^P and σ^P_r for the first two curves, to which m^P is added for the third. However, it is possible to find a closed form solution for σ^P_r by partial differentiation of $-\ln L_{sr}$, so that the fitting procedure searches over only two dimensions for the first two curves, and three for the third. The closed form solution for the recruitment variability σ^P_r is as follows:

$$(\sigma^P_r)^2 = \sum_{y=1985}^{1999} (\ln N^P_{y,0} - \ln N^P_{y,0,sr})^2 \Big/ \sum_{y=1985}^{1999} 1 \qquad \text{A2.1.14}$$

Three more parameters that are required for the management procedure computations can be calculated from the stock-recruit data for a given stock-recruit curve. These are recruitment serial correlation s^P_{cor}, the 1999 standardised recruitment residual value η^P_{1999}, and the carrying capacity K^P. These are calculated as follows:

Let:

$$\varepsilon_y = \ln N^P_{y,0} - \ln N^P_{y,0,sr} \qquad \text{for } y = 1985,\ldots,1999$$

then:

$$s^P_{cor} = \frac{\sum_{y=1985}^{1998} \varepsilon_y \varepsilon_{y+1}}{\sqrt{\left(\sum_{y=1985}^{1998} \varepsilon_y^2\right)\left(\sum_{y=1985}^{1998} \varepsilon_{y+1}^2\right)}} \qquad \text{A2.1.15}$$

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and

$$\eta_{1999}^{P} = \frac{\varepsilon_{1999}}{\sigma_r^P} \qquad \text{A2.1.16}$$

The carrying capacity K^P is essentially the B_N^P value where the replacement line and the function describing expected recruitment intersect, and is calculated as follows for the three types of stock-recruit curves considered:

"SS": $$K^P = a^P e^{\frac{1}{2}(\sigma_r^P)^2}\left[\sum_{a=1}^{5} \overline{w}_a^P e^{-M_{jm}^P-(a-1)M_{ad}^P}\right] \qquad \text{A2.1.17}$$

"BH": $$K^P = a^P e^{\frac{1}{2}(\sigma_r^P)^2}\left[\sum_{a=1}^{5} \overline{w}_a^P e^{-M_{jm}^P-(a-1)M_{ad}^P}\right] - b^P \qquad \text{A2.1.18}$$

"DS": $$K^P = \frac{a^P - m^P b^P}{e^{-\frac{1}{2}(\sigma_r^P)^2}\left[\sum_{a=1}^{5} \overline{w}_a^P e^{-M_{jm}^P-(a-1)M_{ad}^P}\right]^{-1} - m^P} \qquad \text{A2.1.19}$$

where:

$\overline{w}_a^P$ is the mean mass (in grams) of pilchard of age a sampled during each November survey, averaged over all November surveys for which an estimate of mean mass-at-age is available.

The $e^{\frac{1}{2}(\sigma_r^P)^2}$ factor in equations A2.1.17-19 is a bias correction factor, needed given the assumption that recruitment is log-normally distributed about an underlying stock-recruit curve.

When estimating the parameters of the stock-recruit curves, the following constraints are applied:

i) a^P has to be non-negative;

ii) b^P has to be positive;

iii) for the "SS" and "DS" curves, b^P may not be greater than the largest B_N^P value used for the estimation of stock-recruit parameters;

iv) m^P may not equal or exceed the slope (adjusted for log-normal bias) of the replacement line, i.e. it has to be less than $e^{-\frac{1}{2}(\sigma_r^P)^2}\left[\sum_{a=1}^{5} \overline{w}_a^P e^{-M_{jm}^P-(a-1)M_{ad}^P}\right]^{-1}$; and

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v) a penalty factor $(K^P/10000)^2$ is introduced into equation A2.1.13 to avoid K^P values that far exceed 10 million tons.

Other parameters of interest

Apart from the above, management procedure simulations require estimates of 1-5 year old fish at the start of the simulation period ($N^P_{2000,1},\ldots,N^P_{2000,5}$), and estimates of recent fishing selectivities-at-age, which are calculated as follows:

$$S^P_a = \overline{F}^P_a / \overline{F}^P_{\max} \qquad \text{A2.1.20}$$

where:

$$\overline{F}^P_a = \tfrac{1}{5}\sum_{y=1995}^{1999} \frac{C^P_{y,a}}{w^P_{y,ac} N^P_{y,a} e^{-M^P_{ad}/2}}$$

and

$$\overline{F}^P_{\max} = \text{maximum of } \{\overline{F}^P_1;\overline{F}^P_2;\overline{F}^P_3;\overline{F}^P_4\}$$

In the calculation for $\overline{F}^P_a$, only the most recent five years are taken into account because it is assumed that that this more likely represents the exploitation pattern that will continue into the immediate future.

Bootstrap estimation

A Monte Carlo representation of the joint probability density function of the assessment parameter estimates is required to form the basis for management procedure simulations (Bergh and Butterworth 1987, Butterworth and Bergh 1993). A conditioned parametric bootstrap approach, which calculates variances and confidence intervals, is used to provide this. Pseudo-data sets are generated as follows:

$$\begin{aligned}
B^{P,Q}_{y,Nov} &= k^P_N B^P_{y,N} e^{\varepsilon^{P,Q}_{y,Nov}} &,\quad & \varepsilon^{P,Q}_{y,Nov} \text{ from } \mathrm{N}[0;(\sigma^P_{y,Nov})^2 + (\lambda^P_N)^2] \\
N^{P,Q}_{y,rec} &= k^P_r N^P_{y,r} e^{\varepsilon^{P,Q}_{y,rec}} &,\quad & \varepsilon^{P,Q}_{y,rec} \text{ from } \mathrm{N}[0;(\sigma^P_{y,rec})^2 + (\lambda^P_r)^2] \qquad \text{A2.1.21} \\
p^{P,Q}_{y,a,Nov} &= k^{P'}_{p,a} p^P_{y,a} e^{\varepsilon^{P,Q}_{y,a,p}} &,\quad & \varepsilon^{P,Q}_{y,a,p} \text{ from } \mathrm{N}[0;(\sigma^{P'}_p)^2/(n_y p^P_{y,a,Nov})]
\end{aligned}$$

where $\mathrm{N}[0;\sigma^2]$ is a normal distribution with mean zero and variance σ^2, $k^{P'}_{p,a}$ is the bias of the assessment model fit to the proportions-at-age observations for age a, and $\sigma^{P'}_p$ is the σ^P_p value

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adjusted to take into account the proportions-at-age biases. The $p^{P,Q}_{y,a,Nov}$ values are re-normalised such that $\sum_{a=1}^{5} p^{P,Q}_{y,a,Nov} = 1$ for all $y \in Y_3$. $k^{P'}_{p,a}$ and $\sigma^{P'}_{p}$ are calculated as follows:

$$k^{P'}_{p,a} = \exp\left[\frac{\sum_{y\in Y_3} n_y p^{P}_{y,a,Nov}(\ln p^{P}_{y,a,Nov} - \ln p^{P}_{y,a})}{\sum_{y\in Y_3} n_y p^{P}_{y,a,Nov}}\right] \qquad \text{A2.1.22}$$

and

$$(\sigma^{P'}_{p})^2 = \frac{\sum_{y\in Y_3}\sum_{a=1}^{5} n_y p^{P}_{y,a,Nov}\left(\ln p^{P}_{y,a,Nov} - \ln(k^{P'}_{p,a} p^{P}_{y,a})\right)^2}{\left(\sum_{y\in Y_3}\sum_{a=1}^{5} 1\right) - 5} \qquad \text{A2.1.23}$$

where $y \in Y_3$ depicts the years for which proportions-at-age observations are available. The introduction of equations A2.1.22-23 is an *ad hoc* way of ensuring that systematic bias (in the assessment model fit to observations) is preserved as bias when the pseudo data sets are generated (equation A2.1.21), instead of being ignored and thus (incorrectly) treated as random variation.

Each pseudo-data set Q was then used to re-estimate parameters so that, while the parameter estimates based on the true data set were treated as "best" estimates, those based on the pseudo-data sets provided the bootstrap distribution for these "best" estimates. Although, strictly speaking, management procedure simulations would be better having 500 such bootstrap distributions available for improved precision, the number of distributions actually generated was only 100 because of the amount of computing time required. Part of the reason for this process being so computer-intensive was that care was needed to ensure the optimisation routine had indeed converged to a global minimum of the (negative) log-likelihood function when model parameters were estimated. The approach used to ensure this was to duplicate calculations with an increasing number of randomly selected initial parameter vector estimates in the numerical search for each bootstrap replicate, until results stabilised to the level of precision required. De Oliveira (1995) provides a detailed description of this approach.

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APPENDIX 2.2

Pilchard observations

Compilation of age-length keys for commercial catches

During an exercise in 1997 to establish a consistent time-series of age data for commercial catches, Kerstan (2000) aged over 7 000 otoliths from commercial landings on the west, south and east coasts of South Africa, collected over the period 1980-1996. The scale of the exercise, the limited time within which it had to be undertaken, and the existence of only one age-reader meant that all the available otoliths could not be aged. Moloney (1997) undertook a simulation exercise to investigate suitable schemes for sub-sampling the available otolith collection, and recommended the following:

(a) all otoliths in the larger length classes be aged (at least 10 otoliths), to ensure that the older fish were sampled;

(b) 100 otoliths be randomly sub-sampled from the remaining length classes; and

(c) sub-sampling be carried out for only four months (February, May, August and November), with the resulting age-length keys (ALKs) applied to the months on either side of these "core" months.

Moloney (1997) stressed, however, that these measures should be treated as interim only, and that once ALKs for outstanding years were generated, ALKs should then be compiled for outstanding months using the same procedure (a)-(c) above. Finally she recommended that four or five months over the period 1980-1996 should be selected randomly and all otoliths aged to compile ALKs, so as to check against the corresponding "sub-sampled" ALKs, and that further readings be carried out if there were any discrepancies. Although recommendations (a)-(c) were implemented (albeit with differing core months and allocations to other months because of data limitations), the remaining recommendations were not because of limited person-power.
Table A2.2.1 lists the number of otoliths sampled (in the month to which they correspond), together with allocations of the resultant ALKs to other months. ALKs for 1997 and 1998 followed recommendations (a) and (b) for all months, while ALKs for 1999 were derived by ageing all the available otoliths for that year.

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Table A2.2.1: Number of otoliths used to compile ALKs, shown in the month during which these otoliths were collected (a "core" month of the sampling scheme used) from commercial catches. Also shown (in italics) is the allocation of ALKs from "core" months to non-sampled months. ALKs were not derived for months indicated with "-" because commercial catches were not sampled (usually as a result of the scarcity of fish or the closure of the fishery).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1980	*Feb*	112	*Feb*	111	*Apr*	*Apr*	*Apr*	-	-	-	-	-
1981	*Feb*	212*	*Feb*	*Feb*	*Feb*	*Feb*	-	-	-	-	-	-
1982	*Feb*	116	*Feb*	*Feb*	117	*May*	*May*	*May*	-	-	-	-
1983	*Feb*	121	*Feb*	*May*	113	*May*	-	-	-	*May*	*May*	*May*
1984	*Feb*	115	*Feb*	*May*	106	*May*	*May*	-	-	*May*	*May*	-
1985	107	*Jan*	*Apr*	110	*Apr*	*Jul*	117	*Jul*	*Jul*	-	-	-
1986	*Feb*	117	*May*	*May*	109	*Jul*	110	*Jul*	*Jul*	-	-	-
1987	121	*Jan*	*Jan*	114	*Apr*	*Apr*	112	*Jul*	*Jul*	-	-	-
1988	*Feb*	122	*Feb*	*May*	126	*May*	*Aug*	117	*Aug*	112	*Oct*	*Oct*
1989	128	*Jan*	*Apr*	125	*Apr*	*Jul*	123	*Jul*	-	-	-	-
1990	*Feb*	151	*May*	*May*	122	*May*	*Aug*	118	*Aug*	*Aug*	*Aug*	*Aug*
1991	*Feb*	141	*Feb*	*May*	117	*May*	*May*	*Sep*	117	*Sep*	*Sep*	*Sep*
1992	*Feb*	116	*Feb*	*May*	125	*May*	*Aug*	137	*Aug*	*Nov*	124	-
1993	*Feb*	115	*Feb*	*May*	125	*May*	*Aug*	119	*Aug*	*Nov*	127	*Nov*
1994	*Feb*	112	*Feb*	*May*	118	*May*	*Aug*	138	*Aug*	*Nov*	118	*Nov*
1995	*Feb*	118	*Feb*	*May*	135	*May*	*Aug*	122	*Aug*	*Nov*	121	*Nov*
1996	*Feb*	129	*Feb*	*May*	112	*May*	*Aug*	116	*Aug*	*Nov*	110	*Nov*
1997	184	118	120	125	123	128	140	117	122	129	114	119
1998	124	122	116	132	114	115	135	143	125	125	109	-
1999	143	130	781	1002	909	1059	742	519	674	454	344	70

* Age-length keys from February and April were combined, in this case.

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Compilation of monthly raised length frequencies for commercial catches

Commercial catches were sampled at various landing points around the west, south and east coasts of South Africa for the purpose of collecting biological information, including otoliths for ageing and lengths for compiling length frequency distributions. It is not possible to sample all landings made in the pelagic fishery. A sample allocation algorithm therefore exists that allocates length frequencies from sampled landings to unsampled landings with similar characteristics (same dominant species in the landing, temporal and spatial proximity, similar vessel type), and that raises the length frequencies from the samples to the total catch in the corresponding months in a manner that takes these characteristics into account. In this manner, monthly raised length frequencies ($L_{y,m,l}$ for year y, month m and length class l) are derived.

Compilation of raised length frequencies for November surveys

Raised length frequencies for November surveys are obtained as follows. A length frequency taken from a trawl sample is first raised to the trawl catch and then allocated within each stratum to an appropriate set of acoustic intervals for which this sample is considered to be

representative. An initial raising factor (sum of acoustic interval fish densities divided by weight of trawl catch) is calculated for each of these sets and applied to the corresponding length frequency to obtain an initial raised length frequency. A stratum raising factor (stratum biomass divided by sum of all transect densities within the stratum) is applied to the sum of all initial raised length frequencies within each stratum, to provide a stratum raised length frequency. The final raised length frequency is the sum of all stratum raised length frequencies.

Calculation of commercial catch- and mean mass-at-age

The following scheme is used to calculate catch- and mean mass-at-age by year y and month m.

1. Use an algorithm to fill in any "gaps" (i.e. length classes that have no age allocations) in the ALKs from Table A2.2.1. [This algorithm is applied consistently for all ALKs, and is usually based on continuing the pattern of age allocation of length classes on either side of the "gap".]

2. Calculate the age composition by length class as follows:

$$p_{y,m,l,a} = n_{y,m,l,a} / n_{y,m,l}$$
$$n_{y,m,l} = \sum_{a} n_{y,m,l,a} \qquad \text{A2.2.1}$$

   where $n_{y,m,l,a}$ is the number of otoliths in length class l allocated to age a.

3. Calculate the total number of fish of age a in length class l as follows:

$$N_{y,m,l,a} = p_{y,m,l,a} L_{y,m,l} \qquad \text{A2.2.2}$$

   where $L_{y,m,l}$ is the raised length frequency in length class l.

4. Calculate the total mass of fish of age a in length class l as follows:

$$W_{y,m,l,a} = N_{y,m,l,a} f(l)$$
$$f(l) = 0.0096 l^{3.075} \qquad \text{A2.2.3}$$

   where $f(l)$ is the length-weight relationship used for pilchard.

5. Calculate the total number and mass of fish caught of age a:

$$N_{y,m,a} = \sum_{l} N_{y,m,l,a} \qquad \text{A2.2.4}$$

$$W_{y,m,a} = \sum_{l} W_{y,m,l,a} \qquad \text{A2.2.5}$$

6. Calculate mean mass-at-age as follows:

$$w_{y,m,a} = q_{y,m} W_{y,m,a} / N_{y,m,a} \qquad \text{A2.2.6}$$

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where $q_{y,m}$ is a correction factor introduced to ensure consistency with the actual total mass landed in month m ($C_{y,m}$), and is calculated as follows:

$$q_{y,m} = C_{y,m} \Big/ (\sum_{a} W_{y,m,a}) \qquad \text{A2.2.7}$$

In order to obtain the data shown in Table A2.2.2(a) and (b), the following equations are used:

$$C^{P}_{y,a} = \sum_{m} N_{y,m,a} \qquad \text{A2.2.8}$$

and

$$w^{P}_{y,ac} = [\sum_{m} (w_{y,m,a} N_{y,m,a})] / [\sum_{m} N_{y,m,a}] \qquad \text{A2.2.9}$$

Calculation of November survey proportions- and mean mass-at-age

The same scheme as (1)-(6) above is used (omitting month subscript m, and replacing $C_{y,m}$ in equation A2.2.7 with $B^{P}_{y,Nov}$ from Table A2.2.3) to derive the proportions- and mean mass-at-age observations shown in Tables A2.2.3-4. Sample sizes used to derive the ALKs are given in Table A2.2.4. The mean mass-at-age ($w^{P}_{y,a}$) is calculated by using equation A2.2.6. The proportions-at-age data are calculated as follows:

$$p^{P}_{y,a,Nov} = N_{y,a} / [\sum_{a=1}^{5} N_{y,a}] \qquad \text{A2.2.10}$$

where the $N_{y,a}$ are from equation A2.2.4 (omitting m).

Survey estimates and associated sampling CVs

The methodology for calculating survey estimates of abundance and associated sampling CVs is detailed in papers by Hampton (1987, 1992) and Jolly and Hampton (1990). Essentially, estimates of mean density per species are calculated per section of transect (i.e. per interval) using estimates that include mean volume back-scattering strength for the interval and the proportion by weight of the species in trawl samples. The mean density for each transect is calculated from the average density for intervals along the transect, weighted by interval length. The mean density per stratum is calculated from the transect means, weighted by transect length, and is multiplied by the area of the stratum to obtain a biomass for the stratum. The total biomass and variance is then the sum of the stratum biomasses and variances. The target strength expression used in these calculations is the one developed for north Atlantic herring. Corrections are applied to account for fish too close inshore to be surveyed by the research vessel.

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Catch and mean mass of juveniles before the recruit survey

The number of juveniles caught before the recruit survey (Table A2.2.5) is calculated as follows:

$$C^{P}_{y,0bs} = \sum_{m=jan}^{sm-1} N_{y,m,0} \; + \; N_{y,sm,0}[\sum_{d=1}^{sd-1} C^{P,by}_{y,sm,d}]/C^{P,by}_{y,sm} \qquad \text{A2.2.11}$$

where *sm* represents the month in which the recruit survey commences (so that *sm*-1 is the month before the recruit survey commences), *sd* the day the recruit survey commences (so that *sd*-1 is the day before the recruit survey commences), $N_{y,m,0}$ is from equation A2.2.4, and $C^{P,by}_{y,sm} = \sum_{d=1}^{dsm} C^{P,by}_{y,sm,d}$ (*dsm* = total number of days in month *sm*). $C^{P,by}_{y,sm,d}$ represents the daily bycatch of pilchard in landings that have targeted anchovy (see Table A3.2.5 later) in month *sm*. Setting $X = N_{y,sm,0}[\sum_{d=1}^{sd-1} C^{P,by}_{y,sm,d}]/C^{P,by}_{y,sm}$, the mean mass of juveniles caught before the recruit survey (Table A2.2.5) is calculated as follows:

$$w^{P}_{y,0cbs} = [\sum_{m=jan}^{sm-1} w_{y,m,a} N_{y,m,0} + w_{y,sm,a} X]/[\sum_{m=jan}^{sm-1} N_{y,m,0} + X] \qquad \text{A2.2.12}$$

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Tables of observations

Table A2.2.2: Pilchard catch-at-age $C^P_{y,a}$ (billions of fish) and mean mass-at-age $w^P_{y,ac}$ (grams), reflected in (a) and (b) respectively. The ageing method used was the year-class method as set out by Kerstan (2000). The number of decimal places does not reflect the precision of the data, but rather the actual values used in the assessments.

(a)

y	$C^P_{y,0}$	$C^P_{y,1}$	$C^P_{y,2}$	$C^P_{y,3}$	$C^P_{y,4}$
1980	0.62563	0.17242	0.20163	0.06504	0.00430
1981	0.90820	0.20643	0.14439	0.06613	0.00769
1982	0.23690	0.14413	0.16770	0.04800	0.01722
1983	1.81885	0.15188	0.24698	0.07206	0.00505
1984	0.14900	0.14454	0.23593	0.03627	0.00001
1985	1.46851	0.01904	0.08769	0.06128	0.01235
1986	1.06525	0.12990	0.07377	0.02025	0.00610
1987	0.58009	0.07181	0.23024	0.02867	0.00488
1988	0.51054	0.12129	0.16676	0.02761	0.00481
1989	0.73292	0.10288	0.14167	0.02919	0.00515
1990	1.10865	0.09986	0.17532	0.13863	0.02874
1991	0.51737	0.03931	0.22865	0.12030	0.07024
1992	1.69910	0.12566	0.13567	0.11831	0.03465
1993	1.14506	0.14668	0.19324	0.05946	0.05546
1994	1.58527	0.54850	0.14429	0.16257	0.06316
1995	3.39274	0.42867	0.36940	0.10055	0.09303
1996	1.00429	0.43576	0.37367	0.25411	0.05810
1997	0.50248	0.38684	0.60362	0.26627	0.07875
1998	1.57117	0.48572	0.45235	0.31072	0.06088
1999	0.98205	0.58437	0.49437	0.13974	0.03190

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(b)

y	$w^P_{y,0c}$	$w^P_{y,1c}$	$w^P_{y,2c}$	$w^P_{y,3c}$	$w^P_{y,4c}$
1980	22.806	57.627	93.084	112.830	135.146
1981	16.728	53.697	87.100	99.189	121.452
1982	9.871	75.980	91.695	95.646	109.932
1983	13.088	55.357	82.543	99.252	97.184
1984	14.680	47.551	64.031	82.483	143.887
1985	9.436	70.918	93.682	96.923	109.794
1986	10.477	82.000	81.814	102.969	116.688
1987	11.357	79.736	81.701	88.982	106.557
1988	12.526	81.954	96.592	109.340	106.241
1989	11.660	52.628	116.228	125.801	128.522
1990	8.309	72.544	110.943	121.241	127.454
1991	11.344	74.008	87.126	107.378	123.457
1992	9.171	72.172	92.327	94.248	107.485
1993	9.326	60.791	85.742	105.115	113.908
1994	14.389	62.238	81.672	94.260	103.476
1995	8.592	70.023	88.139	92.170	99.061
1996	14.262	55.093	84.593	100.598	100.799
1997	12.143	71.802	82.999	87.695	101.354
1998	10.025	73.805	88.240	93.298	104.089
1999	24.636	75.920	90.759	99.172	107.346
	$\overline{w}^P_{0c}$	$\overline{w}^P_{1c}$	$\overline{w}^P_{2c}$	$\overline{w}^P_{3c}$	$\overline{w}^P_{4c}$
Average: 1980-1999	12.741	64.292	89.050	100.429	113.192

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Table A2.2.3: Estimates derived from the November survey: adult biomass estimates $B^P_{y,Nov}$ (thousand tons) with CVs $\sigma^P_{y,Nov}$; and mean mass-at-age $w^P_{y,a}$ (grams). [Note that for y=1985,...,1988, for which mass-at-age date are not available, $w^P_{y,a}$ is taken to equal $\overline{w}^P_a$. Note also that for all observations, year y corresponds to the November survey of year y-1.]

y	$B^P_{y,Nov}$	$\sigma^P_{y,Nov}$	$w^P_{y,1}$	$w^P_{y,2}$	$w^P_{y,3}$	$w^P_{y,4}$	$w^P_{y,5}$
1985	32	0.87					
1986	54	0.39					
1987	160	0.41					
1988	129	0.32					
1989	113	0.55	31.565	66.561	85.943	106.006	94.556
1990	286	0.21	37.810	76.276	91.339	99.333	100.419
1991	263	0.27	46.590	78.434	88.597	103.464	118.825
1992	441	0.26	29.866	75.052	95.273	109.785	131.427
1993	327	0.36	27.118	49.639	79.072	89.456	109.131
1994	464	0.28	34.558	69.262	78.095	98.321	111.919
1995	597	0.25	45.871	78.218	91.788	102.826	118.925
1996	620	0.36	21.885	66.116	87.703	97.072	117.467
1997	505	0.21	31.653	54.777	81.816	90.576	107.145
1998	791	0.20	28.722	64.663	73.571	83.876	93.431
1999	1334	0.24	28.096	70.505	87.490	92.986	116.727
2000	1337	0.18	48.178	84.938	97.770	110.775	118.334
			$\overline{w}^P_1$	$\overline{w}^P_2$	$\overline{w}^P_3$	$\overline{w}^P_4$	$\overline{w}^P_5$
		Average: 1989-2000	34.326	69.537	86.538	98.706	111.525

Table A2.2.4: Estimates derived from the November survey: proportions-at-age estimates $p^P_{y,a,Nov}$; and the sample size n_y (number of fish) used to compile age-length keys underlying these estimates. [Note that for all observations, year y corresponds to the November survey of year y-1.]

y	$p^P_{y,1,Nov}$	$p^P_{y,2,Nov}$	$p^P_{y,3,Nov}$	$p^P_{y,4,Nov}$	$p^P_{y,5,Nov}$	n_y
1989	0.775	0.146	0.064	0.014	0.001	153
1990	0.618	0.252	0.038	0.065	0.027	202
1991	0.362	0.363	0.131	0.083	0.061	225
1992	0.739	0.111	0.102	0.036	0.012	668
1993	0.713	0.186	0.058	0.030	0.013	604
1994	0.600	0.098	0.231	0.028	0.044	583
1995	0.232	0.340	0.272	0.120	0.037	623
1996	0.645	0.129	0.111	0.053	0.061	861
1997	0.402	0.424	0.124	0.030	0.020	335
1998	0.391	0.155	0.249	0.153	0.052	342
1999	0.743	0.123	0.057	0.051	0.026	722
2000	0.692	0.161	0.109	0.030	0.008	575

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Table A2.2.5: Estimates derived from the recruit survey and required by equation A2.1.4: recruit survey estimates of juveniles $N^P_{y,rec}$ (billions) with CVs $\sigma^P_{y,rec}$; time of the recruit survey after 1 May t^P_y (months); and catches taken from 1 January to the commencement of the recruit survey $C^P_{y,0bs}$ (billions) with the associated mean mass of fish $w^P_{y,0cbs}$ (grams).

y	$N^P_{y,rec}$	$\sigma^P_{y,rec}$	t^P_y	$C^P_{y,0bs}$	$w^P_{y,0cbs}$
1985	2.62	0.50	0.613	0.64670	9.638
1986	3.29	0.50	1.300	0.68239	9.668
1987	5.56	0.50	2.613	0.34882	11.815
1988			1.867	0.29325	9.688
1989	3.38	0.50	1.233	0.53268	12.979
1990	1.75	0.50	0.161	0.32154	8.583
1991	2.34	0.37	0.194	0.34341	10.283
1992	9.23	0.28	0.387	0.33103	9.717
1993	17.01	0.26	0.645	0.28869	10.122
1994	4.04	0.15	0.129	0.48557	17.668
1995	25.88	0.18	1.300	0.86177	6.550
1996	4.95	0.31	1.133	0.72676	12.876
1997	36.60	0.13	0.516	0.04784	22.591
1998	11.40	0.27	0.613	0.69374	10.682
1999	7.6	0.24	0.290	0.14728	18.060
					$\overline{w}^P_{0cbs}$
				Average: 1985-1999	12.061

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CHAPTER 3

Anchovy Assessment

The assessment methodology for South African anchovy is similar to that for pilchard (Chapter 2). No ageing is currently undertaken for anchovy, and catches are split into adults and juveniles based roughly on the time the fishery switches from adults to juveniles. The available age data (1992-1995) are used to determine the mean mass of fish from the November surveys and the proportion of 1-year-olds in these surveys. Estimates of relative abundance (adults and juveniles) from the two acoustic surveys conducted annually are used in the likelihood function together with estimates of absolute abundance (adults) from the daily egg production method and the estimates of proportions of 1-year-olds from the November surveys. Details of the assessment are as for pilchard, except that both the November and the recruitment surveys are treated as relative indices of abundance. When selecting adult and juvenile natural mortalities consistent with the "best, feasible" fits, juvenile natural mortalities lower than those for adults are ignored, while both the ratio of recruit:adult survey bias and the fit to the proportion of 1-year-olds in the November surveys are used to aid this selection. A value of $0.9.year^{-1}$ for both juvenile and adult natural mortality is selected. A range of alternative assessments is selected for the purpose of performing management procedure robustness tests.

3.1 Introduction

The problems associated with using CPUE indices and applying VPA assessment methods to provide biomass and recruitment trends (as in Chapter 2) are particularly acute for anchovy, for several reasons.

- The lack of sufficient age material for the 1960s and 1970s, and consequent application of a single age-length key (a combination of three years of age data; Pollock 1970) to the whole time series of catch data (Crawford *et al.* 1978), means that true changes in catch age-structure throughout the time series are dampened, so that catch data contains a paucity of information on which to base reliable VPA estimates (Armstrong *et al.* 1985).
- A further problem with anchovy ageing was highlighted by Armstrong *et al.* (1985) when they demonstrated, using daily ring deposition rates in anchovy otoliths, that most of the anchovy encountered during November surveys comprised 1-year-old fish. This finding was at odds with the growth studies of Pollock (1970), used in the compilation of catch-at-age data for the VPAs, which interpreted these fish as two to three year olds. A consequence of the findings of Armstrong *et al.* (1985) was that annual purse-seine catches contained an even higher proportion of 0-year-old anchovy than previously thought.
- Anchovy VPA assessments were very sensitive to the choice of terminal (oldest age) fishing mortalities[27], a problem not as important for pilchard because of the greater spread of ages for that resource (Butterworth 1983).

[27] A standard input requirement for the early VPAs.

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- Acoustic surveys confirmed earlier concerns that the pelagic fishery did not exploit the full geographic range of the anchovy, and thus that the low proportions of adults in the catches were a result of the emigration of adults from the fishing areas, rather than due to heavy exploitation. The latter was an implicit assumption of the VPAs as they had been applied (Butterworth 1983, Butterworth 1987, Hampton 1987). This seriously undermined the VPA assessments, the reliability of which was critically dependent on the absence of emigration (Bergh 1986).

The net result of the above was that by 1985, VPA, which relied heavily on catch-at-age information, was not considered a viable assessment method for anchovy, and that no credibility could be given to biomass trends previously estimated for this resource using this method (Butterworth 1987).

The use of stochastic simulation models to investigate harvesting strategies for South African pelagic resources under a variety of assumptions about stock dynamics was pursued by several authors during the early- to mid-1980s (Butterworth 1983, Armstrong *et al.* 1983, Armstrong 1984), but these models continued to use estimates derived from VPAs as a basis for the simulations. Even though it was clear, following the findings (noted above) from the first acoustic surveys and re-assessment of ageing, that a new approach was needed to determine appropriated harvest levels for anchovy, the ideas developed during these initial studies (e.g. that of assigning a probability or risk to a particular outcome) were to provide the foundation for the management procedure approaches currently used.

Following the rejection of VPA as a basis for anchovy assessments, scientists were left with only the acoustic estimates on which to base assessments of the resource, coupled to the assumption that catches consisted entirely of recruits. The first attempt was an adaptation of a model proposed by Beddington and Cooke (1983), based on the Beverton-Holt yield per recruit model and requiring minimal assumptions because of the paucity of data (only one data point, namely the average of the acoustic and egg estimates from the November 1984 acoustic survey, was available; Armstrong and Butterworth 1986). This model required only information on the mean and variance of annual recruitment (the mean being based on back-calculation from the survey estimate), natural mortality, the proportional change in cohort biomass between harvesting and survey, and an appropriate harvest strategy target. Subsequent years saw an extension of this approach as new data became available (e.g. Butterworth 1986), culminating in papers by Bergh and Butterworth (1987) and Butterworth and Bergh (1993), which presented Bayes-like estimation procedures as a basis for harvest strategy simulation.

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The Bayes-like approach essentially generates a composite vector of model parameters by randomly sampling from prior distributions specified for these parameters, and then provides a joint posterior distribution (in the form of numerical realisations), preserving any correlative relationships that may exist between these parameters (Bergh and Butterworth 1987, Butterworth and Bergh 1993). The posterior distribution is defined as that subspace of the joint prior distribution that is consistent with the constraints[28] imposed by the model (similar to equations A3.1.1-4 in Appendix 3.1). A multiplicative weighting factor w^S is calculated for each realisation S of the joint posterior distribution, as follows (De Oliveira 1995):

$$w^S = \prod_i \prod_y \exp\left[-\frac{\left(z_{i,y}^{obs} - z_{i,y}^{\mathrm{mod}}\right)^2}{2\sigma_i^2} \right]$$

where "*obs*" represents an observation, "*mod*" the corresponding model estimate, σ^2 the assumed or estimated variability, i the type of data used (e.g. acoustic or egg estimates), and y the year. These weights are normalised over all "accepted simulations" (i.e. those allocated non-zero weights) and can be used to calculate for each parameter the mean and standard deviation of its marginal distribution corresponding to the joint posterior distribution.

In the presence of few data, the Bayes-like approach was attractive because it allowed for the incorporation of auxiliary information into the estimation procedure (via the use of priors) in order to improve estimation precision (Butterworth and Bergh 1993). However, there was always the danger that the priors were inappropriately specified, and therefore would introduce undesirable biases into the estimates of parameters. The use of a maximum likelihood estimation approach would avoid this problem and was a more direct and flexible method to estimate parameters. By the early 1990s, enough data had accumulated to allow such an approach to be used instead of the Bayes-like approach. Butterworth *et al.* (1993) and De Oliveira (1995) (and later the pelagic results reported in Geromont *et al.* 1999) used the maximum likelihood approach to derive parameter estimates as a basis for management procedure simulations. The assessment procedure presented here is an extension of these approaches.

[28] For example, given a particular set of values for the parameters drawn from their prior distributions, this set then forms a realisation from the joint prior distribution; given historic catches, population numbers calculated by the model are not allowed to be negative, otherwise the joint prior distribution is discarded (by allocating a zero weight to it).

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3.2 Current assessment approach

As for pilchard, maximum likelihood estimation is used for the assessment of anchovy, with details of the approach provided in Appendix 3.1. The likelihood (equation A3.1.7) incorporates four time-series of observations, namely the November survey estimates of adult biomass (with associated CVs), daily egg production method estimates (i.e. egg survey estimates) of adult biomass (with associated CVs) using data from the November survey, estimates of juvenile abundance (with associated CVs) from the mid-year recruit survey, and estimates of the proportions of 1-year-olds in the stock derived from the November survey trawl samples. A "shrinkage to $N_{0,med}$" term is included in the likelihood (final term in equation A3.1.7) to ensure that estimates of recruitment for the early part of the recruitment time series (for which there are no age data) are well behaved. All observations are assumed to be log-normally distributed about their expected values, except for estimates of the proportions of 1-year-olds, for which a logit transformation is used. Likelihood weights (W_N^A, W_g^A, W_r^A, W_p^A and W_0^A in equation A3.1.7) are set to 1 for all results presented below.

The egg survey estimates are assumed to provide absolute estimates of adult abundance ($k_g^A = 1$)[29], and this allows the November survey bias (k_N^A) to be estimated along with the recruit survey bias (k_r^A). However, adult and juvenile natural mortality (M_{ad}^A and M_{ju}^A) still need to be treated as external inputs (as for pilchard) because they cannot be estimated satisfactorily in the likelihood maximisation process given the available data. Additional variances are estimated for all components of the likelihood except the component incorporating the egg survey estimates (see equation A3.1.7 and associated text). The total variance for the likelihood components with an additional variance parameter is the sum of the fixed (σ^2) and additional (λ^2) variance contributions. In the case of the November and recruit survey components, σ is simply the survey sampling CV, but for the proportions of 1-year-olds and "shrinkage to $N_{0,med}$" components, $\sigma = 0.4$ is selected for the following reasons:

- for the "shrinkage to $N_{0,med}$" component, setting $\sigma = 0$ led to unrealistically small values for λ (and hence the total variance), which resulted in too much weight being given to this component – hence an arbitrary value of $\sigma = 0.4$ (still small enough to ensure that λ was always estimated as non-zero) was selected; unrealistically small values for λ when setting

[29] For some results presented, the egg survey estimates are assumed to provide relative estimates of known bias, i.e. k_g^A is fixed at values other than 1.

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$\sigma = 0$ were also a problem for the proportions of 1-year-olds component, but only for certain M-combinations;

- setting σ too high leads to estimates for λ of zero, thereby imposing a minimum constraint on the total variance that is not necessarily justified by the data; $\sigma = 0.4$ for the proportions of 1-year-olds component yielded no more than 25% zero estimates for λ when performing bootstrap simulations (see later), which was regarded as sufficiently small.

The estimable parameters that are not fixed externally (adult and juvenile natural mortality and egg survey bias k_g^A) or estimated by closed-form solution (November and recruit survey biases and all additional variance parameters), are the 20 values for annual anchovy recruitment, corresponding to the number of 0-year-old fish at the beginning of each year ($N^A_{1981,0},\ldots,N^A_{2000,0}$). Results are obtained across a range of M^A_{ad} and M^A_{ju} values (M^A_{ad} = 0.6, 0.9,..., 2.1 year^{-1}; M^A_{ju} = 0.6, 0.9,..., 2.1 year^{-1}), with likelihood values (-lnL_{tot}, -lnL_{Nov}, -lnL_{rec}, -lnL_{egg}, -lnL_{prop1}, and -lnL_0) and estimates for a number of estimable parameters (k^A_N, k^A_r, $k^{A'}_p$, λ^A_N, λ^A_r, λ^A_p and λ^A_0) reported (Appendix 3.1). Apart from M^A_{ad} and M^A_{ju}, the only other parameters to be varied are k^A_g, λ^A_N and λ^A_r (the latter two being either estimated or treated as input parameters with value zero). Results are also presented for the different methods used to obtain estimates of the proportions of 1-year-olds ("Prosch" age-length keys or different cut-off lengths – see Appendix 3.2 for details).

As with pilchard, the ratio k^A_r / k^A_N is used as an important indicator of whether or not model fits are realistic (if the ratio falls far outside the range [0.5; 1], then the corresponding model is considered implausible). Estimates for $k^{A'}_p$, the bias of the assessment model fit to estimates of the proportions of 1-year-olds (equation A3.1.20), are also used for this purpose – models with $k^{A'}_p$ estimates markedly different from 1, reflecting biased fits to the proportions of 1-year-olds observations, are considered less plausible than those with $k^{A'}_p$ estimates closer to 1.

3.3 Results

Table 3.1 shows results for $k^A_g = 1$ and $\lambda^A_N = \lambda^A_r = 0$ using the "Prosch" age-length key for the proportion of 1-year-olds. Unlike the situation for pilchard, for which there appeared to be no

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significant change in -lnL_{tot} when M_{ju}^{P} was varied, there is a significant improvement in -lnL_{tot} when M_{ju}^{A} is decreased for any value of M_{ad}^{A}, so that the "best" model fits appear to be obtained when $M_{ju}^{A} < M_{ad}^{A}$. This seems improbable for anchovy, however, where juveniles are likely subjected to higher levels of natural mortality than adults[30]. This problem may be caused by the fact that no age information is used in the assessment apart from a combined ALK (1992-1995) to calculate mean masses and the proportion of 1-year-olds in the November survey (Appendix 3.2). Under these circumstances, it is prudent to exclude the "biologically improbable" cases where $M_{ju}^{A} < M_{ad}^{A}$ (Burnham and Anderson 2002). The lower triangles of all the $M_{ad}^{A} \times M_{ju}^{A}$ matrices presented for anchovy are therefore ignored. This leaves the diagonal of these matrices, where $M_{ad}^{A} = M_{ju}^{A}$, showing the smallest -lnL_{tot} values for any given M_{ad}^{A}, with $M_{ad}^{A} = 0.9$ yielding the lowest of these in Table 3.1 (although not significantly better than $M_{ad}^{A} = 1.2$).

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[30]Strong biological evidence exists that, within most species, natural mortality is inversely correlated with body size up to the age when senescence sets in; furthermore, where natural mortality has been estimated, it has been shown (e.g. by multi-species VPA) to be higher in the younger age groups (ICCAT 1999).

Table 3.1: Results for the model fits with $\lambda_N^A = 0$, $\lambda_r^A = 0$ and $k_g^A = 1$, using the "Prosch" age-length key for the proportions of 1-year-olds observations.

M_{ju}^A		0.6	0.9	1.2	1.5	1.8	2.1	0.6	0.9	1.2	1.5	1.8	2.1
		$-\ln L_{tot}$						$-\ln L_{egg}$					
M_{ad}^A	0.6	56.91	59.35	61.83	64.29	66.73	69.10	8.73	9.07	9.25	9.55	9.70	9.89
	0.9	51.53	53.61	55.72	57.82	59.91	61.96	6.63	6.84	6.94	7.05	7.13	7.28
	1.2	50.57	52.27	54.00	55.75	57.51	59.27	5.21	5.31	5.45	5.61	5.70	5.77
	1.5	51.52	52.90	54.33	55.81	57.31	58.85	4.43	4.55	4.68	4.76	4.87	5.01
	1.8	53.01	54.19	55.43	56.72	58.07	59.47	3.97	4.11	4.16	4.30	4.35	4.47
	2.1	54.65	55.71	56.84	58.03	59.28	60.59	3.70	3.82	3.90	3.97	4.06	4.15
		$-\ln L_{Nov}$						$-\ln L_{prop1}$					
M_{ad}^A	0.6	10.04	11.62	13.30	15.08	16.67	18.34	13.31	13.06	12.85	12.62	12.50	12.40
	0.9	7.10	8.22	9.95	11.18	12.61	14.02	12.40	12.21	11.97	11.84	11.74	11.57
	1.2	3.81	4.78	5.73	6.78	7.65	8.80	16.16	16.07	16.01	15.93	15.83	15.76
	1.5	2.13	2.77	3.54	4.28	5.14	5.91	20.12	20.08	20.04	20.00	19.96	19.93
	1.8	1.08	1.66	2.36	3.02	3.61	4.39	23.39	23.36	23.33	23.31	23.28	23.25
	2.1	0.62	1.13	1.80	2.36	2.98	3.56	26.02	26.00	25.98	25.96	25.94	25.92
		$-\ln L_{rec}$						$-\ln L_0$					
M_{ad}^A	0.6	8.09	8.53	9.08	9.37	9.95	10.20	16.73	17.06	17.35	17.67	17.92	18.27
	0.9	8.51	9.19	9.43	10.06	10.48	10.95	16.89	17.16	17.43	17.69	17.95	18.14
	1.2	8.11	8.52	8.97	9.40	10.13	10.54	17.28	17.59	17.84	18.03	18.20	18.40
	1.5	7.52	7.94	8.30	8.77	9.17	9.71	17.32	17.56	17.77	18.00	18.17	18.30
	1.8	7.40	7.74	8.02	8.35	8.93	9.34	17.16	17.31	17.56	17.75	17.91	18.02
	2.1	7.41	7.68	7.87	8.28	8.70	9.21	16.89	17.08	17.29	17.47	17.61	17.74
		k_N^A						k_r^A					
M_{ad}^A	0.6	1.130	1.144	1.148	1.159	1.164	1.170	1.133	1.050	0.964	0.886	0.808	0.735
	0.9	1.026	1.034	1.027	1.025	1.022	1.022	0.898	0.821	0.741	0.668	0.600	0.539
	1.2	0.947	0.942	0.946	0.950	0.950	0.940	0.741	0.668	0.604	0.545	0.488	0.433
	1.5	0.898	0.905	0.908	0.907	0.903	0.907	0.641	0.582	0.524	0.469	0.417	0.374
	1.8	0.876	0.890	0.881	0.876	0.879	0.885	0.581	0.529	0.470	0.419	0.375	0.336
	2.1	0.863	0.876	0.873	0.864	0.866	0.874	0.541	0.492	0.439	0.389	0.347	0.312
		$k_p^{A'}$						k_r^A / k_N^A					
M_{ad}^A	0.6	0.769	0.769	0.767	0.768	0.766	0.766	1.003	0.918	0.840	0.764	0.694	0.628
	0.9	1.165	1.163	1.163	1.160	1.157	1.156	0.875	0.795	0.721	0.652	0.587	0.528
	1.2	1.746	1.740	1.738	1.737	1.732	1.727	0.783	0.709	0.638	0.573	0.514	0.460
	1.5	2.581	2.575	2.572	2.563	2.559	2.554	0.714	0.643	0.577	0.517	0.463	0.413
	1.8	3.752	3.745	3.734	3.723	3.714	3.709	0.664	0.595	0.534	0.478	0.426	0.380
	2.1	5.361	5.351	5.336	5.322	5.312	5.305	0.628	0.562	0.503	0.450	0.401	0.357
		λ_p^A						λ_0^A					
M_{ad}^A	0.6	0.542	0.526	0.512	0.498	0.490	0.484	0.390	0.403	0.415	0.428	0.437	0.452
	0.9	0.484	0.473	0.457	0.450	0.443	0.433	0.396	0.407	0.418	0.428	0.439	0.446
	1.2	0.737	0.731	0.726	0.720	0.713	0.708	0.412	0.424	0.434	0.442	0.449	0.457
	1.5	1.065	1.061	1.058	1.053	1.050	1.047	0.413	0.423	0.432	0.441	0.447	0.453
	1.8	1.407	1.403	1.400	1.397	1.394	1.390	0.407	0.413	0.423	0.431	0.437	0.441
	2.1	1.745	1.743	1.740	1.737	1.734	1.732	0.396	0.404	0.412	0.420	0.425	0.430

Further support for $M_{ad}^A = M_{ju}^A = 0.9$ comes from the corresponding k_r^A / k_N^A value, which falls comfortably within [0.5; 1], and from $k_p^{A'}$, which is closest to 1 when $M_{ad}^A = M_{ju}^A = 0.9$ compared to other $M_{ad}^A = M_{ju}^A$ options.

Figures 3.1a and b show model fits to the November, recruit and egg survey observations, and proportions of 1-year-olds for $M_{ad}^A = M_{ju}^A = 0.9$. Also shown are normalised residual plots for different M-combinations. There are indications of trends in the residual plots associated with the fits to the November survey and proportions of 1-year-olds observations, these trends being

opposite for the two data sets, and hence indicating either inappropriate model specification or conflicting information in the two data sets. Further results consider alternative model specifications, and therefore Table 3.1 and Figures 3.1a and b are not discussed in more detail here.

Figure 3.1a: Plots, associated with the results of Table 3.1, of the model fits to the November and recruit survey observations for $M_{ad}^{p} = 0.9$ and $M_{ju}^{p} = 0.9$ (top pair of panels), with normalised residual plots for this and other M-combinations (bottom three pairs of panels). Squares indicate observations, while model estimates are shown joined by straight lines. Survey observations are in thousand tons. The normalised residuals are calculated as $(\ln X_y - \ln \hat{X}_y)/\hat{\sigma}$, where the "^" indicates a model estimate, and $\hat{\sigma}$ includes both sampling and additional variance (see equation A3.1.7).

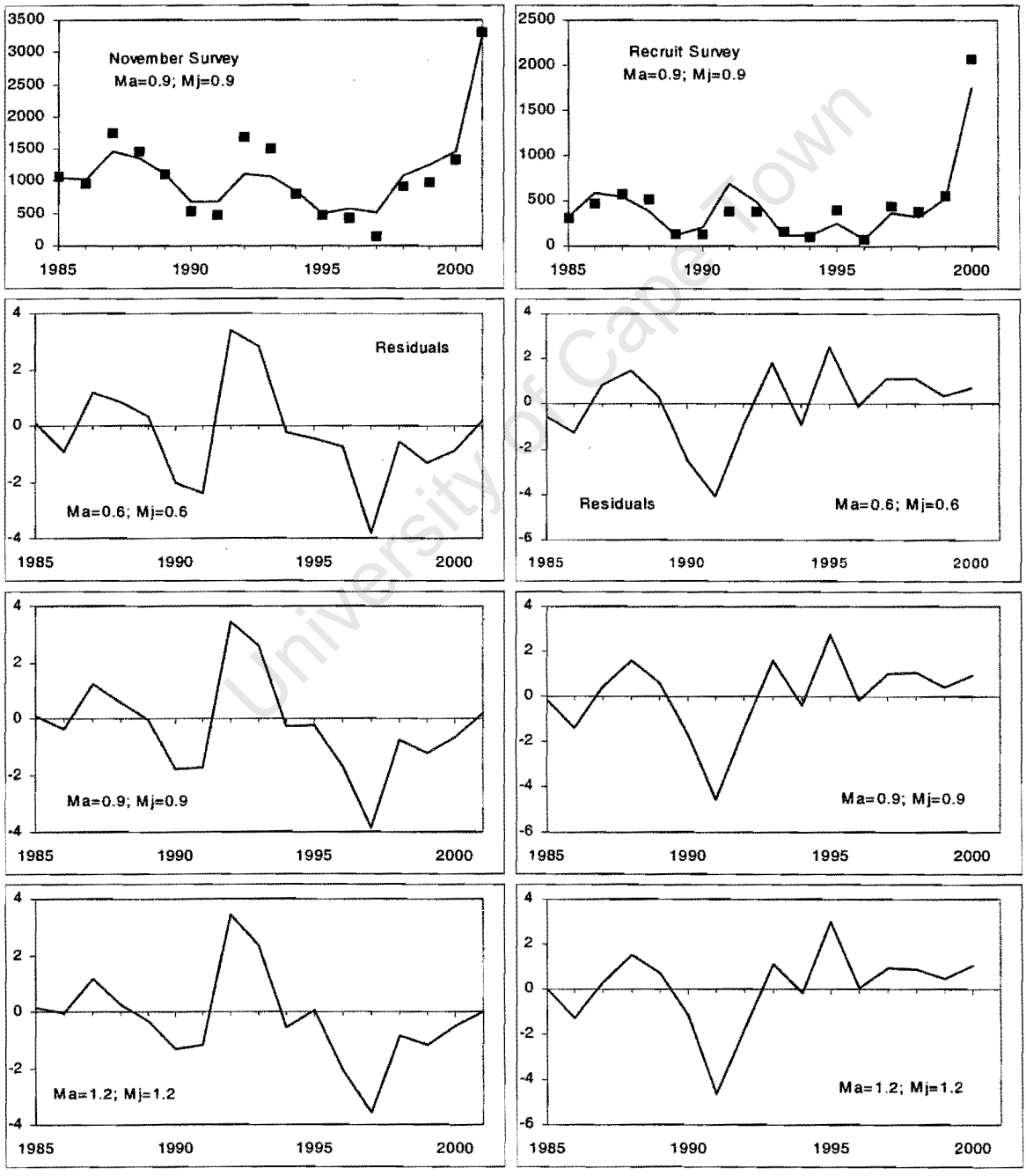

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Figure 3.1b: Further plots, associated with the results of Table 3.1, of the model fits to the egg survey and proportions of 1-year-olds observations from the November survey for $M_{ad}^{p}=0.9$ and $M_{ju}^{p}=0.9$ (top pair of panels), with normalised residual plots for this and other M-combinations (bottom three pairs of panels). Egg survey observations are in thousand tons, and other details are as for the caption to Figure 3.1a.

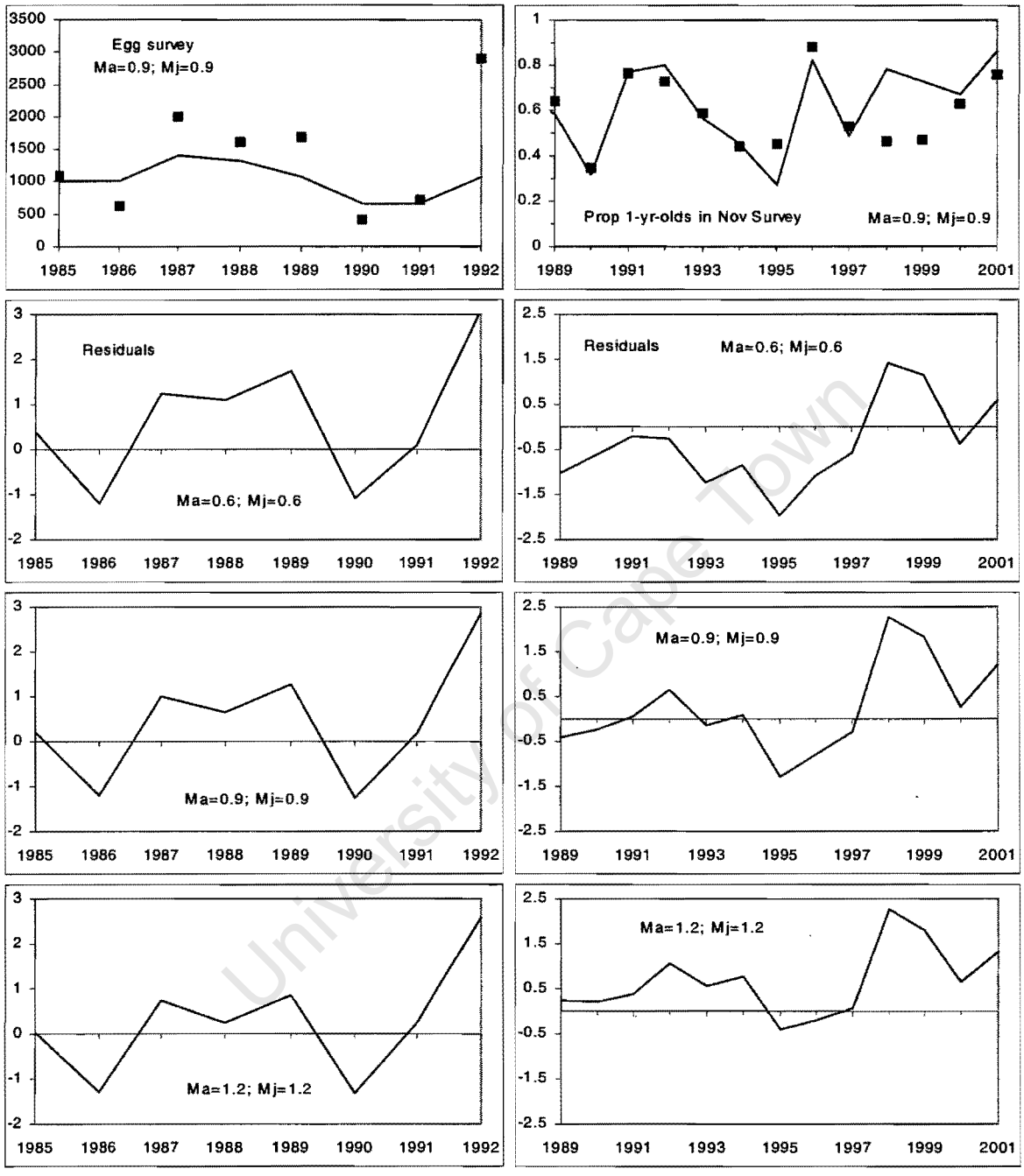

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Table 3.2 shows results for estimating λ_r^A, while λ_N^A remains fixed at 0 (it will be shown later that there is there is justification for fixing λ_N^A at this value). Values of -lnL_{tot} are significantly improved for all M-combinations by 13-22 likelihood "points", most of the improvement coming from -lnL_{Nov}. As before, best results in the upper triangle of the -lnL_{tot} $M_{ad}^{A}\times M_{ju}^{A}$ matrix are achieved for $M_{ad}^{A}=M_{ju}^{A}=0.9$, and values of $k_p^{A'}$ closest to 1 occur for $M_{ad}^{A}=0.9$.

Table 3.2: Results for the model fits with $\lambda_N^A = 0$, λ_r^A estimated and $k_g^A = 1$, using the "Prosch" age-length key for the proportions of 1-year-olds.

M_{ju}^A		0.6	0.9	1.2	1.5	1.8	2.1	0.6	0.9	1.2	1.5	1.8	2.1
		$-\ln L_{tot}$						$-\ln L_{egg}$					
M_{ad}^A	0.6	42.42	43.62	44.79	45.91	46.98	47.99	5.25	5.28	5.39	5.26	5.20	5.21
	0.9	35.99	36.94	37.86	38.74	39.57	40.36	3.73	3.72	3.69	3.69	3.64	3.60
	1.2	35.83	36.59	37.33	38.03	38.70	39.34	2.91	2.91	2.90	2.90	2.89	2.86
	1.5	37.66	38.29	38.90	39.49	40.06	40.60	2.54	2.54	2.54	2.58	2.52	2.53
	1.8	39.63	40.17	40.70	41.22	41.72	42.20	2.36	2.36	2.37	2.37	2.36	2.34
	2.1	41.41	41.90	42.38	42.86	43.32	43.77	2.26	2.26	2.27	2.25	2.26	2.25
		$-\ln L_{Nov}$						$-\ln L_{prop1}$					
M_{ad}^A	0.6	-4.71	-4.59	-4.60	-4.46	-4.50	-4.38	15.69	15.59	15.54	15.47	15.48	15.42
	0.9	-8.01	-7.98	-7.89	-7.91	-7.84	-7.83	14.13	14.13	14.08	14.07	14.04	14.05
	1.2	-9.79	-9.77	-9.70	-9.69	-9.72	-9.75	16.86	16.84	16.81	16.81	16.80	16.82
	1.5	-10.76	-10.77	-10.72	-10.75	-10.74	-10.75	20.47	20.46	20.45	20.44	20.44	20.43
	1.8	-11.38	-11.34	-11.35	-11.37	-11.37	-11.38	23.60	23.58	23.58	23.57	23.56	23.56
	2.1	-11.75	-11.77	-11.82	-11.74	-11.81	-11.76	26.14	26.14	26.14	26.13	26.13	26.12
		$-\ln L_{rec}$						$-\ln L_0$					
M_{ad}^A	0.6	8.19	8.87	9.52	10.19	10.87	11.40	18.00	18.47	18.95	19.46	19.93	20.34
	0.9	8.00	8.48	8.99	9.50	9.95	10.43	18.15	18.60	19.00	19.39	19.77	20.11
	1.2	7.58	7.99	8.37	8.75	9.15	9.56	18.26	18.62	18.94	19.26	19.58	19.85
	1.5	7.36	7.69	8.02	8.30	8.70	9.04	18.05	18.37	18.62	18.92	19.14	19.35
	1.8	7.29	7.58	7.87	8.17	8.46	8.82	17.76	17.99	18.24	18.48	18.70	18.87
	2.1	7.35	7.59	7.89	8.15	8.46	8.71	17.41	17.67	17.91	18.06	18.28	18.44
		k_N^A						k_r^A					
M_{ad}^A	0.6	1.044	1.046	1.056	1.043	1.040	1.038	1.122	1.033	0.954	0.865	0.786	0.712
	0.9	0.990	0.988	0.984	0.985	0.978	0.975	0.920	0.839	0.760	0.690	0.620	0.557
	1.2	0.946	0.945	0.941	0.942	0.941	0.935	0.778	0.705	0.635	0.573	0.515	0.459
	1.5	0.925	0.923	0.919	0.920	0.920	0.918	0.687	0.619	0.556	0.500	0.448	0.400
	1.8	0.913	0.910	0.913	0.909	0.909	0.906	0.628	0.564	0.508	0.454	0.406	0.361
	2.1	0.903	0.904	0.903	0.906	0.900	0.899	0.586	0.528	0.474	0.425	0.377	0.336
		$k_p^{A'}$						k_r^A / k_N^A					
M_{ad}^A	0.6	0.753	0.754	0.756	0.755	0.754	0.755	1.075	0.988	0.903	0.829	0.756	0.686
	0.9	1.149	1.148	1.148	1.149	1.147	1.147	0.930	0.849	0.773	0.701	0.634	0.572
	1.2	1.738	1.738	1.735	1.735	1.733	1.733	0.822	0.746	0.675	0.608	0.547	0.491
	1.5	2.584	2.583	2.578	2.580	2.576	2.575	0.743	0.671	0.605	0.543	0.487	0.436
	1.8	3.762	3.757	3.757	3.753	3.751	3.748	0.687	0.619	0.557	0.499	0.447	0.399
	2.1	5.365	5.367	5.365	5.356	5.356	5.355	0.649	0.584	0.524	0.469	0.420	0.374
		λ_p^A						λ_0^A					
M_{ad}^A	0.6	0.703	0.696	0.692	0.688	0.688	0.684	0.441	0.460	0.479	0.500	0.519	0.536
	0.9	0.596	0.595	0.592	0.592	0.590	0.590	0.447	0.465	0.481	0.497	0.513	0.527
	1.2	0.789	0.788	0.786	0.785	0.785	0.787	0.451	0.466	0.479	0.492	0.505	0.516
	1.5	1.098	1.097	1.095	1.095	1.095	1.094	0.443	0.456	0.466	0.478	0.487	0.495
	1.8	1.431	1.429	1.429	1.429	1.428	1.427	0.431	0.440	0.450	0.460	0.469	0.476
	2.1	1.762	1.763	1.762	1.761	1.761	1.760	0.417	0.427	0.437	0.443	0.452	0.459
		λ_r^A											
M_{ad}^A	0.6	0.370	0.389	0.407	0.427	0.449	0.465						
	0.9	0.367	0.380	0.394	0.409	0.422	0.437						
	1.2	0.356	0.367	0.377	0.388	0.400	0.411						
	1.5	0.350	0.359	0.368	0.375	0.387	0.396						
	1.8	0.347	0.355	0.363	0.371	0.379	0.390						
	2.1	0.348	0.355	0.363	0.370	0.379	0.386						

Comparison of Figures 3.1 and 3.2 show improved model fits to the observations for the latter with less evidence of residual trends. There are a few instances of largish residuals (particularly the model fits to the 1991 recruit and 1997 November survey observations, which appear as spikes in the normalised residual plots – see Figure 3.2a), but these are not much larger than two standard deviations, and in an outlier context are therefore marginal only. It is informative,

however, to explore the cause of these largish residuals. [Note that in this and the following paragraphs, when referring to the "year y November survey observation", the actual observation comes from the November survey held in year y-1. The "November" is merely used as a label (in the same manner as "egg" or "recruit" surveys), and the observation in year y-1 is reflected as a year y observation so that the year to which reference is made corresponds to the year index y in the $N_{y,a}$ used in the computation of the associated model biomass (equation A3.1.4).]

Figure 3.2a: Plots associated with the results in Table 3.2 (see caption to Figure 3.1a for corresponding details).

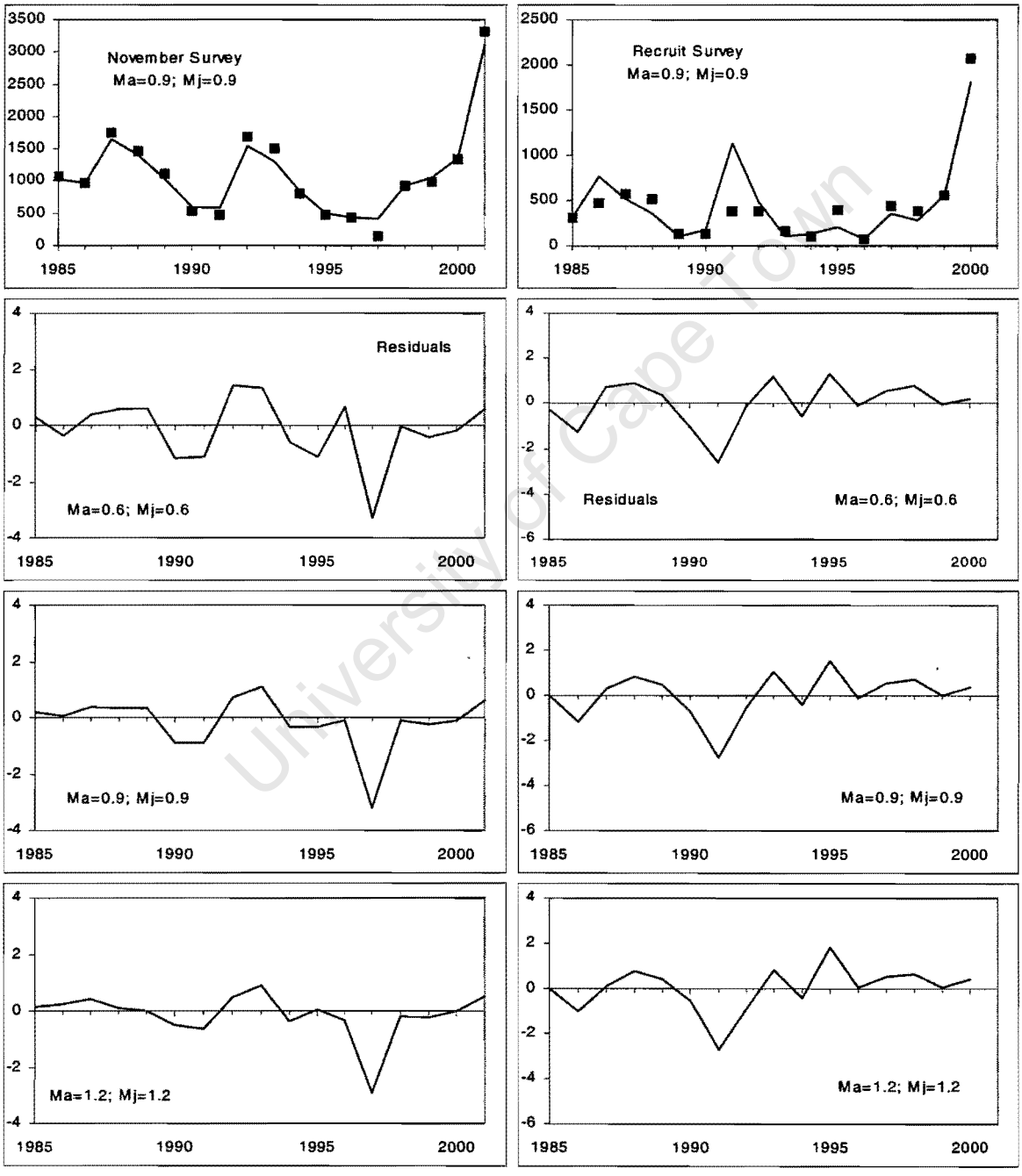

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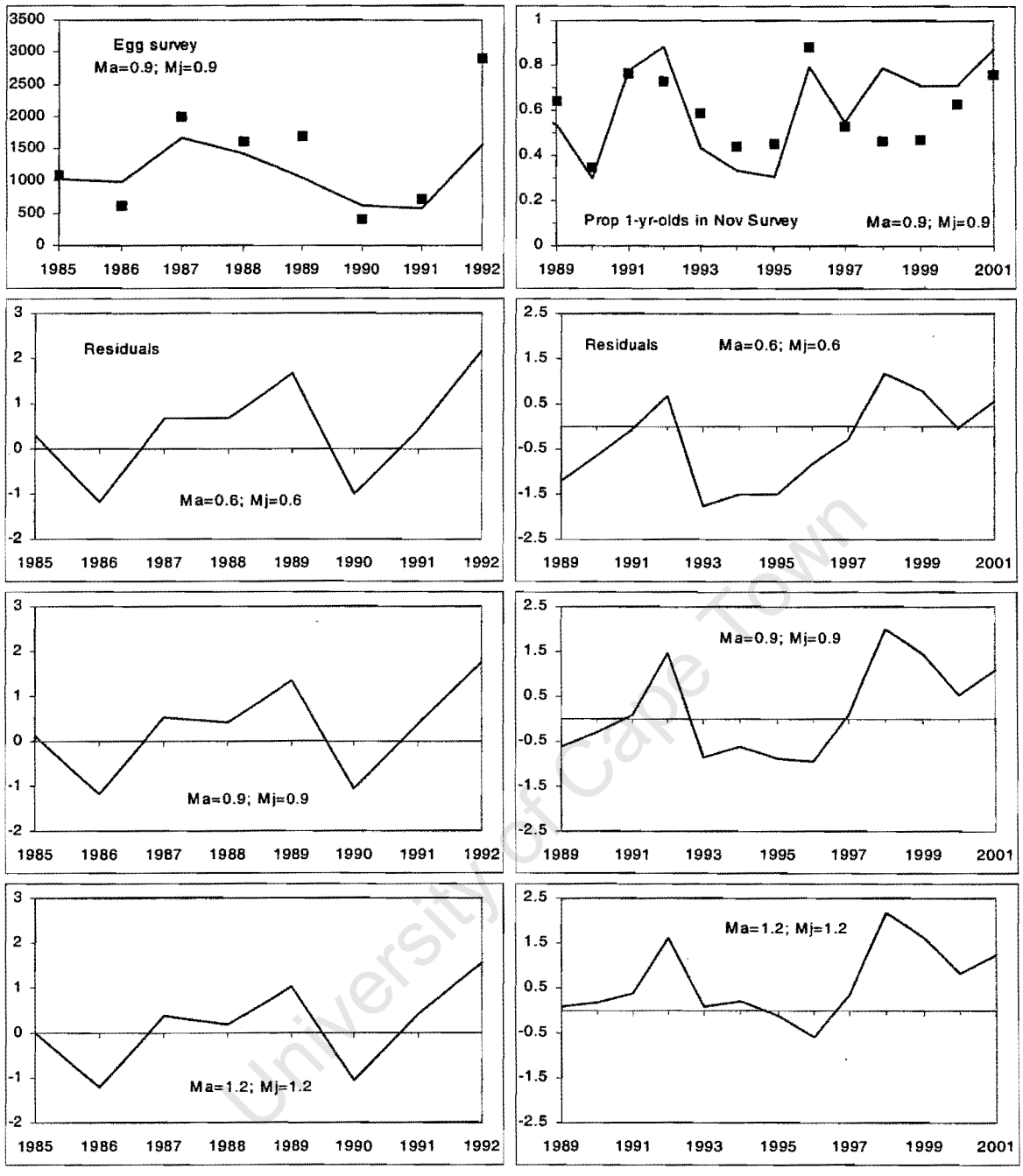
Figure 3.2b: Plots associated with Table 3.2 (see caption to Figure 3.1b for corresponding details).



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Consider first the fit to the 1991 recruit survey observation. There is a large increase in the 1992 November survey observation compared to 1991. Given the assumption of constant M, this presumably resulted from a higher recruitment influx in 1991 than indicated by the 1991 recruit survey, particularly given the relatively poor recruitment in 1989 and 1990. Because the model has difficulty reconciling this large increase in the November survey observation with the moderate observation of recruitment given by the 1991 recruit survey, it overshoots the latter somewhat, particularly as the 1991 to 1992 November increase is supported by both the acoustic and egg survey observations for 1991 and 1992.

In the case of the 1997 November survey observation, the associated CV is double the average for the whole time series (Table A3.2.2); given $\lambda_N^A = 0$, the model down-weights the importance of fitting to this observation relative to others. Furthermore, there is conflict between the model fits to the 1997 November survey observation on the one hand, and the recruit survey observation of 1995 (Figure 3.2a) and proportion of 1-year-olds for 1998 (Figure 3.2b) on the other, which can be explained as follows. A model fit closer to the 1997 November survey observation would necessitate even smaller estimates of recruitment for 1995 and 1996 (Figure 3.2a), rendering the model estimate of recruitment in 1995 (recruitment in 1996 is already very low!) even more disparate from the corresponding observation (Figure 3.2a). Consider the following as a "proxy" to the proportion of 1-year-olds model estimate in year *y*: $B_{y-1,r}^A / (B_{y-1,r}^A + B_{y-1,N}^A)$. A model fit closer to the 1997 November survey observation would also require a lower estimate of $B_{1997,N}^A$ (Figure 3.2a). Using the above "proxy", one can see that this, in turn, would result in an even higher model estimate for the proportion of 1-year-olds in 1998, which renders it more different from its corresponding observation (Figure 3.2b).

Table 3.3 shows results for when both λ_N^A and λ_r^A are estimated. A comparison with Table 3.2 (where λ_N^A is set to zero while λ_r^A is estimated) shows identical results (and an estimate for λ_N^A of zero) for most *M*-combinations, including those *M*-combinations for which the $-\ln L_{tot}$ values are smallest. These results suggest that there is no need to estimate λ_N^A, and that sampling CVs for the November survey observations do not overestimate the overall precision of these observations in relation to the true abundance. Where the results of Table 3.3 are not identical to those of Table 3.2, the estimate of λ_N^A is non-zero, and λ_r^A zero. Figure 3.3 is shown to illustrate the effect of a zero λ_r^A and non-zero λ_N^A on the model fits, and should be compared to the model fits in Figure 3.2a, where the reverse applies for these parameters (i.e. λ_N^A is set to zero, while λ_r^A is estimated as non-zero).

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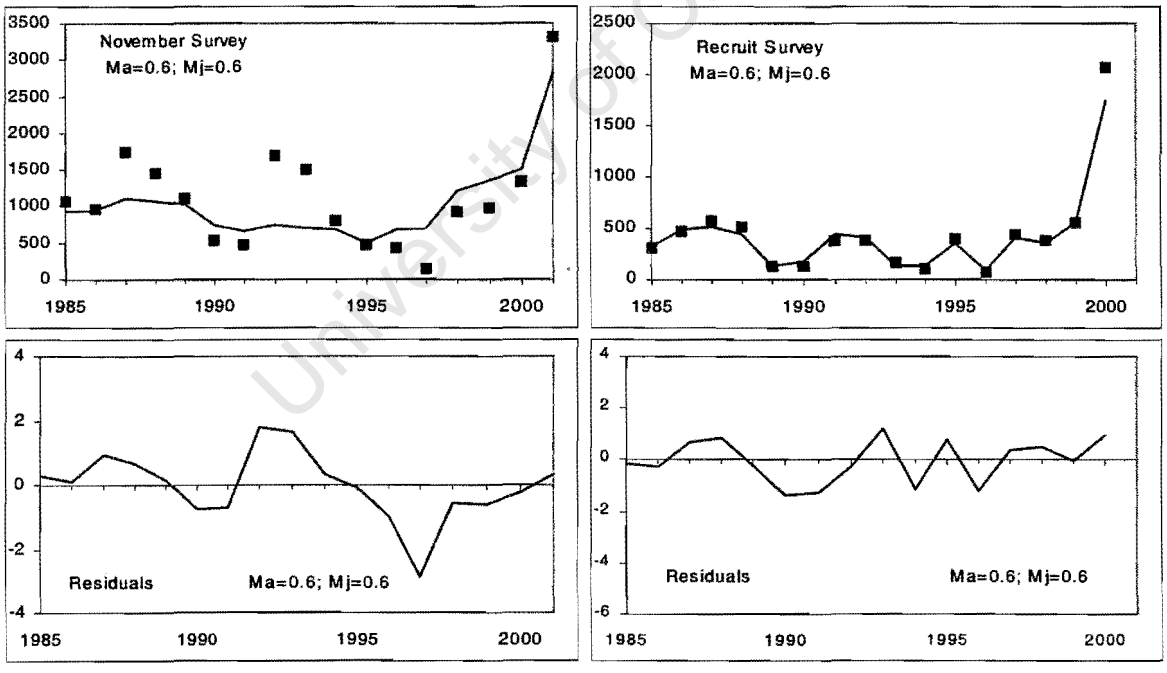
Table 3.3: Results for the model fits with λ_N^A estimated, λ_r^A estimated and $k_g^A = 1$, using the "Prosch" age-length key for the proportions of 1-year-olds.

M_{ju}^{p}		0.6	0.9	1.2	1.5	1.8	2.1	0.6	0.9	1.2	1.5	1.8	2.1
		$-\ln L_{tot}$											
M_{ad}^{A}	0.6	40.84	41.60	42.36	43.11	43.86	44.59						
	0.9	35.99	36.94	37.86	38.74	39.58	41.59						
	1.2	35.83	36.59	37.33	38.03	38.70	39.34						
	1.5	37.66	38.29	38.90	39.49	40.06	40.60						
	1.8	39.63	40.17	40.70	41.22	41.72	42.20						
	2.1	41.41	41.90	42.38	42.86	43.32	43.77						
		$k_p^{A'}$						k_r^A / k_N^A					
M_{ad}^{A}	0.6	0.761	0.756	0.752	0.747	0.743	0.738	1.172	1.070	0.972	0.885	0.800	0.722
	0.9	1.149	1.148	1.148	1.149	1.147	1.137	0.930	0.849	0.773	0.701	0.634	0.591
	1.2	1.738	1.738	1.735	1.735	1.733	1.733	0.822	0.746	0.675	0.608	0.547	0.491
	1.5	2.584	2.583	2.578	2.580	2.575	2.574	0.743	0.671	0.605	0.543	0.487	0.436
	1.8	3.762	3.757	3.757	3.753	3.750	3.748	0.687	0.619	0.557	0.499	0.447	0.399
	2.1	5.365	5.367	5.365	5.356	5.356	5.355	0.649	0.584	0.524	0.469	0.420	0.374
		λ_r^A						λ_N^A					
M_{ad}^{A}	0.6	0.000	0.000	0.000	0.000	0.000	0.000	0.443	0.451	0.456	0.462	0.468	0.476
	0.9	0.367	0.380	0.394	0.409	0.423	0.000	0.000	0.000	0.000	0.000	0.000	0.453
	1.2	0.356	0.367	0.377	0.388	0.400	0.411	0.000	0.000	0.000	0.000	0.000	0.000
	1.5	0.350	0.359	0.368	0.375	0.386	0.396	0.000	0.000	0.000	0.000	0.000	0.000
	1.8	0.347	0.355	0.363	0.371	0.380	0.390	0.000	0.000	0.000	0.000	0.000	0.000
	2.1	0.348	0.355	0.363	0.370	0.379	0.386	0.000	0.000	0.000	0.000	0.000	0.000

Figure 3.3: Plots associated with results in Table 3.3 for $M_{ju}^A = M_{ad}^A = 0.6$ (see caption to Figure 3.1a for relevant details).



Age-length keys for the period 1992-1995 (derived by the method of Prosch – MCM, unpublished data) were used to estimate the proportions of 1-year-olds from November surveys for the period 1989-2001 (see Appendix 3.2 for details). Because of the potential problems associated with applying age-length keys from one period, for which a particular growth pattern applied, to other periods during which these growth patterns may have changed, it was decided

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to use an alternative method for estimating the proportions of 1-year-olds. This alternative method simply applies cut-off lengths, based on the average length of 1- and 2-year-old anchovy, to the raised length frequencies[31] derived from the November survey trawls. Table 3.4 shows results for three choices for these cut-off lengths, namely a central value of 10.5cm, and values 0.5cm either side of it.

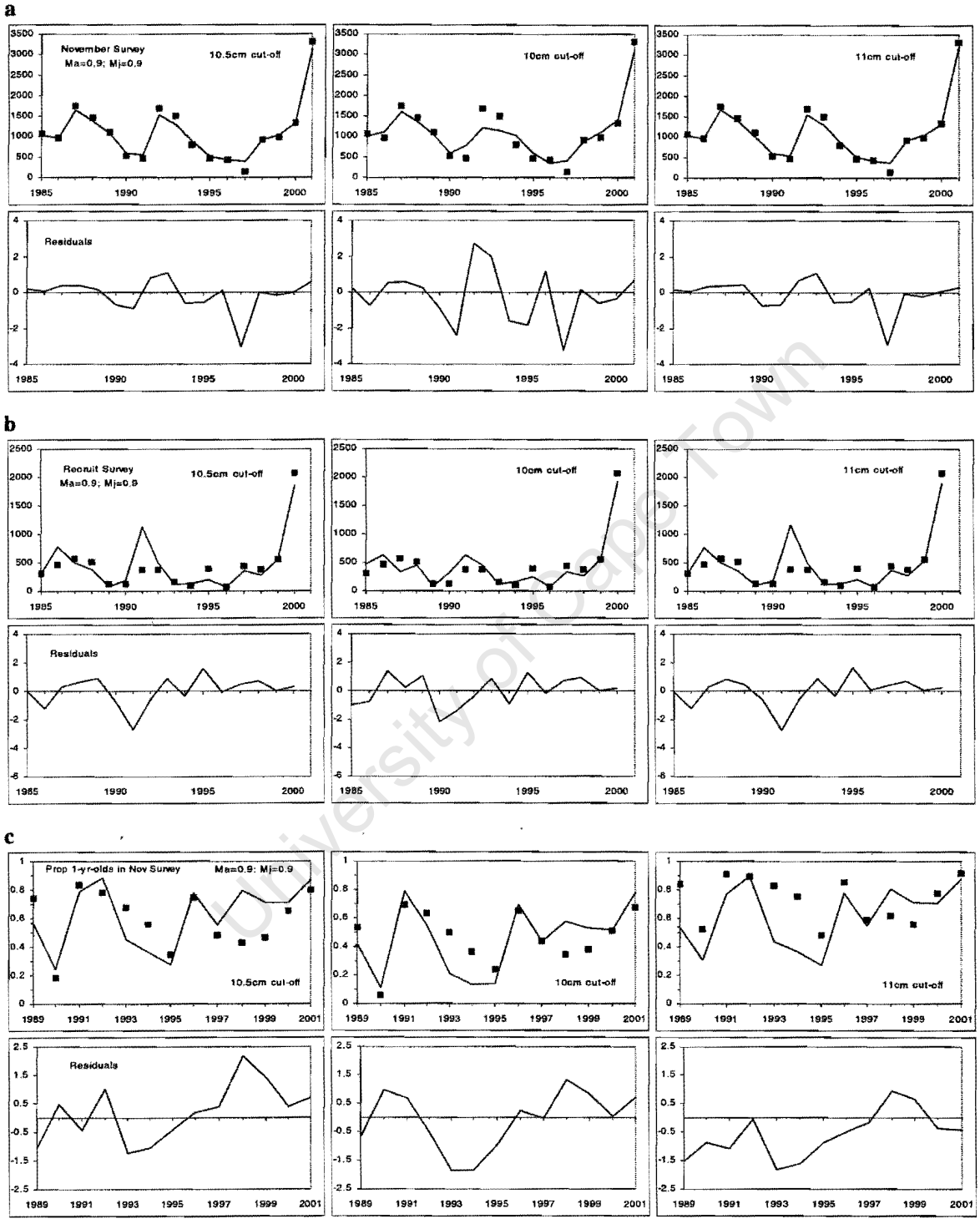
Table 3.4: Results for the model fits with $\lambda_N^A = 0$, λ_r^A estimated and $k_g^A = 1$, using different choices for cut-off lengths for calculating the proportions of 1-year-olds.

		10.5cm cut-off				10cm cut-off				11cm cut-off			
M_{ju}^A		0.6	0.9	1.2	1.5	0.6	0.9	1.2	1.5	0.6	0.9	1.2	1.5
		$-\ln L_{tot}$											
M_{ad}^A	0.6	43.74	44.94	46.10	47.22	42.74	43.99	45.21	46.36	49.05	50.28	51.48	52.62
	0.9	36.63	37.59	38.53	39.42	40.31	41.31	42.27	43.19	40.12	41.08	42.01	42.88
	1.2	36.02	36.79	37.54	38.26	41.33	42.11	42.86	43.58	33.88	34.64	35.37	36.08
	1.5	37.81	38.45	39.06	39.66	42.70	43.34	43.95	44.55	31.60	32.22	32.83	33.42
		k_r^A / k_N^A											
M_{ad}^A	0.6	1.091	1.007	0.922	0.841	1.113	1.023	0.937	0.856	1.098	1.005	0.926	0.848
	0.9	0.943	0.859	0.782	0.710	0.955	0.874	0.795	0.721	0.937	0.854	0.780	0.707
	1.2	0.827	0.751	0.680	0.612	0.831	0.754	0.682	0.616	0.818	0.742	0.672	0.606
	1.5	0.745	0.673	0.606	0.545	0.746	0.674	0.607	0.546	0.739	0.667	0.601	0.540
		$k_p^{A'}$											
M_{ad}^A	0.6	0.754	0.756	0.756	0.759	1.367	1.374	1.378	1.382	0.347	0.347	0.347	0.348
	0.9	1.151	1.152	1.153	1.153	2.123	2.124	2.128	2.131	0.541	0.542	0.541	0.540
	1.2	1.748	1.748	1.748	1.748	3.295	3.297	3.297	3.295	0.824	0.823	0.823	0.823
	1.5	2.611	2.610	2.609	2.608	4.939	4.929	4.930	4.924	1.218	1.218	1.216	1.216
		λ_r^A											
M_{ad}^A	0.6	0.373	0.394	0.410	0.430	0.388	0.407	0.426	0.445	0.378	0.396	0.415	0.437
	0.9	0.371	0.383	0.398	0.412	0.382	0.397	0.411	0.425	0.367	0.381	0.396	0.411
	1.2	0.358	0.369	0.380	0.390	0.364	0.375	0.386	0.397	0.349	0.360	0.371	0.382
	1.5	0.350	0.358	0.368	0.377	0.352	0.362	0.372	0.381	0.342	0.350	0.358	0.368

Comparing Tables 3.2 and 3.4, results are similar for the 10.5cm cut-off, but $-\ln L_{tot}$, k_r^A / k_N^A and $k_p^{A'}$ values point towards lower M values for the 10cm cut-off, and higher M values for the 11cm cut-off. Figure 3.4 shows the corresponding model fits to the November and recruit survey observations, and the proportions of 1-year-olds for $M_{ju}^A = M_{ad}^A = 0.9$. Fits to the November and recruit survey observations in Figures 3.4a and b are similar to those in Figure 3.2a, except for the 10cm cut-off results, where a poorer fit to the November survey observations is apparent. In contrast, fits to observations of the proportions of 1-year-olds (Figure 3.4c) are markedly different to those in Figure 3.2b, mainly because the observations themselves have changed.

[31] A raised length frequency for a survey is calculated by raising the length frequencies from trawl samples to the acoustic estimate of total stock biomass, using acoustic fish densities as weighting factors (see Appendix 2.2 for details).

Figure 3.4: Plots associated with the results in Table 3.4 for $M_{ju}^{A} = M_{ad}^{A} = 0.9$, where each column of plots represents results for a particular cut-off length (from left to right, 10.5cm, 10cm and 11cm) used to calculate the proportions of 1-year-olds. Plots under (a), (b) and (c) show model fits and corresponding normalised residuals (shown directly below the model fits) for the November and recruit survey observations, and the proportions of 1-year-olds. The caption to Figure 3.1a provides further details relevant to these plots.



A final set of results, shown in Table 3.5, was obtained for varying the egg survey bias k_g^A. $-\ln L_{\text{tot}}$ values improve (but not significantly for $M_{ad}^{A} \geq 0.9$) when k_g^A is increased (right-hand column of results), and deteriorate when k_g^A is decreased (left-hand column of results).

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However, $-\ln L_{tot}$, k_r^A / k_N^A and $k_p^{A'}$ values continue to support using $M_{ju}^A = M_{ad}^A = 0.9$ in both cases.

Table 3.5: Results for the model fits for different k_g^A values, with $\lambda_N^A = 0$, λ_r^A estimated and using the "Prosch" age-length key for the proportions of 1-year-olds.

		$k_g^A = 0.75$				$k_g^A = 1.25$			
M_{ju}^A		**0.6**	**0.9**	**1.2**	**1.5**	**0.6**	**0.9**	**1.2**	**1.5**
		$-\ln L_{tot}$							
M_{ad}^A	**0.6**	45.51	46.68	47.79	48.84	39.94	41.10	42.26	43.40
	0.9	37.98	38.87	39.72	40.51	34.41	35.37	36.31	37.23
	1.2	37.03	37.73	38.40	39.04	34.89	35.68	36.45	37.19
	1.5	38.48	39.05	39.61	40.14	37.02	37.68	38.32	38.95
		k_r^A / k_N^A							
M_{ad}^A	**0.6**	1.193	1.093	0.998	0.905	0.979	0.907	0.836	0.765
	0.9	1.008	0.914	0.828	0.746	0.866	0.795	0.726	0.661
	1.2	0.875	0.790	0.711	0.638	0.777	0.707	0.642	0.582
	1.5	0.783	0.703	0.631	0.565	0.708	0.642	0.581	0.524
		$k_p^{A'}$							
M_{ad}^A	**0.6**	0.721	0.721	0.722	0.723	0.787	0.786	0.787	0.788
	0.9	1.113	1.113	1.114	1.114	1.184	1.182	1.183	1.184
	1.2	1.693	1.692	1.691	1.691	1.780	1.782	1.781	1.778
	1.5	2.524	2.520	2.519	2.519	2.646	2.642	2.643	2.636
		λ_r^A							
M_{ad}^A	**0.6**	0.401	0.424	0.442	0.461	0.349	0.367	0.385	0.402
	0.9	0.386	0.400	0.414	0.427	0.354	0.366	0.379	0.393
	1.2	0.368	0.378	0.389	0.400	0.348	0.358	0.369	0.379
	1.5	0.358	0.365	0.374	0.384	0.344	0.353	0.362	0.371

3.4 Discussion

Selection of base-case assessment

Assuming $\lambda_N^A = \lambda_r^A = 0$ yielded opposing residual trends for the fits to the November survey and proportions of 1-year-olds observations (Figure 3.1), which effectively excludes this model specification as a basis for further work. Estimating λ_r^A while keeping $\lambda_N^A = 0$ significantly improved fits for all M-combinations (Table 3.2, Figure 3.2). However, for most M-combinations (including those M-combinations that led to the best fits), estimating both λ_r^A and λ_N^A yielded identical results to keeping $\lambda_N^A = 0$ while estimating λ_r^A (Table 3.3). This indicates that there was no need to free λ_N^A.

A base-case assessment was therefore selected from the model specification for Table 3.2, namely λ_r^A is estimated and λ_N^A fixed at 0. The M-combination selected was $M_{ju}^A = M_{ad}^A = 0.9$, because it yielded the lowest value of $-\ln L_{tot}$ in the upper triangle of the $-\ln L_{tot}$ matrix, and because both the k_r^A / k_N^A and the $k_p^{A'}$ criteria (i.e. that k_r^A / k_N^A fell in the range [0.5; 1], and that

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$k_p^{A'}$ was as close to 1 as possible) were met (Table 3.2). The base-case assessment specifications chosen were therefore: $M_{ju}^{A} = M_{ad}^{A} = 0.9$, λ_r^A estimated, $\lambda_N^A = 0$, "Prosch" age-length key method for the proportions of 1-year-olds observations.

Selection of alternative plausible scenarios

Table 3.6 summarises results taken from Tables 3.1-3.5 for the base-case assessment, A_0, and a range of alternatives A_1-A_{11}, which are treated as "best" estimates with associated bootstrap estimates of precision (given as CVs in the form of percentages, Appendix 3.1). Four of the alternative assessments (A_1, A_2, A_3 and A_4) deal only with changing the M values, and these assessments are selected such that their associated $-\ln L_{tot}$ values are not significantly different from that for A_0 (Table 3.2), and also that the criterion with regard to k_r^A / k_N^A (mentioned above) is met[32]. In the case of A_1, none of these criteria are met, but this case has nevertheless been selected to ensure that there is at least one alternative assessment with M values smaller than those for A_0.

Assessments A_5, A_6 and A_7 use cut-off lengths (10.5, 10 and 11cm respectively) instead of the "Prosch" age-length key to calculate the proportions of 1-year-olds, and as such are not directly comparable, in terms of likelihood values, to each other or to the other assessments. For assessments A_5, A_6 and A_7, M values have been selected from within the corresponding cut-off length "column" of results in Table 3.4 such that they reflect a significantly better $-\ln L_{tot}$ than other M values within this "column" (A_7 not quite meeting this criterion), and also such that the k_r^A / k_N^A ratio falls in the range [0.5; 1] (A_6 not quite meeting this criterion). Furthermore, the $k_p^{A'}$ value should be as close to 1 as possible. $M_{ju}^{A} = M_{ad}^{A} = 1.5$ (instead of 1.2) could have been selected for A_7, but it was considered that these M values were perhaps too extreme, particularly for M_{ad}^{A}, and that for A_0, $M_{ju}^{A} = M_{ad}^{A} = 1.2$ would provide a symmetrical alternative to A_6.

Assessments A_8 and A_9 deal with alternatively fixing or estimating the additional variances λ_N^A and λ_r^A, and assessments A_{10} and A_{11} consider alternative values to 1 for k_g^A with M values selected using the $-\ln L_{tot}$, k_r^A / k_N^A and $k_p^{A'}$ criteria as before.

[32] As for pilchard, these criteria for selecting alternative assessments have been applied somewhat loosely.

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Table 3.6: Likelihood estimates for assessments A_0-A_{11}. Options for M_{ad}^A, M_{ju}^A, the ageing method used for estimating the proportions of 1-year-olds, λ_r^A, λ_N^A and k_g^A are shown on the left, with empty cells taking on the corresponding option shown for A_0. Assessments A_5, A_6 and A_7 are not directly comparable in terms of $-\ln L_{tot}$ to the other assessments and to each other (see main text). The final column shows $k_p^{A'}$ estimates.

	M_{ad}^A	M_{ju}^A	Ageing	λ_r^A	λ_N^A	k_g^A	$-\ln L_{tot}$	$-\ln L_{Nov}$	$-\ln L_{egg}$	$-\ln L_{rec}$	$-\ln L_{prop1}$	$-\ln L_0$	$k_p^{A'}$
A_0	0.9	0.9	Prosch	est	0	1	36.94	-7.98	3.72	8.48	14.13	18.60	1.148
A_1	0.6	0.6					42.42	-4.71	5.25	8.19	15.69	18.00	0.753
A_2	1.2	1.2					37.33	-9.70	2.90	8.37	16.81	18.94	1.735
A_3	1.5	1.5					39.49	-10.75	2.58	8.30	20.44	18.92	2.580
A_4		1.5					38.74	-7.91	3.69	9.50	14.07	19.39	1.149
A_5			10.5cm				37.59	-8.33	3.56	8.62	14.72	19.03	1.152
A_6	0.6	0.6	10cm				42.74	-5.02	4.52	8.90	15.60	18.74	1.367
A_7	1.2	1.2	11cm				35.37	-9.28	3.13	8.13	14.61	18.78	0.748
A_8				0			53.61	8.22	6.84	9.19	12.21	17.16	1.163
A_9					est		36.94	-7.98	3.72	8.48	14.13	18.60	1.148
A_{10}						0.75	38.87	-7.81	3.73	9.19	14.33	19.43	1.113
A_{11}						1.25	35.37	-8.02	3.65	7.95	13.90	17.88	1.182

Other parameter estimates for the operating model

Apart from the parameters already mentioned (M_{ad}^A, M_{ju}^A, k_g^A, k_N^A, k_r^A, λ_N^A, λ_r^A, λ_p^A, λ_0^A), other parameters required for the operating model used to test management procedures are shown in Tables 3.7 and 3.8, together with bootstrap estimates of precision. These are the begin-year numbers-at-age for the first year of the projection period ($N_{2001,1}^A,\ldots,N_{2001,4}^A$) and parameters derived from the stock-recruit curves, namely carrying capacity K^A, recruitment variability σ_r^A, recruitment serial correlation s_{cor}^A, the 2000 recruitment residual value η_{2000}^A, and the actual parameters of the stock-recruit curves, a^A and b^A (equations A3.1.12-13).

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Table 3.7: Estimates of median recruitment, $N^A_{0,med}$, begin-year numbers-at-age for the first year of the management procedure projection period, survey biases and additional variance parameters for assessments A_0-A_{11} with CVs (expressed as percentages in small print). Numbers in italics for λ^A_N and λ^A_r are assumed rather than estimated.

	$N^A_{0,med}$	$N^A_{2001,1}$	$N^A_{2001,2}$	$N^A_{2001,3}$	$N^A_{2001,4}$	k^A_N	k^A_r	k^A_r / k^A_N	λ^A_N	λ^A_r	λ^A_p	λ^A_0
A_0	180.54 10%	309.37 22%	32.66 28%	10.15 28%	3.26 30%	0.988 17%	0.839 16%	0.849 13%	*0*	0.380 61%	0.595 75%	0.465 14%
A_1	117.56 9%	273.15 22%	34.71 35%	14.76 33%	6.30 30%	1.044 16%	1.122 13%	1.075 13%	*0*	0.370 81%	0.703 55%	0.441 16%
A_2	275.39 11%	346.28 19%	28.80 25%	6.84 28%	1.61 21%	0.941 14%	0.635 15%	0.675 13%	*0*	0.377 63%	0.786 29%	0.479 12%
A_3	406.30 10%	376.78 17%	24.00 24%	4.30 25%	0.74 26%	0.920 13%	0.500 15%	0.543 11%	*0*	0.375 63%	1.095 18%	0.478 13%
A_4	302.96 10%	309.38 21%	32.94 30%	9.89 30%	3.23 26%	0.985 14%	0.690 15%	0.701 13%	*0*	0.409 57%	0.592 65%	0.497 14%
A_5	180.16 10%	313.57 22%	32.52 34%	10.07 33%	3.27 33%	0.984 15%	0.846 17%	0.859 12%	*0*	0.383 82%	0.636 50%	0.482 13%
A_6	119.28 7%	282.41 19%	35.44 33%	15.43 35%	6.56 33%	1.003 13%	1.116 14%	1.113 13%	*0*	0.388 70%	0.697 63%	0.471 13%
A_7	273.20 12%	349.32 23%	28.09 25%	6.42 25%	1.59 26%	0.956 16%	0.642 17%	0.672 11%	*0*	0.371 65%	0.628 56%	0.472 12%
A_8	180.67 7%	305.35 16%	31.11 19%	12.23 13%	3.55 18%	1.034 12%	0.821 9%	0.795 9%	*0*	*0.000*	0.473 56%	0.407 13%
A_9	180.54 10%	309.37 24%	32.66 39%	10.15 31%	3.26 29%	0.988 16%	0.839 15%	0.849 13%	0 204%	0.380 79%	0.595 68%	0.465 16%
A_{10}	220.77 10%	414.29 24%	44.38 30%	13.37 28%	4.35 32%	0.735 15%	0.672 18%	0.914 12%	*0*	0.400 73%	0.609 54%	0.498 13%
A_{11}	157.17 8%	248.46 18%	26.02 28%	8.18 32%	2.61 27%	1.234 13%	0.981 14%	0.795 12%	*0*	0.366 68%	0.581 67%	0.436 14%

While assessments A_0-A_{11} use the "SS" stock recruit curve, the "BH" curve is estimated for the results of A_0, with the resultant assessment named A_{12}. Although the same constraints used in the estimation of the parameters of the pilchard stock-recruit curves are also used for anchovy, these constraints were never encountered in the estimation process. Furthermore, b^A was not estimated for the "SS" curve, but rather set equal to $0.2K^A$, because of the lack of stock-recruit estimates near the origin of the stock recruit plots. This is shown in Figure 3.5, which plots "best" estimates, $B^A_{y,N}$ and $N^A_{y,0}$, for assessment A_0 (with 95% bootstrap confidence intervals), together with the "SS" and "BH" curves fitted to these "best" estimates.

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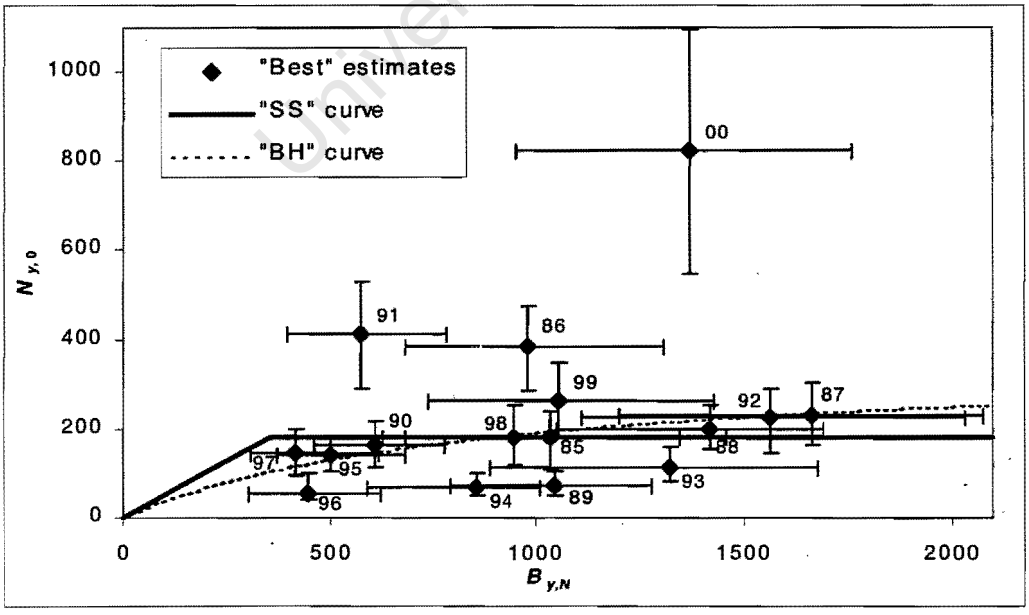
Table 3.8: Estimates of parameters related to the "SS" ("Single-Sloped") stock-recruit curves for assessments A_0-A_{11}, namely carrying capacity K^A, recruitment variability σ_r^A, recruitment serial correlation s_{cor}^A, the 2000 recruitment residual value η_{2000}^A, and the actual parameters of the stock-recruit curves a^A and b^A. [Note: $b^A = 0.2K^A$ for anchovy.] A_{12} represents an assessment identical to A_0, except that the "BH" ("Beverton-Holt") stock recruit curve is fitted instead of the "SS" curve (see Appendix 3.1 for details). Bootstrap CVs are expressed as percentages in small print.

	K^A	σ_r^A	s_{cor}^A	η_{2000}^A	a^A	b^A
	"SS" curve					
A_0	1802 11%	0.685 8%	0.324 30%	2.230 8%	179.0 10%	360.4 11%
A_1	2051 11%	0.663 8%	0.303 34%	2.340 9%	117.2 9%	410.2 11%
A_2	1689 11%	0.697 7%	0.339 26%	2.153 8%	273.0 11%	337.9 11%
A_3	1608 11%	0.696 7%	0.352 24%	2.129 8%	403.3 11%	321.6 11%
A_4	1692 12%	0.713 8%	0.331 33%	2.231 6%	300.5 10%	338.4 12%
A_5	1815 12%	0.700 7%	0.308 37%	2.205 7%	178.5 10%	363.0 12%
A_6	2114 9%	0.688 7%	0.280 40%	2.278 7%	118.8 7%	422.8 9%
A_7	1666 13%	0.691 7%	0.332 26%	2.198 7%	270.2 12%	333.1 13%
A_8	1763 8%	0.637 6%	0.253 32%	2.364 5%	180.8 7%	352.6 8%
A_9	1802 12%	0.685 9%	0.324 39%	2.230 11%	179.0 10%	360.4 12%
A_{10}	2246 13%	0.714 8%	0.330 37%	2.241 7%	218.7 10%	449.1 13%
A_{11}	1544 9%	0.661 7%	0.324 30%	2.217 8%	155.9 8%	308.8 9%
	"BH" curve					
A_{12}	2665 19%	0.645 10%	0.125 73%	2.051 10%	363.0 33%	892.5 68%

Figure 3.5: Two stock-recruit curves fitted to the stock-recruit "best" estimates for assessment A_0 (see Table 3.8 caption and Appendix 3.1 for details), with 95% confidence intervals shown for these "best" estimates, together with corresponding years.



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APPENDIX 3.1

Anchovy assessment model

Model Assumptions

1. All fish have a theoretical birthdate of 1 November, but become available to the fishery for the first time only from 1 January.
2. Anchovy spawn for the first time (and are called adult anchovy) when they turn one year old.
3. Anchovy die once they reach 4 years of age and have spawned a final time.
4. Two surveys are held each year: the first takes place in November (known as the November survey) and surveys the adult stock; the second is in May/June (known as the recruit survey) and surveys juvenile anchovy (also called recruits or 0-year-old anchovy).
5. The November survey provides a relative index of abundance of unknown bias.
6. The recruit survey provides a relative index of abundance of unknown bias.
7. The egg survey observations (derived from data collected during the November survey) provide absolute indices of abundance.
8. The survey strategy is such that any survey bias does not change over time.
9. Pulse fishing occurs three and six months after the birthdate for 1-year-old and 0-year-old anchovy respectively; these are the only ages targeted by the fishery (see caption to Table A3.2.1 and associated text in Appendix 3.2 for motivations for this assumption).
10. Catches are measured without error (but see also corresponding text for pilchard in Appendix 2.1, and "Future work" in Chapter 9).
11. Natural mortality is year-invariant for juvenile and adult fish, and age-invariant for adult fish.

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Basic Dynamics

The basic dynamic equations for anchovy are as follows. [Note that in the equations that follow, an additional year of data was available for anchovy ($y = 2000$) compared to pilchard, because there was no need to wait for the age data to be processed for anchovy, as was the case for pilchard. Routine ageing is currently not carried out for anchovy (Appendix 3.2).]

Numbers-at-age at the beginning of the year:

$$N^A_{y+1,1} = (N^A_{y,0} e^{-M^A_{ju}/2} - C^A_{y,0} / w^A_{y,0c}) e^{-M^A_{ju}/2} \qquad \text{for } y = 1981,\ldots,2000 \qquad \text{A3.1.1}$$

$$N^{A}_{y+1,2} = (N^{A}_{y,1} e^{-M^{A}_{ad}/4} - C^{A}_{y,1} / w^{A}_{y,1c}) e^{-3M^{A}_{ad}/4} \quad \text{for } y = 1982,\ldots,2000 \qquad \text{A3.1.2}$$

$$N^{A}_{y+1,a+1} = N^{A}_{y,a} e^{-M^{A}_{ad}} \quad \text{for the following combinations of } y \text{ and } a: \; y=1983,\ a=2;\ \text{and } y=1984,\ldots,2000,\ a=2,3 \qquad \text{A3.1.3}$$

where:

$N^{A}_{y,a}$ is the number (in billions) of anchovy of age a at the beginning of year y;

$C^{A}_{y,a}$ is the mass (in thousand tons) of anchovy of age a caught in year y;

$w^{A}_{y,ac}$ is the mean mass (in grams) of anchovy associated with the catch $C^{A}_{y,a}$;

M^{A}_{ju} is the natural mortality (in year^{-1}) of juvenile anchovy (i.e. fish of age 0); and

M^{A}_{ad} is the natural mortality (in year^{-1}) of adult anchovy (i.e. fish of age 1+).

Biomass associated with the November survey:

$$B^{A}_{y,N} = \sum_{a=1}^{4} N^{A}_{y,a} w^{A}_{y,a} \quad \text{for } y = 1985,\ldots,2001 \qquad \text{A3.1.4}$$

where:

$B^{A}_{y,N}$ is the biomass (in thousand tons) of adult anchovy at the beginning of year y, associated with the November survey in year y-1; and

$w^{A}_{y,a}$ is the mean mass (in grams) of anchovy of age a sampled during the November survey of year y-1 (note that this differs from the mass of anchovy of the same age in the commercial catch $w^{A}_{y,ac}$).

Number of recruits at the time of the recruit survey:

The following equation projects $N^{A}_{y,0}$ to the start of the recruit survey, taking natural and fishing mortality into account, and assuming pulse fishing of juveniles half way between 1 April (the first time juvenile fish become available to the fishery – see Appendix 3.2) and the start of the recruit survey (similar rationale to that for pilchard – see text above equation A2.1.4).

$$B^{A}_{y,r} = (N^{A}_{y,0} e^{-[5+0.5(1+t^{A}_{y})]M^{A}_{ju}/12} - C^{A}_{y,0bs} / w^{A}_{y,0cbs}) e^{-0.5(1+t^{A}_{y})M^{A}_{ju}/12} w^{A}_{y,rec} \quad \text{for } y = 1985,\ldots,2000 \qquad \text{A3.1.5}$$

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where:

$B^A_{y,r}$ is the biomass (in thousand tons) of juvenile anchovy at the time of the recruit survey in year y;

$C^A_{y,0bs}$ is the mass (in thousand tons) of juvenile anchovy caught between 1 April in year y and the day before the start of the recruit survey that year;

$w^A_{y,0cbs}$ is the mean mass (in grams) of juvenile anchovy associated with the catch $C^A_{y,0bs}$;

$w^A_{y,rec}$ is the mean mass (in grams) of juvenile anchovy associated with the recruit survey estimate $B^A_{y,rec}$ (see Table A3.2.4 below) in year y; and

t^A_y is the time lapsed (in months) between 1 May and the start of the recruit survey that provided the estimate $B^A_{y,rec}$ (see Table A3.2.4 below) in year y. [Note that $t^A_{1990} \neq t^P_{1990}$ because two recruit surveys were held in 1990, with the first survey being used for pilchard, and the second survey for anchovy – the second survey did not provide a reliable estimate for pilchard.]

Proportions of 1-year-olds associated with November survey:

$$p^A_{y,1} = \frac{N^A_{y,1}}{\sum_{a=1}^{4} N^A_{y,a}} \qquad \text{for } y=1989,\ldots,2001 \qquad \text{A3.1.6}$$

where:

$p^A_{y,1}$ is the proportion of anchovy of age a at the beginning of year y, associated with the November survey in year y-1.

Fitting Criterion

The fitting criterion used is the same as for pilchard (i.e. maximum likelihood estimation assuming observations are log-normally distributed, and using sampling CVs (squared) of the untransformed survey observations to approximate the "sampling" component of the total variance of the corresponding log-distributions). However, the proportions of 1-year-olds are

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treated differently, because they are first logit-transformed before being used in the likelihood. Two additional components have also been included: the first incorporates the egg survey observations into the likelihood (second term of equation A3.1.7), while the second ensures that the $N^A_{y,0}$ estimates are well behaved, particularly at the start of the time series (last term of equation A3.1.7).

$$
\begin{aligned}
-\ln L = {} & \tfrac{1}{2} W^A_N \sum_{y=1985}^{2001} \left\{ \frac{\left(\ln B^A_{y,Nov} - \ln(k^A_N B^A_{y,N})\right)^2}{(\sigma^A_{y,Nov})^2 + (\lambda^A_N)^2} + \ln\left[2\pi\left((\sigma^A_{y,Nov})^2 + (\lambda^A_N)^2\right)\right] \right\} \\
& + \tfrac{1}{2} W^A_g \sum_{y=1985}^{1991} \left\{ \frac{\left(\ln B^A_{y,egg} - \ln(k^A_g B^A_{y,N})\right)^2}{(\sigma^A_{y,egg})^2} + \ln\left[2\pi(\sigma^A_{y,egg})^2\right] \right\} \\
& + \tfrac{1}{2} W^A_r \sum_{y=1985}^{2000} \left\{ \frac{\left(\ln B^A_{y,rec} - \ln(k^A_r B^A_{y,r})\right)^2}{(\sigma^A_{y,rec})^2 + (\lambda^A_r)^2} + \ln\left[2\pi\left((\sigma^A_{y,rec})^2 + (\lambda^A_r)^2\right)\right] \right\} \\
& + \tfrac{1}{2} W^A_p \sum_{y=1989}^{2001} \left\{ \frac{\left(\ln q^{A,meth}_{y,1,Nov} - \ln q^A_{y,1}\right)^2}{0.4^2 + (\lambda^A_p)^2} + \ln\left[2\pi\left(0.4^2 + (\lambda^A_p)^2\right)\right] \right\} \\
& + \tfrac{1}{2} W^A_0 \sum_{y=1981}^{2000} \left\{ \frac{\left(\ln N^A_{y,0} - \ln N^A_{0,med}\right)^2}{0.4^2 + (\lambda^A_0)^2} + \ln\left[2\pi\left(0.4^2 + (\lambda^A_0)^2\right)\right] \right\}
\end{aligned}
\qquad \text{A3.1.7}
$$

where:

$$q^A_{y,1} = \frac{1 - p^A_{y,1}}{p^A_{y,1}}$$

$$q^{A,meth}_{y,1,Nov} = \frac{1 - p^{A,meth}_{y,1,Nov}}{p^{A,meth}_{y,1,Nov}}$$

and

$B^A_{y,Nov}$ is the acoustic survey estimate (in thousand tons) of adult anchovy biomass from the November survey in year *y*-1, with associated CV $\sigma^A_{y,Nov}$ and constant of proportionality k^A_N;

$B^A_{y,egg}$ is the egg survey estimate (in thousand tons) of adult anchovy biomass from the November survey in year *y*-1, with associated CV $\sigma^A_{y,egg}$ and constant of proportionality k^A_g;

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$B^A_{y,rec}$ is the acoustic survey estimate (in thousand tons) of anchovy recruitment biomass from the recruit survey in year y, with associated CV $\sigma^A_{y,rec}$ and constant of proportionality k^A_r;

$p^{A,meth}_{y,1,Nov}$ is an estimate of the proportion (by number) of 1-year-old anchovy in the November survey of year y-1, derived by one of two methods (*meth*=Prosch uses the Prosch age length keys, and *meth*=10/10.5/11cm uses a cut-off length in the raised length frequencies for the corresponding survey – see Table A3.2.3 and associated text in Appendix 3.2 for details);

$N^A_{0,med}$ is the median of the $N^A_{y,0}$ time series (see equation A3.1.8 below);

$(\lambda^A_{N/r})^2$ is the additional variance (over and above the survey sampling CV $\sigma^A_{y,Nov/rec}$ that reflects survey inter-transect variance) associated with the November/recruit surveys;

$(\lambda^A_{p/0})^2$ is the additional variance (over and above the fixed variance of 0.4^2) associated with the proportion of 1-year-olds/ $N^A_{y,0}$ terms (4^{th} and 5^{th} terms respectively) of the likelihood, where the fixed variances have been introduced to avoid the associated terms in the likelihood being given too much weight relative to the other terms; and

$W^A_{N/g/r/p/0}$ is the likelihood weight that governs to what extent the associated observations are used in the likelihood (W=0 implies they are not used).

[Note that additional variance was not included for the egg survey component, which is reasonable given the estimate of zero for λ^A_N associated with the November survey (Table 3.3). Furthermore, unlike the recruit survey, the November survey covers the whole distributional range of anchovy, so that variability of the proportion of the stock in the area surveyed, which is thought to be the main contributor to additional variance, is not really an issue for the November, and hence egg, survey estimates.]

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Estimable and input parameters

The estimable parameters of the likelihood L are: M^A_{ju}, M^A_{ad}, $N^A_{1981,0},\ldots,N^A_{2000,0}$, k^A_N, k^A_r, k^A_g, λ^A_N, λ^A_r, λ^A_p and λ^A_0. However, in these applications M^A_{ju}, M^A_{ad} and k^A_g are treated as input

parameters (i.e. they are fixed externally). Given values for these three parameters, partial differentiation of $-\ln L$ leads to closed form solutions for k_N^A, k_r^A, λ_N^A, λ_r^A, λ_p^A and λ_0^A. [Note: in some of the results presented, λ_N^A and λ_r^A are also treated as input parameters.] The numerical optimisation routine therefore requires initial values for $N_{1981,0}^A,\ldots,N_{2000,0}^A$ and searches over a parameter space of 20 dimensions. The closed form solutions for k_N^A, k_r^A, λ_N^A, λ_r^A, λ_p^A and λ_0^A are given below.

The parameterisation for the multi-dimensional search is effected in the same way as for pilchard, i.e. the search is actually performed over $N_{0,med}^A$, $N_{1981,0}^A,\ldots,N_{1999,0}^A$, with $N_{2000,0}^A$ calculated as follows:

$$N_{2000,0}^A = \frac{(N_{0,med}^A)^{20}}{\prod_{y=1981}^{1999} N_{y,0}^A} \qquad \text{A3.1.8}$$

The parameters in each of the following pairs, $\{k_N^A, \lambda_N^A\}$ and $\{k_r^A, \lambda_r^A\}$, are calculated simultaneously, in the same way as the pilchard parameters in the pair $\{k_r^P, \lambda_r^P\}$ were calculated (i.e. using an iterative algorithm – see equation A2.1.8 and associated text), with k_N^A and k_r^A calculated as follows:

$$k_{N/r}^A = \exp\left[\frac{\sum_{y\in Y_{N/r}} \left(\ln B_{y,Nov/rec}^A - \ln B_{y,N/r}^A\right) / \left((\sigma_{y,Nov/rec}^A)^2 + (\lambda_{N/r}^A)^2\right)}{\sum_{y\in Y_{N/r}} 1/\left((\sigma_{y,Nov/rec}^A)^2 + (\lambda_{N/r}^A)^2\right)}\right] \qquad \text{A3.1.9}$$

where $Y_N = \{1985,\ldots,2001\}$ and $Y_r = \{1985,\ldots,2000\}$.

Parameters λ_p^A and λ_0^A are calculated as follows:

$$(\lambda_p^A)^2 = \max\left[0; \left(\sum_{y=1989}^{2001} (\ln q_{y,1,Nov}^{A,meth} - \ln q_{y,1}^A)^2 \Big/ \sum_{y=1989}^{2001} 1\right) - 0.4^2\right] \qquad \text{A3.1.10}$$

$$(\lambda_0^A)^2 = \max\left[0; \left(\sum_{y=1981}^{2000} (\ln N_{y,0}^A - \ln N_{0,med}^A)^2 \Big/ \sum_{y=1981}^{2000} 1\right) - 0.4^2\right] \qquad \text{A3.1.11}$$

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Stock-Recruit Curves

Stock-recruit curves similar to those for pilchard were estimated for anchovy, based on the assessment model estimates of $N^A_{y,0}$ and $B^A_{y,N}$ ($y = 1985,\ldots,2000$ – see equations A3.1.1 and A3.1.4). However, only two types of stock-recruit curves were fitted to these estimates (using maximum likelihood estimation), namely the "SS" ("single-sloped") and "BH" ("Beverton-Holt") curves[33], as follows:

"SS": $$N^A_{y,0,sr} = \begin{cases} a^A & , \text{ if } B^A_{y,N} \geq b^A \\ \dfrac{a^A B^A_{y,N}}{b^A} & , \text{ if } B^A_{y,N} < b^A \end{cases} \qquad \text{A3.1.12}$$

"BH": $$N^A_{y,0,sr} = \frac{a^A B^A_{y,N}}{b^A + B^A_{y,N}} \qquad \text{A3.1.13}$$

The likelihood function is the same as for pilchard (and therefore not repeated here), except that it incorporates an additional year, namely 2000. The estimable parameters are a^A and σ_r^A for both curves, and includes b^A for the "BH" curve ($b^A = 0.2K^A$ for the "SS" curve, K^A as defined below). σ_r^A has a closed form solution as follows:

$$(\sigma_r^A)^2 = \sum_{y=1985}^{2000} (\ln N^A_{y,0} - \ln N^A_{y,0,sr})^2 / \sum_{y=1985}^{2000} 1 \qquad \text{A3.1.14}$$

Other parameters include the recruitment serial correlation:

$$s^A_{cor} = \frac{\sum_{y=1985}^{1999} \varepsilon_y \varepsilon_{y+1}}{\sqrt{\left(\sum_{y=1985}^{1999} \varepsilon_y^2\right)\left(\sum_{y=1985}^{1999} \varepsilon_{y+1}^2\right)}} \qquad \text{A3.1.15}$$

and the year 2000 standardised recruitment residual value:

$$\eta^A_{2000} = \frac{\varepsilon_{2000}}{\sigma_r^A} \qquad \text{A3.1.16}$$

[33] The "DS" curve (Chapter 2) is not considered for anchovy because recruitment is seen to fluctuate around a relatively stable mean, whereas for pilchard, there are perceptions that stock abundance may still be increasing.

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where

$$\varepsilon_y = \ln N^A_{y,0} - \ln N^A_{y,0,sr} \qquad \text{for y=1985,...,2000}$$

Carrying capacity K^A for the different stock-recruit curves is calculated as follows:

"SS": $$K^A = a^A e^{\frac{1}{2}(\sigma_r^A)^2}\left[\sum_{a=1}^{4} \overline{w}_a^A e^{-M^A_{jul}-(a-1)M^A_{ad}}\right] \qquad \text{A3.1.17}$$

"BH": $$K^A = a^A e^{\frac{1}{2}(\sigma_r^A)^2}\left[\sum_{a=1}^{4} \overline{w}_a^A e^{-M^A_{jul}-(a-1)M^A_{ad}}\right] - b^A \qquad \text{A3.1.18}$$

where:

$\overline{w}_a^A$ is the average of $w^A_{y,a}$ defined above (see Table A3.2.2 below).

The $e^{\frac{1}{2}(\sigma_r^A)^2}$ factor in equations A3.1.17-18 corrects for log-normal distribution bias, as for pilchard.

When estimating the parameters of the stock-recruit curves, the following constraints are applied:

i) a^A has to be non-negative;

ii) b^A has to be positive ("BH" curve only); and

iii) for cases where K^A exceeds 10 million tons, a penalty factor $(K^A/10\,000)^2$ is introduced into the likelihood function to avoid unrealistically high values.

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Bootstrap estimation

Bootstrap estimation was performed in the same way as for pilchard, with pseudo-data sets generated as follows:

$$
\begin{aligned}
B^{A,Q}_{y,Nov} &= k^{A}_{N} B^{A}_{y,N} e^{\varepsilon^{A,Q}_{y,Nov}} && , \quad \varepsilon^{A,Q}_{y,Nov} \text{ from } \mathrm{N}[0;(\sigma^{A}_{y,Nov})^2 + (\lambda^{A}_{N})^2] \\
B^{A,Q}_{y,egg} &= k^{A}_{g} B^{A}_{y,N} e^{\varepsilon^{A,Q}_{y,egg}} && , \quad \varepsilon^{A,Q}_{y,egg} \text{ from } \mathrm{N}[0;(\sigma^{A}_{y,egg})^2] \\
B^{A,Q}_{y,rec} &= k^{A}_{r} B^{A}_{y,r} e^{\varepsilon^{A,Q}_{y,rec}} && , \quad \varepsilon^{A,Q}_{y,rec} \text{ from } \mathrm{N}[0;(\sigma^{A}_{y,rec})^2 + (\lambda^{A}_{r})^2] \\
q^{A,meth,Q}_{y,1,Nov} &= k^{A'}_{p} q^{A}_{y,1} e^{\varepsilon^{A,Q}_{y,p}} && , \quad \varepsilon^{A,Q}_{y,p} \text{ from } \mathrm{N}[0;(\sigma^{A'}_{p})^2)]
\end{aligned}
\qquad \text{A3.1.19}
$$

so that

$$p^{A,meth,Q}_{y,1,Nov} = \frac{1}{q^{A,meth,Q}_{y,1,Nov} + 1}$$

$\mathrm{N}[0;\sigma^2]$ is a normal distribution with mean zero and variance σ^2, $k^{A'}_{p}$ is the bias of the assessment model fit to the proportions of 1-year-olds observations, and $\sigma^{A'}_{p}$ is the $\sigma^{A}_{p} = \sqrt{0.4^2 + (\lambda^{A}_{p})^2}$ value adjusted to take into account the proportions-at-age bias. $k^{A'}_{p}$ and $\sigma^{A'}_{p}$ are calculated as follows:

$$k^{A'}_{p} = \exp\left[\sum_{y=1989}^{2001} \left(\ln q^{A,meth}_{y,1,Nov} - \ln q^{A}_{y,1} \right) \Big/ \sum_{y=1989}^{2001} 1 \right] \qquad \text{A3.1.20}$$

and

$$(\sigma^{A'}_{p})^2 = \sum_{y=1989}^{2001} \left(\ln q^{A,meth}_{y,1,Nov} - \ln(k^{A'}_{p} q^{A}_{y,1}) \right)^2 \Big/ \left(\sum_{y=1989}^{2001} 1 - 1 \right) \qquad \text{A3.1.21}$$

Appendix 2.1 provides further details.

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APPENDIX 3.2

Anchovy observations

The methods used to compile data and survey estimates for anchovy are broadly similar to pilchard, and these are not repeated here. However, age length keys (ALKs) for anchovy catch data are not available[34], so assumptions about the age composition of catches are needed. These assumptions stem from the life-history characteristics of anchovy and general fishing patterns (Chapter 1). For example, the bulk of anchovy caught are 0-year-old fish targeted from March/April onwards, with 1-year-old fish comprising most of the remainder, taken in the first three months of the year. It is therefore assumed that fish caught from January to March each year are 1-year-olds only, and from April onwards 0-year-olds only, with 2-year-old and older fish not appearing in the catches at all. Catches during each year are accordingly assigned to 0- and 1-year-old fish (Table A3.2.1).

The only age data used in the anchovy assessment model are ALKs derived by Prosch (unpublished data, Marine and Coastal Management, South Africa) for the November surveys of 1992-1995. A combined 1992-1995 Prosch key was applied to raised length frequencies (see Appendix 2.2) from the November survey for all years except 1992-1995, to obtain mean masses (Table A3.2.2). For surveys held in 1992-1995, the actual ALK corresponding to the survey (as opposed to the combined key) was used to obtain the mean masses for that survey. Two methods were used to obtain the proportion (by number) of 1-year-olds in the November survey of each year (Table A3.2.3), namely:

(a) applying the Prosch ALKs in the manner described above, and

(b) using a cut-off length for the raised length frequencies from the surveys (i.e. no age data are used).

Method (a) was used for the base-case assessment A_0 (see main text), while (b) provided the basis for alternative assessments. Three cut-off lengths were used as criteria for (b), namely 10, 10.5 and 11cm (assessments A_6, A_5 and A_7 respectively).

[34] The compilation of age-length keys for anchovy was abandoned in the mid-1990s because of uncertainty surrounding the reliability of ageing methods used for this species.

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Table A3.2.1: Anchovy catches-at-age $C^A_{y,a}$ (thousand tons) with corresponding mean masses-at-age $w^A_{y,ac}$ (grams). These quantities were derived by making assumptions about the age composition of catches over different time periods (age data were not actually used – see text above for details). Empty cells indicate the relevant data were not needed in the assessment model.

y	$C^A_{y,0}$	$C^A_{y,1}$	$w^A_{y,0c}$	$w^A_{y,1c}$
1981	179		7.85	
1982	199	107	5.80	10.81
1983	213	27	6.97	10.63
1984	221	52	6.23	8.12
1985	246	27	6.34	9.71
1986	254	45	4.89	10.50
1987	282	314	7.92	12.05
1988	379	191	6.90	14.00
1989	197	98	8.02	12.36
1990	136	14	4.61	4.94
1991	119	32	5.75	5.46
1992	294	53	4.80	10.74
1993	179	57	5.04	9.62
1994	112	44	4.41	10.52
1995	149	21	4.07	6.93
1996	29	12	5.01	6.71
1997	60	0*	3.51	7.62
1998	106	2	5.87	8.51
1999	175	4	5.17	10.75
2000	235	32	**	**
			$\overline{w}^A_{0c}$	$\overline{w}^A_{1c}$
		Average: 1981/2-1999***	5.75	9.44

* The anchovy adult catch in this year was zero because the anchovy fishery was closed for the first few months of the year. This was a consequence of the extremely poor survey results for anchovy (both recruit and November) leading up to the start of the 1997 fishing season (see Tables A3.2.2 and A3.2.4).

** These data are not available, so it is assumed that $w^A_{2000,0c} = \overline{w}^A_{0c}$ and $w^A_{2000,1c} = \overline{w}^A_{1c}$

*** $\overline{w}^A_{0c}$ is averaged over all years from 1981, and $\overline{w}^A_{1c}$ from 1982.

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Table A3.2.2: Observations derived from the November survey: adult estimates of abundance $B^A_{y,Nov}$ and $B^A_{y,egg}$ derived by the acoustic and daily egg production methods respectively (both in thousand tons), with associated CVs $\sigma^A_{y,Nov}$ and $\sigma^A_{y,egg}$; and mean masses-at-age $w^A_{y,a}$ (grams). [Note that for y=1985,...,1988, for which mass-at-age data are not available, $w^A_{y,a}$ is taken to equal $\overline{w}^A_a$. Note also that for all observations, year y corresponds to the November survey of year y-1. Furthermore, the time-series of $B^A_{y,egg}$ estimates ends in 1992.]

y	$B^A_{y,Nov}$	$\sigma^A_{y,Nov}$	$B^A_{y,egg}$	$\sigma^A_{y,egg}$	$w^A_{y,1}$	$w^A_{y,2}$	$w^A_{y,3}$	$w^A_{y,4}$
1985	1067	0.23	1100	0.45				
1986	975	0.16	616	0.40				
1987	1747	0.15	2001	0.35				
1988	1456	0.12	1606	0.30				
1989	1104	0.20	1679	0.35	10.25	13.17	15.43	16.89
1990	536	0.13	421	0.35	12.53	14.44	15.46	15.69
1991	469	0.21	723	0.58	8.01	12.43	14.95	16.45
1992	1682	0.12	2913	0.35	8.43	12.31	14.33	15.46
1993	1501	0.13	-	-	8.25	12.91	13.98	17.32
1994	800	0.16	-	-	9.32	13.52	14.25	15.51
1995	476	0.13	-	-	10.96	14.87	16.01	15.79
1996	432	0.17	-	-	8.94	13.88	17.01	16.60
1997	143	0.33	-	-	8.92	16.11	17.60	17.52
1998	919	0.22	-	-	13.60	20.09	23.23	22.76
1999	995	0.20	-	-	9.66	17.86	20.88	19.90
2000	1337	0.14	-	-	9.73	15.04	18.25	18.01
2001	3313	0.10	-	-	8.24	12.43	14.81	15.68
	$\overline{B}^A_{Nov}$				$\overline{w}^A_1$	$\overline{w}^A_2$	$\overline{w}^A_3$	$\overline{w}^A_4$
Average: 1985-2001	1115			Average: 1989-2001	9.76	14.54	16.63	17.20

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Table A3.2.3: Observations derived from the November survey: proportions of 1-year-olds in the survey $p^{A,meth}_{y,1,Nov}$ obtained by two methods, namely *meth*=Prosch (i.e. using the Prosch ALKs), and *meth*=10/10.5/11cm (i.e. choosing a cut-off length for the raised length frequencies of the corresponding survey to estimate the proportion of 1-year-olds). [Note that for all observations, year y corresponds to the November survey of year y-1.]

y	$p^{A,\text{Prosch}}_{y,1,Nov}$	$p^{A,10.5\text{cm}}_{y,1,Nov}$	$p^{A,10\text{cm}}_{y,1,Nov}$	$p^{A,11\text{cm}}_{y,1,Nov}$
1989	0.640	0.740	0.534	0.844
1990	0.350	0.182	0.059	0.521
1991	0.766	0.838	0.696	0.911
1992	0.727	0.783	0.633	0.897
1993	0.588	0.678	0.501	0.832
1994	0.439	0.561	0.364	0.754
1995	0.453	0.345	0.243	0.481
1996	0.884	0.748	0.655	0.853
1997	0.530	0.480	0.442	0.590
1998	0.467	0.430	0.348	0.616
1999	0.468	0.462	0.383	0.561
2000	0.629	0.651	0.510	0.777
2001	0.756	0.800	0.679	0.919

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Table A3.2.4: Observations derived from the recruit survey and required by equation A3.1.5: recruit survey estimates of juvenile biomass $B^A_{y,rec}$ (thousand tons) with associated mean mass of fish $w^A_{y,rec}$ (grams) and survey CVs $\sigma^A_{y,rec}$; estimates of back-calculated recruitment numbers $N^A_{y,rec0}$ (billions – this is essentially $B^A_{y,rec}/w^A_{y,rec}$ back-calculated to 1 November in year y-1, but reported as applying to the beginning of year y – see equation A4.1.6 later), with an associated mean $\overline{N}^A_{y+1,rec0}$ (updated annually – see equation A5.1.19 later); time of the recruit survey after 1 May t^A_y (months); and catches taken from 1 April to the commencement of the recruit survey $C^A_{y,0bs}$ (thousand tons) with the associated mean mass of fish $w^A_{y,0cbs}$ (grams).

y	$B^A_{y,rec}$	$w^A_{y,rec}$	$\sigma^A_{y,rec}$	$N^A_{y,rec0}$	$\overline{N}^A_{y+1,rec0}$	t^A_y	$C^A_{y,0bs}$	$w^A_{y,0cbs}$
1985	310	3.96	0.24	154.0		0.613	114	6.91
1986	466	4.48	0.17	216.4	185.2	1.300	127	5.51
1987	575	5.82	0.15	220.0	196.8	2.613	161	8.51
1988	508	4.35	0.18	233.8	206.1	1.867	111	7.78
1989	132	5.25	0.19	70.9	179.0	1.233	154	8.80
1990	130	3.34	0.25	116.2	168.6	1.700	131	4.50
1991	377	5.34	0.13	124.2	162.2	0.194	46	5.89
1992	388	4.50	0.17	159.3	161.9	0.387	76	5.80
1993	163	1.93	0.19	146.3	160.1	0.645	51	10.78
1994	110	4.29	0.18	49.7	149.1	0.129	26	4.36
1995	398	3.47	0.17	214.8	155.1	1.300	49	4.70
1996	68	2.97	0.23	44.5	145.9	1.133	19	5.53
1997	435	4.66	0.16	152.4	146.4	0.516	1	7.07
1998	376	3.26	0.13	199.7	150.2	0.613	37	5.57
1999	562	4.16	0.14	218.9	154.7	0.290	9	5.73
2000	2080	4.31	0.18	793.8	194.7	0.452	46	*
								$\overline{w}^A_{0cbs}$
							Average: 1985-1999	6.50

* This estimate was not available, so that $w^A_{2000,0cbs} = \overline{w}^A_{0cbs}$ was used.

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Table A3.2.5: Catches of anchovy from landings that have targeted* anchovy ($C^{A}_{y,m}$), for a two-month ("apr:may") and four single-month ("may", "jun", "jul", "aug") periods, with associated recorded landings of pilchard bycatch ($C^{P,by}_{y,m}$). Catches are in thousand tons. The data shown are used in Chapter 5 (see Appendix 5.1).

	$C^{A}_{y,m}$, where m = :					$C^{P,by}_{y,m}$, where m = :				
y	*apr:may*	*may*	*jun*	*jul*	*aug*	*apr:may*	*may*	*jun*	*jul*	*aug*
1987	62.4	14.9	50.6	77.3	67.5	2.1	0.5	1.7	1.8	1.4
1988	60.7	50.2	74.1	60.6	70.4	1.4	1.4	2.4	0.9	0.8
1989	140.7	83.2	39.4	13.6	**	5.6	3.3	2.1	0.4	**
1990	74.7	36.8	59.5	0.6	0.2	4.7	3.1	4.1	0.0	0.0
1991	59.1	22.7	51.6	6.1	1.1	2.0	0.7	2.9	0.0	0.0
1992	126.3	58.7	35.3	44.5	56.6	4.4	1.7	4.9	2.5	4.2
1993	56.8	13.8	1.2	10.9	67.2	4.8	2.9	0.9	0.8	2.0
1994	59.9	41.3	17.4	0.3	29.8	14.2	11.0	2.4	0.2	4.7
1995	35.7	13.3	33.3	30.0	36.7	3.7	2.9	5.0	6.6	10.8
1996	13.3	9.7	13.7	0.1	**	5.3	3.1	3.3	0.0	**
1997	0.6	0.6	0.7	20.4	10.8	0.3	0.3	0.3	1.9	2.7
1998	39.0	23.0	42.2	12.2	3.7	6.8	4.9	5.2	1.5	0.4
1999	27.4	19.0	28.3	20.2	33.2	2.2	1.8	2.6	0.5	1.0

* A landing is assumed to have targeted anchovy when the ratio [anchovy/(total-pilchard bycatch)] for the species landed (in terms of mass) exceeds 0.5.

** These have been omitted because $C^{A}_{y,aug} = 0$, and that would have meant that the ratio $C^{P,by}_{y,aug} / C^{A}_{y,aug}$ could not be used in these cases.

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CHAPTER 4

Development of Management Procedures

A general introduction to management procedures (MPs) is provided, together with a comparison to the more conventional "best assessment" approach. Key features of the MP approach are pre-specification of data to be used, simulation testing of pre-agreed rules (e.g. for setting TACs) to ensure robust performance against prevailing uncertainties, an automated application of these rules over, say, a 3-5 year period resulting in a freeing of resources to prioritise and pursue longer-term research aimed at resolving key uncertainties, and the provision of a framework for dealing with conflicting or very different (but possibly equally plausible) interpretations of data. The more salient features of the mixed species pelagic fishery and its management cycle pertinent to the development of MPs are described, and a detailed account of the historical development of the MPs used to set first anchovy, then both pilchard and anchovy TACs is provided.

4.1 Introduction

The typical process[35] for providing scientific recommendations for management is the selection of the current "best" assessment of the status of a resource, usually on an annual basis. Arising from this would be the specification of the regulatory mechanism to be applied (e.g. a management measure such as TAC or maximum fishing effort), generally based on a biological reference point. Often, in order to help with the selection of such a measure, the "consequences" for the resource of applying a range of candidate measures are shown, for example, in the form of projections of the resource biomass under a fixed series of catches (e.g. Figure 4.1a). Furthermore, because assessments are typically subject to a high degree of uncertainty, this uncertainty is usually incorporated into the projections in a probabilistic manner (i.e. the curves in Figure 4.1a are presented with confidence limits), which may provide some indication of the probability of stock collapse under each candidate measure (Cooke 1999). In itself, however, this is not sufficient to assess the risk that resource managers will be running by selecting a particular management measure (Francis 1992, Cooke 1999). Francis (1992) partially solves this problem by performing "risk analysis" using Monte Carlo simulations, which allows results to be expressed in terms of the probability that "something bad" will occur (e.g. the biomass falling below some threshold level, or the fishery collapsing) within a fixed period of time (Figure 4.1b). The management procedure approach[36] is essentially an extension of risk analysis.

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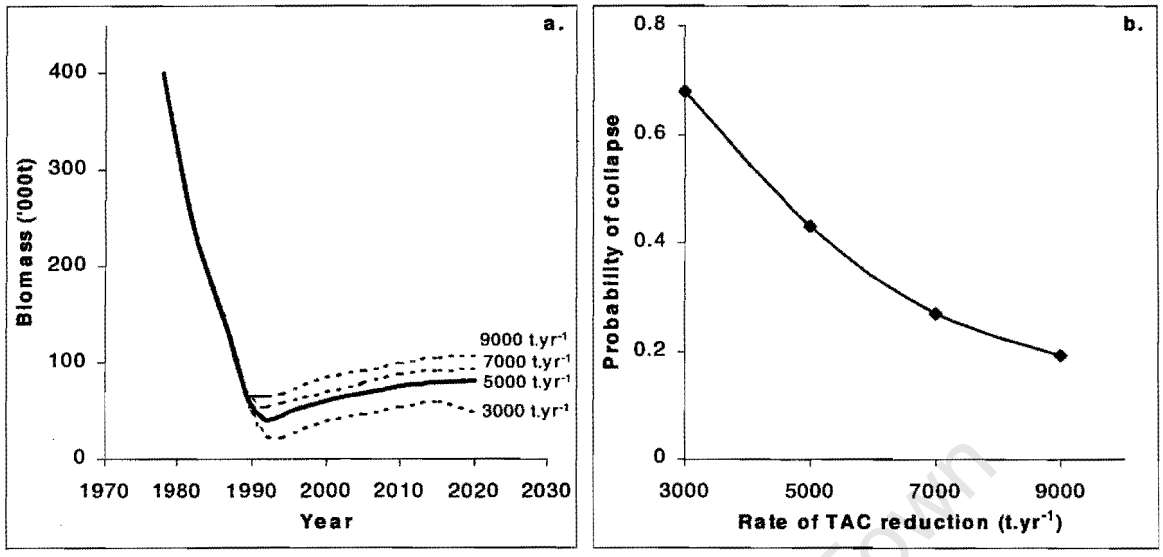
[35] Termed the "conventional" approach later.

[36] A distinction, which will become clear later, is made between management procedures *per se*, and the management procedure approach, which encompasses management procedures.

Figure 4.1 Illustrating the effect of adopting management measures whereby the TAC is reduced by a fixed amount each year (ranging from 3000 to 9000 tons per year) until the target value of 7500 tons was reached, using (a) deterministic projections of resource biomass, and (b) risk analysis, where the effect of each management measure is expressed in terms of the probability of a collapse of the fishery within 5 years. [Adapted from Francis 1992.]



Butterworth *et al.* (1997) describe Management Procedures (MPs) as a set of clearly defined, possibly quite simple rules, which translate data from the fishery into a regulatory mechanism (e.g. TAC or maximum fishing effort) each year. These rules are first tested by simulation to ensure reasonably robust performance in terms of expected catches and risk to the resource, given the prevailing uncertainties about resource status and dynamics. The rules should be agreed upon by all parties concerned (scientists, industry, managers) before being implemented, and should specify exactly how the regulatory mechanism is to be calculated and what data are to be collected and used for this purpose. Once implemented, MPs should be left to operate "automatically" for a period of 3-5 years (i.e. scientists should not seek to alter the recommendations which they provide unless very strong evidence pointing to such a need becomes available). After such a period, MPs should be reviewed and modified as necessary in the light of any changes in understanding of the resource or fishery which may have occurred in the interim (Butterworth *et al.* 1997, Cochrane *et al.* 1998). This approach is referred to here as the MP approach, and a "full blown" MP would have undergone simulation testing within the MP approach.

A key difference between the MP and conventional approach is that the latter requires a regular and time-consuming re-evaluation of data, assessment methodology and the process for setting the regulatory mechanism as well as a (usually annual) update of the actual assessment results. MPs require a more comprehensive re-evaluation but at a less frequent interval (typically only once every 3-5 years), hence arguably leading to a more time-efficient process, and a better basis

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to pursue longer term research aimed at resolving key uncertainties. A motivation for the lower frequency of re-evaluation for MPs is that substantive changes in the scientific understanding of developed fisheries only occur with the addition of a few years of data, rather than just a single year (Butterworth *et al.* 1997). This lower frequency may lead to concerns that the "reality check" that the conventional approach ensures through regular assessments will be lost. However, the MP approach does not preclude, but rather encourages, regular assessment updates (but not the full re-evaluations described above) as new data are collected. This is to verify that "reality" does not lie outside the range of robustness tests considered when developing a given MP; furthermore, a hypothesis to which the MP was designed to be robust might be disproved, so that, for example, the MP might consequently be adjusted to provide higher levels of expected catch for the same perceived level of risk (Anon. 1998a).

The MP approach allows for the fact that a proper appraisal of risk for most fisheries cannot be made for a management decision that applies to a single year only, but needs to be based on the repeated application of a particular management policy over a number of years (Butterworth *et al.* 1997, Cooke 1999). It also allows for a lack of information to be taken into account, consistent with the principles of the precautionary approach (FAO 1996). In order to illustrate this, Cooke (1999) plots utilisation (mean total catch) against information level ($1/[CV]^2$ of abundance estimates) for a given MP, where the MP is tuned so that each point along this curve represents roughly the same "risk of depletion" (Figure 4.2). The curve shows that when the available information is low, uncertainty over stock size is greater so that TACs are set low. On the other hand, more information leads to better utilisation, although the marginal returns diminish as the quantity of information increases because of the shape of the curve (Figure 4.2). Therefore, within the MP framework, there is a positive relationship between information and utilisation, so that the value of information to the fishery is positive. In the face of the lack of information, the conventional approach has tended not to limit harvest levels until there is sufficient information to indicate the need for such limits. Under these circumstances, information has a negative value to the fishery in the short term (Cooke 1999).

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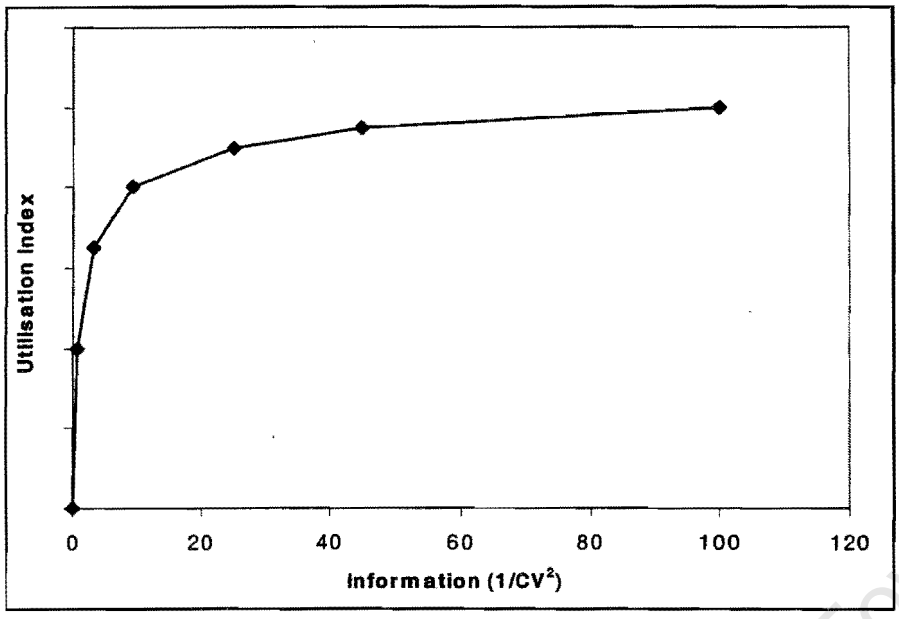
Figure 4.2 Relationship between an utilisation index (mean total catch) and information level $(1/[CV]^2$ of abundance estimates) for an MP, where each point along the curve represents roughly the same "risk of depletion". [Adapted from Cooke 1999.]



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The MP approach provides a framework for dealing with conflicting or very different (but possibly equally plausible) interpretations of data as a result of model structure uncertainty. This is not possible under the conventional approach because of the necessity of selecting a "best" assessment. For example, the ICES assessment of the northern hake stock (*Merluccius merluccius*) produces somewhat different biomass trends depending on specifications for the tuning period, the plus group and F-shrinkage (using Extended Survivor Analysis; ICES 2003). The ICES Working Group dealing with this stock is unable to resolve these issues within the current framework (where the conventional approach is used). On the other hand, Geromont *et al.* (1999) offer an example where industry argued that research survey abundance estimates for Namibian hake were relative indices only and therefore that the resource was under-utilised and TACs should double, while state scientists argued that these estimates were absolute, leading to the opposite conclusion that the resource was over-exploited and therefore TACs should halve. Because there was no immediate prospect of resolving this debate, the conventional approach offered no solution. However, the MP approach offered a way forward by defining an MP (based on trends in the abundance index) that showed catch increases over time if the industry view was correct, but also reduced catches in response to downward trends in the index, thereby ensuring protection against further resource depletion, if the scientists' view was more appropriate (Butterworth and Punt 1999).

This example illustrates another important aspect of the MP approach: it can include an evaluation of potential feedback. In practice, management would never preset catches for a 30-

year period as illustrated in Figure 4.1. As new information becomes available to reduce or resolve uncertainties, TACs would be consequently amended. The MP approach makes allowance for this in evaluating risk, whereas the conventional approach is unable to do this.

An important by-product of the MP approach is that it provides a basis for prioritising research (Butterworth *et al.* 1997, Butterworth and Punt 1999). For example, a particular scenario could require that the MP adopted be relatively conservative to enable robustness tests to satisfy a given risk criterion. If subsequent research disproves the hypothesis underlying this scenario, it may be possible to adopt a less conservative MP, leading to larger average catches for the same perceived risk. Research priorities could therefore be set so as to address those uncertainties that could feasibly be resolved, and for which robustness tests show the largest impacts of this nature on anticipated MP performance (Butterworth and Punt 1999). In this manner, research is re-focused on those issues of greatest relevance to improved management.

Since the International Whaling Commission (IWC) developed the MP approach in the late-1980s for application to commercial whaling (Kirkwood 1992, 1997), it has been applied (though not always implemented) in a number of divergent fisheries, from short-lived pelagic species exploited by purse-seine nets (e.g. anchovy) to long-lived demersal species exploited by bottom trawls (e.g. orange roughy), and is steadily gaining wider acceptance (Butterworth and Punt 1999, Geromont *et al.* 1999, McAllister *et al.* 1999, Smith *et al.* 1999). In the South African context, MPs currently form the basis for the regulation of the three major fisheries, namely the demersal trawl fishery for hake (two species are caught: *Merluccius capensis* and *M. paradoxus),* the purse-seine fishery for pilchard and anchovy, and the fishery for west coast rock lobster (*Jasus lalandii*) (Geromont *et al.* 1999).

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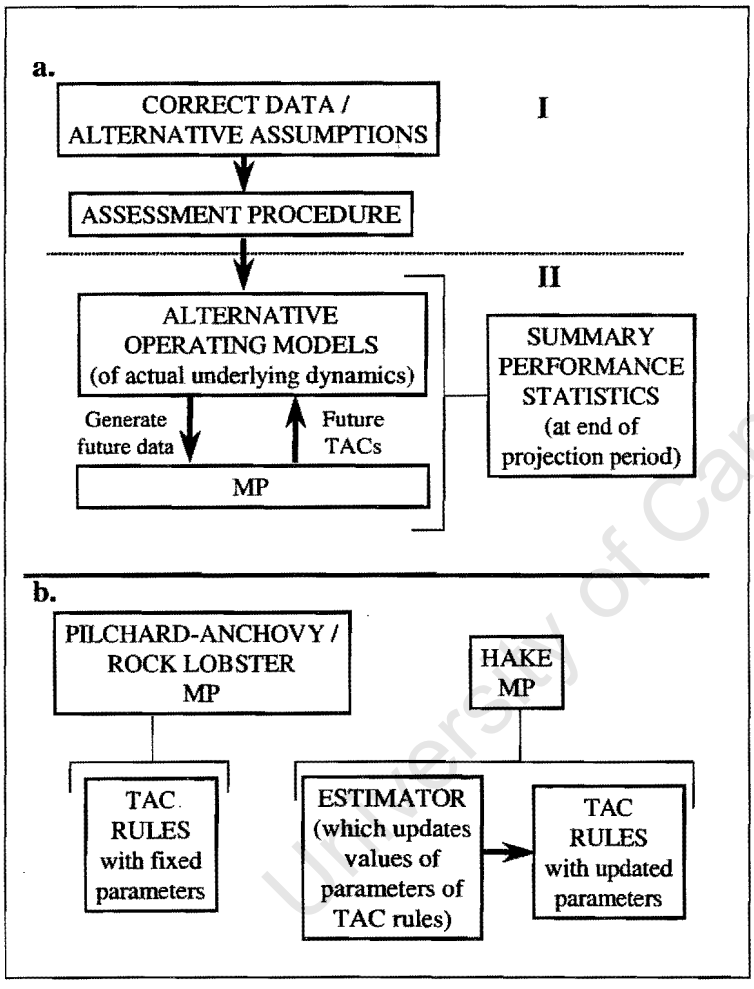
Figure 4.3 illustrates the overall testing process applied to the MPs developed in South Africa. The process is essentially divided into two phases. Phase I deals with the specification of plausible alternative scenarios (depicting the "status" and productivity of the resource), by supplying the assessment procedure[37] with the most plausible data ("correct" data) or alternative assumptions about this data. Phase II involves the development and simulation testing of an array of candidate MPs. These tests are based on the results of phase I (i.e. the alternative scenarios, renamed operating models in phase II), so that the operating models considered remain consistent with the available information. Finally, all parties concerned (scientists, managers,

[37] The assessment procedure provides parameter estimates and the associated joint probability distributions, by fitting models to data, as was done for the pilchard and anchovy resources in Chapters 2 and 3.

industry) participate in selecting an MP whose performance is suitably robust to key uncertainties about model structure, and that achieves an appropriate trade-off in satisfying conflicting objectives such as maximising catch and minimising risk to the resource ("summary performance statistics" in Figure 4.3).

Figure 4.3 Flow diagram for the overall testing process for MPs used in South Africa, where (a) depicts the testing process divided into two phases (separated by the dotted line), and (b) shows that the MP component of (a) has the same structure for pilchard-anchovy and rock lobster, but differs for hake. Details are provided in the main text.



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The structure of the MP component in Figure 4.3 is the same for the pilchard-anchovy and rock lobster fisheries but differs for hake. This is because the MPs for pilchard-anchovy and rock lobster reflect a "Myopic Bayes" approach, i.e. the MPs are based on perceptions of resource parameter values at the time of their development, and no attempt is made to update these values as more data become available. This process is left to the 3-5 yearly review of the procedure itself. In contrast, the MP for hake encompasses feedback control – whereas, for example, the pilchard-anchovy MP sets pilchard TACs as a fixed fraction of the most recent survey biomass estimate, the hake MP updates stock dynamics parameters given new data, and uses these updates in computing its TAC recommendations. Although this re-estimation appears to mimic

the conventional approach, it differs in two important aspects (Butterworth *et al.* 1997). First, the combination of the estimation and the TAC calculation is an automatic process repeated every year and does not necessarily correspond to the "best" assessment of the resource possible at any one time. Secondly, as in the selection of the pilchard-anchovy and rock lobster MPs, this procedure was chosen over other possibilities after extensive tests had been carried out of the anticipated performance of the fishery and its robustness to prevailing uncertainties in the medium term (Punt 1992, 1993). These characteristics shift the process into the realm of a "management procedure" (Butterworth *et al.* 1997).

Apart from actual formulae to set TACs, the "TAC rules" shown in Figure 4.3b may also incorporate both TAC constraints and meta-rules that apply when what is termed "Exceptional Circumstances" are invoked. The TAC constraints are limitations placed on TAC levels and changes, which for the South African pelagic fishery relate to the minimum and maximum levels to set TACs, the maximum amount by which TACs may decrease from one year to the next, and the maximum amount by which TACs may increase within a fishing season (Appendix 4.1, Chapter 5). "Exceptional Circumstances" cater for freak situations that sometimes occur, where application of the usual TAC formulae and constraints could damage the resource (Butterworth *et al.* 1997). They are invoked under pre-agreed criteria (e.g. the acoustic survey abundance estimate falls below a certain level), with meta-rules that set more conservative TACs than under the usual TAC formulae and constraints. The pre-agreed criteria take into account observation error (e.g. survey sampling error), essentially trading off the probability of not taking further action when it is actually necessary, with the disruptive possibility of taking action when it is not really needed (Butterworth *et al.* 1997; Appendix 4.2).

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McAllister *et al.* (1999) present a "fishery management system evaluation", which is a more generalised version of the MP testing process presented in Figure 4.3. In their system, the operating model consists of a stock dynamics model, an observation model ("generate future data" in Figure 4.3), a harvest decision model (to account for managers possibly not following MP-derived TACs because of factors not incorporated when calculating these TACs, such as socio-economic factors), and an implementation model ("future TACs" in Figure 4.3, which includes converting TACs into catches, and takes into account factors that may cause these two quantities to mismatch, such as limitations imposed by bycatch considerations). Apart from the operating model, their system includes a harvest control model, similar to "MP" in Figure 4.3, which can also either be model-based or model-free. The main difference between the two conceptual frameworks is that the harvest decision model of McAllister *et al.* (1999) is omitted

in Figure 4.3 because the MP testing process assumes that this source of uncertainty is negligible. Although recently this may be a reasonable assumption for the South African pelagic fishery, where TAC recommendations derived on the basis of an "operational" MP (OMP)[38] are mostly implemented, this was not always the case. For example, Cochrane *et al.* (1998) report that over the period 1988-1996, TAC recommendations derived on the basis of the OMPs then applicable were overridden in five out of nine years.

The system used in Australia is termed the MSE (management strategy evaluation) approach (Smith *et al.* 1999). This approach is virtually identical in method and philosophy to the MP approach. However, it has a wider scope in that it embraces evaluations that do not necessarily include feedback harvest strategies, and its end-product is not necessarily an agreed MP, but rather the provision of a framework for objective short- and long-term decision-making (Smith *et al.* 1999). Effective stakeholder participation (including industry, science and conservation) in all key areas of fisheries management (from stock assessment and setting research priorities, to enforcement and decision-making) is stressed as a vital component to the MSE approach. This feature is also key to the management procedure approach, and encourages transparency and a "buying into" the process by all stakeholders.

In the case of the South African pilchard-anchovy fishery, MPs that have been used are a set of relatively simple formulae that convert the biomass estimates obtained from annual acoustic surveys into recommended TACs each year. The formulae are chosen (ultimately by the responsible Minister) on the basis of longer-term considerations: achieving catches that are as high as possible on average over a period of time, while at the same time limiting exposure of the resource to undue risk of depletion to unproductive levels and avoiding excessive variations in TACs from one year to the next. Currently, TACs are allocated only for pilchard and anchovy in the pelagic fishery (round herring and other small pelagic species are treated as "non-quota" species, though some precautionary catch limits apply).

4.2 Essential features: pelagic fishery and management cycle

Before commencing with a description of the historical development of MPs in the South African pelagic fishery, it is worth describing some of the more salient features of this fishery and its management cycle pertinent to the development of MPs.

[38] An OMP is taken throughout to mean an MP that has been formally adopted, and therefore used to derive recommendations for management measures (e.g. TACs). However, the original intention of introducing the qualifier "operational" was to distinguish between MPs that could be put into operation because of the availability of data and formulae to do so, from purely conceptual ideas.

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Marine and Coastal Management (MCM) is the section of the South African government department of Environmental Affairs and Tourism that is responsible for implementing, administering and enforcing government policy and regulations with respect to marine fisheries, and provides advice to the government minister for that department. The Pelagic Working Group (PWG) is a body of scientists (either independent or from within MCM)[39] created to provide initial information on the status of pelagic resources, and to advise on their management. Interaction with the pelagic industry has been achieved through a MCM-industry Forum, which has provided fundamental input into the development of MPs for the pilchard-anchovy fishery (Figure 4.4).

The PWG provides advice on the selection of MPs, and TAC recommendations based on these MPs (once they have been adopted) to the Consultative Advisory Forum (CAF) and ultimately the Minister via the Deputy Director-General (Ministry of Environmental Affairs and Tourism), who is responsible for MCM (Figure 4.4). The CAF is a statutory body that provides advice to the Minister, not only on the basis of the scientific input from the PWG, but also incorporating socio-economic and other factors, including concerns from the industry. The CAF has representation from a number of interest groups, which include major fishing industry organisations, trade unions, conservation groups, independent scientists and MCM. There has been debate recently, however, regarding whether the CAF should continue to play its current role (hence the broken lines in Figure 4.4). During the adoption of the most recent pelagic OMP (OMP02), the CAF was effectively by-passed when the Deputy Director-General recommended the adoption of this OMP directly to the Minister (the custom in the past had been for the Deputy Director-General to advise both the Minister and the CAF). This was essentially because there was no CAF at the time, as the term of office of the previous CAF had expired and the process of appointing a new CAF had not yet taken place. The industry provides input at all levels, from the PWG to the Minster (Figure 4.4).

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[39] Scientific representation from the industry is possible, but has not yet occurred within the PWG. Furthermore, a broadening of representation within the PWG to include observers from the industry and other stakeholders seems likely in future.

Figure 4.4 Diagram describing the flow of advice from the Pelagic Working Group within Marine and Coastal Management (the section of the state's Department of Environmental Affairs and Tourism responsible for fisheries management and research) to the Minister. The broken lines associated with "CAF" depict the current uncertainty about this advisory body's role in the management process.

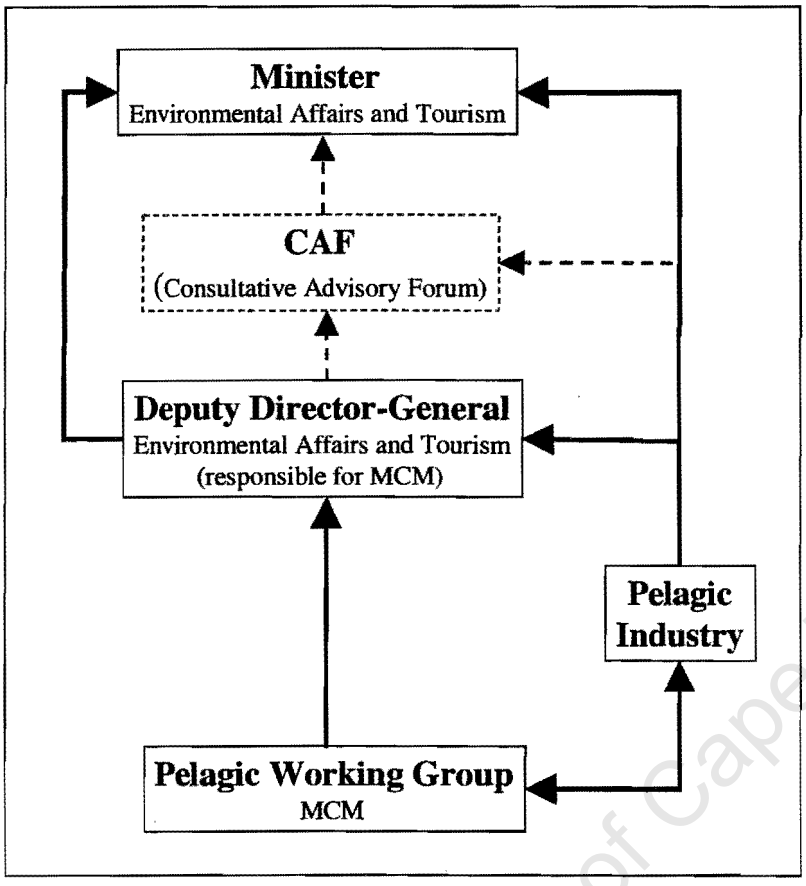

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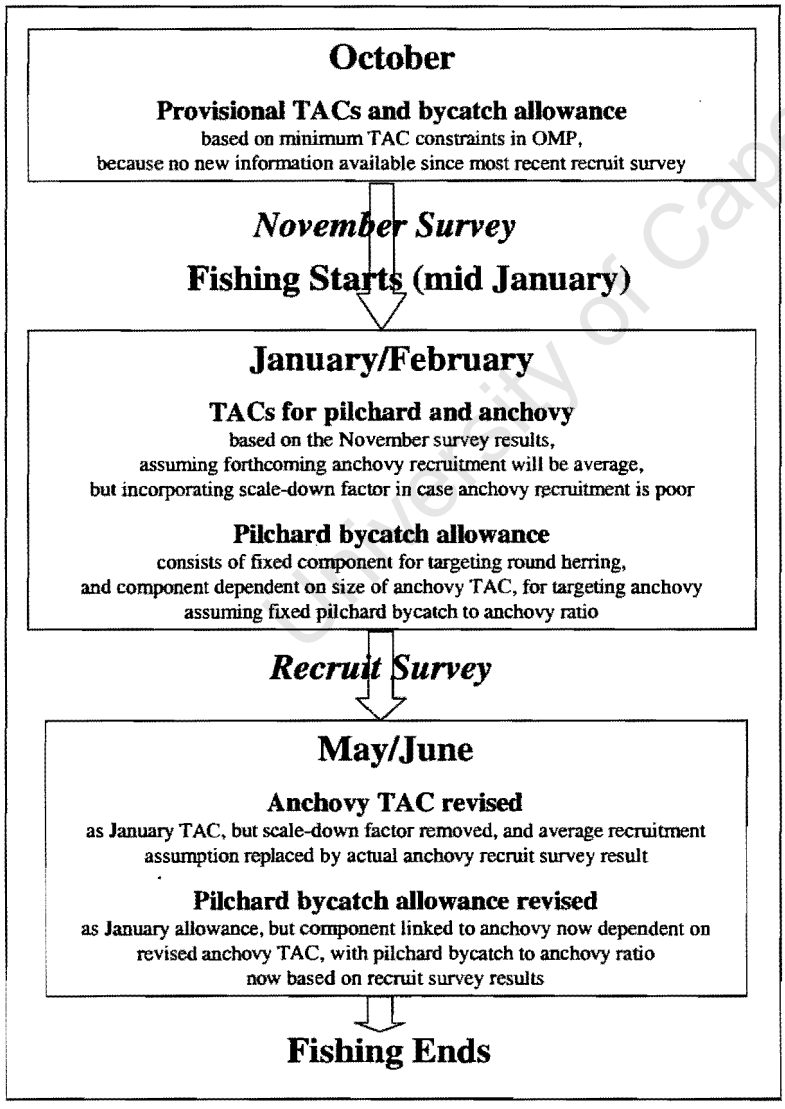
Figure 4.5 shows the typical cycle of events in the pilchard-anchovy fishery each year. TACs and bycatch allowances are based on input from the two main acoustic surveys each year, namely the November survey and the May/June recruit survey. Although not based on any new information from the fishery and research surveys, provisional TACs are provided each year for the following reasons:

- the bureaucratic process between the survey results becoming available (mid-December) and MCM implementing the Minister's decision regarding TACs (usually by late January/February) is lengthy (Figure 4.4);
- vessels in the pelagic fishery cannot operate without a permit, and the fishing season commences well before MCM is ready to allocate quotas and issue permits using TACs (approved by the Minister) that are based on the November survey results;
- provisional TACs provide a mechanism for allocating quotas and issuing permits before the fishing season commences, thus allowing vessels to put to sea on time when the season opens.

Provisional TACs are based simply on the TAC constraints[40] of the OMP in operation (see Appendix 4.1 and Chapter 5), and thus bear no relation to the current status of the stocks. For this reason, scientists have long argued against the use of provisional TACs, particularly because TACs based on actual survey results could, in theory, be allocated before the start of the fishing season if the bureaucratic process described above could be considerably shortened. They have suggested that the role of the Minister should be strategic (e.g. choosing between MPs on the basis of desired trade-offs) rather than tactical (adjusting and adopting TACs), thus allowing for a greater part of the bureaucratic process to be removed, or automated (Butterworth and Punt 1999).

Figure 4.5 Flow diagram describing the annual management cycle for setting pilchard and anchovy TACs and pilchard bycatch allowances.



[40] These constraints form part of the "TAC rules" in Figure 4.3, but in this context relate only to the minimum value for a TAC, or the maximum amount by which a TAC may be reduced from one year to the next. Effectively, the provisional TAC would be set to whichever of these constraints leads to a greater TAC.

The provisional TACs and bycatch allowance are automatically over-ridden by the January/February TACs and bycatch allowance (Figure 4.5). The pilchard directed TAC set at this time remains in force (without alteration) for the remainder of the fishing season (which officially has closed at the end of October, but is usually extended until December). However, the anchovy TAC may be revised within the year for the following reasons:

- unlike the pilchard directed TAC which is intended to target adult pilchard (the next estimate of which is the following November survey, thus avoiding the need for a within-season revision), the bulk of the anchovy TAC will comprise juvenile anchovy, which only start recruiting to the fishery along the west coast from roughly April onwards (Chapter 1);
- a reliable estimate of the abundance of these juvenile anchovy becomes available only once the recruit survey takes place in May/June;
- because it will target as yet "unmeasured" fish, the January/February anchovy TAC assumes forthcoming anchovy recruitment will be average, an assumption that needs to be replaced by the actual estimate when the latter becomes available;
- a scale-down factor is incorporated into the January/February anchovy TAC to safeguard against possible poor recruitment – this factor is no longer necessary once the recruit survey results become available;
- the additional flexibility offered by a within season revision of the anchovy TAC leads to better utilisation of the anchovy resource – the alternative of a single TAC at the start of the year with no within-season revision would necessitate a conservative approach because of the possibility of poor recruitment (Walters 1989, Butterworth *et al.* 1993).

Pilchard bycatch occurs in substantial quantities when round herring is targeted (mainly adult pilchard) and when anchovy is targeted (mainly juvenile pilchard). The pilchard bycatch allowance calculation therefore consists of a component linked to round herring (a fixed tonnage of pilchard is set aside for this) and another linked to the size of the anchovy TAC. The latter is a fixed proportion of the corresponding anchovy TAC, and is revised following the recruit survey for the following reasons:

- the anchovy TAC is revised, and the bycatch allowance needs to reflect this; and

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- the pilchard bycatch that occurs when anchovy is targeted comprises juvenile fish, and must therefore depend on the size of pilchard recruitment – the fixed ratio (used to calculate the January/February allowance linked to anchovy) is adjusted to reflect this[41].

4.3 Management prior to implementation of MPs

Anchovy

Following the rejection of VPA (based upon effort and catch-at-age data) as a basis to set anchovy TACs, methods that focused solely on the acoustic estimates of abundance (with minimal assumptions regarding the age composition of anchovy catches) were developed and implemented for anchovy from 1985 (Chapter 3). These culminated in a method (applied during 1987-1990) that resembled a constant escapement strategy, predicting escapement at the end of the year under a given TAC. When implemented, this approach operated by defining "probability prescriptions" applicable to the TAC decisions made by the Minister in the first year (1987)[42, 43], and then applying these "probability prescriptions" in a consistent manner in subsequent years (1988-1990) to calculate TACs (De Oliveira 1995). Motivation for this approach came from Monte Carlo simulation studies conducted by Bergh and Butterworth (1987), which indicated that substantial increases in yield could be achieved by adopting more flexible harvesting strategies than had been applied previously, even if survey precision was lower than reported. The basis for their simulation studies was a joint posterior distribution of parameter estimates derived by a Bayes-like estimation procedure (Chapter 3).

The "constant escapement" strategy of 1987-1990 cannot be regarded as a "true" MP because the actual process for setting TACs (applying "probability descriptions" defined for the first year to subsequent years) was not subjected to simulation tests (Cochrane *et al.* 1998). Furthermore, although this approach initially found favour, with anchovy catches rising to record levels in 1987 and 1988 (Table 1.2), it started experiencing problems in 1989 following a recruit survey indicating below-average anchovy recruitment, which meant earlier than usual cessation of anchovy fishing that year. The recommendation of a zero anchovy TAC the following year was met with considerable resistance, and was over-ridden by the Minister. The key problem with

[41] The earlier OMPs used only the pilchard recruit estimate to adjust the fixed ratio, but later OMPs incorporated the pilchard to anchovy ratio from both the recruit survey and the industry's catches in May (Chapter 5).

[42] The TAC decisions in 1987 were based on calculations that suggested that these TACs would ensure an escapement of spawner biomass in excess of one million tons, which was considered sufficiently large to ensure adequate recruitment, because similar spawner biomass levels in previous years had yielded adequate recruitment.

[43] These "probability prescriptions" calculated (for each TAC decision in 1987) the probability that escapement at the end of the year would be less than $0.5K$ (K being the average "unexploited" spawner biomass level).

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this approach was that it was likely to yield a zero TAC recommendation, on average, one year in four, which was subsequently considered too risk averse, and did not constitute economically sound management from the industry's point of view (Cochrane *et al.* 1998, Butterworth and Bergh 1993). As a result of these events, the MP approach was used to develop an OMP for anchovy to set TACs from 1991 onwards.

Pilchard

On the basis of biomass trends from a pilchard-only VPA analysis, which indicated that the pilchard resource was severely depleted, the Fisheries Advisory Council (FAC, the then statutory body advising the Minister) adopted a conservative approach in 1984 for harvesting pilchard (Anon. 1986). The aim of this approach was to encourage rebuilding of the pilchard stock, and therefore the scientific advice to the FAC at that time was that catches should be maintained at the "lowest practical level possible" (30 000 tons for 1984-1986; Anon. 1985). This advice was always accompanied by a strong recommendation to avoid catching juvenile fish. Results from acoustic surveys were used directly to set pilchard TACs for the first time over the period 1987-1989 when a constant proportion strategy was implemented (earlier pilchard acoustic estimates were considered too imprecise to have applied this approach – Chapter 2). This strategy calculated TACs as 15% of the November acoustic survey estimate plus 30% of the average recruitment (Punt 1989)[44].

Following the introduction of MLVPA in 1990 (Chapter 2), an $F_{status\text{-}quo}$ strategy was used to set TACs over the period 1990-1993. This strategy (as applied in this instance) set the fishing mortality in the year for which a TAC was needed as the average over a pre-defined period (Punt 1989, Cochrane *et al.* 1998). The move away from the constant proportion strategy used earlier was because Punt (1989) had found that it could lead to large interannual variations in TAC, whereas the $F_{status\text{-}quo}$ strategy yielded TACs that were less variable and more precisely estimated. Furthermore, the constant proportion strategy was based on assumed reliability of the acoustic abundance estimates in absolute terms. In contrast, the $F_{status\text{-}quo}$ strategy sought to keep fishing mortality at the same level[45] as the average over the period 1987-1989, because the pilchard resource had increased over this period, so that a strategy of continuing to apply the corresponding average level of fishing mortality was considered a reasonably safe approach.

[44] The original documentation referenced by Punt (1989) did not specify exactly what was meant by "average recruitment" or how it was calculated.

[45] Even though the magnitude of that level was not well determined because, for example, of uncertainties about the value of natural mortality.

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However, as time progressed, concerns grew that this somewhat *ad hoc* choice of a target level for fishing mortality might not be making the best use of the resource. Furthermore, problems with pilchard bycatch were being encountered that undermined the effectiveness of the recommendations based on the $F_{status\text{-}quo}$ approach (Figure 1.5), and there was an increasing need to specify separate pilchard directed TACs and bycatch allowances[46]. Therefore, an entirely new approach for setting pilchard TACs was used from 1994 onwards, when a joint MP was developed for the pilchard-anchovy fishery.

4.4 Historical development of MPs for the pelagic fishery

The historical development of MPs in the pelagic fishery is summarised in Table 4.1 and discussed in the sub-sections that follow.

Table 4.1 Summary of the historical development of MPs in the pelagic fishery. [Abbreviations are: OMP – Operational Management Procedure; BLE – Bayes-like estimation; MLE – Maximum Likelihood estimation; MLVPA – Maximum Likelihood Virtual Population Analysis.]

Year	OMP adopted	Description
1991	OMP91	• Anchovy-only OMP • BLE procedure provides joint probability distribution for parameters
1994	OMP94	• Joint pilchard-anchovy OMP • Anchovy TACs independent of pilchard, but pilchard bycatch allowances (and consequently future directed TACs) dependent on size of anchovy TACs • Criteria for Exceptional Circumstances developed, but meta-rules not yet defined • Industry involvement in developing OMP • MLE procedure for anchovy provides joint probability distribution for parameters • MLVPA procedure for pilchard provides point estimates for parameters
1995		• Meta-rules for Exceptional Circumstances defined, but not formally incorporated in OMP
1996		• Pragmatic modification to pilchard bycatch calculations because of bycatch problem, but not formally incorporated in OMP
1997	OMP97	• Pilchard-only OMP (anchovy fishery initially closed) • Industry involvement in developing OMP • MLE procedure incorporates more data than previous MLVPA, but provides only point estimates for parameters • Anchovy fishery re-opened following above-average recruitment – anchovy TAC and associated pilchard bycatch set on *ad-hoc* basis
1998		• Revert to joint OMP, but because no OMP yet available, use "hybrid" OMP: a combination of OMP94 and OMP97 • Application of preliminary version of OMP99 to adjust anchovy TAC and pilchard bycatch allowance following recruit survey • First attempt to implement additional sub-season for anchovy fails

[46] Termed "Total Allowable Bycatch", or TAB in Appendix 4.1 and the Chapters that follow.

Year	OMP adopted	Description
1999	OMP99	• Joint pilchard-anchovy OMP • Pilchard and anchovy exploitation levels linked through trade-off curves • Pilchard bycatch linked to anchovy, dependent on pilchard-anchovy "mixture" in recruit survey and commercial catches • Meta-rules for Exceptional Circumstances formally incorporated • Industry involvement in developing OMP • MLE procedure for both pilchard and anchovy, incorporating additional data and correlative relationships, but providing only point estimates in both cases • Additional sub-season for anchovy implemented, but not yet formally incorporated in OMP
2002	OMP02	As OMP99, but: • Implementation error included • Additional sub-season for anchovy formally incorporated • MLE procedure for both pilchard and anchovy, incorporating latest data and providing joint probability distribution for pilchard-anchovy parameters • Rights-holders select "own" preferred pilchard-anchovy trade-off

OMP91

MPs were initially implemented only for anchovy, and developed from the work presented by Bergh and Butterworth (1987). The assessment procedure used to define operating models for MP testing was an extension of the Bayes-like estimation procedure presented by these authors, which provided a joint probability distribution for the parameters used in the operating models. Candidate MPs considered during the testing phase (including OMP91, the MP eventually adopted) were presented by Butterworth and Bergh (1993). Although no formal criteria for invoking Exceptional Circumstances existed for OMP91, these were nevertheless invoked when OMP91 was first implemented in 1991, because the point estimate of escapement at the end of 1990 was "uncomfortably close" to $0.2K$, the level which the MP was designed to avoid (Butterworth and Bergh 1993). As a result, an *ad-hoc* approach was used to adjust the TAC down.

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OMP94

The need for an MP that incorporated both pilchard and anchovy (with linkages between directed catch and bycatch of pilchard, and between pilchard bycatch and anchovy) became clearly evident when problems with juvenile pilchard bycatch in the anchovy fishery (e.g. reports of large-scale dumping) highlighted the strong operational interaction when these species were targeted, and this could no longer be ignored (Cochrane *et al.* 1998). This problem is caused by mixed shoaling of juvenile pilchard and anchovy when they are of a similar size (Chapter 1). This resulted in the development of OMP94, first implemented in 1994, which contained a number of features (over and above the inclusion of pilchard) that had not been included in OMP91:

- Criteria for invoking Exceptional Circumstances were defined, although the meta-rules to be applied under these circumstances were available only from 1995, and were considered *ad hoc* because they did not form part of the evaluation process for OMP94.
- Considerable interaction with industry took place, with industry input being used to help develop some aspects of OMP94 (e.g. the TAC constraints that form part of "TAC rules" in Figure 4.3). An interactive game was also developed to familiarise the industry with some of the concepts related to MPs (Butterworth *et al.* 1993, De Oliveira 1995).
- A MLE procedure replaced the BLE procedure (see caption to Table 4.1 for abbreviations) to provide a joint probability distribution for the anchovy parameters to be used for MP testing (Chapter 3). In contrast, the MLVPA procedure, used previously for the $F_{status\text{-}quo}$ strategy, provided only point estimates for the pilchard parameters for MP testing (Chapter 2; De Oliveira *et al.* 1998b).

Although OMP94 formally incorporated links between anchovy and pilchard bycatch, the anchovy component remained completely independent of pilchard, and could be optimised as if anchovy was being managed on its own[47]. This meant that the only way to optimise pilchard directed catches (consisting of adult pilchards) was to place severe constraints on the pilchard bycatch linked to anchovy (juvenile pilchard). It was this feature that caused serious problems for the implementation of OMP94 (Cochrane *et al.* 1998), to the extent that an *ad-hoc* adjustment was made in 1996 (termed a "pragmatic solution") to the formula used to calculate the pilchard bycatch linked to anchovy (Anon. 1996, Bycatch Procedure 3 in De Oliveira *et al.* 1998b).

OMP97

The November 1996 survey yielded an extremely low anchovy biomass estimate (Figure 1.5) and was preceded by a very poor recruitment estimate from the recruit survey in 1996. [Both these estimates were well below the previous lowest estimates in the corresponding time-series.] It was therefore decided to close the anchovy fishery at the start of 1997, and to implement a pilchard-only MP, OMP97, that allowed no bycatch of juvenile pilchard. MLE replaced MLVPA, and provided point estimates of pilchard parameters to form the basis for MP testing. De Oliveira *et al.* (1998a) report on detailed aspects of OMP97.

The 1997 recruit survey yielded exceptional pilchard and above-average anchovy recruitment estimates. The latter was sufficient to warrant renewed fishing for anchovy, and the anchovy

[47] In fact, the anchovy and pilchard MPs were completely separate computer programs, with TACs from the anchovy MP simulations being fed into the program to test the pilchard MP as a separate file.

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fishery was re-opened following this survey, with a TAC and associated pilchard bycatch allowance set on an *ad-hoc* basis. The "recovery" of anchovy appeared to continue the following year, and in the absence of a suitable joint pilchard-anchovy OMP to set TACs, it was decided to use a weighted combination of the outputs of OMP94 and OMP97 to set TACs at the start of 1998. Neither of these two OMPs could be used in isolation, the former because it was based on a dataset that did not include the recent low acoustic estimates of recruitment and spawner biomass (the lowest in the time-series), and the latter because it excluded anchovy. Furthermore, there was still uncertainty as to whether the pelagic fishery was moving towards a pilchard-dominated fishery, or whether it would remain a mixed-species fishery requiring separate anchovy and pilchard directed TACs. The "hybrid" OMP eventually used gave the outputs from OMP94 and OMP97 equal weighting.

Because of the lack of a suitable joint pilchard-anchovy OMP during 1998, it was decided to use a preliminary version of OMP99, where development was nearing completion, to set the mid-season anchovy TAC and associated pilchard bycatch after the recruit survey in 1998. This was effected in a manner that was consistent with the pilchard-anchovy trade-offs (see OMP99 section) implicit in the hybrid procedure.

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OMP99

The introduction of OMP99 signalled an important shift in emphasis compared to OMP94, the previous multispecies OMP. Whereas OMP94 attempted to optimise both anchovy and directed pilchard catches, necessitating sometimes severe and (so it transpired) impractical constraints on the level of juvenile pilchard bycatch in order to optimise the latter, OMP99 approached this problem from a different angle. It recognised that it was near impossible to restrict the bycatch of juvenile pilchard to levels below the "true" mixture of juvenile pilchard and anchovy in the sea – the continued pressure from the industry for ever higher bycatch allowances, coupled with reports of widespread dumping since 1994 proved beyond doubt that the industry simply were not able to target sufficiently well to avoid pilchard bycatch (Cochrane *et al.* 1998). It also recognised, as a result of this, that it was impossible to optimise anchovy and directed pilchard catches simultaneously. Since resource productivity was limited, a greater catch of directed pilchard necessitated a reduction in the size of juvenile pilchard bycatch, which could realistically be achieved only if anchovy TACs were lowered. Thus was born the concept of a pilchard-anchovy trade-off (in contrast to the directed pilchard-pilchard bycatch trade-off implicit in OMP94), with a strong emphasis on pilchard bycatch allowances that reflected the "true" mixture of juvenile pilchard and anchovy. These bycatch allowances were now treated as

givens (arising from monitored information), and as such were not "up for debate" during the development of OMP99.

Interactions with the industry reflected this shift in mindset, and focussed on reaching agreement on a pilchard-anchovy trade-off that was acceptable to most participants in the fishery. This agreement necessitated a compromise between those participants that favoured pilchard (e.g. rights holders involved in canning or bait) and those that favoured anchovy (e.g. those with greater investments in fishmeal production). However, it became clear during interactions with the industry that they could not agree on an overall trade-off between pilchard and anchovy because of their different preferences. Therefore, the recommendation to the CAF, and subsequently the Minister, was to adopt the pilchard-anchovy trade-off (reflected by β in Appendix 4.1)[48] implicit in the "hybrid" OMP of 1998[49].

When developing OMP99, the MLE procedure was used to derive point estimates for both pilchard and anchovy parameters to be used for MP testing. The testing now also incorporated parameters that reflected correlative relationships between the error distributions associated with the different time-series of data, and included the most recent data. Furthermore, Exceptional Circumstances meta-rules for both pilchard and anchovy were formally incorporated into the joint OMP for the first time.

One of the consequences of the pilchard-anchovy trade-off in OMP99 was that the limitations on juvenile pilchard bycatch, necessary to protect the directed pilchard fishery, would lead to lower anchovy catches than that resource could actually sustain. The anchovy resource would therefore be under-utilised under OMP99. In order to address this concern, the concept of a later sub-season to target "clean" anchovy shoals was introduced[50]. The following information indicated the feasibility of implementing such an additional sub-season.

- Juvenile pilchard and anchovy, which appear in mixed shoals of similar sized fish when they first recruit to the fishery, tend to separate later in the season, because anchovy growth slows.

[48] β is essentially the proportion of the November survey estimate of pilchard abundance taken as the pilchard directed TAC – Chapter 5 describes how each β value implies a certain pilchard-anchovy trade-off.

[49] This resulted in a β value of 0.1375, midway between that associated with OMP94 ($\beta = 0.1$) and OMP97 ($\beta = 0.175$).

[50] A preliminary version of OMP99, which was used in 1998 to set the mid-season anchovy TAC and pilchard bycatch allowance, had already revealed that anchovy would be under-utilised. An initial attempt was therefore made in 1998 to implement the sub-season, but this did not prove successful because of bureaucratic delays in quota allocations.

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- This finding was verified by an examination of pilchard bycatch to anchovy ratios in the commercial catches, which showed that by August these bycatch ratios had typically reduced to half the levels in May (see Appendix 5.1 later).
- There is a narrow time window between when the mixed shoals of juvenile fish have separated (August/September) and when anchovy have moved offshore onto the Agulhas Bank to spawn (November), thus becoming unavailable to the pelagic fleet.

The following conditions were set for the implementation of an additional sub-season for anchovy.

- In order to facilitate the additional anchovy TAC in the sub-season, it would be accompanied by a modest pilchard bycatch allowance (maximum of 2 000 tons) – this was considered small enough to limit the negative impact such bycatch would have on the pilchard resource to an acceptable level.
- The normal season anchovy TAC and pilchard bycatch allowance would be clearly separated from the corresponding additional sub-season quantities[51], and any anchovy and associated pilchard bycatch allowance quotas would not be allowed to be carried over from the normal season to the additional sub-season.
- An on-board observer scheme, to be fully financed and supported by the industry, would be implemented in conjunction with the additional sub-season.

The motivation for these conditions was that pilchard bycatch for the normal season was set at levels within which it would be practical to operate (so avoiding incentives to dump catches with high bycatch levels), and which would not unduly harm the directed pilchard fishery in the future. However, the additional sub-season was predicated on near-pure anchovy catches after the species separated later in the year, and therefore would require a very low pilchard bycatch allowance, with observers on board to check that this was respected. Without these observers, strong incentives to dump to avoid early closure of the sub-season when the bycatch allowance was reached could arise. Furthermore, allowing carry-overs from the normal season to the additional sub-season would create a further incentive to dump catches that were highly mixed in the normal season (which was not subject to observer coverage) in order to save bycatch for the additional sub-season (where bycatch is very limited and more closely monitored).

[51] The distinction between the normal and additional sub-season applied only to anchovy and its associated pilchard bycatch. The pilchard directed fishery and bycatch associated with round herring would typically apply the whole year.

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The anchovy TAC for the additional sub-season was calculated as the difference between the normal-season revised TAC, and the TAC that would have applied had the anchovy resource been fully utilised. It was possible to do this because of the assumption that the additional sub-season TAC would be accompanied by an essentially negligible amount of pilchard bycatch. OMP99 did not formally incorporate the additional sub-season, so the effect on the pilchard resource of this minimal sub-season bycatch was unknown, although not expected to be substantial.

OMP02

The development of OMP02 is fully described in Chapter 5, so this section describes only the additional features in OMP02 when compared to OMP99.

(1) An additional three years of data from surveys and catches have been included, and some data refinements have taken place.

(2) The MLE procedure now includes a bootstrap-generated joint probability distribution for pilchard and anchovy parameters, to be used for MP testing.

(3) The additional sub-season with its associated bycatch is now formally incorporated.

(4) Implementation error is included. This relates to the analysis of bycatch levels in the commercial catches after May, which found that this bycatch ratio (pilchard to anchovy, where the bycatch is taken in the anchovy fishery) tends to drop as the season progresses. The MPs presented in Chapter 5 take this feature into account in the manner they have been tested. More specifically, the operating models estimate the pilchard bycatch each year, which will normally be less than the pilchard bycatch allowance awarded given this drop. [This contrasts with the operating models for OMP99, which assumed that the pilchard bycatch allowance awarded was always caught in full.]

(5) With OMP99, rights were effectively allocated as a percentage of the pilchard fishery, and a percentage of the anchovy fishery, and only after TACs were set for pilchard and anchovy. In order to set the TACs, a decision was required with regard to the trade-off between the pilchard and anchovy fisheries. On previous occasions, this trade-off decision had been made "externally" by the Minister on the advice of the CAF, following consultations with the industry, scientists and resource managers. The new MPs presented in Chapter 5 have been structured to allow for the possibility of the trade-off decision to be made "internally" by each right holder individually; this requires the right to be allocated as a single

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percentage of the pelagic fishery, instead of two percentages, one each for the pilchard and anchovy fisheries.

The main motivation for following the internal trade-off decision approach was that the industry could not agree on an overall trade-off between pilchard and anchovy, a problem that became apparent during the development of OMP99. At the time, the choice of β was argued on the basis of consistency with the "hybrid" OMP of 1998. However, if the external trade-off decision approach was to be followed for OMP02, a similar argument would not be readily available for motivating a choice for β, because of the changes that incorporating (1)-(4) above would introduce, as explained in Chapter 5. Therefore, in the absence of a clear-cut means of selecting a β (and thus a pilchard-anchovy trade-off) for OMP02, the Minister would open himself up to possible litigation by whichever party would loose out by his choice of β, if the external approach was followed. The internal approach avoided this problem.

Chapter 5 first presents MPs incorporating features (1)-(4), and then introduces feature (5). Appendix 4.1 provides a description of OMP99 to facilitate more detailed comparisons with OMP02 in Chapter 5. OMP99 also formed the basis of the work presented in Chapters 7 and 8, essentially because the analyses in Chapters 7 and 8 were completed before OMP02 was fully developed.

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APPENDIX 4.1

Description of OMP99

TAC/B equations

OMP99 provides pilchard and anchovy TACs in two stages during the year (Figure 4.5).

First stage

For the first stage (usually in late January/February after the results of the November survey are available), a pilchard directed TAC, an anchovy 1st TAC, and a pilchard 1st TAB (Total Allowable Bycatch) are set as follows:

Pilchard directed TAC: $$TAC_y^P = \beta\, B_{y,Nov}^P \qquad \text{A4.1.1}$$

Anchovy 1st TAC: $$TAC_y^{1,A} = \alpha\,\delta\,300\left(0.7 + 0.3\frac{B_{y,Nov}^A}{\overline{B}_{Nov}^A}\right) \qquad \text{A4.1.2}$$

Pilchard 1st TAB: $$TAB_y^{1,P} = TAB_{rh}^P + \gamma\, TAC_y^{1,A} \qquad \text{A4.1.3}$$

[Equation A4.1.2 essentially assumes that forthcoming recruitment will be average (compare equations A4.1.2 and A4.1.4) because at this early stage, no information on this recruitment, which will form the bulk of the year's catch, is available. A "scale-down" factor, δ, is therefore introduced to provide a buffer against possible poor recruitment. In equation A4.1.2, the values 300, 0.7 and 0.3 come from previous OMP implementations (Butterworth *et al.* 1993, De Oliveira 1995); 300 reflects the annual anchovy TAC to be expected under average conditions if anchovy is fully utilised ($\alpha = 1$); 0.7 and 0.3 reflect the relative weights given to the recruit and November survey estimates respectively.]

Second stage

For the second stage (usually in May/June after the results of the recruit survey are available), an anchovy 2nd TAC, and a pilchard 2nd TAB are set as follows:

Anchovy 2nd TAC: $$TAC_y^{2,A} = \alpha\, 300\left(0.7\frac{N_{y,rec0}^A}{\overline{N}_{y,rec0}^A} + 0.3\frac{B_{y,Nov}^A}{\overline{B}_{Nov}^A}\right) \qquad \text{A4.1.4}$$

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Pilchard 2nd TAB:

$$TAB_y^{2,P} = TAB_{rh}^P + \lambda\, TAC_y^{1,A} + r_y\,(TAC_y^{2,A} - TAC_y^{1,A}) \qquad \text{A4.1.5}$$

where $\lambda = \max\{\gamma, r_y\}$

In equations A4.1.1-5:

r_y is the ratio of juvenile pilchard to anchovy "in the sea" during May, estimated by taking the average, in year y, of the pilchard bycatch to anchovy ratio by mass as found in the May commercial catches (for this ratio calculation, only those landings where the proportion [anchovy/(total less pilchard bycatch)] was at least 0.5, reflecting anchovy targeting, were considered), and the ratio (multiplied by a factor of 1.29) of pilchard to anchovy recruitment as given by the estimates of numbers of recruits obtained from the mid-year recruit survey [Although OMP99 did not restrict r_y, for the purposes of Chapter 7 r_y is not allowed to exceed 0.5, in order to avoid a situation where the pilchard bycatch with anchovy is much larger than the anchovy catch itself, particularly because of the possibility of regime shifts.];

$B_{y,Nov}^i$ is the adult biomass estimate for species i (in thousand tons; i=P for pilchard or A for anchovy) from the November survey in year y-1;

$\overline{B}_{Nov}^A$ is the mean of the actual $B_{y,Nov}^i$ estimates for anchovy for the years 1984-1997 (945 000 tons), which, unlike $\overline{N}_{y,rec0}^A$, is not updated annually[52];

$N_{y,rec0}^A$ is the anchovy recruitment estimate from the mid-year recruit survey in year y, back-calculated to the start of the year by taking fishing and natural mortality into account (in billions of fish; see equation A4.1.6);

$\overline{N}_{y,rec0}^A$ is the mean of the estimates of $N_{y,rec0}^A$, updated annually (e.g. for 1998, this is the actual mean for the period 1985-1997, which is 173 billion fish);

TAB_{rh}^P is the fixed tonnage of pilchard bycatch set aside for the round herring fishery each year (set at 10 000 tons);

α, β, γ are control parameters which are fixed for the period over which a selected MP is implemented (these are 0.452, 0.1375 and 0.109 respectively for OMP99); and

δ is a "scale down" factor which is used to set a lower anchovy initial TAC to provide a buffer against possible poor recruitment

[52] This is because $\overline{N}_{y,rec0}^A$ is essentially a model constant since recruitment is drawn from the flat-topped "SS" stock recruit curve used in the base case operating model (assessment A_0 in Chapter 3), while $\overline{B}_{Nov}^A$ would change over time if the MP was altered to change the harvesting intensity (Butterworth *et al.* 1993).

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later in the season (set at 0.85 – this value increased from a previous value of 0.7 used in OMP94 to reflect the high premium the pelagic industry places on more definite early indication of the TAC for the whole year to facilitate planning for fishing and marketing).

These decision rules are subject to the following constraints.

Anchovy

1. 1st and 2nd TACs must be at least 60% of last year's 2nd TAC.
2. 1st and 2nd TACs must lie between α×200=90 000 tons and α×600=271 000 tons.
3. The 2nd TAC must be at least as large as the 1st TAC, but must not exceed the 1st TAC by more than α×150=68 000 tons.
4. Exceptional Circumstances apply if the November survey estimate of adult biomass ($B^{A}_{y,Nov}$) is less than 400 000 tons at the time the 1st TAC is set, or if the projected November adult biomass estimate ($B^{A}_{y,proj}$ in equation A4.1.12) is less than 400 000 tons at the time the 2nd TAC is set. The actual formulae used for Exceptional Circumstances for anchovy are given below.

Pilchard

5. The TAC must be at least 75% of last year's TAC.
6. The TAC must lie between ε×70 000 and ε×210 000 tons, where $\varepsilon = \beta/0.1$ if $\beta < 0.1$, and $\varepsilon = 1$ otherwise.
7. Exceptional Circumstances apply if the November survey adult biomass estimate ($B^{P}_{y,Nov}$) is less than 150 000t. The actual formulae used for Exceptional Circumstances are given below.

The above constraints were formulated in consultation with the industry, and are motivated by concerns for stability in the industry (1 and 5), the need for economic viability (2 and 6), limitations on processing capacity (2, 3 and 6), and resource conservation (4 and 7). Furthermore, the within-season adjustment of the anchovy TAC may not be downward (3), because it is possible that the industry would have taken the 1st TAC by the time the 2nd TAC is set. Background to the threshold levels used to invoke Exceptional Circumstances (4 and 7) is provided in Appendix 4.2.

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Back-calculating anchovy recruitment

[See equation A3.1.5 and associated text in Appendix 3.1 for the motivation for this equation.]

$$N^A_{y,rec0} = (N^A_{y,rec} e^{0.5(1+t^A_y)1.2/12} + C^A_{y,0bs} / w^A_{y,0cbs}) e^{[5+0.5(1+t^A_y)]1.2/12} \quad \text{A4.1.6}$$

where

$N^A_{y,rec}$ is the estimate of anchovy recruitment numbers ($B^A_{y,rec} / w^A_{y,rec}$, as in Table A3.2.4) from the recruit survey in year y;

$C^A_{y,0bs}$ is the mass of anchovy landed from the 1st of April to the day before the recruit survey commences in year y, assumed to be 0-year-old fish;

$w^A_{y,0cbs}$ is the mean weight of fish corresponding to $C^A_{y,0bs}$;

t^A_y is the timing of the anchovy recruit survey in year y (number of months) relative to the 1st of May that year (e.g. if the survey commenced on the 15th of June, then t^A_y = 1 + 14/30 = 1.47).

[Note that the 1.2 factor in the exponential terms in equation A4.1.6 (and other equations below) refers to the natural mortality value used for OMP (juvenile M = adult M).]

Exceptional Circumstances

Pilchard directed TAC

Exceptional Circumstances for the pilchard directed TAC apply if:

$$B^P_{y,Nov} < 150 \text{ thousand tons}$$

in which case the TAC under Exceptional Circumstances is calculated as follows:

$$TAC^P_y = TAC^{P*}_y \left(\frac{B^P_{y,Nov}}{150} \right)^2 \quad \text{A4.1.7}$$

where

$$TAC^{P*}_y = \max \text{ of } \begin{cases} \varepsilon\, 70 \\ 0.75\, TAC^P_{y-1} \end{cases}, \text{ where } \varepsilon = \begin{cases} \beta/0.1 & , \beta < 0.1 \\ 1 & , \beta \geq 0.1 \end{cases} \quad \text{A4.1.8}$$

Anchovy 1st TAC

Exceptional Circumstances for the anchovy 1st TAC apply if:

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$$B^{A}_{y,Nov} < 400 \text{ thousand tons}$$

in which case the TAC under Exceptional Circumstances is calculated as follows:

$$TAC^{1,A}_{y} = TAC^{1,A*}_{y} \left(\frac{B^{A}_{y,Nov}}{400} \right)^{2} \qquad \text{A4.1.9}$$

where

$$TAC^{1,A*}_{y} = \max \text{ of } \begin{cases} \alpha\, 200 \\ 0.6\, TAC^{1,A}_{y-1} \end{cases} \qquad \text{A4.1.10}$$

Anchovy 2nd TAC

First, a projected anchovy biomass is calculated as follows.

a) Derive $TAC^{2,A*}_{y}$ in the normal manner by applying the anchovy decision rules and constraints (equation A4.1.4 and anchovy constraints 1-3 listed above).

b) Calculate $B^{A}_{y,proj0}$ (the biomass contribution from the recruits of the year, projected to the end of the year) as follows:

$$B^{A}_{y,proj0} = \max \text{ of } \begin{cases} \left(N^{A}_{y,rec} - \dfrac{TAC^{2,A*}_{y} - C^{A}_{y,1} - C^{A}_{y,0bs}}{\overline{w}^{A}_{0c}} \right) e^{-1.2/2}\, \overline{w}^{A}_{1} \\ 0 \end{cases} \qquad \text{A4.1.11}$$

c) Calculate $B^{A}_{y,proj}$ (the total biomass projected to the end of the year, now adding the contribution from the 1-year-olds; for simplicity, the small 2-year-old contribution is neglected) as follows:

$$B^{A}_{y,proj} = \left(\frac{B^{A}_{y,Nov} e^{-1.2/4}}{w^{A}_{y,1}} - \frac{C^{A}_{y,1}}{w^{A}_{y,1c}} \right) e^{-3\times 1.2/4}\, \overline{w}^{A}_{2} \; + \; B^{A}_{y,proj0} \qquad \text{A4.1.12}$$

d) If $B^{A}_{y,proj} < 400$ thousand tons , then Exceptional Circumstances apply.

[The basic intention of equations A4.1.11-12 is to project the results of the most recent November and recruit surveys forward, taking natural and anticipated fishing mortality into account, in order to provide a proxy ($B^{A}_{y,proj}$) for the forthcoming November survey, and hence have a basis for invoking Exceptional Circumstances, if necessary.]

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If it is established that Exceptional Circumstances apply, then the anchovy revised TAC is calculated as follows:

$$TAC_y^{2,A} = TAC_y^{2,A^*} \left(\frac{0.7\frac{N^A_{y,rec0}}{\overline{N}^A_{y,rec0}} + 0.3\frac{B^A_{y,Nov}}{\overline{B}^A_{Nov}}}{0.7\frac{N^{A^*}_{y,rec0}}{\overline{N}^A_{y,rec0}} + 0.3\frac{B^A_{y,Nov}}{\overline{B}^A_{Nov}}} \right)^2 \qquad \text{A4.1.13}$$

where

$$N^{A^*}_{y,rec0} = (\theta\, e^{0.5(1+t^A_y)1.2/12} + C^A_{y,0bs} / w^A_{y,0cbs})\, e^{[5+0.5(1+t^A_y)]1.2/12} \qquad \text{A4.1.14}$$

and

$$\theta = \frac{[400 - (B^A_{y,proj} - B^A_{y,proj0})]\, e^{1.2/2}}{\overline{w}^A_1} + \frac{TAC_y^{2,A^*} - C^A_{y,1} - C^A_{y,0bs}}{\overline{w}^A_{0c}} \qquad \text{A4.1.15}$$

[Motivation for these equations is as follows. Equation A4.1.15 calculates the recruit survey result θ in year y (in terms of numbers) that would be sufficient to yield a $B^A_{y,proj}$ value of exactly 400 000 tons. Equation 4.1.14 then back-calculates this recruitment to the start of the year in the same way as for the actual recruit survey results in equation A4.1.6. The term in the squared parentheses of equation A4.1.13 is essentially $TAC_y^{2,A}$ calculated with the actual recruitment for year y divided by $TAC_y^{2,A}$ calculated with θ. The idea then is to reduce TAC_y^{2,A^*} by the ratio (squared) of the former to the latter, thus providing a means to reduce the TAC fairly rapidly when the Exceptional Circumstances threshold is surpassed.]

In equations A4.1.11-15 (quantities not previously defined):

$C^A_{y,1}$ is the mass of anchovy landed from 1 January to 31 March in year y, assumed to be 1-year-old fish;

$\overline{w}^A_{1/2}$ is the historical average of the mean weight of 1/2-year-old fish at the start of the year, sampled from November survey trawls (10.41g and 15.82g respectively);

$\overline{w}^A_{0c}$ is the historical average of the mean weight of fish caught from 1 April onwards and assumed to be 0-year-old fish (5.77g);

$w^A_{y,1}$ is the mean weight of 1-year-old fish at the start of year y, sampled from November survey trawls in year y-1; and

$w^A_{y,1c}$ is the mean weight of fish, corresponding to $C^A_{y,1}$.

[Note that all the above equations are as they would apply in practice, using data from the fishery and research surveys. However, for the purposes of MP testing, these data are simulated by the

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selected operating model (see Chapter 5), and in the case of equations A4.1.6 and A4.1.14, the first exponential term (in the parentheses) is omitted, and the second exponential term is simplified to $e^{1.2/2}$. Note also that values for $\overline{w}_{1/2}^{A}$ and $\overline{w}_{0c}^{A}$ differ from those given in Tables A3.2.1-2 because they are the values that applied when OMP99 was developed (i.e. recent data are excluded).]

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APPENDIX 4.2

Threshold levels for invoking Exceptional Circumstances for OMP99

The threshold levels for invoking Exceptional Circumstances for OMP99 (Appendix 4.1) were the same as those developed for OMP94, except for a downward adjustment of the anchovy threshold (from 500 000 to 400 000 tons) because of the period of low anchovy biomass from 1993 to 1998. These threshold levels essentially trade off the probability of not taking further action (by applying the Exceptional Circumstances meta-rules) when it is actually necessary, with that of taking action when it is not really needed. They are computed from the 10 000 realisations of a single MP trial (20 years × 500 simulations) as follows.

1. Group the 10 000 pairs of values $\{B^i_{y,Nov}; B^i_{y,N}\}^Q$ into categories based on the values for $B^i_{y,Nov}$ {e.g. [0,100), [100,200), etc., where bounds are in thousand tons}, where Q indicates the simulation run, i the species (P or A), y the year, Nov that the biomass value is a simulated November survey estimate, and N that it is generated by the operating model (thus depicting the "true" situation – see Figure 4.3).
2. Within each category defined in 1, compute $B^i_{y,N} / K^i$ (K^i is the average pre-exploitation value for $B^i_{y,N}$) and associated cumulative probability curves (cumulative frequency curves normalised to a maximum of 1).
3. Calculate the probability that the "true" biomass ($B^i_{y,N}$) is less than $0.2K^i$ (the level at which recruitment is thought to be impaired), given that the survey estimate ($B^i_{y,Nov}$) falls within that category. The midpoint of the category is a potential Exceptional Circumstances threshold value.
4. Calculate the expected frequency of application of the Exceptional Circumstances meta-rules (10 000 divided by cumulative frequency in 2) for the threshold in 3.

An Exceptional Circumstances threshold value in 3 would be selected if the probability indicated in 3 was sufficiently small (<20% was used for OMP94), and if the expected frequency in 4 was once every 10 years roughly (also used for OMP94). Cumulative probability plots for OMP99, associated with $B^P_{y,Nov}$, $B^A_{y,Nov}$ and $B^A_{y,proj}$ (the latter replacing $B^i_{y,Nov}$ in 1-4 above; Appendix 4.1), are shown in Figure A4.2.1. Table A4.2.1 gives the expected frequency of application of meta-rules associated with each of the curves in Figure A4.2.1.

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Figure A4.2.1 Cumulative probability curves for $B^i_{y,N} / K^i$ ($i = P$ or A), given that the corresponding $B^i_{y,Nov}$ or $B^A_{y,proj}$ values fall within certain categories (indicated in the legends, with bounds in thousand tons). A vertical line is drawn at $B^i_{y,N} / K^i = 0.2$ (the level at which recruitment is thought to be impaired), and the percentages along this line indicate the probability that the "true" biomass ($B^i_{y,N}$) is less than $0.2K^i$, given that survey or projected estimate ($B^i_{y,Nov}$ or $B^A_{y,proj}$) falls within the corresponding category.

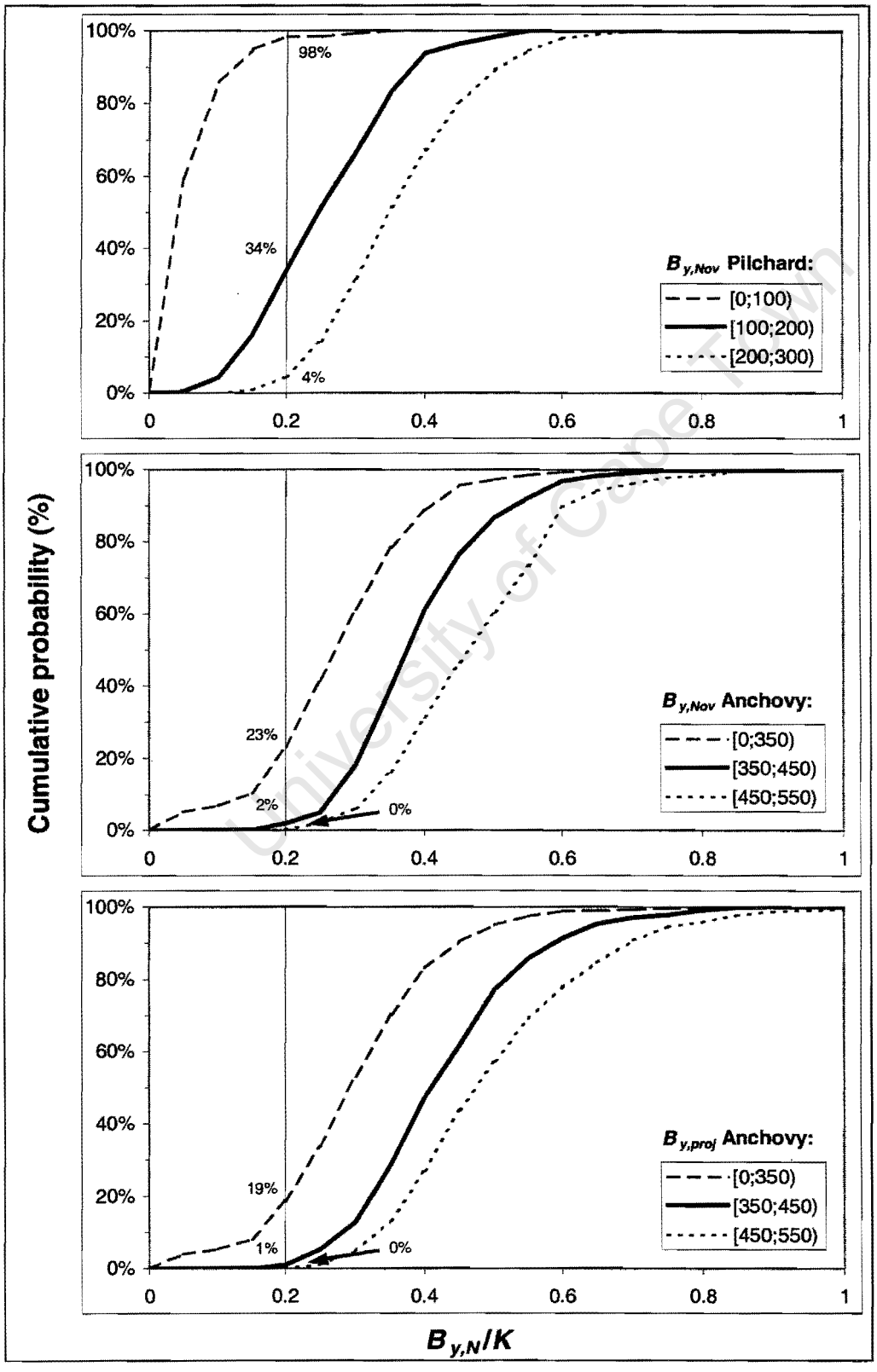

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Table A4.2.1 Frequency of application of Exceptional Circumstances meta-rules (once every "x" years, where the x values are shown in the Table) associated with each of the curves shown in Figure A4.2.1. The category bounds are in thousand tons.

Pilchard		Anchovy		
Category	$B^{P}_{y,Nov}$	Category	$B^{A}_{y,Nov}$	$B^{A}_{y,proj}$
[0;100)	83	[0;350)	26	20
[100;200)	23	[350;450)	12	9
[200;300)	8	[450;550)	6	5

Results in Figure A4.2.1 and Table A4.2.1 suggest that the Exceptional Circumstances threshold value of 400 000 tons was suitable for anchovy under OMP99, but that a higher threshold value (250 000 tons, say, instead of 150 000 tons) would be more suitable for pilchard.

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CHAPTER 5

OMP02 – The Pilchard-Anchovy MP Implemented in 2002

Pilchard and anchovy are managed together under a joint MP because of the operational interaction that occurs when they are targeted. Essentially, pilchard and anchovy shoal together as juveniles of a similar size, and any targeting of juvenile anchovy is accompanied by a bycatch of juvenile pilchard. This has implications for the directed fishery of pilchard in future years, which is based on adults. A trade-off decision between these species is therefore inevitable. A joint MP provides a framework for making such a trade-off decision, taking into account the stock-dynamics for each species as based on historical data from the fishery and research surveys (assessments of Chapters 2 and 3). The trade-off decision is first developed as "external" (the external trade-off decision, or ETD method), where the responsible Minister makes a trade-off decision for the industry as a whole (the approach used in the past). This requires a compromise between those rights holders that prefer pilchard (for canning), and those that prefer anchovy (for reduction). It is then developed as "internal" (the internal trade-off decision or ITD method), where the rights holders themselves make the trade-off decision based on their own preferences. The ETD method specifies a pilchard-anchovy ratio for the whole industry, calculates TACs on the basis of this selection, and then allocates quotas to each rights holder on the basis of a percentage right for each fishery (pilchard and anchovy). The ITD method requires each rights holder to specify a desired pilchard-anchovy ratio, and to be allocated a single percentage of the joint pilchard-anchovy fishery. Rights expressed either as a percentage of each fishery, or as a percentage of the joint fishery, are implicit in the actual allocations for 2001, and a method for converting the two rights into one is presented. When applying the ITD method, a non-linear adjustment factor is introduced to ensure that allocations to individual rights holders are near-identical to those derived using the ETD method. Robustness tests of MPs using the ITD method are presented. After consideration of the robustness tests, OMP02 was selected from a sub-set of candidate MPs.

5.1 Introduction

This Chapter provides a detailed description of the development, testing and selection of OMP02, the multi-species MP implemented for pilchard and anchovy in 2002. Descriptions of the historical development of MPs for South African small pelagic resources, the justification for implementing OMP02, and how OMP02 differs from pelagic OMPs implemented previously are provided in Chapter 4.

The framework within which the MPs presented here are tested is described in detail in Appendix 5.1, and the assessment procedures used to derive parameter distributions for the operating models within this framework are those presented in Chapters 2 and 3 (for pilchard and anchovy respectively). Although already described in Chapter 4, it is worth repeating the typical annual cycle of events for the management of pilchard and anchovy, shown in Figure 5.1, because the decision rules and constraints of the MPs relate to these events.

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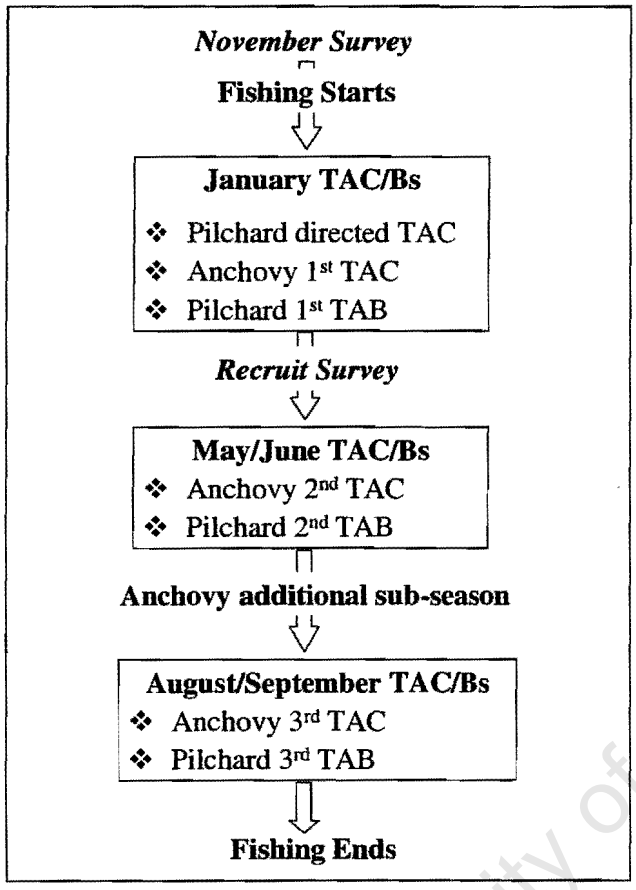
Figure 5.1 The typical cycle of events for the pilchard and anchovy fisheries. Successive TACs and TABs (Total Allowable Bycatches) are essentially revisions of their forerunners (i.e. the 2nd TAC/B is a revision of the 1st, etc.). TABs incorporate pilchard bycatch with both anchovy and round herring. [Note that because the additional sub-season is separate from the normal season for anchovy, the TAC/Bs actually applied in the sub-season are: anchovy 3rd TAC less anchovy 2nd TAC, and pilchard 3rd TAB less pilchard 2nd TAB.]



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5.2 TAC equations and constraints

The equations and associated constraints set out below are used to set TACs in three stages during the year (Figure 5.1). In broad summary, these constraints involve:

(i) maxima and minima for total anchovy and directed pilchard TACs;

(ii) maximum reduction percentages on anchovy and directed pilchard TACs; and

(iii) maximum amounts by which the anchovy TAC may be revised upwards during the year (different maximum limits may apply for the revision from the 1st to the 2nd TAC, and from the 2nd to the 3rd TAC).

However, under Exceptional Circumstances these TAC and associated constraint calculations may be adjusted downwards if the November survey results for pilchard or anchovy (when calculating first stage TACs), and if the projected survey result for anchovy (when calculating second and third stage TACs for anchovy) are below certain threshold levels (150 thousand tons for the pilchard survey result, and 400 thousand tons for both the actual and projected anchovy

survey results). Appendix 4.2 provides motivation for these threshold levels[53], while Appendix 5.2 provides more details on the meta-rules for Exceptional Circumstances, which have been omitted from the equations below for simplicity.

Adjustments in TACs during the year, if applicable, may only be upwards, not downwards, because by the time the 2nd TAC is set, the 1st TAC could have been caught.

[TACs and TABs[54] are in thousand tons, and descriptions of the symbols used in the equations are provided after equation 5.11. The categorisation of the fishing season into a normal season (first and second stage) and additional sub-season (third stage) applies only to anchovy.]

First stage (January)

TACs are based on the results of the immediately preceding November survey.

The directed pilchard TAC is set at a proportion β of the November survey biomass estimate (equation 5.1), but subject to the constraints of a minimum and a maximum value, and also a maximum percentage drop from the previous year's TAC (equation 5.2[55]).

The anchovy 1st TAC is based on how the November survey estimate of anchovy abundance relates to the past average value (equation 5.3). It is assumed that forthcoming recruitment will be average (as evident from comparison of equations 5.3 and 5.6), because at the start of the year, no information on this recruitment, which will form the bulk of the year's catch, is available. A "scale-down" factor, δ, is therefore introduced to provide a buffer against possible poor recruitment. The recruit survey component in the anchovy TAC equations (5.3, 5.6 and 5.9 below) is given more weight because of the importance of the incoming recruits to the year's catch. The anchovy TAC is subject to similar constraints as apply for pilchard (equation 5.4).

The pilchard 1st TAB consists of two components (equation 5.5), one linked to the anchovy fishery (mainly juvenile pilchard), and one to the round herring fishery (mainly adult pilchard). The anchovy component is proportional to the anchovy TAC, and is based on an estimate of the

[53] These threshold levels, associated with previous OMPs, should formally have been re-evaluated for the OMPs presented in this Chapter, but this was not possible because of the time constraints involved in implementing OMP02.

[54] Total Allowable Bycatches

[55] Although equation 5.2 is strictly a set of inequalities, this and other similar expressions will be called "equations" for simplicity.

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ratio of pilchard to anchovy juvenile fish. However, there is no estimate of this ratio at the start of the year, so a conservative value for the control parameter γ is assumed. The round herring component is simply a fixed tonnage (TAB^{P}_{rh}).

Pilchard directed TAC: $$TAC^{P}_{y} = \beta\, B^{P}_{y,Nov} \qquad 5.1$$

subject to:

$$\max\{(1-c^{P}_{mxdn})\,TAC^{P}_{y-1}\,;\,c^{P}_{mntac}\} \le TAC^{P}_{y} \le c^{P}_{mxtac} \qquad 5.2$$

Anchovy 1st TAC: $$TAC^{1,A}_{y} = \alpha_{ns}\,\delta\,300\left(0.7+0.3\frac{B^{A}_{y,Nov}}{\overline{B}^{A}_{Nov}}\right) \qquad 5.3$$

subject to:

$$\max\{(1-c^{A}_{mxdn})\,TAC^{2,A}_{y-1}\,;\,c^{A}_{mntac}\} \le TAC^{1,A}_{y} \le c^{A}_{mxtac} \qquad 5.4$$

Pilchard 1st TAB: $$TAB^{1,P}_{y} = \gamma\, TAC^{1,A}_{y} + TAB^{P}_{rh} \qquad 5.5$$

[Note, the values 300, 0.7 and 0.3 in equation 5.3 (and others below) come from previous OMP implementations and were not newly specified here (Appendix 4.1, Butterworth *et al.* 1993, De Oliveira 1995).]

Second stage (May/June)

The anchovy TAC and pilchard TAB midyear updates are based on the most recent November and recruit surveys.

The anchovy 2nd TAC uses the actual estimate of recruitment and therefore no longer requires the "scale-down" factor δ (compare equations 5.3 and 5.6). Additional constraints are applied, restricting the amount by which the 2nd TAC may exceed the 1st TAC, and ensuring that the former is not less than the latter (equation 5.7).

For the pilchard 2nd TAB (equation 5.8), γ is replaced by an estimate of the ratio r_y of pilchard to anchovy juveniles (obtained from the average of values for the commercial landings during the month of May and for the recruit survey), provided this ratio is larger than γ. An additional term, applying this ratio to the increase in anchovy TAC (if there is one), is added to the equation (compare equations 5.5 and 5.8).

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Anchovy 2nd TAC:
$$TAC_y^{2,A} = \alpha_{ns}\ 300\left(0.7\frac{N_{y,rec0}^{A}}{\overline{N}_{y,rec0}^{A}} + 0.3\frac{B_{y,Nov}^{A}}{\overline{B}_{Nov}^{A}}\right) \quad 5.6$$

subject to:

$$\max\{(1-c_{mxdn}^{A})TAC_{y-1}^{2,A}; TAC_y^{1,A}; c_{mntac}^{A}\} \le TAC_y^{2,A} \le \min\{c_{mxtac}^{A}; TAC_y^{1,A} + c_{mxinc}^{ns,A}\} \quad 5.7$$

Pilchard 2nd TAB:
$$TAB_y^{2,P} = \lambda\, TAC_y^{1,A} + r_y(TAC_y^{2,A} - TAC_y^{1,A}) + TAB_{rh}^{P} \quad 5.8$$

where $\lambda = \max\{\gamma, r_y\}$

Third stage (August/September): the anchovy additional sub-season

The anchovy TAC is adjusted to achieve better utilisation of the anchovy resource, resulting in the anchovy 3rd TAC (note that α_{ns} in equation 5.6 is replaced by α_{ads} in equation 5.9), while the pilchard TAB is equal to the pilchard 2nd TAB plus a small tonnage, this being either the fixed tonnage TAB_{ads}^{P} or 10% of the difference between the anchovy 2nd and 3rd TACs, whichever is less (equation 5.11)[56]. The anchovy 3rd TAC is subject to constraints similar to those applied earlier (compare equations 5.7 and 5.10). Because the anchovy additional sub-season is completely separate from the anchovy normal season, the anchovy TAC and pilchard TAB actually applied during the sub-season are $TAC_y^{3,A} - TAC_y^{2,A}$ and $TAB_y^{3,P} - TAB_y^{2,P}$ respectively.

Anchovy 3rd TAC:
$$TAC_y^{3,A} = \alpha_{ads}\ 300\left(0.7\frac{N_{y,rec0}^{A}}{\overline{N}_{y,rec0}^{A}} + 0.3\frac{B_{y,Nov}^{A}}{\overline{B}_{Nov}^{A}}\right) \quad 5.9$$

subject to:

$$\max\{TAC_y^{2,A}; c_{mntac}^{A}\} \le TAC_y^{3,A} \le \min\{c_{mxtac}^{A}; TAC_y^{2,A} + c_{mxinc}^{ads,A}\} \quad 5.10$$

Pilchard 3rd TAB:
$$TAB_y^{3,P} = TAB_y^{2,P} + \min\left\{TAB_{ads}^{P}; 0.1(TAC_y^{3,A} - TAC_y^{2,A})\right\} \quad 5.11$$

[56] Appendix 5.1 provides motivation for using the factor 0.1 in equation 5.11.

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In equations and constraints 5.1-11:

$B^{i}_{y,Nov}$ is the adult biomass at the beginning of year y, from the simulated[57] November survey in year y-1 for species i (in thousand tons; $i = P$ for pilchard or A for anchovy; equation A5.1.16);

$\overline{B}^{A}_{Nov}$ is the mean of the actual $B^{A}_{y,Nov}$ estimates for anchovy for y = 1985,...,2001 (1.115 million tons – see Table A3.2.2), which unlike $\overline{N}^{A}_{y,rec0}$ is not updated annually (Appendix 4.1 provides an explanation for this);

r_y is the simulated average of the juvenile pilchard to anchovy ratio in the commercial catches in May and in the recruit survey, in year y (see equation A5.1.27-29);

$N^{A}_{y,rec0}$ is the simulated anchovy recruitment estimate from the mid-year recruit survey, back-calculated to the start of the year by taking fishing and natural mortality into account (in billions of fish; equation A5.1.18[58]);

$\overline{N}^{A}_{y,rec0}$ is the mean of the estimates of $N^{A}_{y,rec0}$, updated annually according to equation A5.1.19 and associated text in Appendix 5.1 ($\overline{N}^{A}_{2001,rec0}$ = 194.7 billion fish – see Table A3.2.4);

TAB^{P}_{rh} is the fixed tonnage of adult pilchard bycatch set aside for the round herring fishery each year (set at 10 thousand tons);

TAB^{P}_{ads} is the maximum fixed tonnage of juvenile pilchard bycatch set aside for the anchovy additional sub-season each year (2 000 tons);

α_{ns}, α_{ads}, β are control parameters that are fixed for the period over which a selected MP is implemented;

γ is the proportion of the 1st anchovy TAC used to calculate the 1st pilchard TAB (set at 0.1);

δ is a "scale down" factor which is used to set a lower anchovy initial TAC to provide a buffer against possible poor recruitment later in the season;

c^{i}_{mntac} is the minimum TAC to be set for species i (= P or A; in thousand tons);

c^{i}_{mxtac} is the maximum TAC to be set for species i (= P or A; in thousand tons);

c^{i}_{mxdn} is the maximum proportional amount by which the TAC for species i (= P or A) can be reduced from one year to the next; and

[57] Simulated values are used when testing MPs, but in application (e.g. when OMP99 was applied in practice – see Appendix 4.1), actual data from the fishery and surveys are used throughout.

[58] In application (i.e. applying OMP02) equation A4.1.6, where 1.2 is replaced with 0.9, would be used.

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$c^{j,A}_{mxinc}$ is the maximum amount (in thousand tons) by which the anchovy TAC is allowed to be increased within the year ($j = ns$ for the normal season increase, and $j = ads$ for the normal to the additional sub-season increase).

5.3 Summary performance statistics

The summary statistics considered may be grouped into two categories: those dealing with resource conservation, and those related to economic performance.

Resource conservation

The following resource conservation summary statistics are considered:

$risk^{P}_{20\%}$ the probability that adult pilchard biomass, $B^{P}_{y,N}$, falls below 20%[59] of K^P (the average adult pilchard biomass in the absence of exploitation – see Appendix 5.1) at least once during the projection period[60];

$risk^{P}_{B}$ as $risk^{P}_{20\%}$, but "20% of K^P" is replaced with the average of the $B^{P}_{y,N}$ estimates (provided by the assessments in Chapter 2) for the period 1991-1994 – this period reflects a period of low-abundance for pilchard, and $B^{P}_{y,N}$ levels prevalent at the time should be avoided[61];

$risk^{A}_{15\%}$ the probability that adult anchovy biomass, $B^{A}_{y,N}$, falls below 15% of K^A at least once during the projection period;

$depl^{i}_{K}$ the average adult biomass at the end of the projection period, $B^{i}_{2021,N}$, as a proportion of K^i for species i (= P or A); and

$depl^{i}_{0}$ the average adult biomass at the end of the projection period, $B^{i}_{2021,N}$, as a proportion of its average at the beginning of the projection period, $B^{i}_{2001,N}$, for species i (= P or A).

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[59] Motivation for the threshold levels selected for *risk* statistics for both pilchard and anchovy are given in Appendix 5.3.

[60] The projection period is 20 years (2001-2020), with stock biomass and numbers-at-age calculated at the end of each year (reflected as the beginning of the following year), so that estimates of stock biomass and numbers-at-age are available for all years including 2021. An additional projection year (2000) is required for pilchard because there is one year's less data for pilchard compared to anchovy, caused by delays in processing age data for pilchard (routine ageing is no longer performed for anchovy – Appendix 3.2).

[61] $risk^{P}_{B}$ was introduced to provide a *risk* measure that was independent of the estimate of K^P and reflected how successfully an MP was able to avoid pilchard biomass dropping to levels similar to those over the 1991-1994 period.

Economic performance

The following economic performance summary statistics are considered[62]:

$\overline{C}^{P}_{dir}$ — the average of $C^{P}_{y,dir} = \sum_{a=1}^{4} C^{P}_{y,a} - TAB^{P}_{rh}$ (see equation A5.1.20), the annual directed catch of pilchard, over the projection period;

$\overline{C}^{P}_{byc,tot}$ — the average of $C^{P}_{y,byc,tot} = C^{P**}_{y,0} + TAB^{P}_{rh}$ (see equation A5.1.32 and A5.1.42), the annual bycatch of pilchard (sum of the bycatch with anchovy during the normal and additional sub-seasons, and with round herring) over the projection period;

$\overline{C}^{A}_{j}$ — the average of $C^{A}_{y,j}$, the annual catch of anchovy during season j (= *ns* or *ads*), over the projection period, where $C^{A}_{y,ns} = C^{A*}_{y,0} + C^{A}_{y,1}$ (see equations A5.1.21 and A5.1.41) and $C^{A}_{y,ads} = TAC^{3,A}_{y} - TAC^{2,A}_{y}$ $= C^{A**}_{y,0} - C^{A*}_{y,0}$ (see equations A5.1.43);

$\overline{C}^{A}_{tot}$ — the average annual total catch of anchovy ($\overline{C}^{A}_{ns} + \overline{C}^{A}_{ads}$) over the projection period;

$\overline{V}^{P}$ — the mean annual change (as a proportion) in $C^{P}_{y,dir}$, calculated as $\overline{V}^{P} = \frac{1}{500}\sum_{Q=1}^{500}\left[\sum_{y=2001}^{2020}\left|C^{P,Q}_{y,dir} - C^{P,Q}_{y-1,dir}\right| \Big/ \sum_{y=2001}^{2020} C^{P,Q}_{y,dir}\right]$, where Q represents a particular simulation; and

$\overline{V}^{A}_{j}$ — the mean annual change (as a proportion) in $C^{A}_{y,j}$ for season j (= *ns* or *ads*), calculated in the same way as $\overline{V}^{P}$.

Performance of an MP is generally considered to be best when $risk^{P}_{20\%}$, $risk^{P}_{B}$, $risk^{A}_{15\%}$, $\overline{V}^{P}$ and $\overline{V}^{A}_{ns}$ are minimised, $depl^{i}_{K}$ ($i = P$ or A) values are kept as high as possible, and $depl^{i}_{0}$ ($i = P$ or A), $\overline{C}^{P}_{dir}$, $\overline{C}^{A}_{ns}$ and $\overline{C}^{A}_{tot}$ are maximised. Naturally these objectives are in conflict, so that a trade-off choice is needed. In particular, it is not possible to simultaneously maximise average directed pilchard and anchovy TACs, because of the juvenile pilchard bycatch with anchovy. A plot of average directed pilchard against average anchovy catches expected under a candidate MP is referred to below as a "trade-off" curve (see, for example, Figures 5.3).

5.4 Comparing alternative management procedures

Several candidate management procedures were investigated and the results presented to industry, who helped narrow the number considered by advising on appropriate choices for

[62] All catch-related statistics are subject to an upper limit on the industry's fishing efficiency, through the assumption that no more than 95% of the "exploitable" stock might be captured.

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constraint values. Nine of these candidate management procedures are described here, together with a subset of these selected for robustness tests. For ease of presentation, the base case procedure, M_1, is presented upfront as the one most likely to be selected for implementation (in the form of OMP02), although such a selection could only be made after due consideration of all results and tests.

[Note that for the purpose of this Chapter, management procedures can differ in the choice of constraint values and δ, or in the choice of control parameters α_{ns}, α_{ads} and β. For the former (constraints and δ) they would lie on different pilchard-anchovy trade-off curves, while for the latter, they would lie on the same trade-off curve (see discussion following Table 5.1, and Figure 5.7 later). Therefore, one can speak of the M_1 trade-off curve, which refers to the suite of management procedures with the same choice of constraints and δ as M_1, or one could refer to M_1 as the point on the M_1 curve with the particular choice of control parameters associated with M_1.]

The choice of constraint values and δ associated with the M_1 curve are shown in Table 5.1. When other candidate management procedures (or curves) are compared to M_1 (or the M_1 curve), only the constraint whose value has changed is shown.

Table 5.1 Constraint values and δ associated with the base case management procedure M_1. These constraints (generally only c^i_{mntac} and c^i_{mxdn}) will be over-ridden if Exceptional Circumstances apply (Appendix 5.2).

Constraint/δ	Description	Value
δ	"Scale-down" factor for the anchovy 1st TAC	0.85
c^i_{mntac}	Minimum TAC to be set for species i	$i=P$: 90 000t $i=A$: 150 000t
c^i_{mxtac}	Maximum TAC to be set for species i	$i=P$: 250 000t $i=A$: 600 000t
c^i_{mxdn}	Maximum proportional amount by which the TAC for species i may be reduced from one year to the next	$i=P$: 0.2 $i=A$: 0.3
$c^{j,A}_{mxinc}$	Maximum amount by which the anchovy TAC may increase at particular stages during the year ($j=ns$ for the normal season increase, and $j=ads$ for the normal to additional sub-season increase)	$j=ns$: 150 000t $j=ads$: 100 000t

Pilchard-anchovy trade-off curves were constructed by varying β from 0 to 0.6 in steps of 0.01. For each β value, the procedure was tuned by alternately varying α_{ns} and α_{ads} until $risk^P_{20\%} \leq 0.1$ and $risk^A_{15\%} \leq 0.3$, so that points on the trade-off curve are determined by either the pilchard or

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the anchovy (or both) *risk* constraints being met. The effect of this tuning is that as β is increased (moving from the bottom right to the top left of the trade-off curves in Figures 5.5-7), α_{ns} decreases (reflecting the trade-off between these two species) and α_{ads} increases (reflecting better utilisation of the anchovy resource, which is possible because bycatch of juvenile pilchard is limited to a maximum amount of 2 000t in the additional sub-season). Therefore, even though β, α_{ns} and α_{ads} represent (apparently) three free parameters, their relationship above is such that only one free parameter (conveniently β) remains.

α_{ads} was capped at the value of 2 because the $c^{ads,A}_{mxinc}$ constraint (the maximum anchovy catch during the additional sub-season) effectively means that there is nothing more to be gained by a choice exceeding this value. Furthermore, the constraint $\alpha_{ads} \geq \alpha_{ns}$ was implemented to ensure consistency[63] with equation 5.10, where $TAC^{3,A}_{y} \geq TAC^{2,A}_{y}$. In the Figures following (e.g. Figures 5.4-7), the trade-off curves are determined by the pilchard *risk* constraint coming into operation, except for the vertical segment on the right hand side, which is a reflection of the anchovy *risk* threshold coming into play.

Two problems were encountered when constructing these trade-off curves.

(a) The c^{i}_{mntac} constraints (minimum TACs) did not allow pilchard directed catches to be zero when $\beta = 0$, and the anchovy catches to likewise be zero when $\alpha_{ns} = 0$. An additional problem was that when $\alpha_{ns} = 0$, $\alpha_{ads} = 2$, which gave rise to the unrealistic situation that even though the trade-off selection was to have no anchovy, anchovy would still be allocated in the additional sub-season. These problems were solved by replacing the minimum TACs c^{i}_{mntac} with c^{i*}_{mntac} as follows:

$$c^{P*}_{mntac} = \begin{cases} c^{P}_{mntac} & , \beta \geq \beta_0 \\ \beta\, c^{P}_{mntac} / \beta_0 & , \beta < \beta_0 \end{cases} \qquad 5.12$$

where $\beta_0 = 0.1$

$$c^{A*}_{mntac} = \begin{cases} c^{A}_{mntac} & , \alpha_{ns} \geq \alpha_0 \\ \alpha_{ns} c^{A}_{mntac} / \alpha_0 & , \alpha_{ns} < \alpha_0 \end{cases} \qquad 5.13$$

where $\alpha_0 = 0.4$

[63] This becomes important later when allocating sets of control parameters to each individual rights holders under the ITD method, but constraints continue to be applied globally.

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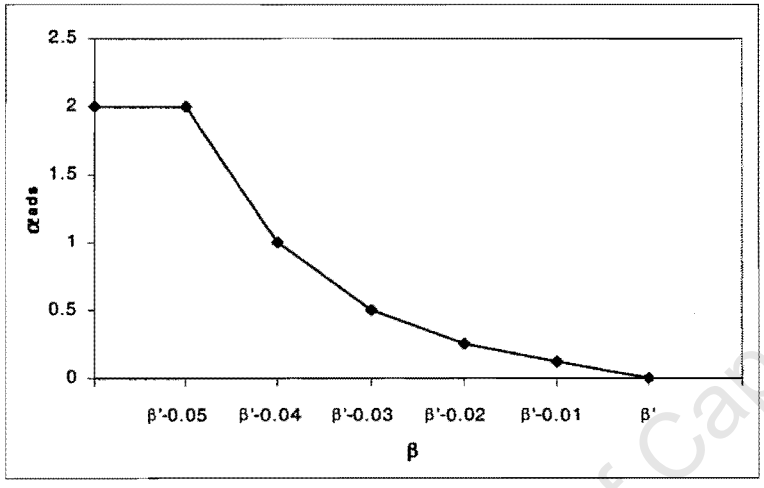
What this means is that for β choices reflecting a desired low pilchard catch to allow for high anchovy catches, the minimum pilchard TAC is reduced proportional to β once β drops below 0.1. A similar adjustment is made to α_{ns} for the desired low anchovy catch situation. In addition, α_{ads} was forced to zero in the manner shown in Figure 5.2 and described in the caption to that Figure.

Figure 5.2 Illustration of how α_{ads} was reduced to zero to coincide with when $\alpha_{ns} = 0$ for the first time (which occurs at $\beta = \beta'$) when constructing pilchard-anchovy trade-off curves. Essentially, the value of α_{ads} is halved at each point, from $\beta = \beta'$-0.05 to $\beta = \beta'$-0.01, and then set equal to zero when $\beta = \beta'$.



The values for β_0 and α_0 in equations 5.12 and 5.13 were selected on the basis of the results shown in Figure 5.3, which indicate the smoothest curves for $\beta_0 = 0.1$, with $\alpha_0 = 0.4$ a suitable intermediate value (too big a value would mean c^A_{mntac} would be reduced for most options of α_{ns}, while too small a value would start reducing the directed pilchard catch to guarantee the higher c^A_{mntac} value).

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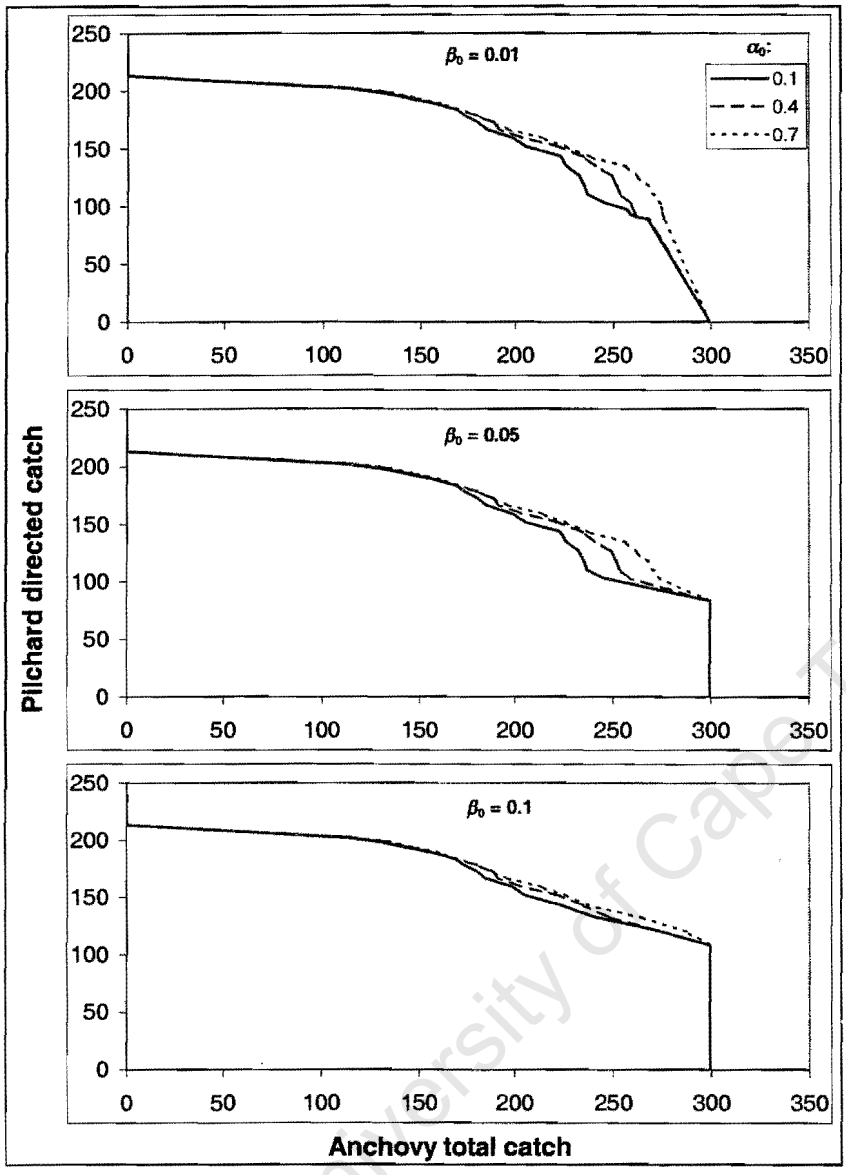
Figure 5.3 Trade-off curves for different values of β_0 and α_0 (equations 5.12 and 5.13). Catches are in thousand tons, and reflect expected averages over a 20-year projection period.



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(b) When the trade-off curves were first constructed, they were not monotonic in terms of anchovy total catch for low values of β (Figure 5.4). This hardly makes sense, as it suggests that in some circumstances dropping pilchard catches necessitates lowering anchovy catches, rather than being able to increase them. The problem arises essentially because, for low β values (i.e. the bottom right of the curve), the "risk frontier" is governed by $risk^{A}_{15\%}$ rather than $risk^{P}_{20\%}$ (i.e. the trade-off curve was determined by "hitting" the anchovy *risk* rather than pilchard *risk* threshold). This meant that several combinations of α_{ns} and α_{ads} were possible for the same value of $risk^{A}_{15\%}$ (= 0.3), without overstepping the pilchard risk threshold. This feature arises because anchovy *risk* depends on the total anchovy catch, which can be split in different ways between the normal and additional sub-season. A higher total anchovy catch is

possible for the same value of $risk^{A}_{15\%}$ if less anchovy is taken in the normal season (lower α_{ns}) and more in the additional sub-season (higher α_{ads}). This is because such a combination of α_{ns} and α_{ads} would provide a buffer against poor recruitment (thereby leading to better utilisation of anchovy) that a combination of higher α_{ns} with lower α_{ads} (for the same $risk^{A}_{15\%}$) would not. The combination of α_{ns} and α_{ads} initially chosen fell into the latter category, and therefore yielded the kink shown in Figure 5.4. This was solved by selecting a combination of α_{ns} and α_{ads} for which there was no such kink (Figure 5.5), and for which $risk^{A}_{15\%} = 0.3$ was maintained (without exceeding the pilchard risk threshold).

Figure 5.4 An illustration of the problem caused by having a particular combination of α_{ns} and α_{ads} for low β values, leading to non-monotonic ("kink") behaviour in the pilchard-anchovy trade-off curves. The curve shown is based on M_1. Catches are in thousand tons. $\overline{C}^{P}_{dir}$ is plotted on the y-axis and $\overline{C}^{A}_{tot}$ on the x-axis. [Note that anchovy total catch includes catches from both the normal and additional sub-season.]

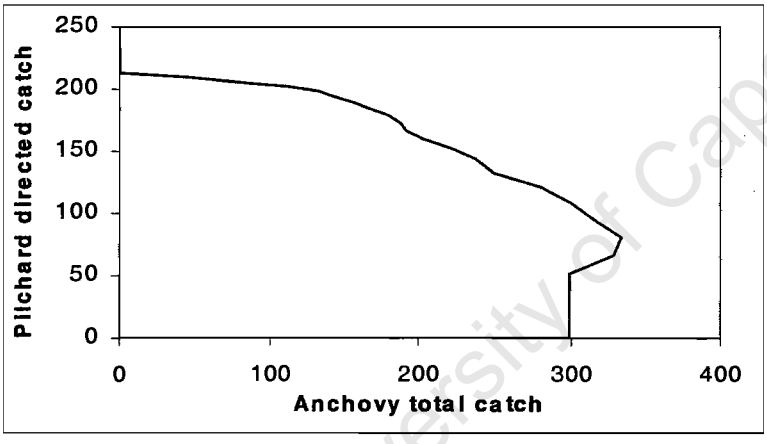

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Figure 5.5 plots the trade-off curve shown in Figure 5.4 (but with the kink removed) on the same graph as the trade-off curve associated with OMP99 (Chapter 4). The data updates and additional features now incorporated (M_1) have led to a considerable improvement in the average catches possible from the fishery. The bars around the $\beta = 0.1$ point on the M_1 curve emphasise the considerable variation in annual catches associated with such MPs. Figure 5.6 illustrates the improvement in the performance of OMP99 in terms of average catches as successive changes were introduced when developing the MPs presented in this Chapter (see the comparison between OMP99 and OMP02 in Chapter 4).

Figure 5.5 Comparing the OMP99 pilchard-anchovy trade-off curve with the base case MP (M_1) curve. The solid diamonds are points on each curve associated with $\beta = 0.1$, and the open squares with $\beta = 0.15$. The bars around the $\beta = 0.1$ point on the M_1 curve are to indicate that 50 and 90% of all values fall within the inner and outer limits respectively. Points on each curve are obtained by varying β from 0 (bottom right) to 0.6 (top left) in steps of 0.01. [Note however that the curves intersect the y-axis long before $\beta = 0.6$, the exact β value for which this happens varying from procedure to procedure.]

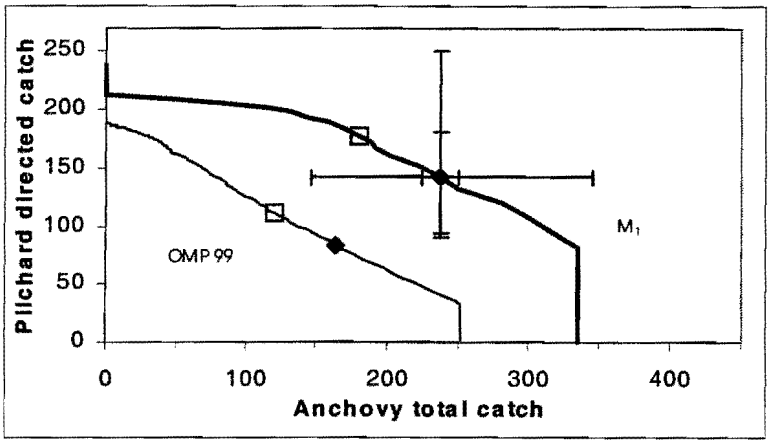

Figure 5.6 Improvements in the performance of OMP99 in terms of average catch as various changes (discussed in Chapter 4) were successively introduced when developing the MPs presented in this Chapter. Curve (a) is the curve associated with OMP99; curve (b) incorporates new/updated data and bootstrap parameter distributions used in testing; curve (c) incorporates the additional anchovy sub-season; and curve (d) incorporates the fact that the pilchard bycatch ratio declines from May to August. [Note, $c^{P}_{mxtac} = 210\,000$ tons for all curves, which is why (d) in this plot does not correspond to M_1 in Figure 5.5.]

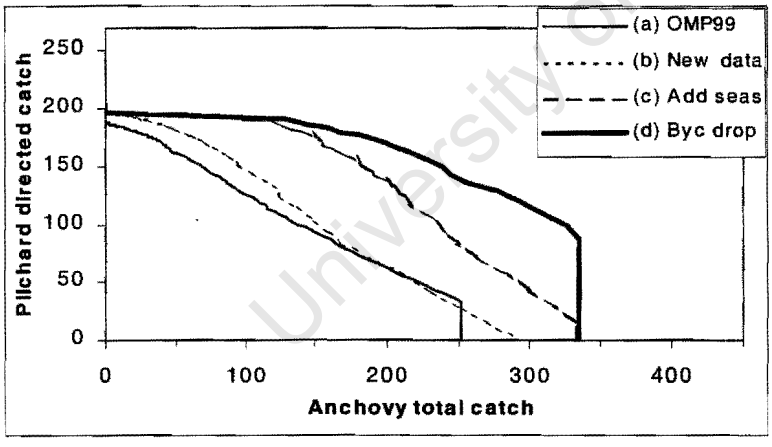

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Figure 5.7 contrasts the performance of M_1 in terms of average catch with that for ten other MP candidates. For the same β value, increasing the maximum pilchard TAC constraint c^{P}_{mxtac} ((a)) increases pilchard catches but loses anchovy catch on average. However, reducing δ from 0.85 to 0.7 for a greater buffer against poor anchovy recruitment ((d)) appears to have little effect on average catches except for improving anchovy catches when an option reflecting low pilchard catches is selected. Decreasing the maximum downward adjustment constraint for pilchard c^{P}_{mxdn} ((b)) is associated with a relatively large loss of anchovy average catch, but trade-off curves

appear to be relatively insensitive to changes in the equivalent constraint for anchovy c^{A}_{mxdn} ((e)). Although decreases in the minimum TAC constraints c^{i}_{mntac} don't appear to improve average catches by much ((c) and (f)), catches are relatively sensitive to increases in these constraints, particularly for low β values in the case of anchovy.

Figure 5.7 Pilchard-anchovy trade-off curves for the base case MP M_1 (thick curve) and variants thereof. Only one constraint is changed at a time as follows: (a) c^{P}_{mxtac}; (b) c^{P}_{mxdn}; (c) c^{P}_{mntac}; (d) δ; (e) c^{A}_{mxdn}; (f) c^{A}_{mntac}. The solid diamonds correspond to $\beta = 0.1$, and the open squares to $\beta = 0.15$.

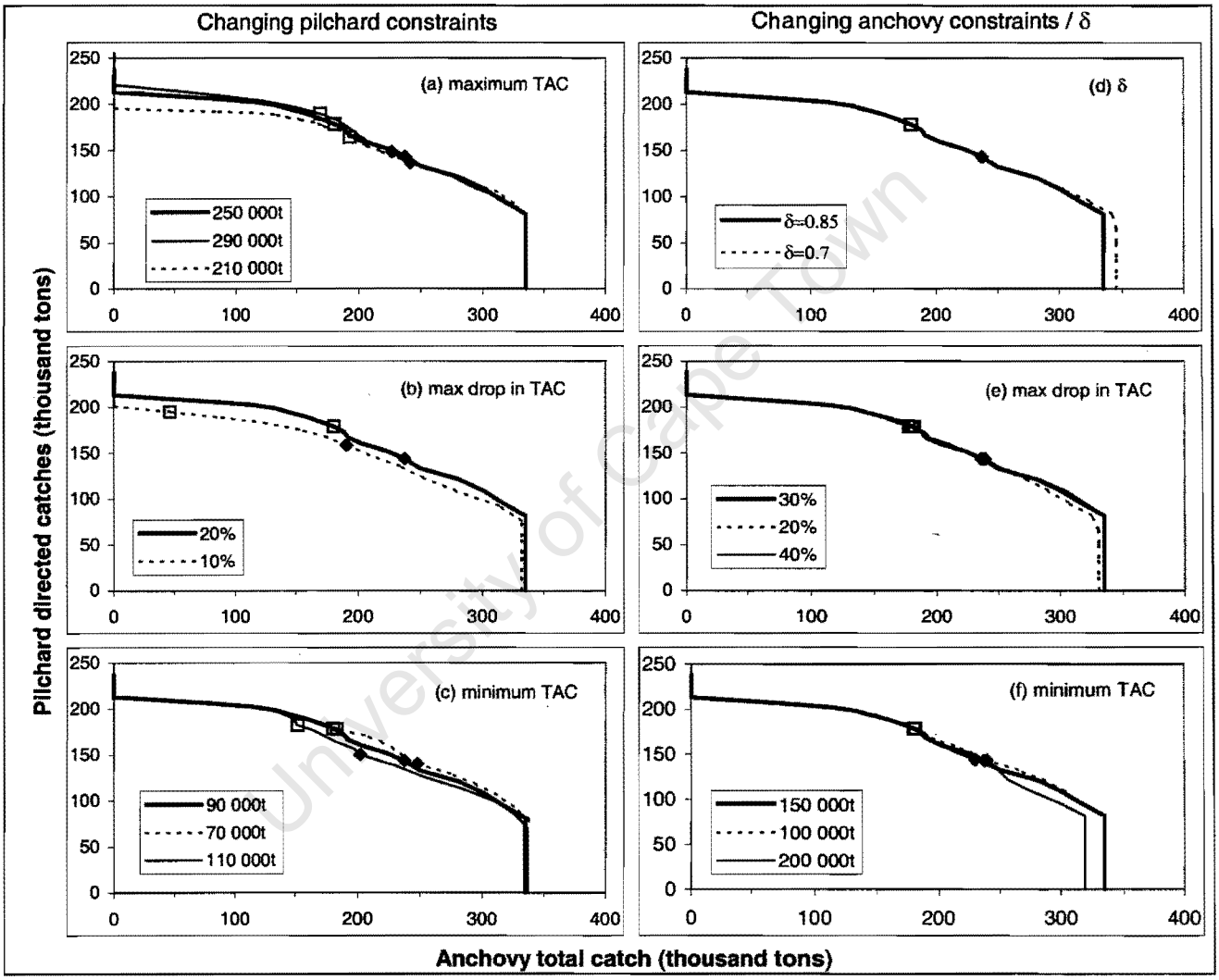

Table 5.2 repeats the results of Figure 5.7, showing the values for all summary performance statistics, but only for $\beta = 0.1375$, which was the value of β used for OMP99 (Chapter 4). These results are shown to provide some indication of the values of the summary statistics not shown in Figure 5.7. Of particular interest is that under $\beta = 0.1375$, lower anchovy catches are obtained on average in the normal season (lasting roughly 8 months) compared to the additional season (lasting no longer than 4 months) for almost all MP variants. Decreasing the maximum percentage by which the pilchard TAC may drop from one year to the next (variant 3) also has a

severe impact on anchovy catches and associated inter-annual variability in the normal season. However, all the depletion statistics are fairly insensitive to the different MP variants considered.

Table 5.2 Summary performance statistics for base case MP M_1 and variants thereof, for $\beta = 0.1375$ (the value of β used for OMP99). All MPs incorporate the same constraints as M_1 (Table 5.1) apart from the changes indicated in the second column "MP variants". In all cases, $risk^{P}_{20\%} = 0.1$, $c^{P}_{mxtac} = 250$, and $c^{P*}_{mntac} = c^{P}_{mntac}$ because $\beta > 0.1$ (see equation 5.12). Catches are in thousand tons.

	MP variants	α_{ns}	α_{ads}	c^{A*}_{mntac}	$\overline{C}^{P}_{dir}$	$\overline{C}^{P}_{byc,tot}$	$\overline{C}^{A}_{ns}$	$\overline{C}^{A}_{ads}$	$\overline{C}^{A}_{tot}$	$\overline{V}^{P}$	$\overline{V}^{A}_{ns}$	$\overline{V}^{A}_{ads}$	$depl^{P}_{K}$	$depl^{P}_{0}$	$depl^{A}_{K}$	$depl^{A}_{0}$	$risk^{A}_{15\%}$
1	M_1	0.208	2	78	171	21.0	94	97	190	0.21	0.24	0.10	0.72	0.74	0.82	0.41	0.140
2	δ=0.7	0.208	2	78	171	21.0	93	97	190	0.21	0.24	0.10	0.72	0.74	0.82	0.41	0.140
3	$c^{P}_{mxdn} = 0.1$	0.060	2	23	187	14.6	28	99	127	0.14	0.59	0.07	0.73	0.75	0.89	0.45	0.062
4	$c^{P}_{mntac} = 70$	0.260	2	98	169	23.2	115	95	211	0.22	0.21	0.11	0.71	0.73	0.80	0.40	0.190
5	$c^{P}_{mntac} = 110$	0.154	2	58	175	18.7	70	97	168	0.20	0.29	0.09	0.72	0.75	0.85	0.43	0.100
6	$c^{A}_{mxdn} = 0.2$	0.190	2	71	171	20.6	89	97	186	0.21	0.23	0.10	0.72	0.74	0.83	0.42	0.126
7	$c^{A}_{mxdn} = 0.4$	0.213	2	80	171	21.1	94	96	191	0.21	0.24	0.10	0.72	0.74	0.82	0.41	0.140
8	$c^{A}_{mntac} = 100$	0.240	2	60	171	20.9	94	97	191	0.21	0.31	0.09	0.72	0.74	0.82	0.41	0.114
9	$c^{A}_{mntac} = 200$	0.166	2	83	171	20.8	90	96	186	0.21	0.19	0.10	0.72	0.74	0.83	0.42	0.158

5.5 External vs. internal trade-off decision

When selecting an MP from a particular trade-off curve, a decision needs to be made regarding the desired trade-off between catches of pilchard and anchovy. For OMP99, this trade-off decision was made externally (the External Trade-off Decision, or ETD, approach) by the Minister (though the real motivation for the choice of $\beta = 0.1375$ for OMP99 was that it was consistent with the "hybrid" OMP applied in 1998 – Chapter 4). This meant that OMP99 first provided pilchard and anchovy TACs, which were then allocated to rights holders according to separate pilchard and anchovy rights (respectively, percentages of the pilchard and anchovy TAC) specified for each rights holder. This process is described in the top panel of Figure 5.8. The problem with the ETD approach was two-fold.

a) The industry could not agree on an overall pilchard-anchovy trade-off (and hence choice for β).

b) The above argument of consistency used for OMP99 when selecting an overall pilchard-anchovy trade-off, and hence β, could no longer be used for M_1. This was essentially because the additional features in M_1 compared to OMP99 (Figure 5.6) meant that the same choice of β for the two OMPs no longer implied the same pilchard-anchovy trade-off (compare the solid diamonds in Figure 5.5).

Under these circumstances, the ETD approach had the potential for litigation from any party who perceived themselves as having lost out.

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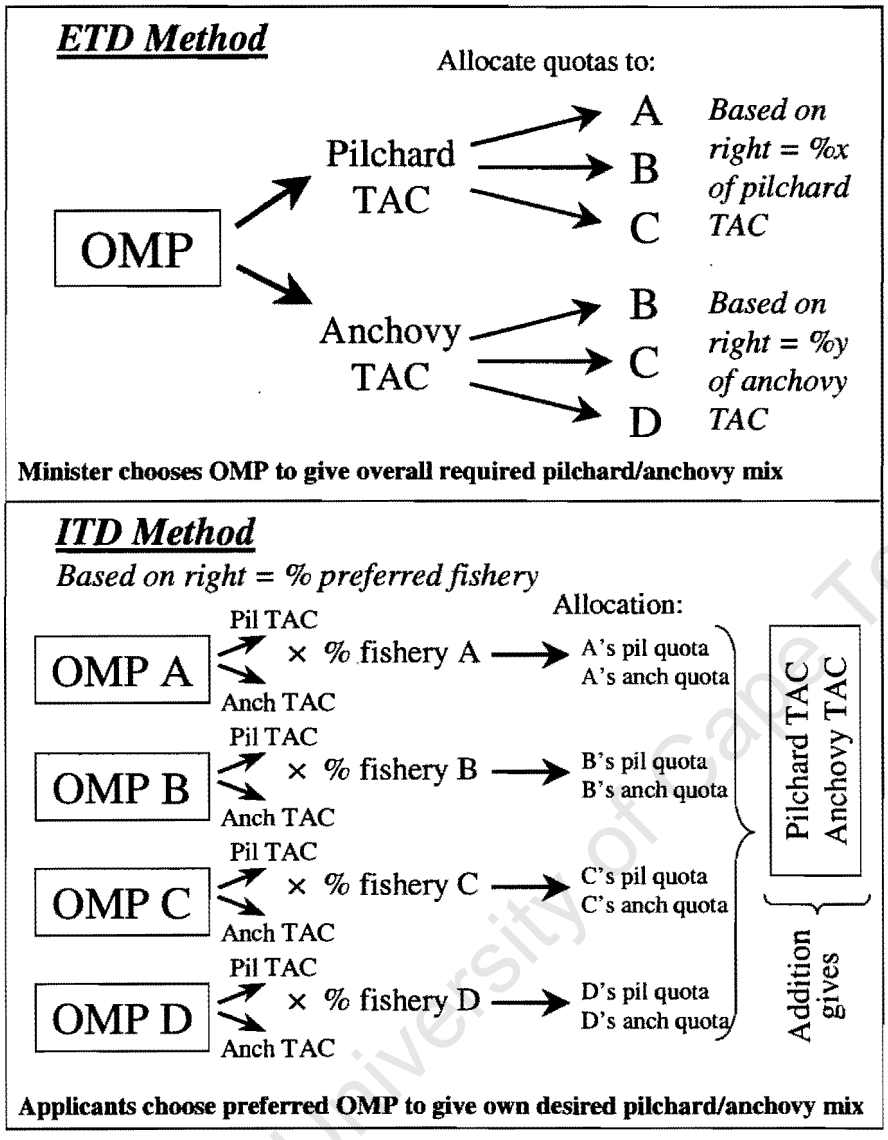
Figure 5.8 Difference between the ETD and ITD methods, where for the former a trade-off decision is made for the Industry as a whole by the Minister ("OMP" in the upper panel), in contrast to the latter, where each rights holder makes their own trade-off decision ("OMP A", "OMP B", etc. in the bottom panel). Rights are based on a percentage for each resource (x and y) for the ETD method, and on a single percentage of the rights holder's preferred fishery for the ITD method.



The Internal Trade-off Decision (ITD) approach was introduced to overcome the problems faced by the ETD approach. Under the ITD approach, the trade-off decision is made internally, which means that each rights holder is able to select their own pilchard-anchovy trade-off (reflected by their choice of a pilchard-anchovy ratio[64] desired on average). Effectively, rights holders would be selecting their own preferred OMPs. Under this scheme, a right is expressed as a single percentage of the rights holder's preferred fishery[65], instead of as separate percentage rights for pilchard and for anchovy. Once a right has been allocated to each rights holder, and rights holders have specified their preferred pilchard-anchovy ratios, quotas are computed for each

[64] This ratio is expressed as [pilchard/(pilchard + anchovy)].

[65] A hypothetical fishery in which the rights holder's trade-off decision is implemented for the whole fishery.

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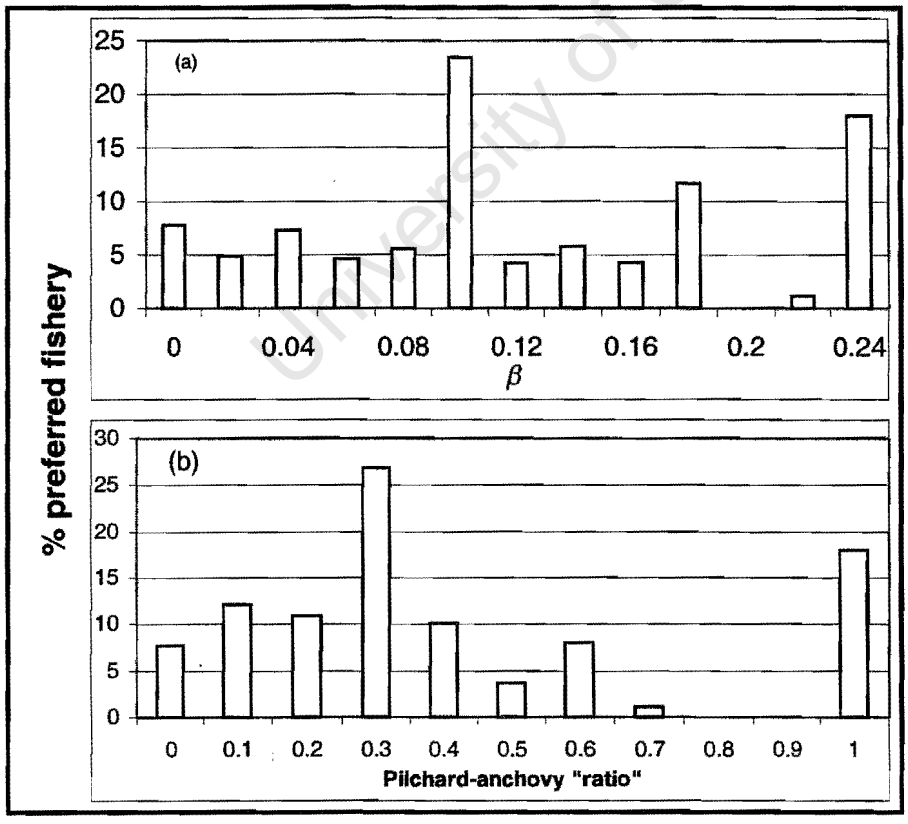
rights holder, and then summed to yield TACs for pilchard and anchovy, as shown in the bottom panel of Figure 5.8. The remainder of the Chapter develops the ITD approach further.

In order to assist in the allocation of rights for 2002 as a single percentage of the fishery, an equivalent percentage right (EPR) of a rights holder's preferred fishery was obtained by converting the two rights corresponding to pilchard and anchovy quotas allocated for 2001 into an EPR. The method to do this is explained in Appendix 5.4. Essentially, the method matches the ratios implicit in the 2001 realisation of the M_1 trade-off curve[66] with the ratios of the actual 2001 allocations of pilchard and anchovy to each rights holder. In this manner it is possible to associate a set of control parameters with each rights holder, which define where along this trade-off curve they are placed. The EPR for each rights holder is then calculated by dividing the 2001 allocation of that rights holder by the 2001 TAC realisation for M_1, and then normalising all EPRs so that they sum to 1. Figure 5.9 plots the 2001 distribution of β values and associated pilchard-anchovy catch ratios based on calculating EPRs from the M_1 curve.

Figure 5.9 Distribution of (a) β values and (b) pilchard-anchovy "ratios" [pilchard/(pilchard+anchovy)] based on calculating EPRs (equivalent percentage rights of a preferred fishery) using the M_1 curve and the quota allocations made for 2001.



[66] The 2001 realisation is derived by applying the control parameters associated with the M_1 trade-off curve to the actual survey results of 2001.

When applying the ITD approach, the quotas are calculated for each rights holder according to the following scheme.

1. Allocate an EPR ($p_{EPR,d}$) and select a set of control parameters (β_d, $\alpha_{ns,d}$, $\alpha_{ads,s}$) for each rights holder d on the basis of their actual quota allocations for 2001 (Appendix 5.4).

2. Calculate the "effective" overall control parameters as follows:

$$\beta^* = \sum_d \beta_d \; p_{EPR,d} \; f^P_{NLA,d} \qquad 5.14$$

$$\alpha^*_{ns} = \sum_d \alpha_{ns,d} \; p_{EPR,d} \; f^{ns,A}_{NLA,d} \qquad 5.15$$

$$\alpha^*_{ads} = \sum_d \alpha_{ads,d} \; p_{EPR,d} \; f^{ads,A}_{NLA,d} \qquad 5.16$$

where $f^P_{NLA,d}$, $f^{ns,A}_{NLA,d}$ and $f^{ads,A}_{NLA,d}$ are factors that are initially set equal to 1 (here and in 4 below) for all rights holders d.

3. Replace β, α_{ns} and α_{ads} with β^*, α^*_{ns} and α^*_{ads} respectively in equations 5.1, 5.3, 5.6 and 5.9, and modify equations 5.12 and 5.13 as follows:

$$c^{P**}_{mntac} = \sum_d p_{EPR,d} \; \Phi^P_d \; c^P_{mntac} \qquad \text{where } \Phi^P_d = \begin{cases} 1 & , \beta \geq 0.1 \\ \beta_d / 0.1 & , \beta < 0.1 \end{cases} \qquad 5.17$$

$$c^{A**}_{mntac} = \sum_d p_{EPR,d} \; \Phi^A_d \; c^A_{mntac} \qquad \text{where } \Phi^A_d = \begin{cases} 1 & , \alpha_{ns,d} \geq 0.4 \\ \alpha_{ns,d} / 0.4 & , \alpha_{ns,d} < 0.4 \end{cases} \qquad 5.18$$

Then proceed as usual (calculating TAC/Bs, and applying constraints and Exceptional Circumstances provisions where necessary, using equations 5.1-5.11, 5.17 and 5.18, and those of Appendix 5.2).

4. Calculate quotas Q for each rights holder as follows:

Pilchard directed quotas:

$$Q^P_{y,d} = \beta_d \; p_{EPR,d} \; f^P_{NLA,d} TAC^P_y / \beta^* \qquad 5.19$$

Anchovy quotas:

$$Q^{1,A}_{y,d} = \alpha_{ns,d} \; p_{EPR,d} \; f^{ns,A}_{NLA,d} TAC^{1,A}_y / \alpha^*_{ns} \qquad 5.20$$

$$Q^{2,A}_{y,d} = \alpha_{ns,d} \; p_{EPR,d} \; f^{ns,A}_{NLA,d} TAC^{2,A}_y / \alpha^*_{ns} \qquad 5.21$$

$$Q^{3,A}_{y,d} = Q^{2,A}_{y,d} + \alpha_{ads,d} \; p_{EPR,d} \; f^{ads,A}_{NLA,d} (TAC^{3,A}_y - TAC^{2,A}_y) / \alpha^*_{ads} \qquad 5.22$$

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Pilchard bycatch allowance quotas:

$$Q_{y,d}^{1,Pbyc} = \gamma\, Q_{y,d}^{1,A} + p_{EPR,d}\, TAB_{rh}^{P} \qquad 5.23$$

$$Q_{y,d}^{2,Pbyc} = \lambda\, Q_{y,d}^{1,A} + r_y (Q_{y,d}^{2,A} - Q_{y,d}^{1,A}) + p_{EPR,d}\, TAB_{rh}^{P} \qquad 5.24$$

$$\text{where} \quad \lambda = \max\{\gamma\,;\, r_y\}$$

$$Q_{y,d}^{3,Pbyc} = Q_{y,d}^{2,Pbyc} + \alpha_{ads,d}\; p_{EPR,d}\; f_{NLA,d}^{ads,A}\; \Theta / \alpha_{ads}^{*} \qquad 5.25$$

$$\text{where} \quad \Theta = \min\{TAB_{ads}^{P}\,;\, 0.1(TAC_{y}^{3,A} - TAC_{y}^{2,A})\}$$

Once quotas are calculated for each rights holder using the ITD approach, they can be compared to the quotas for each rights holder derived by the ETD method (the β value for the ETD method was specified as 0.1375 for this comparison). Ideally, the two methods should yield similar quotas given the values of $p_{EPR,d}$, β, α_{ns} and α_{ads} calculated on the basis of the 2001 realisation of M_1. However, Figure 5.10 shows that this was initially not the case for all rights holders, which required the introduction of "non-linear adjustment" (NLA) factors, which appear in equations 5.14-25 as $f_{NLA,d}^{P}$, $f_{NLA,d}^{ns,A}$ and $f_{NLA,d}^{ads,A}$. The reason that these extra factors are needed is evident from consideration of the two trade-off curves in Figure 5.5. For OMP99, the curve is linear for the most part, which would lead to near equivalence of quotas computed by either approach. However, for M_1, the trade-off curve becomes non-linear, particularly for higher β values, as a result of the maximum constraint on the directed pilchard catch coming into play more frequently, thus necessitating the introduction of the NLA factors. Essentially the objective of these factors is to ensure that the conversion of separate proportional rights in the pilchard and anchovy fisheries to an EPR does not result in relative disadvantage for some choices of a preferred pilchard-anchovy ratio when M_1 is implemented.

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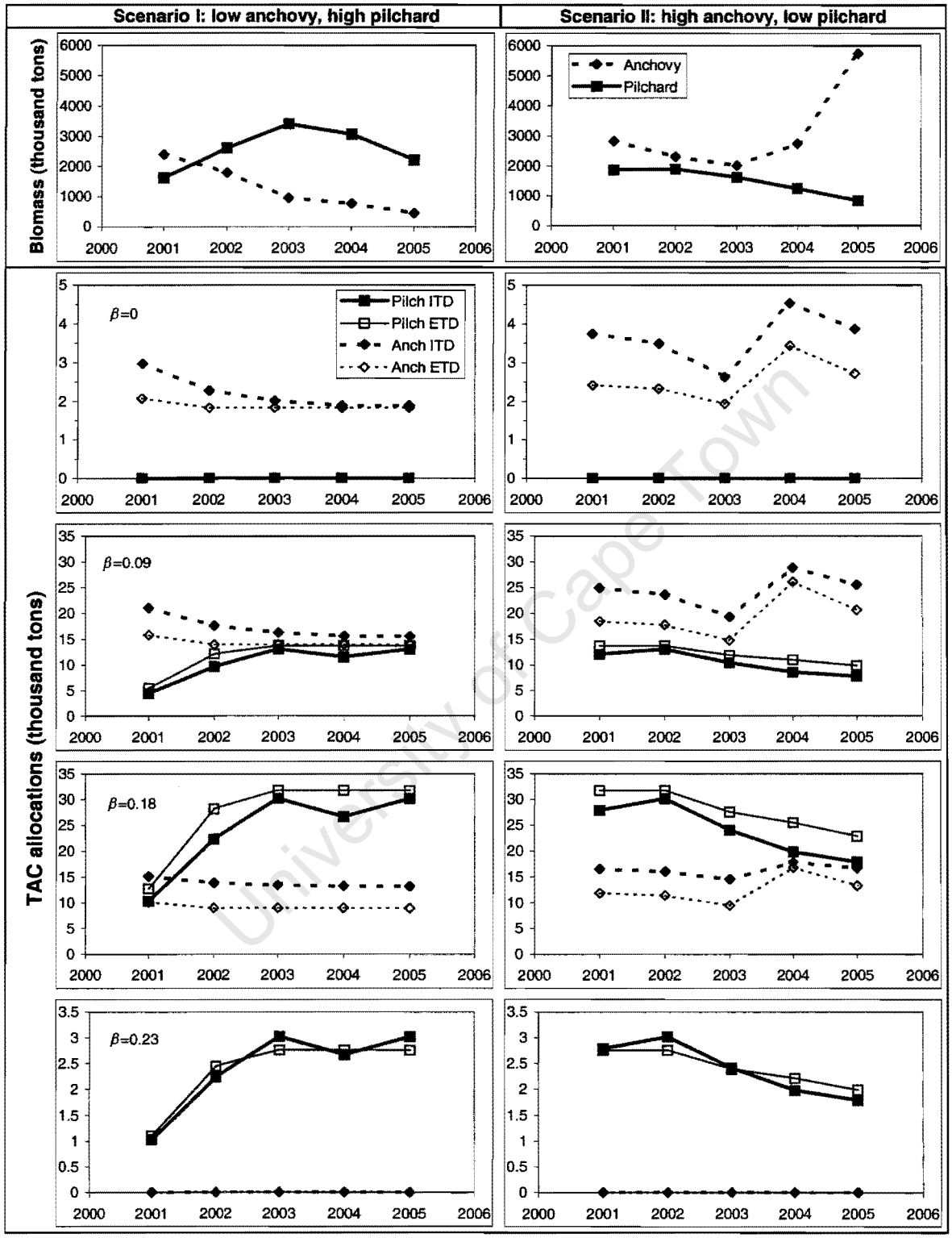
Figure 5.10 Five-year projections of TACs using two methods for allocating rights: the external trade-off decision (ETD) method and the internal trade-off decision (ITD) method. Results are shown for two possible future biomass scenarios (top panel) and four hypothetical rights holders with different percentage rights in the fishery (reflected by the different scales for the y-axes) and different trade-off selections (reflected by the β value). Non-linear adjustment (NLA) factors have not been included in this plot.



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5.6 Non-linear adjustment factors

Non-linear adjustment (NLA) factors were introduced to reduce the ITD and ETD differences evident in Figure 5.10. The NLA factors were calculated as follows:

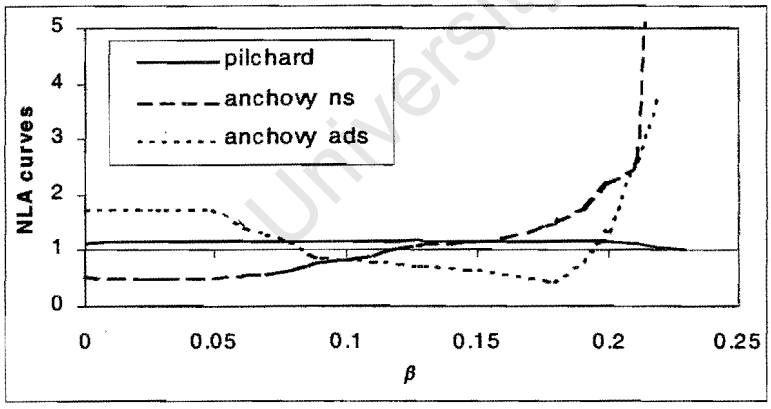
$$f^{P}_{NLA,d} = \overline{Q}^{P}_{d}(ETD) / \overline{Q}^{P}_{d}(ITD) \quad 5.26$$

$$f^{ns,A}_{NLA,d} = \overline{Q}^{2,A}_{d}(ETD) / \overline{Q}^{2,A}_{d}(ITD) \quad 5.27$$

$$f^{ads,A}_{NLA,d} = \frac{\overline{Q}^{3,A}_{d}(ETD) - \overline{Q}^{2,A}_{d}(ETD)}{\overline{Q}^{3,A}_{d}(ITD) - \overline{Q}^{2,A}_{d}(ITD)} \quad 5.28$$

where $\overline{Q}$ represents an average over simulations for the next 20 years. Figure 5.11 plots these NLA factors for a range of β values. Figure 5.12 repeats the results of Figure 5.10, but this time incorporating the NLA factors. Although quotas under the two methods (ETD and ITD) are still not absolutely identical, the differences are very small[67], and the appreciable differences for different choices by a rights holder of a pilchard:anchovy trade-off (and hence β value) shown in Figure 5.10 no longer occur with the introduction of the NLA factors.

Figure 5.11 NLA curves (equations 5.26-28) for calculations based on the M_1 curve. Similar curves were calculated for the other eight MPs considered (Table 5.2).



[67] The reason results in Figure 5.12 are not absolutely identical is that these are for two possible realisations of future pilchard and anchovy abundances only. The criteria implicit in equations 5.26-28 to define the NLAs achieve exact identity for the average over all possible future realisations.

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Figure 5.12 Results of Figure 5.10 are repeated, but this time incorporating the NLA factors.

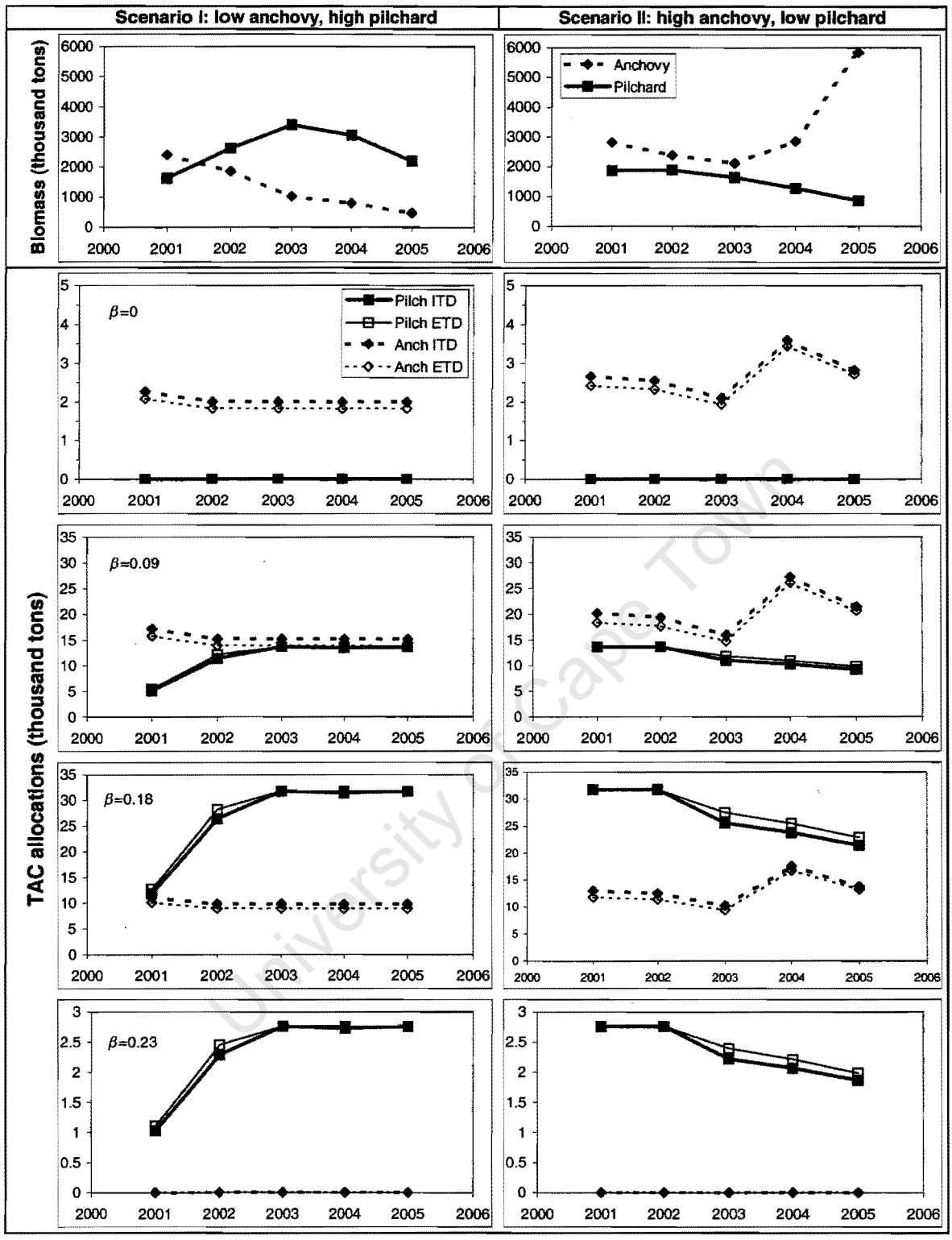

Table 5.3 repeats the results of Table 5.2, but instead of selecting a particular value of β along the M_1 curve (ETD method), the distribution of β corresponding to 2001 quota allocations shown in Figure 5.9, and the associated α_{ns} and α_{ads} values are used (ITD method). The effective values of these control parameters (equations 5.14-16) are shown in Table 5.3(a), together with the effective values for the constraints c^i_{mntac} (equations 5.17 and 5.18). The results of Table 5.3

therefore give some idea of how M_1 and the other MP candidates would perform for the fishery as a whole if trade-off selections reflected the same "choices" as implicit in the 2001 quota allocations.

Table 5.3 Results in Table 5.2 are repeated for the distribution of β values shown in Figure 5.9. NLA factors have been calculated for each MP shown. Effective values for the control parameters and minimum TAC constraints are shown in (a), and the full set of summary statistics is shown in (b). Catches are in thousand tons.

(a)

	MP variants	β^*	α^*_{ns}	α^*_{ads}	c^{P**}_{mntac}	c^{A**}_{mntac}
1	M_1	0.128	0.245	1.47	69	95
2	δ=0.7	0.129	0.259	1.44	69	96
3	$c^P_{mxdn}=0.1$	0.116	0.071	1.24	69	79
4	$c^P_{mntac}=70$	0.128	0.306	1.43	54	98
5	$c^P_{mntac}=110$	0.128	0.184	1.47	84	89
6	$c^A_{mxdn}=0.2$	0.128	0.220	1.43	69	94
7	$c^A_{mxdn}=0.4$	0.129	0.253	1.47	69	96
8	$c^A_{mntac}=100$	0.130	0.256	1.45	69	66
9	$c^A_{mntac}=200$	0.127	0.210	1.41	68	116

(b)

	MP variants	$\overline{C}^P_{dir}$	$\overline{C}^P_{byc,tot}$	$\overline{C}^A_{ns}$	$\overline{C}^A_{ads}$	$\overline{C}^A_{tot}$	$\overline{V}^P$	$\overline{V}^A_{ns}$	$\overline{V}^A_{ads}$	$depl^P_K$	$depl^P_0$	$depl^A_K$	$depl^A_0$	$risk^P_{20\%}$	$risk^P_B$	$risk^A_{15\%}$
1	M_1	164	22.8	111	95	206	0.22	0.20	0.12	0.72	0.74	0.81	0.41	0.094	0.268	0.170
2	δ=0.7	164	23.1	114	95	209	0.22	0.21	0.13	0.72	0.74	0.80	0.40	0.096	0.270	0.166
3	$c^P_{mxdn}=0.1$	172	19.8	78	95	174	0.15	0.14	0.12	0.72	0.74	0.84	0.42	0.116	0.290	0.096
4	$c^P_{mntac}=70$	163	24.0	125	94	219	0.23	0.23	0.13	0.71	0.74	0.79	0.40	0.102	0.278	0.174
5	$c^P_{mntac}=110$	165	21.5	97	95	192	0.22	0.18	0.11	0.72	0.75	0.82	0.41	0.088	0.264	0.146
6	$c^A_{mxdn}=0.2$	164	22.7	109	95	204	0.22	0.18	0.12	0.72	0.74	0.81	0.41	0.100	0.276	0.162
7	$c^A_{mxdn}=0.4$	164	22.8	112	95	207	0.22	0.21	0.12	0.72	0.74	0.81	0.41	0.092	0.268	0.168
8	$c^A_{mntac}=100$	166	21.5	100	97	197	0.22	0.29	0.10	0.73	0.75	0.82	0.41	0.088	0.262	0.108
9	$c^A_{mntac}=200$	162	24.0	122	92	214	0.23	0.13	0.16	0.71	0.73	0.80	0.40	0.096	0.280	0.186

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5.7 Robustness tests

Robustness tests were performed for only six of the nine MPs shown in Tables 5.2 and 5.3. To aid the reader, they are described in Table 5.4, which also shows the effective values for their control parameters and minimum TAC constraints. Essentially, the MPs selected for robustness testing were those that involve modifying values for the constraints on minimum TACs and the maximum % drop in TAC between years for each species, namely MP variants 1, 3, 5, 6, 7 and 9 (Table 5.3). MP variants 2, 4 and 8 were omitted from robustness tests because they were more conservative with regard to resource utilisation, and would therefore likely perform better than the other variants from a resource conservation point of view, and would therefore attract less concern in the context of robustness regarding *risk*.

Table 5.4 Description of the MPs for which robustness tests are performed. All constraints are shown, together with the effective values for the control parameters and minimum TAC constraints. Empty cells take on the value of the corresponding cells for M_1. Catch constraints are in thousand tons. Changes in constraint inputs compared to M_1 are marked in bold.

MP variant	β^*	α^*_{ns}	α^*_{ads}	δ	c^P_{mntac}	c^{P**}_{mntac}	c^A_{mntac}	c^{A**}_{mntac}	c^P_{mxtac}	c^A_{mxtac}	c^P_{mxdn}	c^A_{mxdn}	$c^{ns,A}_{mxinc}$	$c^{ads,A}_{mxinc}$
M_1	0.128	0.245	1.47	0.85	90	68.8	150	95.0	250	600	0.2	0.3	150	100
M_2	0.116	0.071	1.24			68.6		78.5			**0.1**			
M_3	0.128	0.184	1.47		**110**	83.9		88.6						
M_4	0.128	0.220	1.43			68.5		93.8				**0.2**		
M_5	0.129	0.253	1.47			69.0		96.0				**0.4**		
M_6	0.127	0.210	1.41			68.3	**200**	116.2						

Table 5.5 shows the full suite of robustness test results for M_1 in Table 5.4, with (a) describing the operating models (OMs) used in the robustness tests (Chapters 2 and 3, Appendix 5.1), and (b) showing results for all summary statistics. OMs additional to those presented in Chapters 2 and 3 are P_{13}-P_{15} and A_{13}-A_{15}. These six OMs are not based on "fits" to historical data (as are P_0-P_{12} and A_0-A_{12}), but rather on future scenarios that, although not evident within the time-range of the existing historical data, are nevertheless considered plausible[68]. These additional OMs are described below.

Increase in recruitment variability (P_{13} and A_{13}):
Based on P_0 and A_0 (Chapters 2 and 3), these OMs increase the extent of variability about the "SS" stock-recruit curve (σ^i_r [$i = P$ or A] in equation A5.1.15) by 50%. This reflects the possibility that in the future, such environmental conditions as influence recruitment could become more variable.

Total variance from surveys inversely proportional to abundance (P_{14} and A_{14}):
To account for the possibility that the total variance (sampling and additional[69]) associated with survey estimates may be inversely proportional to abundance, the following adjustments to σ^i_j ($i = P$ or A, $j = Nov$ or rec; equations A5.1.4 [and subsequent section] and A5.1.16) are made:

$$\sigma^{i*}_{Nov} = \begin{cases} \frac{1}{2}\sigma^i_{Nov}\left(1 + \bar{B}^i_N / B^i_{y,N}\right) & , B^i_{y,N} \geq \bar{B}^i_N \sigma^i_{Nov} / (10 - \sigma^i_{Nov}) \\ 5 & , B^i_{y,N} < \bar{B}^i_N \sigma^i_{Nov} / (10 - \sigma^i_{Nov}) \end{cases} \qquad 5.29$$

[68] P_{14} and A_{14} could, strictly speaking, have been investigated on the basis of historical data, but this route was not followed, as it was felt that considering these OMs in the realm of projections only was adequate to investigate their implications.

[69] Additional variances refer to λ_{Nit} in Tables 2.7 and 3.7.

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$$\sigma_{rec}^{i*} = \begin{cases} \frac{1}{4}\sigma_{rec}^{i}\left(3+\overline{N}_{r}^{i}/N_{y,r}^{i}\right) & , N_{y,r}^{i} \geq \overline{N}_{r}^{i}\sigma_{rec}^{i}/(20-3\sigma_{rec}^{i}) \\ 5 & , N_{y,r}^{i} < \overline{N}_{r}^{i}\sigma_{rec}^{i}/(20-3\sigma_{rec}^{i}) \end{cases} \quad 5.30$$

where $B_{y,N}^{i}$ are from equations A5.1.13 and A5.1.14, $N_{y,r}^{i}$ from equation A5.1.17, and $\overline{B}_{N}^{i}$ and $\overline{N}_{r}^{i}$ are the averages of $B_{y,N}^{i}$ and $N_{y,r}^{i}$ respectively, from the assessments of Chapters 2 and 3 (equations A2.1.3, A2.1.4, A3.1.4 and A3.1.5, where for the latter, $N_{y,r}^{A} = B_{y,r}^{A}/w_{y,rec}^{A}$). The difference between equations 5.29 and 5.30 reflects the fact that survey sampling error for the November surveys seems to represent a greater proportion of the overall variance than for the case of the recruit surveys.

Halving of carrying capacity (P_{15} and A_{15}):

To account for the possibility of a reduction in carrying capacity, K^i ($i = P$ or A, Table A5.1.1) is reduced linearly from the 5th year of projections, so that it is half its value from the 10th year onwards. This is to reflect the possibility of a "negative" regime shift (Chapter 7 provides a more detailed investigation of this effect, using sinusoidal curves to model regime shifts).

Table 5.5 shows results for all robustness tests, but only for M_1 because the purpose of this Table is to isolate those robustness tests that require further attention. The summary statistics that are of most concern for this purpose are the *risk* statistics. For the top panel of Table 5.5(b), $risk_{20\%}^{P}$ is analysed for all "pilchard" OMs except P_{11}, P_{12} and P_{13}, for which $risk_{B}^{P}$ is compared to the corresponding value for P_0. The reason for this is that one's perception of K changes markedly for these three OMs because of the shape of the stock recruit curve for P_{11} and P_{12}, and the halving of K for P_{13}. A statistic based on 20% of K (as $risk_{20\%}^{P}$ is) therefore makes comparison between MPs in absolute terms difficult. The use of $risk_{B}^{P}$ avoids this problem. For the bottom panel of Table 5.5(b), $risk_{15\%}^{A}$ is considered as the appropriate *risk* statistic for all "anchovy" OMs.

For pilchard, OMs P_3, P_5, P_7 and P_{13} all show $risk_{20\%}^{P}$ values larger than the threshold value of 0.1. Furthermore, P_{15} shows a markedly higher $risk_{B}^{P}$ value than P_0. For anchovy, all OMs give results within the 0.3 threshold level of $risk_{15\%}^{A}$ except for A_{13}. Nevertheless, those OMs that showed markedly higher $risk_{15\%}^{A}$ values than A_0 were also retained for further analysis. The OMs

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selected for further analysis were therefore the base case OMs P_0 and A_0, the pilchard OMs P_3, P_5, P_7, P_{13} and P_{15}, and the anchovy OMs A_1, A_6, A_{11}, A_{12}, A_{13} and A_{15}.

Table 5.5 Robustness test results for M_1. Operating Models ("OMs" – assessments of Chapters 2 and 3) are described in (a), and results for all summary statistics given in (b). Assessments P_0-P_{12} and A_0-A_{12} are detailed in Chapters 2 and 3 respectively (Tables 2.7-9 and 3.6-8). P_{13} and A_{13} increase σ_r, the extent of variability about the "SS" stock-recruit relationship (see Chapters 2 and 3) by 50%, while P_{14} and A_{14} allow for the total variances associated with survey estimates to be inversely proportional to stock abundance (equations 5.29 and 5.30). Finally, P_{15} and A_{15} allow for the halving of carrying capacity K from the 5th year to the 10th year of the projection period. Empty cells in (a) take on the value in the corresponding cells of P_0/A_0, and catches are in thousand tons.

(a)

Pilchard Operating Models (OMs)								Anchovy Operating Models (OMs)							
OM	M^P_{ad}	M^P_{ju}	k^P_N	W^P_p	λ^P_N	λ^P_r	S/R curve	OM	M^A_{ad}	M^A_{ju}	Ageing	λ^A_r	λ^A_N	k^A_g	S/R curve
P_0	0.4	0.8	1	1	est	est	SS	A_0	0.9	0.9	Prosch	est	0	1	SS
P_1	0.3														
P_2	0.5														
P_3		0.4													
P_4		1.2													
P_5	0.3		1.5												
P_6	0.5		0.5												
P_7				0											
P_8					0										
P_9						0									
P_{10}					0	0									
P_{11}							BH								
P_{12}							DS								
P_{13}							SS, 1.5 σ_r								
P_{14}					$\propto \frac{1}{B^P_{y,N}}$	$\propto \frac{1}{N^P_{y,r}}$									
P_{15}							SS, ½K								
								A_1	0.6	0.6					
								A_2	1.2	1.2					
								A_3	1.5	1.5					
								A_4		1.5					
								A_5			10.5 c/o				
								A_6	0.6	0.6	10 c/o				
								A_7	1.2	1.2	11 c/o				
								A_8				0			
								A_9					est		
								A_{10}						0.75	
								A_{11}						1.25	
								A_{12}							BH
								A_{13}							SS, 1.5 σ_r
								A_{14}				$\propto \frac{1}{N^A_{y,r}}$	$\propto \frac{1}{B^A_{y,N}}$		
								A_{15}							SS, ½K

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(b)

OM		Pilchard Summary Statistics							Anchovy Summary Statistics							
		$\overline{C}^{P}_{dir}$	$\overline{C}^{P}_{byc,tot}$	$\overline{V}^{P}$	$depl^{P}_{K}$	$depl^{P}_{0}$	$risk^{P}_{20\%}$	$risk^{P}_{B}$	$\overline{C}^{A}_{ns}$	$\overline{C}^{A}_{ads}$	$\overline{C}^{A}_{tot}$	$\overline{V}^{A}_{ns}$	$\overline{V}^{A}_{ads}$	$depl^{A}_{K}$	$depl^{A}_{0}$	$risk^{A}_{15\%}$
P_0	A_0	164	22.8	0.22	0.72	0.74	0.094	0.268	111	95	206	0.20	0.12	0.81	0.41	0.170
P_1	A_0	193	23.2	0.18	0.74	0.88	0.076	0.092	111	95	206	0.20	0.12	0.81	0.41	0.166
P_2	A_0	134	21.9	0.34	0.68	0.72	0.094	0.616	111	95	206	0.21	0.12	0.81	0.41	0.168
P_3	A_0	158	22.5	0.24	0.69	0.73	0.102	0.328	111	95	206	0.20	0.12	0.81	0.41	0.172
P_4	A_0	162	22.6	0.24	0.71	0.75	0.090	0.272	111	95	206	0.20	0.12	0.81	0.41	0.170
P_5	A_0	142	21.7	0.28	0.54	0.68	0.278	0.590	111	95	206	0.20	0.12	0.81	0.41	0.172
P_6	A_0	152	22.8	0.23	0.86	0.78	0.026	0.272	111	95	206	0.20	0.12	0.81	0.41	0.168
P_7	A_0	130	22.8	0.22	0.74	0.89	0.102	0.404	111	95	206	0.20	0.12	0.81	0.41	0.170
P_8	A_0	168	22.9	0.22	0.73	0.77	0.056	0.164	111	95	206	0.20	0.12	0.81	0.41	0.172
P_9	A_0	164	22.8	0.22	0.73	0.82	0.074	0.188	111	95	206	0.20	0.12	0.81	0.41	0.168
P_{10}	A_0	158	22.8	0.22	0.74	0.97	0.024	0.110	111	95	206	0.20	0.12	0.81	0.41	0.172
P_{11}	A_0	173	23.4	0.20	0.68	1.26	0.108	0.246	111	95	206	0.20	0.12	0.81	0.41	0.170
P_{12}	A_0	178	23.0	0.21	0.70	0.86	0.104	0.216	111	95	206	0.20	0.12	0.81	0.41	0.170
P_{13}	A_0	173	22.9	0.21	0.89	0.87	0.254	0.424	111	95	206	0.20	0.12	0.81	0.41	0.170
P_{14}	A_0	161	22.8	0.21	0.73	0.75	0.080	0.256	111	95	206	0.20	0.12	0.81	0.41	0.170
P_{15}	A_0	111	21.8	0.25	0.56	0.32	0.372	0.872	112	95	206	0.21	0.12	0.81	0.41	0.168
P_0	A_1	164	22.9	0.22	0.72	0.74	0.092	0.272	111	94	205	0.20	0.13	0.71	0.43	0.288
P_0	A_2	164	22.6	0.22	0.72	0.74	0.092	0.272	111	95	206	0.20	0.13	0.89	0.40	0.090
P_0	A_3	164	22.5	0.22	0.72	0.74	0.092	0.268	111	94	205	0.20	0.13	0.92	0.37	0.074
P_0	A_4	164	22.7	0.22	0.72	0.74	0.096	0.268	113	95	208	0.21	0.12	0.86	0.41	0.106
P_0	A_5	164	22.8	0.22	0.72	0.74	0.092	0.268	112	95	207	0.21	0.12	0.82	0.41	0.170
P_0	A_6	164	23.0	0.23	0.72	0.74	0.092	0.270	112	94	206	0.22	0.13	0.73	0.45	0.278
P_0	A_7	164	22.6	0.22	0.72	0.74	0.092	0.268	110	95	205	0.20	0.12	0.88	0.38	0.106
P_0	A_8	164	22.4	0.22	0.72	0.74	0.092	0.268	107	97	205	0.17	0.09	0.81	0.40	0.078
P_0	A_9	164	22.6	0.22	0.72	0.74	0.092	0.266	110	95	205	0.20	0.12	0.82	0.42	0.124
P_0	A_{10}	164	22.7	0.22	0.72	0.74	0.092	0.272	112	95	207	0.20	0.12	0.87	0.40	0.102
P_0	A_{11}	164	22.7	0.22	0.72	0.74	0.090	0.266	110	95	205	0.20	0.12	0.77	0.42	0.224
P_0	A_{12}	164	23.3	0.22	0.72	0.74	0.098	0.274	121	96	216	0.22	0.11	0.70	0.51	0.266
P_0	A_{13}	163	24.0	0.23	0.71	0.73	0.100	0.282	125	88	213	0.27	0.21	1.19	0.60	0.400
P_0	A_{14}	164	22.8	0.22	0.72	0.74	0.092	0.270	110	94	205	0.21	0.13	0.80	0.40	0.174
P_0	A_{15}	165	22.2	0.22	0.73	0.75	0.090	0.266	94	73	167	0.23	0.39	0.70	0.18	0.218

Table 5.6 indicates how often constraints were encountered during the 10 000 realisations (500 simulations of 20-year projections) of an MP application, with (a) showing results for the full suite of robustness tests for M_1 (associated with the results shown in Table 5.5), and (b) showing results for the base case robustness test (P_0/A_0) for M_1-M_6 (see Table 5.4). An analysis of how often constraints are encountered allows an improved understanding of how the constraints operate, and to what extent they affect the summary statistics.

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Table 5.6 Summary of the number of times (expressed as a %) that constraints are encountered during 10 000 applications (500 simulations of a 20-year projection) of a MP. (a) provides the summary for M_1 across all robustness tests, while (b) compares results for M_1-M_6 for operating model P_0/A_0. Anchovy constraints are shown for the 1st, 2nd and 3rd stage TACs where applicable. Results are also shown in the final columns for the number of times (as a %) that Exceptional Circumstance provisions are invoked, and therefore meta-rules used to modify TACs (Appendices 4.2 and 5.2).

(a) [Refer to Table 5.5(a) for a description of the OMs.]

OM		Minimum TAC				Maximum TAC				Max % drop in TAC			Max increase in anchovy TAC		Exceptional Circumstances			
		C^{P**}_{mntac}	C^{A**}_{mntac}			C^{P}_{mxtac}	C^{A}_{mxtac}			C^{P}_{mxdn}	C^{A}_{mxdn}		$C^{ns,A}_{mxinc}$	$C^{ads,A}_{mxinc}$	Pilchard	Anchovy		
			1st	2nd	3rd		1st	2nd	3rd		1st	2nd				1st	2nd	3rd
P_0	A_0	5	78	5	1	16	0	0	29	43	72	56	2	92	1	5	3	5
P_1	A_0	3	78	5	1	35	0	0	29	32	72	55	2	91	1	5	3	5
P_2	A_0	12	78	5	1	7	0	0	28	48	72	55	2	91	6	5	3	5
P_3	A_0	7	78	5	1	15	0	0	29	44	72	56	2	92	3	5	3	5
P_4	A_0	5	78	5	1	17	0	0	29	42	72	56	2	91	3	5	3	5
P_5	A_0	12	78	5	1	11	0	0	28	48	72	55	2	91	6	5	3	5
P_6	A_0	5	79	5	1	11	0	0	29	44	72	56	2	91	1	5	3	5
P_7	A_0	12	79	5	1	5	0	0	29	45	72	56	2	91	1	5	3	5
P_8	A_0	2	79	5	1	16	0	0	28	41	72	55	2	91	0	5	3	5
P_9	A_0	4	79	5	1	15	0	0	29	41	72	56	2	91	1	6	3	5
P_{10}	A_0	3	78	5	1	11	0	0	29	43	72	56	2	91	0	5	3	5
P_{11}	A_0	4	78	5	1	24	0	0	29	38	72	56	2	92	1	5	3	5
P_{12}	A_0	3	78	5	1	22	0	0	29	39	72	56	2	92	1	5	3	5
P_{13}	A_0	7	78	5	1	24	0	0	29	41	72	56	2	92	3	5	3	5
P_{14}	A_0	4	78	5	1	14	0	0	29	38	72	56	2	92	1	5	3	5
P_{15}	A_0	31	78	5	1	5	0	0	29	57	72	56	2	92	10	5	3	5
P_0	A_1	5	76	5	1	16	0	0	31	43	62	51	1	93	1	5	3	5
P_0	A_2	5	80	6	1	16	0	0	28	43	77	57	2	91	1	6	3	5
P_0	A_3	5	80	6	1	16	0	0	27	43	79	58	2	90	1	6	3	5
P_0	A_4	5	78	5	1	16	0	0	29	43	75	56	2	91	1	5	3	4
P_0	A_5	5	78	5	1	16	0	0	29	43	73	55	2	92	1	6	3	5
P_0	A_6	5	76	5	1	16	0	0	31	43	66	52	2	92	1	5	3	5
P_0	A_7	5	80	5	1	16	0	0	27	43	76	57	2	91	1	6	3	5
P_0	A_8	5	83	3	0	16	0	0	27	43	67	52	1	95	1	3	1	3
P_0	A_9	5	80	5	1	16	0	0	28	43	72	56	1	92	1	5	3	5
P_0	A_{10}	5	79	5	1	16	0	0	29	43	74	56	2	91	1	5	3	5
P_0	A_{11}	5	79	5	1	16	0	0	28	43	70	54	1	92	1	6	3	5
P_0	A_{12}	5	69	4	1	16	0	0	40	43	66	49	3	93	1	4	3	4
P_0	A_{13}	5	67	9	3	16	0	1	37	43	71	57	5	85	2	10	7	9
P_0	A_{14}	5	79	5	1	16	0	0	29	43	72	55	2	92	1	5	3	5
P_0	A_{15}	5	90	25	5	16	0	0	12	43	75	72	1	70	1	26	21	29

(b) [Refer to Table 5.4 for a description of the MP variants.]

MP	Minimum TAC				Maximum TAC				Max % drop in TAC			Max increase in anchovy TAC		Exceptional Circumstances			
	C^{P**}_{mntac}	C^{A**}_{mntac}			C^{P}_{mxtac}	C^{A}_{mxtac}			C^{P}_{mxdn}	C^{A}_{mxdn}		$C^{ns,A}_{mxinc}$	$C^{ads,A}_{mxinc}$	Pilchard	Anchovy		
		1st	2nd	3rd		1st	2nd	3rd		1st	2nd				1st	2nd	3rd
M_1	5	78	5	1	16	0	0	29	43	72	56	2	92	1	5	3	5
M_2	2	100	4	1	13	0	0	20	62	100	95	0	90	2	4	2	3
M_3	9	90	5	1	16	0	0	29	44	88	66	1	93	1	5	3	4
M_4	5	74	5	1	16	0	0	27	43	93	71	1	91	1	5	3	4
M_5	5	83	5	1	16	0	0	29	43	31	41	2	91	1	5	3	5
M_6	5	94	6	1	16	0	0	26	43	93	73	1	86	1	6	4	5

At this point, it is useful to consider constraint relations 5.2, 5.4, 5.7 and 5.10 again (where β is replaced by β^*, α_{ns} by α^*_{ns}, α_{ads} by α^*_{ads}, and c^i_{mntac} by c^{i**}_{mntac}, $i = P$ or A). In the context of these equations and how they relate to the results of Table 5.6, it is important to note that constraints are implemented in the order that they appear within the "max{}" or "min{}" operators, although the overall effect is that the constraint that is either the maximum or minimum (depending on the operator) will override the other constraints within each set of curly

parentheses. Figure 5.13 illustrates that the number of times constraints are encountered depends partly on the order in which they are implemented in equations 5.2, 5.4, 5.7 and 5.10. Even though this may change the results shown in Table 5.6, it will not affect the results in Table 5.5.

Figure 5.13 An illustration of how changing the order that constraints are applied in equations 5.2, 5.4, 5.7 and 5.10 can affect the results in Table 5.6. I, II and III refer to different possible combinations of TAC_y and $(1\text{-}c_{mxdn})TAC_{y-1}$ values, given c^{**}_{mntac}. "A" refers to applying the c^{**}_{mntac} constraint before the c_{mxdn} constraint, while "B" refers to the opposite (c_{mxdn} before c^{**}_{mntac}). The thin/thick arrows indicate that constraint c^{**}_{mntac} / c_{mxdn} has been encountered and TAC_y adjusted accordingly. [For convenience, superscripts *P/A* have been omitted.]

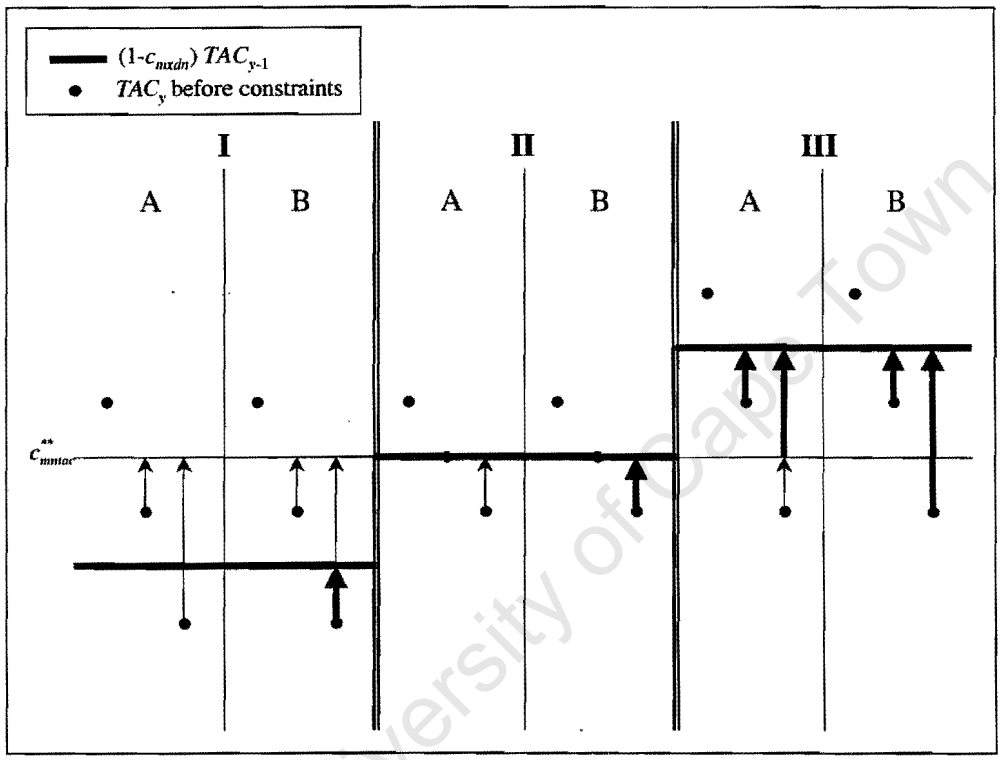

Table 5.6(a) is discussed first, with the constraints considered in broad categories, followed by a discussion of Table 5.6(b). [In order to simplify the discussion that follows, a "frequency" for a constraint refers to how often it is encountered (expressed as a percentage), not its actual value. Furthermore, superscript i (= P or A) is omitted when commenting in general, but added when referring specifically to pilchard or anchovy alone.]

"Minimum TAC" and "Max % drop in TAC" constraints

Frequencies for c^{**}_{mntac} and c_{mxdn} in Table 5.6 are derived from I-B, II-B and III-B in Figure 5.13 (c_{mxdn} is implemented before c^{**}_{mntac} in equations 5.2, 5.4, 5.7 and 5.10). Therefore, the only case where c^{**}_{mntac} is encountered is I-B, where TAC_y (before constraints are applied) is less than $(1\text{-}c_{mxdn})TAC_{y-1}$ or lies between c^{**}_{mntac} and $(1\text{-}c_{mxdn})TAC_{y-1}$. Low frequencies for c^{**}_{mntac} in

Table 5.6 coupled with high frequencies for c_{mxdn} would indicate that scenarios II-B and III-B are prevalent, and therefore that c_{mxdn} dominates (as proves to be the case for pilchard and the 2nd stage TACs for anchovy). On the other hand, high frequencies for both of these constraints (1st stage TACs for anchovy) would indicate that scenario I-B is prevalent, and therefore that c^{**}_{mntac} dominates. c^{P**}_{mntac} and the 2nd c^{A**}_{mntac} are generally low, except for the robustness test where the carrying capacity K is halved (P_{15} and A_{15} respectively). The 1st c^{A**}_{mntac} is high throughout, a consequence of the very conservative TAC formula used for anchovy at the start of the season (see equation 5.3). c_{mxdn} is high for both species, indicating the important role of this constraint when evaluating TACs. A further point to note is that, because the constraint $TAC^{2,a}_y \geq TAC^{1,a}_y$ is implemented before c^{A**}_{mntac} (equation 5.7), one might expect the latter to have a zero frequency for the 2nd stage TAC – however, this doesn't happen because Exceptional Circumstances are sometimes brought into play for the 1st stage TAC, and these could (though not always) cause this TAC to drop below c^{A**}_{mntac}.

"Maximum TAC"

c^{P}_{mxtac} occurs with a frequency of around 15% in most cases, with higher values occurring when adult natural mortality for pilchard is lower (P_1), a different shape for the stock-recruit curve is used (P_{11} and P_{12}), or greater variability around this curve is assumed (P_{13}). Low values are encountered when adult natural mortality is higher (P_2), the proportion-at-age data are omitted (P_7), and K is halved (P_{15}).

c^{A}_{mxtac} is hardly ever encountered, except for the 3rd stage TAC (frequency of 12-40%), which is not surprising for this TAC because it aims for better utilisation of the anchovy stock.

"Max increase in anchovy TAC"

It is perhaps surprising that the frequency of $c^{ns,A}_{mxinc}$ is low, which indicates further scrutiny. This constraint is encountered when $TAC^{2,A}_y$ (before constraints) $> TAC^{1,A}_y + c^{ns,A}_{mxinc}$. Substituting 150 for $c^{ns,A}_{mxinc}$ and 0.85 for δ, this inequality can be re-cast in terms of $N^{A}_{y,rec0}$, using equations 5.3 and 5.6, as follows:

$$N^{A}_{y,rec0} > \omega \, \overline{N}^{A}_{y,rec0}$$

$$\text{where } \omega = 0.85 + 0.786(B^{A}_{y,Nov} / \overline{B}^{A}_{Nov}) + 1/(1.4\alpha_{ns}) \qquad 5.31$$

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Table 5.7 calculates ω, given different values for $B^A_{y,Nov} / \overline{B}^A_{Nov}$ and α_{ns} in the above equation. Results indicate that, for the values of α_{ns} associated with MPs M_1-M_6 (Table 5.4), and for a wide range of $B^A_{y,Nov} / \overline{B}^A_{Nov}$ values (from ¼ to 4), $N^A_{y,rec0}$ will have to exceed $\overline{N}^A_{y,rec0}$ by at least a multiplicative factor of 3.9 before the $c^{ns,A}_{mxinc}$ constraint is encountered, which explains why this constraint is encountered fairly infrequently.

At the other extreme, $c^{ads,A}_{mxinc}$ occurs over 90% of the time (except when K^A is halved, when this figure drops to 70%), once again emphasising the under-utilisation of anchovy in the normal season under these MPs.

Table 5.7 Results for ω in equation 5.31, given values for $B^A_{y,Nov} / \overline{B}^A_{Nov}$ and α_{ns}. The values for α_{ns} are taken from Table 5.4.

		$B^A_{y,Nov} / \overline{B}^A_{Nov}$				
		0.25	0.5	1	2	4
α_{ns}	0.071 (M_2)	11.1	11.3	11.7	12.5	14.1
	0.184 (M_3)	4.9	5.1	5.5	6.3	7.9
	0.210 (M_6)	4.4	4.6	5.0	5.8	7.4
	0.220 (M_4)	4.3	4.5	4.9	5.7	7.2
	0.245 (M_1)	4.0	4.2	4.6	5.3	6.9
	0.253 (M_5)	3.9	4.1	4.5	5.2	6.8

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"Exceptional Circumstances"

Exceptional Circumstances (Appendix 5.2) occur with a frequency of less than 10% in most cases, only reaching or exceeding this level when K is halved for both species (P_{15} and A_{15}), and when variability around the stock-recruit curve is increased for anchovy (A_{13}). The link between Exceptional Circumstances on the 1st stage TAC and c^{A**}_{mntac} on the 2nd stage TAC for anchovy has already been alluded to in the section '*"Minimum TAC" and "Max % drop in TAC" constraints*' above.

Table 5.6(b) shows similar patterns to Table 5.6(a) when other MP variants are considered (tested under OMs P_0 and A_0), but marked differences between the MP variants do occur for c_{mxdn} and, to a lesser extent, c^{**}_{mntac} (the differences being more acute for anchovy than pilchard in absolute terms). These differences are largely due to the changes in the control parameters (β^*, α^*_{ns} and α^*_{ads}) as a result of the changes to the constraints that are input and the associated c^{**}_{mntac} values (Table 5.4). For example, a decrease in c^P_{mxdn} (M_2 in Table 5.4) causes this constraint to be

invoked more frequently (Table 5.6(b)), but also causes 100% occurrences of c^{A}_{mxdn} and c^{A**}_{mntac} because of the drop in α^{*}_{ns} associated with M_2 (Table 5.4). This is because situation I-B illustrated in Figure 5.13 applies (see discussion in the section '*"Minimum TAC" and "Max % drop in TAC" constraints*' above), and with such a low α^{*}_{ns} value, the lowest TAC_y value for I-B will always occur (Figure 5.13), and hence both constraints c^{A}_{mxdn} and c^{A**}_{mntac} will always be encountered.

In Table 5.6, the frequency of c^{A}_{mxdn} is higher for the 1st stage TAC than the 2nd in all cases but M_5, the MP variant where c^{A}_{mxdn} is increased to 0.4 compared to M_1. An explanation for this can be found by plotting frequency distributions for the quantities $TAC^{1,A}_{y} / [(1-c^{A}_{mxdn})TAC^{2,A}_{y-1}]$ and $TAC^{2,A}_{y} / [(1-c^{A}_{mxdn})TAC^{2,A}_{y-1}]$ before constraints are applied (see equations 5.4 and 5.7), shown in Figure 5.14. The omission of δ shifts the latter distribution to the left, but the introduction of the recruitment estimate (compared to assuming it is average) causes this distribution to widen and have longer tails on both ends (compare equations 5.3 and 5.6, and the two curves in Figure 5.14). A value of less than 1 for the above quantities means that the c^{A}_{mxdn} constraint is encountered – the lower the value of the denominator (i.e. the higher the value of c^{A}_{mxdn}) the more towards the left of the frequency distributions of the above quantities a value of 1 will occur. Because the frequency distribution of the second quantity has a longer tail, it will have a higher cumulative frequency to start with, hence the reason for a higher frequency of c^{A}_{mxdn} for the 2nd stage TAC compared to the 1st for M_5.

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Figure 5.14 Frequency distributions for the fractions $TAC_y^{1,A}/[(1-c_{mxdn}^A)TAC_{y-1}^{2,A}]$ and $TAC_y^{2,A}/[(1-c_{mxdn}^A)TAC_{y-1}^{2,A}]$ for the first and second stage anchovy TACs before constraints are applied, as associated with the results for M_5 in Table 5.6(b).

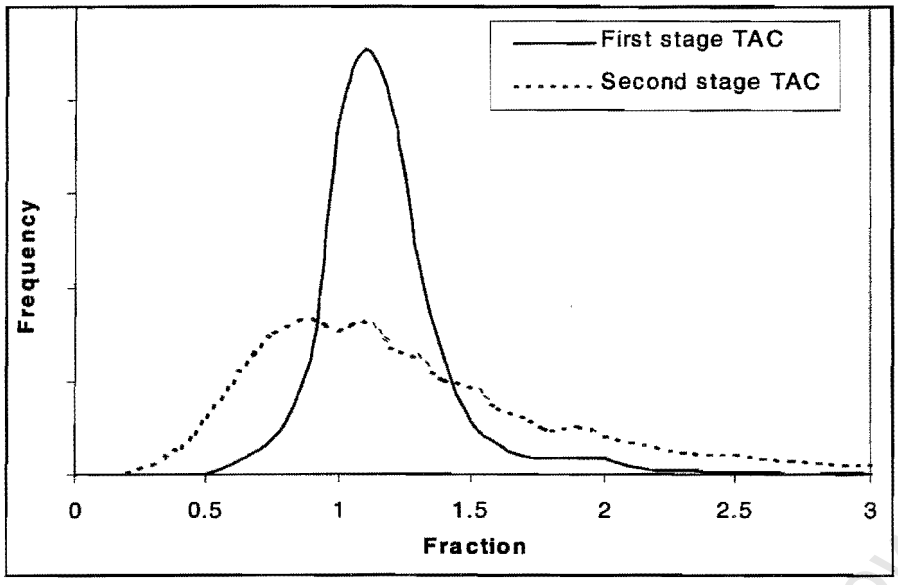

Table 5.8 shows results for a reduced set of robustness tests and summary statistics for M_1-M_6. Furthermore, Figure 5.15 provides a visual summary of the full set of robustness test results for these MP variants for a selection of summary statistics, indicating median values together with 90% probability intervals (where appropriate). In Figure 5.15, (a) shows the pilchard robustness tests, and (b) those for anchovy. Because the material presented in Table 5.8 and Figure 5.15 is necessarily complex, it is easier to first consider the plots shown in Figure 5.15 to get an overall impression of the results, and then if necessary refer back to Table 5.8 for the details.

Comparisons in Figure 5.15 should be made between MP variants within each plot, so that their performance relative to one another, given a particular robustness test, can be compared for each summary statistic. Comparisons of summary statistics are not made between robustness tests, and therefore the scales on the y-axes are specific to each plot and no attempt is made to standardise these axes.

Figure 5.15 shows that M_2 and M_3 perform poorly in terms of average anchovy catch, relative to the other MP variants. However, performance in terms of average pilchard catch is similar throughout for all the MPs. The lower average anchovy catch for M_2 is coupled with a lower anchovy risk and lower pilchard and anchovy catch variability, but is also associated with a higher pilchard risk (both types) than the other MPs. M_2 was therefore rejected. M_3 was similarly rejected, even though it offered better risk levels for pilchard compared to the other MPs, because of the lower average anchovy catch, particularly as the decrease in the average came

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almost exclusively from the normal anchovy season (compare Tables 5.8(a) and (c)). The Industry would much rather prefer to have more anchovy catch during the normal season.

M_6 performs poorly in terms of both $risk^A_{15\%}$ and $risk^P_B$, exceeding the threshold level of 0.3 for the former for OMs A_1 and A_6, whereas for these OMs, the other MPs managed to stay below this threshold. M_6 was therefore rejected. M_4 was also rejected because of the relatively poor $risk^P_B$ values in some cases (it often performed third worst in terms of this statistic, and in one instance [P_6] performed worse than any other MP).

Although there is little to choose between M_1 and M_5, the one sometimes outperforming the other in terms of $risk^P_B$ (e.g. compare OMs P_1 and P_{13}), the former was preferred because it yielded less variable average anchovy catches (Figure 5.15) without sacrificing too much pilchard or anchovy catch on average (compare Tables 5.8(a) and (e)). M_1 was therefore accepted and implemented as OMP02.

Chapter 6 discusses the implementation of OMP02 and certain problems encountered.

Table 5.8 Results for Table 5.5 are repeated here for M_1-M_6 ((a)-(f) respectively) but for a selection of OMs and summary statistics. Empty cells take on the value of the corresponding cells for P_0/A_0, and catches are in thousand tons.

(a) M_1

OM		Pilchard Operating Models (OMs)					Anchovy Operating Models (OMs)					Pilchard			Anchovy		
		M^P_{ad}	M^P_{ju}	k^P_N	W^P_p	S/R curve	M^A_{ad}	M^A_{ju}	Ageing	k^A_g	S/R curve	$\overline{C}^P_{dir}$	$risk^P_{20\%}$	$risk^P_B$	$\overline{C}^A_{ns}$	$\overline{C}^A_{tot}$	$risk^A_{15\%}$
P_0	A_0	0.4	0.8	1.5	1	SS	0.9	0.9	Prosch	1	SS	164	0.094	0.268	111	206	0.170
P_3	A_0		0.4									158	0.102	0.328	111	206	0.172
P_5	A_0	0.3		2								142	0.278	0.590	111	206	0.172
P_7	A_0				0							130	0.102	0.404	111	206	0.170
P_{13}	A_0					SS, 1.5 σ_r						173	0.254	0.424	111	206	0.170
P_{15}	A_0					SS, ½K						111	0.372	0.872	112	206	0.168
P_0	A_1						0.6	0.6				164	0.092	0.272	111	205	0.288
P_0	A_6						0.6	0.6	10 c/o			164	0.092	0.270	112	206	0.278
P_0	A_{11}									1.25		164	0.090	0.266	110	205	0.224
P_0	A_{12}										BH	164	0.098	0.274	121	216	0.266
P_0	A_{13}										SS, 1.5 σ_r	163	0.100	0.282	125	213	0.400
P_0	A_{15}										SS, ½K	165	0.090	0.266	94	167	0.218

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(b) M_2 [c^P_{mxdn} = 0.1 instead of 0.2]

OM		Pilchard Operating Models (OMs)					Anchovy Operating Models (OMs)					Pilchard			Anchovy		
		M^P_{ad}	M^P_{ju}	k^P_N	W^P_p	S/R curve	M^A_{ad}	M^A_{ju}	Ageing	k^A_g	S/R curve	$\overline{C}^P_{dir}$	$risk^P_{20\%}$	$risk^P_B$	$\overline{C}^A_{ns}$	$\overline{C}^A_{tot}$	$risk^A_{15\%}$
P_0	A_0	0.4	0.8	1.5	1	SS	0.9	0.9	Prosch	1	SS	172	0.116	0.290	78	174	0.096
P_3	A_0		0.4									166	0.114	0.340	78	173	0.104
P_5	A_0	0.3		2								150	0.290	0.628	78	173	0.100
P_7	A_0				0							135	0.112	0.418	78	174	0.092
P_{13}	A_0					SS, 1.5 σ_r						180	0.296	0.436	78	174	0.096
P_{15}	A_0					SS, ½K						118	0.438	0.888	78	174	0.096
P_0	A_1						0.6	0.6				172	0.116	0.288	78	173	0.210
P_0	A_6						0.6	0.6	10 c/o			172	0.116	0.288	78	173	0.196
P_0	A_{11}									1.25		172	0.116	0.290	78	174	0.146
P_0	A_{12}										BH	172	0.116	0.290	79	175	0.192
P_0	A_{13}										SS, 1.5 σ_r	172	0.116	0.292	79	168	0.336
P_0	A_{15}										SS, ½K	172	0.110	0.292	74	149	0.154

(c) M_3 [c^P_{mnlac} = 110 instead of 90]

OM		Pilchard Operating Models (OMs)					Anchovy Operating Models (OMs)					Pilchard			Anchovy		
		M^P_{ad}	M^P_{ju}	k^P_N	W^P_p	S/R curve	M^A_{od}	M^A_{ju}	Ageing	k^A_g	S/R curve	$\overline{C}^P_{dir}$	$risk^P_{20\%}$	$risk^P_B$	$\overline{C}^A_{ns}$	$\overline{C}^A_{tot}$	$risk^A_{15\%}$
P_0	A_0	0.4	0.8	1.5	1	SS	0.9	0.9	Prosch	1	SS	165	0.088	0.264	97	192	0.146
P_3	A_0		0.4									160	0.100	0.308	97	192	0.154
P_5	A_0	0.3		2								144	0.268	0.572	97	192	0.152
P_7	A_0				0							132	0.102	0.402	97	192	0.148
P_{13}	A_0					SS, 1.5 σ_r						174	0.244	0.412	97	192	0.146
P_{15}	A_0					SS, ½K						115	0.388	0.870	97	192	0.144
P_0	A_1						0.6	0.6				165	0.090	0.258	96	191	0.264
P_0	A_6						0.6	0.6	10 c/o			165	0.090	0.260	97	191	0.262
P_0	A_{11}									1.25		165	0.086	0.264	96	191	0.206
P_0	A_{12}										BH	165	0.090	0.266	103	199	0.240
P_0	A_{13}										SS, 1.5 σ_r	165	0.100	0.266	107	196	0.384
P_0	A_{15}										SS, ½K	166	0.084	0.256	85	160	0.190

(d) M_4 [c^A_{mxdn} = 0.2 instead of 0.3]

OM		Pilchard Operating Models (OMs)					Anchovy Operating Models (OMs)					Pilchard			Anchovy		
		M^P_{ad}	M^P_{ju}	k^P_N	W^P_p	S/R curve	M^A_{ad}	M^A_{ju}	Ageing	k^A_g	S/R curve	$\overline{C}^P_{dir}$	$risk^P_{20\%}$	$risk^P_B$	$\overline{C}^A_{ns}$	$\overline{C}^A_{tot}$	$risk^A_{15\%}$
P_0	A_0	0.4	0.8	1.5	1	SS	0.9	0.9	Prosch	1	SS	164	0.100	0.276	109	204	0.162
P_3	A_0		0.4									158	0.108	0.324	109	204	0.162
P_5	A_0	0.3		2								142	0.276	0.594	109	204	0.156
P_7	A_0				0							129	0.104	0.406	109	204	0.156
P_{13}	A_0					SS, 1.5 σ_r						173	0.256	0.422	109	204	0.162
P_{15}	A_0					SS, ½K						111	0.376	0.870	109	204	0.162
P_0	A_1						0.6	0.6				164	0.092	0.272	108	202	0.286
P_0	A_6						0.6	0.6	10 c/o			164	0.096	0.272	109	203	0.278
P_0	A_{11}									1.25		164	0.094	0.270	108	203	0.216
P_0	A_{12}										BH	164	0.102	0.280	118	214	0.258
P_0	A_{13}										SS, 1.5 σ_r	163	0.112	0.290	125	212	0.402
P_0	A_{15}										SS, ½K	165	0.088	0.268	92	165	0.216

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(e) M_5 [c^A_{mxdh} = 0.4 instead of 0.3]

OM		Pilchard Operating Models (OMs)					Anchovy Operating Models (OMs)					Pilchard			Anchovy		
		M^P_{ad}	M^P_{ju}	k^P_N	W^P_p	S/R curve	M^A_{ad}	M^A_{ju}	Ageing	k^A_g	S/R curve	$\overline{C}^P_{dir}$	$risk^P_{20\%}$	$risk^P_B$	$\overline{C}^A_{ns}$	$\overline{C}^A_{tot}$	$risk^A_{15\%}$
P_0	A_0	0.4	0.8	1.5	1	SS	0.9	0.9	Prosch	1	SS	164	0.092	0.268	112	207	0.168
P_3	A_0		0.4									158	0.102	0.326	112	207	0.174
P_5	A_0	0.3		2								142	0.274	0.594	112	206	0.170
P_7	A_0				0							130	0.104	0.406	112	206	0.168
P_{13}	A_0					SS, 1.5 σ_r						173	0.252	0.428	112	207	0.168
P_{15}	A_0					SS, ½K						111	0.368	0.872	112	207	0.166
P_0	A_1						0.6	0.6				164	0.092	0.270	112	206	0.290
P_0	A_6						0.6	0.6	10 c/o			164	0.092	0.268	112	206	0.278
P_0	A_{11}									1.25		164	0.090	0.266	111	205	0.226
P_0	A_{12}										BH	164	0.092	0.270	121	216	0.266
P_0	A_{13}										SS, 1.5 σ_r	164	0.098	0.272	124	212	0.398
P_0	A_{15}										SS, ½K	165	0.090	0.268	95	168	0.218

(f) M_6 [c^A_{mntac} = 200 instead of 100]

OM		Pilchard Operating Models (OMs)					Anchovy Operating Models (OMs)					Pilchard			Anchovy		
		M^P_{ad}	M^P_{ju}	k^P_N	W^P_p	S/R curve	M^A_{ad}	M^A_{ju}	Ageing	k^A_g	S/R curve	$\overline{C}^P_{dir}$	$risk^P_{20\%}$	$risk^P_B$	$\overline{C}^A_{ns}$	$\overline{C}^A_{tot}$	$risk^A_{15\%}$
P_0	A_0	0.4	0.8	1.5	1	SS	0.9	0.9	Prosch	1	SS	162	0.096	0.280	122	214	0.186
P_3	A_0		0.4									156	0.108	0.344	122	214	0.188
P_5	A_0	0.3		2								139	0.302	0.626	122	214	0.188
P_7	A_0				0							128	0.126	0.420	122	214	0.196
P_{13}	A_0					SS, 1.5 σ_r						171	0.264	0.440	122	214	0.188
P_{15}	A_0					SS, ½K						109	0.406	0.878	122	214	0.182
P_0	A_1						0.6	0.6				162	0.096	0.280	120	212	0.322
P_0	A_6						0.6	0.6	10 c/o			162	0.096	0.282	121	213	0.318
P_0	A_{11}									1.25		162	0.096	0.278	121	213	0.238
P_0	A_{12}										BH	162	0.096	0.282	127	220	0.304
P_0	A_{13}										SS, 1.5 σ_r	162	0.108	0.286	130	215	0.424
P_0	A_{15}										SS, ½K	163	0.092	0.278	108	176	0.270

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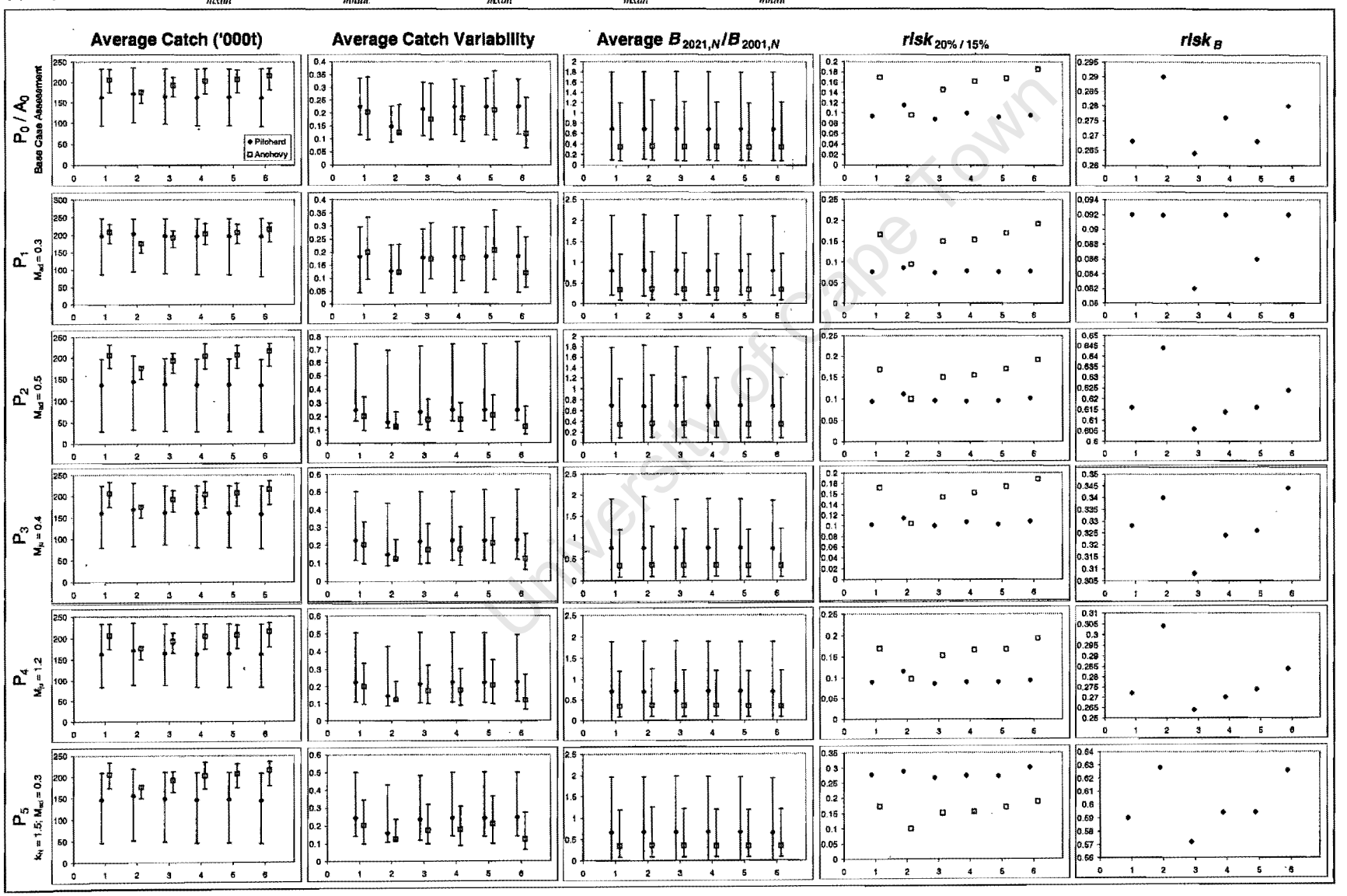
Figure 5.15 Visual summary of the full suite of robustness tests described in Table 5.5(a) for a selection of MPs, M_1-M_6, described in the "Management procedure" legend. Each row is associated with a pilchard (a) or anchovy (b) robustness test; only those factors that are different to those for the default tests, P_0 and A_0, are shown, but the first row always repeats the P_0/A_0 test results for comparison. Each column of plots depicts results for a particular summary statistic, as indicated.

(a) M_1: base case; M_2: $c^P_{mxdn} = 0.1$; M_3: $c^P_{mnac} = 110$; M_4: $c^A_{mxdn} = 0.2$; M_5: $c^A_{mxdn} = 0.4$; M_6: $c^A_{mnac} = 200$.



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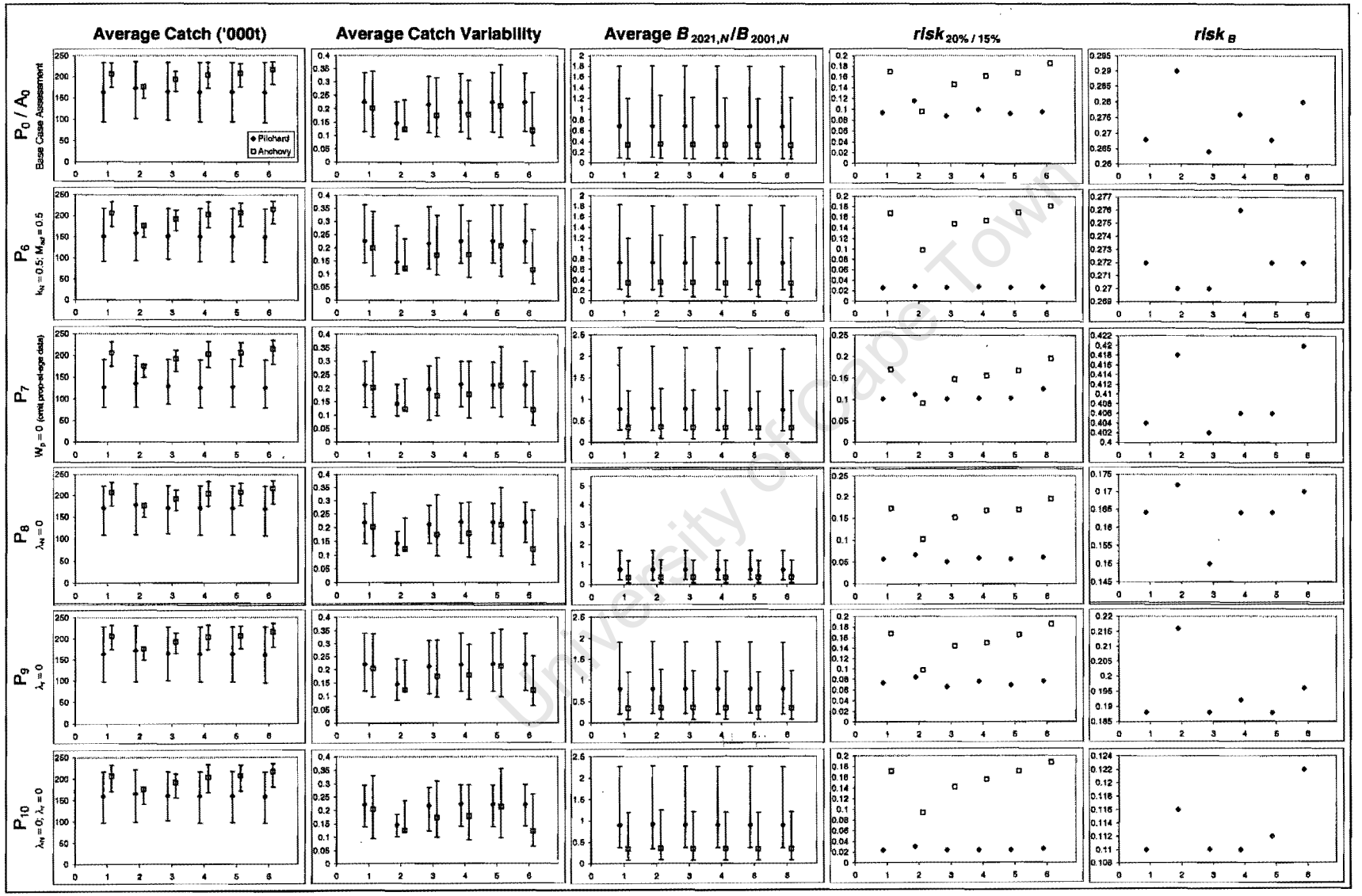
(a) continued $\mathbf{M_1}$: base case; $\mathbf{M_2}$: $c^{P}_{mxdh} = 0.1$; $\mathbf{M_3}$: $c^{P}_{mmac} = 110$; $\mathbf{M_4}$: $c^{A}_{mxdh} = 0.2$; $\mathbf{M_5}$: $c^{A}_{mxdh} = 0.4$; $\mathbf{M_6}$: $c^{A}_{mmac} = 200$.



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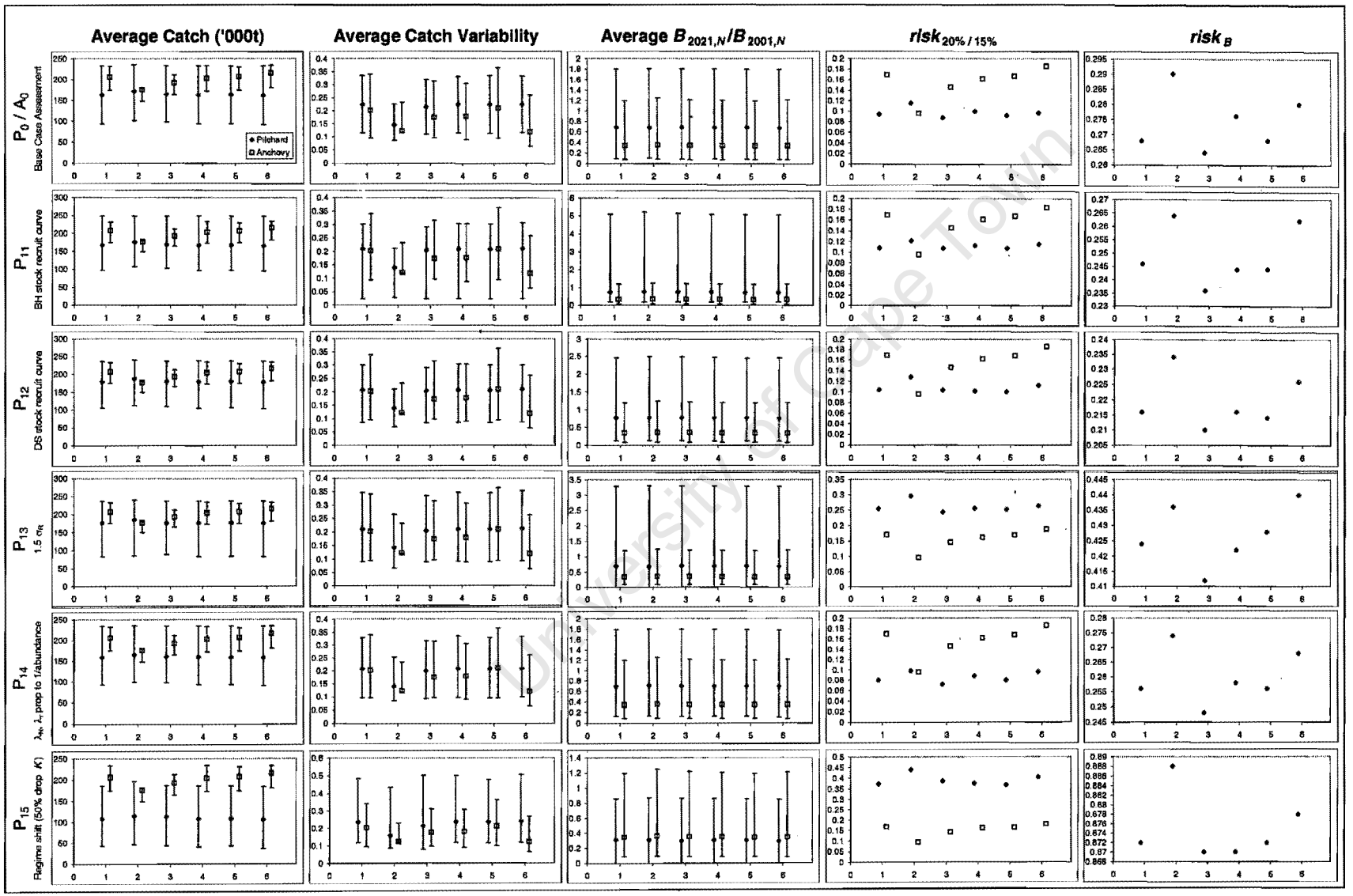
(a) continued $\mathbf{M_1}$: base case; $\mathbf{M_2}$: $c^{P}_{mxdn} = 0.1$; $\mathbf{M_3}$: $c^{P}_{mntac} = 110$; $\mathbf{M_4}$: $c^{A}_{mxdn} = 0.2$; $\mathbf{M_5}$: $c^{A}_{mxdn} = 0.4$; $\mathbf{M_6}$: $c^{A}_{mntac} = 200$.



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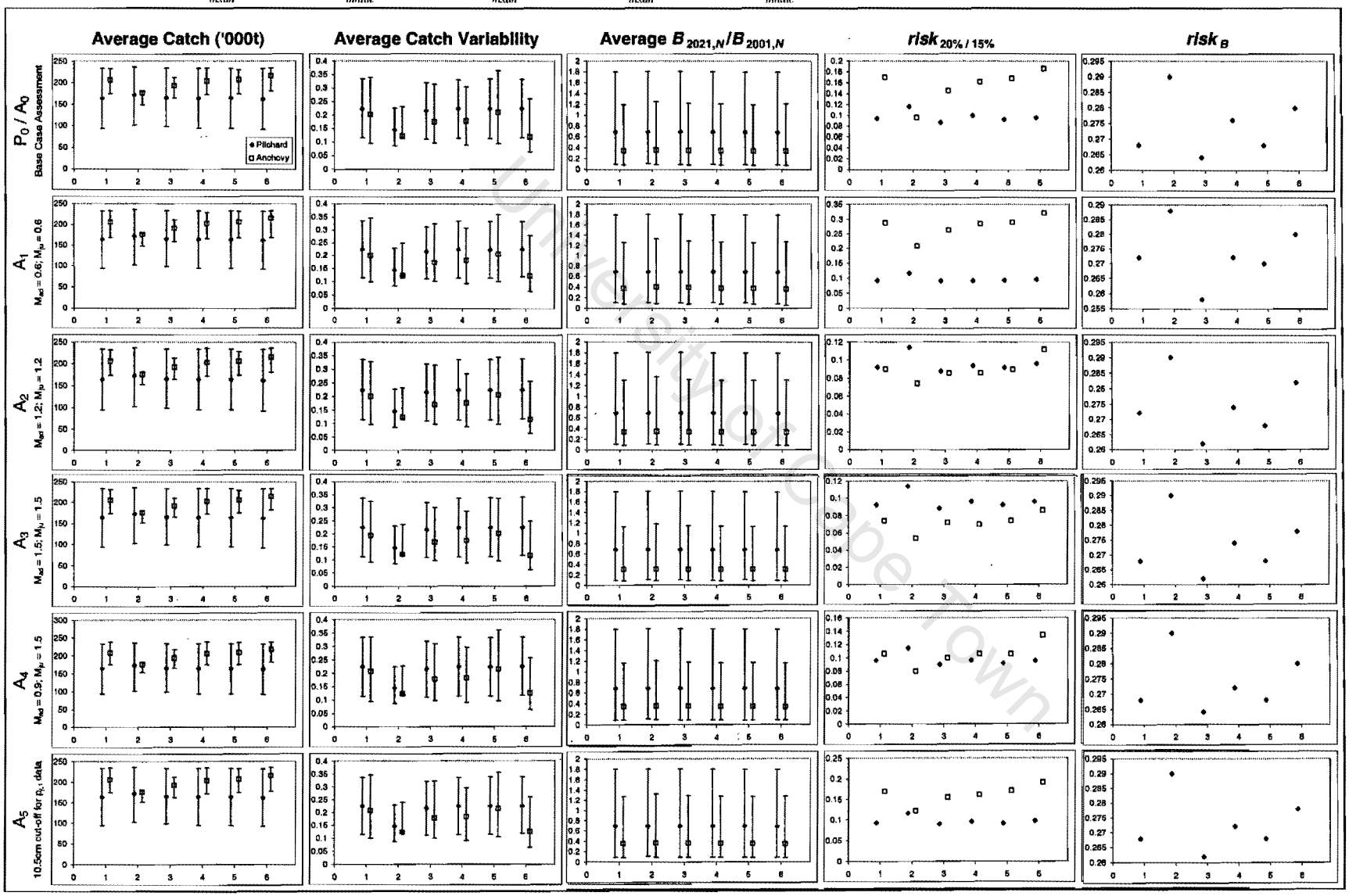
(b) M_1: base case; M_2: $c^{P}_{mxdn} = 0.1$; M_3: $c^{P}_{mntac} = 110$; M_4: $c^{A}_{mxdn} = 0.2$; M_5: $c^{A}_{mxdn} = 0.4$; M_6: $c^{A}_{mntac} = 200$.



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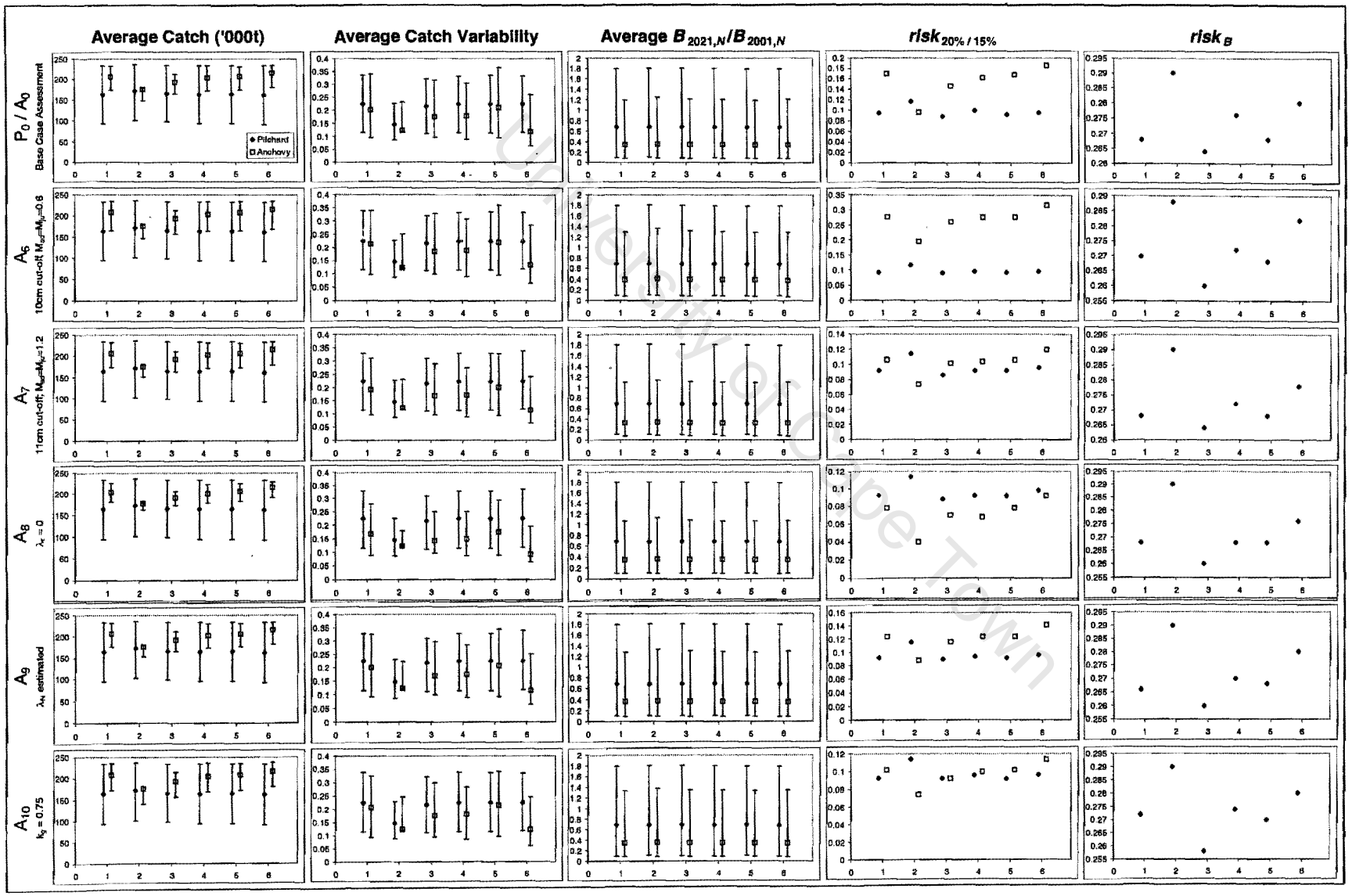
(b) continued. $\mathbf{M_1}$: base case; $\mathbf{M_2}$: $c^{P}_{mxdh} = 0.1$; $\mathbf{M_3}$: $c^{P}_{mntac} = 110$; $\mathbf{M_4}$: $c^{A}_{mxdh} = 0.2$; $\mathbf{M_5}$: $c^{A}_{mxdh} = 0.4$; $\mathbf{M_6}$: $c^{A}_{mntac} = 200$.



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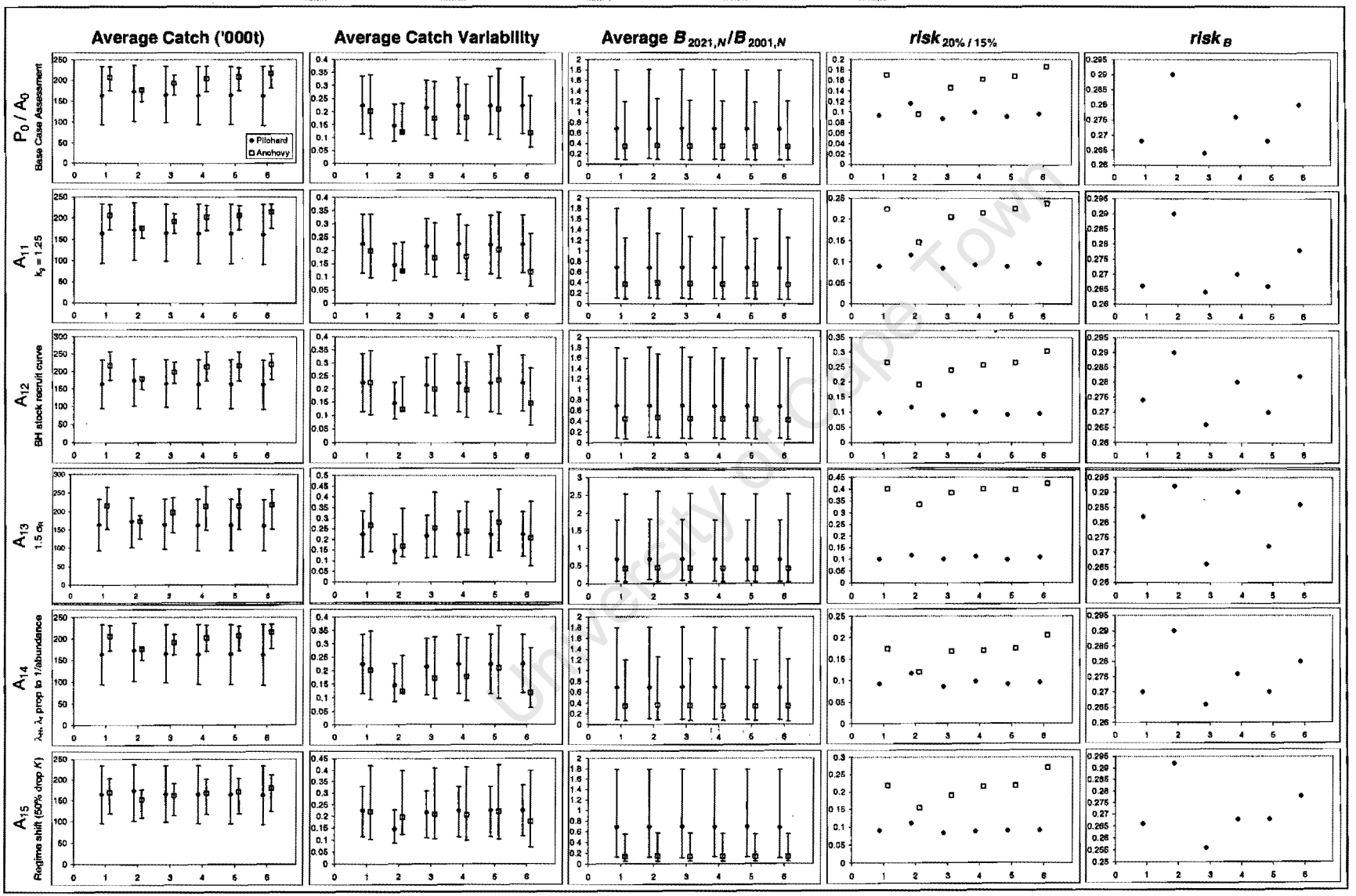
(b) continued. M_1: base case; M_2: $c^{P}_{mxdh} = 0.1$; M_3: $c^{P}_{mntac} = 110$; M_4: $c^{A}_{mxdh} = 0.2$; M_5: $c^{A}_{mxdh} = 0.4$; M_6: $c^{A}_{mntac} = 200$.



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APPENDIX 5.1

Framework for testing alternative MPs

The framework used to test alternative MPs consists of four components (Figure A5.1.1). These are:

- the assessment procedure that provides estimates of population parameters,
- the operating model that reflects possible "true" underlying dynamics of the resource and is based upon the parameters estimated by the assessment procedure,
- the MP itself, with its decision rules and constraints (these rules and constraints involve no exact knowledge of the actual underlying dynamics, and have to be applied to data of the type and subject to the errors to be expected in practice), and
- the summary performance statistics.

The MP and summary statistics are discussed in the main text of Chapter 5, while the operating model is described below. Estimates from the assessment procedures are reported in Chapters 2 and 3, and are briefly described below.

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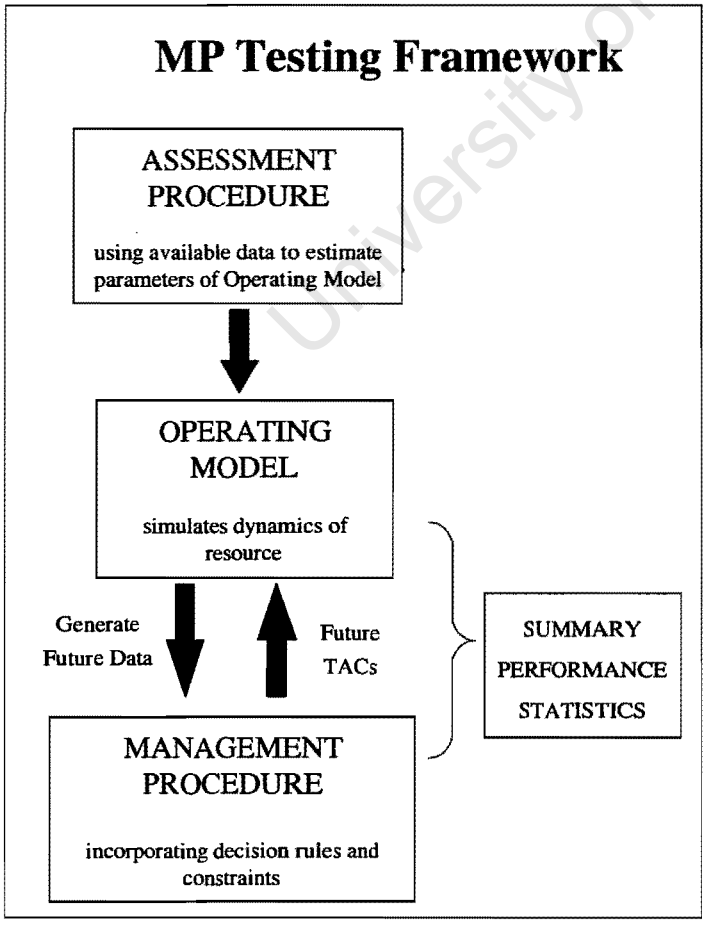
Figure A5.1.1 A simplified version of the MP testing framework presented in Chapter 4 (Figure 4.3), as it is currently used for developing MPs to be applied in the pilchard-anchovy fishery.



The Assessment Procedure

The assessment procedures used for pilchard and anchovy are discussed in detail in Chapters 2 and 3 respectively. Table A5.1.1 provides a brief description of the parameters, estimated from or specified for these assessments, that are then used in the operating models utilised for MP testing.

Table A5.1.1 Description of parameters estimated from or specified for the assessments of Chapters 2 and 3, which are used in the operating models for MP testing, together with a list of where estimates/values for these parameters can be found.

Parameters	Description	Source
M^P_{ad}, M^P_{ju}	Natural mortality of adult and juvenile pilchard (per year)	Table 2.7
M^A_{ad}, M^A_{ju}	Natural mortality of adult and juvenile anchovy (per year)	Table 3.6
k^P_N, k^A_N	The constant of proportionality between the assessment and November survey estimates of adult biomass for pilchard and anchovy (the value for pilchard is assumed)	Tables 2.7 and 3.7 respectively
k^P_r, k^A_r	The constant of proportionality between the assessment and recruit survey estimates of recruitment for pilchard and anchovy	Tables 2.7 and 3.7 respectively
$N^P_{2000,a}$, $a = 1,\ldots,5$	Pilchard numbers-at-age at the beginning of 2000 (billions of fish)	Table 2.8
$N^A_{2001,a}$, $a = 1,\ldots,4$	Anchovy numbers-at-age at the beginning of 2001 (billions of fish)	Table 3.7
S^P_a , $a = 1,\ldots,4$	Selectivities-at-age for pilchard	Table 2.8
$\eta^P_{1999}, \eta^A_{2000}$	The error component of stock-recruit relationship in 1999 for pilchard and 2000 for anchovy	Tables 2.9 and 3.8 respectively
s^P_{cor}, s^A_{cor}	The serial correlation in recruitment associated with the stock-recruit relationship for pilchard and for anchovy	Tables 2.9 and 3.8 respectively
σ^P_r, σ^A_r	Standard deviation of residuals about the log of the stock-recruit relationship for pilchard and anchovy recruitment	Tables 2.9 and 3.8 respectively
K^P, a^P, b^P, m^P	Parameters associated with the stock recruit curve for pilchard, where K^P (thousand tons) is the average adult pilchard biomass in the absence of exploitation	Table 2.9
K^A, a^A, b^A	Parameters associated with the stock recruit curve for anchovy, where K^A (thousand tons) is the average adult anchovy biomass in the absence of exploitation	Table 3.8
$\overline{w}^P_{ac}$, $a = 0,\ldots,4$	Mean mass-at-age for pilchard in the commercial catches (g)	Table A2.2.2
$\overline{w}^A_{ac}$, $a = 0, 1$	Mean mass-at-age for anchovy in the commercial catches (g)	Table A3.2.1
$\overline{w}^P_a$, $a = 1,\ldots,5$	Mean mass-at-age for pilchard at the beginning of the year (g)	Table A2.2.3
$\overline{w}^A_a$, $a = 1,\ldots,4$	Mean mass-at-age for anchovy at the beginning of the year (g)	Table A3.2.2
$\overline{w}^P_{0cbs}, \overline{w}^A_{0cbs}$	Mean mass of 0-year-old pilchard and anchovy in the commercial catches before the recruit survey takes place (g)	Tables A2.2.5 and A3.2.4 respectively

The operating models also preserve any correlative relationships in the residuals for the pilchard and anchovy survey estimates (November and recruit surveys), and in the residuals between the pilchard bycatch to anchovy ratio estimates for May and the subsequent months. Table A5.1.2

provides a brief description of these parameters, and is followed by a detailed description of how these parameters were derived, and what the associated estimates and CVs were for the operating models used (shown in Table A5.1.3). The role of these correlation parameters will become clearer in the context of the operating model, as presented later.

Table A5.1.2 Brief description of correlation parameters, for which detailed descriptions are provided in this Appendix, and for which estimates and associated CVs are shown in Table A5.1.3. [Note that other correlation parameters and associated standard deviations that appear in this Appendix are intermediate parameters used to calculate ρ_{byc}, and therefore do not appear in this Table or in Table A5.1.3.]

Parameters	Description
ρ_{Nov}, σ^{P}_{Nov}, σ^{A}_{Nov}	Correlation between residuals from assessment model fits to the pilchard and to the anchovy November survey estimates (ρ), with associated standard deviations for pilchard and anchovy respectively (σ).
ρ_{rec}, σ^{P}_{rec}, σ^{A}_{rec}	Correlation between residuals from assessment model fits to the pilchard and to the anchovy recruit survey estimates (ρ), with associated standard deviations for pilchard and anchovy respectively (σ).
ρ_{may}, $\sigma_{apr:may}$, σ_{may}	Correlation between residuals (from the relationship between the pilchard to anchovy ratio in the commercial catches and the assessment model estimates of this ratio) for commercial catches over April-May (for which the corresponding assessment model estimates are at the beginning of the year) and during May (for which the corresponding assessment model estimates are projected forward to the time of the recruit survey) (ρ), with associated standard deviations (σ).
$k_{apr:may}$, k_{may}	Constant of proportionality associated with $\sigma_{apr:may}$ and σ_{may} respectively.
k_{sur}	Constant of proportionality between the pilchard to anchovy ratio in the commercial catches in May and during the recruit survey.
ρ_{byc}	Correlation between residuals (from the relationship between the pilchard to anchovy ratio in the commercial catches and the assessment model estimates of this ratio at the time of the recruit survey) for commercial catches in successive months from May to August.

Correlation in pilchard/anchovy November survey residuals:

Set

$$\varepsilon^{i}_{y} = \ln B^{i}_{y,Nov} - \ln(k^{i}_{N} B^{i}_{y,N}) \qquad \begin{matrix} , i = P,\ y = 1985-2000 \\ i = A,\ y = 1985-2001 \end{matrix} \qquad \text{A5.1.1}$$

where $B^{i}_{y,Nov}$ is from Tables A2.2.3 for $i = P$ and Table A3.2.2 for $i = A$, $B^{i}_{y,N}$ is the corresponding assessment estimate from Chapter 2 or 3, and k^{i}_{N} is the constant of proportionality between $B^{i}_{y,Nov}$ and $B^{i}_{y,N}$, from Chapter 2 or 3.

Calculate

$$s^{i} = \sqrt{\sum_{y=1985}^{2000} \left(\varepsilon^{i}_{y}\right)^{2} \Big/ \sum_{y=1985}^{2000} 1} \qquad , i = P, A \qquad \text{A5.1.2}$$

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Then the correlation in the residuals between the pilchard and anchovy November survey estimates, and associated standard deviations, are calculated as follows:

$$\rho_{Nov} = \frac{\sum_{y=1985}^{2000} \varepsilon_y^P \varepsilon_y^A}{\left(\sum_{y=1985}^{2000} 1\right) s^P s^A} \qquad \text{A5.1.3}$$

and

$$\sigma_{Nov}^P = s^P$$

$$\sigma_{Nov}^A = \sqrt{\sum_{y=1985}^{2001} \left(\varepsilon_y^A\right)^2 \Big/ \sum_{y=1985}^{2001} 1} \qquad \text{A5.1.4}$$

[Note: $\sigma_{Nov}^A \neq s^A$, to allow one further year's data to be taken into account (Appendix 3.1).]

Correlation in pilchard/anchovy recruit survey residuals:

The calculations for ρ_{rec}, σ_{rec}^P and σ_{rec}^A are similar to those indicated by equations A5.1.1-4, except that a recruit survey estimate is not available for pilchard for 1988, so that calculations are modified to take account of this.

Simulating catch of 0-year-old pilchard before the recruit survey

In order to simulate the tonnage of 0-year-old pilchard caught before the recruit survey (see equation A5.1.17 and A5.1.23 later), the ratio of begin-year pilchard to anchovy recruitment from the operating model is used to generate the pilchard bycatch to anchovy ratio in the commercial catches over April-May. This is done by first investigating the relationship between the historical pilchard bycatch to anchovy ratio in the catches over April-May, and the pilchard to anchovy begin-year recruitment estimates derived from the assessment procedures of Chapters 2 and 3. The constant of proportionality and time series of residuals are as follows:

$$k_{apr:may} = \exp\left\{\sum_{y\in Y}\left[\ln(C_{y,apr:may}^{P,byc} / C_{y,apr:may}^{A}) - \ln(N_{y,0}^{P} / N_{y,0}^{A})\right] \Big/ \sum_{y\in Y} 1\right\} \qquad \text{A5.1.5}$$

and

$$\varepsilon_{y,apr:may} = \ln(C_{y,apr:may}^{P,byc} / C_{y,apr:may}^{A}) - \ln(k_{apr:may} N_{y,0}^{P} / N_{y,0}^{A}) \qquad , y \in Y \qquad \text{A5.1.6}$$

where $C_{y,apr:may}^{P,byc}$ and $C_{y,apr:may}^{A}$ are from Table A3.2.5, $N_{y,0}^{P/A}$ is the pilchard/anchovy begin-year recruitment in year y (estimable parameters recorded in Chapter 2/3), and $Y = \{1987,$

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1988,...,1999}, the subset of years for which the catch data and assessed recruitment estimates for both species are available.

Simulating pilchard bycatch to anchovy ratios in May using catches in the recruit survey and the commercial fishery in May

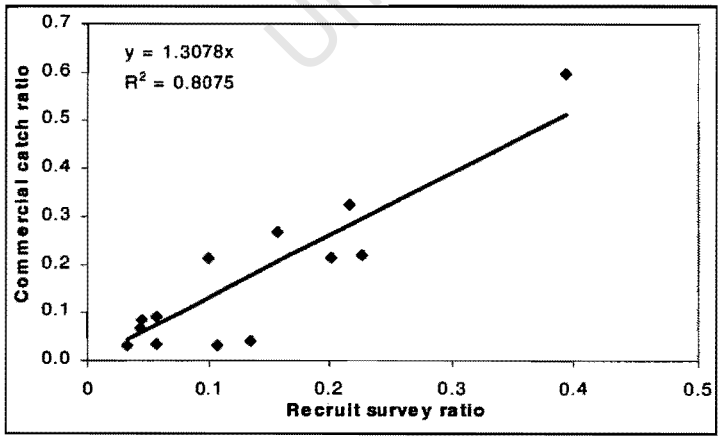
An estimate of the ratio of juvenile pilchard to anchovy "in the sea" during May (equation 5.8 and A5.1.27) can be calculated from:

(a) the recruit survey, and

(b) the pilchard bycatch to anchovy ratios in the commercial catches during May.

For (a), the relationship between the pilchard to anchovy ratio in the recruit survey ($N^{P}_{y,rec} / N^{A}_{y,rec}$)[70], and the pilchard bycatch to anchovy ratio in the commercial catches in May ($C^{P,byc}_{y,may} / C^{A}_{y,may}$)[71] is estimated for historical observations (1987-1999, except 1988 because of the lack of pilchard recruit survey estimate for that year). Figure A5.1.1 plots these historical observations and fits a linear regression, forced through the origin, which indicates a slope of k_{sur} = 1.3078 (used in equation A5.1.28). k_{sur} is then applied to simulated recruit survey data ($N^{P}_{y,rec} / N^{A}_{y,rec}$, given by equation A5.1.16) to obtain an estimate of the ratio of juvenile pilchard to anchovy in catches in May.

Figure A5.1.1 Relationship between the pilchard to anchovy ratio in the recruit survey ($N^{P}_{y,rec} / N^{A}_{y,rec}$), and the pilchard bycatch to anchovy ratio in commercial catches in May ($C^{P,byc}_{y,may} / C^{A}_{y,may}$) for the years 1987-2000 (1988 is omitted because of the lack of a pilchard recruit survey estimate for that year). The slope of the linear regression line forced through the origin is k_{sur} = 1.3078.



[70] See Tables A2.2.5 and A3.2.4, where for the latter table, $N^{A}_{y,rec} = B^{A}_{y,rec} / w^{A}_{y,rec}$

[71] See Table A3.2.5

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For (b), a similar process to that used for equations A5.1.5 and A5.1.6 is followed in order to simulate the pilchard to anchovy ratio in the commercial catches in May. First, a constant of proportionality (used in equation A5.1.29) is calculated, followed by a time series of residuals, which is then used in conjunction with the residuals given by equation A5.1.6 to calculate a correlation coefficient and associated standard deviations (used in equations A5.1.23, A5.1.29 and A5.1.30), as follows:

$$k_m = \exp\left\{\sum_{y\in Y}\left[\ln(C^{P,byc}_{y,m}/C^{A}_{y,m}) - \ln(N^{P}_{y,r}/N^{A}_{y,r})\right]\Big/\sum_{y\in Y}1\right\} \qquad , m = may \qquad \text{A5.1.7}$$

and

$$\varepsilon_{y,m} = \ln(C^{P,byc}_{y,m}/C^{A}_{y,m}) - \ln(k_m N^{P}_{y,r}/N^{A}_{y,r}) \qquad , m = may,\ y\in Y \qquad \text{A5.1.8}$$

where $C^{P,byc}_{y,m}$ and $C^{A}_{y,m}$ are from Table A3.2.5, Y is from equations A5.1.5-6, and $N^{P/A}_{y,r}$ is the pilchard/anchovy begin-year recruitment in year y, projected forward to the time of the recruit survey[72, 73]. Standard deviations of the residuals are calculated as follows:

$$\sigma_m = \sqrt{\sum_{y\in Y}\left(\varepsilon_{y,m}\right)^2\Big/\sum_{y\in Y}1} \qquad , m = apr:may \text{ or } may \qquad \text{A5.1.9}$$

and correlation coefficient:

$$\rho_{may} = \frac{\sum_{y\in Y}\varepsilon_{y,apr:may}\varepsilon_{y,may}}{\left(\sum_{y\in Y}1\right)\sigma_{apr:may}\sigma_{may}} \qquad \text{A5.1.10}$$

Simulating pilchard bycatch to anchovy ratio in catches after May

When simulating pilchard bycatch to anchovy ratios in the catches in June, July and August, it is assumed the correlations between the residuals in successive months follow the following pattern:

	June	July	August
May	ρ_{byc}	$(\rho_{byc})^2$	$(\rho_{byc})^3$
June		ρ_{byc}	$(\rho_{byc})^2$
July			ρ_{byc}

[72] See equations A2.1.4 and A3.1.5, where for the latter, $N^{A}_{y,r} = B^{A}_{y,r}/w^{A}_{y,rec}$

[73] Begin-year recruitment projected forward to the time of the recruit survey was not used in equations A5.1.5-6 as it was here. This is because it was inappropriate to do so: equations A5.1.5-6 were simulating 0-year-old pilchard caught before the recruit survey.

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However, in order to estimate the value of ρ_{byc} to be used in the operating model, the actual correlations between the residuals in successive months were calculated using the catches for the corresponding months (Table A3.2.5) and the forward-projected recruitments from Chapters 2 and 3 (equations A2.1.4 and A3.1.5). This was done by first calculating the constants of proportionality, k_{jun}, k_{jul} and k_{aug} using equation A5.1.7 (replace m with *jun*, *jul* or *aug*, as appropriate, and use Y for *jun* and *jul*, but Y_{aug} for *aug*, where Y_{aug} is the same as Y except the years 1989 and 1996 are omitted because of zero catches), and the corresponding time series of residuals, $\varepsilon_{y,jun}$, $\varepsilon_{y,jul}$ and $\varepsilon_{y,aug}$, using equation A5.1.8 (with Y for the first two ε's and Y_{aug} for the last, as before). The standard deviations, σ_{jun}, σ_{jul} and σ_{aug}, associated with these residuals are calculated using equation A5.1.9 (with Y for the first two σ's and Y_{aug} for the last, as before). It is then possible to calculate the actual correlations, $\rho_{m,j}$ (i.e. the correlation between the residual time series in month m, and the jth month prior to month m), using equation A5.1.10. For example, for m=*jul* and j=2,

$$\rho_{jul,2} = \frac{\sum_{y \in Y} \varepsilon_{y,may} \varepsilon_{y,jul}}{\left(\sum_{y \in Y} 1\right) \sigma_{may} \sigma_{jul}}$$

so that the following correlations are calculated:

	June	July	August
May	$\rho_{jun,1}$	$\rho_{jul,2}$	$\rho_{aug,3}$
June		$\rho_{jul,1}$	$\rho_{aug,2}$
July			$\rho_{aug,1}$

[Note that because of the difference in length of August time series compared to the other months (i.e. Y_{aug} compared to Y), k_{may}, k_{jun}, and k_{jul}, as well as $\varepsilon_{y,may}$, $\varepsilon_{y,jun}$ and $\varepsilon_{y,jul}$, and consequently σ_{may}, σ_{jun} and σ_{jul}, need to be recalculated using Y_{aug} instead of Y, in order to calculate $\rho_{aug,1}$, $\rho_{aug,2}$ and $\rho_{aug,3}$.]

Finally, ρ_{byc}, shown in the first correlation table, is estimated by differentiating the following objective function, g (derived by summing the squared differences between the two correlation tables), with respect to ρ_{byc}:

$$g = \sum_{m=jun,jul,aug} [\rho_{byc} - \rho_{m,1}]^2 + \sum_{m=jul,aug} [(\rho_{byc})^2 - \rho_{m,2}]^2 + [(\rho_{byc})^3 - \rho_{aug,3}]^2 \qquad \text{A5.1.11}$$

and setting the result to zero, so that solutions for ρ_{byc} are obtained by finding the roots of the following equation:

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$$3(\rho_{byc})^5 + 4(\rho_{byc})^3 - 3\rho_{ag,3}(\rho_{byc})^2 + [3-2\sum_{m=jl,ag}\rho_{m,2}]\rho_{byc} - \sum_{m=jn,jl,ag}\rho_{m,1} = 0 \qquad \text{A5.1.12}$$

It can be shown that equation A5.1.12 has only one real root. Estimates for ρ_{byc} and the other correlation parameters presented above are shown in Table A5.1.3, with associated CVs, for the assessments of Chapters 2 and 3.

Table A5.1.3 Estimates and associated CVs of correlation parameters presented in this Appendix, for the assessments ("Assess.") of Chapters 2 and 3.

Assess.		ρ_{Nov}	σ^P_{Nov}	σ^A_{Nov}	ρ_{rec}	σ^P_{rec}	σ^A_{rec}	ρ_{may}	$\sigma_{apr:may}$	σ_{may}	$k_{apr:may}$	k_{may}	ρ_{byc}
P_0	A_0	0.027 1512%	0.374 43%	0.143 23%	-0.010 1291%	0.745 22%	0.342 38%	0.906 2%	0.773 9%	0.799 10%	0.973 10%	1.093 11%	0.519 15%
P_1	A_0	0.018 1657%	0.374 47%	0.143 23%	0.031 20675%	0.740 20%	0.342 38%	0.910 2%	0.780 9%	0.781 10%	1.109 13%	1.262 15%	0.537 17%
P_2	A_0	-0.005 941%	0.399 62%	0.143 23%	0.001 1452%	0.764 25%	0.342 38%	0.913 2%	0.791 11%	0.837 12%	0.845 12%	0.938 13%	0.547 17%
P_3	A_0	-0.009 1264%	0.385 69%	0.143 23%	0.023 1356%	0.732 22%	0.342 38%	0.911 2%	0.776 9%	0.800 10%	1.390 14%	1.263 16%	0.504 16%
P_4	A_0	0.029 764%	0.383 64%	0.143 23%	-0.026 640%	0.726 27%	0.342 38%	0.906 2%	0.777 9%	0.821 10%	0.656 13%	0.907 14%	0.527 16%
P_5	A_0	-0.026 855%	0.416 55%	0.143 23%	-0.047 1205%	0.759 20%	0.342 38%	0.912 2%	0.775 11%	0.810 11%	1.751 13%	1.600 14%	0.499 17%
P_6	A_0	0.011 2764%	0.357 54%	0.143 23%	-0.033 26634%	0.749 23%	0.342 38%	0.913 2%	0.796 9%	0.838 11%	0.505 12%	0.557 13%	0.559 13%
P_7	A_0	0.011 1116%	0.269 33%	0.143 23%	0.010 33868%	0.199 33%	0.342 38%	0.910 2%	0.791 10%	0.780 13%	1.138 11%	1.302 12%	0.337 26%
P_8	A_0	-0.037 559%	0.351 31%	0.143 23%	-0.046 596%	0.741 26%	0.342 38%	0.907 2%	0.770 8%	0.790 9%	0.992 10%	1.114 12%	0.519 16%
P_9	A_0	0.022 1351%	0.348 62%	0.143 23%	0.040 1591%	0.483 20%	0.342 38%	0.897 2%	0.735 9%	0.762 10%	0.956 11%	1.068 13%	0.472 18%
P_{10}	A_0	-0.033 1198%	0.353 29%	0.143 23%	0.002 1722%	0.325 24%	0.342 38%	0.870 4%	0.652 11%	0.649 13%	0.999 10%	1.136 12%	0.288 30%
P_0	A_1	0.028 5900%	0.374 43%	0.143 24%	-0.048 913%	0.745 22%	0.298 40%	0.900 2%	0.762 8%	0.819 8%	0.617 10%	0.789 12%	0.498 15%
P_0	A_2	-0.038 1624%	0.374 43%	0.139 23%	0.012 4085%	0.745 22%	0.310 37%	0.910 1%	0.770 8%	0.778 8%	1.494 12%	1.461 13%	0.535 14%
P_0	A_3	0.019 3803%	0.374 43%	0.142 28%	-0.016 14373%	0.745 22%	0.309 35%	0.911 2%	0.765 8%	0.758 9%	2.252 13%	1.889 14%	0.542 13%
P_0	A_4	-0.028 2805%	0.374 43%	0.142 25%	-0.015 1093%	0.745 22%	0.358 38%	0.912 2%	0.795 8%	0.803 9%	1.559 12%	1.269 13%	0.501 16%
P_0	A_5	0.007 4174%	0.374 43%	0.147 21%	-0.001 2172%	0.745 22%	0.294 43%	0.907 2%	0.785 8%	0.837 9%	0.938 11%	1.049 13%	0.545 14%
P_0	A_6	0.015 565%	0.374 43%	0.152 22%	0.004 4418%	0.745 22%	0.310 40%	0.902 2%	0.802 8%	0.876 9%	0.624 9%	0.793 11%	0.539 14%
P_0	A_7	-0.016 2103%	0.374 43%	0.138 27%	-0.020 1061%	0.745 22%	0.309 37%	0.907 2%	0.754 9%	0.773 10%	1.460 13%	1.431 14%	0.524 13%
P_0	A_8	-0.038 1279%	0.374 43%	0.142 24%	0.002 26056%	0.745 22%	0.124 21%	0.908 1%	0.756 7%	0.809 7%	1.004 8%	1.141 9%	0.566 10%
P_0	A_9	0.046 1896%	0.374 43%	0.142 39%	0.045 702%	0.745 22%	0.319 44%	0.909 2%	0.776 9%	0.811 9%	0.974 10%	1.107 11%	0.511 14%
P_0	A_{10}	-0.032 1140%	0.374 43%	0.147 24%	0.005 1784%	0.745 22%	0.310 41%	0.916 1%	0.795 8%	0.805 9%	1.167 13%	1.336 14%	0.503 18%
P_0	A_{11}	-0.029 692%	0.374 43%	0.152 25%	0.025 939%	0.745 22%	0.324 37%	0.902 2%	0.764 8%	0.799 9%	0.863 10%	0.951 11%	0.526 13%

The Operating Model

Projecting numbers-at-age forward

The operating model is used to project numbers-at-age forward, given the values for future catches provided by the procedure being tested and the parameter values from the assessment procedure, as follows.

Pilchard

$$\left.\begin{aligned} N^P_{y+1,1} &= \left(N^P_{y,0}\mathrm{e}^{-M^P_{ju}/2} - \frac{C^P_{y,0}}{\overline{w}^P_{0c}}\right)\mathrm{e}^{-M^P_{ju}/2} \\ N^P_{y+1,a+1} &= \left(N^P_{y,a}\mathrm{e}^{-M^P_{ad}/2} - \frac{C^P_{y,a}}{\overline{w}^P_{ac}}\right)\mathrm{e}^{-M^P_{ad}/2} \qquad , \quad a=1,\ldots,4 \\ B^P_{y+1,N} &= \sum_{a=1}^{5} N^P_{y+1,a}\overline{w}^P_a \end{aligned}\right\} \quad \text{A5.1.13}$$

Anchovy

$$\left.\begin{aligned} N^A_{y+1,1} &= \left(N^A_{y,0}\mathrm{e}^{-M^A_{ju}/2} - \frac{C^A_{y,0}}{\overline{w}^A_{0c}}\right)\mathrm{e}^{-M^A_{ju}/2} \\ N^A_{y+1,2} &= \left(N^A_{y,1}\mathrm{e}^{-M^A_{ad}/4} - \frac{C^A_{y,1}}{\overline{w}^A_{1c}}\right)\mathrm{e}^{-3M^A_{ad}/4} \\ N^A_{y+1,a+1} &= N^A_{y,a}\mathrm{e}^{-M^A_{ad}} \qquad , \quad a=2,3 \\ B^A_{y+1,N} &= \sum_{a=1}^{4} N^A_{y+1,a}\overline{w}^A_a \end{aligned}\right\} \quad \text{A5.1.14}$$

where $C^i_{y,a}$ are catches of a-year-old fish of species i (i=P for pilchard or A for anchovy) and y = 2001,…,2020[74]. Future recruitment $N^i_{y,0}$ is assumed to be log-normally distributed about a stock-recruit relationship as follows:

$$N^i_{y,0} = f(B^i_{y,N})\,\mathrm{e}^{\varepsilon^i_y \sigma^i_r} \quad \text{A5.1.15}$$

where

$$\varepsilon^i_y = s^i_{cor}\varepsilon^i_{y-1} + \sqrt{1-(s^i_{cor})^2}\;\omega^i_y \qquad , \quad \omega^i_y \sim \mathrm{N}[0;1]$$

Note that $\varepsilon^P_{1999} = \eta^P_{1999}$ and $\varepsilon^A_{2000} = \eta^A_{2000}$ (Table A5.1.1), and N[0; 1] represents a normal distribution with mean 0 and variance 1. Furthermore, $f(B^i_{y,N})$ represents one of the stock-recruit curves described in Chapters 2 and 3, with parameters a^i, b^i, m^P (the latter for the "DS" curve used for pilchard) with associated K^i.

[74] An additional year (y = 2000) is needed for pilchard because there is one year's less data available than for anchovy (compare Chapters 2 and 3), but for this additional year, the actual catches made are used (as distinct from MP-generated TACs) by applying equation A5.1.20 to disaggregate these catches by age.

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Generating survey data

The survey estimates for adult biomass and recruitment are generated by the operating model as follows ($i = P$ or A):

$$B^i_{y,Nov} = k^i_N B^i_{y,N} e^{\varepsilon^i_{y,Nov}}$$
$$N^i_{y,rec} = k^i_r N^i_{y,r} e^{\varepsilon^i_{y,rec}} \qquad \text{A5.1.16}$$

where

$$\left.\begin{aligned} \varepsilon^P_{y,j} &= \eta^P_{y,j}\sigma^P_j \\ \eta^P_{y,j} &\sim \mathrm{N}[0;1] \end{aligned}\right\} \text{for } j = Nov \text{ or } rec$$

$$\left.\begin{aligned} \varepsilon^A_{y,j} &= (\rho_j \eta^P_{y,j} + \sqrt{1-(\rho_j)^2}\ \eta^A_{y,j})\,\sigma^A_j \\ \eta^A_{y,j} &\sim \mathrm{N}[0;1] \end{aligned}\right\}$$

and

$$N^i_{y,r} = \left[N^i_{y,0} e^{-M^i_{ju}/2} - \frac{C^i_{y,0bs}}{\overline{w}^i_{0cbs}} \right] \qquad \text{A5.1.17}$$

where $C^i_{y,0bs}$ are the catches of 0-year-old fish of species i taken before the recruit survey (equations A5.1.22 and A5.1.23). However, the anchovy TAC equations require that $N^A_{y,rec}$ be back-calculated to the start of the year (see equations 5.6 and 5.9), assuming a fixed value of 0.9 (per year) for M^A_{ju} (regardless of the operating model used), as follows:

$$N^A_{y,rec0} = \left[N^A_{y,rec} + \frac{C^A_{y,0}}{\overline{w}^A_{0cbs}} \right] e^{0.9/2} \qquad \text{A5.1.18}$$

so that

$$\overline{N}^A_{y,rec0} = \left(\overline{N}^A_{y-1,rec0}(y-1-1985) + N^A_{y-1,rec0}\right)/(y-1985) \qquad , y > 2001$$
$$\overline{N}^A_{2001,rec0} = \sum_{y=1985}^{2000} N^A_{y,rec0}/16 \qquad \text{A5.1.19}$$

where the $N^A_{y,rec0}$ in equation A5.1.19 come from actual back-calculated recruit survey data (Table A3.2.4; equation A4.1.6 but replacing 1.2 with 0.9) for $y \le 2000$, and from the operating model (equation A5.1.18) for $y > 2001$.

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Splitting TACs into catches-at-age for the whole year

The *TAC*s given by the MP (equation 5.1-5.18) are split between the age groups for the whole year (this sub-section), and before and after the recruit survey (next two sub-sections respectively) as follows.

Pilchard 1-year-old and older catches:

$$C^P_{y,a} = N^P_{y,a} S^P_a F_y e^{-M^P_{ad}/2} \overline{w}^P_{ac} \quad , \quad a = 1,...,4 \qquad \text{A5.1.20}$$

where

$$F_y = \frac{TAC^P_y + TAB^P_{rh}}{\left(\sum_{a=1}^{4} N^P_{y,a} S^P_a \overline{w}^P_{ac}\right) e^{-M^P_{ad}/2}}$$

Splitting TACs into catches-at-age before the recruit survey

Anchovy 1-year-old catch:

$$C^A_{y,1} = \tfrac{3}{7} TAC^{1,A}_y \qquad \text{A5.1.21}$$

The $\frac{3}{7}$ factor comes from previous OMP implementations and is derived as follows: assuming $\delta = 0.7$ (used in these earlier OMPs) and average recruitment, $TAC^{1,A}_y$ = 70% of $TAC^{2,A}_y$, so that using $\frac{3}{7}$ of this amount for calculating $C^A_{y,1}$ implies 30%[75] of the anchovy catch during the normal season comprises 1-year-old anchovy taken from January to March, with the remainder taken from April onwards comprising 0-year-old anchovy.

Anchovy 0-year-old catch before the recruit survey:

$$C^A_{y,0bs} = \tfrac{2}{7} TAC^{1,A}_y \qquad \text{A5.1.22}$$

Here it is assumed that half the 0-year-old catch taken by the time the 2nd TAC is set will be taken before the recruit survey commences.

Pilchard 0-year-old catch before the recruit survey:

$$C^P_{y,0bs} = k_{apr:may} \frac{N^P_{y,0}}{N^A_{y,0}} e^{\sigma_{apr:may}\eta_{y,apr:may}} (C^A_{y,0bs} + C^A_{y,1}) \qquad \text{A5.1.23}$$

[75] Corresponds roughly to the average proportion of the January-August anchovy catch made in January-March, before there were problems (from the mid-1990s) with bureaucratic delays in starting the fishing season.

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where $k_{apr:may}$ and $\sigma_{apr:may}$ from equations A5.1.5 and A5.1.9 respectively, and

$$\eta_{y,apr:may} \sim \mathrm{N}[0;\ 1] \qquad \text{A5.1.24}$$

[Although equation A5.1.23 is developed on the basis of catches for April-May (see also equations A5.1.5-6), $C^{A}_{y,1}$ is included in equation A5.1.23 because pilchard has a more protracted spawning season than anchovy (Chapter 1) and juvenile pilchard also occur with anchovy taken in January-March.]

Splitting TACs into catches-at-age after the recruit survey

Anchovy 0-year-old catch:

$$C^{A}_{y,0} = TAC^{2,A}_{y} - C^{A}_{y,1} \qquad \text{A5.1.25}$$

Pilchard 0-year-old catch:

$$\begin{aligned} C^{P}_{y,0} &= \lambda\, TAC^{1,A}_{y} + r_{y}(TAC^{2,A}_{y} - TAC^{1,A}_{y}) \\ \lambda &= \max\{\gamma, r_{y}\} \end{aligned} \qquad \text{A5.1.26}$$

where γ is the initial bycatch ratio (equation 5.5), and r_y is the ratio of juvenile pilchard to anchovy "in the sea" during May, calculated as follows:

$$r_{y} = \tfrac{1}{2}(r_{y,sur} + r_{y,com}) \qquad \text{A5.1.27}$$

which is derived from recruit survey estimates:

$$r_{y,sur} = k_{sur}\frac{N^{P}_{y,rec}}{N^{A}_{y,rec}} \qquad \text{A5.1.28}$$

where $N^{P/A}_{y,rec}$ are from equation A5.1.16, and the simulated pilchard bycatch to anchovy ratio in commercial catches in May is given by:

$$r_{y,com} = k_{may}\frac{N^{P}_{y,r}}{N^{A}_{y,r}} e^{\sigma_{may}\,\varepsilon_{y,may}} \qquad \text{A5.1.29}$$

where $N^{P/A}_{y,r}$ are from equation A5.1.17, k_{may} from equation A5.1.7, σ_{may} from equation A5.1.9, and finally,

$$\varepsilon_{y,may} = \rho_{may}\eta_{y,apr:may} + \sqrt{1-(\rho_{may})^{2}}\ \eta_{y,may} \qquad \text{A5.1.30}$$

where ρ_{may} is from equation A5.1.10, $\eta_{y,apr:may}$ from equation A5.1.24, and

$$\eta_{y,may} \sim \mathrm{N}[0;\ 1] \qquad \text{A5.1.31}$$

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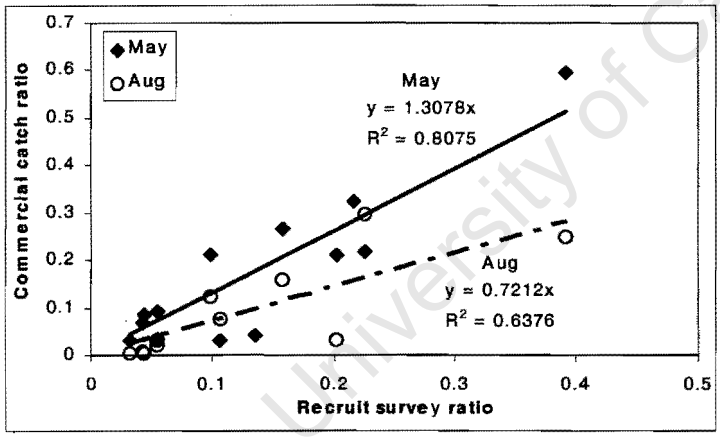
Bycatch drop-off after May

$C^{P}_{y,0}$ in equation A5.1.26 assumes that the juvenile pilchard to anchovy ratio "in the sea" in May, r_y, will remain at this level for the remainder of the season. However, Figure A5.1.2 (a repeat of Figure A5.1.1, but with August commercial catch data added) shows that there is a drop-off in this ratio of about 50% by August. This implies that the level of bycatch set after the recruit survey ($TAB^{2,P}_{y}$ in equation 5.8) may be "too generous" and that $C^{P}_{y,0}$ may be somewhat different to this. This effect is simulated by adjusting $C^{P}_{y,0}$ to reflect the actual level of 0-year-old pilchard to be expected in the catches, given the historical pattern of pilchard bycatch to anchovy ratio changes (usually a drop-off) from May to August. The anchovy catch, $C^{A}_{y,0}$, is also adjusted if the adjusted $C^{P}_{y,0}$ exceeds $TAB^{2,P}_{y} - TAB^{P}_{rh}$ (equation 5.8), in order to reflect the closure of the anchovy fishery once the pilchard bycatch allowance linked to anchovy is reached.

Figure A5.1.2 A repeat of Figure A5.1.1, but with commercial catch data for August ($C^{P,byc}_{y,aug} / C^{A}_{y,aug}$ from Table A3.2.5) added.



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Adjusting $C^{P}_{y,0}$*:*

Equation A5.1.26 is modified as follows (see also equation 5.5):

$$C^{P*}_{y,0} = TAB^{1,P}_{y} - TAB^{P}_{rh} + r_{y,jun}C^{A}_{y,jun} + r_{y,jul}C^{A}_{y,jul} + r_{y,aug}C^{A}_{y,aug} \qquad \text{A5.1.32}$$

The pilchard bycatch to anchovy ratios, $r_{y,m}$, are derived in a similar way to $r_{y,com}$ in equation A5.1.29 as follows:

$$r_{y,m} = k_m \frac{N^{P}_{y,r}}{N^{A}_{y,r}} e^{\sigma_m \varepsilon_{y,m}} \qquad , m = jun, jul, aug \qquad \text{A5.1.33}$$

where $N_{y,r}^{P/A}$ are from equation A5.1.17, k_m and σ_m from equations A5.1.7 and A5.1.9 (where Y is replaced by Y_{aug} for calculations involving $m = aug$), and

$$\varepsilon_{y,jun} = \rho_{byc}\varepsilon_{y,may} + \sqrt{1-(\rho_{byc})^2}\,\eta_{y,jun}$$

$$\varepsilon_{y,jul} = (\rho_{byc})^2\varepsilon_{y,may} + \rho_{byc}\sqrt{1-(\rho_{byc})^2}\,\eta_{y,jun} + \sqrt{1-(\rho_{byc})^2}\,\eta_{y,jul} \qquad \text{A5.1.34}$$

$$\varepsilon_{y,aug} = (\rho_{byc})^3\varepsilon_{y,may} + (\rho_{byc})^2\sqrt{1-(\rho_{byc})^2}\,\eta_{y,jun} + \rho_{byc}\sqrt{1-(\rho_{byc})^2}\,\eta_{y,jul} + \sqrt{1-(\rho_{byc})^2}\,\eta_{y,aug}$$

reflecting the correlative relationships between successive months, where ρ_{byc} is from equation A5.1.12, $\varepsilon_{y,may}$ from equation A5.1.30, and

$$\eta_{y,m} \sim \mathrm{N}[0;\,1] \qquad , m = jun, jul, aug \qquad \text{A5.1.35}$$

The anchovy catches in equation A5.1.32, $C_{y,m}^{A}$ ($m = jun$, jul and aug), are derived as follows:

$$C_{y,jun}^{A} = p_{jun}(TAC_y^{2,A} - TAC_y^{1,A})$$
$$p_{jun} \sim \mathrm{U}[0;\,1] \qquad \text{A5.1.36}$$

where U[0; 1] represents a uniform random distribution between 0 and 1[76]. Furthermore,

$$C_{y,jul}^{A} = p_{jul}(TAC_y^{2,A} - TAC_y^{1,A} - C_{y,jun}^{A}) \qquad \text{A5.1.37}$$

where p_{jul} is related to p_{jun} in the same way as observed historically in the catches. In order to derive this relationship, logit transformations[77] of historical anchovy monthly catches (Table A3.2.5) were calculated as follows:

$$q_m = \ln\left(\frac{1 - C_{y,m}^{A} / \sum_{m'=m}^{aug} C_{y,m'}^{A}}{C_{y,m}^{A} / \sum_{m'=m}^{aug} C_{y,m'}^{A}}\right) \qquad , m = jun,\ jul \qquad \text{A5.1.38}$$

Figure A5.1.3 plots q_{jul} against q_{jun}, and shows a fitted linear regression line.

[76] A uniform distribution from 0 to 1 was used because data for the period 1987-1999 showed that, for anchovy, the June catch as a percentage of the June-August catch varied from 1% in 1993 to 99% in 1996 (see Table A3.2.5).

[77] A logit transformation was used to allow the application of linear regression.

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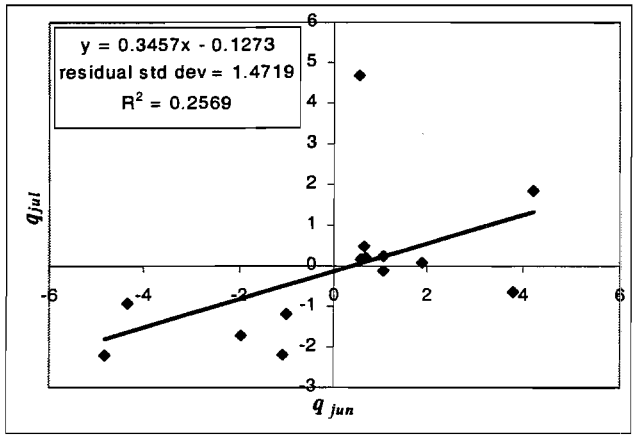
Figure A5.1.3 A plot of q_{jul} against q_{jun} (equation A5.1.38), based on historical anchovy monthly catches (Table A3.2.5). A fit of a linear regression line to the transformed data is shown, with an estimate of the residual standard deviation.



p_{jul} is therefore derived as follows:

$$p_{jul} = 1/\left\{\exp\left[0.3457\ln[(1-p_{jun})/p_{jun}] - 0.1273 + \eta_{jul}\right] + 1\right\}$$
$$\eta_{jul} \sim \mathrm{N}[0; 1.4719^2] \qquad \text{A5.1.39}$$

Finally,

$$C^{A}_{y,aug} = TAC^{2,A}_{y} - TAC^{1,A}_{y} - C^{A}_{y,jun} - C^{A}_{y,jul} \qquad \text{A5.1.40}$$

Adjusting $C^{A}_{y,0}$, *when* $C^{P*}_{y,0} + TAB^{P}_{rh} > TAB^{2,P}_{y}$:

The adjustment to $C^{A}_{y,0}$ when $C^{P*}_{y,0} + TAB^{P}_{rh} > TAB^{2,P}_{y}$ assumes that the anchovy TAC is taken at the same rate as the pilchard bycatch allowance, and therefore equation A5.1.25 is modified as follows:

$$C^{A*}_{y,0} = TAC^{2,A}_{y}\left[TAB^{2,P}_{y} / (C^{P*}_{y,0} + TAB^{P}_{rh})\right] - C^{A}_{y,1} \qquad \text{A5.1.41}$$

Additional sub-season

A final adjustment is made to $C^{P*}_{y,0}$ and $C^{A*}_{y,0}$ to reflect the catches taken in the additional sub-season, as follows:

$$C^{P**}_{y,0} = C^{P*}_{y,0} + \min\left\{TAB^{P}_{ads}; 0.1(TAC^{3,A}_{y} - TAC^{2,A}_{y})\right\} \qquad \text{A5.1.42}$$

and

$$C^{A**}_{y,0} = C^{A*}_{y,0} + TAC^{3,A}_{y} - TAC^{2,A}_{y} \qquad \text{A5.1.43}$$

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where 0.1 in equation A5.1.42 is consistent with the value used for γ at the start of the year (equation 5.5), and ensures that the bycatch in the additional sub season is at most 10% of that portion of the anchovy 3rd TAC taken in the sub-season.

General

For all catches simulated in the operating model, an upper limit is placed on the industry's efficiency by assuming that no more than 95% of the "exploitable" stock may be caught. Furthermore, appropriate adjustments are made to ensure non-negative values for catches. The summary performance statistics for each test are calculated from quantities of interest derived from 500 simulations of 20-year projections, with the 20-year trajectories differing from one another because of the error components in the above equations. However, when alternative MPs are compared, the same series of 20×500 error "realisations" are used to reduce the effect of Monte Carlo variation on the differences between summary statistics, and the operating model is left unchanged. When testing the sensitivity of a particular MP to alternative scenarios (e.g. alternative stock-recruit relationships), changes are made to the operating model, while the MP (i.e. the decision rules and constraints described in the main text, and equation A5.1.18) is left unchanged.

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APPENDIX 5.2

Exceptional Circumstances

This Appendix describes the Exceptional Circumstances meta-rules to be applied when Exceptional Circumstances are invoked by the MP being tested. All quantities are as defined in the main text of Chapter 5 and in Appendix 5.1. This is essentially a repeat of the "Exceptional Circumstances" sub-section of Appendix 4.1, but now cast in the mould of the MP testing process (in contrast to how the meta-rules would apply in practice, as shown in Appendix 4.1), and with modifications to account for the differences between OMP99 and OMP02. Therefore motivations for the type of equations used are not repeated here (refer rather to Appendix 4.1). Motivation for the threshold levels used to invoke Exceptional Circumstances can be found in Appendix 4.2.

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Pilchard directed TAC

Exceptional Circumstances for the pilchard directed TAC apply if:

$$B^{P}_{y,Nov} < 150 \text{ thousand tons}$$

in which case the TAC under Exceptional Circumstances is calculated as follows:

$$TAC^{P}_{y} = TAC^{P*}_{y}\left(\frac{B^{P}_{y,Nov}}{150}\right)^{2} \qquad \text{A5.2.1}$$

where $B^{P}_{y,Nov}$ is in thousand tons, and TAC^{P*}_{y} is calculated using equation 5.1, 5.2, 5.14 and 5.17.

Anchovy 1st TAC

Exceptional Circumstances for the anchovy 1st TAC apply if

$$B^{A}_{y,Nov} < 400 \text{ thousand tons}$$

in which case the TAC under Exceptional Circumstances is calculated as follows:

$$TAC^{1.A}_{y} = TAC^{1,A*}_{y}\left(\frac{B^{A}_{y,Nov}}{400}\right)^{2} \qquad \text{A5.2.2}$$

where $B^{A}_{y,Nov}$ is in thousand tons, and $TAC^{1,A*}_{y}$ is calculated using equations 5.3, 5.4, 5.15 and 5.18.

Appendix 5.2

Anchovy 2nd TAC

First, a projected anchovy biomass is calculated as follows:

1. Derive $TAC_y^{2,A*}$ in the usual manner by applying equations 5.6, 5.7, 5.15 and 5.18.

2. Calculate $B_{y,proj0}^A$ as follows:

$$B_{y,proj0}^A = \max \text{ of } \begin{cases} \left(N_{y,rec}^A - \dfrac{TAC_y^{2,A*} - C_{y,1}^A - C_{y,0bs}^A}{\overline{w}_{0c}^A} \right) e^{-0.9/2} \overline{w}_1^A \\ 0 \end{cases} \quad \text{A5.2.3}$$

Calculate $B_{y,proj}^A$ as follows:

$$B_{y,proj}^A = \left(\frac{B_{y,Nov}^A e^{-0.9/4}}{\overline{w}_1^A} - \frac{C_{y,1}^A}{\overline{w}_{1c}^A} \right) e^{-3\times 0.9/4} \overline{w}_2^A + B_{y,proj0}^A \quad \text{A5.2.4}$$

If $B_{y,proj}^A < 400$ thousand tons , then Exceptional Circumstances apply.

If it is established that Exceptional Circumstances apply, then the anchovy revised TAC is calculated as follows:

$$TAC_y^{2,A} = TAC_y^{2,A*} \left(\frac{0.7 \dfrac{N_{y,rec0}^A}{\overline{N}_{y,rec0}^A} + 0.3 \dfrac{B_{y,Nov}^A}{\overline{B}_{Nov}^A}}{0.7 \dfrac{N_{y,rec0}^{A*}}{\overline{N}_{y,rec0}^A} + 0.3 \dfrac{B_{y,Nov}^A}{\overline{B}_{Nov}^A}} \right)^2 \quad \text{A5.2.5}$$

where

$$N_{y,rec0}^{A*} = \left(\theta + \frac{C_{y,0bs}^A}{\overline{w}_{0cbs}^A} \right) e^{0.9/2} \quad \text{A5.2.6}$$

and

$$\theta = \frac{[400 - (B_{y,proj}^A - B_{y,proj0}^A)]\, e^{0.9/2}}{\overline{w}_1^A} + \frac{TAC_y^{2,A*} - C_{y,1}^A - C_{y,0bs}^A}{\overline{w}_{0c}^A} \quad \text{A5.2.7}$$

However, if $TAC_y^{2,A} < TAC_y^{1,A}$ after Exceptional Circumstances meta-rules have been applied, then set $TAC_y^{2,A} = TAC_y^{1,A}$.

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Anchovy 3rd TAC

The same procedure as for the anchovy 2nd TAC is followed, except that equations 5.9, 5.10, 5.16 and 5.18 are used to calculate TAC_y^{3,A^*}, which then replaces TAC_y^{2,A^*} in equations A5.2.3, A5.2.5 and A5.2.7. Furthermore, $TAC_y^{3,A}$ replaces $TAC_y^{2,A}$ in equation A5.2.5. Finally, if $TAC_y^{3,A} < TAC_y^{2,A}$, then set $TAC_y^{3,A} = TAC_y^{2,A}$.

[Note that when the above meta-rules are applied in practice, actual data from the fisheries and research surveys is used (see Appendix 4.1).]

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APPENDIX 5.3

Risk

Risk is defined as the probability that adult biomass drops below a pre-specified threshold level at least once during a 20-year projection period. Butterworth and Punt (1999) argue that these threshold levels should take into account the biological characteristics of the species under consideration. For example, anchovy is a shorter-lived species and is subject to higher levels of recruitment variability (compare σ_r^i in Tables 2.9 and 3.8). It is therefore more likely to be resilient to depletion to a particular level ($0.2K^i$ for example)[78], so that a lower threshold compared to pilchard is likely justified. Apart from the possibility of threshold levels differing, the target *risk* levels for pilchard and anchovy used to tune MPs actually differ (0.1 and 0.3 respectively for the two species – see main text), not only for the reasons given above (regarding the thresholds used in the definition of *risk*), but also because survey results for anchovy are considered more reliable than for pilchard (Cochrane *et al.* 1998; Chapter 1). Furthermore, the policy with regard to managing pilchard has been to encourage recovery of the resource, so that more conservative *risk* levels have been used for that species (Cochrane *et al.* 1998).

Although the threshold level used for pilchard in OMP02 has remained unchanged ($0.2K^P$) compared to OMP99, it has changed from $0.2K^A$ to $0.15K^A$ for anchovy. The main reason for this is that the estimate of σ_r^i has increased for anchovy (0.62 to 0.69 from OMP99 to OMP02), but remained virtually unchanged for pilchard (0.50 and 0.51 respectively). Figure A5.3.1 plots σ_r^i for pilchard and anchovy ($i = P$ or A), with symbols indicating point estimates for both OMPs and solid lines indicating the frequency distribution for OMP02 (OMP99 did not use a joint probability density function for the pilchard and anchovy assessment parameters, only point estimates).

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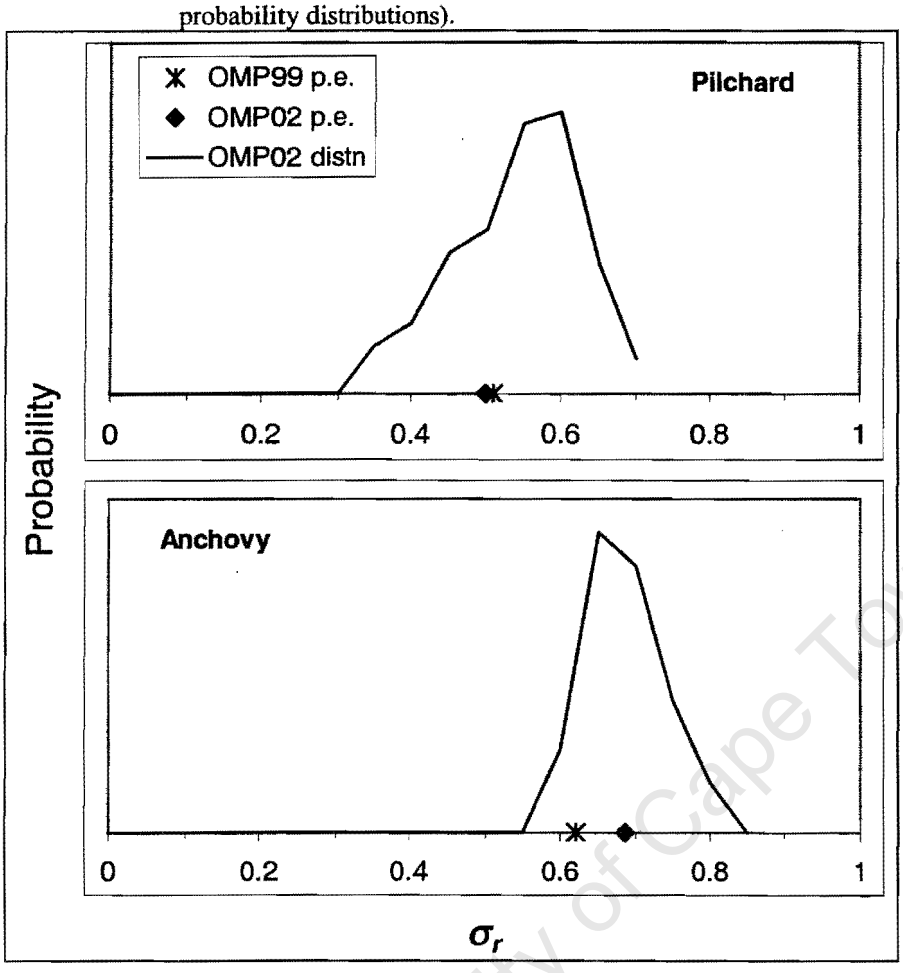
[78] K^i is the average pre-exploitation level of $B_{y,N}^i$ for species i (= P or A).

Figure A5.3.1 Point estimates and probability distributions for σ_r^i, for pilchard (top, $i = P$) and anchovy (bottom, $i = A$), with symbols indicating point estimates ("p.e.") and solid lines frequency distributions ("distn"). Results are shown for OMP99 (point estimates only) and OMP02 (point estimates and probability distributions).



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There were several options for dealing with the changed perception of *risk* for anchovy for OMP02 compared to OMP99, as follows.

1. *Risk* could be re-defined by changing the threshold used in the definition of *risk*.
2. TAC constraints in OMP02 could be modified so that the probability of dropping the adult biomass below a pre-specified level was the same for OMP99 and OMP02.
3. The definition of *risk* could remain the same (i.e. threshold level not changed) but stake-holders could be encouraged to accept higher levels of *risk* given the increased level of recruitment variability

Option 1 was the most attractive because stakeholders were more familiar with the target level of *risk* (0.3, which would be changed under option 3) than with the actual definition of *risk*, so it was more important to keep the target level unchanged. Option 2 would essentially have introduced a new method for tuning the MPs, which would have been more difficult to "sell" to stakeholders than achieving the same result by using already familiar concepts (Option 1).

Figure A5.3.2 compares point estimates of the threshold levels $0.15K^A$ and $0.2K^A$ for anchovy. The $0.15K^A$ threshold level for OMP02 is closer to $0.2K^A$ for OMP99 than is the $0.2K^A$ threshold level for OMP02. The Figure also shows that $0.2K^A$ for OMP99 lies in the centre of the $0.15K^A$ distribution for OMP02, but towards the bottom of the $0.2K^A$ distribution. A choice of $0.15K^A$ for OMP02 would therefore be more consistent with OMP99 than would $0.2K^A$.

Figure A5.3.2 Point estimates (p.e.) and probability distributions for threshold levels (0.15*K* and 0.2*K*) used in the definition of *risk* for anchovy, with symbols indicating point estimates ("p.e.") and solid lines probability distributions ("distn"). Results are shown for OMP99 (point estimates only) and OMP02 (point estimates and probability distributions).

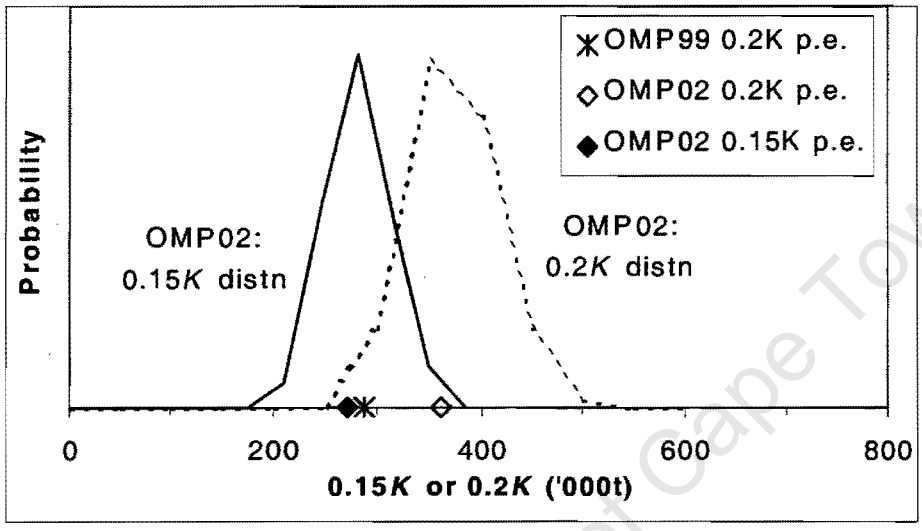

Figure A5.3.3 plots $B^i_{y,N} / K^i$ with and without exploitation for OMP99 and OMP02 (using the ETD method and a β value of 0.1375 for OMP02, to be consistent with OMP99 – see main text). In Figure A5.3.3, (a) shows the extent to which implementation of the OMP affects the distribution of $B^i_{y,N} / K^i$ values, while (b) compares the two OMPs to one another. OMP02 appears to be less conservative for anchovy than OMP99, but this is perhaps not surprising because OMP02 incorporates the additional sub-season for anchovy, which attempts better utilisation of anchovy, whereas OMP99 did not.

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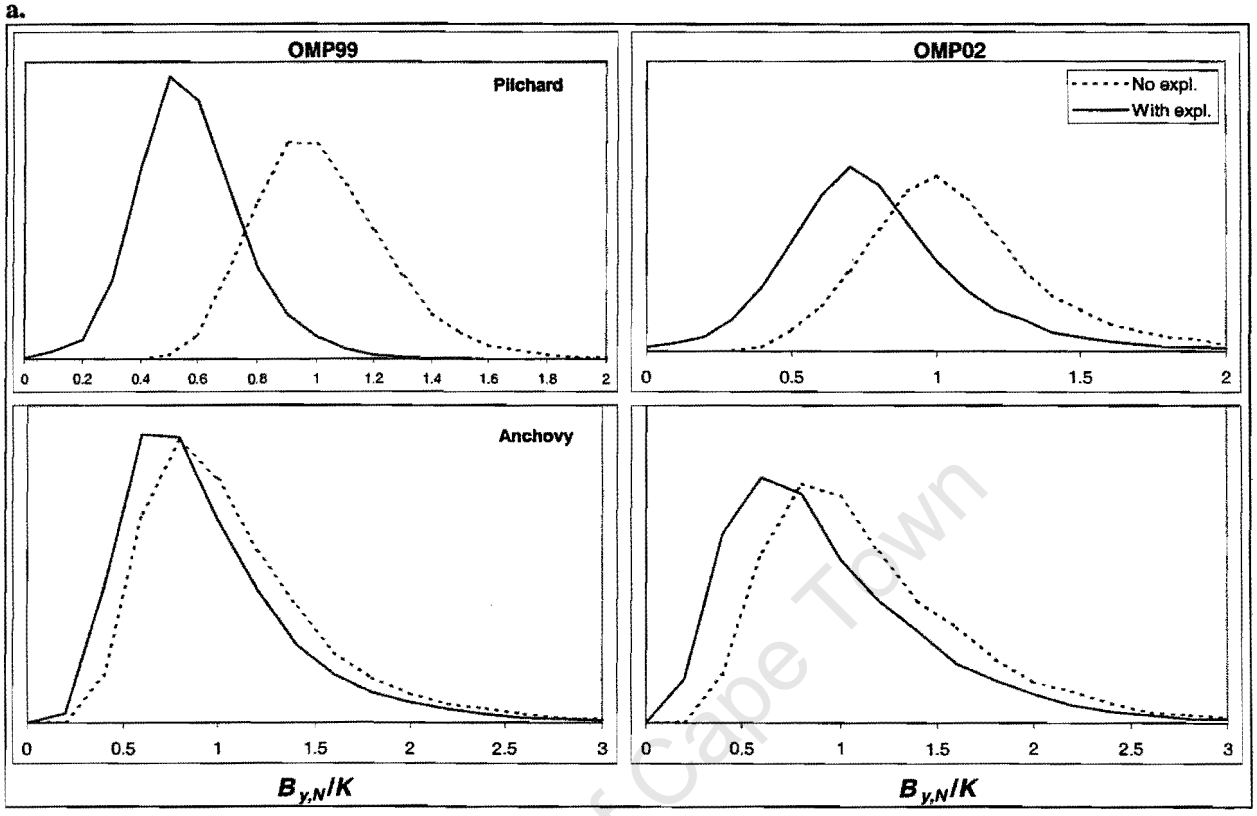
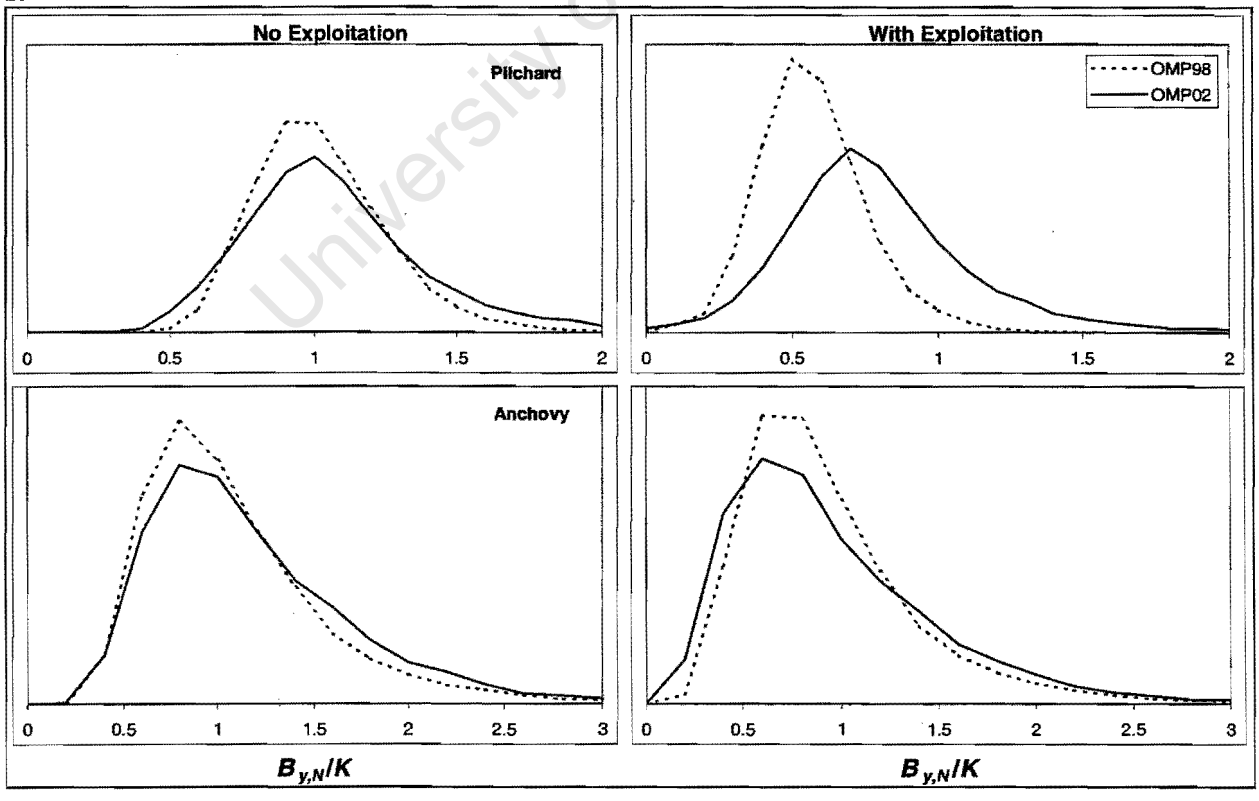
Figure A5.3.3 Probability distributions of $B^i_{y,N} / K^i$ for pilchard (top) and anchovy (bottom) with and without exploitation, for both OMP99 and OMP02. The "with exploitation" options use $\beta = 0.1375$ for both OMPs. (a) plots the "With expl." and "No expl." cases for each OMP, while (b) compares the two OMPs, both with and without exploitation.

a.



b.



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APPENDIX 5.4

Relating 2001 pilchard and anchovy allocations to an Equivalent Percentage Right

The process of computing an Equivalent Percentage Right (EPR) in ones "own" preferred fishery is developed by relating individual allocations of pilchard and anchovy quotas in 2001 to management procedure M_1, and hence to the TACs that would have resulted had that MP been applied in 2001.

Figure A5.4.1 shows the pilchard-anchovy trade-off curve for M_1. This curve shows the trade-off between anchovy and directed pilchard catches on average. The curve specific to a particular year will differ from this, because both pilchard and anchovy abundances may differ from their averages. Figure A5.4.1 also shows the trade-off curve that would have applied for 2001, given the anchovy and pilchard abundance estimates from surveys for that year. It is this 2001 curve that is used to compute the EPRs, as follows.

1) Take a particular Company (X) and establish what its directed pilchard and anchovy allocations were for 2001. Use this information to establish the proportion of this total comprised of pilchard.
   Ex: Company X was allocated 6226 tons of anchovy and 2008 tons of directed pilchard for 2001. These comprised 1.380% and 1.103% respectively of the TACs of these two species of 451000 and 182000 tons. The pilchard proportion of Company X's allocation was therefore 0.244.

2) Find the point on the trade-off curve for 2001 in Figure A5.4.1 that corresponds to this same proportion of pilchard in the total catch (the two TACs combined). This turns out to reflect TACs of TAC-P tons pilchard and TAC-A tons anchovy. Compute the proportion that Company X's pilchard quota for 2001 comprises of TAC-P, which is termed prop-X. Note that (by construction) one would get exactly the same result for prop-X by dividing Company X's anchovy quota for 2001 by TAC-A.
   Ex: For the example above of a company with a pilchard proportion of 0.244, the corresponding point on the 2001 trade-off curve is TAC-A = 385000 tons and TAC-P = 124000 tons. Dividing the 2008 pilchard quota for 2001 by TAC-P = 124000 tons gives prop-X = 0.01618 or 1.618%.

3) The prop-X values are computed for every company awarded one or both of a pilchard quota and an anchovy quota for 2001, and these values are added together to get Sum-prop-X.

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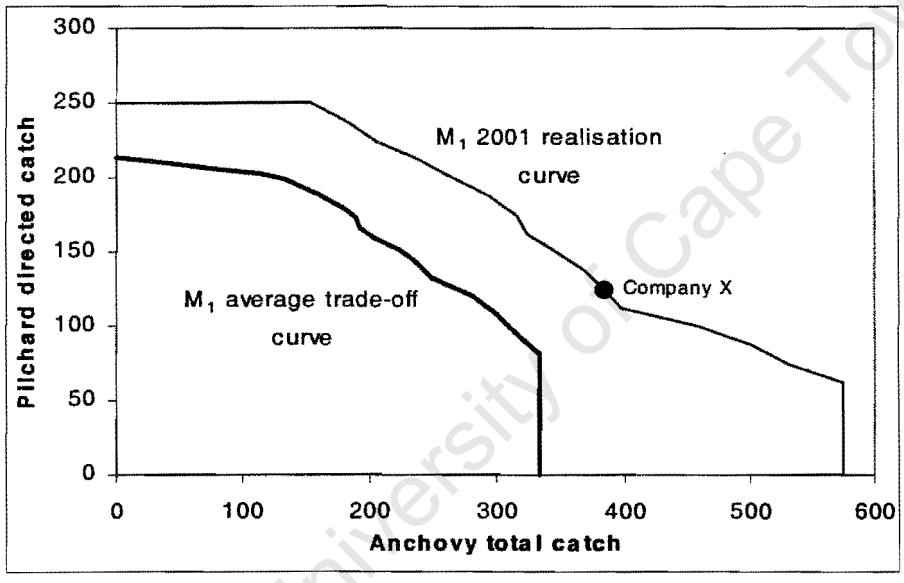
Ex: Repeating this exercise for every company awarded a quota in 2001 gives a value of Sum-prop-X of 1.33286, or 133.286%[79].

4) Company X's equivalent percentage right (in its own "preferred" fishery) - referenced as "EPR" - is given by dividing prop-X by Sum-prop-X. Note that this means that if one adds the equivalent percentage rights for all companies with quotas in 2001, the result will be 100%.

Ex: For Company X, prop-X = 0.01618 and Sum-prop-X = 1.33286, so that EPR = 0.01214 or 1.214%.

Figure A5.4.1 A plot of the M_1 trade-off curve ("M_1 average trade-off curve"), together with what this curve looks like for 2001 ("M_1 2001 realisation curve") given the pilchard and anchovy abundance estimates for that year. The trade-off implicit in the allocations of pilchard and anchovy to Company X in 2001 is shown.



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[79] The reason that this sum exceeds 100% is linked to the non-linear nature of the M_1 2001 realisation curve, which in turn arises from the overall catch constraints imposed on the MP formulae.

CHAPTER 6

Implementation of OMP02

The implementation of OMP02 took place against the backdrop of a re-allocation of rights to South Africa's major commercial fishing sectors, including the pelagic fishery. The ITD method was adopted for OMP02 partly because of concerns over litigation if the ETD method was used, and partly because it allowed rights holders the additional freedom of selecting their own preferred average pilchard-anchovy catch ratios. Delays in the rights allocation process caused several problems, including an eventual greater than expected shift in the distribution of preferred pilchard-anchovy ratios towards pilchard for the industry as a whole, compared to the distribution of ratios implicit in the 2001 quota allocations. This necessitated the implementation of a 15% cap (phased in over two years) on the amount by which the ratios originally specified on the application forms for rights were revised upwards when successful applicants were given a one-off opportunity to specify such a revision. It also necessitated a final round of robustness tests to confirm that a re-calibration of OMP02 was not necessary.

6.1 Introduction

The development and implementation of OMP02 took place under challenging circumstances. Transformation in the pelagic industry had already started in the early 1990s with the introduction of new entrants into the fishery (Chapter 1, Sauer *et al.* 2002). No attempt was made initially to remove existing rights holders (for example on the basis of transformation criteria), though their allocations as percentages of the TACs were reduced. An unsatisfactory result of these early transformation initiatives was the development of many new quota holders operating only as "paper" quota holders[80]. In order to address the above problems ("untransformed" and "paper" quota holders) and speed up the transformation process, a first attempt to re-allocate rights in various fisheries sectors (including the pelagic fishery) was made in 1999 (for the 2000 fishing season) following the adoption of the Marine Living Resources Act (Anon. 1998b) in 1998. This attempt scored applicants for rights in these fishing sectors on the basis of criteria such as historical involvement in the relevant sector, viability of the business plan each provided and level of transformation (from the point of view of involvement or proportion of ownership by previously disadvantaged groups in the rights applicant's business). This attempt at "full-blown" transformation failed however, because of fundamental flaws in the process used[81], which led to widespread litigation (Kleinschmidt *et al.* 2003).

[80] "Paper" quota holders were rights holders who had no investment in the industry and would simply sell their allocated quotas to a third party (usually one of the "traditional" rights holders with large investments in the industry– see Chapter 1) for catching and processing.

[81] For example, the criteria used to score applicants were challenged as being too subjective to be used as a basis for excluding applicants from the rights allocation process, and the administrative structures in place were inadequate to cope with the sheer volume of applications for rights, which resulted in long delays in the allocation of fishing rights.

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A moratorium on re-allocation was introduced for the 2001 season to stabilise the fishing industry and to prepare for a fresh attempt to transform the various sectors and award rights for a four-year period. To be eligible for rights, all prospective participants had to apply for rights in the various sectors by September 2001. MCM was anxious to avoid the litigation problems it had encountered previously, so a legal team was assembled as an integral component of the new re-allocation process, to be completed in time for the 2002 season in the case of the pelagic fishery. Kleinschmidt *et al.* (2003) provide an in-depth account of the new re-allocation process.

It was against this background that OMP02 was developed. In part because of the concerns over litigation, MCM decided to adopt the ITD (internal trade-off decision) method for OMP02 (see Chapters 4 and 5), for the pelagic fishery. Furthermore, it was careful to avoid linking the allocation process with OMP02, because an integral part of developing OMP02 was the participation of the existing pelagic industry (for feedback on desired levels of constraints, for example). If such a link was evident, prospective new entrants, who had not had the opportunity to contribute to the development of OMP02, could claim that the allocation process had favoured existing rights holders, which could constitute grounds for litigation. There was also concern that if such a link was perceived by existing rights holders, it could be used by them to influence OMP02 to favour their own allocations. Although OMP02 (management procedure M_1 in Chapter 5) was used to provide the EPRs[82] to inform the allocation process (Chapter 5; Appendices 5.4 and 6.1), these EPRs were used by MCM merely as guidelines to compare to the percentage right it eventually awarded to successful rights applicants[83]. In this manner, MCM avoided a direct link between the allocation process and OMP02.

All the results shown in Chapter 5 were based on the EPRs and the pilchard-anchovy ratios implicit in the allocations to rights holders in 2001. For the actual implementation of OMP02 in 2002, these two pieces of information were to be replaced, because a new set of rights holders (mostly existing participants, but some new entrants) were about to be confirmed for the pelagic fishery. The first was replaced by the percentage right to the pelagic fishery allocated by MCM to each newly-confirmed rights holder in the fishery, and the second by the preferred pilchard-anchovy ratio (from which a β value could be calculated) specified by that rights holder on their application form, when they had applied for rights in the fishery in September 2001. The algorithm that applied once these two pieces of information were obtained was similar to that in

[82] An EPR, or equivalent percentage right, essentially translated the two rights for existing rights holders in 2001, into a single equivalent right for the combined fishery.

[83] The EPRs used by MCM in this manner included the refinements detailed in Appendix 6.1.

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Chapter 5 (incorporating equations 5.14-5.25), except that the EPR value, $p_{EPR,d'}$, calculated for each 2001 rights holder (d') on the basis of their quota allocations for 2001, was now replaced by $p_{PR,d}$, the percentage right MCM had allocated to each newly-confirmed rights holder d for 2002-2005. Furthermore, a set of control parameters (β_d, $\alpha_{ns,d}$ and $\alpha_{ads,d}$) was associated with each rights holder d by matching that rights holder's choice of preferred pilchard-anchovy ratio with the ratios implicit in the 2001 realisation of OMP02 (M_1 in Chapter 5 – see also Appendix 5.4)[84].

The original plan for the implementation of OMP02 towards the end of 2001 was as follows.

1. The percentage right $p_{PR,d}$ allocated by MCM to each newly-confirmed rights holder d would be announced by the first week of December 2001.
2. A meeting would be convened in the second week of December to allow each newly-confirmed rights holder a one-off opportunity to revise the preferred pilchard-anchovy ratio they had specified on the application forms for rights to the pelagic fishery, submitted in September 2001.
3. TACs, bycatch allowances and associated quotas, based on OMP02 (this having been formally adopted by the Minister), the November 2001 survey results and inputs from 1 and 2 above, would be announced towards the end of December 2001.

The reasons for allowing a one-off opportunity for all newly confirmed rights-holders to revise their preferred pilchard-anchovy ratios (2 above) were as follows.

- Rights holders that were new to the fishery, and thus had had no exposure to the principles and discussions underlying OMP02, could argue disadvantage at not having had the information necessary to make an informed decision regarding their desired pilchard-anchovy ratio when submitting their application for rights in September 2001. This situation arose because, although it may have been feasible to convene a meeting of all applicants (there were 187 in total compared to the 114 rights holders in 2001), there were concerns within MCM regarding the expectations (related to allocation of rights) that such a meeting would foster amongst rights applicants, and the message it might mistakenly send regarding the rights allocation process (i.e. that it had somehow been "flawed" in the way it was implemented). A decision was therefore taken to hold the meeting as soon after percentage rights were announced as possible, so that only successful applicants would attend such a meeting.

[84] Once again, this process included the refinements presented in Appendix 6.1.

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- Over the years, the structure of the pelagic fishery had developed a strategic flaw, with too many rights holders having pilchard-only or anchovy-only allocations. This situation had the potential to give rise to severe hardship for these rights holders, because it is not uncommon for pelagic fisheries to undergo large fluctuations (up to two orders of magnitude) within a relatively short period of time (Lluch-Belda 1989), and to be subject to regime shifts (e.g. the virtual disappearance of anchovy off Namibia towards the late 1990s – Boyer and Hampton 2001). The opportunity to revise ratios allowed scientists to highlight this concern to industry, and to demonstrate that they could acquire a reasonable quantum of the other species while hardly reducing quotas for their species of primary interest (see Figure 6.1, which shows typical quotas to be expected for a hypothetical rights holder allocated 1% as a percentage right in the pelagic fishery, given a range of choices for the pilchard-anchovy ratio). This would allow risk to be spread in the interest of sounder and more stable management of the pelagic fishery.
- With additional information (such as Figure 6.1, which was not available at the time of the September 2001 deadline for applications), rights holders had the opportunity to make a choice better attuned to their needs. This would lead to a lower likelihood of dumping as each sought their desired species mix in catches. However, it was stressed to industry that their preferred pilchard-anchovy ratio would only be achieved on average. This is because the large fluctuations typical of pelagic species are not necessarily in the same direction or to the same extent for two species in the same system (Figure 1.5). These fluctuations are reflected in the changing TACs set from year to year. Therefore, the exact mix of pilchard to anchovy actually realised will not always coincide with the choice of preferred pilchard-anchovy ratio every year, but should nevertheless do so on average. The 90% probability regions shown by bars in Figure 6.1(d) show the extent to which the selected ratios will not always coincide with ratios actually realised.

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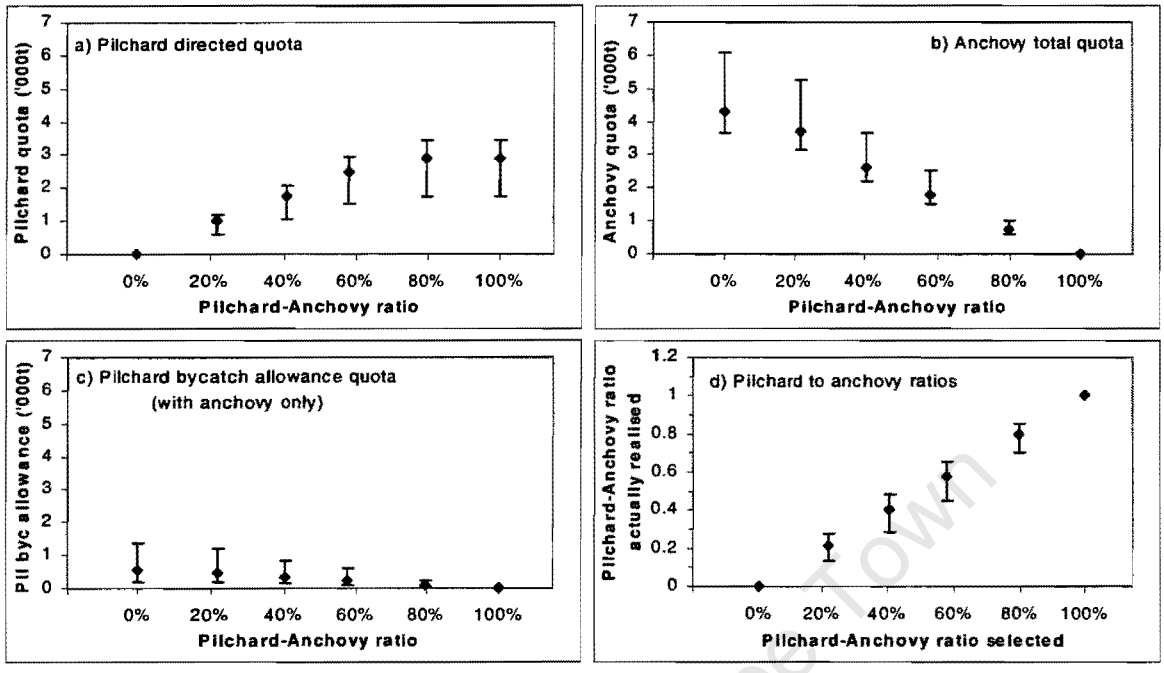
Figure 6.1 Five-year summaries of quotas for different pilchard-anchovy ratios (calculated as P/(P+A), and expressed as a %) shown on the horizontal axis of each graph. Solid diamonds indicate averages over five years. Bars indicate the variation to be expected around these averages (i.e. 90% of all values to be expected for a selected pilchard-anchovy ratio occur within these bars). [Note that these results include the refinements discussed in Appendix 6.1.]



6.2 Implementation difficulties

The process (due to be completed in the first week of December) of announcing successful applicants to the pelagic fishery, together with the percentage right of the fishery awarded to each of them, fell behind schedule. These rights were eventually announced only very late in December, so that it was not possible before the 2002 fishing season would commence in early January to hold the meeting to allow for a one-off opportunity for revising preferred ratios. Accordingly, it was decided to use the preferred ratios specified on the application forms submitted in September 2001 to provide TAC/Bs and initial quota allocations. It was also decided to simultaneously announce percentage rights and initial quota allocations for each successful rights applicant, which meant that the results from the November 2001 survey were not available in time to form part of this process. Consequently, OMP99 was used to provide provisional TAC/Bs[85]. Because it was necessary to ensure consistency with future applications of OMP02 (and thus the ITD method), the approach used to calculate quota allocations was to apply OMP02 (with the allocated percentage rights and originally specified preferred ratios as

[85] Although generally not favoured by scientists because they are not based on any new information (Chapter 4), there was no other alternative but to use these provisional TACs. They are based simply on the minimum or maximum reduction constraints of OMP99 (Chapter 4).

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inputs), but then to scale the TAC/Bs that resulted from summing the quota allocations provided by OMP02 so that they matched the provisional TAC/Bs that OMP99 provided.

The meeting for the one-off opportunity to revise preferred pilchard-anchovy ratios, and to provide further information about OMP02, was finally held in early February 2002. Once specified, these revised pilchard-anchovy ratios would remain fixed for a period of four years, and would be used in the first "proper" implementation of OMP02[86], to set the pilchard directed TAC, anchovy 1st TAC and pilchard 1st TAB, and subsequent TAC/Bs (Figure 5.1), and hence also the quota allocations that made up these TAC/Bs (equations 5.19-5.25).

Once the process of revising the pilchard-anchovy ratios was complete (final rights having already been fixed), it was necessary to re-test OMP02 under the full suite of robustness tests shown in Chapter 5, in case some re-calibration was necessary. This re-testing was one of the recommendations from the BENEFIT Stock Assessment Workshop held in November 2001, Cape Town (Anon. 2001b). One of the concerns expressed at this Workshop (at which results shown in Chapter 5 were presented) was that a large change in the distribution of pilchard-anchovy ratios (and hence in the β-distribution – see Figure 5.9) which moved its peak appreciably towards one or the other species, could lead to a marked rise in *risk* for that species beyond acceptable levels because of the non-linear nature of the pilchard-anchovy trade-off curve (Figure 5.6). In their applications for rights to the pelagic fishery, the industry had already shown a marked shift towards pilchard compared to 2001, and the opportunity to revise these ratios provided responses that continued this trend, although there was also a move away from rights holders requesting 100% pilchard (Figure 6.2).

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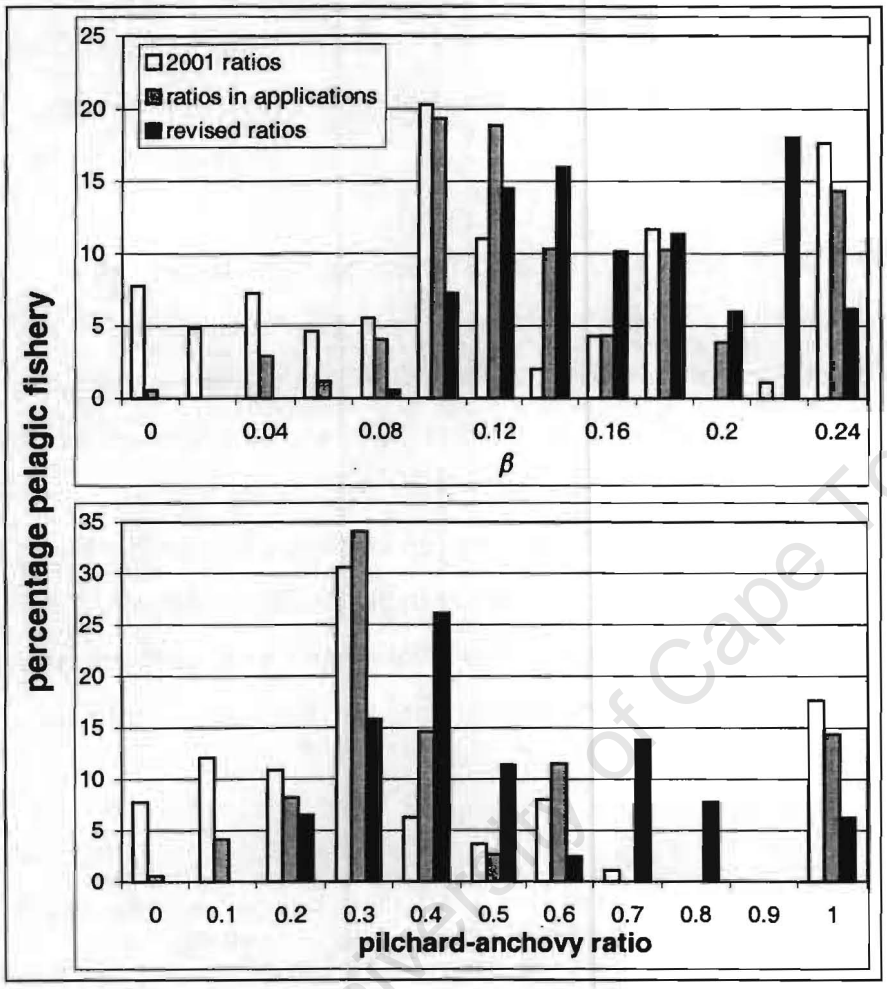
[86] The provisional allocations for 2002 were not a "proper" implementation of OMP02, because TACs were scaled to match the provisional TACs provided by OMP99.

Figure 6.2 Distribution of β values and the corresponding pilchard-anchovy ratios to which these β values relate (with the "ratios" calculated as pilchard/[pilchard + anchovy]) at three different stages during the development and implementation of OMP02: "2001 ratios" are those shown in Figure 5.9 (but incorporating the refinements discussed in Appendix 6.1); "ratios in applications" are the preferred ratios that eventually successful rights applicants entered on their applications forms in September 2001; "revised ratios" are the ratio selections that resulted from the one-off opportunity given to rights holders to revise their preferred ratios. [Note that the revised ratios indicated here include a 15% cap on the shift towards pilchard, as explained later – see Figure 6.4.]



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6.3 Cap on shift towards pilchard

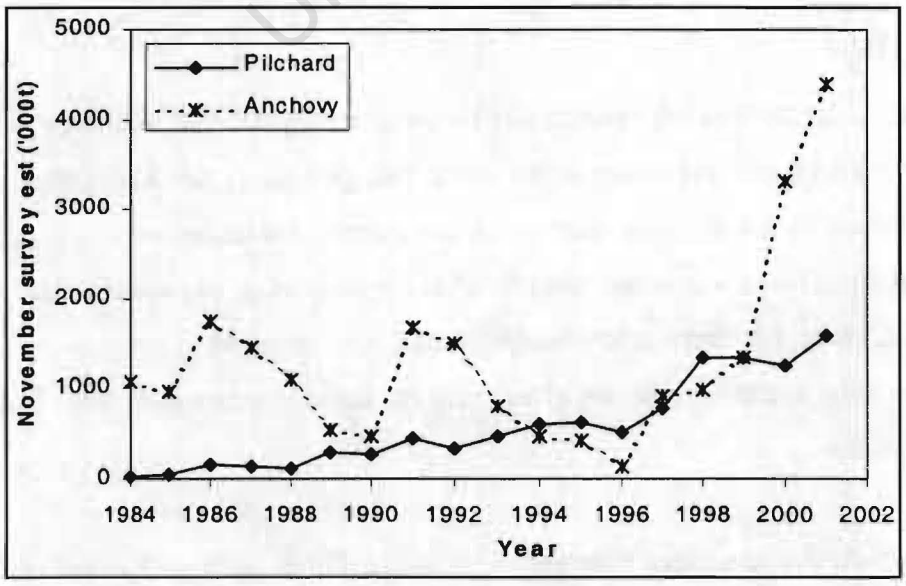
When rights holders were accorded the one-off opportunity to revise their preferred pilchard-anchovy ratios (after they were awarded percentage rights of the pelagic fishery for 2002-2005 and provisional quota allocations for 2002), there were a few companies that requested particularly large changes in these ratios – in some cases by over 30 percentage points towards pilchard. Incorporating the full extent of these ratio changes would have resulted in a much lower *risk* to and catches from the anchovy resource, effectively resulting in wastage of this resource through under-utilisation.

There was also a further problem that arose as a result of the continued high pilchard November survey result for 2001 (Figure 6.3), and the consequent capping of the pilchard directed TAC for

2002 at 250 thousand tons (the maximum value allowed for the pilchard directed TAC, according to OMP02). Under normal circumstances, the ITD method is such that one rights holder (say rights holder A) changing his/her ratio would not affect allocations made to another rights holder (say rights holder B), had rights holder B decided not to change his/her ratio. This is because a request by rights holder A for an increased pilchard-anchovy ratio would result in increased pilchard and decreased anchovy quotas for this rights holder, with the overall pilchard and anchovy TACs moving up and down respectively by the identical amounts, so that rights holder B would not be affected (see Figure 5.8).

However, the capping of the pilchard directed TAC for 2002 meant that rights holders who increased their preferred pilchard-anchovy ratios for the first "proper" implementation of OMP02 would gain an even bigger share of the pilchard directed TAC at the expense of others who did not ask for such an increase. Because of the unavoidable delays in the allocation process (as mentioned earlier), rights holders were aware of the 2001 November survey results (Figure 6.3) and also that the pilchard directed TAC would be capped before they revised their preferred pilchard-anchovy ratios to be used for the first proper implementation of OMP02. This is the reason why a number of rights holders (particularly those with larger percentage rights) asked for a larger increase in the pilchard-anchovy ratio than their long term interests may have dictated.

Figure 6.3 November acoustic survey estimates ("capped") of spawner biomass for pilchard and anchovy (thousand tons), as given in Figure 1.5, but with the addition of the 2001 survey results. [Note that, as in Figure 1.5, although this Figure reflects survey results in the year that they took place, the convention adopted is that estimates from the November survey of year y are reflected as estimates for the beginning of year y+1.]



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Assuming that all rights holders had elected to keep the preferred pilchard-anchovy ratios they specified in the application forms for pelagic rights, all rights holders would have received an 83% increase in their pilchard quota following the first "proper" implementation of OMP02, which gave rise to an increase in the pilchard directed TAC up to the maximum limit of 250 thousand tons. However, the move by some rights holders to increase their preferred ratios, while others did not, meant that the former would receive more and the latter less than an 83% increase in their directed pilchard quotas. This had the potential for strong objections from some in the industry, despite the fact that there would have been a longer-term balancing out effect, and that those who received less than 83% increase in directed pilchard quotas would also have consequently received larger increases in their anchovy quotas than might otherwise have been expected. In order to pre-empt such objections in a manner perceived to be equitable, and to counter very large changes in ratios that would have led to appreciable under-utilisation of anchovy, the following principles were applied for the implementation of OMP02 (Anon. 2002).

i) Revised ratio changes (limited by a maximum increase in the pilchard-anchovy ratio of 15 percentage points) would be phased in over two years, so that for 2002, the average of allocations computed with and without ratio changes would apply.

ii) If under i) (and for 2002 only), a directed pilchard quota from the first proper implementation of OMP02 (the final directed pilchard quota for the year) was less than (the "expected") 83% increase in the provisional quota, it would be increased to reflect an 83% increase.

iii) No anchovy quota for 2002, from the first proper implementation of OMP02, would be less than the corresponding provisional anchovy quota.

Although principle iii) had negligible impact on the anchovy TAC, involving only an additional 20 tons, principle ii) required the pilchard TAC to exceed 250 thousand tons by almost eight thousand tons. This was, however, considered to be scientifically acceptable, as it posed no real additional *risk* to the pilchard resource, given the "positive" exceptional circumstances resulting from record levels of pilchard abundance (Figure 6.3; Anon. 2002). Figure 6.4 illustrates the β and pilchard-anchovy ratio changes with and without the 15% cap introduced by principle i).

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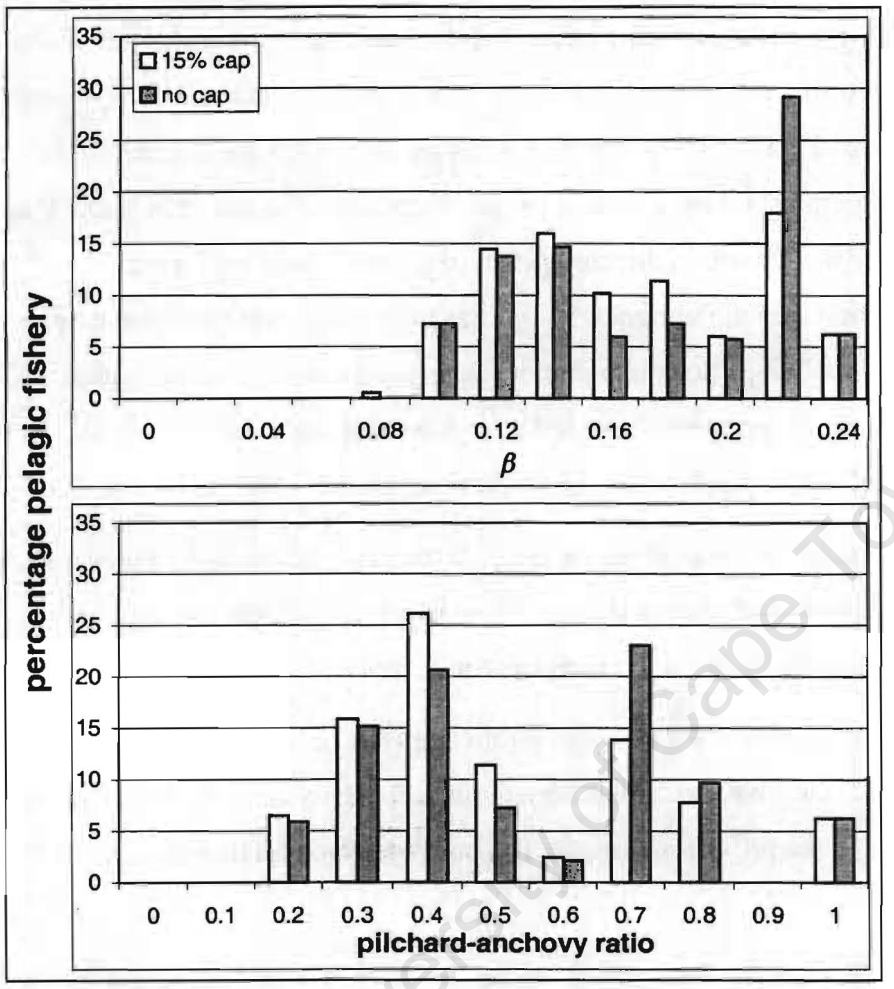
Figure 6.4 A repeat of the distribution of β values and corresponding pilchard-anchovy ratios for the "revised ratio" option of Figure 6.2, which includes a 15% cap on increases above the ratios specified in application forms for rights in the pelagic fishery. This is compared to the option when not applying this cap. The top panel indicates the distribution of β-values, and the bottom panel the corresponding distribution of pilchard-anchovy ratios. [These distributions incorporate the refinements of Appendix 6.1.]



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6.4 Final robustness tests

Following a recommendation from the BENEFIT Stock Assessment Workshop (as mentioned earlier), a re-test of OMP02 subject to the full suite of robustness tests listed in Chapter 5, was performed and the results are shown in Table 6.1. These were based upon the 15 percentage point cap on the amount by which the revised pilchard-anchovy ratios could exceed the ratios specified on the original application forms for rights to the pelagic fishery for 2002-2005. Although the results in Table 6.1 indicated a slight rise in *risk* for pilchard (and corresponding decrease in *risk* for anchovy) compared to Table 5.5, this increase in pilchard *risk* was deemed sufficiently small to render a re-calibration of OMP02 unnecessary.

Table 6.1 Robustness test results for OMP02, assuming a 15% cap on revised pilchard-anchovy ratios as shown in Figure 6.4. This is essentially a repeat of Table 5.5, to which reference should be made for definitions. Proportional increases in $risk^P_{20\%}$ of over 35% compared to Table 5.5 are highlighted in bold.

		Pilchard Summary Statistics							Anchovy Summary Statistics							
OM		$\overline{C}^P_{dir}$	$\overline{C}^P_{bye,tot}$	$\overline{V}^P$	$depl^P_K$	$depl^P_0$	$risk^P_{20\%}$	$risk^P_B$	$\overline{C}^A_{ns}$	$\overline{C}^A_{ads}$	$\overline{C}^A_{tot}$	$\overline{V}^A_{ns}$	$\overline{V}^A_{ads}$	$depl^A_K$	$depl^A_0$	$risk^A_{15\%}$
P_0	A_0	193	19.2	0.19	0.69	0.72	0.120	0.320	75	96	171	0.27	0.11	0.85	0.43	0.076
P_1	A_0	216	19.4	0.14	0.73	0.87	0.100	0.098	75	96	171	0.26	0.11	0.85	0.43	0.064
P_2	A_0	163	18.6	0.31	0.64	0.69	0.112	0.678	75	96	171	0.27	0.11	0.85	0.43	0.076
P_3	A_0	187	19.0	0.21	0.67	0.71	0.124	0.354	75	96	171	0.26	0.11	0.85	0.43	0.080
P_4	A_0	188	19.0	0.21	0.68	0.72	0.108	0.308	75	96	171	0.26	0.11	0.85	0.43	0.074
P_5	A_0	168	18.4	0.26	0.51	0.64	0.326	0.632	75	96	171	0.27	0.11	0.85	0.43	0.072
P_6	A_0	186	19.2	0.20	0.84	0.77	0.030	0.304	75	96	171	0.27	0.11	0.85	0.43	0.080
P_7	A_0	163	19.2	0.20	0.71	0.86	**0.138**	0.456	75	96	171	0.27	0.11	0.85	0.43	0.074
P_8	A_0	197	19.2	0.18	0.70	0.74	0.062	0.200	75	96	171	0.27	0.11	0.85	0.43	0.078
P_9	A_0	193	19.2	0.19	0.70	0.79	0.088	0.212	75	96	171	0.27	0.11	0.85	0.43	0.074
P_{10}	A_0	191	19.2	0.19	0.72	0.94	0.032	0.140	75	96	171	0.26	0.11	0.85	0.43	0.072
P_{11}	A_0	199	19.5	0.17	0.66	1.24	0.134	0.300	75	96	171	0.27	0.11	0.85	0.43	0.076
P_{12}	A_0	204	19.3	0.17	0.68	0.84	**0.150***	0.238	75	96	171	0.26	0.11	0.85	0.43	0.076
P_{13}	A_0	196	19.2	0.18	0.87	0.84	0.286	0.456	75	96	171	0.27	0.11	0.85	0.43	0.076
P_{14}	A_0	193	19.2	0.18	0.70	0.72	**0.110**	0.302	75	96	171	0.27	0.11	0.85	0.43	0.076
P_{15}	A_0	136	18.5	0.25	0.53	0.30	0.426	0.898	75	96	171	0.27	0.11	0.85	0.43	0.076
P_0	A_1	193	19.2	0.19	0.69	0.72	0.120	0.316	75	96	171	0.26	0.10	0.76	0.46	0.158
P_0	A_2	193	19.0	0.19	0.70	0.72	0.112	0.316	74	95	170	0.26	0.12	0.92	0.41	0.056
P_0	A_3	193	19.0	0.19	0.70	0.72	0.114	0.314	74	95	169	0.26	0.12	0.94	0.38	0.046
P_0	A_4	193	19.2	0.19	0.69	0.72	0.116	0.320	76	96	172	0.27	0.11	0.89	0.43	0.064
P_0	A_5	193	19.2	0.19	0.69	0.72	0.118	0.318	75	96	171	0.27	0.11	0.86	0.43	0.090
P_0	A_6	193	19.3	0.19	0.69	0.72	0.118	0.318	75	96	172	0.28	0.11	0.78	0.48	0.162
P_0	A_7	193	19.0	0.19	0.70	0.72	0.112	0.314	74	96	170	0.26	0.11	0.91	0.39	0.062
P_0	A_8	193	18.9	0.19	0.70	0.72	0.114	0.312	72	98	169	0.24	0.08	0.85	0.42	0.028
P_0	A_9	193	19.0	0.19	0.70	0.72	0.114	0.312	74	96	170	0.26	0.11	0.85	0.44	0.064
P_0	A_{10}	193	19.1	0.19	0.69	0.72	0.116	0.316	75	96	171	0.27	0.11	0.90	0.42	0.062
P_0	A_{11}	193	19.1	0.19	0.69	0.72	0.118	0.314	74	96	171	0.26	0.10	0.82	0.44	0.124
P_0	A_{12}	192	19.6	0.19	0.69	0.72	0.122	0.322	83	97	180	0.29	0.09	0.76	0.55	0.154
P_0	A_{13}	192	20.2	0.19	0.69	0.71	0.134	0.326	87	90	177	0.33	0.18	1.23	0.62	0.302
P_0	A_{14}	193	19.1	0.19	0.69	0.72	0.118	0.314	74	96	170	0.26	0.11	0.85	0.43	0.094
P_0	A_{15}	193	18.7	0.19	0.70	0.72	0.108	0.302	64	78	142	0.27	0.34	0.74	0.19	0.122

* Note that for P_{11}, P_{12} and P_{13}, the increase in $risk^P_B$ is of greater concern (Chapter 5). Therefore, although the increase in $risk^P_{20\%}$ is large for P_{12}, the increase in $risk^P_B$ is only 10% (compared to 22% for P_{11} and 8% for P_{13}).

6.5 Conclusion

The "capped" version of OMP02 (15% cap to be phased in over two years) was approved and consequently used to compute the quota allocations eventually awarded. This constituted the first "proper" implementation of OMP02 and the resultant quota allocations superseded the provisional allocations for the 2002 fishing season made earlier.

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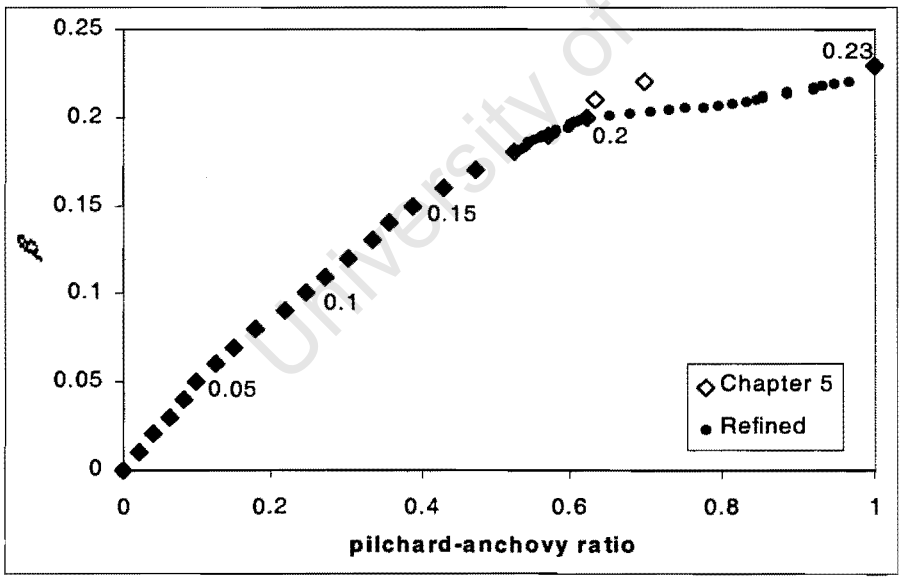
APPENDIX 6.1

Refinement of OMP02

The EPRs used by MCM as a guideline to compare to the percentage right eventually awarded to successful rights applicants, and the algorithm used for matching a rights holder's preferred pilchard-anchovy ratio with a corresponding β value, and hence set of control parameters[87] (Appendix 5.4), required a refinement of OMP02 for the following reason. Although the 2001 realisation curve for OMP02 used for computing EPRs and matching preferred ratios to β values (Appendix 5.4) is continuous, it is possible to compute only a finite number of points when compiling this realisation curve because of constraints on computer processing time. The grid of β values first used for compiling the 2001 realisation curve did not initially present a problem for the EPRs of Chapter 5, even though this grid resulted in no matching pilchard-anchovy ratios over the range (0.7; 1). This was because there were no rights holders in 2001 with a pilchard-anchovy ratio that fell in this range (open diamonds of Figure A6.1.1).

Figure A6.1.1 Values for β and the pilchard-anchovy ratio implicit in the 2001 realisation curve of OMP02, for the realisation curve used in Chapter 5 (Appendix 5.4) and the refined version shown later (Figure A6.1.3). The values shown along the curves are those for β.



The initial β grid proved to be inappropriate, however, for the algorithm used to match preferred ratios to β values, when the peak of the distribution of β values/preferred ratios moved towards pilchard (i.e. towards the right in Figure 6.2). This meant that preferred ratios were being selected in a part of the pilchard-anchovy range that was not well represented in Figure A6.1.1,

[87] β is the only free parameter when computing a trade-off curve, so that a set of control parameters is associated with each β value (Chapter 5).

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and for which linear interpolation did not work well because of the large increase from a ratio of 0.7 to a ratio of 1 for a relatively small increase in β (0.22 to 0.23). This flattening of the curve in Figure A6.1.1 was partially caused by α_{ads} not being reduced quickly enough to zero to enable pilchard-anchovy ratios to be more evenly spread. This problem was addressed by reducing α_{ads} to zero more quickly, and by inserting more points between $\beta = 0.18$ and 0.23 when constructing the average trade-off curve for OMP02, and thus also the 2001 realisation curve for OMP02, as shown in Figure A6.1.2. The effect of these refinements on the average trade-off and 2001 realisation curves for OMP02 are shown in Figure A6.1.3.

Figure A6.1.2 An illustration of how α_{ads} was reduced more quickly to zero ("refined" curve) in order to get a better spread of pilchard-anchovy ratios for ratios closer to 1 than the "Chapter 5" curve (see Figure 5.2). The formula used to achieve this is $\alpha_{ads} = 2\,(0.18/\beta)^{25}$ for $\beta = 0.180, 0.181, \ldots, 0.220$, and $\alpha_{ads} = 0$ for $\beta = 0.23$.

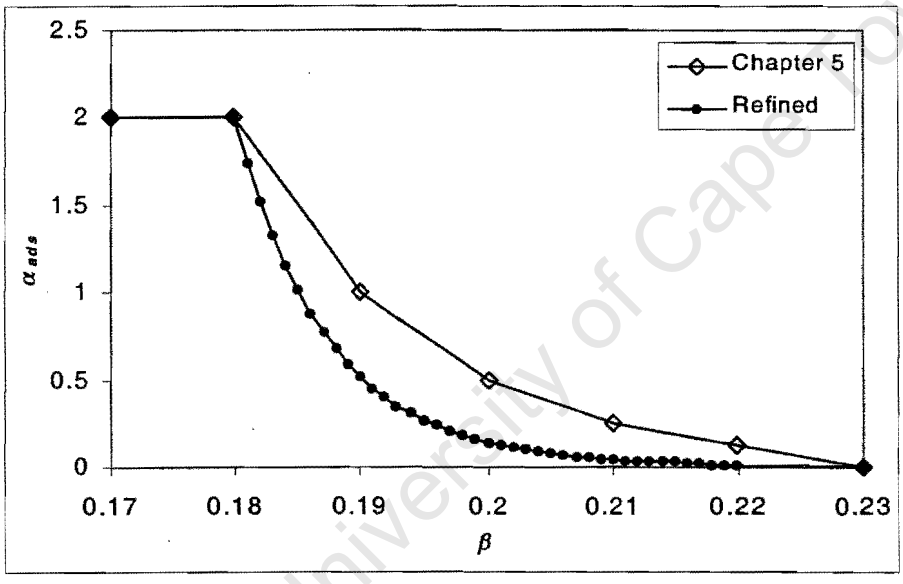

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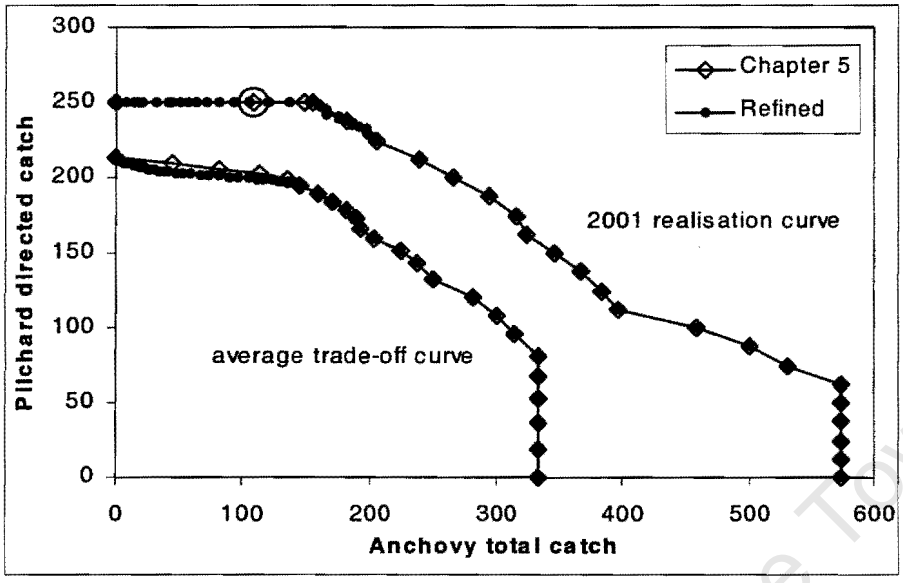
Figure A6.1.3 A repeat of Figure A5.4.1 (see also Figure 5.5), illustrating both the average trade-off curve, and the 2001 realisation of this curve for OMP02. The plot compares the curves developed in Chapter 5 to corresponding curves that incorporate the refinements shown in Figures A6.1.1-2. The dots and open diamonds illustrate the β-values along the curves, starting from $\beta = 0$ on the horizontal axis to $\beta = 0.23$ on the vertical axis. The circle on the 2001 realisation curve highlights the main (and small) difference between the "Chapter 5" and "refined" results, with β-values of 0.220 and 0.203 for the former and latter respectively within this circle. Catches are in thousand tons.



The refinements of Figures A6.1.1-3 also meant that the non-linear adjustment (NLA) factors of Figure 5.11 had to be re-calculated, and these are shown for both the anchovy normal and additional seasons in Figure A6.1.4 (the pilchard results are not shown as they hardly differ from those shown in Figure 5.11). The refined NLA factors in Figure A6.1.4 were used for all robustness tests of OMP02 presented in Chapter 6.

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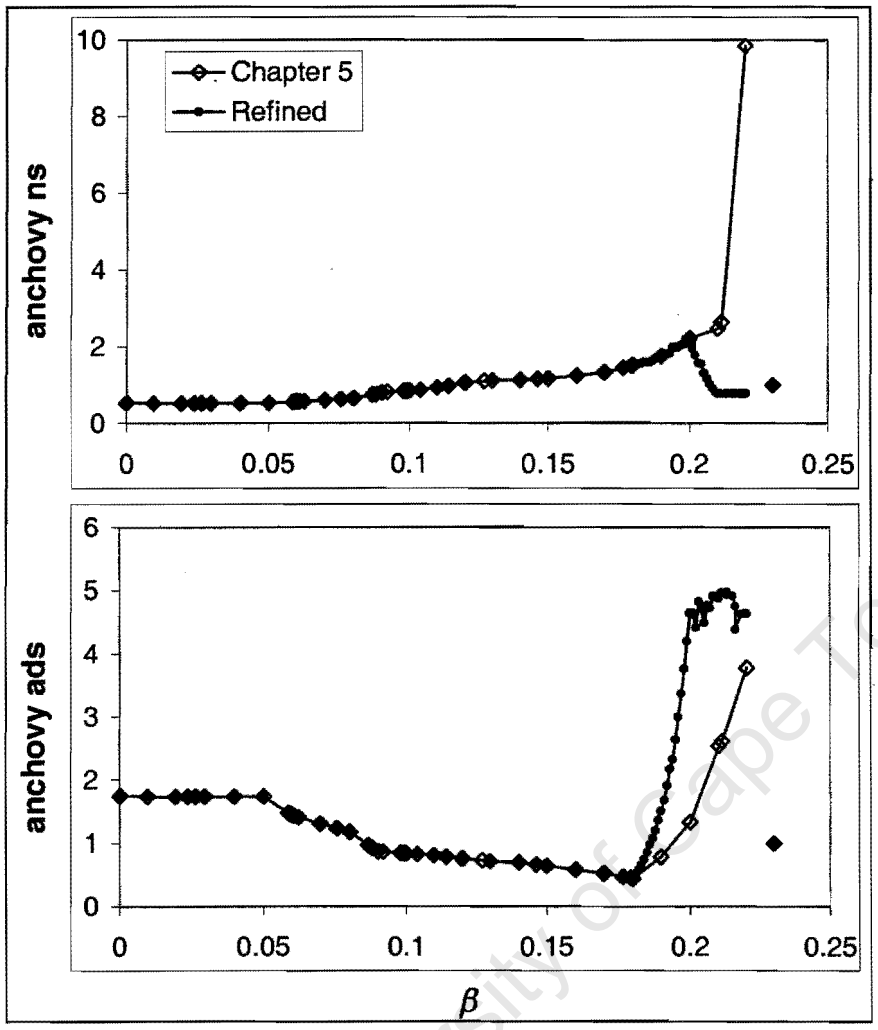
Figure A6.1.4 NLA factors for the anchovy normal (top panel) and additional (bottom panel) seasons, denoted "anchovy ns" and "anchovy ads". The plots compare the results of Chapter 5 with the results taking the refinements of Figures A6.1.1-3 into account.



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CHAPTER 7

Long-Term Harvest Strategies Under Regime Shifts

MPs are used to evaluate long-term harvesting strategies under conditions of environmental regime change, based on the South African pilchard-anchovy fishery. The MPs considered have similar features to OMP99, an earlier version of OMP02, described in Chapter 4. Summary statistics incorporate an economic sub-model, based on actual data from the fishery, which calculates the net present value of future profits and the proportion of future years that experience zero or negative profit. Regime shifts are modelled as sinusoids and are incorporated in the functions used to generate future recruitment to the pilchard and anchovy resources. Cycles for the two species are 180° out of phase, and a range of amplitudes (from zero to halving/doubling of recruitment) and periods (30 and 50 years) are considered. Two types of estimators are used to "track" the pilchard adult biomass, namely a 6-year running mean, and the actual position in the cycle subject to different levels of measurement error. The MPs considered differ according to the management action taken when the estimators show the pilchard cycle to be in a trough. These management actions include reducing anchovy catches to avoid juvenile pilchard, reducing the juvenile pilchard bycatch ratio with anchovy that is initially allowed, and reducing directed catches of pilchard. These MPs are compared to one another, and to a baseline MP, where no management action based on the estimators is taken. Key results of this Chapter are as follows.

- Comparing the estimators, the 6-year running mean outperforms knowledge of the actual position in the pilchard cycle in most cases. Where there are any gains for the latter, these would need to be judged against the feasibility and likely cost of obtaining the necessary information.
- MPs not focussed on fishery-related interactions (e.g. those that reduce only the pilchard directed catches) do not show improvements compared to the baseline MP. These MPs show rapid deterioration in performance as the amplitude of regime cycles increases.
- Effective management of fishery-related interactions becomes more important for pilchard as the amplitude of regime cycles increases, to the extent that it is possible to maintain levels of average catch and profit even though the frequency of low pilchard biomass values and no-profit situations increases with increasing regime cycle amplitude.

7.1 Introduction

Fisheries for small pelagic species in upwelling systems (e.g. Peru/Chile, Japan, Namibia/South Africa, Northwest Africa and California – Chapter 1) are characterised by "regime shifts" in which the average abundance of pilchard and of anchovy (both in absolute terms and relative to one another) undergo extensive changes, typically on a time-scale of several decades (Lluch-Cota *et al.* 1997). This inter-decadal variability is caused by poorly understood environmental forcing and creates substantial problems for the fishing industry and for fisheries management, leading to changes in average annual catches of each stock that can exceed an order of magnitude. The annual fluctuations impact on fishing practices, marketing and management. However, the underlying long-term changes are difficult to detect in the short-term as they are masked by both inter-annual variability and uncertainty in estimates of abundance. Hence, the fishing industry and managers are normally uncertain as to where in a regime cycle they are at any given time, and hence how best to plan for the medium-term future.

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Environmentally driven long-term changes in fish populations, which can play a major role in determining how these populations respond to fishing pressure, are rapidly being recognised as a critical problem in fisheries science (MacCall 2002). This is because these long-term changes cause severe confusion in management systems when assessment scientists are unable to distinguish between impacts that result from the environment, and those that result from fishing (Walters and Parma 1996). The "environment vs. fishing" debates that ensue from such confusion can lead to damaging delays in corrective action, particularly as there is little prospect that fisheries research will provide sufficiently fast answers to such debates (Walters and Collie 1988). Under these circumstances, Walters and Parma (1996) suggest the development of management strategies that are robust to causes of fluctuations, are easily understood by all stakeholders and are practical to implement.

In the spirit of Walters and Parma (1996), this Chapter aims to use the MP approach to investigate different harvesting strategies in the pilchard-anchovy fishery in order to identify improved general approaches to management in the face of both short- and long-term uncertainty. The MP used as a basis for this investigation is OMP99 (briefly described in Chapter 4 and Appendix 4.1), but with a few modifications[88]. This MP is renamed BL (baseline) in this Chapter. Parameter estimates and a description of the operating model used to test BL are provided in Appendix 7.1.

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7.2 Summary performance statistics

The summary performance statistics used here are slightly different to those presented in Chapter 5, but have been used in the same manner (see sub-section "General" at the end of Appendix 5.1), i.e. these summary statistics are used to evaluate a range of MP variants, and to investigate their robustness to different underlying Operating Models (OMs). However, the only OMs considered in this Chapter are those dealing with regime shifts (modelled as sinusoids – see discussion below) (Appendix 7.1). The summary statistics can be categorised under "resource conservation" and "economic performance" as before. [For ease of presentation, superscripts indicating P/A for pilchard/anchovy have been omitted below.]

[88] The projection period used is 100 years, in contrast to the 20 used to evaluate OMP99, and a constraint has been placed on r_y (see Appendix 4.1 for definition). OMP99 was used instead of OMP02 because the work in Chapters 7 and 8 was completed before OMP02 was fully developed.

Resource conservation

Two summary statistics are considered here, namely:

risk	the probability that adult biomass falls below 20% of K_y (the average adult biomass in the absence of exploitation, which varies over time – see Chapters 2 and 3) at least once during the projection period; and
depl	an abbreviation of "depletion", which measures the average adult biomass at the end of the projection period as a proportion of K_y at the time concerned (equation A7.1.1).

Economic performance

Four summary statistics are considered here, namely:

$\overline{C}$	the average of the annual total catch (C_y) over the projection period;
V	the mean annual change in C_y;
NPV	the Net Present Value of future profits, calculated as an average (Appendix 7.2); and
Loss	the proportion of years that experience zero or negative profit.

Performance of an MP is generally considered to be best when *risk*, *V* and *Loss* are minimised, *depl* is kept as high as possible, and $\overline{C}$ and *NPV* are maximised.

7.3 Alternative scenarios considered

The only difference between the various operating models presented in this Chapter is in the parameters used to model regime shifts (Appendix 7.1). The motivation for using sinusoids as the class of regime shifts considered in this Chapter comes from studies on fish-scale-deposition rates, which show regime shifts to be roughly periodic for pilchard and anchovy in the California current system (Soutar and Isaacs 1969, Baumgartner *et al.* 1992). Furthermore, using spectral analysis and removing low frequency variability (periods > 150 years) from the original pilchard and anchovy scale-deposition rate series by applying a low-pass filter, Baumgartner *et al.* (1992) found a dominant 57-year peak in the resultant spectra for both species. This would suggest the use of a Fourier series with a sinusoid as a dominant first order term and a period of 50-60 years to model regime shifts. The analysis of Baumgartner *et al.* (1992) did not, however, consider periods shorter than 50 years due to the sample resolution of their data (10 years). Because of the potentially more serious impact of cycles with shorter periods on short- to medium-term management, it was decided to consider sinusoids (termed cycles below) with periods (g_2) of 30 or 50 years in the analysis that follows.

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The amplitude of the cycle is reflected by the amplitude factor g_1, and the following values were considered: {1; 1.2; 1.5; 2}. A value of g_1=1 means that there are no regime cycles (so g_2 need not be specified in this case). A value of g_1=2 reflects a doubling (at the peak of the cycle) and halving (at the trough) of the functions used to generate recruitment (equations A7.1.2 and A7.1.3). [Note the additional variation in recruitment arising from equation A7.1.3 over and above the regime cycle of equation A7.1.2. This means that for g_1=2 (say), a "good" recruitment event generated at the peak of the regime cycle could be much more than just double the very long-term average recruitment.]

Equation A7.1.2 is written so that the cycles commence in 1998, initially increasing for pilchard and decreasing for anchovy. This reason this was done is to capture the end-of-the-1990s situation, which suggested a shift towards pilchard (Figure 1.5).

7.4 Alternative MPs considered

If management in the presence of regime cycles is to succeed, information is required about the underlying position in the regime cycle at any given time. One can then decide how to manage the resources using this information. When investigating alternative MPs, this Chapter has therefore considered two aspects, namely defining estimators that provide information about the regime cycle, and developing decision rules (and hence alternative MPs) that use this information.

Estimators

Two approaches were considered, denoted D1 and D2.

D1 This approach assumes that no direct information on the regime cycle is available and therefore uses an indirect method to obtain the necessary information. The approach simply calculates, in year y, an x-year running mean ($\mu_{y,x}$), and an overall mean (μ_y) of the survey estimates of pilchard adult biomass (equation A5.1.16) as follows

$$\mu_{y,x} = \frac{1}{x} \sum_{j=y-(x-1)}^{y} B^P_{j,Nov}$$

$$\mu_y = \frac{1}{y-1983} \sum_{j=1984}^{y} B^P_{j,Nov} \qquad 7.1$$

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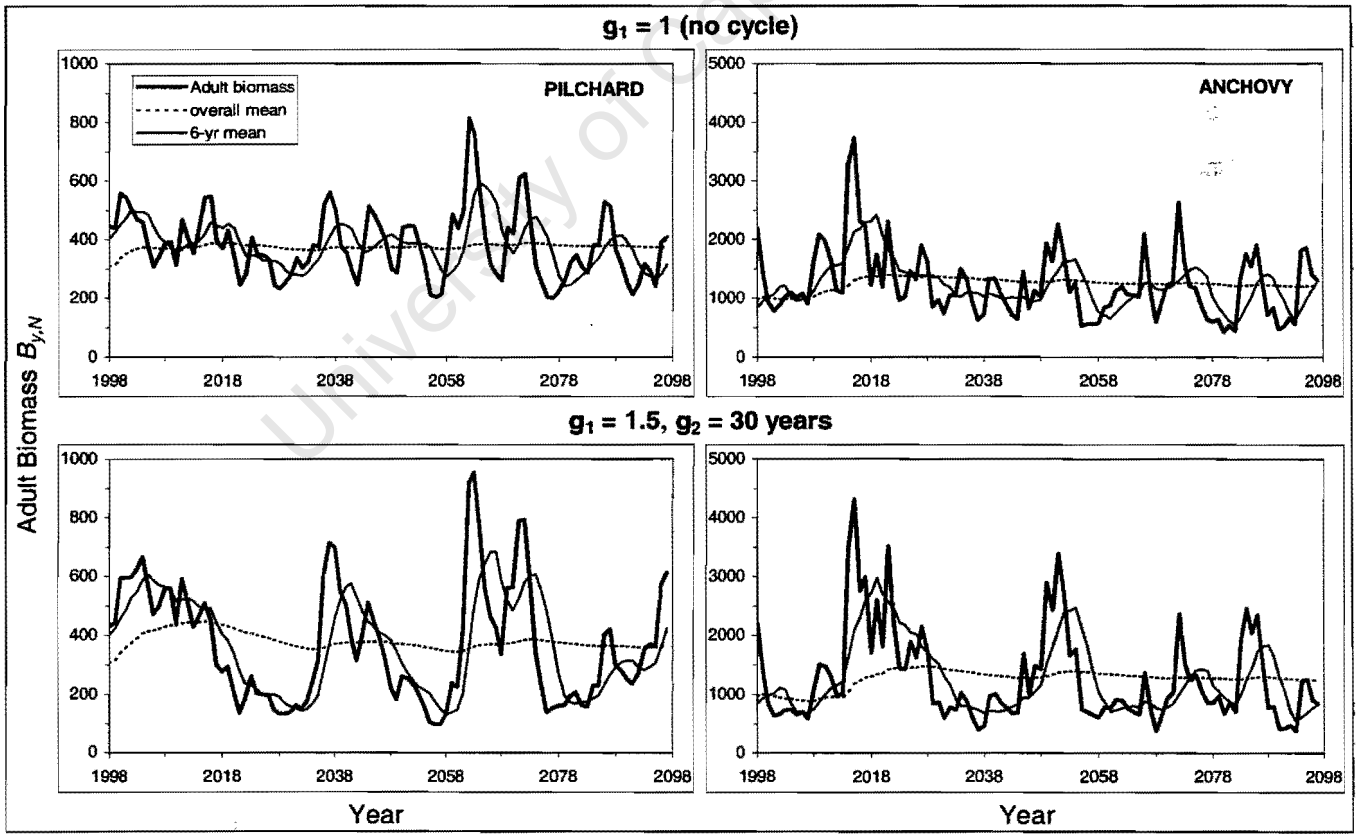
[In equation 7.1, the actual survey estimates for 1984-1996 were used. Thereafter, simulated estimates were substituted.] The method then calculates the following:

$$d_{y,1} = \frac{\mu_{y,x}}{\mu_y} \qquad 7.2$$

Values of x considered are {2; 4; 6; 8; 10; 12; 14}. Figure 7.1 illustrates a typical simulation run where $\mu_{y,x}$, and μ_y are calculated for "true" adult biomass values (i.e. $B_{y,Nov}$ in equation 7.1 replaces $B_{y,N}$ as calculated in equations A5.1.13-14) both with and without regime cycles for both pilchard and anchovy. The optimal choice for x differs, depending on the MP option used, as discussed later.

Figure 7.1 A typical example of simulated 100-year trajectories of "true" adult biomass (see equations A5.1.13-14), which results from an application of BL, for pilchard (left) and anchovy (right). Each of these trajectories is smoothed with an overall mean of all past values, updated annually, and with a 6-year running mean. The top panel shows the trajectories without any cycle (g_1=1), while the bottom panel shows the trajectories for a cycle of period 30 years and an amplitude factor of 1.5 (g_1=1.5, g_2=30 – see equation A7.1.2).



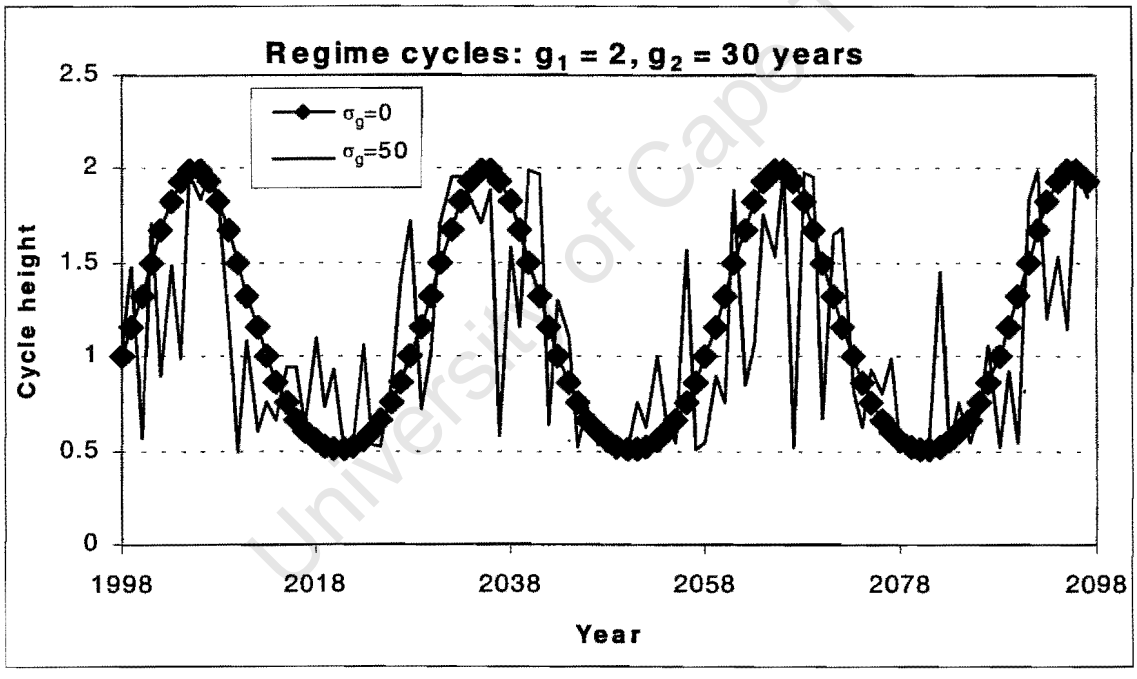
D2 This approach assumes it is possible to obtain direct information on the regime cycle (although it does not specify how). It uses the actual position

of the resource in the cycle (equation A7.1.2), but subject to a varying extent of measurement error. The method calculates the following[89]:

$$d_{y,2} = e^{(\ln g_1)\sin(360(y-1988)/g_2+\sigma_g\eta)} \qquad 7.3$$

where η is drawn from N[0; 1], and σ_g reflects the maximal uncertainty as to where in the cycle one is at any time. Values of σ_g considered (in degrees) are {0; 10; 30; 50; 100}. A value of σ_g=0° implies the position in the regime cycle is known exactly, while σ_g=10° implies roughly a 95% certainty that one is within 20° of the actual position in the cycle. Figure 7.2 shows the effect of increasing σ_g (from 0° to 50°).

Figure 7.2 An illustration of a regime cycle for pilchard with an amplitude factor (g_1) of 2 and a period (g_2) of 30 years, with and without measurement error, σ_g (equation A7.3). For this example, the corresponding cycle without error for anchovy (not shown) is identical to that for pilchard, but lags the pilchard cycle by 180°.



Both D1 and D2 consider only pilchard when calculating $d_{y,1}$ and $d_{y,2}$ respectively. The reason for this is that the pilchard TAB is dependent on the size of the anchovy TAC (equations A4.1.3 and A4.1.5). Because the two species follow cycles that are 180° out of phase (equation A7.1.2), low pilchard recruitment coincides with high anchovy abundance and therefore increased bycatch pressure. This magnifies the vulnerability of the pilchard stock in the troughs of the pilchard cycle, making it more important to track the pilchard cycle. The pilchard resource also consists of more age-classes (Table A7.1.1) and is less variable than anchovy (Chapter 1,

[89] Note for simplicity of explanation, the argument of sine is reflected in degrees rather than radians.

Figure 1.5), which means that pilchard will be less influenced by random fluctuations than anchovy.

Alternative MP options

The current approach to managing pilchard and anchovy in South Africa accepts that pilchard bycatch is inevitable, and that the purse-seine industry has not in the past been able to keep pilchard bycatch levels (particularly juvenile pilchard occurring with anchovy) low (Figure 1.5; Chapter 4). Pilchard bycatch is therefore regarded as a "non-negotiable" component of BL, and is set in the MP to realistic levels by using an estimate of the bycatch ratio for the year concerned, r_y, based on direct measurements of the juvenile pilchard to anchovy mix in both the recruit survey and the commercial catches (equations A5.1.27-A5.1.29). Except for being restricted to a maximum of 0.5, this ratio is not "controlled" in the MP[90]. Pilchard bycatch can only be controlled by reducing anchovy catches (reducing α – equations A4.1.2 and A4.1.4), reducing pilchard directed catches (reducing β – equation A4.1.1, which thereby allows for a greater anchovy catch), or reducing the initial bycatch ratio, γ (equation A4.1.3, but also appears in equation A4.1.5), which is not based on any information on the likely mix of juvenile pilchard to anchovy (as this information is not available at the start of the year).

The alternative MPs considered in this Chapter centre around the three control parameters, α, β and γ and the estimators of $d_{y,j}$ (j=1 or 2), and are as follows:

M1 This MP reduces anchovy catches as $d_{y,j}$ falls below 1. This is an effective means of reducing pilchard bycatch, but leads to greater under-utilisation of anchovy than BL.

$$\alpha_y^* = \begin{cases} d_{y,j}\alpha & ,d_{y,j} < 1, \quad j = 1 \text{ or } 2 \\ \alpha & ,d_{y,j} \geq 1, \quad j = 1 \text{ or } 2 \end{cases} \qquad 7.4$$

α_y^* then replaces α in equations A4.1.2 and A4.1.4 (but not in the constraints in Appendix 4.1).

M2 This MP reduces the initial bycatch ratio, γ, as $d_{y,j}$ falls below 1. This approach was considered a good potential approach because of the likelihood that mixing of juvenile pilchard and anchovy (and hence bycatch) becomes less of a problem with low pilchard and high anchovy

[90] r_y is not allowed to exceed 0.5 in order to avoid a situation where the pilchard bycatch with anchovy is much larger than the anchovy catch itself, particularly because of the possibility of regime shifts.

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abundance – Figure 1.5 shows an increase in the bycatch ratio from 1994 when the two species had similar abundances, but low bycatch ratios prior to 1994 when anchovy was far more prevalent than pilchard.

$$\gamma_y^* = \begin{cases} d_{y,j}\gamma & ,d_{y,j} < 1, \quad j = 1 \text{ or } 2 \\ \gamma & ,d_{y,j} \geq 1, \quad j = 1 \text{ or } 2 \end{cases} \qquad 7.5$$

γ_y^* then replaces γ in equation A4.1.3.

M3 This MP reduces the directed pilchard catch as $d_{y,j}$ falls below 1. Previously this has not been considered to be an effective means of managing bycatch, as a large amount of pilchard directed catch would need to be sacrificed for a small amount of extra bycatch for the same *risk* (De Oliveira *et al.* 1998b).

$$\beta_y^* = \begin{cases} d_{y,j}\beta & ,d_{y,j} < 1, \quad j = 1 \text{ or } 2 \\ \beta & ,d_{y,j} \geq 1, \quad j = 1 \text{ or } 2 \end{cases} \qquad 7.6$$

β_y^* then replaces β in equation A4.1.1(but not in the constraints in Appendix 4.1).

M1+2 A combination of M1 and M2 (i.e. both anchovy and the initial bycatch ratio is reduced as $d_{y,j}$ falls below 1).

M1+2+3 A combination of M1, M2 and M3 (effectively reducing all three control parameters as $d_{y,j}$ falls below 1).

M4 As for M1, but α is also increased as $d_{y,j}$ increases above 1. This option attempts to "alleviate" the under-utilisation of anchovy in M1.

$$\alpha_y^* = \begin{cases} d_{y,j}\alpha & ,d_{y,j} < 1 \\ \alpha'(d_{y,j} - 1) - \alpha(d_{y,j} - 2) & ,1 \leq d_{y,j} < 2 \\ \alpha' & ,d_{y,j} \geq 2 \end{cases} \qquad 7.7$$

all for j = 1 or 2; α_y^* then replaces α in equations A4.1.2 and A4.1.4 (but not in the constraints in Appendix 4.1). The values of α' considered are $\{\alpha, 0.6; 0.8; 1\}$. [Note that M1 is a special case of M4, with $\alpha'=\alpha$.]

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7.5 Preliminary investigations

r_y and the projection period

When applied in 1999 to manage pilchard and anchovy, OMP99 had been selected based on a 20-year projection period with unrestricted r_y. Before continuing, it is important to investigate the effect of restricting r_y to a maximum of 0.5 and lengthening the projection period from 20 to 100 years, these two changes being essentially the only ones made to OMP99 to derive BL in this Chapter. Results are shown in Table 7.1. The increase in *risk* for both species when lengthening the projection period is expected because each resource will be "exposed to the elements" for a longer period of time, and will therefore have an increased chance of falling below 20% of K at least once for the longer period compared to the shorter one. The decrease in *risk* for pilchard when moving from an unrestricted to restricted r_y (r_y does not affect anchovy) is also expected because of the extra protection accorded to juvenile pilchard when restricting r_y. For the rest of this Chapter, BL corresponds to the final row of Table 7.1.

Table 7.1 Summary performance statistics for OMP99, for a 20- and 100-year projection period, and for unrestricted and restricted r_y (equation A4.1.5). [Empty cells acquire the corresponding value in the first non-empty cell above them in the same column.]

	Pilchard				Anchovy			
Changes to OMP99	$\overline{C}$ **('000t)**	***risk***	***depl***	***V***	$\overline{C}$ **('000t)**	***risk***	***depl***	***V***
20-yr proj, unrestricted r_y	135.3	0.102	0.532	0.230	145.2	0.058	0.861	0.241
20-yr proj, $r_y \leq 0.5$	134.8	0.086	0.545	0.229				
100-yr proj, unrestricted r_y	129.5	0.460	0.497	0.230	145.9	0.354	0.847	0.229
100-yr proj, $r_y \leq 0.5$	129.6	0.414	0.514	0.230				

g_1 and g_2

Figures 7.3 and 7.4 show the performance of BL in terms of *risk* and the average annual catch $\overline{C}$ for a wide range of alternative operating models (i.e. alternative regime-cycle scenarios defined by ranges of g_1 and g_2 values). In catch-*risk* plots of this kind, an MP performs best when its performance statistics lie towards the bottom right corner of the plot. Performance deteriorates as these statistics move in a diagonal towards the top left corner of the plot as further operating models are used for testing. However, when the point corresponding to the performance statistic for the MP moves from the top right to the bottom left corner of the plot (or *vice versa*), overall

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performance is more difficult to judge as, for example, a decrease in *risk* (which is desirable) is accompanied by a decrease in $\overline{C}$ (which is not desirable). This basis for comparison holds both for plots showing the performance of a particular MP subject to alternative operating models (as in these Figures), and for alternative MPs subject to the same operating model (as in later Figures).

In the top panel of Figure 7.3, each curve corresponds to a particular value of g_2 for a range of g_1 values. The performance of BL for pilchard consistently deteriorates in terms of both *risk* and $\overline{C}$ with increasing g_1. In order to see the effect of changing g_2 on BL more clearly, the bottom panel of Figure 7.3 shows curves corresponding to particular values for g_1, for a range of g_2 values. There is a general pattern of deterioration as g_2 decreases, with g_2=50 being the exception. This is probably as a result of the balance of peaks and troughs in the 100-year projection period defined by the g_2 value: for g_2 =20 and 50, there are equal numbers of peaks and troughs for pilchard (equation A7.1.2), while there are more peaks than troughs when g_2 =40 and 60 (and to a lesser extent when g_2 =30). This effect could have been reduced by randomising over the start of the cycle so as to average the effect out, whatever the value chosen for g_2. The argument, nevertheless, for starting the cycle in 1998 with pilchard increasing was to capture the end-of-the-1990s situation, which suggested a shift towards pilchard.

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Figure 7.3 Sensitivity of BL performance statistics for pilchard, when tested using alternative operating models defined by different $\{g_1; g_2\}$ combinations. In the top panel, each curve corresponds to a particular g_2 value, with the points within each curve corresponding to different g_1 values ranging from 1.1 (closest to the "no cycle" option, for which g_1=1, at the bottom right of the plot) to 3 in steps of 0.1. In the bottom panel, curves are shown for particular g_1 values with points within each curve corresponding to different g_2 values ranging from 20 years to 60 years, in steps of 10 years, with 60 being closest to the bottom-right corner for all curves. [Note that for illustrative purposes, this Figure considers a wider range of g_1 and g_2 values than used elsewhere.]

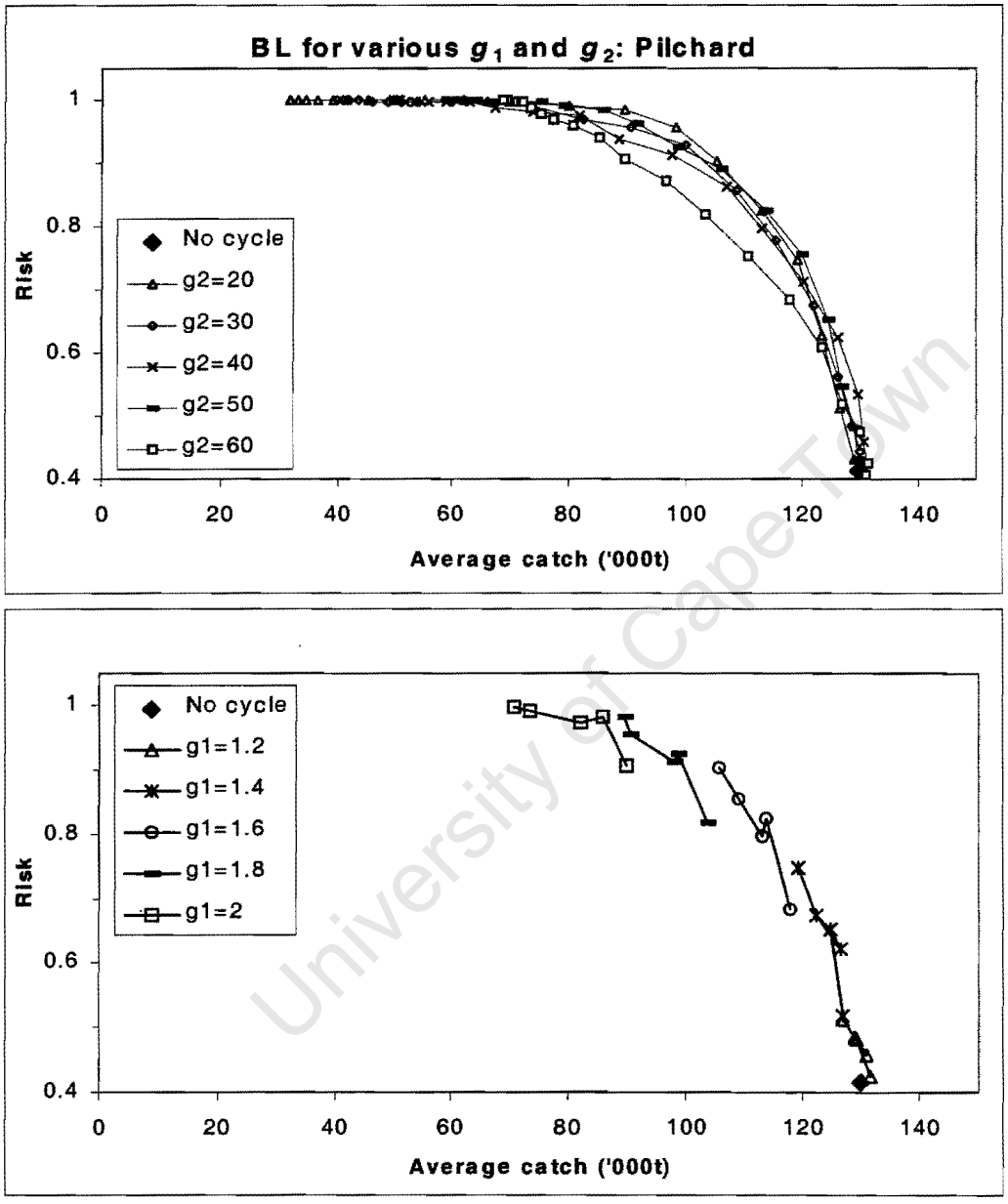

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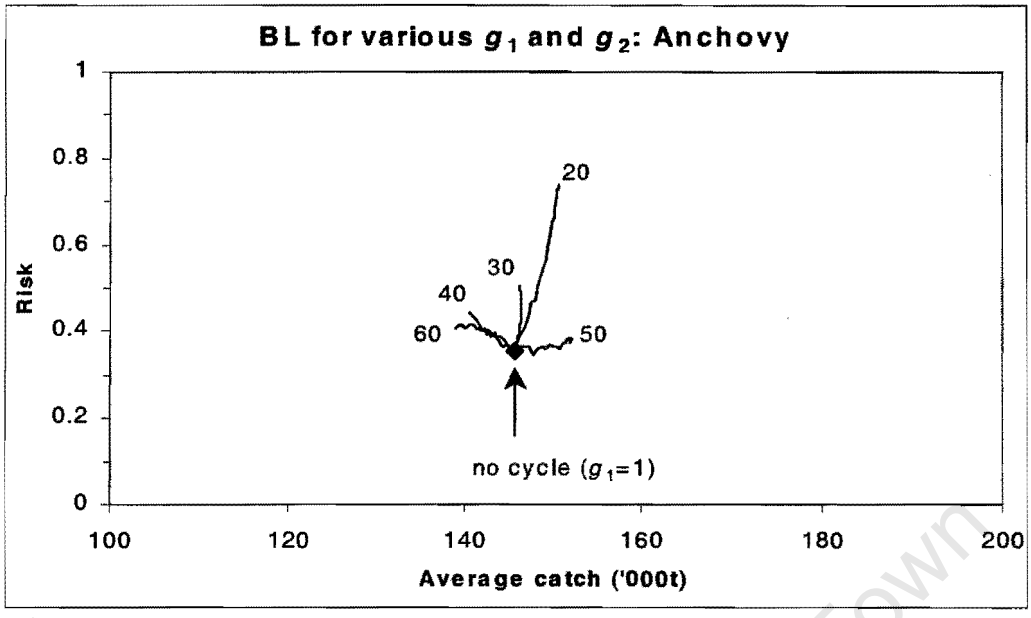
Figure 7.4 shows results for anchovy, which correspond to the top panel of Figure 7.3 for pilchard. In this case, the pattern is a general deterioration of *risk* for increasing g_1, but not necessarily of $\overline{C}$. $\overline{C}$ improves for g_2 =20 and 50, but deteriorates for g_2 =40 and 60. The reasons for this are likely similar to those given for pilchard regarding the number of abundance peaks and troughs that arise depending on the value selected for g_2.

Figure 7.4 Sensitivity of BL performance statistics for anchovy, this plot corresponding to the top panel of Figure 7.3, with g_2 values shown in the plot (see caption to Figure 7.3), the g_1 values increasing away from the "no cycle" point.



Choice of x for $\mu_{y,x}$

Tables 7.2 and 7.3 investigate the effect of using estimator D1 for MP options M1, M2 and M3 when the OM has no regime cycle. The aim of this investigation is to determine which period x would be the most appropriate choice to specify the running mean $\mu_{y,x}$ for estimator D1 across all three MPs (and any combinations of these) for both pilchard and anchovy.

Option M1 aims to reduce pilchard bycatch when pilchard abundance is low by reducing anchovy catches. Table 7.2 shows that pilchard performs better for smaller x values across all summary statistics except (very slightly) for V. This is because smaller values of x result in D1 being able to respond almost immediately to changes in pilchard abundance. Consequently, occurrences of $d_{y,1}$ below 1 (equation 7.2) increase as x gets smaller. Anchovy catches are therefore reduced more often (equation 7.4), which is always advantageous for pilchard as there will be a corresponding drop in bycatch. The lower bycatch leads to more efficient utilisation of pilchard, and therefore increased directed pilchard catches. However, a higher frequency of reductions of anchovy catches implies that anchovy is further under-utilised (*depl* closer to 1) compared to BL, and anchovy catches are slightly more variable (V is higher) for smaller x. Therefore, although a smaller value of x is advantageous for pilchard, this has to be weighed against lower and more variable catches for anchovy.

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Table 7.2 Performance statistics for MP option M1 using estimator D1 for various periods x for the running means $\mu_{y,x}$ (equation 7.1) when the OM has no regime cycle (g_1=1). Results for BL (where estimator D1 is not used) are included for comparison.

Estimator	Pilchard				Anchovy			
	$\overline{C}$ ('000t)	*risk*	*depl*	*V*	$\overline{C}$ ('000t)	*risk*	*depl*	*V*
BL	129.6	0.414	0.514	0.230	145.9	0.354	0.847	0.229
D1, x=2	133.0	0.318	0.558	0.231	136.2	0.336	0.860	0.239
D1, x=4	132.6	0.344	0.553	0.230	138.6	0.330	0.858	0.231
D1, x=6	132.1	0.370	0.547	0.230	139.9	0.340	0.857	0.229
D1, x=8	131.9	0.382	0.544	0.230	140.8	0.340	0.856	0.228
D1, x=10	131.5	0.390	0.540	0.230	141.3	0.346	0.855	0.227
D1, x=12	131.3	0.392	0.537	0.230	141.8	0.346	0.855	0.227
D1, x=14	131.0	0.394	0.534	0.230	142.1	0.344	0.854	0.227

Options M2 and M3 avoid the problems of further under-utilisation and more variable catches of anchovy because they do not reduce anchovy as part of their management action (equations 7.5 and 7.6). Table 7.3 shows similar trends for M2 as for M1: for the former, reducing the initial bycatch ratio (γ in equation A4.1.3) more often than not leads to lower bycatch levels, which is always advantageous for pilchard (now all summary statistics including V improve for lower x compared to BL). This is not the case for M3, however, where $\mu_{y,6}$ appears to be the most effective estimator in terms of almost all the summary statistics. This is probably because $\mu_{y,6}$ is the best compromise between the extremes, $\mu_{y,2}$ and $\mu_{y,14}$. For example, $\mu_{y,2}$ responds too rapidly to changes in $B^P_{y,Nov}$, which is subject to measurement error (equation A5.1.16), so it is more readily influenced by random effects, which tend to mask the actual biomass trend. On the other hand, $\mu_{y,14}$ is sluggish in its response because of the substantial lag behind the actual trend (greater than that shown in Figure 7.1 for $\mu_{y,6}$), so that any signal that it provides on trends is delayed and can be very weak. It should also be noted that, in the operating model used, pilchard is assumed to consist of 6 age classes (Appendix 7.1), so it is not surprising that a 6-year mean is a reasonably good indicator of biomass trend, albeit with a slight lag (Figure 7.1).

Tables 7.2 and 7.3 and the arguments presented above indicate that M1 and M2 simply demonstrate no more than that any reduction of bycatch (achieved by an $x > 0$) will be beneficial for pilchard. They are not really of much assistance in discriminating between the different options for x. The choice of $x = 6$ for all subsequent D1-based analyses in this Chapter was therefore based upon the results for M3.

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Table 7.3 Performance statistics for MP options M2 and M3 using estimator D1 for various periods x for the running mean $\mu_{y,x}$ (equation 7.1) when the OM has no regime cycle (g_1=1). These options have no effect on anchovy, so that the anchovy results are as for BL in Table 7.2 and are therefore not shown. The pilchard results for BL are included for comparison.

Estimator	M2				M3			
	$\overline{C}$ ('000t)	*risk*	*depl*	*V*	$\overline{C}$ ('000t)	*risk*	*depl*	*V*
BL	129.6	0.414	0.514	0.230	129.6	0.414	0.514	0.230
D1, x=2	134.0	0.358	0.554	0.229	128.9	0.410	0.516	0.227
D1, x=4	133.7	0.388	0.551	0.229	128.4	0.408	0.518	0.223
D1, x=6	133.5	0.392	0.550	0.229	128.5	0.404	0.518	0.224
D1, x=8	132.9	0.394	0.546	0.229	128.6	0.414	0.518	0.225
D1, x=10	132.1	0.398	0.539	0.229	128.7	0.412	0.517	0.226
D1, x=12	131.8	0.402	0.536	0.229	128.8	0.414	0.517	0.226
D1, x=14	131.5	0.404	0.534	0.229	128.9	0.414	0.517	0.227

MP option M4

Figure 7.5 shows results for M4, which attempts to overcome the under-utilisation of anchovy under M1 by increasing the exploitation of anchovy when pilchard abundance is high (equation 7.7). The four values of α' considered range from α to 1. The increase in $\overline{C}$ for anchovy is offset by an increase in *risk*, so there is no clear gain for anchovy. However, there is a marked deterioration with increasing α' for both these summary statistics in the case of pilchard. This option is therefore not considered further in this Chapter.

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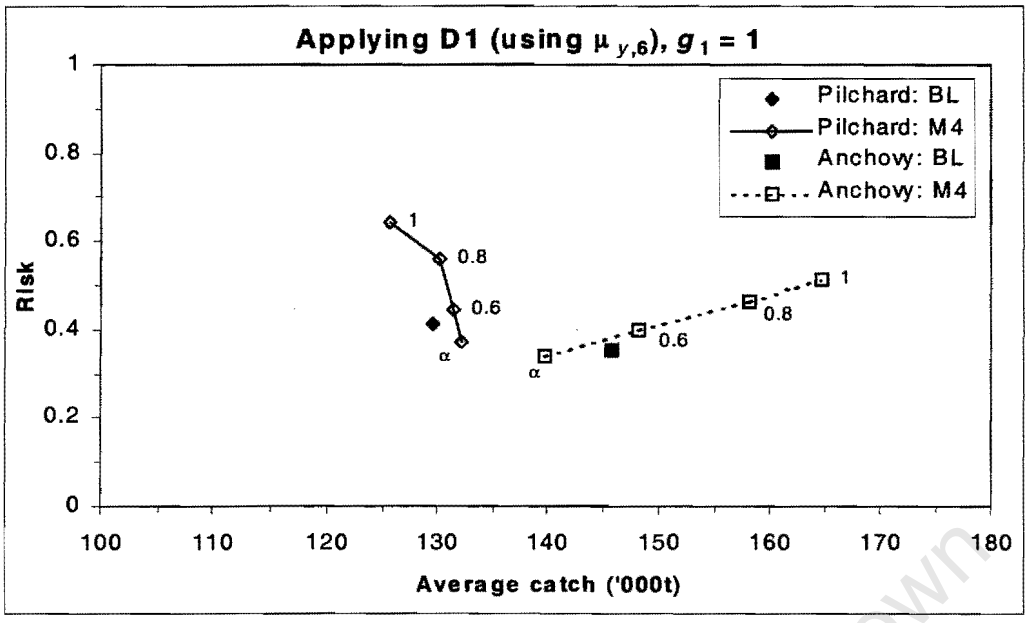
Figure 7.5 Applying estimator D1 for M4 using a 6-year running mean, $\mu_{y,6}$, for pilchard and anchovy with g_1=1. For M4, the α' values are shown on the plot.



7.6 Results

Results are shown in Figures 7.6-10. They compare the six MP options BL, M1, M2, M3, M1+2, and M1+2+3 using estimators D1 (with $\mu_{y,6}$) and D2 (with σ_g = 0, 10, 30, 50 and 100) for a variety of regime cycle scenarios. Each plot shown (there are 12 plots for each Figure, six each under parts **a** and **b** of the Figure) refers to a particular regime-cycle scenario (reflecting a particular operating model). Furthermore, each plot compares a number of MPs, each of which has several sub-options corresponding to the use of estimator D1 or D2. The set of plots under **a** in each Figure correspond to regime cycles of period 30 years (g_2), and under **b** of 50 years. The left-hand column of plots for each Figure refers to pilchard, while the right-hand column refers to anchovy. The top row of plots for both **a** and **b** in each Figure correspond to an amplitude factor (g_1) of 1.2, the middle row to one of 1.5 and the bottom row one of 2.

Risk and average catch

To aid the interpretation of Figure 7.6, results will be discussed first at the plot level (i.e. within each plot), where the performance of individual MPs can be compared to one another, then across plots to consider the effect of increasing g_1, and finally plots in **a** will be compared to those in **b** to investigate the effect of changing g_2.

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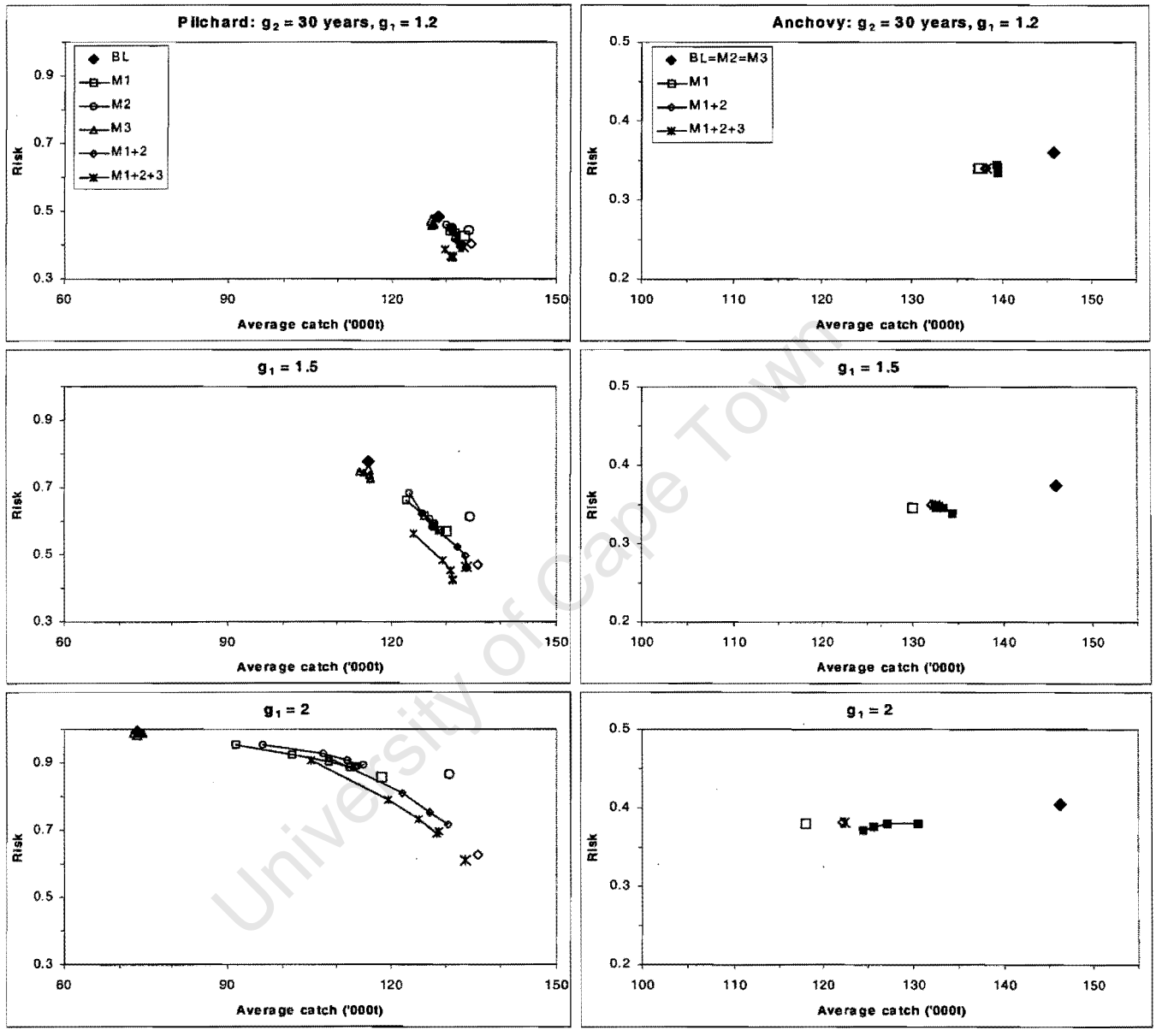
Figure 7.6 Performance of MP options BL, M1, M2, M3, M1+2 and M1+2+3 in terms of the summary performance statistics *risk* and $\overline{C}$. Points with the same symbol refer to the same MP option, where the larger symbols indicate use of the estimator D1 with $\mu_{y,6}$, and smaller symbols joined by a line refer to estimator D2 for the following σ_g values: 0°, 10°, 30°, 50° and 100° (for pilchard for each MP, σ_g=0° lies closest to the bottom right corner of the plot, with the symbol moving closer to the top left corner as σ_g increases; for anchovy, σ_g=0° has the lowest $\overline{C}$, with $\overline{C}$ increasing as σ_g increases).

a



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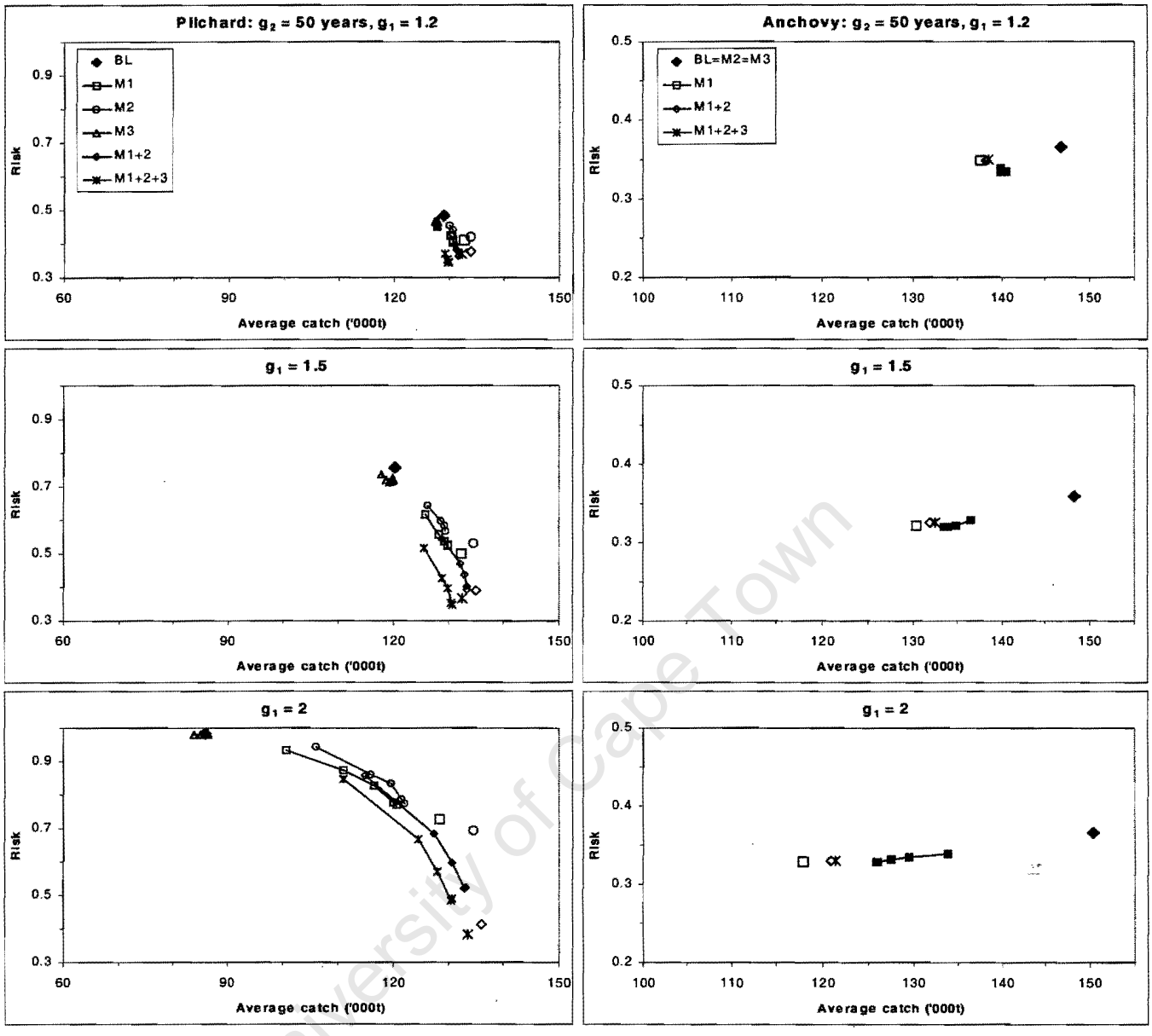
b



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Comparing the performances of alternative MPs

To ease visual interpretation, first only the plots in Figure 7.6a for g_1=1.5 are considered. Apart from M3, all MP options perform better than BL for pilchard. This is because although M3 reduces pilchard directed catches when pilchard abundance is low, it still doesn't solve the bycatch problem, which all the other options attempt to minimise. When σ_g is varied for each of the options, σ_g=0 at the one extreme performs best, while σ_g=100 at the other extreme performs worst for pilchard. This is not surprising because an increasing σ_g implies more uncertainty as to the underlying position in the regime cycle one at any time.

Options M1+2 and M1+2+3 perform best overall for pilchard, although it is not clear when comparing these to each other which performs better overall (M1+2 performs better in terms of

$\overline{C}$, but worse in terms of *risk*). The same argument applies when comparing M1 and M2 to one another. M1 and M2 don't perform as well as M1+2 and M1+2+3 for pilchard, however, particularly in terms of *risk* (although for estimator D1, $\overline{C}$ is slightly worse for M1+2+3 compared to M2). For anchovy, M2 and M3 (whose performances are identical to BL) perform better than M1, M1+2 and M1+2+3 in terms of $\overline{C}$. This is because they do not reduce anchovy catches (Table 7.3). All options apart from M2 and M3 perform worse for anchovy than BL in terms of $\overline{C}$, but only marginally better in terms of *risk*.

g_1 increases

Figure 7.6a shows a marked deterioration, in terms of *risk*, in the performance of all MP options for both pilchard and anchovy as g_1 increases (confirming the results of Figures 7.3 and 7.4). It is also evident that the "performance gap" between all the options widens as g_1 increases. This means that the worst performers (BL and M3 for pilchard) deteriorate most as g_1 increases, while the deterioration for the best performers is not as marked.

For pilchard, performance in terms of $\overline{C}$ improves very slightly for estimator D1, but deteriorates markedly for estimator D2, when increasing g_1. When g_1=2, D1 also performs better than D2 (with σ_g=0) in terms of both summary statistics for all MPs. This suggests that with cycles of high amplitude, it may be better to simply use a running mean to track biomass trends instead of attempting some measure of the underlying position in the regime cycle. However, for smaller g_1 values, although D1 performs better than D2 in terms of $\overline{C}$ for all the options (except M3), it performs worse than D2 in terms of *risk* when σ_g is small. This deterioration in *risk* for D1 compared to D2 (with small σ_g) would need to be judged against the feasibility and likely cost of obtaining relatively precise information about the underlying position in the regime cycle at any time, which D2 requires for small σ_g.

g_2 changes

When comparing the plots in Figure 7.6**a** with those in **b**, there is a general shift of results towards the right and down for **b**, indicating an overall improvement in performances when g_2 changes from 30 to 50 years. This is consistent with the results of Figures 7.3 and 7.4, which show a general improvement in performance for both pilchard and anchovy for g_2=50 compared to g_2=30.

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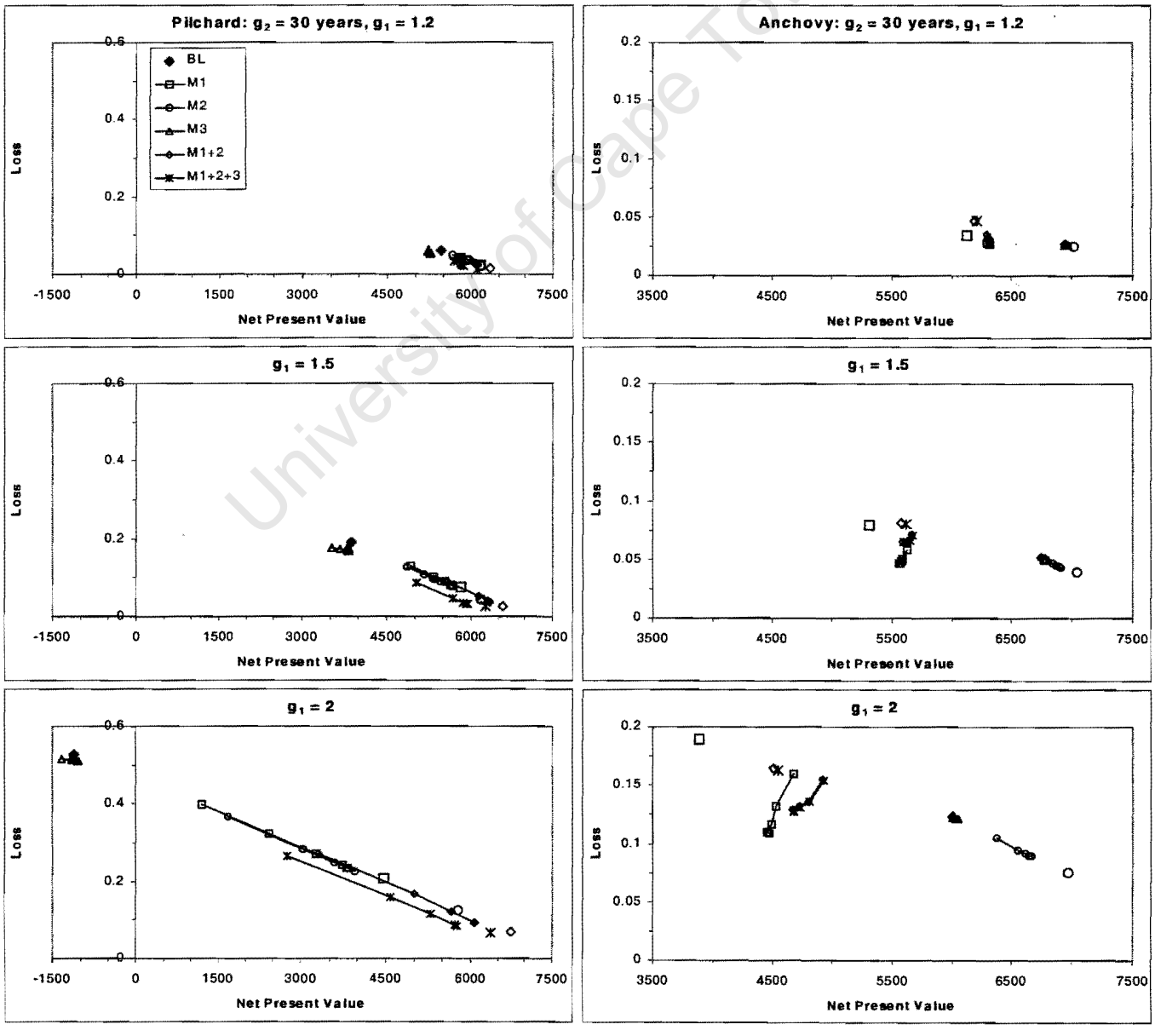
NPV and Loss

Figure 7.7 plots *Loss* against *NPV* to provide an economic equivalent to the catch-*risk* curves of Figure 7.6. The interpretation of "better performance" is similar to that of Figure 7.6, namely MPs perform best when they lie towards the bottom-right corner of the plots. The general behaviour of MPs in Figure 7.7 is broadly similar to that in Figure 7.6 for pilchard, but quite different for anchovy. Although Figure 7.7 provides a broad summary of results, symbols are difficult to distinguish in some of the plots. Therefore, most of the discussion below will focus on separate plots for *NPV* (Figure 7.8) and *Loss* (Figure 7.9).

Figure 7.7 Performance of MP options BL, M1, M2, M3, M1+2 and M1+2+3 in terms of the summary performance statistics *Loss* and *NPV*. Description of the plots is as for Figure 7.6, except that for anchovy, *Loss* and *NPV* for M2 and M3 are not identical to BL, and these options are therefore now shown. Furthermore, in the anchovy plots, estimator D2 with σ_g=0° has the lowest *Loss* value, with *Loss* increasing as σ_g increases.

a



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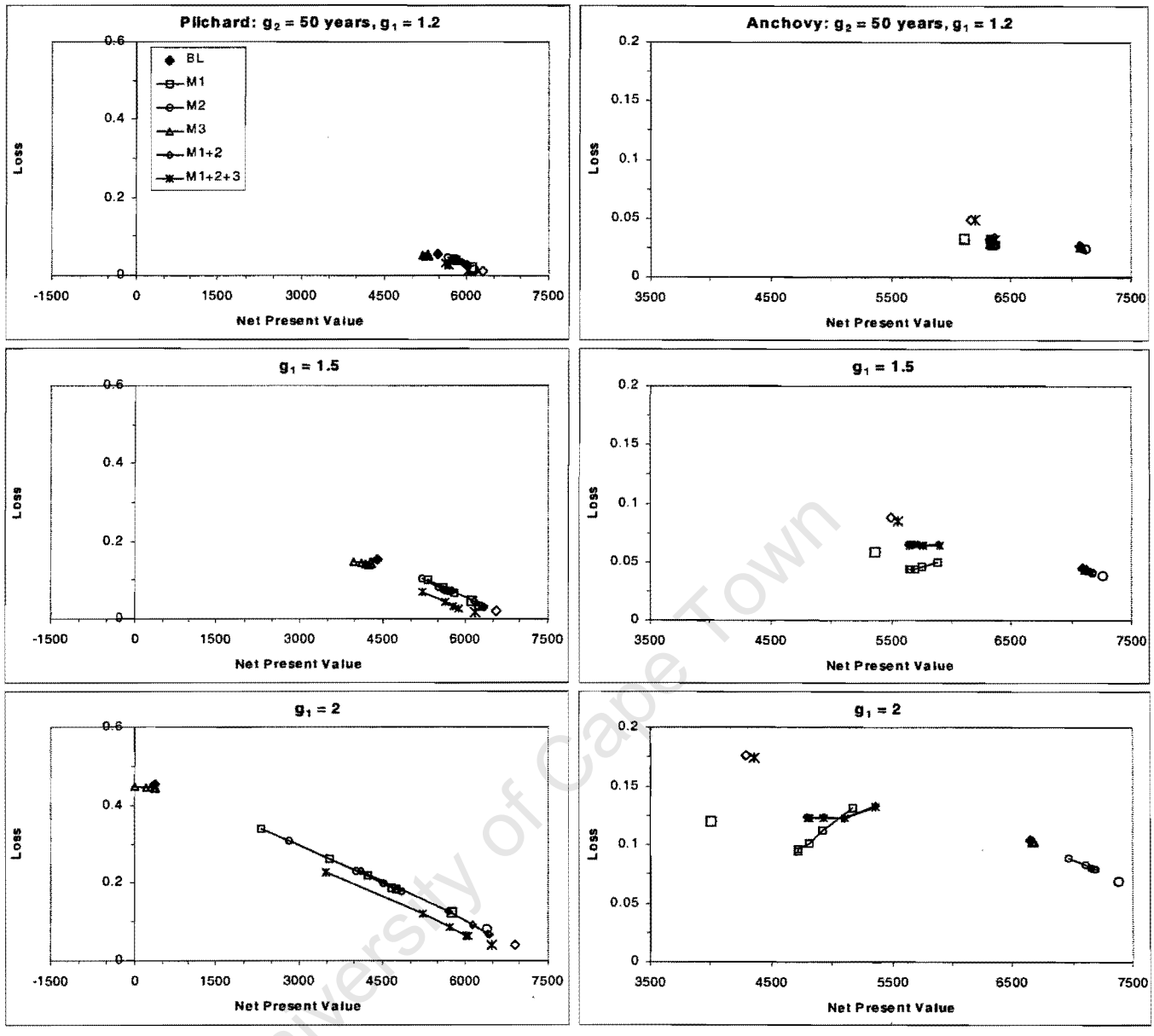
b



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Pilchard

Figure 7.8 shows superior performance in terms of *NPV* for all MPs considered when estimator D1 is used rather than D2, whatever the value of g_1. This was also the case for the results in Figure 7.6 when considering *risk*, but there only for g_1=2. All MPs except M3 perform consistently better than BL, with BL and M3 showing negative *NPV*s for g_1=2. As before, MP performance deteriorates with increasing σ_g, this deterioration becoming worse as g_1 increases. Patterns shown in Figure 7.9 for *Loss* are generally the same (with higher *Loss* values indicating poorer performance in terms of this statistic). MP options M1+2 and M1+2+3 show the best performance overall in terms of both *NPV* and *Loss*. Comparing Figure 7.7**a** and **b**, performance is generally better in the latter for all options, once again consistent with the results of Figure 7.3.

Figure 7.8 Performance of MP options BL, M1, M2, M3, M1+2 and M1+2+3 in terms of the summary performance statistic *NPV*. Differences between plots are as described for **a** in the caption for Figure 7.6.

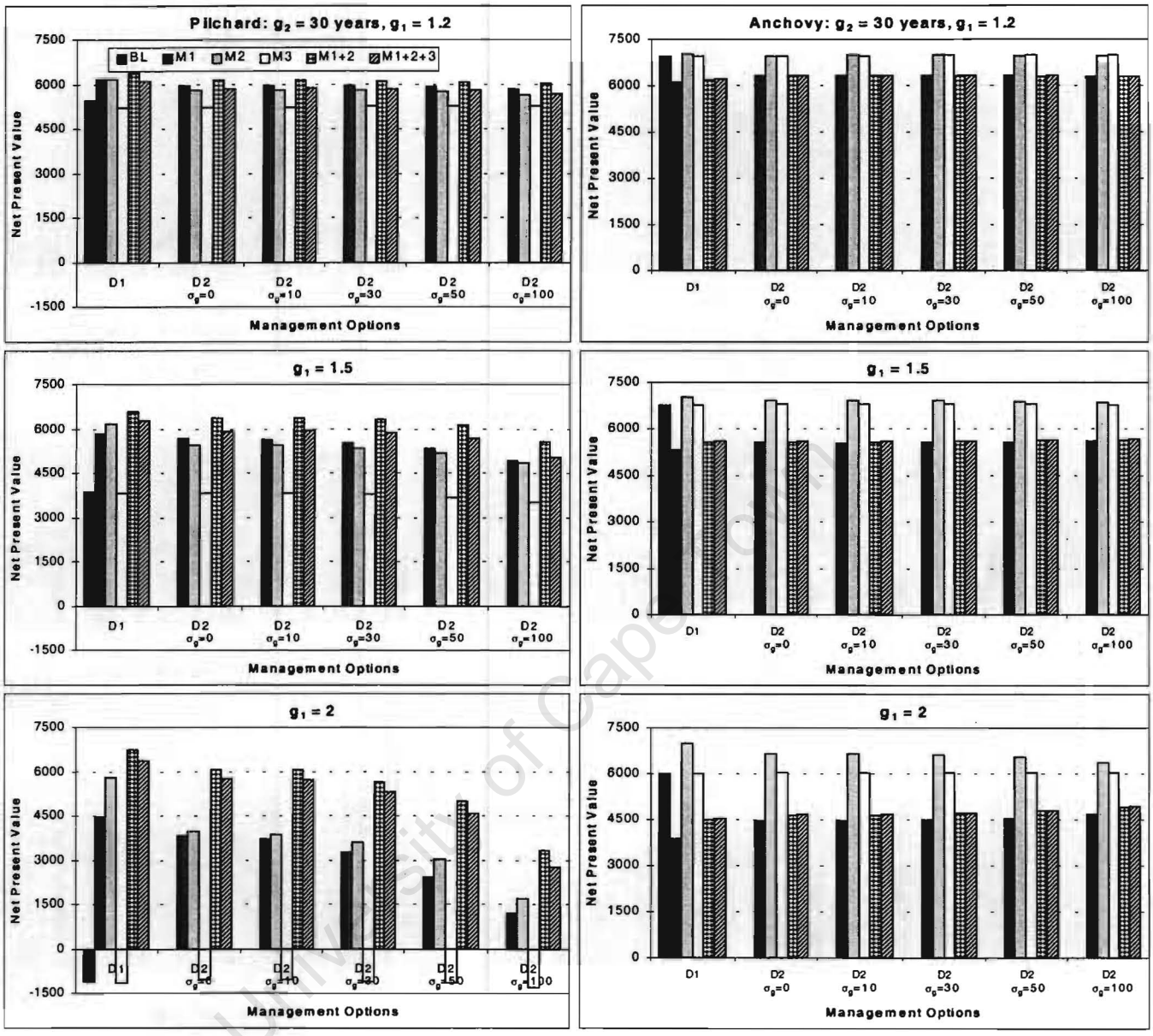

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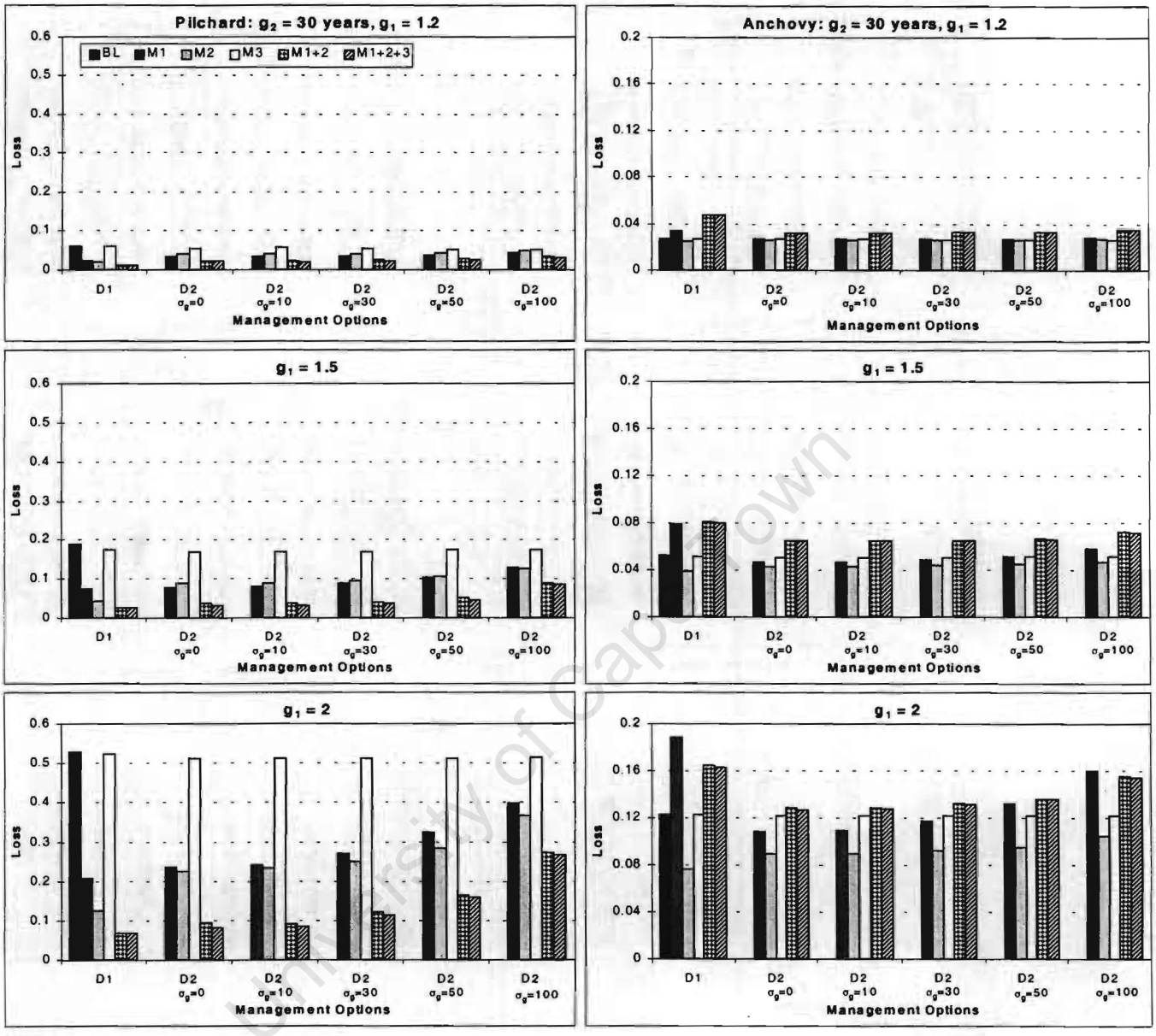
Figure 7.9 Performance of MP options BL, M1, M2, M3, M1+2 and M1+2+3 in terms of the summary performance statistic *Loss*. Differences between plots are as described for part a in the caption for Figure 7.6.



Anchovy

When considering anchovy in Figures 7.7-9, it should be noted that *NPV* and *Loss* are based on not only anchovy, but also pilchard bycatch (landed with anchovy – Appendix 7.2). In Figures 7.8 and 7.9, there is a general deterioration for all MPs in terms of both *NPV* and *Loss*, as g_1 increases. M1 performs worst in terms of *NPV* (and *Loss* for g_1=2) for estimators D1 and D2 (with high σ_g), because anchovy catches are reduced when the pilchard cycle is in a trough, thereby reducing contributions to *NPV*. Options M1+2 and M1+2+3 perform better than M1 in terms of *NPV* (and *Loss* for estimators D1 and D2, with high σ_g, when g_1=2). This is because, in addition to these options reducing the anchovy catches, the M2 component of these options also reduces the initial bycatch ratio γ when pilchard is in a trough, thereby protecting the low

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pilchard resource from potentially damaging levels of initial pilchard TABs (pilchard troughs coincide with anchovy peaks under the OMs used, and therefore imply higher bycatch levels initially if γ is not reduced). Therefore, although M1+2 and M1+2+3 reduce pilchard bycatch while M1 does not, they lead (counter-intuitively) to higher *NPV* values (which result from pilchard bycatch and anchovy catches) than M1 because of the lower *risk* that arises as a consequence of the extra protection accorded to pilchard (see Figure 7.6). Thus more pilchard (including bycatch) is available to be harvested.

In Figures 7.8 and 7.9, MP option M2 consistently performs the best in terms of both *NPV* and *Loss* for anchovy. This is because anchovy catches remain intact (they are not reduced for M2 and M3, unlike the other options). Both these anchovy catches and the additional pilchard bycatch that is gained (as a result of the extra protection accorded to the pilchard resource by not setting initial TABs that are too high) contribute towards increasing *NPV* and decreasing *Loss*. M3 is almost identical to BL for anchovy because decreasing pilchard directed catches when pilchard is in trough has little impact on anchovy catches and pilchard bycatch (Figure 7.6).

Patterns are similar when g_2 is increased to 50 years (compare **a** and **b** of Figure 7.7 for anchovy), with a general improvement in performance across the board in terms of the two summary statistics shown, except for estimator D1 for MP options M1+2 and M1+2+3, for which both summary statistics deteriorate. This behaviour is counter-intuitive because there is an improvement across the board (including for M1+2 and M1+2+3) for estimator D2. When comparing Figure 7.7**a** and **b**, the movement of points corresponding to estimator D1 in the opposite direction to those for D2 for these two MPs must therefore be a consequence of the estimator itself. This may imply that the efficiency of $\mu_{y,6}$ in following the biomass trend may change for different g_2 values (e.g. it may become less efficient for smaller g_2 values), an aspect that is beyond the scope of what is considered in this Chapter.

Another interesting feature that arises from the comparison of Figure 7.7**a** and **b** for anchovy is the relatively large decrease in *Loss* for M1 using estimator D1 when compared to estimator D2 for this MP, particularly for g_1=2 (one would expect the decrease to be to the level of D2 with σ_g=0). The decrease itself is not surprising because g_2=30 contains more troughs for anchovy than does g_2=50, and $\overline{C}$ is lower in the corresponding pilchard plots. However, the magnitude of the decrease may once again point to the change in efficiency of $\mu_{y,6}$ as g_2 is changed.

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Interannual catch variability

Figure 7.10 shows changes in V, the interannual catch variability, for all MP options with their associated D1/D2 estimator combinations. It is important to note that for pilchard, V is the interannual catch variability of the directed catch only.

Pilchard

There is a general decrease in V for pilchard as g_1 increases, probably because the maximum and minimum TAC constraints (constraint 6 for pilchard in Appendix 4.1) come into play more frequently with increasing g_1, thereby limiting variations in catch. MP options M3 and M1+2+3 are the most sensitive to increases in σ_g because M3 reduces the actual pilchard directed catches themselves, and increases in σ_g lead to more variable adjustments to the directed catches (see Figure 7.2), and therefore higher V. All MP options provide improvements in V compared to BL, except for M3 under estimator D2 with σ_g=100. Trends are similar when comparing Figure 7.10**a** and **b**, with **b** generally showing slightly lower V values.

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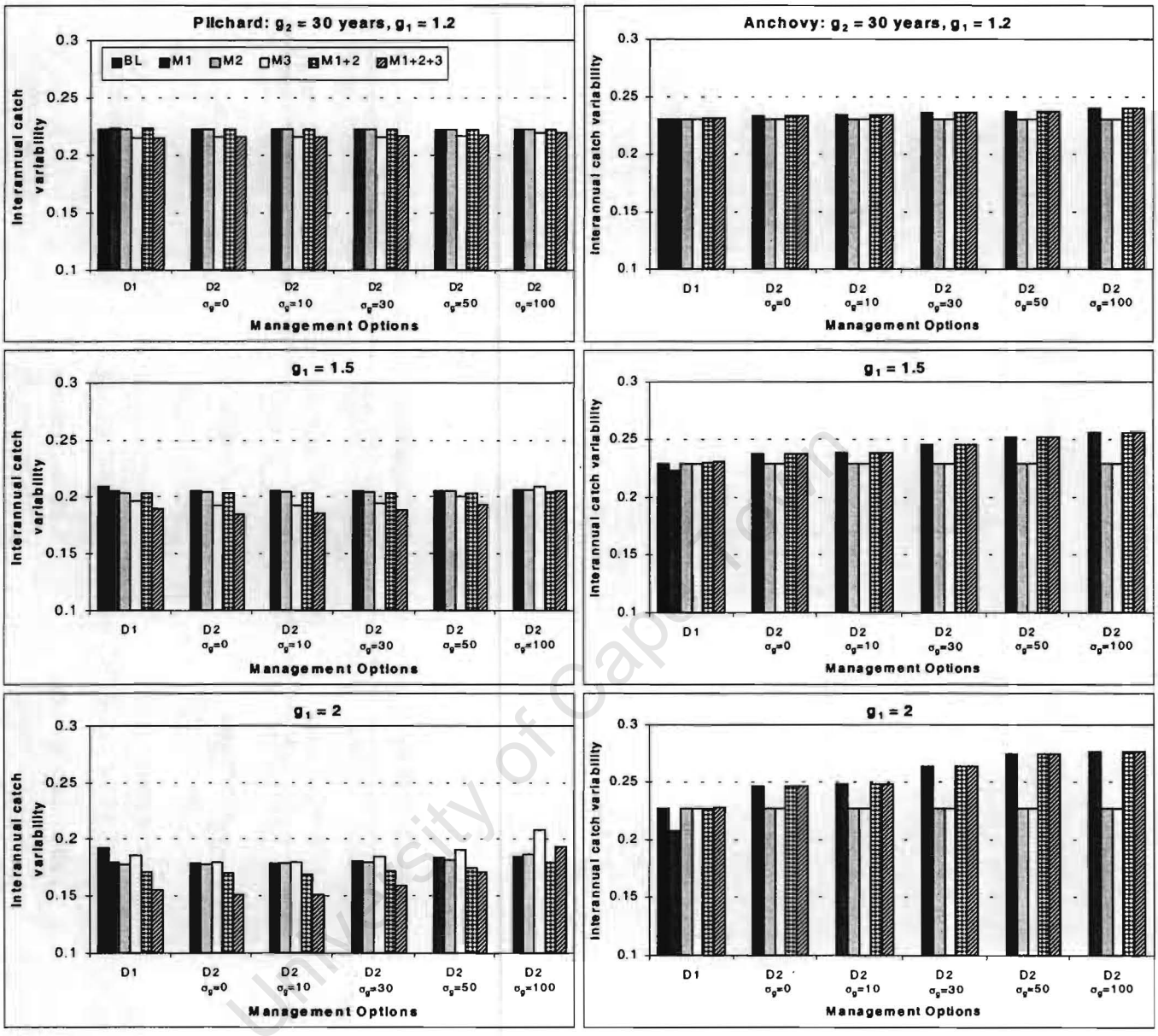
Figure 7.10 Performance of MP options BL, M1, M2, M3, M1+2 and M1+2+3 in terms of the summary performance statistic *V*. Differences between plots, and parts **a** and **b** are as described in the caption to Figure 7.6.

a



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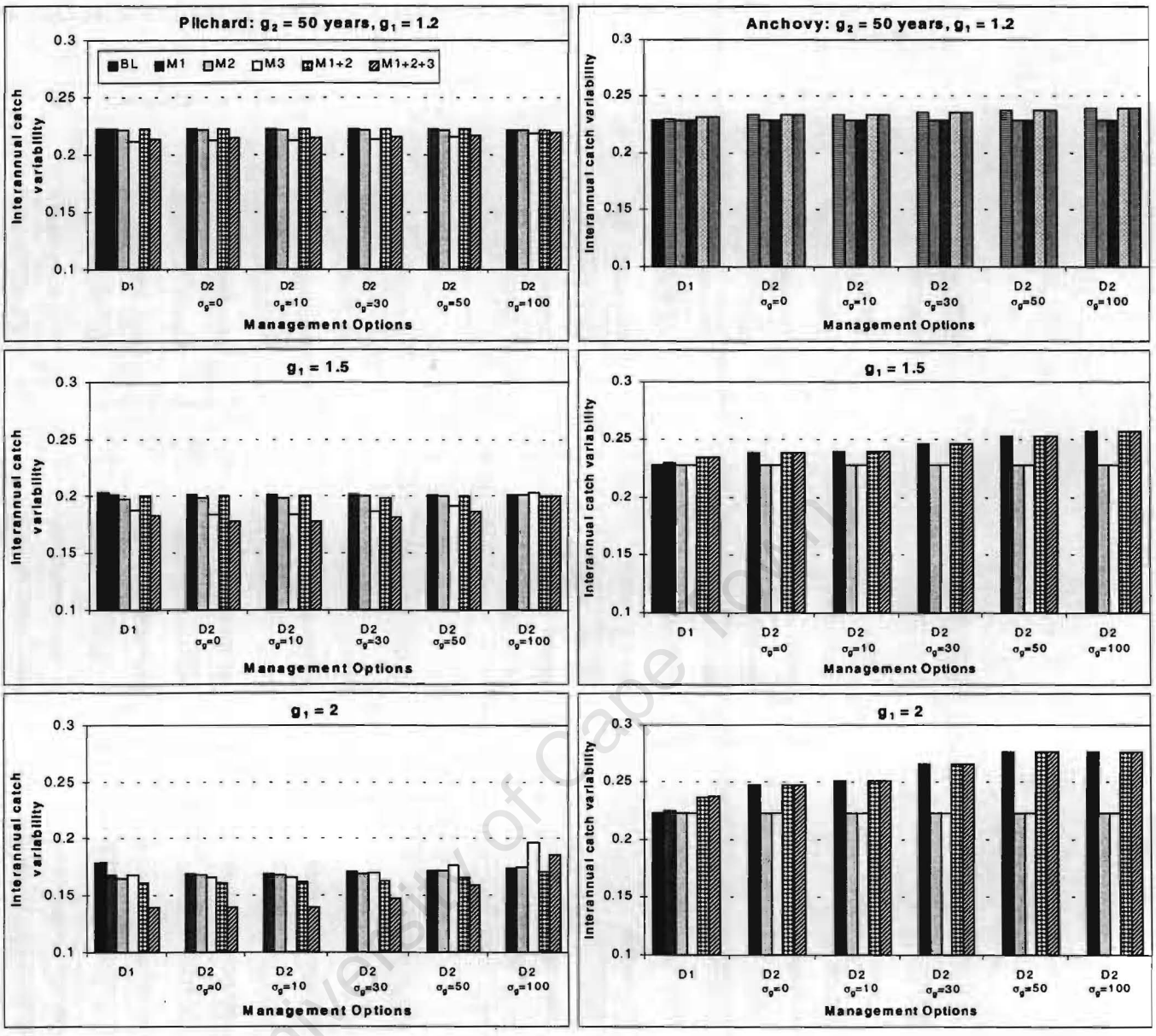
b



Anchovy

For anchovy, the V values for M2 and M3 are insensitive to increases in g_1 and σ_g because these MP options do not reduce anchovy catches as part of the management action for pilchard troughs. The V values for M1, M1+2 and M1+2+3 are identical to one another for estimator D2 for the following reasons:

- the M2 and M3 components of these options do not affect anchovy catches directly; and
- estimator D2 tracks the actual position in the pilchard cycle and not the biomass, so is therefore not sensitive to the management actions affecting pilchard bycatch and directed catch in options M2 and M3.

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This is not the case for estimator D1 however, because it tracks the adult pilchard biomass, which is affected by reductions in both pilchard bycatch (M2) and directed catch (M3). V is generally lower for estimator D1 compared to D2, particularly for option M1 and higher g_1 values. V increases slightly for estimator D2 when σ_g increases, for the same reason as with M3 and M1+2+3 for pilchard.

In Figure 7.10**a** for anchovy, when estimator D1 is used, the V value for M1 decreases relative to BL and the other MP options as g_1 increases. This pattern is not maintained, however, when D1 is used and g_2 changed from 30 to 50 years – in this case, V values for M1+2 and M1+2+3 increase relative to BL and the other MP options. There is no such change in pattern evident for D2 when changing g_2, which leads to the same conclusion as for Figures 7.7-9, namely that the optimal choice for the period x over which the running mean $\mu_{y,x}$ is taken may depend on the value of g_2.

Removing TAC constraints

All the results considered thus far are subject to the same TAC constraints as listed in Appendix 4.1, because even though the control parameters are adjusted for the various MP options (equations 7.4-7), these adjusted parameters are used only in equations A4.1.1-A4.1.5 (i.e. not in the constraints listed after equation A4.1.5 in Appendix 4.1). Table 7.4 compares MP option M1+2 with an option that is identical except that there are no upper constraints on both the pilchard and anchovy TACs (i.e. the upper bounds of constraints 2 and 6 in Appendix 4.1 for anchovy and pilchard respectively have been removed). This option is labelled M1+2' and a comparison is made for the scenarios with no regime cycle (g_1=1), and g_1=1.2, 1.5 and 2. For ease of comparison, M1+2' is "tuned" to the same pilchard *risk* level as M1+2 for each of the scenarios considered (the caption to Table 7.4 explains how this is achieved), and only estimator D1 is considered.

When comparing the two MP options, pilchard shows increasing gains in $\overline{C}$ for the same *risk* as g_1 increases, but at the cost of much higher V values and much lower anchovy $\overline{C}$ values. The trends in the V values for pilchard are consistent with an inference drawn from Figure 7.10, namely that a decreasing V with increasing g_1 is a result of the TAC constraints playing a more prominent role for M1+2 as g_1 increases. This is not the case for M1+2', which removes the upper bounds on TACs. Whereas pilchard does show an improvement in terms of $\overline{C}$ for the same *risk*, there is no clear gain for anchovy, with lower $\overline{C}$ accompanied by lower *risk*.

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Table 7.4 MP option M1+2 compared to a related version, M1+2', which is identical except that the latter has no upper bounds on TACs for both pilchard and anchovy (i.e. the upper bounds of constraints 2 and 6 in Appendix 4.1 for anchovy and pilchard respectively are omitted). Pilchard *risk* for M1+2' is "tuned" to the same value as for M1+2 by adjusting α in both equations A4.1.1-A4.1.5 and the constraints in Appendix 4.1. The estimator used throughout is D1, with g_1>1, g_2=30 years.

Management Option	Pilchard				Anchovy			
	$\overline{C}$ ('000t)	*risk*	*depl*	*V*	$\overline{C}$ ('000t)	*risk*	*depl*	*V*
No cycle ***(g_1=1)***								
M1+2	133.6	0.358	0.560	0.230	140.5	0.342	0.856	0.231
M1+2'	141.1	0.358	0.565	0.281	118.7	0.238	0.877	0.231
g_1=1.2								
M1+2	134.6	0.402	0.593	0.224	138.1	0.340	0.826	0.231
M1+2'	143.4	0.402	0.582	0.280	118.8	0.252	0.848	0.232
g_1=1.5								
M1+2	135.8	0.470	0.640	0.203	132.2	0.350	0.793	0.230
M1+2'	149.6	0.470	0.608	0.280	115.3	0.278	0.814	0.233
g_1=2								
M1+2	135.8	0.628	0.713	0.171	122.2	0.382	0.755	0.227
M1+2'	161.9	0.628	0.640	0.289	110.2	0.306	0.773	0.233

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7.7 Discussion

If there were no operational interaction (the pilchard bycatch) between the pilchard and anchovy fisheries then, given a certain set of TAC constraints, it appears as if there would be little (if any) gain in using management procedures markedly different to BL to take account of regime shifts. This is evident from results for options M4 in Figure 7.5 and M3 in Figure 7.6. M4 tries to overcome the under-utilisation of anchovy by increasing exploitation levels of anchovy when pilchard abundance allows, showing a bottom-left to top-right movement with increasing α' in the *risk* vs. average catch plot, with the performance for BL lying very close to this trend-line. This implies no overall gain for anchovy, because gains in $\overline{C}$ are accompanied by increases in *risk* (although the objective of a less under-utilised anchovy resource is achieved).

Furthermore, M3 (see Figure 7.6) tries to improve upon the performance of BL by reducing exploitation of adult pilchard when the adult pilchard biomass is low, but with little success. Therefore, when changes are made to the exploitation of the adult biomass for each species, there

is little gain for that species. This indicates that when each species is considered in isolation, by ignoring the operational interaction between them, BL already provides "optimal" utilisation. This is because BL uses a constant proportion strategy for both species (essentially tracking the status of the adult biomass of each species), with Exceptional Circumstances to buffer against "freak" events when continued use of the normal MP decision rules might be detrimental to the resource (Appendix 4.1). Therefore, the operational interaction between pilchard and anchovy aside, there appears to be little (if any) overall gain to be made by changing BL, even if one were given "perfect" knowledge of the underlying position in the regime cycle at any time (σ_g=0). However, the analyses in this Chapter do not provide a comprehensive evaluation of this matter, which warrants further investigation, particularly in the light of the results of Table 7.4, which show possible gains when the TAC constraints of OMP99 are relaxed.

This Chapter shows, nevertheless, that gains are possible, particularly for pilchard, when focussing on the operational interactions between pilchard and anchovy. Reduction of juvenile pilchard bycatch (landed with anchovy) by adjusting the control parameters α and γ (options M1 and M2 and combinations thereof – see equations A4.1.2-5 and 7.4-5) offer the best performance for pilchard under regime cycles of varying amplitudes for summary statistics $\overline{C}$, *risk*, *Loss* and *NPV*. Adding the adjustments of M3 (which reduces β when pilchard abundance is low, but does not focus on the actual operational interaction, i.e. bycatch – see equations A4.1.1 and 7.6) to M1+2 (to form M1+2+3), leads to marginally lower *risk* and *Loss* (almost no improvement, in fact, for the latter) than M1+2, but for lower $\overline{C}$ and *NPV*, and thus shows no overall gain.

Effective management to take account of the operational interactions between pilchard and anchovy becomes more important as the amplitude of the regime cycles increases. This is shown in Figures 7.6 and 7.7 for pilchard by the increasing difference, as g_1 increases, in overall performance between M1 and M2 (and combinations thereof) on the one hand, and BL and M3 on the other. An interesting result is that even though *risk* and *Loss* deteriorate as g_1 increases, $\overline{C}$ and *NPV* are maintained at the same levels (and even increase) for M1+2 and M1+2+3 in combination with estimator D1, whereas *NPV* becomes negative and *Loss* deteriorates markedly for BL and M3. This indicates the importance of effective management under regime-cycle scenarios from the economic point of view. [It should be noted that the range $g_1 \leq 2$, as considered in this Chapter, might not capture the full extent of possible variability of systems of small pelagic species. Further work may therefore need to consider larger g_1 values to deal with this concern.]

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A surprising result is that, for pilchard, estimator D1 outperforms estimator D2 (with its additional information) in terms of *Loss*, *NPV* and $\overline{C}$ for MP options M1 and M2 and combinations thereof for all regime-cycle scenarios considered, and in terms of *risk* when σ_g is high, and when g_1 is high (then even for low σ_g). Furthermore, any gains in terms of *risk* for lower g_1 and σ_g values would need to be judged against the feasibility and likely cost of obtaining sufficiently precise information (a requirement of low σ_g for D2) on the underlying position in the cycle at any time. For anchovy, estimator D1 also outperforms D2 in terms of *Loss* and *NPV* for option M2 across all regime-cycle scenarios considered. D1 therefore appears to be a more effective basis to proceed than D2, probably because tracking the actual biomass with an appropriate running mean (which dilutes incorrect signals caused by measurement error) follows the "genuine" highs and lows caused by both short- and long-term external factors (e.g. environmental forcing) more effectively than other attempts to follow the underlying position in the cycle, which do not take the shorter-term external factors into account.

If one were looking for an option that performs better than BL for both pilchard and anchovy, then M2 seems the ideal candidate. Although it doesn't perform as well as M1+2 and M1+2+3 for pilchard, it performs best overall for anchovy, as is particularly noticeable in Figures 7.7-9 when considering *Loss* and *NPV*. M2 is effective for pilchard because of the extra protection afforded to juvenile pilchards as a result of setting lower initial bycatch ratios (γ is reduced) when pilchard abundance is low. Although the initial pilchard TAB will be lower as a result, this option remains attractive because the revised pilchard TAB will still be realistic as it is based on the "measured" ratios of juvenile pilchard to anchovy in the commercial catches and recruit survey (Appendix 4.1). M2 is also attractive for anchovy as it does not reduce anchovy catches, and therefore does not further under-utilise anchovy. Furthermore, the additional pilchard bycatch that becomes available as a result of the more efficient utilisation of pilchard[91] contributes to higher *NPV* and lower *Loss* for anchovy. A concern for this option, however, is if the bycatch ratio remains high even when anchovy abundance is high and pilchard abundance low (contrary to what Figure 1.5 suggests). Reducing γ would then amount to unrealistic expectations of the industry to keep initial pilchard bycatch ratios at low levels, leading to illegal dumping of fish when these expectations cannot be met. Nevertheless, the circumstances of a high pilchard bycatch ratio given such abundances would seem unlikely to occur.

[91] The extra protection of juveniles offered by M2 leads to lower bycatch during years of low pilchard abundance with lower *risk* as a result, and higher catches in the long run.

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Some aspects of the analyses of this Chapter that warrant further investigation include the following:

- the efficiency of different choices for the period x of the running mean $\mu_{y,x}$ for estimator D1 over a range of periods (g_2 values) for regime cycles;
- the effect of changing the TAC constraints for both species (these remained unchanged for most of the analyses of this Chapter);
- the consequences of not knowing the phase difference between pilchard and anchovy (set at 180° in the existing model), or of a phase difference that is variable;
- considering results for a wider range of regime cycle amplitudes (i.e. $g_1 \geq 2$);
- removing the end effects of different choices for the regime cycle period by randomising over the start of the cycle to average out these effects, or projecting over much longer periods than 100 years to reduce the size of these effects;
- considering a wider range of options for modelling regime shifts than sinusoid curves;
- developing more dynamic and refined versions of the economic component, with different assumptions about the effort function (Appendix 7.2); and
- broadening the study to incorporate
  (a) other upwelling systems (this Chapter focuses on the South African Benguela system only); and
  (b) different management strategies such as constant catch and constant effort (only the constant proportion approach was considered in this Chapter).

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APPENDIX 7.1

Framework for testing alternative MPs under regime shifts

The framework used to test alternative MPs is the one shown in Appendix 5.1. The MPs and summary statistics are discussed in the main text (further details on the economic statistics are provided in Appendix 7.2), while the assessment procedure and operating model are described below.

The Assessment Procedure

The assessment procedures that provided parameter estimates for the Operating Models (OMs) used to test OMP99 (and BL and other MP variants considered in Chapter 7) are not discussed in detail here, because they are very similar to the assessment procedures for pilchard and anchovy presented in Chapters 2 and 3. For the purposes of Chapter 7 a narrower range of OMs, that focus only on the different characteristics of regime cycles for pilchard and anchovy, are considered compared to Chapter 5. Hypotheses concerning regime cycles are not based on data, and these cycles are assumed to come into operation only in the future, so that the underlying parameter estimates for all the OMs considered remain unchanged. Values for the parameter estimates used for all the OMs in Chapter 7 are shown in Table A7.1.1 under "OMs for OMP99", together with the comparable estimates used for OMs P_0/A_0 in Chapter 5, listed for comparison under "OMs for OMP02".

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Table A7.1.1 Values for the parameter inputs used for all the Operating Models (OMs) considered in Chapter 7, listed under "OMs for OMP99", together with comparable estimates for the OMs P_0 and A_0 used in Chapter 5, listed for comparison under "OMs for OMP02". For the latter (but not for the former), a joint probability distribution is available for the parameters, though only point estimates are shown here. Where appropriate, units are given in square parentheses. Values are given in the same order as under the column headed "Parameters/Data". Values in italics indicate parameters that are input rather than estimated.

Parameters/Data	OMs for OMP99	OMs for OMP02
M^P_{ad}, M^P_{ju}	*0.6*; *1.0* [per year]	*0.4*; *1.0* [per year]
M^A_{ad}, M^A_{ju}	*1.2*; *1.2* [per year]	*0.9*; *0.9* [per year]
k^P_N, k^A_N	*1.5*; 0.942	*1.0*; 0.988
k^P_r, k^A_r	1.109; 0.639	0.954; 0.839
$N^P_{y^P,a}$, $a = 1,\ldots,5$	3.195; 4.563; 0.000; 0.000; 0.634 (y^P = 1997) [billions]	14.919; 7.134; 1.810; 0.681; 1.124 (y^P = 2000) [billions]
$N^A_{y^A,a}$, $a = 1,\ldots,4$	62.552; 5.947; 3.329; 0.304 (y^A = 1998) [billions]	309.373; 32.663; 10.155; 3.256 (y^A = 2001) [billions]
S^P_a , $a = 1,\ldots,4$	0.220; 1.000; 0.796; 0.101	0.537; 1.000; 0.852; 0.445
$\eta^P_{y^P-1}, \eta^A_{y^A-1}$	-0.690; 0.094	1.336; 2.230

Appendix 7.1

Parameters/Data	OMs for OMP99	OMs for OMP02
s^P_{cor}, s^A_{cor}	-0.149; 0.222	0.374#; 0.324
σ^P_r, σ^A_r	0.509; 0.621	0.499; 0.685
K^P, a^P, b^P	751; 14.54; 212.1	1552; 21.64; 413.7
K^A, a^A, b^A	1435; 225.36; *0.2* K^A	1802; 179.0; *0.2* K^A
$\overline{w}^P_{ac}$, $a = 0,\ldots,4$	11.97; 64.09; 89.19; 102.54; 116.89 [g]	12.74; 67.29; 89.05; 100.43; 113.19 [g]
$\overline{w}^A_{ac}$, $a = 0, 1$	5.77; 9.42 [g]	5.75; 9.44 [g]
$\overline{w}^P_{a}$, $a = 1,\ldots,5$	29.68; 65.71; 92.24; 114.20; 120.86 [g]	34.33; 69.54; 86.54; 98.71; 111.53 [g]
$\overline{w}^A_{a}$, $a = 1,\ldots,4$	10.41; 15.82; 19.15; 19.15 [g]	9.76; 14.54; 16.63; 17.20 [g]
$\overline{w}^P_{0cbs}, \overline{w}^A_{0cbs}$	10.45; 6.63 [g]	12.06; 6.50 [g]
k_{sur}	1.290	1.308
$k_{may}, k_{apr:may}$	1.620; 1.374	1.089; 0.966
ρ_{Nov}, ρ_{rec}	0.123; 0.688	0.278#; 0.561#
$\sigma^P_{Nov}, \sigma^P_{rec}$	0.380; 0.642	0.254; 0.731
$\sigma^A_{Nov}, \sigma^A_{rec}$	0.287; 0.427	0.266; 0.401
ρ_{may}	0.857	0.888
$\sigma_{may}, \sigma_{apr:may}$	0.690; 0.653	0.725; 0.703

these values have CVs of over 50%

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The Operating Model

The OMs considered in Chapter 7 are as described in Appendix 5.1 (both the "Assessment Procedure" and "Operating Model" sections) except for the shorter time-series of data used here, the use of point estimates from the assessment procedures instead of a joint probability distribution, and the omission of considerations described in the sub-sections "Simulating bycatch to anchovy ratio in catches after May", "Bycatch drop-off after May" and "Additional sub-season" (see Chapter 4 for comparison between OMP99 and OMP02). Furthermore, only the "SS" stock-recruit curve is used to generate recruitment for both pilchard and anchovy (see Chapters 2 and 3 for a description of the stock-recruit curves used), and a 100-year projection period is used instead of just 20 years.

Regime cycles are modelled by replacing K^i (i = P or A) in Table A7.1.1 with the following (assuming an "SS" stock-recruit) curve:

$$K^i_y = a^i_y e^{\frac{1}{2}(\sigma^i_r)^2}\left[\sum_{n=1}^{n^i} \overline{w}^i_n e^{-M^i_{ju}-(n-1)M^i_{ad}}\right] \qquad \text{A7.1.1}$$

where n^P=5, n^A=4, and

$$a^P_y = a^i e^{(\ln g_1)\sin(360(y-1998)/g_2)}$$
$$a^A_y = a^i e^{-(\ln g_1)\sin(360(y-1998)/g_2)} \qquad \text{A7.1.2}$$

where the a^i are from Table A7.1.1, g_1 is the amplitude factor for the regime cycle (e.g. g_1=2 means a^i_y will fluctuate between $2a^i$ and $0.5a^i$), and g_2 is the period of the cycle (values used for g_1 and g_2 are given in the main text).

Future recruitment is generated as follows from an "SS" stock-recruit curve:

$$N^i_{y,0} = \begin{cases} a^i_y \, e^{\varepsilon^i_y \sigma^i_r} & , \text{ if } B^i_{y,N} \geq b^i_y \\ \dfrac{a^i_y B^i_{y,N}}{b^i_y} \, e^{\varepsilon^i_y \sigma^i_r} & , \text{ if } B^i_{y,N} < b^i_y \end{cases} \qquad \text{A7.1.3}$$

where

$$\varepsilon^i_y = s^i_{cor} \varepsilon^i_{y-1} + \sqrt{1-(s^i_{cor})^2} \; \omega^i_y \qquad , \quad \omega^i_y \sim \text{N}[0;1]$$

with σ^i_r, s^i_{cor}, $\varepsilon^i_{y^i-1} = \eta^i_{y^i-1}$ and y^i from Table A7.1.1. Furthermore, b^i_y is calculated in the same way as a^i_y (using equation A7.1.2 with b replacing a, where the b^i come from Table A7.1.1), and $B^i_{y,N}$ is computed by the OM using equations similar to A5.1.13 and A5.1.14.

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APPENDIX 7.2

Economic sub-model used to calculate NPV and Loss

The economic factors used to calculate *NPV* and *Loss* amount to a simple model, based on the formulations in BEAM 4 (Sparre and Willmann 1993) which calculates fixed costs linked to the number of vessels in the purse-seine fleet for pilchard and anchovy, and variable costs linked to both effort and landed catch. The purse-seine fleet may be divided into four categories, each with different requirements for the species targeted, the amount of fuel and ice used, the number of crew employed and the cost of vessels.

Category 1
Vessels in this category are smaller than 19m in length and carry ice, concentrating on adult pilchard for bait.

Category 2
Vessels are in the size range 19-26m in length and do not carry ice. They target anchovy for fishmeal. Any bycatch of pilchard with anchovy is also turned into fishmeal.

Category 3
Vessels are in the size range 19-26m in length and have the capacity to carry ice. They target anchovy for fishmeal (for which ice is not necessary) and adult pilchard for canning, using ice for the latter to maintain freshness of the fish. Any bycatch of pilchard with anchovy is turned into fishmeal.

Category 4
Vessels are 27m or more in length. They have refrigeration facilities on board, which require an initial amount of ice when used. They target anchovy for fishmeal (for which the refrigeration facility is not used) and adult pilchard for canning, with the latter needing to be cooled to maintain freshness. Any bycatch of pilchard with anchovy is turned into fishmeal.

The parameters used in the economic component and their actual values are given in Table A7.2.1.

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Appendix 7.2

Table A7.2.1 A description of the parameters used in deriving the economic summary performance statistics *Loss* and *NPV*, with actual values used. For the purpose of this Chapter these values are only "ball-park" figures. All parameters are year-invariant. Where appropriate, units are given in parentheses under "Description". [These data were obtained in 1999 from the South African pelagic industry and Marine and Coastal Management databases by Jan van der Westhuizen and Johan de Goede, both from Marine and Coastal Management, Cape Town, South Africa.]

Parameters	Description	Values			
		cat 1	cat 2	cat 3	cat 4
By category					
$p_{ves,j}$	Cost of a vessel in category j (thousand Rands per vessel)	2400	4500	4500	8000
$p^{P}_{crew,j}$	Earnings of crew in category j (thousand Rands per thousand tons landed) when targeting pilchard	25		10	10
$p^{A}_{crew,j}$	Earnings of crew in category j (thousand Rands per thousand tons landed) when targeting anchovy		8	8	8
$u_{ves,j}$	Number of vessels in category j	15	9	48	12
$u_{ice,j}$	Amount of ice used per trip in category j (tons per trip)	5		55	10
$u_{fuel,j}$, j=1,2,3 $u_{fuel,4a}$ $u_{fuel,4b}$	Amount of fuel used per trip-hour by vessels in category j (litres per trip-hour) – for category 4, 240 is used when targeting anchovy and an additional 55 (for refrigeration) when targeting pilchard	25	118	118	240 and 55 resp.
$u_{crew,j}$	Number of crew members per vessel in category j	8	9	9	10
t^{P}_{j}	Average number of trip-hours per trip by a vessel in category j when targeting pilchard	10		10	18
q^{P}_{j}	Proportion of the total catch of adult pilchard taken by category j vessels each year	0.08		0.43	0.49
q^{A}_{j}	Proportion of the total catch of anchovy taken by category j vessels each year		0.16	0.59	0.25
For all categories					
δ_{depr}	Depreciation of capital (per year) – here, $1/\delta_{depr}$ gives the number of years to replace a vessel relative to when it was purchased	0.05			
p_{ice}	Cost of ice (thousand Rands per ton)	0.13			
p_{fuel}	Cost of fuel (thousand Rands per litre)	0.002			
p^{P}, p^{A}	Wholesale value of pilchard and anchovy landed (thousand Rands per thousand tons)	3100 and 600 respectively			
C^{P}_{break}, C^{A}_{break}	"Break-even" points for landed catch in terms of profit for pilchard and anchovy (in thousand tons) [Note, the break-even point for anchovy includes pilchard bycatch landed with anchovy.]	60 and 100 respectively			

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Fixed costs

It is assumed here that the depreciation costs of vessels in categories 3 and 4 are shared equally between the pilchard and anchovy fisheries, because vessels in these categories target both pilchard and anchovy.

Pilchard: $$\varphi^{P}_{fix} = \tfrac{1}{2}\delta_{depr}(p_{ves,3}u_{ves,3} + p_{ves,4}u_{ves,4}) + \delta_{depr}p_{ves,1}u_{ves,1} \quad \text{A7.2.1}$$

Anchovy: $$\varphi^{A}_{fix} = \tfrac{1}{2}\delta_{depr}(p_{ves,3}u_{ves,3} + p_{ves,4}u_{ves,4}) + \delta_{depr}p_{ves,2}u_{ves,2} \quad \text{A7.2.2}$$

Variable costs

Ice (per trip-hour)

Ice is used only when targeting pilchard. Ice is loaded onto the vessel once, when it sets out to sea, so the average number of trip-hours per trip is required in this calculation.

Pilchard: $$\varphi^{P}_{var,ice} = \sum_{j=1,3,4}(q^{P}_{j}u_{ice,j}/t^{P}_{j})\,p_{ice} \quad \text{A7.2.3}$$

Fuel (per trip-hour)

Pilchard fishing requires extra fuel in category 4 because of the refrigeration capacity of vessels in this category.

Pilchard: $$\varphi^{P}_{var,fuel} = [q^{P}_{1}u_{fuel,1} + q^{P}_{3}u_{fuel,3} + q^{P}_{4}(u_{fuel,4a} + u_{fuel,4b})]p_{fuel} \quad \text{A7.2.4}$$

Anchovy: $$\varphi^{A}_{var,fuel} = [q^{A}_{2}u_{fuel,2} + q^{A}_{3}u_{fuel,3} + q^{A}_{4}u_{fuel,4a}]p_{fuel} \quad \text{A7.2.5}$$

Crew (per ton landed)

For this Chapter, it has been assumed that opportunity costs of labour are exactly the earnings of the crew manning the vessels, because the Chapter focuses on the "microcosm" of the fleet without taking "outside" effects into account. This makes the implicit assumption that the fleet and costs associated with it are not influenced by outside effects, which is unrealistic, but regarded as a first step in taking economic effects into account.

Pilchard: $$\varphi^{P}_{var,crew} = \sum_{j=1,3,4}q^{P}_{j}u_{crew,j}p^{P}_{crew,j} \quad \text{A7.2.6}$$

Anchovy: $$\varphi^{A}_{var,crew} = \sum_{j=2,3,4}q^{A}_{j}u_{crew,j}p^{A}_{crew,j} \quad \text{A7.2.7}$$

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Profit

Profit is the difference between the price achieved for the landed catch, and the fixed and variable costs of the fleet. [Note that in the operating model used (Appendix 7.1) it is assumed that, unless the TAC/B exceeds the natural limitation of what can be caught, the whole TAC/B will be taken (i.e. no under- or over-catching of the TAC/B occurs). This assumption applied to OMP99 (Chapter 4); in contrast, OMP02 (Chapter 5) does not assume that the anchovy TAC and pilchard TAB is always taken.]

Pilchard: $$\pi_y^P = p^P TAC_y^P - \varphi_{fix}^P - (\varphi_{var,ice}^P + \varphi_{var,fuel}^P)E_y^P - \varphi_{var,crew}^P TAC_y^P \quad \text{A7.2.8}$$

Anchovy: $$\pi_y^A = p^A(TAC_y^{2,A} + TAB_y^{2,P}) - \varphi_{fix}^A - \varphi_{var,fuel}^A E_y^A - \varphi_{var,crew}^A(TAC_y^{2,A} + TAB_y^{2,P}) \quad \text{A7.2.9}$$

where E_y^i is the effort (in trip-hours) used when targeting species *i* in year *y*, and the TAC/Bs are as given in equations A4.1.1-A4.1.5 of Appendix 4.1.

Calculating Effort

CPUE is not a good index of abundance for pilchard and anchovy because of the shoaling behaviour of these fish. This is because CPUE may remain constant even when abundance drops because of the effect of "mining out" shoals. This feature of CPUE implies that effort increases and decreases with catch. It is therefore assumed that effort is proportional to the TACs set for directed catches. It is further assumed that there is a level of catch for directed pilchard, and for anchovy that includes the pilchard bycatch landed with anchovy (C_{break}^P for pilchard and C_{break}^A for anchovy – see Table A7.2.1), below which that fishery will operate at a loss. By setting $TAC_y^P = C_{break}^P$, $E_y^P = E_{break}^P$ and $\pi_y^P = 0$ in equation A7.2.8, and $TAC_y^{2,A} + TAB_y^{2,P} = C_{break}^A$, $E_y^A = E_{break}^A$ and $\pi_y^A = 0$ in equation A7.2.9, these equations can be solved for E_{break}^P and E_{break}^A respectively. Effort in year *y* can then be calculated as follows:

Pilchard: $$E_y^P = \frac{E_{break}^A TAC_y^P}{C_{break}^P} \quad \text{A7.2.10}$$

Anchovy: $$E_y^A = \frac{E_{break}^A (TAC_y^{2,A} + TAB_y^{2,P})}{C_{break}^A} \quad \text{A7.2.11}$$

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Calculating *NPV* and *Loss*

The Net Present Value, *NPV*, for species *i* is calculated as follows:

$$NPV \text{ (for species } i) = \frac{1}{100}\sum_{k=1}^{100}\left(\frac{1}{1+\delta_{disc}}\right)^{k}\pi^{i}_{1997+k} \qquad \text{A7.2.12}$$

where δ_{disc} is the discount rate for the pelagic fishery. [Note that if more than one simulation of a 100-year trajectory is used, as is the case in this Chapter, then *NPV* is also averaged over the number of simulations.] For this Chapter, a value of δ_{disc}=0 has been used under the assumption that national objectives override those of individual companies, and that these objectives involve managing for the very long term. *Loss* is simply the number of years (out of the total number in the projection period, i.e. 100 years) where the contribution to *NPV* for that year in equation A8.2.12 is either zero or negative (*Loss* is also averaged over the number of simulations).

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CHAPTER 8

Use of Environmental Indices in MPs

Environmental indices that provide short-term predictions of recruitment have the potential to improve the average yield from highly productive resources that sustain recruit fisheries without an associated increase in *risk*. This is particularly true for cases where a measurement of recruitment is not available until after substantial fishing on this recruitment has already taken place. The South African anchovy resource meets these criteria, and forms the basis for a simulation study to investigate the benefits of using environmental indices. Simulations, based on OMP99 (Chapter 4) investigate how such benefits are related to the proportion of variation in recruitment explained by the environmental index. Furthermore, they investigate how these benefits are compromised by uncertainties related to the degrees of freedom effect (over-fitting data), the selection of explanatory variables (danger of spurious correlations), and errors in the values of explanatory variables (including measurement error). Five recruitment prediction models are investigated incorporating the above uncertainties. These predictions are used to adjust TACs depending on whether they indicate forthcoming recruitment to be in the top or bottom third of the distribution of possible recruitment values. Results indicate that an environmental index needs to explain roughly 50% or more of the total variation in recruitment ($r^2 \geq 0.5$) before the MP starts showing benefits in terms of the summary statistics *risk* and average catch. Comparable benefits are possible at a lower r^2 when TAC constraints are removed, but there is a large associated increase in inter-annual catch variation. Further work is needed, however, because these results may be too optimistic in terms of the potential utility of environmental indices, as a result of some of the simplifying assumptions used (e.g. that the form of the recruit vs. index relationship is linear).

8.1 Introduction

Several authors have investigated the incorporation of environmental indices to improve fisheries management. For example, based on further development of the work originally presented by Bergh and Butterworth (1987), Cochrane and Starfield (1992) found that the average catch for South African anchovy (a highly productive stock) could be increased by up to 48% given very precise short-term predictors of recruitment. For gadoid-like species (i.e. ones of relatively low productivity), Basson (1999) concluded that there were no gains when an environmental index was used for the short-term prediction of recruitment. However, when it was used to change fishing mortality references points for the longer term, gains were possible if the environmental index could be well predicted. Walters (1989) found that improvements in management performance depended strongly on the average productivity of the stock concerned, and the flexibility of the in-season regulatory system used to manage that stock. For example, productive stocks managed with inflexible annual quotas showed very large improvements (30-50%) if perfect pre-season forecasting was practical, but unproductive stocks showed only modest improvements regardless of the in-season regulatory system used. Walters' findings are consistent with those mentioned above.

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The South African anchovy stock is certainly a worthy candidate for investigating the use of environmental indices in MPs, because it is a highly productive resource that sustains a recruit fishery for which a measurement of recruitment is not available until after substantial fishing on that recruitment has already taken place (Chapter 4). In this context, environmental indices might be able to provide short-term predictions of recruitment that, if used in the TAC equations of Chapter 5 to cover a period before recruit survey results become available, would do better in terms of MP performance than assuming forthcoming recruitment to be average. A key to the use of such indices is that, desirably (though this is not an absolute requirement), the relationship assumed with recruitment should follow from an *a priori* hypothesis based upon a causal relationship suspected, given the underlying biology (Burnham and Anderson 2002). Furthermore, for actual implementation, the parameters of the relationship need to be estimable with reasonable precision from the data: even though *a priori* ideas provide the form to be expected, almost certainly the parameters of the relationship would need to be estimated empirically.

Butterworth *et al.* (1986) conducted a simulation study which, assuming there was indeed a causal relationship with recruitment in terms of relatively few explanatory environmental variables, investigated why and to what extent the success of regression or similar objective procedures to estimate such a relationship might be limited or misleading. The possible reasons they gave were as follows.

1. The degrees of freedom effect – the problem of over-fitting data, where a high standard (as opposed to predictive) correlation coefficient does not necessarily mean that the associated relation will have good predictive capabilities[92].
2. The selection of explanatory variables – the problem that one will always find an apparently good causal relationship with a high correlation coefficient through a regression exercise if one searches long and hard enough through a potentially infinite number of environmental variables. In this context, Myers (1998) found that the proportion of published environment-recruitment correlations verified when tested with new data was low. A proper selection of explanatory variables requires information independent of that used in the regression, or

[92] A "Predictive" correlation coefficient R is related to the standard correlation coefficient ρ as follows (Butterworth *et al.* 1986): $R^2 = \rho^2 - (1-\rho^2)2m/(n-m-2)$, where n is the number of years of data and m the number of explanatory variables fitted. It measures how well (in RSME terms) a regression relationship predicts a new value compared to simply using the mean of previous values: $R^2 = 1$ (when $\rho = 1$) reflects perfect prediction; $R = 0$ gives no improvement over use of the aforementioned mean, and $R^2 < 0$ indicates that the regression gives less reliable predictions (than simply using the mean) as a result of over-fitting data.

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alternatively a cross validation approach, such as splitting a given data series in half and basing the selection of variables on the first half, with the predictive relation provided (if still justified thereby) by the regression fits to these variables using the second half of the data.

3. Errors in values of the explanatory variables – this may involve more than just the "typical" measurement error associated with a single measurement, and may include the extent to which a proxy used for an environmental variable (which itself may be difficult to measure, hence the need for a proxy) relates to the actual value for this variable that determines recruitment.

4. Errors in functional forms assumed (model mis-specification) – although quantitative relationships might be determined by a regression process, the more complex the relationship hypothesised, the more parameters there will be to estimate, and therefore the poorer the predictive capabilities of the relationship.

In their study, Butterworth *et al.* (1986) sought input from scientists with knowledge of those "measurable" variables considered the most likely to affect anchovy recruitment. The functional form problem (4 above) was ignored, and only linear and quadratic relationships were considered in order to restrict the number of potential parameters. Simulations were conducted by generating environmental data for a number of years, with associated recruitment values according to an underlying model. The environmental data were then corrupted by measurement error, and subjected to a stepwise regression procedure in order to select explanatory variables and estimate parameters – this selection was based on data generated for a set of candidate variables, only some of which were actually related to recruitment in the underlying model. The assessed environmental relationship was then used to predict recruitment for the forthcoming year, and compared with the actual recruitment generated by the ("true") underlying model. Results were depicted as the number of times stepwise regression produced a prediction better, equivalent or worse than simply using the historic average recruitment. This approach allowed an investigation of the limitations imposed by problem areas 1-3 above. Findings were that, even for the more optimistic case considered[93], there was half as much likelihood of selecting a spurious variable than one having a real effect, and that predictive improvement (compared to using the historic average) was miniscule, even after 100 years.

[93] Two cases were considered: the more optimistic selected for three variables, accounting for 75% of the "true" variation in recruitment, from a set of five candidate variables; the less optimistic selected for nine variables (explaining 90% of "true" recruitment variation) from a set of 15.

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This Chapter repeats the work of Cochrane and Starfield (1992), but broadens this work to consider the effect of incorporating the problems listed by Butterworth *et al.* (1986), i.e. 1-4 above. The aim is therefore to see how the benefits of incorporating short-term predictors of recruitment (as demonstrated by Cochrane and Starfield 1992) are eroded as the different levels of uncertainty associated with the use of environmental indices to predict recruitment, and hence modify TACs, are incorporated into the analysis of MPs.

8.2 Modelling "true" and "predicted" recruitment

The assessment parameter estimates and operating model described in Appendix 7.1 (omitting the regime cycles component of equation A7.1.2), and the MP rules and constraints presented in Appendix 4.1, form the basis of the simulations in this Chapter. A distinction is made between "true" recruitment, generated by the underlying operating model, and environmental variable based "predicted" recruitment, which is used to decide how to adjust anchovy TACs in the manner described below. [In the equations shown in this Chapter, superscript "A" (used in other Chapters to indicate that equations refer to anchovy) has been omitted for simplicity. Furthermore, the superscripts "true", "pred" and "merr" are used to distinguish between true and predicted recruitment, and between the true environmental index, and that index after it has been corrupted by measurement error, respectively.]

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True recruitment

True recruitment is generated as follows:

$$N_{y,0}^{true} = f(B_{y,N})e^{\varepsilon_y^{true}}$$
$$\varepsilon_y^{true} = r\sigma_r T_y^{true} + \sqrt{1-r^2}\,\sigma_r \varepsilon_y \qquad 8.1$$

where the environmental index T_y^{true} is modelled as:

$$T_y^{true} = s_{cor} T_{y-1}^{true} + \sqrt{1-(s_{cor})^2}\,\xi_y$$
$$T_{1997}^{true} = 0 \qquad 8.2$$
$$\xi_y \sim \mathrm{N}[0;1]$$

and the "unexplained" variation as:

$$\varepsilon_y = s_{cor}\varepsilon_{y-1} + \sqrt{1-(s_{cor})^2}\,\omega_y$$
$$\varepsilon_{1997} = \eta_{1997} \qquad 8.3$$
$$\omega_y \sim \mathrm{N}[0;1]$$

In equations 8.1-3 (and equations to follow), function f represents the "SS" stock-recruit curve shown in equation A7.1.3, as follows:

$$f(B_{y,N}) = \begin{cases} a & \text{, if } B_{y,N} \geq b \\ \dfrac{a B_{y,N}}{b} & \text{, if } B_{y,N} < b \end{cases} \qquad 8.4$$

The parameters a, b, σ_r, s_{cor} and η_{1997} in equations 8.1-4 are as defined in Appendix 7.1. Furthermore, r^2 is the proportion of the overall variation in recruitment explained by the environmental index T_y^{true}. It should be noted that equations 8.1-3 reduce to equation A7.1.3 (see also equation A5.1.15) when $r = 0$.

Predicted recruitment

Predicted recruitment is generated in five ways, each time incorporating additional levels of uncertainty, as follows.

I *Parameters known exactly, no measurement error:*

$$N_{y,0}^{pred} = f(B_{y,N}) e^{r\sigma_r T_y^{true}} \qquad 8.5$$

Here it is assumed that the relationship between the environmental index T_y^{true} and recruitment (strictly the log-residual ε_y^{true} in equation 8.1) is known exactly (i.e. it is a linear relationship through the origin with a known slope $r\sigma_r$). If $r = 1$, equations 8.1 and 8.5 are identical (i.e. $N_{y,0}^{pred}$ is a perfect predictor of true recruitment), but if $r = 0$, there is no relationship between the environmental index and recruitment.

II *Parameters estimated, no measurement error:*

$$N_{y,0}^{pred} = f(B_{y,N}) e^{\hat{b}_0 + \hat{b}_1 T_y^{true}} \qquad 8.6$$

As in case I, but the relationship between ε_y^{true} and T_y^{true} is no longer assumed to be known exactly, so needs to be estimated from time-series for these quantities. Therefore, the parameters $\hat{b}_0$ and $\hat{b}_1$ are estimated from a 30-year time-series $\{\varepsilon_y^{true}; T_y^{true}\}$[94].

[94] For each simulation run, these values are generated prior to the first year of the projection period (i.e. for the years 1967-1996, where $\varepsilon_{1967}^{true} = T_{1967}^{true} = 0$) using equations 8.1-3. [Note: values for $\varepsilon_{1997}^{true}$ and T_{1997}^{true} are as shown in equations 8.2-3.]

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III *Parameters estimated, measurement error included:*

$$N_{y,0}^{pred} = f(B_{y,N})e^{\hat{b}_0+\hat{b}_1 T_y^{merr}} \quad 8.7$$

As in case II, but $\hat{b}_0$ and $\hat{b}_1$ are estimated from 30-year time-series $\{\varepsilon_y^{merr}; T_{y,1}^{merr}\}$, where ε_y^{merr} and $T_{y,1}^{merr}$ are calculated in the same way as ε_y^{true} and T_y^{true}, but have been corrupted by measurement error as follows:

$$\varepsilon_y^{merr} = \varepsilon_y^{true} + 0.25\omega_y^{merr}$$
$$\omega_y^{merr} \sim \mathrm{N}[0;1] \quad 8.8$$

and

$$T_{y,1}^{merr} = T_y^{true} + 0.5\xi_y^{merr}$$
$$\xi_y^{merr} \sim \mathrm{N}[0;1] \quad 8.9$$

where it is assumed that measurement error is typically relatively larger for the environmental index than for recruitment. [The concern here was to look at the effect of measurement error associated with the environmental index, not with recruitment; hence the lower measurement error size in equation 8.8 compared to equation 8.9.]

IV *Parameters estimated and selected (p=5%), measurement error included:*

$$N_{y,0}^{pred} = f(B_{y,N})e^{\hat{b}_0+\hat{b}_1 T_{y,1}^{merr}+\hat{b}_2 T_{y,2}^{merr}+\hat{b}_3 T_{y,3}^{merr}} \quad 8.10$$

where

$$T_{y,2/3}^{merr} = \eta_{y,2/3}^{true} + 0.5\xi_{y,2/3}^{merr}$$
$$\eta_{y,2/3}^{true} \sim \mathrm{N}[0;1] \quad 8.11$$
$$\xi_{y,2/3}^{merr} \sim \mathrm{N}[0;1]$$

This is an extension of case III, where selection is now made between three environmental variables, only one of which ($T_{y,1}^{merr}$) is really related to recruitment (equations 8.1 and 8.9). Environmental variables $T_{y,2}^{merr}$ and $T_{y,3}^{merr}$ are generated in the same way as $T_{y,1}^{merr}$, but bear no relationship to recruitment (compare equations 8.2, 8.9 and 8.11). Parameters $\hat{b}_0, \hat{b}_1, \hat{b}_2$ and $\hat{b}_3$ are estimated from a stepwise multiple regression technique using forward selection, with a p value of less than 5% serving as a criterion for inclusion of a parameter in the model. Therefore, a situation where (incorrectly) $\hat{b}_1 = 0$, and $\hat{b}_{2/3} \neq 0$ is possible.

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V *Parameters estimated and selected (p=50%), measurement error included:*
As IV but the selection criteria (for inclusion of a parameter by forward selection in a multiple regression) is not as strict (a p value of 50% instead of 5%). This allows for a greater chance of including variables that truly impact recruitment, but also of including spurious correlations when predicting recruitment.

Adjusting TACs on the basis of $N_{y,0}^{pred}$

The 1st TAC, TAC_y^1 (equation A4.1.2), is adjusted according to how $N_{y,0}^{pred}$ compares with the expected distribution of $N_{y,0}^{true}$ values, as follows:

$$TAC_y^1 = \begin{cases} TAC_y^1 - TAC_{adj} & , N_{y,0}^{pred} < a\,e^{-0.431\sigma_r} \\ TAC_y^1 & , a\,e^{-0.431\sigma_r} \le N_{y,0}^{pred} \le a\,e^{0.431\sigma_r} \\ TAC_y^1 + TAC_{adj} & , N_{y,0}^{pred} > a\,e^{0.431\sigma_r} \end{cases} \qquad 8.12$$

where $a\,e^{-0.431\sigma_r}$ and $a\,e^{0.431\sigma_r}$ (a from equation 8.4) are the exponentiated values of $\ln(N_{y,0}^{true})$ for which the area to the left under the corresponding Normal distribution curve is ⅓ and ⅔ respectively[95]. Therefore, TAC_y^1 is adjusted down if $N_{y,0}^{pred}$ falls within the bottom third of the expected distribution for $N_{y,0}^{true}$, and up if it falls within the top third of this distribution; otherwise no adjustment is made. Values of TAC_{adj} considered were 0 (i.e. the environmental indices are effectively not used), 50, 100 and 200 thousand tons.

8.3 Results

For a given level of *risk* (40%[96], *risk* as defined in Chapter 7), Table 8.1 summarises the improvements in average catch for TAC_{adj} = 50, 100 and 200 thousand tons for different values of r^2 (0, 0.1, 0.25, 0.5 and 1) for each of the five prediction models (I-V) above, when compared to the case where environmental indices are not used (TAC_{adj} = 0). Figure 8.1 shows catch-*risk* curves for r^2=0.25 and 0.5 for all five prediction models (I-V above), with each panel showing curves for a range of TAC_{adj} values. The results in Table 8.1 are essentially the points where a horizontal line drawn at *risk* = 40% intersects with the catch-*risk* curves shown in Figure 8.1.

[95] Note that in this formulation, the descending limb of the "SS" stock-recruit curve (equation 8.4) is ignored. Furthermore, the values of a and σ_r are taken to be known, and are in fact equal to the true values.

[96] The threshold *risk* level used for anchovy has, in the recent past, been 30% (see Chapters 5 and 7). The reason 40% is used here instead of 30% is purely illustrative, because for the constraints used in OMP99, *risk* = 30% occurs near where the catch-*risk* curves flatten (Figure 8.1), which would make it difficult to provide informative comparisons in Table 8.1.

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Table 8.1 Improvements in average catch for a *risk* level of 40%, compared to the situation when no environmental indices are used [this improvement, expressed as a percentage, is calculated as $\{C(TAC_{adj}>0)-C(TAC_{adj}=0)\}/C(TAC_{adj}=0)$, where C is the average catch over the 20-year period]. Results are shown for a range of r^2 and TAC_{adj} values for all five recruitment prediction models (I-V).

	r^2=0.00	r^2=0.10	r^2=0.25	r^2=0.50	r^2=1.00
	TAC_{adj} = 50 000t				
I	0%	1%	2%	7%	11%
II	1%	0%	2%	7%	11%
III	0%	0%	0%	5%	8%
IV	0%	0%	1%	4%	8%
V	0%	-1%	1%	4%	8%
	TAC_{adj} = 100 000t				
I	0%	1%	3%	6%	15%
II	0%	0%	2%	6%	15%
III	-1%	-2%	0%	5%	11%
IV	-1%	-1%	1%	4%	11%
V	-2%	-5%	2%	5%	11%
	TAC_{adj} = 200 000t				
I	0%	-4%	3%	5%	20%
II	-2%	-5%	1%	5%	20%
III	-3%	-5%	-3%	4%	15%
IV	-2%	-7%	-6%	2%	15%
V	-8%	-10%	-6%	2%	14%

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Table 8.1 shows that gains in terms of average catch (compared to the case when no environmental indices are used) exceed 2-4% only for the cases shown with r^2 at least 0.5. In other words, if roughly 50% or more of the variation in recruitment could be explained by the environmental index, then notable gains in terms of average catch could be attainable. Gains in average catch are eroded as one moves from prediction models I to V for all values of TAC_{adj} considered. This is essentially because the greater the measurement errors or number of parameters from which to choose, the less likely it is that TAC_{adj} will be applied correctly (i.e. to increase the TAC when recruitment is high, and *vice versa*), and hence the more likely errors become. Furthermore, the higher TAC_{adj} is set, the worse one does in terms of average catch when r^2 is 0.5 or less. In certain instances (low r^2 and high TAC_{adj}), using the environmental indices leads to poorer performance than not using them.

Performance is generally better when $r^2 = 0$ compared to when $r^2 = 0.1$. This is because for the former, there is a higher likelihood of TAC_y^1 not being adjusted due to the lack of relationship between the environmental index and recruitment compared to the latter (i.e. the parameters in situations II-V are more likely to be estimated close to zero when $r^2 = 0$ than when $r^2 = 0.1$, so that the middle option in equation 8.12 is more likely to be applied). This would offer some

protection against erroneously adjusting TAC_y^1 when the environmental index indicates that recruitment is good, but it is in fact poor, a situation that is possible because of the low r^2.

In Figure 8.1, better performances in terms of *risk* and average catch are reflected by a shift towards the bottom right-hand corner of a plot. The deterioration in performance as one moves from prediction models I to V, and as one moves from a higher to lower r^2 value is evident. [Note, within each column of plots, the "no index" curve remains the same.]

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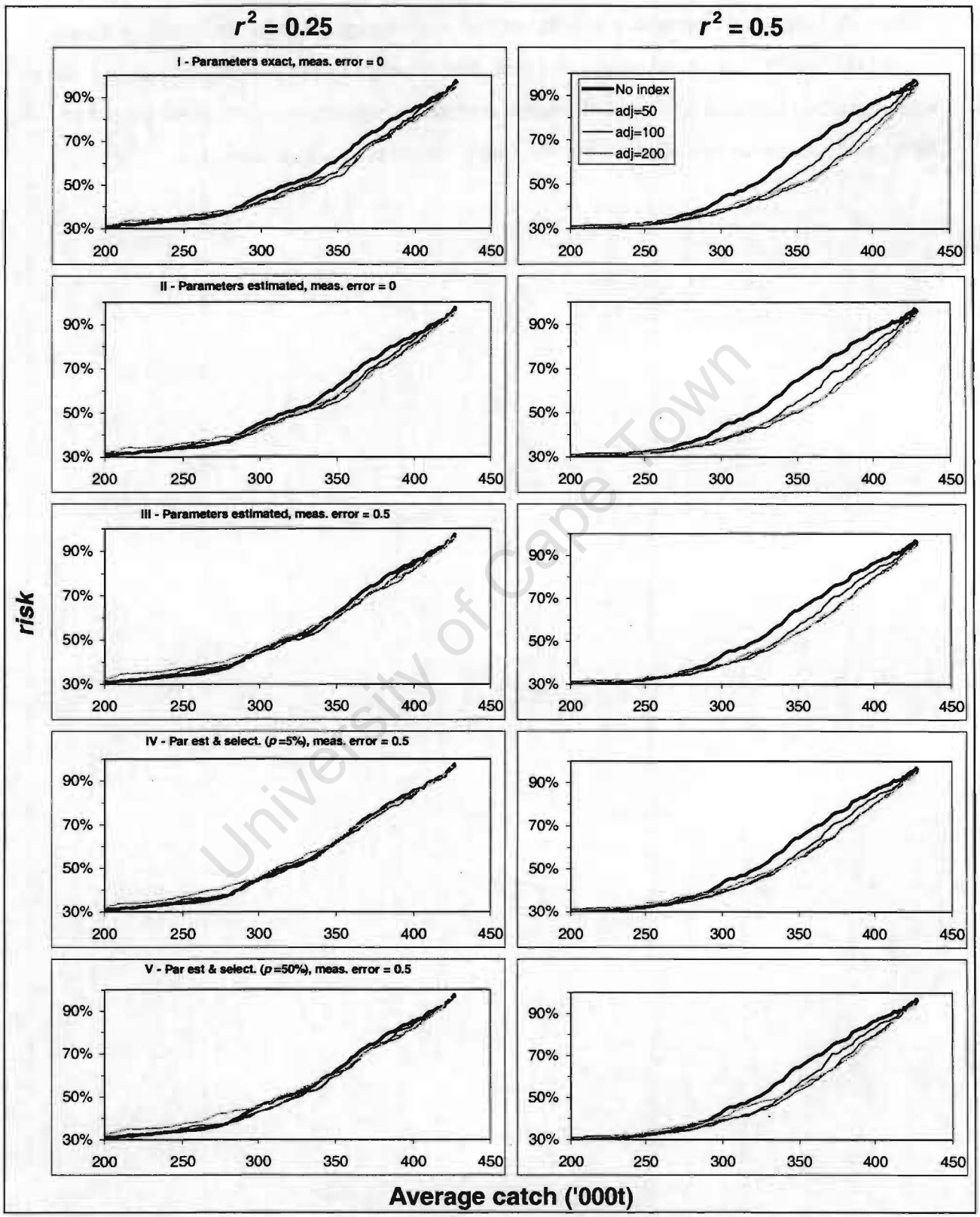
Figure 8.1 Catch-*risk* curves for recruitment prediction models I-V for r^2=0.25 and 0.5. Average catches are in thousand tons, and *risk* is expressed as a percentage. The value for TAC_{adj} is expressed as "adj" in the legend. Generally, the curves appear in the same order as in the legend (except for the "adj=200" curves which have higher *risk* values for low expected catches for the simpler prediction models, but increasingly overlap the other curves as one moves from prediction model I-V).



In Table 8.1 and Figure 8.1, TACs are subject to a number of constraints that attempt to keep them from moving downwards too rapidly, and to ensure that they remain within bounds that are

acceptable to the fishing industry (Chapters 5 and 7). Improvements in performance in terms of average catch and *risk* are possible if these TAC constraints are relaxed. Table 8.2 repeats the results of Table 8.1, but with all the TAC constraints relaxed. A comparison between Tables 8.1 and 8.2 indicates some improvement in average catch when these TAC constraints are removed. This is also evident in Figure 8.2, which contrasts catch-*risk* curves with and without constraints for both r^2=0.25 and 0.5 for recruitment prediction model IV. [Note that for the purposes of this Chapter, improved performance in Figure 8.2 is judged by comparing "like" curves. This is because a curve with constraints is not comparable to a curve without constraints for the issues under consideration here. Clearly, removing all TAC constraints leads to superior performance in terms of both *risk* and average catch.]

Table 8.2 A repeat of the results of Table 8.1 (again for *risk* = 40%), but with all TAC constraints removed.

	r^2=0.00	r^2=0.10	r^2=0.25	r^2=0.50	r^2=1.00
	TAC_{adj} = 50 000t				
I	0%	2%	4%	8%	11%
II	0%	2%	4%	7%	11%
III	0%	2%	3%	7%	11%
IV	0%	1%	3%	7%	11%
V	0%	0%	4%	8%	11%
	TAC_{adj} = 100 000t				
I	0%	2%	7%	11%	20%
II	0%	3%	5%	11%	20%
III	0%	3%	5%	10%	20%
IV	-1%	1%	3%	9%	19%
V	-2%	1%	5%	10%	20%
	TAC_{adj} = 200 000t				
I	0%	3%	9%	16%	32%
II	-1%	2%	10%	15%	32%
III	-1%	2%	6%	10%	29%
IV	-2%	0%	2%	9%	29%
V	-4%	-2%	5%	9%	29%

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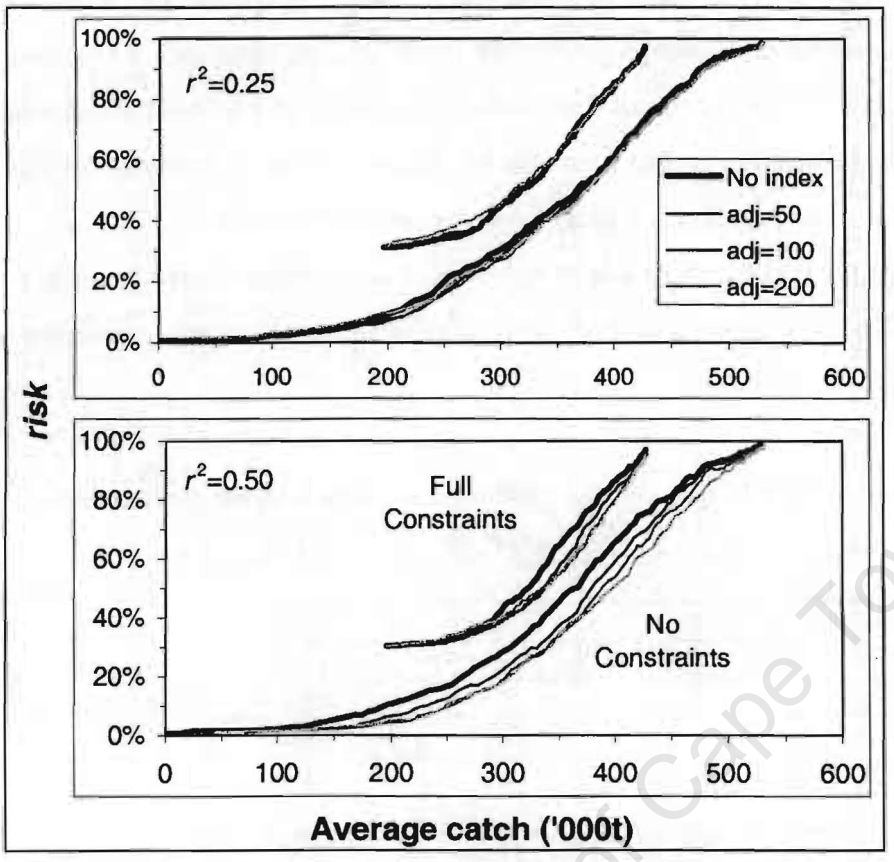
Figure 8.2 Catch-*risk* curves for recruitment prediction model IV for r^2=0.25 and 0.5. Results are shown for when TAC constraints are included (upper left hand side curves, corresponding to Figure 8.1) and for when no TAC constraints are applied (lower right hand side curves). Refer to the caption to Figure 8.1 for further details.



The improved performance in terms of *risk* and average catch compared to the "no index" case (Table 8.2, Figure 8.2) comes at a cost. Table 8.3 compares the mean annual change in catch (see Chapter 5 for definition) associated with the results for TAC_{adj} = 50 thousand tons, both with (Table 8.1) and without (Table 8.2) constraints. The "no constraints" case has much higher levels of inter-annual change in catch than the "full constraints" case.

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Table 8.3 Mean annual change in catch for *risk* = 40%. Results are shown for a range of r^2 values for the case where no indices are used and for all five recruitment prediction models (I-V). The upper set of results applies when TAC constraints are included, and the lower when they have been excluded. For all five prediction models, the level of TAC adjustment TAC_{adj} = 50 thousand tons.

	r^2=0.00	r^2=0.10	r^2=0.25	r^2=0.50	r^2=1.00
	Full Constraints				
No index	29%	29%	29%	29%	29%
I	29%	29%	30%	31%	32%
II	29%	29%	30%	31%	32%
III	29%	29%	30%	31%	32%
IV	29%	29%	30%	31%	32%
V	29%	29%	30%	31%	32%
	No constraints				
No index	48%	48%	48%	48%	47%
I	48%	49%	50%	52%	52%
II	49%	49%	50%	51%	52%
III	49%	49%	50%	51%	51%
IV	49%	49%	49%	51%	51%
V	49%	49%	50%	51%	51%

A final option investigated was where TACs are adjusted downwards only when the predicted recruitment indicates that forthcoming recruitment will be poor. Equation 8.12 is therefore amended by removing "+ TAC_{adj}" in the bottom line. Results are shown in Table 8.4. Negative values have almost entirely disappeared under this option, but it also leads to marginally poorer performance when r^2 is high (compare Tables 8.1 and 8.4). As in Table 8.1, appreciable gains in average catch (≥2%) occur only when r^2 is at least 0.5.

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Table 8.4 As Table 8.1, but TACs are adjusted only when the level of recruitment predicted by use of the environmental indices suggests that forthcoming recruitment will be poor.

	r^2=0.00	r^2=0.10	r^2=0.25	r^2=0.50	r^2=1.00
	TAC_{adj} = 50 000t				
I	0%	0%	1%	5%	8%
II	0%	0%	1%	5%	8%
III	0%	0%	0%	4%	7%
IV	0%	0%	1%	2%	6%
V	0%	0%	0%	3%	6%
	TAC_{adj} = 100 000t				
I	0%	0%	1%	6%	11%
II	0%	0%	1%	5%	11%
III	0%	0%	0%	3%	9%
IV	0%	-1%	1%	2%	9%
V	0%	0%	0%	3%	9%
	TAC_{adj} = 200 000t				
I	0%	0%	1%	6%	11%
II	0%	0%	1%	5%	11%
III	0%	0%	0%	3%	9%
IV	0%	-1%	1%	3%	9%
V	0%	0%	0%	3%	9%

8.4 Discussion

It appears that the environmental index needs to explain roughly 50% or more of the total variation in recruitment ($r^2 \geq 0.5$) before an OMP which takes account of such information starts to show benefits in terms of *risk* and/or average catch. Comparable benefits in terms of average catch are achieved at a lower r^2 value when TAC constraints are removed, but this may not be in the best interest of the fishing industry because of the large associated increased levels of inter-annual variation in catch.

There are several factors, however, that require further investigation because they may reveal that the results shown in this Chapter about the potential benefits of taking account of the environmental indices are possibly too optimistic. This is because the analyses presented here:

- assume that the form of both the actual and the estimated recruit vs. index relationship is linear;
- assume that this relationship does not change over time, and hence holds throughout the implementation period of the MP;
- assume that the environmental index is subject to the same serial correlation as recruitment; and

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- assume that as many as 30 years of data are available to estimate the parameters of the recruitment–environment relationship.

Each of these assumptions is unlikely to be met in reality. A further element of optimism in the computations is that the estimator used by the MP to incorporate the environmental information makes assumptions that happen to be correct in terms of the operating model used (for example, the values of a and σ_r in equation 8.12 are taken to be known, and equal to the operating model values). Had these assumptions not been correct in terms of the operating model, they would likely have led to worse performance than reflected in the results presented here.

A further question arises about whether TAC adjustment formulae other than those in equation 8.12 (for example a linear function rather than a step function) would have led to better performance. This is unlikely, however, because the key issue is the correct application of these adjustment formulae. The greater the uncertainty that is introduced into the analysis or the lower the r^2 value, the less likely it is that the adjustment formulae will be applied correctly. The TAC adjustment formulae considered capture the essence of this

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CHAPTER 9

In Conclusion

This Chapter summarises the key results into three broad areas, namely the assessments (Chapters 2-3), the development and implementation of OMP02 (Chapters 5-6), and wider aspects of applications of management procedures to these pilchard and anchovy resources (Chapters 7-8). This is followed by suggestions of possible future work in each of these areas to refine and improve the analyses presented. The Chapter ends with concluding remarks for the thesis as a whole.

9.1 Assessments

Pilchard

Maximum likelihood estimation indicates that the best fits of a population model to the abundance and age data are achieved for an adult natural mortality value of 0.4.year^{-1}, but provides little discrimination across values for juvenile natural mortality. This is because estimates of juvenile natural mortality and recruit survey bias are confounded. Additional information on the ratio of recruit:adult survey bias, provided by scientists responsible for acoustic surveys, is therefore used together with maximum likelihood considerations to motivate a selection of a juvenile natural mortality value of 1.0.year^{-1}.

Estimates for the additional variance associated with the recruit survey are large when the proportion-at-age estimates from the November survey are incorporated in the likelihood (λ_r^P between 0.68 and 0.88 in Table 2.4), which indicates some conflict between these estimates and the recruit survey indices. A closer examination of the proportion-at-age estimates (Table A2.2.4) reveals that they are hardly internally consistent and provide little indication of strong and weak cohorts, which may be a consequence of substantial ageing error. Despite the considerable uncertainties associated with pilchard ageing, there do nevertheless constitute consistent time-series of age information for surveys and catch data. Furthermore, the inclusion of proportion-at-age estimates from the November survey in the likelihood function contributes towards a greater contrast in values for the likelihood function across a range of values for adult natural mortality, thus providing a stronger basis for selecting a "best-fit" value for the latter.

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Anchovy

When selecting adult and juvenile natural mortalities consistent with the "best, feasible" maximum likelihood fits, juvenile natural mortalities lower than those for adults are ignored. Furthermore, both the ratio of recruit:adult survey bias and the fit to the proportion of 1-year-olds in the November surveys are used to aid this selection. A value of 0.9.year^{-1} for both juvenile and adult natural mortality is selected. When the additional variance associated with the November survey is a free parameter in the likelihood, a value of zero is estimated for the best fits, suggesting that sampling CVs for the November estimates of anchovy abundance do not overestimate the overall precision (i.e. do not underestimate overall variance) of these estimates in relation to the true abundance.

9.2 Development and implementation of OMP02

Pilchard and anchovy shoal together as juveniles, so that a bycatch of juvenile pilchard occurs in the recruit-based fishery for anchovy. This operational interaction implies a trade-off between these species, and necessitates that they are managed together. The management procedure (MP) approach provides a framework for quantifying this trade-off while ensuring that acceptable *risk* levels are not exceeded for either resource. A particular challenge when selecting a suitable trade-off for the pelagic fishery as a whole is the divergent nature of rights holders in this fishery: some have predominantly pilchard interests, and others anchovy. An externally specified trade-off decision (the ETD method) would have necessitated a compromise between these rights holders, which under the particular circumstances of allocations for 2002 (re-allocation of rights; no unique trade-off choice consistent with previous MPs) had the potential for litigation from whichever group (possibly both!) considered themselves to have been unfairly treated by the decision. A method for specifying trade-off decisions "internally" (the ITD method) was developed to solve this problem. Whereas the ETD method effectively specifies an average pilchard-anchovy catch ratio for the whole industry, calculates TAC/Bs (total allowable catches or bycatches) on the basis of this selection, and allocates quotas to each rights holder on the basis of a separate percentage right for each fishery (pilchard and anchovy), the ITD method requires that each rights holder specify a desired pilchard-anchovy ratio, and be allocated a single percentage right for the joint pilchard-anchovy fishery. It then computes quota allocations for each rights holder and sums these to provide TAC/Bs.

OMP02, the MP implemented in 2002, incorporates the ITD method partly because of concerns over litigation if the ETD method had been used, and partly because it allows rights holders the

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additional freedom of selecting average pilchard-anchovy catch ratios more suited to their needs. The use of non-linear adjustment factors ensures that allocations to individual rights holders are near-identical (on average, over time) to those derived using the ETD method[97]. Rights holders were given a one-off opportunity to revise the average desired pilchard-anchovy catch ratios specified on their original application forms. However, delays in the rights allocation process, coupled with the knowledge that the high November 2001 survey estimates would lead to a capping of the pilchard TAC for 2002, led to a greater than expected shift in the distribution of pilchard-anchovy ratios towards pilchard in this revision. This led to the implementation of a 15% cap on any increases in this ratio, phased in over two years.

The basis for managing the South African pilchard and anchovy resources is somewhat complex, and it is perhaps reasonable that arguments for adopting a simpler approach should arise. However, this complex system has evolved primarily to accommodate the flexibility necessary for the optimal utilisation of pilchard and anchovy, given the constraints imposed by the operational interaction when these species are targeted. Under a simpler, less flexible system, TACs would likely have to be kept lower to avoid undue *risk* to either of the two resources, leading to sub-optimal utilisation of these resources over time (as occurred, for example, before the introduction of the additional sub-season for anchovy).

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9.3 Wider aspects of applications of MPs

Management under regime shifts

A question that arises given the possible existence of regime shifts (assumed here to manifest sinusoid-like behaviour) is whether the performance of MPs can be improved if information about such regime cycles are taken into account, rather than simply ignoring them, when setting TACs. This problem is investigated by considering performance in terms of both the usual summary performance statistics (average catch, *risk*, interannual catch variability and resource depletion levels) and an economic sub-model that computes net present value of future profits and the proportion of years that experience negative or zero profit. Two types of estimators that provide information about regime cycles are considered, namely a 6-year running mean of the November survey estimate for pilchard, and a measurement of the actual position in the pilchard cycle (if such could be developed) which is subject to different levels of measurement error. The

[97] This aspect of near-identical results on average strictly applies only to the estimate of β for the whole fishery identical to that for OMP99 (namely $\beta = 0.1375$) - β is the proportion applied to the pilchard November survey estimate to compute the pilchard directed TAC, and will be linked to a particular value for the average pilchard-anchovy catch ratio.

MPs considered use these estimators, and reduce either anchovy catches, the initial juvenile pilchard bycatch level, or pilchard directed catches when these estimators suggest the pilchard regime cycle to be in a trough.

Perhaps a surprising result is that MPs using the 6-year running mean outperform those using a measurement of the actual position in the regime cycle in most cases; where there are gains for the latter approach (which occur only for fairly precise measurements), these would need to be judged against the feasibility and likely cost of obtaining the precise measurements necessary. Another result of interest relates to MPs that take regime cycles into account but do not take consequential action (e.g. by reducing levels of pilchard bycatch or anchovy catch) with regard to the operational interaction between pilchard and anchovy when either of the two estimators indicates the pilchard regime cycle to be in a trough. These MPs do not show improvements compared to the baseline MP that essentially ignores regime cycles. Finally, the effective management of operational interactions becomes more important for pilchard as the amplitude of regime cycles increases, to the extent that it is still possible to maintain levels of average catch and profit even though the frequency of low pilchard biomass values and no-profit situations increases with increasing regime cycle amplitude.

Incorporation of environmental indices

Environmental indices that provide short-term predictions of recruitment could in principle help to improve average yield, without simultaneously increasing *risk*, from resources that sustain recruit fisheries in cases where a measurement of recruitment is not available until after substantial fishing has taken place on this recruitment. The South African anchovy fishery fits these criteria, and therefore was used as the basis for a simulation study to investigate the benefits of incorporating environmental indices in MPs, in the face of uncertainties related to using such indices (e.g. parameter selection and estimation, and measurement error). Results indicate that an environmental index needs to explain roughly 50% or more of the total variation in recruitment ($r^2 \geq 0.5$) before the MP starts showing benefits in terms of the summary performance statistics of *risk* and/or average catch. Comparable benefits are possible at a lower r^2 when TAC constraints (such as limits on the extent of interannual TAC reductions) are removed, but there is a large associated increase in inter-annual catch variation. Further work is needed, however, because these results may be overly optimistic as to the utility of environmental indices as a result of some of the simplifying assumptions used (e.g. that the form of the recruit vs. index relationship is linear).

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9.4 Future work

Although OMP02 and its associated assessments presented major advances over OMP99 and previous assessments, there remain a number of areas where further improvements may be possible. These are listed under the three broad categories used above, and are followed by a brief discussion on priorities in the "Concluding remarks" section below.

Assessments

Pilchard ageing

Questions have arisen about pilchard ageing, which is a serious concern given the importance of age data in the pilchard assessments. Given the conflict between the recruit survey indices and proportion-at-age estimates, an analysis needs to be undertaken to check whether this results from ageing error, or whether it is a consequence of variations in pilchard somatic growth and/or natural mortality rates from year to year. Therefore:

- a thorough review of ageing is needed, including a review of the compilation of age-length keys, the sampling methods used, and the extent of within- and between-reader variability of age estimates; and
- data on length and weight should be examined to assess whether length-weight relationships are time-invariant, as is currently assumed in the assessments.

Furthermore, in terms of the assessment:

- incorporation of an ageing error matrix for the proportion-at-age estimates should be considered;
- allowance should be made for process error (i.e. interannual variability) in natural mortality; and
- a catch-at-age model that allows variation in selectivity over time should be fitted to the data – this would help address the uncertainty associated with the age composition of commercial catches.

Implications of dumping

Both the pilchard and anchovy assessments currently assume that catches are measured without error. Although this is a reasonable assumption for the South African pelagic fishery (the sampling procedures and the overall coverage of landings are such that actual landings are fairly accurately represented), unknown and variable levels of dumping are known to exist. Dumping is

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particularly a problem when pilchard bycatch allocations in the anchovy fishery are in danger of being exceeded, when fish in directed catches of pilchard are too small to can, and when operational targets (in terms of tonnage of fish landed) set by the canning factories are exceeded. Given further insight into the magnitude of this problem (through, for example, a recently introduced observer programme with wide coverage of the pelagic fleet), subsequent analyses should consider the implications of dumping.

Survey errors

Currently, November and recruit survey estimates of abundance are based on EK400 echo-sounder technology, with estimates derived by the more modern EK500 echo-sounder having to be capped to simulate the saturation experienced by the EK400 sounder, so as to provide a consistent time-series of "capped" estimates (Coetzee 1998). Work is also currently under way to identify and quantify the major sources of survey error (Hampton *et al.* 1998).

- Once a method is available to calibrate the old series to the newer technology, the "uncapped" series should be used in assessments.
- Once work on the distribution of the overall bias in the acoustic surveys is completed, this distribution should serve as a basis for placing a lower bound on the extent of additional variance. Furthermore, the results of this work should be incorporated directly into the assessment, particularly for the choice of a value for this bias when re-specifying the base case pilchard operating model.
- Furthermore, the bias in the pilchard recruit survey is potentially high and a minimum ratio of 0.5 for k_r^P / k_N^P may be rather low (Chapter 2). This is an issue that should be seen as a high priority question for the experts in the field of acoustic surveys, given the importance of the ratio k_r^P / k_N^P in the assessment.

The likelihood function

There are various ways in which the likelihood function used for parameter estimation might be improved to provide more reliable and more precise results.

- Consideration should be given to basing likelihoods for age-composition estimates and abundance indices on the "robust" formulations[98] of Fournier *et al.* (1990). These

[98] These "robust" formulations aim to retain the advantages of maximum likelihood estimation, but allow the model structure to incorporate a few large deviations from the model's hypotheses, whilst continuing to provide an adequate description of the data (Fournier *et al.* 1990).

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formulations avoid having to make modifications of an *ad hoc* nature to the likelihood, such as introducing the weighting factor in the proportions-at-age term of the pilchard likelihood to avoid giving undue importance to data based on a few samples only.

- A penalty function could be included in the likelihood to penalise ratios of recruit:adult survey bias that exceed 1. This ratio was used in the pilchard and anchovy assessments to help select a value for juvenile mortality.
- Although the total variation associated with surveys is modelled as a function of density for the robustness tests considered for pilchard and anchovy, this might be incorporated into the baseline assessments themselves for these species by allowing a component of the additional variance in the likelihood function to be inversely proportional to abundance.
- Currently, selectivity-at-age parameters associated with proportions-at-age observations are assumed to be constants equal to one in the likelihood function (i.e. the assessment assumes the survey to have uniform selectivity). However, the fit to the data suggests some model mis-specification in this respect, so that the model estimates of proportions-at-age are adjusted for systematic bias when generating bootstrap samples. Consideration should be given to replacing this approach by one in which at least some of the selectivities-at-age parameters are treated as free (i.e. estimable) parameters in the likelihood maximisation, thus avoiding the need for this adjustment in the bootstrap sample generation process.
- Spawning stock and recruitment "data" points included when fitting the stock-recruit relationship should be weighted in relation to their estimated uncertainty.
- A Bayesian approach could be adopted, whereby all operating models are integrated over their prior distributions to get a single likelihood weighted joint posterior to be used in the MP testing process. However, prior weighting of the different hypotheses would be difficult, and it may accordingly be best to check robustness to each individually.

Extending pilchard assessments back in time

The availability of annual length frequency distributions for commercial catches dating back to the 1950s, and tagging data from the 1950s and 1960s, allows for the possibility of obtaining a relatively long time series of pilchard abundance estimates using models based on length. Currently, estimates for the earlier years are based on unreliable VPA assessments, for which an age-length key from the post-mid 1960s collapse period was applied to an earlier period when growth was plausibly slower (because of higher abundance). This may prove to be useful for investigating the possible causes of the collapse of the pilchard fishery in the 1960s, and for

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relating abundance levels before the pilchard collapse to current-day levels. The latter is particularly important to provide some insight into the productive potential of the pilchard resource, and the associated implications for future yields (i.e. to provide guidance as to the extent of possible further increases in the recent high pilchard abundance levels that might be possible).

Incorporating predator index data

Data on the diet composition of pilchard and anchovy predators (such as Cape gannets *Morus capensis*) have been collected since the 1970s, and these have potential as indices of prey abundance (Crawford 1998, Hutchings *et al.* 1998). If reliable, such indices could improve assessment precision and provide backup as input into a OMPs for example when a research vessel is unable to undertake a survey. Analyses need to establish whether preference functions[99] can be estimated adequately to allow these data to be incorporated into assessments.

Other potential indices of abundance

Other data offer potential for incorporation as indices of abundance in future quantitative assessments of pilchard and anchovy, as follows.

- Pre-recruit surveys provide an early indication of the year's recruitment strength for pilchard and anchovy (van der Lingen and Merkle 1998). These surveys are conducted, typically in March, on the nursery grounds of the west coast and assess the distribution and abundance of pilchard and anchovy pre-recruits (late larvae and early juveniles) using Methot trawls and acoustic survey techniques. Pre-recruit indices of abundance are currently being developed.
- Mean monthly egg and larval abundance estimates for pilchard and anchovy are based on weekly samples of ichthyoplankton, collected along a transect cutting across the jet current off the Cape Peninsula as part of the Sardine and Anchovy Recruitment Programme (SARP; Huggett *et al.* 1998). There is concern, however, about whether these SARP surveys are sufficiently intensive to provide reasonably precise estimates.
- The daily egg production method for obtaining unbiased estimates of pilchard abundance, using a continuous underway fish egg sampler (CUFES) for estimating egg density (van der Lingen 1998), could play a similar "scaling" role (for abundance in absolute terms) in the pilchard assessments as the equivalent estimates derived for anchovy 1980s.

[99] A preference function refers to the ratio of pilchard/anchovy in the diet to the ratio of pilchard/anchovy biomass, with the additional problem that this ratio may not be constant if prey switching occurs when one of the two prey species drops to a low level.

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Management Procedures

- OMP02 may need to be revisited once current re-analyses regarding survey errors and biases (Coetzee 2001, Hampton *et al.* 2001) are completed. This is because these analyses suggest that pilchard abundance may well be greater than that assumed for most trials used in the development and testing of OMP02. If amendments to OMP02 are found to be justified, then an associated evaluation of the implications for rights holders' catches in terms of the rights allocations awarded for the 2002-2005 period would need to be undertaken.

- The operating model currently assumes that there is no uncertainty related to the split of anchovy catches amongst ages, and that this can be achieved simply be differentiating the periods before and after 1 April in the commercial catches. Allocating the catches to 0 and 1+ anchovy in this manner (i.e. purely using a fixed date, 1 April, to allocate fish caught to these age-groups) could result in large errors in fishing mortality allocated to 0 and 1+ anchovy, and should be examined. Furthermore, the possibly of including a density-dependent split in this allocation should be investigated. Allowance should also be made in the trial process for the possibility that the 1st anchovy TAC is not taken before the recruit survey (as is done for the 2nd anchovy TAC).

- The operating model should consider natural mortality values that are density-dependent and have trends over time.

- Acoustic surveys provide vital input into OMPs, but these surveys are expensive in terms of research vessel time. An analysis of how a reduction in survey intensity might affect survey sampling CVs, and in turn MP performance in terms of average catches for the same level of *risk*, should be carried out. Although this appears to be a trivial exercise, it is not because survey sampling variance is not simply inversely proportional to cost, as there are also fixed costs involved to ensure the vessel covers the complete spatial range of the survey.

- Consideration should be given to adjusting the OMP to take into account survey CVs – for example, TACs should be higher for more precise surveys. Furthermore, TAC formulae that use a combination of, say, the last three survey estimates (instead of using just the most recent one) should be investigated. Such TAC formulae have the property of smoothing out short-term "noise" and may lead to more stable TACs.

- Although current observations of record pilchard and anchovy abundance levels appear to support the hypothesis that there is no competition between these two species (an implicit

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assumption in the operating models currently used), a careful statistical analysis is needed to investigate how strongly the data support this hypothesis compared to other possibilities.

- Exceptional Circumstances do not currently consider meta-rules for "positive" exceptional circumstances (such as exceptionally high survey estimates of abundance), and these should be considered for incorporation into future revisions of OMP02.

Wider aspects of applications of MPs

Managing under regime shifts

Some aspects of the analysis of MP performance under regime shifts that require further attention are as follows.

- The behaviour of the running mean estimator for different options of the number of years included in that mean over a range of regime cycle periods.
- The effect of changing TAC constraints for both pilchard and anchovy.
- Biological interactions between the two species (such as competition).
- Incorporation of a wider range of regime cycle amplitudes.
- Comparisons of results are affected by the different numbers of peaks and troughs in the projection period under consideration caused by different choices for the regime cycle period. This should be addressed by, for example, projecting over a much longer period than 100 years, or randomising over the start of the cycle.
- Development of a more dynamic and refined version of the economic sub-model.
- Consideration of a wider range of options for regime shifts than the sinusoid curves used.
- Broadening the analysis to include different upwelling systems (i.e. other than the Benguela) and different management strategies (other than the constant proportion approach underlying the MPs applied in the South African case).

Incorporation of environmental indices

Possibilities for taking the work on incorporating environmental indices into MPs further are as follows.

- Relax some of the simplifying assumptions used in Chapter 8 (the form and stationarity assumptions of the recruit vs. index relationship, and the assumptions about serial correlation and the number of years of data available to estimate the recruit-index relationship).

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- Generalise the study to include species in other upwelling systems.
- Consider the effect of lead-time (from when the environmental index is available to when the actual recruitment measure takes place) on the potential benefits achieved when using environmental indices.
- Investigate the use of indices as longer-term indicators of regime shifts (in a manner similar to the estimators of the regime shift work in Chapter 7) rather than as short-term predictors of recruitment (as in Chapter 8).
- Investigate the simultaneous use of indices that reflect short-term and long-term environmentally-induced variability, because the short- and long-term variability co-exist and may even be caused by similar environmental factors.
- Consideration of other performance indicators (e.g. keeping average biomass high to better support natural predators).

9.5 Concluding remarks

OMP02, based on the ITD method that allows for the incorporation of average pilchard-anchovy catch ratios specified by individual rights holders to meet their particular needs, presents a unique application of the MP approach. It tackles within a single framework the issues of

- managing two dynamic resources whose associated fisheries are inter-dependent and require a trade-off decision;
- catering for a divergent industry with differing interests in the two resources; and
- incorporating uncertainty in model hypotheses and data.

In order to maintain the flexibility needed for optimal utilisation of these resources, it has evolved into a complex system, and therefore carries the danger of being "mistrusted" by those that have not fully understood its underlying rationale or what it aims to achieve. Special care will therefore need to be taken when communicating the basic features and aims of OMP02 and its associated results.

An important question raised by both the expense of the surveys and the great sophistication and demands in time and high-level expertise of the whole OMP02 approach, is whether these factors will ultimately prove to be self-destructive in a country struggling to meet enormous social and economic needs. Could there be a less sophisticated approach that would equally be able to meet the demands of the pelagic industry, and how would the cost of such an approach compare to

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OMP02? An analysis by Barange and De Oliveira (1999) showed that the value of additional landings that could be achieved on average for the same level of *risk* if information from surveys was used to set TACs in an OMP setting (instead of following a less sophisticated constant TAC policy) far outweighed the cost of these surveys (wholesale value of additional landings of over R130 million per year, compared to the cost for both surveys of roughly R2 million per year). Furthermore, the complex nature of OMP02 is motivated by the desire for optimal utilisation of the mixed-species pelagic fishery (an objective for management stated in the 1998 Marine Living Resources Act – Anon. 1998b), coupled with the need to satisfy the individual and sometimes conflicting preferences of rights holders in the fishery. A less sophisticated approach is likely to fall short in one or other of these aspects.

The most pressing concern for OMP02 is a possible revision of MP trials, with consequent modifications to OMP02 and associated implications for rights holders, which may be justified on the basis of the work currently underway regarding acoustic survey errors. This is of particular importance for pilchard, for which an assumption regarding the bias in the November survey estimates of abundance in absolute terms has to be made (unlike anchovy, for which the daily egg production method provides unbiased estimates of absolute abundance used to "scale" the November survey estimates). The (conservative) approach used for OMP02 was to assume a multiplicative bias of one, halfway between that used previously (OMP99 assumed that acoustic surveys overestimated biomass by 50%) and the provisional values indicated by the as-yet incomplete work on survey errors. A move towards the latter may imply the TAC levels for pilchard currently set by OMP02 may be overly conservative.

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The development of the daily egg production method to provide a time-series of unbiased estimates of pilchard abundance would help take some of the "heat" off the debate on an appropriate assumption for November survey bias for pilchard, because it would allow an independent estimation of this bias. The work on developing the daily egg production method for pilchard should therefore be accorded a high priority.

The assessments of Chapter 2 assume no error in the age-composition observations from the commercial catches and November surveys, and consequently interpret the conflict between the November proportions-at-age estimates and the recruit survey indices as a consequence of fairly imprecise recruit surveys. Age determination is therefore quite likely a problem in the pilchard assessments, and given its importance in these assessments, needs to undergo a thorough review, as set out under "Future work".

The existence of reasonably accurate pilchard ageing is also important from the point of view of the trade-off between pilchard and anchovy. Bycatches of juvenile pilchard resulting from the industry targeting anchovy can have a serious impact on future catches of adult pilchard. It is therefore important to obtain a reasonably accurate split between juvenile and adult pilchard in the commercial catches (which requires reliable ageing), as used in the pilchard assessment to enable an improved quantification of the pilchard-anchovy trade-off when subsequently testing MPs.

Finally, the work on alternative applications of MPs to investigate management under regime shifts, and on the utility of environmental indices, have highlighted the advantages of using the MP approach to perform these investigations. These include pursuing an investigation within the framework of the likely uncertainties to be encountered in reality, working from a "best-case" scenario (e.g. what is the best result possible given "perfect" knowledge), and investigating the utility of an approach before any decision is made to perhaps pursue a possibly costly information-gathering exercise to enable the application of this approach.

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